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ACCELERATOR PHYSICS REQUIREMENTS FOR ELECTRON COOLER AT THE EIC INJECTION ENERGY

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Abstract

An electron cooler using RF-accelerated electron beam is presently under design to provide required cooling of protons at the EIC injection energy of 24 GeV. In this paper, we describe accelerator physics requirements and design considerations of such 13 MeV electron cooler, including associated challenges.

INTRODUCTION

The Electron-Ion Collider (EIC) is a partnership project between Brookhaven National Laboratory (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) [1].

In order to achieve the design emittances of the hadron beam, hadron beams are injected into the HSR and precooled to the target emittances at injection energy of protons of 24 GeV. After the target emittances are achieved, the HSR is ramped to the collision energy, and the hadron beam is cooled during collision using high-energy cooling system. Several options of such high-energy cooling system, based on Coherent Electron Cooling (CeC) [2, 3] and on Electron Cooling using storage ring [4-6], are being considered.

Precooling of protons at 24 GeV will be done using conventional electron cooling technique which requires 13 MeV electron accelerator. The design of such a Precooler is based on RF-accelerated electron bunches, similar to LEReC [7], but scaled to higher energy. The Precooler energy can be extended to 22 MeV to provide cooling of protons at collision energy of 41 GeV.

COOLER REQUIREMENTS

The Precooler design is based on the non-magnetized cooling approach with zero magnetic field on the cathode and no magnetic field in the cooling region [7].

The friction force acting on the ion with charge number Z inside a non-magnetized electron beam with velocity distribution function $f(v_e)$ is

$$\vec{F} = -\frac{\bullet \pi n_e e^{\bullet} Z^{\bullet}}{m} \int \bullet\bullet \left(\frac{\rho_{\bullet\bullet\bullet}}{\rho_{\bullet\bullet}}\right) \frac{\vec{V}_i - \vec{v}_e}{\left|\vec{V}_i - \vec{v}_e\right|^{\bullet}} f \bullet v_e \bullet d^{\bullet} v_e, \quad (1)$$

where e and m are the electron charge and mass, V and v_e are the ion and electron velocities respectively, and n_e is electron density in the particle rest frame (PRF).

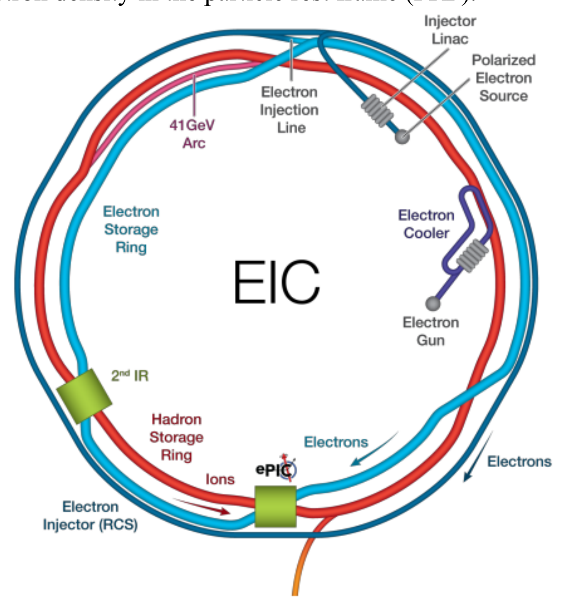

Figure 1: The layout of the Electron-Ion Collider (EIC). The Hadron Storage Ring (HSR), Electron Storage Ring (ESR), and the Rapid Cycling Synchrotron (RCS) labels are color-coded to their respective rings; the current and proposed IRs are shown at IR6 and IR8, with both Precooler and high-energy cooling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

As cooling of protons (Z=1) is the most challenging task compared to cooling of heavy ions, in this report we focus on cooler parameters considering only proton beams.

To maximize the cooling power and to preserve transverse distribution of hadrons under cooling, the electron beam rms velocity spreads are chosen close to those of the hadron beam. At injection energy in the EIC with γ=25.4, the proton beam with bunch intensities N=2.8×10^{11} will have rms longitudinal momentum spread of about σ_p=5-6$\times10^{-4}$. This sets the requirement for the rms momentum spread of electron beam < 5×10^{-4}. For the rms normalized emittance of the proton beam around 2 μm and 200 m beta function in the cooling section, the hadron beam rms angular spread in the lab frame is 0.02 mrad. This gives the requirement for the electrons angular spread θ in the cooling section around 0.02 mrad (as presented in Table 1).

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Table 1: Electron Beam Parameters in the Cooling Section

Electrons kinetic energy, MeV	12.5
Charge per single electron bunch, nC	1.3-2
Number of bunches in macrobunch	2-3
Total charge in macrobunch, nC	4
Average current, mA	98
RMS normalized emittance, μm	< 1.5
Angular spread, μrad	< 25
RMS energy spread	$<5 \times 10^{-4}$
RMS bunch length, cm	5
Beta function, m	150
Length of cooling sections, m	120

With the friction force maximum being located close to the longitudinal rms velocity spread of the electrons, one gets a requirement for matching electron and beam energies to better than the rms velocity spread, which for our parameters is about 3×10^{-4}. Energy stability of the electron beam should be better than this, at about 1×10^{-4} rms.

The largest contributions to the angles in the cooling section come from the electron beam emittance and the space charge of electron and proton beams. In addition, to keep the transverse angle of the electron beam trajectory <10 μrad an integral of residual transverse magnetic field in cooling region should be kept below 1 Gauss·cm. A shielding of residual magnetic field to such level will be provided by several concentric cylindrical layers of high permeability alloy [8]. Some cooling section space will be taken up by short solenoids (to control angular spread due to the transverse space charge of electron beam), steering dipoles and beam position monitors to keep the electron and ion beam in close relative alignment.

In simulations shown in Fig. 2, we assumed the total angular spread of the electrons in the cooling section to be 20 μrad. Both horizontal and vertical emittances are being cooled to slightly different values due to different IBS rates in the two planes. For IBS calculations we assumed single harmonic RF with Gaussian protons bunches and uncoupled betatron motion so that IBS in the vertical plane is minimized. Presently, a plan is to provide cooling in both transverse planes simultaneously until lifetime of cooled protons becomes affected by the space charge. The cooled proton beam with small emittances in both planes will then be accelerated to the top energy at which the horizontal emittance can be increased to a required level.

The goal of precooling is to provide strong cooling in the vertical plane only. Using 24.6 MHz RF for protons at injection energy allows us to have long bunch length, around 0.8 m rms. However, even for long proton bunches, the space charge for the protons could become very large due to cooling of beam emittances which would affect protons lifetime.

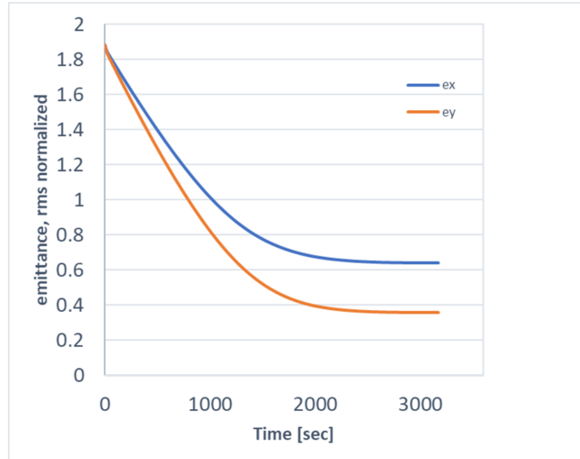

Figure 2: Cooling of protons at γ=25.4, with decoupled transverse motion (simulations with IBS, using single harmonic RF, and cooling only). Horizontal emittance (top curve, blue) and vertical emittance (bottom curve, orange).

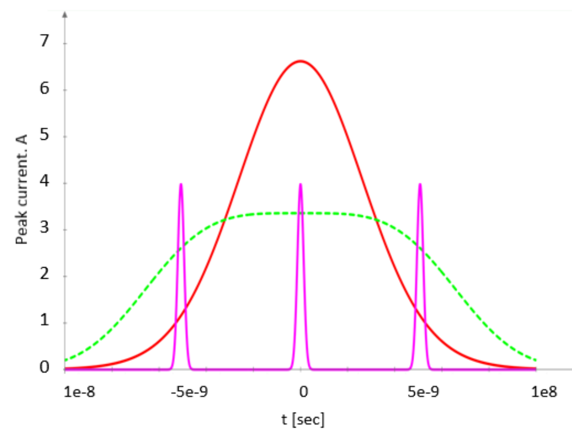

Figure 3: Three electron bunches (magenta) spaced by 5.1 ns placed on a single proton bunch (red: single RF harmonic; green: double RF harmonic).

To mitigate space-charge effects during cooling, one can provide heating of emittance in the horizontal plane while cooling in the vertical plane, however this will slow down vertical cooling due to large horizontal angles [9]. Instead, space charge for cooled protons bunches could be alleviated using second harmonic RF which allows us to produce flattened distribution of proton bunches (green curve in Fig. 3) with peak current reduced by a factor of two compared to a single harmonic RF (red curve in Fig. 3). A similar approach was used during RHIC operation at low energies with electron cooler LEReC [10]. With the second harmonic RF (peak current of 3.35 A) for proton beam emittances at the end of cooling shown in Fig. 2, space-charge tune shifts for proton beam are estimated to be 0.06 and 0.11, for the horizontal and vertical planes, respectively. For flattened protons bunches with second harmonic RF, IBS will be reduced as well due to reduced peak current. As a result, one should be able to provide even stronger cooling than shown in Fig. 2 (where single harmonic RF was assumed) if the space charge of protons bunches can be mitigated further.

ELECTRON ACCELERATOR

Electron beam will be generated by illuminating a multi-alkali CsK_2Sb photocathode with green light (532 nm) from a laser. The photocathode is inserted into a DC gun with design operational voltage of around 400 kV. The 197 MHz laser will produce bunch trains with individual electron bunches of about 500 ps full length at 24.6 MHz bunch train repetition frequency. The bunch train repetition rate will be the same as the repetition rate of proton bunches in the HSR at injection energy.

After the gun, an electron beam is first accelerated in 3 MeV injector and then merged into the 197 MHz linac and accelerated to final energy of 13 MeV. Simulations of electron beam dynamics show that required electron beam parameters can be obtained at the end of 13 MeV linac for electron bunches with 2 nC charge, Figs. 4-5.

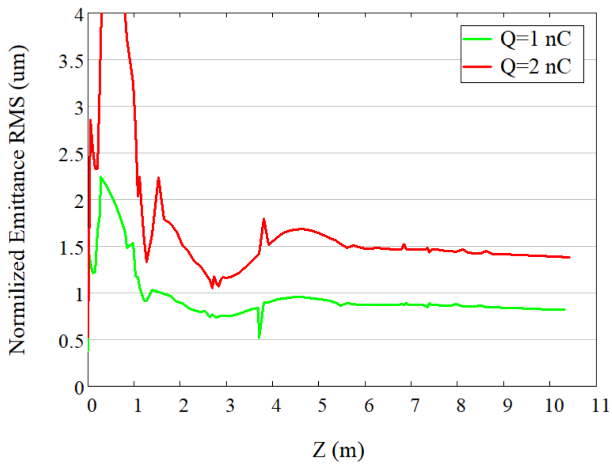

Figure 4: Simulated emittance for electron bunch charges of 1 and 2 nC at the end of 13 MeV linac.

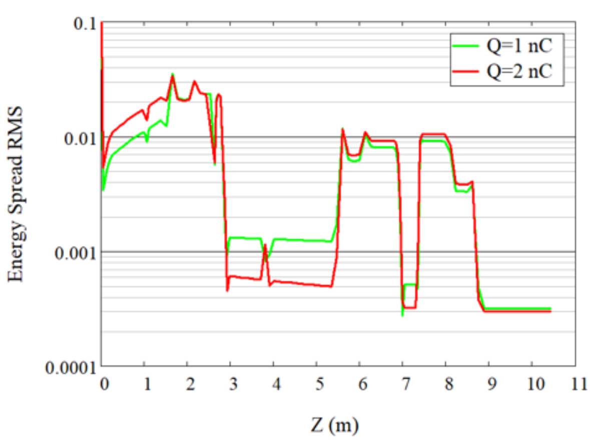

Figure 5: Simulated energy spread for electron bunch charges of 1 and 2 nC at the end of 13 MeV linac.

The 197 MHz repetition rate of electron bunches, corresponding to 5.1 ns spacing, allows us to place either two electron bunches with 2 nC charge each or three electron bunches with 1.33 nC charge (as shown in Fig. 3) on a single proton bunch to provide total required charge of electrons of 4 nC per proton bunch. Simulations shown in Figs. 4-5 include main 197 MHz RF and 3^{rd} harmonic RF for energy correction. Adding higher RF harmonic cavity (9^{th} harmonic of 197 MHz) could allow us to operate with longer electron bunches and achieve even better electron beam parameters. The corresponding optimization is presently in progress.

After acceleration to 13 MeV, an electron beam is transported to the first cooling section in the HSR ring, cools protons in the first cooling section, separated from hadrons after the first cooling section to bypass hadron beam chicane (required for high-energy cooler based on the CeC), transported and merged again with the protons in the second cooling sections, turned around and transported to the beam dump. Present integration of injection energy Precooler with high-energy cooler based on the CeC is reported in [11].

Design of electron beam optics in the mergers and cooling sections is ongoing and aims to provide largest space available for effective cooling and to minimize contribution to electron angles from the space charge of electrons.

CHALLENGES

Presently, maximum available space for the cooling sections is limited to about 120 m total length due to integration of Precooler with the high-energy cooler based on the CeC approach. This requires CW operation of Precooler electron accelerator with high beam current of up to 98 mA. If length of cooling section can be increased, for example to 180 m, as in the design assumed in [4-6], required current for Precooler can be decreased to about 65 mA.

The easiest operation of Precooler would be similar to LEReC, sending electron beam after cooling sections directly to a beam dump without energy recovery. If electron beam, after interaction with protons in two cooling sections and with resulting large tails in beam distribution due to the space charge, needs to go through return beam line for energy recovery in the linac, it would require special consideration of collimation of the tails of beam distribution.

The attainment of required low energy spread in the electron bunch relies on RF gymnastics. A tight requirement on impedance budget requires detailed wake fields simulations and special design of every vacuum element including instrumentation devices. The repeatability of low energy electron transport is challenging due to remnant fields in the optics and hardware. Quality of electron beam should be preserved through the entire beam transport since the same beam will be used in two cooling sections of the HSR.

The achievement of very low transverse angular spread for the electron beam should be addressed by a proper beam transport and engineering design of the cooling sections. The required electron angles in cooling section are about factor of five smaller than achieved in LEReC.

Integration of 13 MeV Precooler with high-energy cooler based on the CeC approach adds additional constraints: 1) limited space for effective cooling, 2) additional merges and optics matching section due to split into two separate cooling sections, 3) finding proper solution for mu-metal shielding of cooling sections with many magnetic elements. These challenges are presently being addressed by optimization of Precooler and high-energy cooler parameters.

SUMMARY

Electron cooler based on the RF acceleration of electron bunches is being developed to provide cooling of protons at the EIC injection energy of 24 GeV. Various challenges are being addressed by a proper physics and engineering design.

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REFERENCES

[1] C. Montag *et al.,* "Design status of the Electron-Ion Collider", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 136-139. doi:10.18429/JACoW-IPAC2023-MOPA049J

[2] 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

[3] 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

[4] H. Zhao, J. Kewisch, M. Blaskiewicz, and A. Fedotov, "Ring-based electron cooler for high energy beam cooling", *Phys. Rev. Accel. Beams* 24, 043501, 2021. doi:10.1103/PhysRevAccelBeams.24.043501

[5] J. Kewisch et al., "Optics for an electron cooler for the EIC based on electron storage ring", presented at FLS'23, Luzern, Switzerland, Aug. 2023, paper WE4P24, to be published.

[6] S. Seletskiy, A. Fedotov, J. Kewisch, "Parameters optimization for EIC ring cooler", presented at COOL'23, Montreux, Switzerland, Oct. 2023, paper WEPAM1R1, this conference.

[7] A.V. Fedotov *et al.,* "Accelerator Physics Design Requirements and Challenges of RF Based Electron Cooler LEReC", in *Proc. NAPAC'16*, Chicago, IL, USA, Oct. 2016, pp. 867–869. doi:10.18429/JACoW-NAPAC2016-WEA4CO05

[8] S. Seletskiy *et al.,* "Magnetic Shielding of LEReC Cooling Section", in *Proc. NAPAC'16*, Chicago, IL, USA, Oct. 2016, pp. 1030–1032. doi:10.18429/JACoW-NAPAC2016-WEPOB61

[9] S. Seletskiy and A. Fedotov, "Explicit expressions for non-magnetized bunched electron cooling", presented at COOL'23, Montreux, Switzerland, Oct. 2023, paper THPOSRP04, this conference.

[10] C. Liu *et al.*, "Gold-gold luminosity increase in RHIC for a beam energy scan with colliding beam energies extending below the nominal injection energy", *Phys. Rev. Accel. Beams*, vol. 25, p. 051001, May 2022. doi:10.1103/PhysRevAccelBeams.25.051001

[11] K.E. Deitrick *et al.*, "Development of an ERL for coherent electron cooling at the Electron-Ion Collider", presented at COOL'23, Montreux, Switzerland, Oct. 2023, paper THPOSRP17, this conference.