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# MULTI-STAGE ELECTRON COOLING SCHEME FOR JLEIC*

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*Abstract*

JLEIC is the future electron ion collider under design at Jefferson Lab, which will provide a luminosity up to $10^{34}$ cm$^{-2}$s$^{-1}$. Electron cooling is essential for JLEIC to overcome the intrabeam scattering effect, reduce the ion beam emittance and thus achieve the high luminosity. The cooling time is approximately in proportion to the square of the energy and the 6D emittance. To avoid the difficulty of cooling the ion beam with large emittance at high energy, a multi-stage cooing scheme was designed for JLEIC. The ion beam was cooled at the low energy to reduce the emittance. Then it was ramped up to the collision energy. During the collision, electron cooling is implemented to maintain the emittance and the luminosity. Simulations for proton beam and lead ion beam at various stages are presented in this paper.

## JLEIC MULTI-STAGE COOLING SCHEME

To reach the frontier in Quantum Chromodynamics, the JLab Electron Ion Collider (JLEIC) will provide an electron beam with energy up to 10 GeV, a proton beam with energy up to 100 GeV, and heavy ion beams with corresponding energy per nucleon with the same magnetic rigidity. The center-of-mass energy goes up to 70 GeV. Two detectors, a primary one with full acceptance and a high-luminosity one with less demanding specification, are proposed. To achieve the ultrahigh luminosity close to $10^{34}$ cm$^{-2}$s$^{-1}$ per detector with large acceptance, the traditional electron cooling will be implemented strategically. [1]

The JLEIC ion complex consists of ion sources, an SRF linac, a booster ring and a collider ring, as shown in Fig 1. In the booster ring, a low energy DC cooler will be installed only for heavy ion beam injection. In the collider ring, both a DC cooler and an ERL based bunched beam cooler will be installed. The cooling section of the ERL cooler consists four 15 m long solenoids and it provides a mangetized bunched electron beam with charges up to 3.2 nC/bunch. The cooling section of the DC cooler is 30 m long and it provides a magnetized DC electron beam up to 2 A. We assume the magnetic field in the cooling section is 1 T for both coolers and the DC cooler shares two solenoids with the ERL cooler.

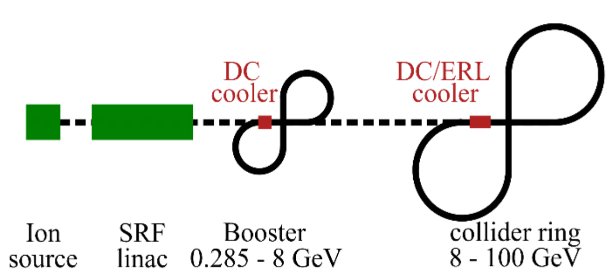


Figure 1: Components of JLEIC ion complex.

As shown in Eq. (1) , the cooling time is proportional to $\gamma^2$, with $\gamma$ representing the Lorentz factor, and the 6D normalized emittance of the ion beam. It tells us the

$$\tau_{\mathrm{cool}} \propto \gamma^2 \frac{\Delta\gamma}{\gamma} \sigma_z \varepsilon_{4\mathrm{d}} \tag{1}$$

cooling will be easier when the ion beam energy is low or the ion beam emittance is small. This is the theoretical foundation of the mulit-stage cooling scheme for JLEIC. Being aware of the difficulty of cooling the high energy ion beam, JLEIC cooling is separated into two steps: (1) pre-cool the ion beam to reduce the emittance when the ion beam energy is low (8 GeV/u) and (2) use cooling to maintain the already reduced emittance after the ion beam is accelerated to the collision energy. In this way, the most difficult scenario, cooling the high energy ion beam with large emittance, is avoided.

The cooling stages for both the proton beam and the lead ion beam for JLEIC are listed in Table 1. The proton beam cooling includes two stages. The pre-cooling stage starts after the stacking of the proton beam in the collider ring when the proton beam kinetic energy is 7.9 GeV. At this stage, using the DC cooler we seek to reduce the normalized emittance of the proton beam to the desired value in collision. Then the proton beam is accelerated to the collision energy (up to 100 GeV). In the second stage the ERL cooler is used to maintain the emittance during collision. The heavy ion cooling includes four stages, taking an example of the lead ion. The first stage happens in the booster ring. A DC cooler is used to help accumulation of the heavy ions during the injection. The lead ion kinetic energy is 0.1 GeV/u and the respective cooling electron beam kinetic energy is 0.054 MeV. DC cooling technique at this energy is mature. The lead ion will be accelerated to 2.04 GeV/u in the booster and then be injected to the collider ring. To fill the collider ring, seven injections are needed. During this stacking process,

Table 1: JLEIC Multi-Stage Cooling Scheme

| Ring | Functions | Proton energy (GeV) | Lead ion energy (GeV/u) | Cooler |
|---|---|---|---|---|
| Booster | Accumulation | | 0.1 | DC |
| Collider | Stacking | | 2 | DC |
| Collider | Pre-cool | 7.9 | 7.9 | DC |
| Collider | collision | 100 | 40 | ERL |

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the second stage cooling is implemented. Due to the limit of the space charge tune shift, we cannot reduce the emittance, which will increase the tune shift. At this stage, the DC cooling is used to compensate the IBS effect and maintain a constant emittance. After the stacking, the lead ion beam is accelerated to 7.9 GeV/u for the third stage of cooling. At this energy, the space charge tune shift is not an issue any more. We use the DC cooling to reduce the emittance to the desired value. The final cooling stage happens during the collision. The ERL based bunched cooling is used to maintain the emittance.

## JSPEC DEVELOPMENT

JSPEC (Jlab Simulation Package for Electron Cooling) [2,3] is an open source numerical package for IBS effect and electron cooling process simulation developed at JLab. The goal of JSPEC is to enhance the simulation capability for electron cooling in JLEIC project. It will preferentially fulfil the needs of JLEIC design. The program simulates the evolution of the macroscopic beam parameters, such as emittances, momentum spread and bunch length, in different electron cooling scenarios with any combination of bunched or coasting ion beam with DC or bunched cooling electron beam. JSPEC has been thoroughly benchmarked with BETACOOL [4] for accuracy and efficiency. We have observed a large improvement of efficiency. For a typical simulation with both the IBS effect and electron cooling for JLEIC, JSPEC can be more than ten times faster than BETACOOL. JSPEC is under active maintenance and improvement. A GUI and an online version has been developed by Radiasoft LLC [5,6], which helps the users to set up the simulation, visualize the results and share their work. JSPEC has been actively used in our simulation study on electron cooling at JLab. The following simulations are performed using JSPEC.

## SIMULATION FOR PROTON BEAM

First we simulate the evolution of the proton beam during the stacking process. There is no cooling in the stacking for proton beam, so the emittance and momentum spread will increase due to the IBS effect. The kinetic energy is 7.9 GeV, initial emittance 2.2 mm·mrad, the rms bunch length 7 m, and the particle number $6.58 \times 10^{11}$/bunch. Figure 2 show the proton beam expansion in one hour. The stacking only last 10 minutes, during which the increases of emittance and momentum spread are very

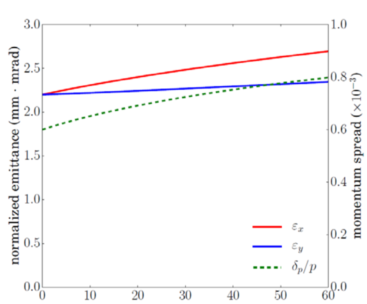


Figure 2: Proton beam IBS expansion at 7.9 GeV.

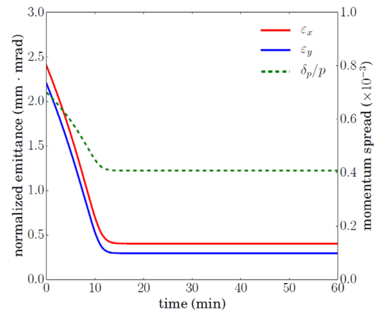


Figure 3: Pre-cooling for the proton beam at 7.9 GeV.

limited. This is why cooling is not needed in the stacking process for the proton beam.

The pre-cooling stage starts after the stacking of the proton beam in the collider ring. The DC cooler, 30 m long providing 3 A cooling electron beam, is used to reduce the normalized emittance to the desired value in collision. Figure 3 shows the pre-cooling process for the proton beam at 7.9 GeV. The equilibrium is reached within 15 minutes. The emittance is reduced below 0.5 mm · mrad and the momentum spread to $4 \times 10^{-4}$. Acceleration to the collision energy does not change the normalized emittance.

The second and final cooling stage for the proton beam happens during the collision. JLEIC covers a wide center-of-mass (CM) energy range from 21.9 GeV to 63.3 GeV. The property of the proton beam varies for different CM energies. In the following simulation, we choose the proton beam for 44.7 GeV CM energy. The kinetic energy of the proton beam is 100 GeV. We propose to deliver bunched proton beam with 0.75 A current, 0.5/0.1 mm·mrad transverse emittance, and 1 cm rms bunch length. Each bunch contains $0.98 \times 10^{10}$ protons and the collision frequency is 476 MHz. In Figure 4, it shows a proton beam at 100 GeV cooled by a 3.2 nC/bunch electron beam. The emittance remains constant. Momentum spread decreases very slowly. The current of the proton beam is 82% of the proposed value, with $0.8 \times 10^{10}$ protons per bunch. The emittance (0.5/0.15 mm·mrad) and the rms bunch length (1.5 cm) are also slightly larger than the proposed value. Transverse coupling of 40% is assumed. The luminosity with such a proton beam is slightly lower than the proposed luminosity of $2.14 \times 10^{34}$ cm$^{-2}$s$^{-1}$, but still above $10^{34}$ cm$^{-2}$s$^{-1}$. The proposed luminosity is considered achievable after deeper understanding and further optimization of the cooling process in future.

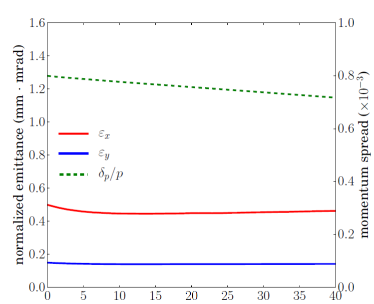


Figure 4: Proton beam cooling during collision.

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## SIMULATION FOR LEAD ION BEAM

The lead ion ($^{208}Pb^{82+}$) beam has a much stronger IBS effect during the stacking in the collider ring. The kinetic energy is 2.0 GeV/u, the initial emittance is 1.5 mm·mrad, the rms bunch length 7 m, Without cooling, the emittance and momentum spread will expand as shown in figure Fig. 5 (left). Even in ten minutes, the emittance increases to about 5.5 mm·mrad. It will vitiate the luminosity and make the cooling in the following stage more difficult if the IBS effect is not mitigated. Using the DC cooling with 3 A electron beam, one can overwhelm the IBS effect. But the emittance should not be reduced at this stage to prevent large space charge tune shift. Simulations show that a DC cooling with 0.62 A electron beam can compensate the IBS effect and keep the emittance constant during the stacking as shown in Fig. 5 (right).

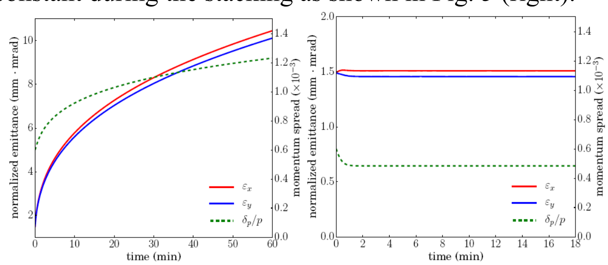

Figure 5: Lead ion beam stacking at 2.0 GeV without (left) and with (right) cooling.

After the stacking, the lead ion beam is accelerated to 7.9 GeV/u for pre-cooling. At this energy, the space charge tune shift is much smaller, which allows us to reduce the emittance. The same DC cooler for stacking is also used for pre-cooling, but with a higher current of 2 A. As shown in Fig. 6, the equilibrium is reached within one minute. The emittance can be reduced below 0.5 mm·mrad, and the momentum spread to $4 \times 10^{-4}$.

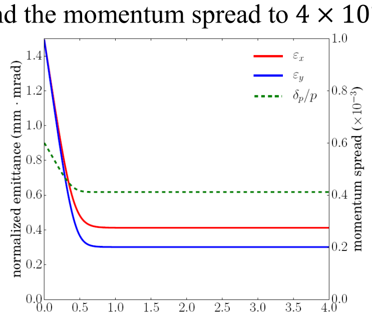

Figure 6: Pre-cooling for the lead ion beam at 7.9 GeV/u.

At the last stage, the lead ion beam is accelerated to 40 GeV/u for collision. The current is 0.75 A with $1.20 \times 10^8$ ions per bunch. The normalized emittance is 0.5/0.3 mm·mrad. The rms bunch length is 1 cm. Cooling the lead ion beam is easier than cooling the proton beam. A simulation is shown in Fig. 7, in which an electron beam of only 0.8 nC/bunch is used to cool the lead ion beam. Equilibrium is reached within two minutes and the emittance remains close to the proposed value consistently. The current of the cooling electron beam is only 25% of the current in the simulations for the proton beam. If needed, we could further reduce the lead ion beam emittance by increasing the cooling electron beam current. Comparing with the proton beam cooing, the technical risk of the heavy ion beam cooing is much lower.

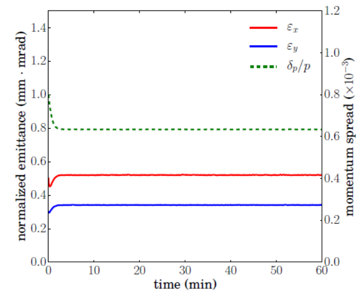

Figure 7: Lead ion beam cooling during collision.

## SUMMARY

To achieve the high luminosity up to $10^{34}$ cm$^{-2}$s$^{-1}$ of JLEIC, magnetized electron cooling is chosen to overcome the strong IBS effect and to reduce the emittance of the ion beam. A multi-stage cooling scheme has been proposed and simulated for both the proton beam and the lead ion beam. In this scheme, the emittance of the ion beam is reduced to the desired value by pre-cooling at the lower energy (7.9 GeV/u). Then the ion beam is accelerated to the collision energy. During the collision, we keep cooling the ion beam to compensate the IBS effect and to maintain the already reduced emittance. This scheme avoids reducing the large emittance for a high energy ion beam by electron cooling, which is extremely difficult. Preliminary simulations suggest the multi-stage cooling is applicable assuming the ERL based bunched beam cooler can provide up to 3.2 nC/bunch electron beam.

## ACKNOWLEDGEMENT

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