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ELECTRON COOLING FOR FUTURE HIGH-ENERGY HADRON ACCELERATORS*

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Abstract

Electron cooling is an important method to reduce the emittance and momentum spread of hadron beams, and it has been successfully applied in several facilities around the world. In 2019, the world's first RF-based electron cooler (LEReC) was commissioned at BNL for the RHIC BES-II project, and the integrated luminosity of RHIC is finally doubled. In addition, electron cooling is also a must for the future Electron-Ion Collider (BNL EIC). However, the high energy requirement of the electron beam (150 MeV) is far beyond what all present coolers can achieve (<4.3 MeV). For that, an electron ring cooler with strong radiation damping is proposed and designed, in which the non-magnetized and dispersive cooling techniques are applied. In this paper, I will introduce the physical design and some important considerations of the ring cooler.

INTRODUCTION

Electron cooling is a powerful method to shrink the size and momentum spread of the stored ion beams for accumulation and high-precision experiments. Since it was first proposed by G. I. Budker in 1967, this technique has been widely applied and developed in many heavy ion accelerators around the world [1, 2]. With the development of particle accelerators and the higher requirements for experimental physics, beam cooling with much higher energy electron beam is demanded.

Up to now, all electron coolers built around the world are based on dc electron beams, which are accelerated by electrostatic fields. The highest-energy electron cooling system with 4.3 MeV electrons has been successfully constructed and operated at Fermi National Accelerator Laboratory in 2005 [3]. Recently, the world's first rf-based electron cooler is successfully commissioned at BNL and the cooling of gold beams in RHIC by 1.6 MeV and 2.0 MeV electron was successfully achieved [4]. It provides the possibility to use similar approach to develop high-energy electron coolers in the future.

Brookhaven National Laboratory (BNL) is designing an Electron-Ion Collider (EIC), which will be a new discovery machine that opens new frontiers for the researches in nuclear physics and quantum chromodynamics [5]. In order to maintain the high luminosity during long collision runs, it is desirable to cool the hadron beam (275 GeV proton) to counteract the emittance growth caused by intrabeam scattering (IBS) [6]. However, the conventional coolers and the rf-based coolers are no longer suitable for such high energy beam cooling in EIC. In fact, various proposals and new cooling schemes have been proposed, but the technical and experimental demonstrations are still lacking. In this paper, we present a design of electron storage ring cooler with bunched electron beam for the EIC [7].

EIC COOLING DEMANDS

For the EIC, the most demanding case is to cool the proton beam at the energy of 275 GeV. During the long collision stores, the emittance growth of proton beam due to IBS is the dominant limitation for the luminosity. The requirement for the hadron beam cooling is mainly to counteract the IBS heating effect. The evolution of the 275 GeV proton beam emittance caused by IBS is shown in Fig. 1. It shows that the IBS heating effect for the flattened proton beam is dominated by the horizontal and longitudinal planes. As a result, vertical cooling is not needed for EIC. So, one can effectively use horizontal dispersion to redistribute the cooling rates between the longitudinal and horizontal planes, and achieve required cooling performance.

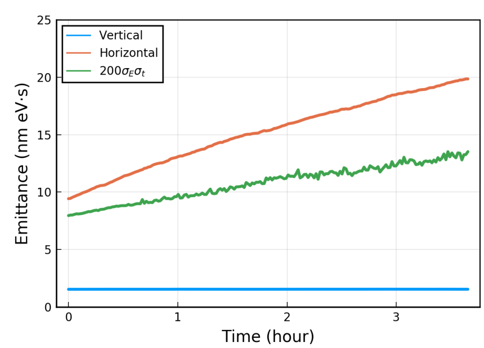

Figure 1: Emittance growth of the 275 GeV proton beam caused by IBS in EIC.

RING COOLER DESIGN

Overview

The electron storage ring has a race track shape, with the cooling section located in one long straight section and wigglers in the other. The ring is mirror symmetric around the center of the cooling section, and the top view of the ring is shown in Fig. 2. The cooling section has a length of 170 m and it fits into the straight section of the hadron ring. There are four arcs with radius of 3.42 m, each of them has 10 dipoles and a 90 degree phase advance per cell. The wiggler section is also mirror symmetric with four pairs of wigglers in each half. In our setup, the alternating horizontal and

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vertical wigglers are used, and the wiggler poles are shaped as combined function sector dipoles. The optics of the ring cooler is shown in Fig. 3, and the parameters of the ring are list in Table 1.

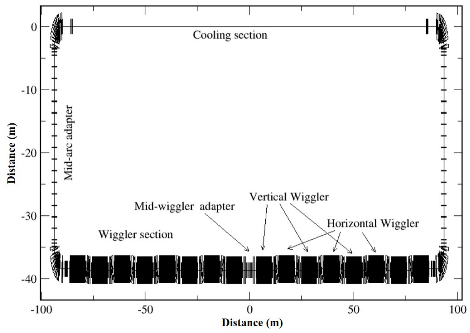

Figure 2: Layout of the ring cooler.

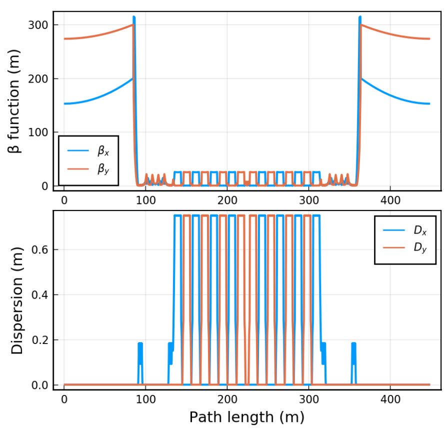

Figure 3: Optics of the ring cooler.

Because of the edge focusing of the dipoles, the wigglers and bending dipoles will create a large chromaticity. As a consequence, the required strong sextupoles strongly affects the dynamic aperture. In order to reduce the strength of the sextupoles, the sextupoles are placed inside the wiggler magnets, where a small dispersion is available throughout the length of the magnet. Also, since the edge focusing is only in one plane, a large ratio between horizontal and vertical beta functions can be maintained, making the chromaticity compensation more effective.

Considering IBS effect, the increase of the transverse emittance which is proportional to $H = \gamma D^2 + 2\alpha DD' + \beta D'^2$, must be minimized. The beta function in wiggle plane is chosen to be 25 m, which makes the D'^2 term of the H function two orders of magnitude bigger than the other terms. Therefore, the dispersion in the wiggler section doesn't have to be small as long as D' is kept small. We set the dispersion function in wiggler section to 75 cm, which works well for both chromaticity correction and dynamic aperture.

Beam Parameters

In the ring cooler, the cooling performance is directly determined by the electron beam quality. Based on the lattice design, the equilibrium electron beam parameters can be calculated by considering the radiation damping, quantum excitation, the IBS effect and the Beam-Beam Scattering (BBS) effect. The differential equation of the emittance of electron beam is given by

Table 1: Parameters of the Ring Cooler

Circumference [m]	449.079
Length of cooling section [m]	170
Average β function in cooling section [m]	170/280
Dispersion in arc [cm]	18.5
Wiggler field [T]	1.88
Length of wiggler [m]	7.44
Bend radius of wiggler [m]	0.246
Poles in wiggler	158
Wiggler period [cm]	4.8
β function in wiggler [m]	25
Max. Dispersion in wiggler [cm]	75
Number of wiggler magnets	16
Tune (Q_x/Q_y)	59.92/59.85
Chromaticity before correction (x/y)	-117.8/-114.4
Momentum compaction factor α	-3.21×10^{-3}
Natural emittance (x/y) [nm]	3.1/3.1
Natural momentum spread	2.6×10^{-4}

$$\frac{d\epsilon}{dt} = (-2\lambda_{damp} + \lambda_{IBS} + \lambda_{BBS})\epsilon + C_q \tag{1}$$

where λ_{damp} is the radiation damping rate, C_q is the factor of quantum excitation, λ_{IBS} and λ_{BBS} are the heating rates from IBS and BBS, respectively. The equation of momentum spread has the same form as Eq. (1). It is known that the heating rates from IBS λ_{IBS} and BBS λ_{BBS} depend on beam parameters dynamically. In order to get the equilibrium beam parameters in the ring cooler, a simulation code was developed which allows to perform turn-by-turn tracking.

In the simulation, the radiation damping rates are calculated from the radiation integrals based on the optics of the ring [8]. The factor of quantum excitation can be obtained by $C_q = 2\lambda_{damp}\epsilon_{nat}$, where ϵ_{nat} is the natural emittance of electron beam. The Bjorken-Mtingwa IBS model with horizontal and vertical dispersion is used in the code [9]. As of BBS, we derived a new formula using the full Landau collision integral that allows for different temperatures in all three dimensions [10–12]. Considering all above effects, the evolution of the electron beam in the ring cooler with two sets of arbitrary initial parameters is shown in Fig. 4. After several thousand turns, the electron beam converges to an equilibrium state, which is the final e-beam parameters for hadron beam cooling.

Dispersive Cooling

At high energy, the horizontal anglular spread of electron beam in the rest frame is much larger than in the longitudinal plane, which makes the horizontal cooling much slower than the longitudinal cooling. Here, we introduce the dispersions both for the hadron and electron beams to increase

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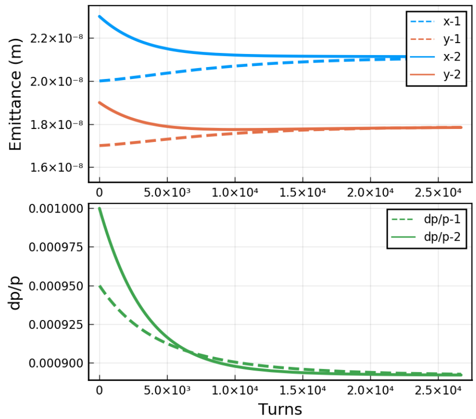

Figure 4: Evolution of the electron beam parameters in the ring cooler with two sets of arbitrary initial parameters.

the horizontal cooling rate at the expense of the longitudinal cooling [13]. As we known, dispersion on ions couples the horizontal coordinate with the longitudinal momentum, thus the cooling effect on momentum spread can be transferred to the horizontal plane. Figure 5 shows an example of the dispersive cooling, in which a dispersion and a transverse graident are necessary. Even though the change of beam density caused by dispersion will reduce the cooling rates in all three dimensions, the horizontal cooling rate still can be enhanced by the coupling effect, as long as the dispersion is not too large.

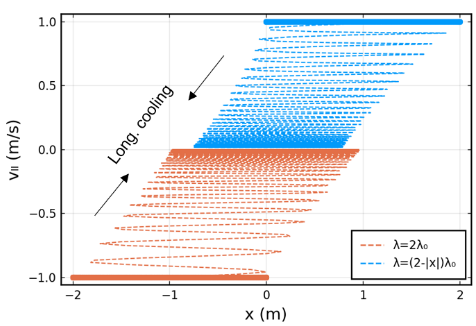

Figure 5: Schematic demonstration of dispersive cooling, in which a dispersion and a transverse graident are necessary.

Other Effects

In the ring cooler design, there are also some important effects need to be investigated, such as the beam dynamics, beam lifetime, dynamic aperture, instabilities and so on. These studies are not presented here, and the details can be found in Ref. [7]. In summary, the final electron beam parameters are summarized in Table 2.

Table 2: E-beam Parameters in the Ring Cooler

Beam energy [MeV]	149.8
Number of electrons per bunch	3×10^{11}
Peak current [A]	48.3
Number of bunches	135
Average current [A]	4.4
RMS emittance (x/y) [nm]	21/18
RMS Momentum spread	8.9×10^{-4}
RMS Bunch length [cm]	12
Required RF voltage [kV]	6.1
Synchrotron tune Q_s	1.63×10^{-3}
Max. space charge (x/y)	0.19/0.21
Damping rates (x/y/s) [s^{-1}]	32/32/64
IBS rates (x/y/s) [s^{-1}]	54/53/68
BBS rates (x/y/s) [s^{-1}]	-0.4/1.0/49
Dynamic aperture (x/y/s)	$6\sigma/6\sigma/13\sigma$
Momentum aperture	0.79%
Quantum lifetime [hour]	2.8
Touschek lifetime [s]	<55

COOLING SIMULATION

Based on the simulation code TRACKIT [14], the cooling process is performed with the electron beam parameters list in Table 2. Figure 6 shows the evolution of the hadron beam transverse and longitudinal emittance with cooling. When there is no dispersion, it shows that there is almost no transverse cooling but a strong longitudinal cooling, which is due to the large difference in cooling gradients. By applying the dispersion both for the proton and electron beam in the cooling section with $D_i = 2.5$ m and $D_e = 2$ m, the proton beam can be cooled more effectively in the horizontal plane. With cooling, the proton beam emittance is essentially unchanged within two hours, which satisfies the requirement in the EIC.

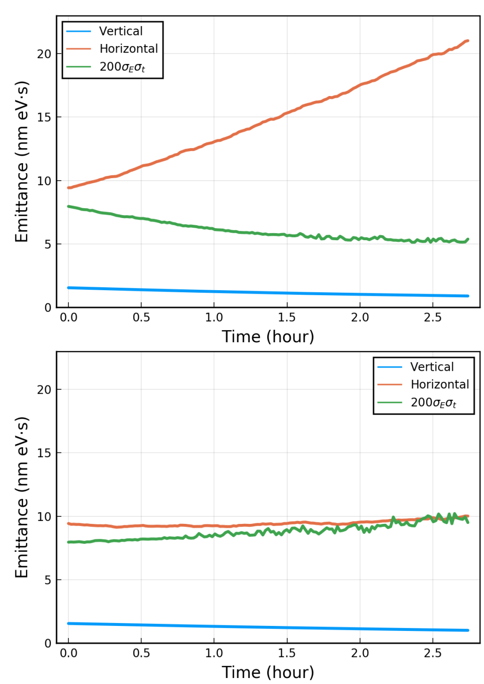

Figure 6: The evolution of the hadron beam emittance during cooling. (Upper plot: $D_i = 0\ m$, $D_e = 0\ m$, Bottom plot: $D_i = 2.5\ m$, $D_e = 2\ m$)

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CONCLUSION

The hadron beam cooling at high energy is an important part of the EIC. In this paper, we present a possible design of such high-energy ring-based electron cooler using bunched electron beam. The electron beam can continously cool the hadrons while electrons are being cooled by the radiation damping in the storage ring. This approach strongly depends on the design of electron ring which is described here in detail. Based on such ring cooler design, the cooling performance on the hadron beam is simulated, in which the dispersions of the ion and electron beams in the cooling section are effectively employed to redistribute the cooling rate between the longitudinal and horizontal planes. Although there are still some challenges, it appears that the ring-based electron cooler concept offers a viable path for cooling of protons at the top energy in the EIC.

REFERENCES

[1] Budker, Gersh Itskovich, "An effective method of damping particle oscillations in proton and antiproton storage rings", *Soviet Atomic Energy*, vol. 22, no. 5, pp. 438–440, 1967.

[2] Poth, Helmut, "Applications of electron cooling in atomic, nuclear and high-energy physics", *Nature*, vol. 345, no. 6274, pp. 399–405, 1990.

[3] Nagaitsev, Sergei, *et al.*, "Experimental demonstration of relativistic electron cooling", *Physical review letters*, vol. 96, no. 4, p. 044801, 2006.

[4] Fedotov, A. V., *et al.*, "Experimental demonstration of hadron beam cooling using radio-frequency accelerated electron bunches." *Physical Review Letters* vol. 124, no. 8, p. 084801, 2020.

[5] EIC: Colliding Electrons with Ions at Brookhaven Lab. `https://www.bnl.gov/eic/eRHIC.php`

[6] Montag, Christoph, "eRHIC design overview", No. BNL-212130-2019-COPA. Brookhaven National Lab.(BNL), Upton, NY (United States), 2019.

[7] H. Zhao, *et al.* "Ring-based electron cooler for high energy beam cooling", *Physical Review Accelerators and Beams*, vol. 24, no. 4, p. 043501, 2021.

[8] S. Y. Lee, "Accelerator physics", *World scientific publishing*, 2018.

[9] Nagaitsev, Sergei. "Intrabeam scattering formulas for fast numerical evaluation", *Physical Review Special Topics-Accelerators and Beams*, vol. 8, no. 6, p. 064403, 2005.

[10] E. M. Lifschitz and L. P. Pitajewski, "Phycical kinetics", Textbook of theoretical physics, 10, 1983.

[11] R. D. Hazeltine, "Coulomb collision operator", *Tech. Rep.*, University of Texas, Austin, 2006. `http://w3fusion.ph.utexas.edu/ifs/ifsreports/1140_Hazeltine.pdf`

[12] H. Zhao and M. Blaskiewicz, "Electron Heating by Ions in Cooling Rings", in *Proc. of North American Particle Accelerator Conference (NAPAC'19)*, Lansing, MI, USA, September 1-6. 2019.

[13] H. Zhao and M. Blaskiewicz, "Rate redistribution in dispersive electron cooling", *Physical Review Accelerators and Beams*, vol. 24, no. 8, p. 083502, 2021.

[14] Code available at `https://github.com/hezhao1670/ECool-TRACKIT`.