

DESIGN OF RING ELECTRON COOLER *

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Abstract

Electron cooling at high energy requires large average current in the cooling section (CS), which can be achieved by reusing the same electron beam on many passes through the CS. One of the options to realize this cooling scheme is to use an electron storage ring. In this paper we describe a conceptual design of the Ring Electron Cooler (REC), as a potential future application for the Electron Ion Collider. The REC uses 150 MeV electrons to cool protons in hadron ring while electrons themselves are being cooled by radiation damping wigglers installed in electron storage ring. Design of the REC considers electrons' space charge, an effect of proton-electron focusing, a beam-beam scattering in the CS and electrons' intra-beam scattering in the storage ring, as well as other collective effects. In this paper we discuss the status of the REC design and describe multiparametric optimization involved in the design efforts.

INTRODUCTION

Cooling of protons in the Electron Ion Collider (EIC) [1] at top energy ($\gamma = 273$) to counteract the IBS-driven emittance growth will be beneficial to the EIC performance. Electron Cooling [2] can provide such a capability.

Expanding electron cooling to the high energies requires substantial electron current in the cooling section. To relax requirements to an injector, one can reuse the same electron beam on multiple turns. In this paper we consider a multi-turn electron cooling based on the Ring Electron Cooler.

Electron bunches, used in the REC, are stored in a dedicated storage ring, and the same e-bunches are reused for the cooling on multiple turns. The electrons' emittances are preserved during the storage cycle by counteracting heating caused by various scattering mechanisms with radiation damping facilitated by dedicated damping wigglers.

The REC utilizes a non-magnetized RF-based electron cooling, which was successfully applied at LEReC [3-6] during RHIC operation in 2019-2021 runs.

RING ELECTRON COOLER

The Ring Electron Cooler is located in the IR2 region of the EIC Hadron Storage Ring sharing the cooling section with the EIC Low Energy Cooler (LEC) [7].

While the LEC “precools” the protons at the injection energy to the design emittances (Table 1), the REC's preserves the emittances at the collision energy by providing horizontal and longitudinal cooling times of 2 and 3 hours respectively.

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REC Layout and Lattice

The REC layout is shown in Fig. 1. The REC lattice is shown in Fig. 2.

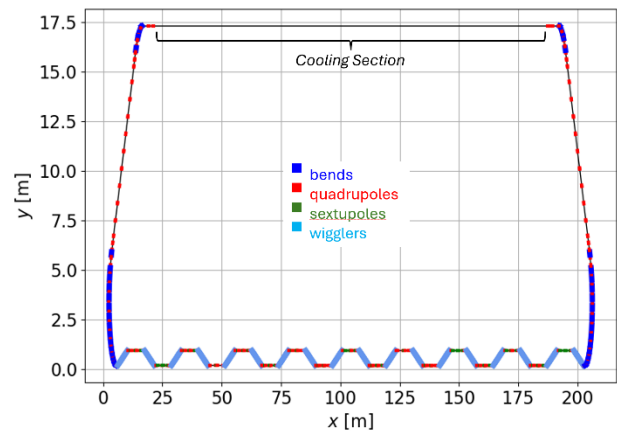


Figure 1: The Ring Electron Cooler layout.

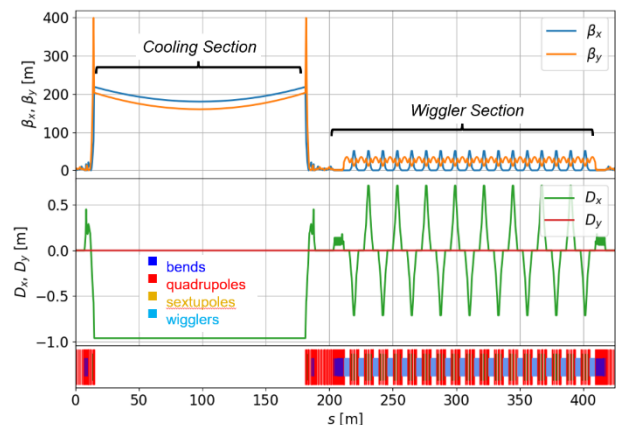


Figure 2: The Ring Electron Cooler lattice.

The REC includes a 170 m long cooling section shielded by several layers of μ -metal. The BPMs and correctors are located every 12 m in the CS.

Opposite to the cooling section there is a wiggler section containing 18 damping wigglers. The wigglers must provide enough radiation cooling of the electron bunches to counteract the effects of the IBS and beam-beam scattering (BBS) of electrons on protons in the CS.

The arcs connecting the wiggler section and the CS contain 10 m long straight sections with adjustable optics suitable for placement of the REC injection and RF systems.

REC Parameters

The REC parameters are listed in Tables 1 and 2.

Table 1: The REC Parameters (Protons in the CS)

| Parameter | Value | Units |
|-----------------------------|---------------------|-------|
| Relativistic γ | 293 | |
| Protons per bunch | $6.9 \cdot 10^{10}$ | |
| Geometric emittance (x,y) | 11.3, 1 | nm |
| Relative momentum spread | $6 \cdot 10^{-4}$ | |
| rms bunch length | 6 | cm |
| CS β -function (x,y) | 300, 700 | m |
| Horizontal dispersion in CS | 2.1 | m |
| Cooling time (x,y,z) | 2, 4, 3 | hrs |

Table 2: The REC Parameters (Electron Storage Ring)

| Parameter | Value | Units |
|-------------------------------------|----------------------|-----------------|
| Relativistic γ | 293 | |
| Ring Circumference | 426 | m |
| CS length | 180 | m |
| Horizontal dispersion in CS | 1 | m |
| CS β -function (x,y) | 180, 160 | m |
| Momentum compaction | $-1.5 \cdot 10^{-3}$ | |
| Geometric emittance (x,y) | 7.8, 7.8 | nm |
| Relative momentum spread | $9.8 \cdot 10^{-4}$ | |
| FWHM bunch length | 34 | cm |
| Charge per bunch | 21 | nC |
| Peak current | 17.5 | A |
| Number of bunches | 140 | |
| Average current | 2 | A |
| Space charge tune shift x/y | 0.14, 0.14 | |
| Beam-beam parameter x/y | 0.04, 0.09 | |
| Number of wigglers | 18 | |
| Wiggler field | 2.4 | T |
| Wiggler length | 4.2 | m |
| Wiggler gap | 2 | cm |
| Wiggler period | 23 | cm |
| Damping rate (x,y,z) | 31, 31, 62 | s ⁻¹ |
| IBS rate (x,y,z) | 31, 31, 48 | s ⁻¹ |
| BBS rate (x,y,z) | 0.8, -0.3, 12 | s ⁻¹ |
| Main RF frequency | 98.6 | MHz |
| Main RF voltage | 50 | kV |
| 2 nd harmonic RF voltage | 25 | kV |

Following sections explain various aspects of obtaining the REC parameters. More details can be found in [8].

COOLING OPTIMIZATION

The exact formulas used to calculate and optimize the REC cooling rates are given in [8]. Here, we give a rough scaling relations between the rate and beam parameters:

$$\lambda \propto \frac{N_e L_{CS}}{\gamma^2 \left(\frac{\varepsilon_{ne}}{\beta_e} + \frac{\varepsilon_{ni}}{\beta_i} \right) (\varepsilon_{ne} \beta_e + \varepsilon_{ni} \beta_i) \sqrt{\sigma_{\delta e}^2 + \sigma_{\delta i}^2} \sqrt{\sigma_{ze}^2 + \sigma_{zi}^2}} \quad (1)$$

While cooling rate drops quadratically with beam energy, it grows linearly with number of electrons N_e and length of the cooling section L_{CS} . Smaller ion emittance ε_{ni} , energy spread $\sigma_{\delta i}$ and bunch length σ_{zi} , as well as smaller e-bunch phase space volume (defined by its emittance ε_{ne} , energy spread $\sigma_{\delta e}$ and length σ_{ze}), farther increase the cooling rate.

The proton bunch parameters are defined by the EIC design and are obtained by the LEC.

Electron bunch parameters in the REC are determined by an equilibrium between the radiation damping rate (λ_{damp}) and the overall heating rate characterized by the IBS rate (λ_{IBS}), the BBS rate (λ_{BBS}), and quantum excitations ($C_q = \lambda_{damp} \varepsilon_{nat}$), where ε_{nat} is a natural emittance:

$$\frac{d\varepsilon}{dt} = (-\lambda_{damp} + \lambda_{IBS} + \lambda_{BBS})\varepsilon + C_q \quad (2)$$

A dedicated code [9] based on solving Eq. (2) was created to find equilibrium electron beam parameters. The details of relevant calculations can be found in [8, 10, 11].

Optimal cooling requires redistribution of cooling decrements between longitudinal and horizontal directions. This is achieved by introducing electron and proton horizontal dispersions in the REC CS [8, 12].

An iterative multiparametric optimization of cooling in the REC comprises the following steps:

- Choosing field profile of damping wigglers.
- Solving Eq. (2) for equilibrium parameters.
- Choosing e- and p-bunches parameters in the CS.
- Checking resulting cooling rates, BBS rate and beam-beam effect and beam lifetime.
- Optimizing the REC dynamic and momentum apertures and adjusting the REC lattice.

An example of one of the steps on a final iteration is demonstrated in Fig. 3. Here, the electron bunch β -functions and horizontal dispersion in the CS are kept constant, the longitudinal cooling time is kept at $\tau_z = 3$ hours and for each combination of ions β -functions the horizontal cooling time is minimized by varying ions' horizontal dispersion (D_i) in the CS.

After each iteration the equilibrium e-beam parameters were recalculated and the beam-beam effect on electrons' emittance [13] was checked.

The red dot in Fig. 3 shows the choice of protons Twiss parameters which maximize the cooling rate while keeping tolerable BBS rate and beam-beam effect.

Optimization of dynamic and momentum apertures is discussed in detail in [14]. The optimization includes choosing a proper field profile for damping wigglers, fine-tuning a phase advance over the "wiggler-sextupoles blocks", using two families of octupoles to reduce the

nonlinear motion, and adjusting the betatron tunes. The resulting apertures of $A_x = 10\sigma_x$, $A_y = 9\sigma_y$, and $A_\delta = 0.5\%$ are shown in Fig. 4.

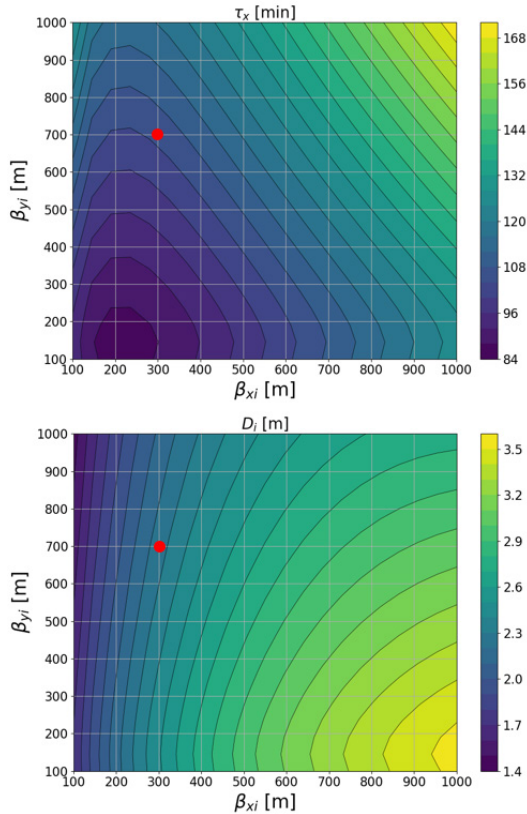


Figure 3: Optimization of protons parameters in the REC cooling section.

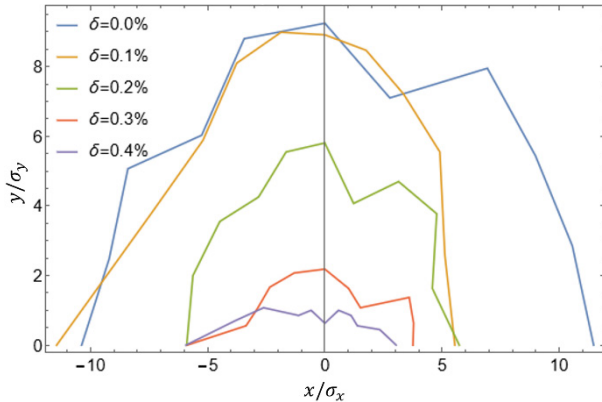


Figure 4: Dynamic aperture at various relative momenta.

REC SYSTEMS

Damping Wigglers

The wigglers parameters are listed in Table 1. The wigglers are inclined with respect to the axis of the wiggling section with an angle alternating in sign. This design produces dispersion in between the wigglers, which allows placing sextupoles for controlling chromatic effect.

Wigglers have small D_x and large D'_x . Thus, keeping small $\beta_x = 30$ cm allows to minimize H -function, respectively minimizing the IBS-driven emittance growth.

A proper choice of wiggler field profile allowed us to minimize their contribution to the REC chromaticity.

Details of the wigglers design are given in [8, 15, 16].

RF System

The REC is utilizing a double RF system. Its main parameters are given in Table 1.

The REC RF produces a flat-top electron bunch, thus reducing its peak current and limiting the space charge effects. Simulations of beam dynamics with the REC double RF are described in [8].

Injection System

The REC uses a top-off injection with a pulsed septum delivering the injected beam, and a closed four-bump fast kick moving the stored beam closer to the injected one. The parameters of the injection magnets are listed in Table 3.

Table 3: The REC Injection System

| Parameter | Kicker | Septum |
|------------------------|-----------|--------|
| Maximum field [G] | 760 | 7000 |
| Magnetic length [m] | 0.2 | 0.38 |
| Pulse shape | trapezoid | sin |
| Rise/fall time [ns] | 200 | N/A |
| Flat-top duration [ns] | 284 | N/A |
| Wavelength [us] | N/A | 200 |
| Repetition rate [Hz] | 3-5 | |

The injection time structure is driven by the beam lifetime, which is defined by the elastic scattering and is equal to 16.2 s (for 0.5 nTorr residual gas pressure). The top-off injection will be done into 1/5 of the ring with 3 Hz frequency. The initial injection has a 5 Hz frequency. The injector provides trains of 100 MHz 28 bunches with charge of 1.75 pC per bunch.

CONCLUSION

The Ring Electron Cooler is designed to provide the cooling required for the EIC operation at the top energy.

Optimization of the REC parameters allowed us to reduce the bunch charge and average current by a factor of 2.3 as compared to [9], which helps with the collective effects significantly.

The realistic lattice for the REC compatible with the EIC Low Energy Cooler was developed and optimized. The damping wigglers with realistic fields and optimized chromaticity contribution were developed. The conceptual design of the injection system was devised.

A detailed study of collective effects in the REC is left for future work.

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