MEIC ELECTRON COOLING SIMULATION USING BETACOOL*

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Abstract

Electron cooling of ion beams is the most critical R&D issue in Jefferson Lab's medium energy electron-ion collider (MEIC). In the present MEIC design concept, a high current bunched electron beam driven by an energy-recovery SRF linac assisted by a circulate ring will be utilized to cool protons or ions in the collider ring with energies up to 100GeV/u, a parameter regime that electron cooling has never been applied. It is essential to understand how efficient that electron cooling is, particularly in the high energy range, in order to confirm the feasibility of the design. Here we will present first results of the start-to-end simulation studies of electron cooling processes in the collider ring of MEIC using BETACOOL code.

INTRODUCTION

The MEIC can deliver a luminosity above $10^{34}\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ at a center-of-mass energy up to 65 GeV. It offers an electron energy up to 11 GeV, a proton energy up to 100 GeV, and corresponding energies per nucleon for heavy ions with the same magnetic rigidity [1]. The conventional electron cooling is chosen to reduce or preserve the emittance of the MEIC ion 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 components of the MEIC Ion Complex is as shown in Fig. 1. We may have coolers installed in the pre-booster and/or in the collider ring, and our multi-phase electron cooling strategy includes the following steps: (1) low energy (3 GeV) DC cooling at the pre-booster, (2) ERL circulate cooling at the injection energy (20 GeV) of the collider ring, and (3) ERL circulate cooling at the top energy (100 GeV) of the collider ring.

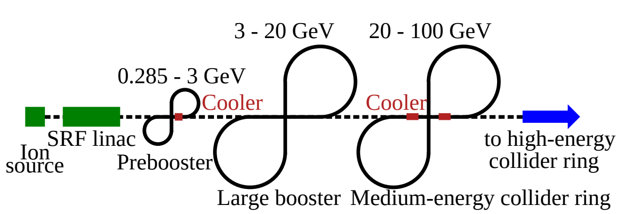

Figure 1: Components of MEIC ion complex

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Table 1: Key Parameters for Different Cooling Schemes

	Pre-Booster	**Collider Ring**	**Collider Ring**
p^+ Energy	3 GeV	20 GeV	100 GeV
p^+ Bunch Length	Coasting	Coasting	1 cm
Cooler Type	DC cooler (B=1T)	ERL circulate cooler	ERL circulate cooler
Cooler Length	10 m	2×30 m	2×30 m
e^- Beam Current	3 A	1.5 A	1.5 A
e^- Bunch Length		1.2 cm	1.2 cm
Cooling Scheme 1	✖	✓	✓
Cooling Scheme 2	✓	✓	✓
Cooling Scheme 3	✓	✖	✖

COOLING SIMULATIONS USING BETACOOL

Start-to-end simulations have been performed using BETACOOL for the following three cooling schemes: (1) using only the DC cooler in the pre-booster, (2) using only the ERL circulate cooler in the collider ring, and (3) using both the DC cooler in the pre-booster and the ERL circulate cooler in the collider ring. In the pre-booster, a DC cooler with electron beam current of 3A is used to cool coasting proton beam of 3 GeV, which is simulated by the model beam method [4] in BETACOOL. Space charge effect of the electron beam is included. In the collider ring, Gaussian bunched electron beam of 1.5 A is used to cool coasting (very long bunch) proton beam at the injection energy (20 GeV), and the same electron beam is used to cool Gaussian bunched proton beam at the top energy (using proton energy 60 GeV instead of 100 GeV in the simulations below). Both processes are simulated by the RMS dynamic method with single particle model [4] for friction force calculation in BETACOOL. In all stages, we use Martini model [4, 5] to calculate the IBS effects and use the thin lens model for the coolers. Typical parameters for the different cooling schemes are presented in Table 1.

DC Cooling

In the pre-booster, top kinetic energy of the proton beam is 3 GeV. Its normalized emittance 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, smaller than the space charge tune shift limit. 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 shows the evolvement of the normalized emittance and the momentum spread of the proton beam during the cooling process. After about 600 s, the emittance reaches the equilibrium at about (0.6, 0.2) $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$. Because we need to accumulate 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 up 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. 3. After being accelerated at 60 GeV, without cooling the horizontal emittance of the proton beam keeps increasing due to IBS effect. As Fig. 4 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.

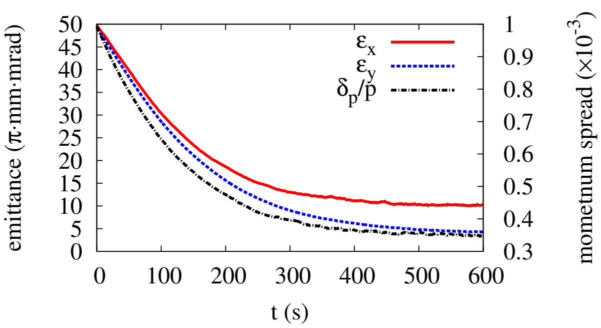

Figure 2: DC cooling in the pre-booster

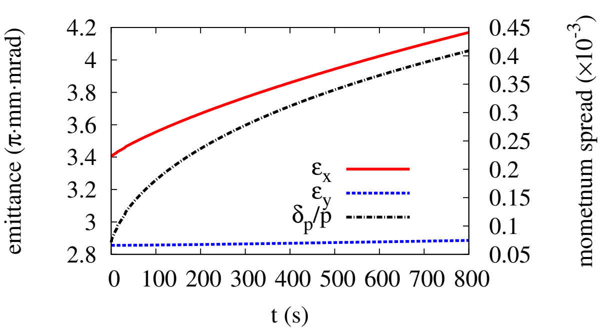

Figure 3: IBS expansion in the collider ring at 20 GeV

ERL Circulate Cooling

Without cooling in the pre-booster, the initial normalized emittance of the proton beam in the collider ring at 20 GeV is assumed to be 31.5 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, and the momentum spread 3×10^{-3}, both limited by the space charge

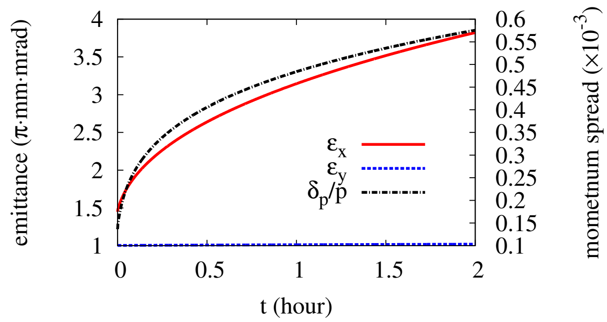

Figure 4: IBS expansion in the collider ring at 60 GeV

tune shift. 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 very efficient as shown in Fig. 5. The emittance reaches the equilibrium within 250 s. Simulations also suggest that coupling is helpful for the cooling at 60 GeV. 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 gets bunched, the emittance can be further reduced to 0.17 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ within 20 s with 100% coupling in transverse directions as shown in Fig. 6. 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. 7, which provides a flat beam.

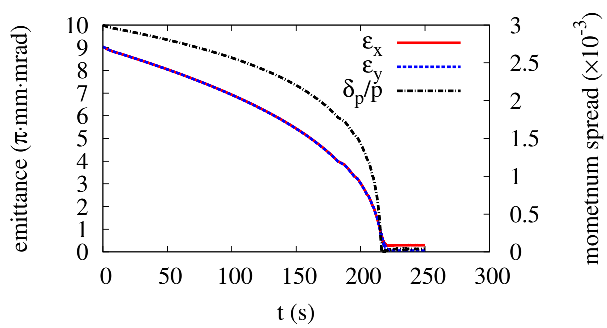

Figure 5: Cooling in collider ring at 20 GeV

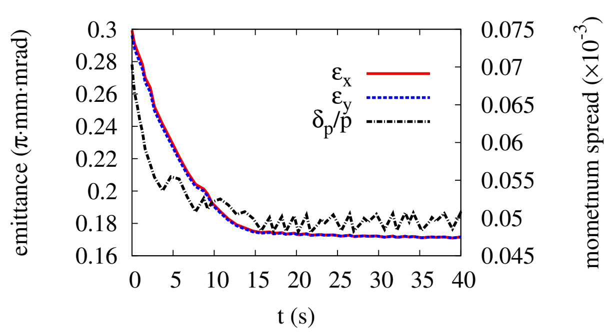

Figure 6: Cooling in collider ring, 60 GeV, 100% coupled

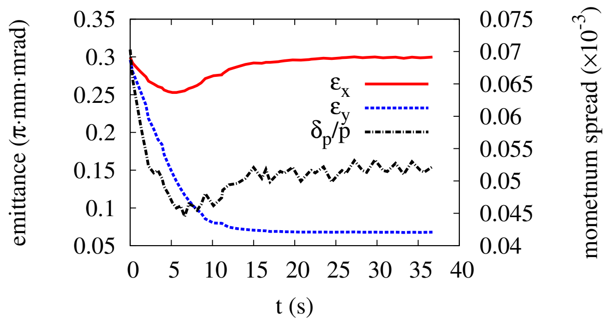

Figure 7: Cooling in collider ring, 60 GeV, 40% coupled

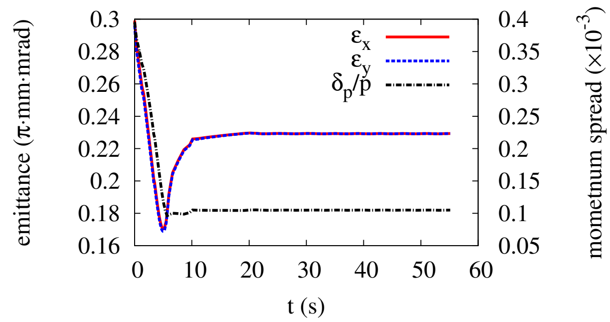

Figure 9: Cooling in collider ring, 60 GeV, 100% coupled

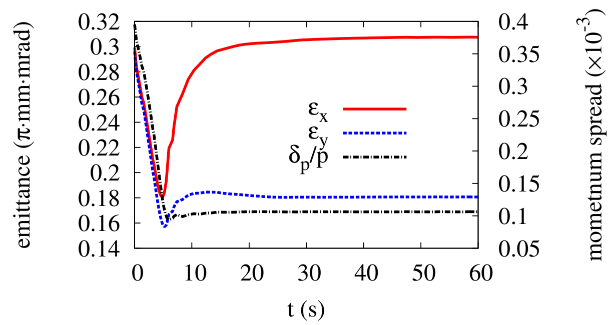

Figure 10: Cooling in collider ring, 60 GeV, 50% coupled

DC Cooling Together with ERL Circulate Cooling

When we use both the DC cooler in the pre-booster and the ERL circulate Cooler in the collider ring, cooling in the pre-booster is the same as shown in Fig. 2. 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. 8. When the emittance is reduced to about 0.3 $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, according to Fig. 8, the momentum spread is in the order of 10^{-6}, which leads to very strong IBS for bunched beam at the length of around 1 cm. So it is reasonable to assume the momentum spread will increase during the bunching process. In the following simulations for the cooling at 60 GeV, an initial momentum spread of 3.7×10^{-4} is used. As Fig. 9 and Fig. 10 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.

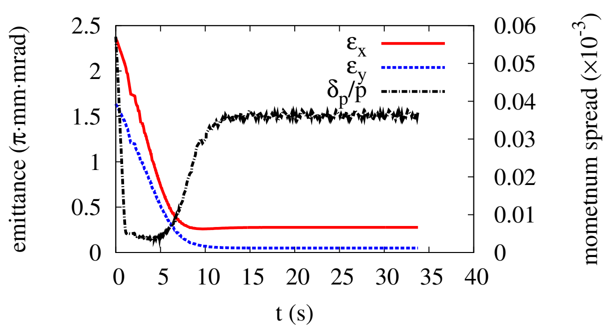

Figure 8: Cooling in collider ring, 20 GeV

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. 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 beam repeatedly 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.

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