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Original Publication Citation

Dhital, B., Derbenev, Y.S., Douglas, D., Krafft, G.A., Zhang, H., Lin, F., Morozov, V.S., Zhang, Y. (2022) Cooling performance in a dual energy storage ring cooler. In F. Zimmerman, H. Tanaka, P. Sudmuang, P. Klysubun, P. Sunwong, T. Chanwattana, C. Petit-Jean-Genaz, & V.R.W. Schaa (Eds.), *Proceedings of the 13th International Particle Accelerator Conference* (pp. 568-571) Journal of Accelerator Conferences Website. http://dx.doi.org/10.18429/JACoW-IPAC2022-MOPOTK047

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13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK047

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COOLING PERFORMANCE IN A DUAL ENERGY STORAGE RING COOLER*

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Abstract

The longitudinal and transverse emittance growth in hadron beams due to intra-beam scattering (IBS) and other heating sources deteriorate the luminosity in a collider. Hence, a strong hadron beam cooling is required to reduce and preserve the emittance. The cooling of high energy hadron beam is challenging. We propose a dual energy storage ring-based electron cooler that uses an electron beam to extract heat away from hadron beam in the cooler ring while the electron beam is cooled by synchrotron radiation damping in the high energy damping ring. In this paper, we present a design of a dual energy storage ring-based electron cooler. Finally, the cooling performance is simulated using Jefferson Lab Simulation Package for Electron Cooling (JSPEC) for proton beams at the top energy of 275 GeV for Electron-Ion Collider.

INTRODUCTION

The method of electron cooling was first introduced by G. I. Budker in 1966 [1]. Later this method became one of the most powerful technique to shrink the size and momentum spread of the stored heavy charged particles (ions, protons, etc.) beams through their interaction with cold electron beam co-propagating at the same average velocities. After first successful demonstration of this cooling method at NAP-M ring in 1974, later this method was widely applied and developed in many heavy ion accelerators around the world [2–4].

An Electron-Ion Collider (EIC) is to be built at Brookhaven National Laboratory (BNL) [5]. In such a collider to maintain a higher luminosity during long collision runs, it is desirable to cool the hadron beams to balance the emittance growth rates due to intra-beam scattering (IBS). The proposed highest proton beam energy in EIC is 275 GeV and this requires some cooling mechanism with cooling rates which exceed the IBS growth rates. A single ring-based electron cooler for high energy beam cooling has been proposed [6], where the electron beams which continuously interact with the hadron beams to extract heat away are being cooled by synchrotron radiation damping. This single ring-based electron cooler concept make use of damping wigglers to enhance the radiation damping in a storage ring.

* Work supported by U.S. DOE Contract Nos. DE-AC05-06OR23177, DE-AC02-06CH11357, DE-AC05-00OR22725, and Jefferson Lab EIC Fellowship2020.
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To cool the hadron beam in the energy range 41-275 GeV, the required cooling electron beam energy is in the range 22-150 MeV. At such a low electron beam energy, the IBS effect is very strong giving very short IBS times of the order of tens of millisecond. Further, the synchrotron radiation damping effect is very weak giving long damping times of the order of seconds up to a minute. To get a balance between IBS and radiation damping, we proposed a dual energy storage ring with a high energy section to enhance the synchrotron radiation and a low energy section for the cooling [7, 8]. To enhance the damping effect, the use of wigglers in the high energy section may be another option, but it is known that for damping ring designs above around 350 MeV, it is less costly to omit wigglers and increase the energy of the high energy ring to achieve a required radiation damping rate. So, instead of using wigglers, our design uses Radio Frequency (RF) cavities to increase the energy of the high energy ring to 500 MeV which provides the enough damping to the electron beam to reach the equilibrium.

BEAM COOLING REQUIREMENT

Cooling methods enhance the beam quality and provides sharply collimated beams that is required for precise high energy physics experiments. Beam cooling aims at reducing the size and energy spread of a particle beam circulating in a storage ring and consequently enhance the luminosity. The luminosity in a collider is defined by [9]

$$L = \frac{N_1 N_2 f_0}{4\pi\sigma_x\sigma_y} \approx \frac{N_1 N_2 f_0}{\varepsilon\beta_y^*} \quad (1)$$

where N_1 and N_2 are particle densities, f_0 is revolution frequency, σ_x, σ_y are the horizontal and vertical beam sizes and ε is the emittance of the beam respectively. The luminosity L will be higher if ε or the corresponding beam sizes are smaller and N_1, N_2 are bigger values. Hence the goal is to 'compress' the same number of particles into a beam of smaller size and energy spread, i.e. to increase the particle density. The phase space density is a general figure of merit of a particle beam. And cooling technique greatly improves this figure of merit.

DUAL ENERGY STORAGE RING COOLER

A high current electron storage ring cooler may provide a solution to cool the hadron beams at higher energy. To cool the hadron beam at energy range of few hundred GeV,

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK047

we proposed a dual energy storage ring cooler as shown in Fig. 1. The optics design of such a cooler has been completed

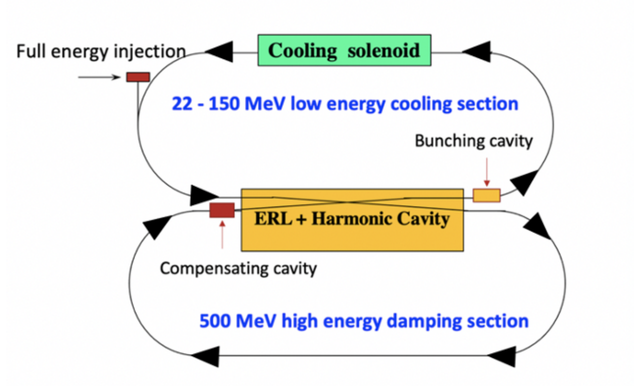

Figure 1: Schematic drawing of a dual energy storage ring cooler.

and the detailed beam dynamics studies has been carried out [8]. The superconducting radio frequency (SRF) system in common beamline consists of an energy recovery linac (ERL) and harmonic cavity. The ERL has the main cavities running on the crest that accelerates the electron beam from low energy E_L to high energy E_H. During the decelerating pass going from E_H to E_L, the main cavity runs 180° from the crest. When the main cavity runs at crest during the beam acceleration, the harmonic cavity next to the main cavity runs with a decelerating phase. And when the main cavity runs 180° from the crest during beam deceleration, the harmonic cavity runs on the crest. Hence, the total voltage gain during the acceleration is exactly cancelled by the total voltage loss during the deceleration. To provide the longitudinal focusing on the system, a bunching cavity running at a zero-crossing phase outside the common beamline is used. A compensating cavity running at crest is used to compensate the energy loss due to the synchrotron radiation.

COOLING PERFORMANCE

To study the cooling performance, we consider different aspects in a ring cooler such as beam parameters, cooling forces, and cooling simulation. The evaluation of electron and proton beam parameters are necessary before running the cooling simulation. Electron ring lattice is designed to get the desired equilibrium beam parameters, and the proton ring lattice is designed to get the high performance in terms of beam quality in a collider. An appropriate friction force is necessary to evaluate the cooling interaction between electron and ion beams.

Beam Parameters

Cooling simulation is performed with the electron beam parameters listed in Table 1. The cooled proton beam parameters are listed in Table 2. Calculations show that the cooling times in all three dimensions are shorter than the IBS times. It means 275 GeV proton beam can be cooled with 150 MeV electron beam in a dual energy storage ring cooler.

Table 1: Electron Beam Parameters

Energy	**149.8 MeV**
Relativistic factor γ	293.1
Bunch intensity	6.9 $\times 10^{10}$
Bunch charge	11.1 nC
Bunch current	52.9 A
Average current	1.08 A
RMS bunch length	6.0 cm
FWHM bunch length	15.0 cm
Total ring circumference	532.8 m
Average β function in the cooler h, v	0.25 , 0.25 m
Normalized emittance h,v	670 , 108 µm
RMS beam size @ cooler h,v	0.74 , 0.16 mm
RMS angle spread @ cooler	608 µrad
Energy spread @ cooler [$\times 10^{-4}$]	7.4
Space charge tune shift	0.006
IBS time h, v, l	5 , 12 328 , 0.44 s
SR damping time h, v, l	3.2 , 0.69 , 0.25 s

h, v, l = horizontal, vertical, longitudinal

Table 2: Proton Beam Parameters

Energy	**275 GeV**
Relativistic factor γ	293.1
Bunch intensity	6.9 $\times 10^{10}$
Bunch charge	11.1 nC
RMS bunch length	6.0 cm
Cooling channel length	120.0 m
Magnetized cooling	Strong
Cooling solenoid	4.0 T
Horizontal dispersion	2.5 m
Vertical dispersion	0.5 m
IBS coupling factor	0.2
Normalized emittance h,v	2.8 , 0.45 µm
Energy spread [$\times 10^{-4}$]	6.8
IBS time h, v, l	2.6 , 3.7 , 4.1 h
Cooling time h, v, l	0.65 , 1.38 , 1.5 h

Cooling Interaction and Intra-Beam Scattering (IBS)

In magnetized cooling, a strong magnetic field is applied along the longitudinal direction inside the cooler. This causes the electron motion to follow a spiral trajectory around the magnetic field line called Larmor rotation. Electron and ion beams interact with each other via Coulomb interaction, the momentum and energy exchange of interacting particles diverges logarithmically in the region of large impact parameter and must be cut off at some point, above which the interaction is effectively reduced [10]. When the maximum impact parameter is larger than radius of electron Larmor rotation so called "magnetized collisions" between

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ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK047

ion and electron take place. In this case the electron beam is attracted by the ion, which pulls it along the magnetic field line. Depending on the different ranges of the ion velocity and impact parameter compared with the radius of electron Larmor rotation, the collisions can be classified into three categories: fast, adiabatic, and magnetized. The detailed on the theory of magnetized electron cooling is presented in the following references [10, 11].

The IBS in the ion beam enhances diffusion growth of 6D phase space volume of the ion beam. The emittance growth of 275 GeV proton beam caused by IBS effect in the absence of cooling is shown in Fig. 2. There are several models for IBS calculation. Besides the Martini model [12], the Bjorken-Mtingwa (BM) model [13] is another widely used model for the IBS expansion rate calculation. During the cooling simulation in the case of magnetized cooling, we use BM model for the IBS expansion rate calculation in a dual energy storage ring cooler.

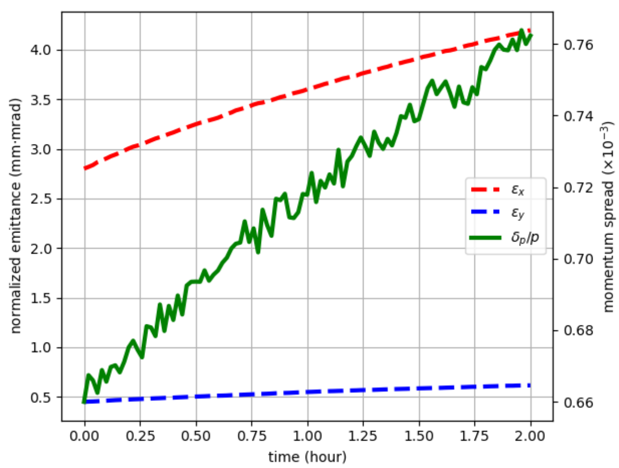

Figure 2: Emittance growth of 275 GeV proton beam caused by IBS effect in the absence of cooling.

Cooling Simulation

To study the cooling performance, JLab Simulation Package for Electron Cooling (JSPEC) [14] was used considering the 3D magnetised cooling force, IBS and the dispersion in the cooling section. The asymptotic formula by Meshkov [15] is used to calculate the friction force between the electron beam and proton beam. The appropriate horizontal and vertical dispersion in proton beam are included in the cooling section to redistribute the cooling. Finally, the cooling simulation is performed using JSPEC.

Figure 3 shows the evolution of the proton beam transverse and longitudinal emittance with cooling. In the absence of dispersion, there is no cooling effect in the horizontal but a strong cooling in the longitudinal direction as shown in Fig. 3. The magnetic field of 4.0 T is applied in the cooling solenoid with the matched optics. When we introduce horizontal dispersion D_x = 2.5 m, vertical dispersion D_y = 0.5 m and IBS coupling factor = 0.2 in the cooler for the proton beam, there exists a strong cooling both in transverse and longitudinal directions. The introduction of dispersion in the cooling section greatly enhance the transverse cooling.

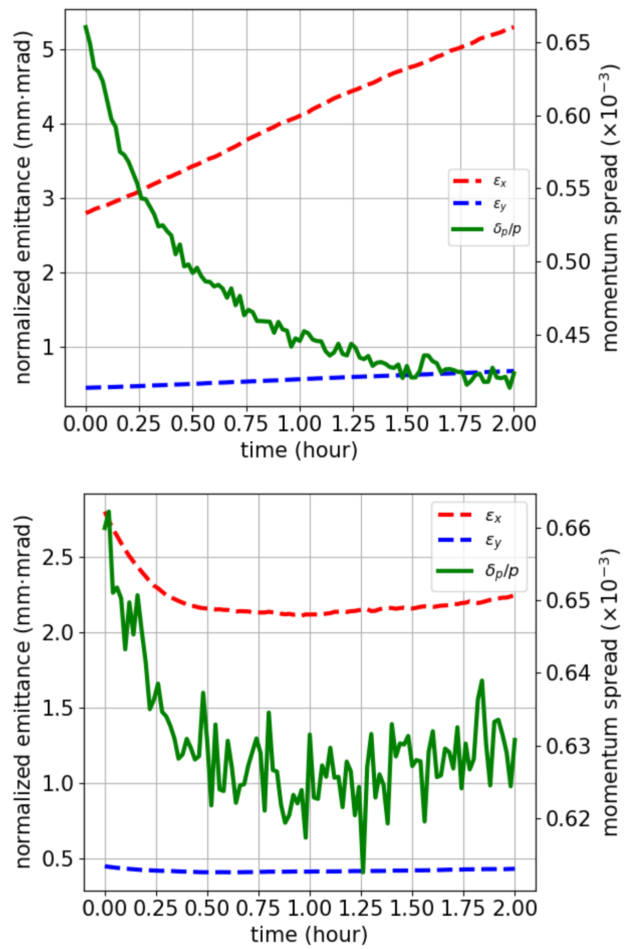

Figure 3: The evolution of the horizontal (ε_x), vertical (ε_y), and longitudinal (δ_p/p) proton beam emittance during cooling. Upper plot: D_i = 0 m; bottom plot: D_x = 2.5 m, D_y = 0.5 m and IBS coupling factor = 0.2.

CONCLUSION

The feasibility and applicability of a dual energy storage ring cooler to cool the proton beams at 275 GeV has been studied. Based on calculated electron beam parameters, the cooling performance on the proton beam at 275 GeV is simulated using JSPEC code. Meshkov asymptotic force formula is used to calculate the friction force between electron and proton beams. The cooling performance shows that the this type of ring-based electron cooler provides a feasible path for cooling of ion beams in a collider, for example EIC.

ACKNOWLEDGEMENTS

The authors would like to thank Steve Benson and Todd Satogata at JLab for very useful discussions in this work.

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ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK047

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