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ELECTRON COOLING STUDY FOR MEIC*

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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 booster ring and bunched beam electron cooling in the collider ring at both the injection energy and the collision energy. We explored the feasibility of using both magnetized and non-magnetized electron beam for cooling, and concluded that a magnetized electron beam is necessary. Electron cooling simulation results for the newly updated MEIC design is also presented.

INTRODUCTION

The medium energy electron ion collider (MEIC) proposed by JLab can deliver a luminosity above 10^{34} $\mathrm{cm^{-2}s^{-1}}$ at a center-of-mass energy up to 65 GeV. It offers an electron energy up to 10 GeV, a proton energy up to 100 GeV, and corresponding energies per nucleon for heavy ions with the same magnetic rigidity [1]. Cooling of proton and ion beams is essential for reduction of beam emittance, suppressing the intra-beam scattering (IBS) effect thus achieving the high luminosity. The conventional electron cooling technique is chosen and a multi-stage cooing strategy has been developed.

Figure 1 shows the schematic layout of the MEIC ion complex, including a DC cooler in the booster and a bunched beam cooler in the collider ring. Since the electron cooling time is in proportion to the energy and the 6D emittance of the ion beam, it is preferred to begin the process of cooling the ion beam to the desired emittance at the lower energy. In addition, it is necessary to apply cooling during collision to maintain the emittance, otherwise the strong IBS effect will lead to a quick increase of the ion beam emittance and the luminosity will collapse. The cooling scheme for the proton beam includes the following three stages: (1) DC cooling for 2 GeV proton beam in the booster, (2) bunched beam cooling for proton beam at the injection energy (8 GeV) in the collider ring, and (3) bunched beam cooling for proton beam at the collision energy in the collider ring.

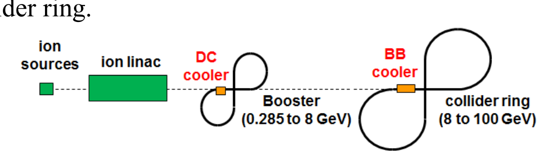

Figure 1: MEIC ion complex layout.

The technology of DC cooling is mature. A magnetized DC cooler with similar performance required by MEIC has been successfully built and commissioned at the COSY facility at Juelich [2]. The cooling by a bunched electron beam is beyond the state-of-art. The MEIC bunched beam cooler is composed of two 30 meter long cooling sections and an ERL circulator ring, which allows to repeatedly use the electron bunch tens of times. In the following we will discuss the necessity of using magnetized electron beam in the bunched beam cooler and present some simulation results.

MATCHING OF BETATRON FUNCTION IN SOLENOID

The transfer matrix of a solenoid can be written as

$$M=\begin{pmatrix} C^2 & SC/k & SC & S^2/k \\ -kSC & C^2 & -kS^2 & SC \\ -SC & -S^2/k & C^2 & SC/k \\ kS^2 & -SC & -kSC & C^2 \end{pmatrix},$$

where $k=B_0/(2B\rho)$, B_0 is the magnetic field inside the solenoid, $B\rho$ is the magnetic rigidity of the reference particle moving along the central trajectory, $C=\cos kL$, $S=\sin kL$, and L is the effective length of the solenoid [3]. Assuming the incoming beam is round with no correlation in the transverse directions, the Σ matrix of the incoming beam can be written as

$$\Sigma_i=\begin{pmatrix} \sigma_{11} & \sigma_{12} & 0 & 0 \\ \sigma_{12} & \sigma_{22} & 0 & 0 \\ 0 & 0 & \sigma_{11} & \sigma_{12} \\ 0 & 0 & \sigma_{12} & \sigma_{22} \end{pmatrix}.$$

At the exit of the solenoid, we have

$$\Sigma_f=M\Sigma_i M^T=\begin{pmatrix} \Sigma_{xf} & 0 \\ 0 & \Sigma_{yf} \end{pmatrix},$$

where M^T is the transpose of M, $\Sigma_{xf}=\Sigma_{yf}=\Sigma$ and component-wisely

$$\Sigma_{11}=C^2\sigma_{11}+\frac{2CS}{k}\sigma_{12}+\frac{S^2}{k^2}\sigma_{22},$$

$$\Sigma_{12}=\Sigma_{21}=-kSC\sigma_{11}+(C^2-S^2)\sigma_{12}+\frac{SC}{k}\sigma_{22},$$

$$\Sigma_{22}=k^2S^2\sigma_{11}-2kCS\sigma_{12}+C^2\sigma_{22}.$$

To keep the transverse bunch size constant inside the solenoid, we need to have constant β function, which means $\beta(s)=\beta$ and $\alpha(s)=0$ for $0\le s\le L$. Thus we have $\sigma_{12}=0$ and $\sigma_{22}=\varepsilon/\beta=\sigma_{11}/\beta^2$ in the solenoid. Since the transverse bunch size does not change, we have

$$\sigma_{11}=C^2\sigma_{11}+\frac{2CS}{k}\sigma_{12}+\frac{S^2}{k^2}\sigma_{22}=C^2\sigma_{11}+\frac{S^2}{k^2\beta^2}\sigma_{11}.$$

So that

$$\beta=\frac{1}{|k|}=\frac{2B\rho}{B_0}=\frac{2p}{qB_0}, \qquad (1)$$

where p, and q are momentum and the charge number of the particle. Eq. (1) is the matching condition for the transverse β function in a solenoid.

The Larmor frequency of a charged particle inside a solenoid is $\omega=Bq/\gamma m_0$, where m_0 is the mass of the

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particle, and γ is the Lorentz factor. During the cooling process, the proton beam and the electron beam have the same γ, however the proton mass is about 2000 times larger than the electron mass, thus the Larmor frequency of the electron is about 2000 times higher than that of the proton. The magnetic field of the cooler solenoid is 2 T and the length of it is 30 m. When the kinetic energy of the proton is 100 GeV, the kinetic energy of the electron is 54.5 MeV. The Lorentz factor is $\gamma = 107.6$. The Larmor frequency of the electron is 3.27 GHz, and when the electron passes through the solenoid, it will finish more than 327 periods of its Larmor rotation. To avoid severe variance of the transverse bunch size, the β function of the electron beam should satisfy the above matching condition. The Larmor frequency of the proton is only 1.8 MHz. The proton can only make 0.18 period of its Larmor motion when it passes through the solenoid. In this case, it is not necessary to match the β function of the proton beam. As a result, the transverse bunch size of the proton beam will change inside the solenoid. Assuming the β function of the proton beam at the center of the solenoid is 10 m, at the end of the solenoid $\beta_{end} = \beta_{center} + \frac{(0.5*L)^2}{\beta_{center}} = 32.5$ m. As an example of the proton energy during collision, with the kinetic energy of 100 GeV and the normalized transverse emittance of 0.3 μm · rad, the bunch size and respective temperature of the proton beam at the center and the end of the solenoid is listed in table 1.

Table 1: Proton Beam at Collision Energy ($\gamma = 107.6$)

ε_n	σ_{center}	σ_{end}	T_{center}	T_{end}
μm · rad	Mm	mm	eV	eV
0.3	0.2	0.36	3028	932

NON-MAGNETIZED COOLING

The cooling electron beam has the same Lorentz factors with the ion beam and usually has a larger transverse bunch size than the ion beam. To cool the 100 GeV proton beam in table 1, it is reasonable to assume the electron beam bunch size to be 0.4 mm, larger than the proton beam bunch size everywhere in the solenoid. The β function of the electron beam should satisfy the matching condition, which can be calculated using Eq. (1). The normalized emittance ε_n and the bunch size σ are related by $\sigma = \sqrt{\beta_\perp \cdot \frac{\varepsilon_n}{\beta\gamma}}$, so the normalized emittance can be calculated once $\beta_\perp$, the transverse β function, and σ, the bunch size, are determined. Then the temperature can be calculated by $T_\perp = \varepsilon_n^2\, m\, c^2/\sigma^2$. The matched β function, bunch size, normalized emittance and temperature of the electron beam for different magnetic field are listed in table 2. When B = 1 or 2 T, the temperature of the electron beam is much larger than that of the proton beam. The proton beam will be heated instead of being cooled. To reduce the temperature while keeping large enough transverse bunch size for the electron beam, we have to reduce the magnetic field substantially, which allows much larger matched β. For example, if we reduce the magnetic field to 0.1 T, the electron beam temperature is 70.34 eV. The non-magnetized cooling rate can be estimated by

$$R_c = \frac{3\pi r_p r_e c n_e L_C}{\sqrt{2}\gamma^2\left(2\cdot\left(\frac{T_e}{m_e c^2}\right)^{\frac{3}{2}} + \left(\frac{T_p}{m_p c^2}\right)^{\frac{3}{2}}\right)} \cdot \frac{l_c}{C}, \qquad (2)$$

where r_p, r_e, T_e, T_p, m_e, and m_p are the classical radius, temperature, and mass of the proton and the electron, c is the speed of light, n_e is the charge density of the electron, γ is the Lorentz factor, L_C is the Coulomb logarithm, which is close to 20, l_c is the total length of the cooling section, and C is the circumference of the ring [4]. When B = 0.1 T, The cooling rate will be $7.9\times10^{-5}\ \mathrm{s}^{-1}$. The cooling effect is not strong enough to compensate the IBS effect, due to which the increase rate of emittance is in 10^{-4} to 10^{-3} level for the proton beam.

We notice that the two terms at the bottom of Eq. (2) for non-magnetized cooling rate should be comparable for efficient cooling, which means the temperature of the electron beam should be about 2000 times smaller than that of the proton beam. However, to keep the electron bunch large enough with the small matched β, we need large emittance, which leads to high temperature. The two requirements conflict. Within our parameter range, we cannot find a set of parameters that simultaneously satisfy them. The conclusion is non-magnetized beam will not be able to cool the proton beam for MEIC. We have to use magnetized beam.

Table 2: Electron Beam Parameters ($\gamma = 107.6$)

B	ε_n	β	σ_e	T_e
T	μm · rad	cm	mm	eV
2	93.86	18.34	0.4	3×10^4
1	46.93	36.68	0.4	7×10^3
0.1	4.69	314	0.4	70.34

MAGNETIZED COOLING

Magnetized beam are generated inside a cathode immersed in a solenoid field. The motion of a magnetized electron has two canonical components: the Larmor motion and the drift motion. The respective dynamic invariants are the Larmor emittance ε_c and the drift emittance ε_d. When the two motions are uncoupled and $\varepsilon_c \ll \varepsilon_d$, such a beam is called the calm beam. One can manage to make the magnetized beam inside the cathode in the calm status. As long as the transport section between the cathode and the solenoid satisfies the matching condition, the calm status can be restored inside the solenoid [5].

Under a specific β function, the transverse bunch size of the magnetized electron beam is determined only by the drift emittance. When $B = 2$ T and $\sigma_e = 0.4$ mm, the

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drift emittance $\varepsilon_d = 93.8\,\mu\text{m}\cdot\text{rad}$. The Larmor emittance ε_c is much less than ε_d. A reasonable guess is $\varepsilon_c = 1.5\,\mu\text{m}\cdot\text{rad}$. Then the traditional emittance $\varepsilon_n = \sqrt{\varepsilon_d\cdot\varepsilon_c} = 11.9\,\mu\text{m}\cdot\text{rad}$. The magnetized cooling time can be estimated using the empirical formula from V. Parkhomchuk [6]:

$$t_c = \frac{\gamma^2}{4\pi r_e r_p c\left(\frac{l_c}{C}\right) L_c}\left(\frac{\gamma\varepsilon_p}{\beta_p}\right)^{\frac{3}{2}},$$

where ε_p and β_p are the emittance and the β function for the proton beam. The Coulomb logarithm $L_C = 20$. At the collision energy, the cooling time $t_c = 24.1$ s, which suggests the magnetized electron beam can be used for the high energy cooling in MEIC.

ELECTRON COOLING SIMULATION

We have performed simulations for all the three cooling stages using the well-developed BETACOOL code. As to the following results, Martini model [7] is used for IBS effect calculation, and the RMS dynamic method with the single particle model is used for both the DC cooling and the bunched electron beam cooling simulation [8].

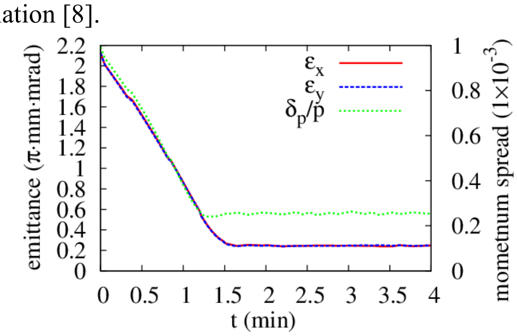

Figure 2: DC Cooling of a proton beam in the MEIC booster, the proton energy is 2 GeV.

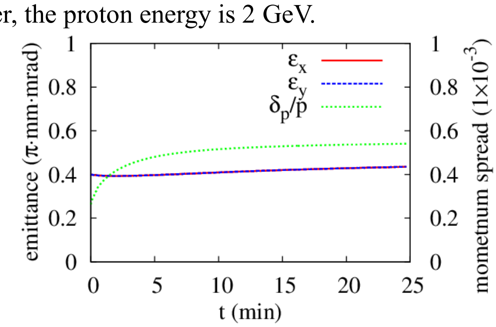

Figure 3: Cooling of 8 GeV proton beam by a bunched electron beam in the MEIC collider ring.

In the booster, the initial normalized emittance of the proton beam is assumed to be 2.2 $\mu\text{m}\cdot\text{rad}$ in both transverse directions, limited by the space charge tune shift. The momentum spread is assumed to be 0.001. The radius of the electron beam is 0.80 cm, which is three times of the rms radius of the proton beam. The current of the electron beam is 2 A. Figure 2 shows the evolution of the normalized emittance and the momentum spread of the proton beam during the cooling process. The emittance is reduced to about 0.3 $\mu\text{m}\cdot\text{rad}$ in 1.5 minutes.

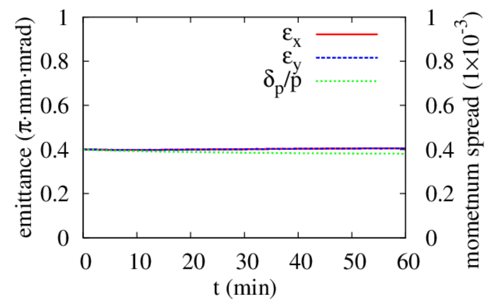

Figure 4: Cooling of 100 GeV proton beam by a bunched electron beam in the MEIC collider ring.

In the collider ring, bunched beam cooling is used to maintain the proton beam emittance at both the injection energy and the collision energy. Figure 3 and 4 show the emittance and momentum spread under the equilibrium between the IBS effect and the electron cooling effect for 8 GeV coasting proton beam and 100 GeV bunched proton beam respectively. In both cases, the normalized emittance is maintained at 0.4 $\mu\text{m}\cdot\text{rad}$ with electron beam current less than 1.1 A.

CONCLUSION

To keep a constant bunch size inside a long solenoid, the β function of electron beam has to satisfy the matching condition. To achieve the desired bunch size, the small matched β function of non-magnetized electron beam, leads to large emittance and high temperature. So that it is not suitable to use non-magnetized beam in cooling for MEIC. Magnetized electron beam can achieve the desired bunch size while maintaining low temperature, since its bunch size is only determined by the drift emittance and the Larmor emittance is much smaller than the drift emittance. Preliminary simulations suggest the nominal design parameters of MEIC cooling system are achievable using magnetized electron beam.

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