SIMULATION STUDY ON JLEIC HIGH ENERGY BUNCHED ELECTRON COOLING*

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Abstract

In the Jefferson Lab (JLab) Electron Ion Collider (JLEIC) project the traditional electron cooling technique is used to reduce the ion beam emittance at the booster ring, and to compensate the intrabeam scattering effect and maintain the ion beam emittance during the collision at the collider ring. Different with other electron coolers using DC electron beam, the proposed electron cooler at the JLEIC ion collider ring uses high energy bunched electron beam, provided by an ERL. In this paper, we report the new electron cooling simulation program developed at JLab to fulfil specific simulation requirements of JLEIC and some recent simulation study on how the electron cooling rate will be affected by the bunched electron beam properties, such as the correlation between the longitudinal position and momentum, the bunch size, and the Larmor emittance.

JLEIC TWO-STAGE COOLING SCHEME

To reach the frontier in Quantum Chromodynamics, the 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. Since the electron cooling time is in proportion to the energy and the 6D emittance of the ion beam, which means it is easier to reduce the emittance at a lower energy, a multi- stage cooling scheme has been developed. A low energy DC cooler will be installed at the booster ring, which will reduce the emittance to the desired value for ion beams with the kinetic energy of 2 GeV/u. In the current JLEIC baseline design, An Energy-Recovery-Linac (ERL) based bunched beam cooler will be installed at the collider ring, which has 60 meter long cooling section with 2 T magnetic field inside and provides a bunched electron beam of 420 pC/bunch to compensate the intrabeam scattering (IBS) effect and maintain the emittance of the ion beam during the injection process and during the collisions. For future luminosity upgrades, a circulator ring based bunched beam cooler is proposed, which allows to reuse the electron bunches tens of times before they finally be dumped through the ERL. Repeated usage of the electron beam reduces the burden of the electron source, thus an electron beam up to 2 nC/bunch for stronger cooling. [1]

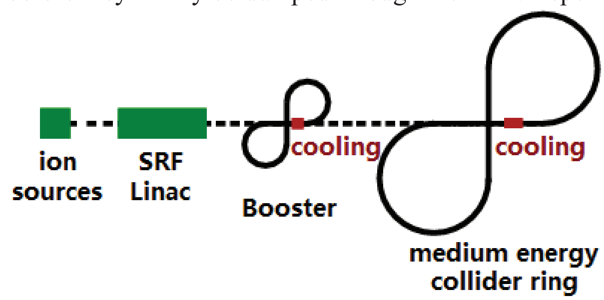

Figure 1: Components of JLEIC ion complex.

SIMULATION CODE DEVELOPMENT

The DC cooler is within the state-of-art. [2] But the bunched beam cooler, using high energy (up to 55 MeV) electron bunches, is out of the state-of-art, and needs significant R&D. Numerical simulation is inevitable for the design and optimization of the JLEIC electron cooling system. BETACOOL [3] has been used in our preliminary study and it has successfully supported the JLEIC design. As the study goes more in-depth, it will be beneficial to have a more efficient and more flexible tool to fulfil some specific needs of JLEIC, and a new electron cooling simulation program has been developed at JLab. [4]

Similar with BETACOOL, The new program calculates the evolution of the macroscopic beam parameters, such as emittances, momentum spread and bunch length. It can simulate both DC cooling and bunched beam cooling, including the IBS effect. Since BETACOOL has provided a collection of physical models for various electron cooling simulations, we decided to follow the models in BETACOOL, whenever they are applicable, and revise them when necessary. Martini model [5] is chosen for IBS expansion rate calculation. Martini model assumes Gaussian distribution for the ion beam, which is reasonable at least for the first order, and the absence of vertical dispersion of the lattice, which is true for JLEIC booster ring and collider ring. Parkhomchuk formula has been implemented for magnetized friction force calculation, because both the coolers at JLEIC are magnetized. Two models, the single particle model and the Monte Carlo model, are borrowed from BETACOOL to calculate the electron cooling rate. The whole cooling process can be simulated by a four-step procedure: 1. Create sample ions; 2. Calcu-

* Work supported by the Department of Energy, under Contract No. DE-AC05-06OR23177 and DE-AC02-06CH11357.
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late the IBS rate and electron cooling rate; 3. Update the 6D coordinates of the sample ions and the beam parameters, with respect to the IBS effect, the electron cooling effect, the betatron oscillation and the synchrotron oscillation; 4. Repeat from step 2 till equilibrium or the end of time. Both the RMS dynamic method and the model beam method from BETACOOL for electron cooling dynamic simulation can be fitted into this procedure. The new code has been thoroughly benchmarked with BETACOOL for all possible scenarios, and they agree very well as long as the same model is implemented. For typical electron cooling simulations for JLEIC, we have observed an improvement of more than ten times in efficiency using the new code, if compared with BETACOOL. Parallelization on a GPU provides another five-time improvement in efficiency. The new code is being actively used in simulation studies for JLEIC cooler design.

ISSUES ON BUNCHED BEAM COOLING

In the following we will discuss three issues related to the high energy bunched electron beam cooling for JLEIC: the proper electron bunch size to achieve high cooling rate; cooling with correlated electron beam; and the effect of the electron beam Larmor emittance on the cooling rate.

Proper Electron Bunch Size

In the current baseline design of JLEIC, the ERL based cooler provides a bunched electron beam of 420 pC/bunch. The current, or the electron number per bunch, is limited by the capability of the cathode and the instability due to the collective effect during beam transport. There are two competing factors to obtain the highest cooling rate with a bunched electron beam. One factor is the volume of the electron bunch. The larger the volume, the more ions are covered by the electron bunch and get cooled. The other factor is the local electron density around an ion. The higher the density, the higher the cooling rate for the ion. However when the total charge per bunch is limited, the larger the volume, the lower the local electron density.

Assume the electron bunch has a beer can shape, and the proton bunch has Gaussian distribution. Kinetic energy of the proton beam is 100 GeV; transverse normalized emittance 0.4 μm·rad; momentum spread 4×10^{-4}; rms bunch length 2 cm. The electron bunch temperature is 0.1 eV in both the transverse direction and the longitudinal direction. As shown in Fig. 2 and Fig. 3, transverse cooling rate and longitudinal cooling rate are calculated for electron bunches whose radius R is one, two, and three times of the rms transverse ion bunch size $\sigma_{x,y}$ respectively and whose length varies from zero to six times of the rms ion bunch length σ_s. When the electron bunch length l increases from zero, the cooling rate increases until l equals σ_s, from where the cooling rate starts to decrease. This is as expected since the bunch volume and the local electron density are competing. The volume dominates in the beginning, and the cooling rate increases

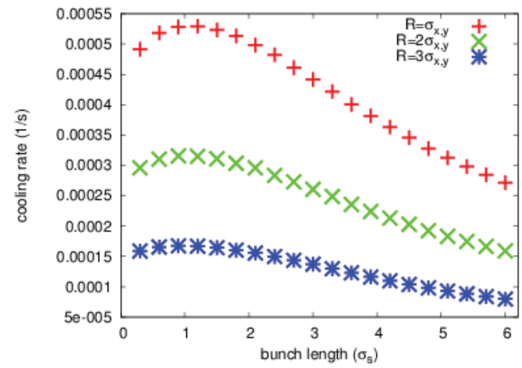

Figure 2: Transverse cooling rate for various electron bunch sizes.

when more ions are enclosed by the electron bunch. Then the local electron density dominates when the volume is large enough. From these plots, we conclude the highest cooling rate is achieved when $R \approx \sigma_{x,y}$ and $l \approx \sigma_s$. But this is under the assumption that all the ions will move through the center of the Gaussian bunch due to the betatron oscillation and the synchrotron oscillation, so that on average the cooling effect is evenly distributed to the whole ion bunch. This assumption needs to be further investigated.

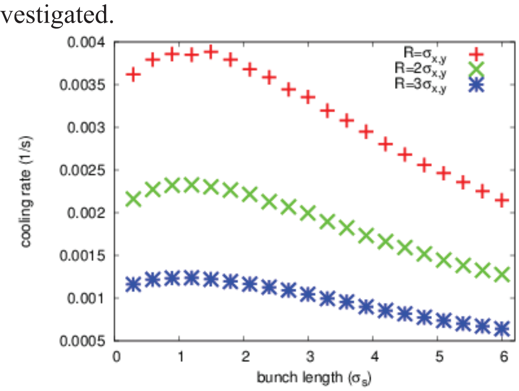

Figure 3: Longitudinal cooling rate for various electron bunch sizes.

Cooling with Correlated Electron Beam

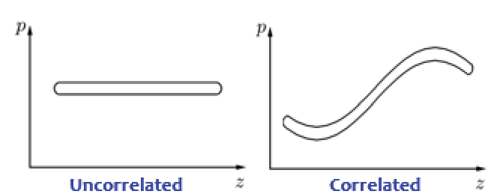

Figure 4: Phase space (z-p_z) distribution of uncorrelated (left) and correlated (right) electron beam.

As a result of the collective effects during beam transition, a correlation can be formed between the momentum and the longitudinal position of the electron. The uncorrelated bunch has the same momentum and the same momentum spread everywhere all through the bunch, while the momentum of the correlated bunch varies longitudinally along the bunch but the local momentum spread remains unchanged, as illustrated in Fig. 4.

The correlation in the z-p_z phase space will affect the cooling rate. We model the correlation as $p = A\sin(\frac{z}{3\sigma_s}\pi)$, where σ_s is the rms bunch length of the electron bunch. Considering an electron bunch with Gaussian distribution, the total charge is 2 nC; rms transverse size 0.02 cm, rms length σ_s 2.1 cm, transverse temperature 0.1 eV. For 100 GeV proton beam with parameters mentioned in the previous subsection, we calculate the cooling rate with uncorrelated electron bunch and correlated electron bunch with different local momentum spread σ_p, assuming the amplitude of the momentum variance $A = 2\sigma_p$ and remains constant when the electron bunch passes through the cooler. The Parkhomchuk formula is derived in a frame where the average velocity of the electrons are zero. In such a frame, the ions will have a shift on its velocity according to its position with respect to the electrons. This velocity shift should be included in the computation for the magnetized friction force. The cooling rates are presented in table 1, from which we can see that they are reduced by the correlation. Especially in the longitudinal direction, a reduction up to 40% happens for $\sigma_p = 5\times10^{-4}$. The result suggests the correlation needs to be controlled or mitigated.

Table 1: Cooling Rate for Uncorrelated/Correlated e^- Beam

	Uncorrelated		Correlated	
σ_p $\times10^{-4}$	$R_{x,y}$ $\times10^{-3}$	R_s $\times10^{-2}$	$R_{x,y}$ $\times10^{-3}$	R_s $\times10^{-2}$
1	1.59	1.66	1.60	1.60
2	1.54	1.50	1.53	1.30
3	1.48	1.34	1.43	1.02
4	1.41	1.19	1.33	0.79
5	1.34	1.06	1.23	0.61

Effect of Larmor Emittance on Cooling Rate

The emittance ε of an magnetized beam can be decomposed into the Larmor emittance ε_L and the drift emittance ε_d, such as $\varepsilon = \sqrt{\varepsilon_L\varepsilon_d}$. The Larmor emittance is an important parameter for cooler design and electron source design. The Larmor emittance is directly related with the transverse velocity $V_\perp$ as $\varepsilon_L = \frac{\beta\gamma V_\perp^2}{c^2}\beta_\perp$, where β, γ are Lorentz factors, c the speed of light, and $\beta_\perp$ the TWISS function. So when the Larmor emittance is fixed, the transverse temperature of the electron beam is determined. Cooling benefits from a smaller Larmor emittance, which means a colder electron beam. But it may be technically challenging to produce the electron beam with very low Larmor emittance. However, if the Larmor emittance out of the cathode is too large, it is almost impossible to reduce it and the cooling will suffer from it. So it has to be carefully selected.

Cooling rates are calculated for a 100 GeV proton beam, whose normalized emittance is 1.2/0.6 μm·rad, momentum spread 8×10^{-5}, rms bunch length 2.5 cm, and which is cooled by a Gaussian electron bunch of 420 pC. The rms transverse size of the electron bunch is 0.035 cm, rms length is 0.84 cm, longitudinal temperature is 0.1 eV,

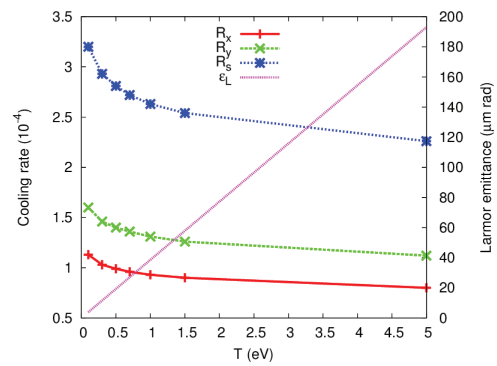

Figure 5: Cooling rate for various temperatures and Larmor emittance.

and the drift emittance 143.7 μm·rad. When the transverse temperature changes from 0.1 eV to 5 eV, the Larmor emittance changes from 3.86 μm·rad to 193 μm·rad, as shown in a straight line in Fig. 5. The cooling rates in all the three directions decrease as the electron temperature goes up, as shown in dot-lines in Fig. 5. The computation is carried out for electron bunches with various parameters in the attempt to find the Larmor emittance acceptable for cooling with moderate technique risk.

CONCLUSION

The two-stage electron cooling scheme for JLEIC includes a low energy DC cooler and a high energy bunched beam cooler. The DC cooler is within the state-of-art. The bunched beam cooler is challenging, however possible. A new program for electron cooling simulation has been developed to fulfil the requirements of JLEIC high energy bunched electron cooling design. It has been benchmarked with BETACOOL regarding both accuracy and efficiency. A significant improvement of efficiency has been achieved. Now the program is being actively used in JLEIC cooling design and study. Effects on the bunched beam cooling rate due to the electron bunch size, longitudinal phase distortion and Larmor emittance have been numerically studied. The preliminary result suggests the highest cooling rate can be achieved if the electron bunch is deployed at the center of the ion bunch. Correlation in the z-p_z phase space will reduce the cooling rate and its effect should be controlled in an acceptable range. A proper Larmor emittance should be chosen with the compromise between the cooling requirements and the technical risk.

ACKNOWLEDGMENT

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177 and DE-AC02-06CH11357.

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