MEIC ELECTRON COOLING SIMULATION USING BETACOOL*

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Abstract

Electron cooling of ion beams is one critical R&D issue in Jefferson Lab's medium energy electron-ion collider (MEIC). In the present MEIC design concept, a multi-phase cooling scheme is adopted. In the ion pre-booster, a DC electron cooler is responsible for assisting ion beam accumulation and initial cooling. In the ion collider ring, the ion beams with energies up to 100 GeV/u are cooled by a high current bunched electron beam driven by an energy-recovery SRF linac assisted by a circulator ring. It is essential to understand how efficient that electron cooling is, particularly in the high energy range, and how the cooling electron bunches in the circulator cooler ring are affected by the cooling process and other collective beam effects, in order to confirm the feasibility of the design. Here we present first results of the simulation studies of electron cooling processes of MEIC using BETACOOL code.

INTRODUCTION

The MEIC is designed to deliver a peak luminosity above 10^{34} cm^{-2}s^{-1} and covers a CM energy range up to 65 GeV. It offers an electron energy up to 12 GeV, a proton energy up to 100 GeV, and corresponding energies per nucleon for heavy ions with the same magnetic rigidity [1]. The MEIC ion complex consists of ion sources, a linac, two boosters and a medium energy collider ring, as shown in Fig. 1. The conventional electron cooling is chosen to assist cumulation of ions from the linac and to reduce and preserve the emittance of the MEIC ion beam. We propose to have electron coolers installed both in the pre-booster and in the collider ring, and our multi-phase electron cooling scheme includes the following steps: (1) low energy (up to 2 MeV) DC cooling at the pre-booster, (2) bunched electron cooling at the ion injection energy (up to 20 GeV/u) of the collider ring, and (3) bunched cooling at the top ion energy (100 GeV/u) of the collider ring. An important feature of this scheme is continuous electron cooling of the ion beams during their collision with the electron beam.

While the electron cooling mechanism is well developed and successfully tested with low energy DC beam applications world wide, we are challenged by the high density and high energy of the MEIC ion beam [2, 3]. The present design concept calls for an ERL for the high energy cooler in the collider ring for meeting the request of a very high RF power and additionally a circulator ring for mitigating the electron gun life time challenge [1]. There are a number of critical R&Ds for this design concept, for example, (1) what is the cooling efficiency at the high energy range with a bunched electron beam; (2) how the cooling electron bunches in the circulator cooler ring are affected by the cooling process and other collective beam effects; and further (3) how the cooling efficiency is affected by the continually (slow) degradation of the cooling bunches during circulation of the cooling. In the report, we present our initial results for the simulation studies of the first issue listed above. For simplicity, the coupling to the electron beam dynamics in the circulator cooler ring is ignored. The latter is currently also under studied [4]. In other words, the cooling electron bunches in the simulations are assumed ideal, fresh from the electron source, for each cooling, instead of being a real beam circulating in the cooler ring. At a later time, these two studies will be combined as we expect.

Table 1: Key Parameters for Different Cooling Schemes

		Pre-Booster	Collider Ring
p^+ Energy	GeV	3	20/100
p^+ Bunch Length	cm	Coasting	Coasting/1
Cooler Type		DC	ERL circulator
Magnetization	T	1	0
Cooler Length	m	10	2×30
e^- Beam Current	A	3	1.5
e^- Bunch Length	cm		1.2
Cooling Scheme 1		✓	
Cooling Scheme 2			✓
Cooling Scheme 3		✓	✓

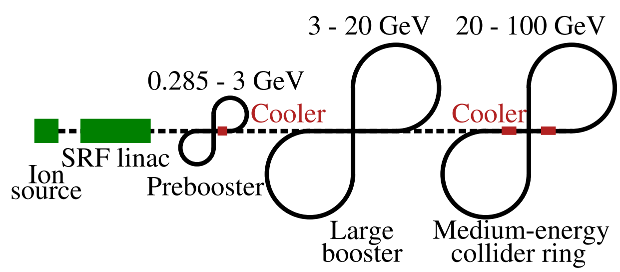

Figure 1: Components of MEIC ion complex

MODELS AND METHODS

Ideally a start-to-end simulation should be carried out for the entire process of MEIC ion beam formation and cooling, nevertheless, presently there is no such a code capa-

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ble of taking such a task. Therefore, we simulate various physics processes independently.

To explore the capability and limitations of both the low energy DC cooler and high energy ERL cooler, we have performed simulations for the following three hypothetical cooling schemes: (1) only the DC cooler in the pre-booster, (2) only the ERL circulator cooler in the collider ring, and (3) using both the DC cooler in the pre-booster and the ERL circulator cooler in the collider ring. It is expected that such simulations will shed the lights of the nominal MEIC cooling design scheme.

The highest kinetic energy of protons in the pre-booster is 3 GeV, the corresponding energy of the cooling electron energy is about 2 MeV. Space charge effect of the DC electron beam is included. In the collider ring, a Gaussian bunched electron beam of 1.5 A is used to cool a coasting (very long bunch) proton beam at the injection energy (20 GeV), and the same electron beam is used to cool a Gaussian bunched proton beam at the collision energy (60 GeV for the nominal design point). The beam and cooler parameters for the different cooling schemes are presented in Table 1.

We utilized the well developed BETACOOL code, which provides various formulas for the intra-beam scatterings (IBS) effect and cooling force calculation, along with various models for dynamic simulations [5]. As to the following results, Martini model [6] is used for IBS effect calculation, the model beam method is for DC cooling simulation and the RMS dynamic method with single particle model is for bunched electron beam cooling simulation [5].

SIMULATION RESULTS

Cooling in Pre-booster Only

In the pre-booster, the initial normalized emittance of the proton beam is assumed to be 3.15 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ in both transverse directions, which is limited by the space charge tune shift. The momentum spread dp/p is assumed to be 0.001. The radius of the electron beam is 0.832 cm, which is three times of the rms radius of the proton beam. The current of the electron beam is 3A. Fig. 2(a) shows the evolvement of the normalized emittance and the momentum spread of the proton beam during the cooling process. After about 600 s, the transverse emittance of the proton beam reaches the equilibrium at about (0.6, 0.2) $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$. Because we need to stack five injections in the collider ring, 600 s is too long. We would like to stop cooling after 200 s, when the emittance was reduced to (1.18, 0.99) $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$. After the pre-booster, we inject the proton beam into the large booster, accelerate it to 20 GeV, and then inject it to the collider ring. The first long bunch needs to wait 800 s for the following four bunches before we accelerate them together to 60 GeV. During this 800 s, the horizontal emittance of the proton bunch will increase up to 1.45 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ due to the IBS effect, which is shown in Fig. 2(b). After being accelerated to 60 GeV, without cooling the horizontal emittance keeps increasing due to IBS effect. As Fig. 2(c) shows, after two hours the horizontal emittance will be about 3.8 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$. For both energy stages, the vertical emittance remains almost unchanged because the vertical IBS effect is much smaller than the horizontal one.

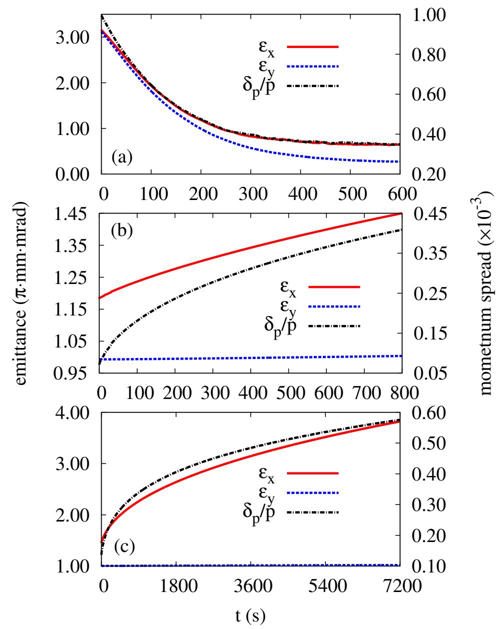

Figure 2: Cooling in the pre-booster (a) and IBS induced emittance and momentum spread expansion in the collider ring at 20 GeV (b) and 60 GeV (c).

Cooling in Collider Ring Only

Without cooling in the pre-booster, we assume the initial normalized emittance of the proton beam in the collider ring at 20 GeV to be 3.15 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, limited by the space charge tune shift, and the momentum spread 3×10^{-3}. We will cool the coasting (very long bunch) proton beam at 20 GeV first, and then cool the bunched proton beam at 60 GeV. Cooling at 20 GeV turns out to be quite efficient as shown in Fig. 3(a). The emittance reaches the equilibrium within 250 s. When the proton beam is bunched at 60 GeV, its IBS effect is about two orders of magnitude higher in the horizontal direction than in the vertical direction, while the friction forces in both directions are roughly the same. Hence there is a tendency to over cool the beam in the vertical direction, which as a result of the over cooling makes the cooling in horizontal direction even more difficult. If the transverse motion of the proton beam is coupled, the emittance growth due to IBS effect will be redistributed in the two directions according to the coupling rate, which makes the cooling in the horizontal direction easier and also provides a way to control the transverse bunch sizes. Simulation results also support this hypothesis. If the emittance at 20 GeV is reduced to 0.30 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, then at 60 GeV after the proton beam is bunched, the emittance can be further reduced to 0.17 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ within 20 s with 100% coupling in trans-

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verse directions as shown in Fig. 3(b). Or the emittance can be reduced to (0.30,0.07) $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ with 40% transverse coupling as shown in Fig. 3(c), which provides a flat beam.

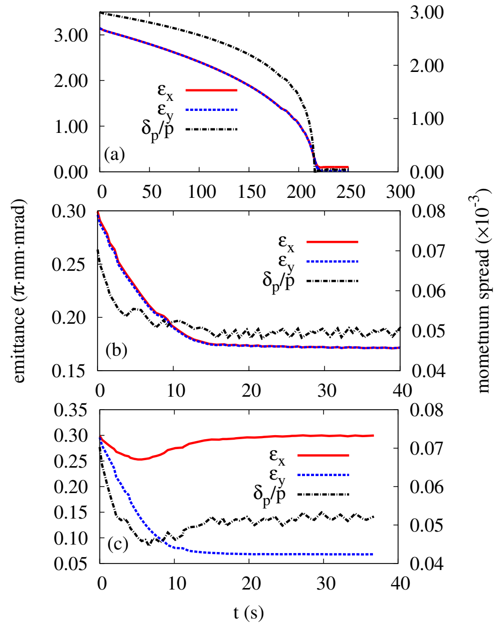

Figure 3: Cooling in the collider ring at 20 GeV (a) and at 60 GeV for 100% (b) and 40% (c) coupled p^+ beam.

Cooling in Pre-booster and Collider Ring

Now we consider both the DC cooling in the pre-booster and the ERL circulator Cooling in the collider ring. the DC cooling in the pre-booster is the same as shown in Fig. 2(a). Assuming the normalized emittance of the proton beam out of the pre-booster is (0.83,0.57) $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ and we start to cool from this emittance in the collider ring at 20 GeV, the evolvement of the emittance and momentum spread of the proton beam is shown in Fig. 4(a). Initially the longitudinal cooling is strong and the momentum spread reaches the lowest point within five seconds and then starts to increase again. When the emittance is reduced to about 0.3 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, dp/p is in the order of 10^{-6} and it is increasing, according to Fig. 4(a), which means energy is transferring from the transverse directions to the longitudinal direction. If we stop cooling the coasting beam at this point, it is reasonable to assume dp/p will increase during the following accelerating and bunching process. In the following simulations for the cooling at 60 GeV, an initial dp/p of 3.7×10^{-4} is used. As Fig. 4(b) and Fig. 4(c) show, the emittance can be reduced to 0.23 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ within 20 s when fully coupled in the transverse directions or (0.31,0.18) $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ within 30s when 50% coupled.

SUMMARY AND DISCUSSION

Preliminary simulation results suggest the design parameters of MEIC cooling system are achievable. We did similar simulations for heavy ions, the cooling of which turned out easier than that of protons. There are some points we want to note as follows. Transverse coupling is helpful for the cooling in the collider ring, but its dynamic effect needs to be studied. In the above simulations, we assume the ion beams always have Gaussian distributions. However, this is not necessarily true. We need to study how the ion beam distribution evolves in different cooling processes and how much it affects the results if the distribution deviates from Gaussian. Analytical formulas are used to calculate the friction force, and their accuracy under the MEIC parameters need to be checked and confirmed. We plan to use the electron bunches multiple times in cooling, so it is crucial to understand how the electron bunches are affected by the proton bunches, which is currently out of the ability of BETACOOL. New method, such as N-particle simulations, may need to be developed and applied.

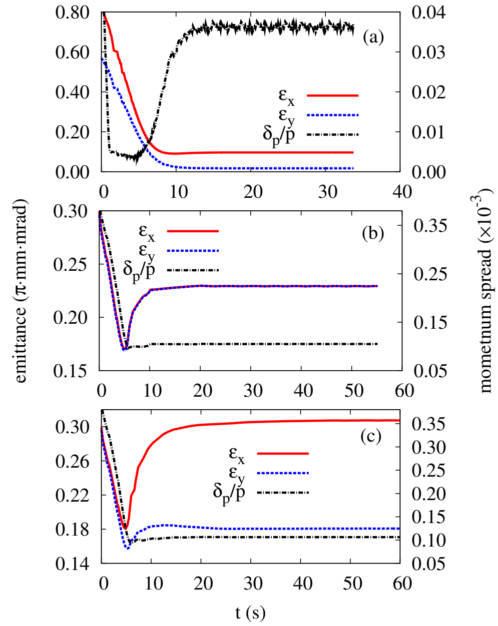

Figure 4: Cooling in the collider ring at 20 GeV (a) and at 60 GeV for 100% (b) and 50% (c) coupled p^+ beam.

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