SIMULATION STUDY FOR MEIC ELECTRON COOLING*

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Abstract

Electron cooling of the ion beams is one critical R&D to achieve high luminosities in JLab’s MEIC proposal. In the present MEIC design, a multi-staged cooling scheme is adapted, which includes DC electron cooling in the pre-booster and bunched electron cooling in the collider ring at both the injection energy and the collision energy. The high electron energy and current needed in the bunched electron cooling of MEIC is beyond the state-of-the-art. A concept of an ERL driven electron cooler with a circulator ring has been developed to meet these technical challenges. In this paper, we present simulation studies of electron cooling in MEIC. We also explore the MEIC luminosity performance if applying weak cooling (namely, with a reduced electron beam current) only or no cooling in the collider ring.

INTRODUCTION

The MEIC is designed to deliver high luminosities over a broad CM energy range with the peak luminosity above $10^{34}$ cm$^{-2}$s$^{-1}$ per interaction point (IP). It offers collisions of 3 to 12 GeV electrons with 25 to 100 GeV protons, or all-stripped light to heavy ions of corresponding energies per nucleon with the same magnetic rigidity [1].

The MEIC ion complex consists of ion sources, an SRF linac, two booster synchrotrons and a medium energy collider ring, as shown by a schematic drawing in Fig. 1. The conventional electron cooling is chosen to assist accumulation of ions from the linac and to reduce and preserve the emittance of the MEIC ion beam. It is proposed to have electron coolers installed both in the pre-booster and in the collider ring. A multi-phased electron cooling scheme has been adopted for achieving high cooling performance. The scheme includes the following steps: (1) DC electron cooling in the injection energy of the pre-booster for assisting accumulation of positive ions; (2) low energy (up to 2 MeV) DC cooling at the pre-booster for an initial emittance reduction; (3) bunched cooling at the ion injection energy (25 GeV/u) of the collider ring for further emittance reduction; and (4) bunched cooling at the top ion energy (up to 100 GeV/u) of the collider ring. The advantage of two pre-cooling stages (step 2 and 3) is relatively high cooling efficiency at low energy and low emittance. An important feature of this scheme is continuous electron cooling of the ion beams during their collision with the electron beam for suppressing the intra-beam scattering (IBS) induced emittance growth.

While the conventional electron cooling technology is well developed and successfully tested with low energy cooling schemes, we are challenged by the high intensity and high energy of the MEIC ion beam [2, 3]. The nominal design concept calls for an ERL for 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]. The high electron current (up to 1.5 A) and the fast kicker needed to transport the electrons between the ERL and the circulator ring are beyond the state-of-the-art. To reduce reliance on the ERL and circulator ring, we explored the effectiveness of weak cooling using a reduced electron current in the collider ring. In the weak cooling scheme, the circulator ring (and the fast kicker) is not needed. We also studied the case that there is only the DC cooling in the pre-booster, but no cooling applied in the collider ring.

In this report, we present the simulation studies of the cooling efficiency and the achievable luminosity for the three different cooling scenarios. In the nominal design, the collective effects in the circulator ring may affect the property of the electron bunch, thus further affect the cooling efficiency, which is currently also under study [4]. However, in this paper, as the first phase of studies and for simplicity, the coupling to the electron beam dynamics in the circulator cooler ring is ignored. 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. In the next phase, these two studies will be combined as we expect.

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 capable 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 cooling processes: (1) DC electron cooling in the pre-booster, (2) bunched electron cooling for coasting ion beam in the collider ring at the injection energy, and (3) bunched electron cooling for bunched ion beam in the collider ring at the collision energy. For the latter two processes, we simulated for both the nominal design parameters and the weak cooling parameters. We also

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simulated the evolution of the ion beam when there is no cooling in the collider ring.

The highest kinetic energy of protons in the pre-booster is 3 GeV, the corresponding kinetic energy of the cooling electron energy is about 1.63 MeV. The space charge effect of the DC electron beam is included. In the collider ring, a Gaussian bunched electron beam of 1.5 A for the nominal design or 0.375 A for the weak cooling is used to cool a coating (very long bunch) proton beam at the injection energy (25 GeV), and the same electron beam is used to cool a Gaussian bunched proton beam at the collision energy (up to 100 GeV). The beam and cooler parameters for the different cooling schemes are presented in Table 1. $E_p$, $N_p$, and $l_p$ mean the kinetic energy, particle number and the bunch length of the proton beam. $B$ is the longitudinal magnetic field inside the cooler, $l_c$ is the cooler length. $l_e$ and $l_c$ are current and bunch length of the electron beam. The fourth and the fifth columns are parameters for strong and weak cooling in the collider ring respectively.

Table 1: Key Parameters for Different Cooling Schemes

<table>
<thead>
<tr>
<th></th>
<th>Pre-Booster</th>
<th>Collider Ring</th>
</tr>
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<tbody>
<tr>
<td>$E_p$ (GeV)</td>
<td>3</td>
<td>25-100</td>
</tr>
<tr>
<td>$N_p$ (10^12)</td>
<td>2.52</td>
<td>12.6</td>
</tr>
<tr>
<td>$l_p$ (cm)</td>
<td>Coasting</td>
<td>Coast./1</td>
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<tr>
<td>$B$ (T)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$l_c$ (m)</td>
<td>10</td>
<td>2×30</td>
</tr>
<tr>
<td>$I_e$ (A)</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>$l_e$ (cm)</td>
<td>−1.2</td>
<td>−1.2</td>
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We utilized the well developed BETACOOL code, which provides various formulas for the 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 used for DC cooling simulation and the RMS dynamic method with the single particle model is used for bunched electron beam cooling simulation [5].

**SIMULATION RESULTS**

**DC Cooling in the Pre-booster**

In the pre-booster, the initial normalized emittance of the proton beam is assumed to be 1.75 $\pi \cdot$ mm $\cdot$ mrad in both transverse directions, which is limited by the space charge tune shift. The momentum spread is assumed to be 0.001. The radius of the electron beam is 0.65 cm, which is three times of the rms radius of the proton beam. The current of the electron beam is 3 A. Fig. 2 shows the evolution of the normalized emittance and the momentum spread of the proton beam during the cooling process, while IBS effect is also included. After about 250 s, the transverse emittance of the proton beam reaches the equilibrium of cooling and IBS at about (0.58, 0.30) $\pi \cdot$ mm $\cdot$ mrad. After the pre-booster, the proton beam will be injected into the large booster, the circumference of which is five times that of the pre-booster. To avoid instability, the space charge tune shift in the large booster at its injection energy to be less than 0.2. Then the space charge tune shift in the pre-booster at the extraction energy should be less than 0.04, which put a lower limit of 0.55 $\pi \cdot$ mm $\cdot$ mrad for the transverse emittance. According to Fig. 2, if the cooling is terminated at 120 s, the transverse emittance will be (0.80, 0.55) $\pi \cdot$ mm $\cdot$ mrad. And the momentum spread is $5 \times 10^{-4}$.

![Figure 2: Cooling in the pre-booster](image)

**Strong Cooling in the Collider Ring**

The proton beam will be accelerated to 25 GeV in the large booster, and then injected into the collider ring. Five very long bunches of protons will be accumulated in the collider ring. The long bunches will be de-bunched into a coasting beam, and then re-bunched into more than 3000 short bunches. The cooling in the collider ring includes the following two different stages.

![Figure 3: Cooling in the collider ring at 25 GeV](image)

The first stage is to use bunched electron beam to cool coating proton beam at the injection energy of 25 GeV. In the MEIC nominal design, the total charge of each electron bunch is 2 nC, the frequency is 750 MHz, thus the average current of the cooling electron beam is 1.5 A. The total proton number in the ring is $1.26 \times 10^{12}$. We assume the initial normalized emittance of the proton beam is (0.81, 0.58) $\pi \cdot$ mm $\cdot$ mrad, and the
The initial momentum spread is $5 \times 10^{-4}$. The evolution of the emittance and the momentum spread during the cooling process is shown in Fig. 3. As we can see, the cooling is very efficient. After 70 seconds, the proton emittance reaches the equilibrium values $(0.088, 0.014) \pi \cdot \text{mm} \cdot \text{mrad}$ and the momentum spread is $1.7 \times 10^{-4}$. However, such a low emittance will be very difficult to maintain during collision. So we would like to stop cooling at 40 second, when the emittance is $(0.30, 0.25) \pi \cdot \text{mm} \cdot \text{mrad}$. The corresponding space charge turn shift is 0.015, much less than 0.2. Basically in the collider ring, space charge turn shift will not limit the emittance due to the high energy.

The second stage is to use the bunched electron beam to cool the bunched proton beam before and during the collision. We simulated the cooling process at two energy points, 60 GeV and 100 GeV, respectively. For both cases, we assume the initial emittance is $(0.30, 0.25) \pi \cdot \text{mm} \cdot \text{mrad}$ and the momentum spread is $4 \times 10^{-4}$. The proton number in each bunch is $4.16 \times 10^9$. The initial proton bunch length is slightly longer than 1 cm and it will reduce to 1 cm at equilibrium. The evolution of the emittance and the momentum spread during the cooling process at 60 GeV is shown in Fig. 4. After carefully adjusting the coupling in the transverse directions and the dispersion function in the cooler for the proton beam, which helps to redistribute the IBS effect and the cooling effect in different directions, the emittance can be slightly reduced to $(0.28, 0.05) \pi \cdot \text{mm} \cdot \text{mrad}$ and maintained at this value. It takes only 200 seconds to reach the equilibrium. The evolution of the same physical quantities for 100 GeV cooling is shown in Fig. 5. The emittance is also slightly reduced to $(0.29, 0.23) \pi \cdot \text{mm} \cdot \text{mrad}$ and maintained, although it takes much longer to reach the equilibrium.

**Weak Cooling in the Collider Ring**

The beam current of MEIC high energy ERL based electron cooler is drastically reduced without a circulator ring. Such a weak cooling will not be able to deliver the required beam emittance supporting the MEIC nominal luminosity design goal. In the following we will report results of weak electron cooling in the collider ring using 0.375 A electron current, which means 0.5 nC per bunch in 750 MHz.

The weak cooling in the collider ring also includes two stages: cooling of the coasting proton beam at the injection energy of 25 GeV and cooling of the bunched proton beam at the collision energy of up to 100 GeV. As it shows in Fig. 6, even with a low-current electron beam, the cooling of the coasting proton beam at 25 GeV is still very efficient. In four minutes, the emittance is reduced to $(0.18, 0.02) \pi \cdot \text{mm} \cdot \text{mrad}$. But to prevent over cooling, we terminate cooling at about 2.5 minutes, when the emittance is $(0.30, 0.20) \pi \cdot \text{mm} \cdot \text{mrad}$. In this simulation, we still assume the total proton number is $1.26 \times 10^{13}$. The weak cooling at 60 GeV is shown in Fig. 7. If the proton number per bunch is as high as the nominal design, the cooling effect will not be strong enough to compensate the IBS effect. We reduce the
proton number per bunch from $4.16 \times 10^9$ to $3 \times 10^9$, then the emittance can be maintained at $(0.30, 0.22) \, \pi \cdot \text{mm} \cdot \text{mrad}$. Similarly, at 100 GeV we have to reduce the proton number per bunch to $1.16 \times 10^9$. Then the emittance will be maintained at $(0.29, 0.23) \, \pi \cdot \text{mm} \cdot \text{mrad}$.

No Cooling in the Collider Ring

The DC cooler in the pre-booster is within the-state-of-the-art. A two MeV DC cooler with similar parameters with ours has been successfully built and is currently under commissioning at COSY, in Juelich, Germany [7]. The DC cooler at the MEIC pre-booster will have similar parameters with the one at COSY. So we do not expect large technical difficulty to build our DC cooler. The high energy bunched electron cooler in the collider ring needs significant R&D. To investigate the bottom line of the MEIC cooling scheme, we consider a case that only the DC cooling is applied in the pre-booster and study the evolution of the proton beam with no cooling in the collider ring. After the DC cooling, the normalized emittance is reduced to $(0.80, 0.55) \, \pi \cdot \text{mm} \cdot \text{mrad}$ and the momentum spread is $4 \times 10^{-4}$. Without cooling in the collider ring, the emittance and the momentum spread will increase due to the IBS effect as shown in Fig. 9 and Fig. 10. In both cases, the horizontal emittance increases to about $4.5 \, \text{mm} \cdot \text{mrad}$, while the vertical emittance almost unchanged, because the IBS effect is much weaker in the vertical direction. The momentum spread increases to $8.7 \times 10^{-4}$ at 60 GeV and $7.2 \times 10^{-4}$ at 100 GeV.

Luminosity

Figure 11 and 12 show the MEIC luminosity for the three different cooling schemes, the nominal design scheme, the weak cooling scheme, and the DC cooling in pre-booster only scheme, at 60 GeV and 100 GeV respectively. For the luminosity calculations, both beams are assumed to be Gaussian and the following parameters are used. Electron beam energy is 5 GeV. Electron number per bunch is $2.5 \times 10^{10}$. The normalized emittance of the electron beam is $(53.5, 10.7) \, \pi \cdot \text{mm} \cdot \text{mrad}$. The $\beta$ functions at the interaction point are 10 cm and 2 cm in horizontal direction and vertical direction respectively, same for both the electron beam and the proton beam. As Fig. 11 shows, at 60 GeV, the nominal design provides the highest luminosity of $6.5 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$. The weak cooling scheme provides a luminosity of $3 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$. When there is no cooling in the collider ring, the luminosity will decreases from $2 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$, which is achieved by the DC cooling in the pre-booster only. In two hours, the luminosity decreases to $1 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$. Figure 12 shows the luminosities for the three cooling schemes at 100 GeV. The nominal design still provides the highest luminosity of $5.5 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$. With only the DC cooling in the pre-booster, a luminosity of $3 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$ can be achieve initially in the collider ring. Then it will decreases due to the IBS effect. After two hours, the luminosity is about $1.7 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$. The luminosity of the weak cooling scheme is the lowest, as...
about $1.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$, which is due to the lowest proton beam current. The benefit of using weak cooling is that the luminosity can be kept at $1.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$ constantly as long as needed. So the bottom line is the machine will be able to operate with the luminosity above $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$ continuously for at least two hours.

**SUMMARY AND DISCUSSION**

Preliminary simulation results suggest the nominal 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. The simulation result for the weak cooling scheme is also encouraging. Although to reduce the IBS effect the proton beam current has to be reduced, we can still achieve a luminosity more than $10^{33}$ cm$^{-2}$s$^{-1}$. However, 0.375 A or 0.5 nC per bunch is still a challenge with current technology. We wish to reduce the electron beam current to 0.1 A. Even without cooling in the collider ring, the simulation results show that the luminosity can be maintained above $10^{33}$ cm$^{-2}$s$^{-1}$ for at least two hours. Cooling in the pre-booster takes about two minutes. Then it will takes about ten minutes to accumulate five bunches in the collider ring. If we refresh the proton beam every two hours, the duty factor will be around 92%, which is very good.

There are some points we want to note as follows. (1) Transverse coupling is helpful for the cooling in the collider ring. Usually the horizontal IBS effect is much stronger than the vertical IBS effect. But due to the symmetry, the cooling effects on both transverse directions are almost the same. When there is surplus cooling in the vertical direction, there may be not enough cooling in the horizontal direction. Furthermore, if the beam is overcooled in the vertical direction, the IBS effect in both direction will increase, which makes it more difficult to cool in the horizontal direction. The coupling in the transverse directions will help to balance the IBS effect in the transverse directions, thus it helps for cooling. But its dynamic effect needs to be studied. (2) In the above simulations on the high energy bunched electron cooling in the collider ring, RMS dynamic model is used, which assumes the proton beams always have Gaussian distributions. However, when a strong cooling is applied, the Gaussian distribution is unlikely to be maintained during the cooling process. We need to study how the ion beam distribution evolves in different cooling processes and how much it affects the luminosity if the distribution deviates from Gaussian. (3) Analytical formulas are used to calculate the friction force, and their accuracy under the MEIC parameters need to be checked and confirmed. (4) The electron bunches are repeatedly used for 10 to 100 times in the ERL circulator cooler. The collective effects, such as CSR effect, in the circulator ring may change the property of the electron bunch, which could result in a reduction of the cooling rate. This effect is ignored in the above simulations, but it has to be addressed later. (5) It is also important to understand how the electron bunch may be 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. (6) When calculating the friction force, the ion is treated as a small perturbation to the electron beam. But in the weak cooling scheme, the charge density of the proton beam and the electron beam is close to each other. In this case it may not be proper to treat the proton as a perturbation any more. The cooling effect when the proton beam and the electron beam has similar density needs to be understood. The study on the above issues is being carried on.

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