ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-P1001

SIMULATION OF HIGH ENERGY PROTON BEAM COOLING IN EICC*

F. Ma†[1], J. Li, X. M. Ma, L. J. Mao, X. P. Sha, M. T. Tang, J. C. Yang, X. D. Yang, H. Zhao, H. W. Zhao, Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, China
[1]Also at University of Chinese Academy of Sciences, 100049 Beijing, China

Abstract

The hadron beam cooling plays an important role in the future e-i collider machines to achieve various physical goals. In EicC, two-stage beam cooling scheme is proposed to maintain the luminosity during the long time collision. First, a traditional electron cooler will be used to pre-cool the low energy proton beam in the BRing. Then, an ERL-based electron cooler will be applied at the pRing to cool the proton beam at high energy. The main purpose of cooling is to counteract the emittance growth due to the IBS. In this paper, we focus on the high energy beam cooling and present some simulation studies on how the cooling rate will be affected by the electron bunch size, magnetic field, and ring parameters in the cooling section, which would be helpful for the cooler design.

INTRODUCTION

EicC is proposed to study of hadron structure and the strong interaction and to carry out the frontier research on both nuclear and particle physics [1]. It will be constructed based on the High Intensity heavy ion Accelerator Facility (HIAF) with an additional newly constructed electron ring and a proton ring. The proposed collider will provide highly polarized electrons (with the polarization ~80%) and protons (with the polarization ~70%) with the variable center of mass energies from 15 to 20 GeV and the luminosity of $(2-4)\times 10^{33}\ cm^{-2}s^{-1}$. The ion accelerator complex of the EicC accelerator facility mainly consists of a polarized ion source, the iLinac, the booster ring BRing, and the collider ring pRing with proton beam energy up to 19.08 GeV, and the electron accelerator complex is composed of an electron injector and an electron collider ring eRing. There are two identical interaction regions in the EicC accelerator design, as shown in Fig. 1.

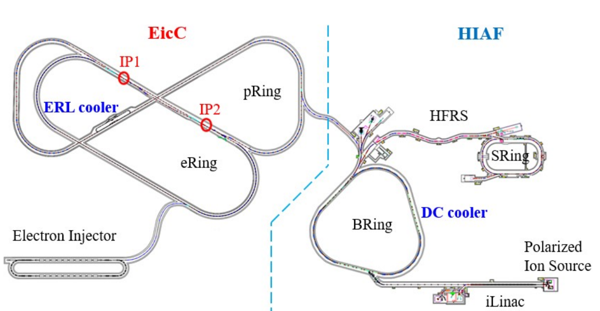

Figure 1: General layout of the EicC accelerator complex.

* This work was supported by the National Key R&D Program of China, Grant No.2019YFA0405400.
† mafu121@impcas.ac.cn

To achieve the high luminosity and long collision lifetime, beam cooling is required to counteract the emittance growth caused by IBS. In the past decades, electron cooling has become one of the most effective and well-developed methods. Based on ref. [2], the cooling rate will be significantly weakened at high energy, as described by Eq. (1).

$$\frac{1}{\tau_{cool}} \propto \frac{Z^2}{A}\frac{n_e L_c}{\beta^4\gamma^5\theta_{rel}^3} \tag{1}$$

Considering this effect, the EicC will adopt a two-stage electron cooling scheme to improve the cooling efficiency. In the first cooling stage, an electron cooler, based on conventional electrostatic high voltage acceleration, will be installed in the BRing to reduce the transverse emittance and the momentum spread of the medium-energy ion beams. In the second cooling stage, a high energy electron cooler, based on ERL, will be installed in the pRing to compensate the IBS effect and maintain the emittance of the ion beam during the collisions, which can ensure high luminosity and long collision life required by the scientific goals. Due to reduced emittance after the low-energy cooling in the first stage, the cooling time for the high-energy beam can also be largely reduced, leading to a shortened total cooling time and enhanced cooling efficiency.

STUDIES ON BUNCHED BEAM COOLING IN PRING

In order to calculate the bunched beam cooling parameters efficiently and accurately, a flexible multiparticle tracking code is developed based on BETACOOL physics guide [3] and JSPEC code [4]. The magnetized friction force is calculated through the semi-empirical formula by V. Parkhomchuk [5] and the Martini model [6] is chosen for IBS calculation in this code. It has been benchmarked with BETACOOL program and they agree very well. In the following, we will give some simulation results and select the optimal parameters to achieve a high cooling rate. All the simulation input parameters are shown in Table 1.

IBS Effect During the Collision

Because of the long collision time, the emittance growth during the collision must be considered which have a great effect on the luminosity. Here we only considered the IBS effect, as shown in Fig. 2, beam emittance in three dimensions are all increased, which significantly affect the luminosity. Especially for the horizontal emittance growth rate, it will grow from 0.3 um to 0.7 um in three hours and the growth rate is about $2.3\times 10^{-4}\ s^{-1}$. The luminosity will decrease to $1.4\times 10^{33}\ cm^{-2}s^{-1}$ within three hours. To obtain a great

ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-P1001

luminosity lifetime, the horizontal cooling rate must not be less than $2.3 \times 10^{-4}\ s^{-1}$.

Table 1: Simulation Parameters of Bunched Beam Cooling in pRing.

Parameters	**Value**
Particle type	proton
Kinetic energy	19.08 GeV
Number of particles per bunch	1.25×10^{11}
rms emittance x/y	0.3/0.18 π mm mrad
rms momentum spread	0.002
rms bunch length	4 cm
Number of electrons per bunch	2.5×10^{10}
Electron beam size (σx/σy/σs)	3/3/40 mm
Electron beam normalized rms emittance	2.5 π mm mrad
Electron beam rms momentum spread	0.0005
Length of cooling section	50 m
Longitudinal magnetic field in the cooling section	1.5 T
Parallelism of magnetic field	1.0×10^{-4}
Betatron function in the cooling section	30 m
Dispersion function in the cooling section (horizontal)	2 m

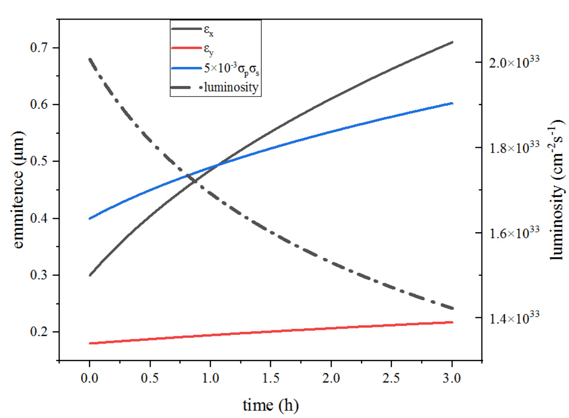

Figure 2: Evolution of ion beam emittance and luminosity during the collision.

Proper Electron Bunch Size

In the current baseline of the cooling of EicC, the ERL-based electron cooler provides a bunched electron beam with the charge of 4 nC and the energy of 10.4 MeV. Both the volume of the electron bunch and the local electron beam density affect the cooling rate, and they are contradictory. The larger the volume, the more ions are covered by the electron bunch and get cooled. However, the larger the volume, the lower the local electron density as the total charge per bunch is limited. Assume the electron bunch has round Gaussian distribution, transverse cooling rates are calculated for electron bunches with different radius and lengths while keeping electron beam emittance constant, as shown in Fig. 3. The parameters used in the calculation are list in Table 1. When the rms electron bunch length σ_{se} increases from 0.1 to 1.5 rms ion bunch length σ_s, the cooling rate increases until $\sigma_{se} = 0.75\sigma_s$, from where the cooling rate starts to decrease. For the electron bunch size, the turning point of the cooling rate is at $\sigma_{xe} = 0.45\sigma_x$. This is as expected since the bunch volume and the local electron density is competing. The volume dominates at the beginning and the cooling rate increases when more ions are enclosed by the electron bunch. Then the local electron density dominates when the volume is large enough. Another reason is that when local density is very large, the plasma oscillating frequency plays an important role on the collision parameters of cooling force formula. The change of longitudinal cooling rate is the same. According to the calculation, the highest cooling rate is achieved when the electron bunch is a little smaller than the ion bunch. And the cooling effect is distributed to the whole ion bunch via the transverse betatron oscillation and the longitudinal synchrotron oscillation.

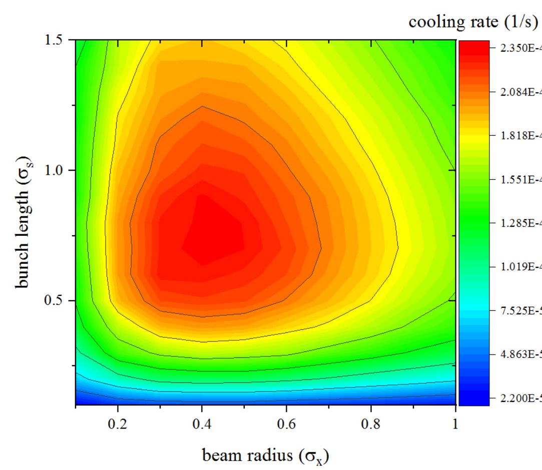

Figure 3: Transverse cooling rate for various electron bunch sizes.

Magnetic Field Parameters in the Cooling Section

The magnetic field strength and the parallelism of the magnetic field in the cooling section also have a great influence on the cooling rate in the magnetized electron cooling system. As shown in Fig. 4. The left one presents the transverse cooling rate as a function of the magnetic field strength in the cooling section, and the right one shows the transverse cooling rate change with different parallelism of the magnetic field. In the case of other fixed parameters, the cooling rate increases with the magnetic field strength and decreases with the increasing parallelism of the magnetic field in the cooling section. For the cooling in pRing, the magnetic field strength will be selected as 1.5 T and the parallelism of the magnetic field must be less than 1×10^{-4}.

ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-P1001

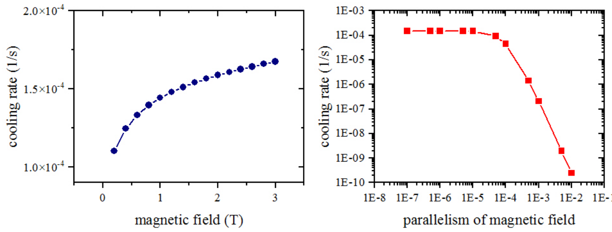

Figure 4: The transverse cooling rate as a function of the magnetic field strength (left) and the parallelism of the magnetic field (right) in the cooling section.

Lattice Function in the Cooling Section

Figure 5 gives the dependence of cooling rate on the transverse betatron function in the cooling section. We chose the same bunch size of the electron beam with the ion beam all the time in these calculations. One can see that the transverse cooling rate is increasing with a larger betatron function, however longitudinal is the opposite. The highest cooling rate in the transverse is achieved when the betatron function is equal to about 80 m. In the presence of dispersion, the horizontal cooling rate is enhanced with the expense of longitudinal cooling rate due to the coupling. And the vertical cooling rate decreases all the time because of the change of the ion beam size. The maximum horizontal cooling rate is achieved when the dispersion function reaches to 6 m, which is a little different from the theoretical results 2 m in the article [7]. The reason is the nonlinear terms of the cooling force depend on the large velocity spread of the ion beam. Based on the calculation, a small betatron function with dispersion in the cooling section is better to balance the cooling rate and compensate for the IBS effect in all dimensions.

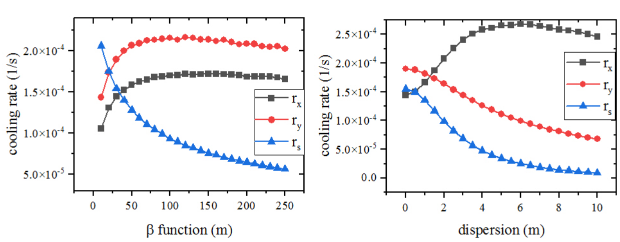

Figure 5: The cooling rate as a function of the betatron function (left) and the dispersion function (right) in the cooling section.

SIMULATION OF THE COOLING PROCESS IN PRING

By optimizing the above parameters, the proton beam cooling process in pRing is simulated. The electron bunch size is chosen as the same as ion beam to avoid the possible strong space charge effect of small electron bunch size. Due to the larger IBS growth rate in horizontal than both vertical and longitudinal, a dispersive electron cooling is chosen. By applying the dispersion on the proton beam in the cooling section with $D_x = 2$ m, $\beta_{x/y} = 30$ m, and introducing transverse coupling with 55% to transfer the IBS effect from the horizontal direction to the vertical direction, the proton beam can be cooled more effectively in all three dimensions. As shown in Fig. 6, the proton beam emittance is essentially unchanged within one hour with cooling, and the luminosity stays above $2 \times 10^{33}\ cm^{-2}s^{-1}$, which is close to the requirement in EicC.

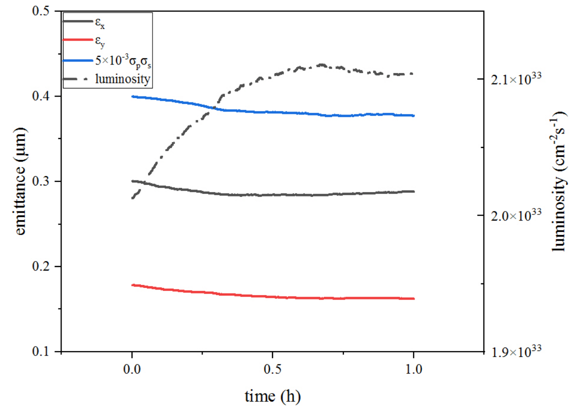

Figure 6: The evolution of the ion beam emittance and luminosity with cooling during the collision.

SUMMARY

The high energy bunched beam cooler of the two-stage electron cooling scheme for EicC is challenging, but possible. Based on the simulation results, the largest cooling rate can be achieved when the 4 nC charged electron bunch size is smaller than the ion bunch. The magnetic field strength of 1.5 T and 1.0×10^{-4} parallelism of the magnetic field is chosen based on the cooling requirement and technical risk. A dispersive beam cooling is suggested to suppress the large emittance growth by the IBS effect in the horizontal plane. The optimal ring parameters of betatron function and dispersion function are selected as 30 m and 2 m respectively in the cooling section. However, there are still many parameters to be optimized and many technical problems to be solved, especially for the stable operation of the ERL with 4 nC charge per bunch. The optical design is also an important work to optimize the IBS effect in the horizontal plane. The way to complete the design of the high energy bunched beam cooler is still very long.

ACKNOWLEDGMENT

The authors would like to thank members of the EicC design group. We also like to thank H. Zhang for his contribution to the simulation program.

REFERENCES

[1] Daniele P. Anderle *et al.*, “Electron-ion collider in China”, *Frontiers of Physics*, Vol. 16 Issue (6):64701, 2021.

[2] "Electron cooling: theory, experiment, application", *Phys. Rep.* 196, Nos. 3 & 4, 135-297, North-J-Iolland, 1990.

ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-P1001

[3] I. Meshkov *et al.*, "BETACOOL Physics Guide", 2007. http://betacool.jinr.ru/

[4] JSPEC on GitHub, https://github.com/JeffersonLab/ElectronCooling

[5] V.V. Parkhomchuk, "New insights in the theory of electron cooling", *Nucl. Instrum. Methods Phys. Res. Sect. A* 441, 2000.

[6] M. Martini, "Intrabeam Scattering in the ACOL-AA Machines", CERN PS/84-9 AA, 1984.

[7] H. Zhao and M. Blaskiewicz, "Rate redistribution in dispersive electron cooling", *Phys. Rev. Accel. Beams* 24, 083502, 2021.