

# ACCELERATOR PHYSICS REQUIREMENTS AND CHALLENGES OF RF BASED ELECTRON COOLER FOR EIC INJECTION ENERGY\*

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## Abstract

Cooling of hadrons in Electron Ion Collider (EIC) at the injection energy is critical to achieving EIC design parameters. A 13 MeV electron cooler fit for the task is presently under design. This cooler will use RF-accelerated electron bunches and will provide strong cooling of the hadrons having energy of 24 GeV/nucleon. The paper describes optimization of the cooling performance, taking into account space charge, IBS and other effects, and provides physics requirements for the cooler.

## 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 in the Electron Storage Ring (ESR) [1].

In order to achieve the design emittances of the hadron beam, hadron beams are injected into the HSR and cooled to the target emittances at injection energy of protons of 23.8 GeV. After the target emittances are achieved, the HSR is ramped to the collision energy.

Cooling of protons at 23.8 GeV will be done using conventional electron cooling technique which requires 13 MeV electron accelerator. The design of such Low-Energy Cooler (LEC) is based on the RF-accelerated electron bunches, similar to the LEReC [2] approach, but scaled to higher energy.

## COOLER REQUIREMENTS

The LEC design is based on the non-magnetized cooling approach with zero magnetic field on the cathode and no magnetic field in the cooling region [2]. The layout of the LEC accelerator is shown in Fig. 2.

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

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{\vec{V}_i - \vec{v}_e}{|\vec{V}_i - \vec{v}_e|^3} f(v_e) d^3 v_e \quad , \quad (1)$$

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).

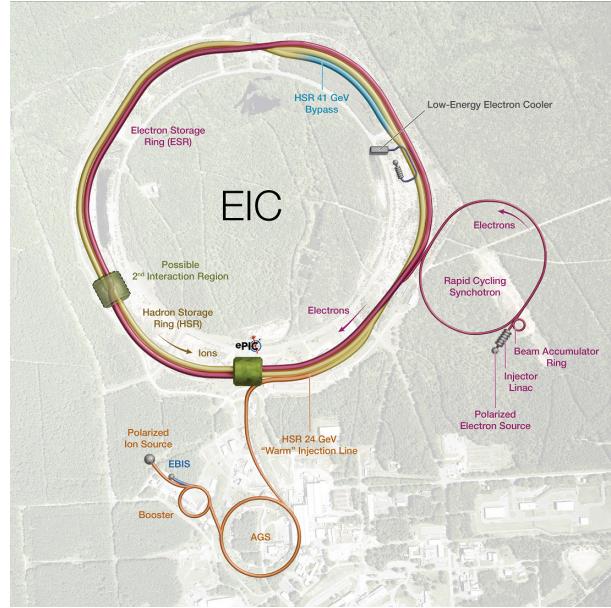


Figure 1: The layout of the Electron-Ion Collider (EIC). The Hadron Storage Ring (HSR), Electron Storage Ring (ESR), and the Rapid Cycling Synchrotron (RCS) labels are color-coded to their respective rings; the current and proposed IRs are shown at IR6 and IR8, with the Low-Energy Cooling (LEC) system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

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  $\gamma=25.4$ , the proton beam with bunch intensities  $N=2.8\times 10^{11}$  will have rms longitudinal momentum spread of about  $\sigma_p=7\times 10^{-4}$ . The requirement for the rms momentum spread of electron beam are  $< 4\times 10^{-4}$ . For the rms normalized emittance of the proton beam around  $2 \mu\text{m}$  and  $150 \text{ m}$  minimum beta function in the cooling section, the hadron beam rms angular spread in the lab frame is  $0.023 \text{ mrad}$ . This gives the requirement for the total electrons angular spread in the cooling section to be around  $0.025 \text{ mrad}$ .

The total angular spread of electrons in the cooling section has several contributions, with the dominant contributions coming from electron beam emittance and electron beam space charge. As a result, special efforts are being made to develop proper electron beam transport to and through the cooling section to ensure that requirements on angular spread are satisfied.

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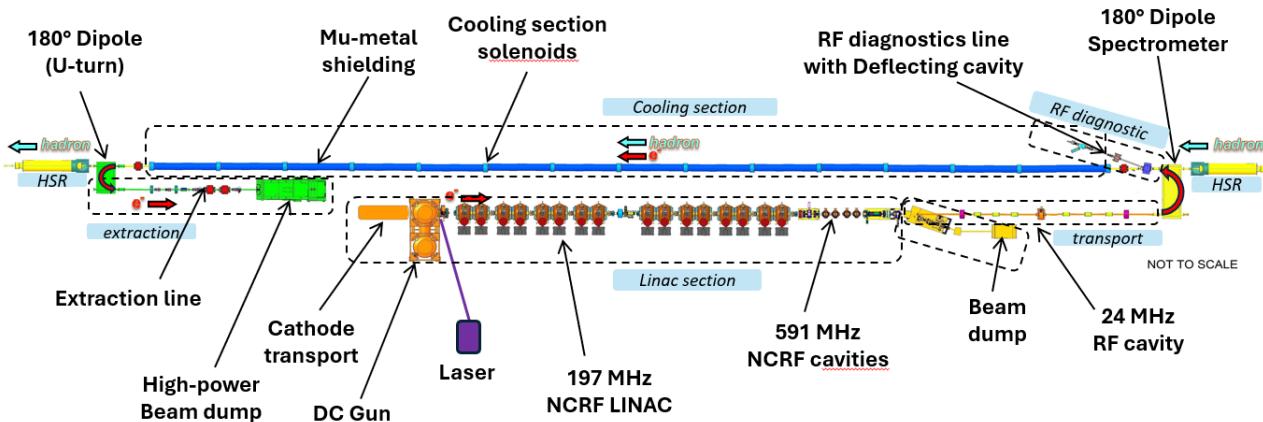


Figure 2: Layout of the LEC accelerator (not to scale).

Table 1: Electron Beam Parameters in the Cooling Section

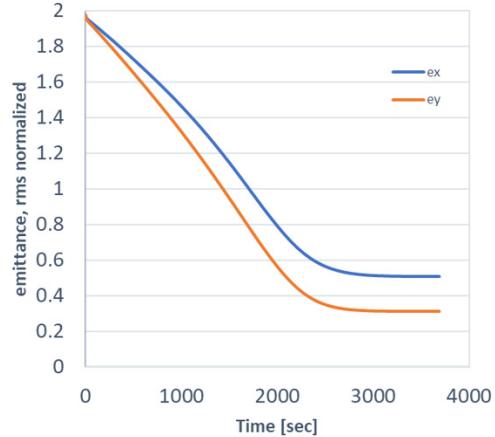
|   |                      |
|---|----------------------|
| Relativistic gamma                        | 25.38                |
| Charge per single electron bunch, nC      | 1.0                  |
| Number of bunches in macrobunch           | 3                    |
| Total charge in macrobunch, nC            | 3                    |
| Average current, mA                       | 74                   |
| RMS normalized emittance, $\mu\text{rad}$ | < 1.5                |
| Angular spread, $\mu\text{rad}$           | < 25                 |
| RMS energy spread                         | $< 4 \times 10^{-4}$ |
| RMS bunch length, cm                      | 4                    |
| Beta function, m                          | 150                  |
| Length of cooling sections, m             | 160                  |

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  $3 \times 10^{-4}$ . Energy stability of the electron beam should be better than this, at about  $1 \times 10^{-4}$  rms. See all parameters in Table 1.

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  $< 10 \mu\text{rad}$  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 [3]. 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. 3, we assumed the total angular spread of the electrons in the cooling section to be

$25 \mu\text{rad}$ . Both horizontal and vertical emittances are being cooled to slightly different values due to different IBS rates in the two planes. For optimum cooling performance, cooling should be provided in both transverse planes simultaneously, because the vertical cooling rate is affected by the horizontal angles as well. However, if stability of such cooled proton bunches becomes a problem one can provide heating of the horizontal emittance while cooling vertically, as the goal of the LEC is to achieve small emittance in the vertical plane only.

Figure 3: Cooling of protons at  $\gamma=25.38$ , with decoupled transverse motion. Horizontal emittance (top curve, blue) and vertical emittance (bottom curve, orange).

Using 24.6 MHz RF for protons at injection energy allows us to have long bunch length around 1.0 m rms. However, even for long proton bunches, the space charge for the protons can become very large due to cooling of beam emittances which would affect protons lifetime. To mitigate space-charge effects during cooling the second harmonic RF will be used to produce flattened distribution of proton bunches (green curve in Fig. 4) with peak current reduced by about factor of two compared to a single harmonic RF (orange curve in Fig. 4). With the second harmonic RF and emittances at the end of cooling shown in Fig. 3, space-charge tune shifts for proton beam are

estimated to be 0.06 and 0.11, for the horizontal and vertical planes, respectively.

The 197 MHz repetition rate of electron bunches, corresponding to 5.1 ns spacing, allows us to place three electron bunches with 1.0 nC charge each (as shown in Fig. 4) on a single proton bunch to provide total required charge of electrons of 3 nC per proton bunch.

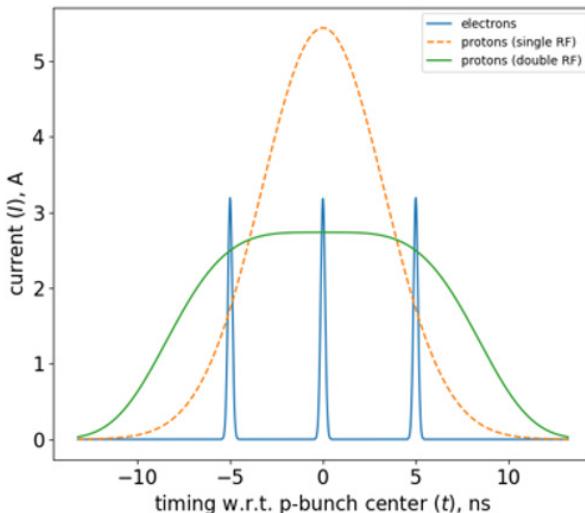


Figure 4: Three electron bunches (blue) spaced by 5.1 ns placed on a single proton bunch (orange dashed line: single RF harmonic; green solid line: double RF harmonic).

## ELECTRON ACCELERATOR

Electron beam will be generated by illuminating a multi-alkali CsK<sub>2</sub>Sb 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 400 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 accelerated in the 197 MHz linac to the final kinetic energy of 12.46 MeV. The 3<sup>rd</sup> harmonic RF cavities are used for energy correction. An additional 24.6 MHz RF cavity is used to correct energy spread due to the beam-loading for the macro-bunch of electrons which consists of three electron bunches separated by 5.1 ns. Main parameters of electron accelerator are given in Table 2.

After acceleration to 12.46 MeV kinetic energy, an electron beam is transported to the cooling section in the HSR ring, merged with proton beam, cools protons by propagating together over 160 m of cooling section, turned around and transported to the high-power beam dump.

Simulations of electron beam dynamics show that required electron beam parameters can be achieved with sufficient safety margin. The design of electron beam optics in the transport and cooling section aims to provide largest space available for effective cooling and to minimize contributions to the electron angles.

Table 2: Parameters of Electron Accelerator

|                                       |       |
|---------------------------------------|-------|
| DC gun voltage, kV                    | 400   |
| Final electron kinetic energy, MeV    | 12.46 |
| Laser repetition frequency, MHz       | 197   |
| Bunch train repetition frequency, MHz | 24.6  |
| Main RF frequency, MHz                | 197   |
| Number of 197MHz NCRF cavities        | 17    |
| Voltage per 197MHz RF cavity, kV      | 850   |
| Energy correction RF frequency, MHz   | 591   |
| Voltage per 591MHz cavity, kV         | 380   |
| Number of 591MHz cavities             | 4     |
| Number of 591MHz deflecting cavities  | 1     |
| Voltage of deflecting cavity, kV      | 150   |
| Number of 24.6MHz cavities            | 1     |
| Voltage of 24.6MHz cavity, kV         | 10    |
| Average electron current, mA          | 74    |
| Final beam dump power, kW             | 922   |

## CHALLENGES

Stable long-term operation of the gun with 74 mA average current is challenging. An ongoing R&D is presently underway to establish such operation.

Extracting 12.46 MeV electron beam with 74 mA current requires 922 kW beam dump. Spreading of electron beam inside such beam dump requires special consideration.

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. Quality of electron beam should be preserved through the entire beam transport and long cooling section.

The achievement of very low transverse angular spread for the electron beam should be addressed by a proper beam transport and design of the cooling sections. The required electron angles in cooling section are about factor of five smaller than achieved in LEReC [4], which sets strict requirements on the design of the cooling section.

## SUMMARY

Electron cooler based on the RF acceleration of electron bunches is being developed to provide strong cooling of protons at the EIC injection energy of 23.8 GeV. Various challenges are being addressed by a proper physics and engineering design.

## ACKNOWLEDGMENTS

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