DEVELOPMENT OF THE ELECTRON COOLING SIMULATION PROGRAM FOR MEIC*

H. Zhang#, J. Chen, R. Li, Jefferson Lab, Newport News, VA 23606, USA
H. Huang, L. Luo, Old Dominion University, Norfolk, VA 23529, USA

Abstract

In the medium energy electron ion collider project at Jefferson Lab, 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 collision at the collider ring. A DC cooler at the booster ring and a bunched beam cooler at the collider ring are proposed. To fulfil the requirements of and the cooler design for MEIC, we are developing a new program, which allows us to simulate the following cooling scenarios: DC cooling to coasting ion beam, DC cooling to bunched ion beam, bunched cooling to bunched ion beam, and bunched cooling to coasting ion beam. The new program has been benchmarked with existing code in aspect of accuracy and efficiency. The new program will be adaptive to the modern multicore hardware. We will present our models and some simulation results.

MEIC COOLING SCHEME

At Jefferson Lab, the medium energy electron ion collider (MEIC), to reach the frontier in Quantum Chromodynamics, 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 MEIC ion complex consists of ion sources, an SRF linac, a booster ring and a medium energy 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. A bunched beam cooler will be installed at the collider ring, which helps to compensate the intrabeam scattering (IBS) effect and maintain the emittance of the ion beam during the injection process and during the collision.

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#hezhang@jlab.org

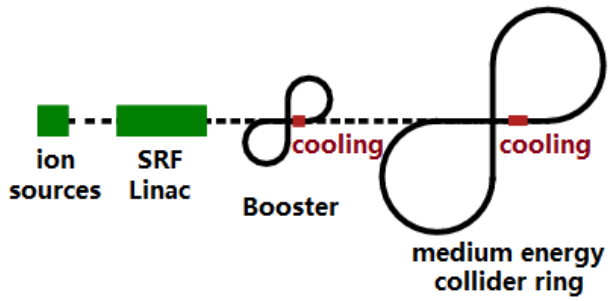

Figure 1: Components of MEIC ion complex.

CODE DEVELOPMENT GOALS

The DC cooler is within the state-of-art. [2] But the bunched beam cooler is out of the state-of-art and needs significant R&D. Numerical simulation is inevitable for the design and optimization of the MEIC electron cooling system. BETACOOL has been used in our preliminary study and it has successfully supported the MEIC 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 MEIC.

The goal of this new simulation program is to enhance the simulation capability for electron cooling in MEIC project. It will preferentially fulfil the needs of MEIC design. The program simulates the evolution of the macroscopic beam parameters, such as emittances, momentum spread and bunch length, in different electron cooling scenarios: DC cooling, bunched electron to bunched ion cooling, bunched electron to coasting ion cooling, etc.

Since BETACOOL has provided a collection of physical models for various electron cooling simulations [3], we decided to follow the models in BETACOOL, whenever they are applicable, and revise them when necessary. We also want to improve the efficiency by strategical arrangement of the calculation and/or by implementation of the models on modern multicore platform.

INTRABEAM SCATTERING

The intrabeam scattering (IBS) effect can cause significant increase of the emittance of the ion beam, due to the high intensity of them, in MEIC in a short time, which ruins the luminosity of the collider. The emittance change rate due to the IBS effect can be calculated using several different formulas under different assumption of the ion beam profile and lattice parameters. [4-7] Here we choose Martini model [5] for the IBS rate calculation for MEIC. Martini model assumes Gaussian distribution for the ion beam, which is reasonable at least for the first

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order, and the absence of vertical dispersion of the lattice, which is true for MEIC booster ring and collider ring. In Martini model the IBS expansion rate has the following expressions:

$$\frac{1}{\tau_p} = \langle \frac{nA}{2}(1-d^2)f_1 \rangle,$$
$$\frac{1}{\tau_x} = \langle \frac{A}{2}\left[f_2 + (d^2+\tilde{d}^2)f_1\right] \rangle,$$
$$\frac{1}{\tau_z} = \langle \frac{A}{2} f_3 \rangle.$$

The brackets indicate to take average over all the elements. Function f_i is a 3D integral as follows:

$$f_i = k_i \iiint \sin\mu g_i(\mu,\nu) \exp[-D(\mu,\nu)z] \ln(1+z^2) d^3V$$

The grid (μ, ν, z) for the 3D integral is user defined. The integral in z can be replaced by the Coulomb logarithm, which is typically around 20. Function g_i is defined as

$$g_1(\mu,\nu) = 1 - 3\sin^2\mu\cos^2\nu,$$
$$g_2(\mu,\nu) = 1 - 3\sin^2\mu\sin^2\nu + 6\tilde{d}\sin\mu\sin\nu\cos\nu\,/a,$$
$$g_3(\mu,\nu) = 1 - 3\cos^2\mu.$$

All the other parameters can be derived from the TWISS parameters and/or the beam parameters.

The calculation of f_i is very expansive in time and it needs to be repeated for all the elements, the number of which easily goes up to a few hundred or more. However, most of the components of g_i only depends on the user defined grid of (μ, ν, z). The values of these components will remain the same no matter when and where they are calculated, once the grid is defined by the user. Those values only need to be calculated once and saved in the memory. They will be reused for all the elements. Avoiding the repeated computation of g_i for different elements, one can reduce the computation time significantly.

ELECTRON COOLING RATE

The electron cooling rate is defined as the emittance change in a unit time due to the electron cooling effect. We borrow two models from BETACOOL for electron cooling rate calculation: the single particle model and the Monte Carlo model. Using the single particle model, the ion beam will be sampled as a group of ions distributed evenly in the ellipsoid of the given emittance in the phase space. Using the Monte Carlo model, the ion beam will be sampled as a Gaussian bunch whose rms size is determined by the given emittance and the TWISS parameter at the cooler. The friction force on each ion will be calculated. Assuming the friction force is constant while the ion passes through the cooler, the change of momentum of each ion can be calculated. Then the new emittance and the change rate of the emittance can be calculated statistically. Although there are different formulas for friction force calculation, currently we only implement the Parkhomchuk formula in the program, because both the coolers for MEIC are magnetized.

During the injection from the booster ring to the collider ring, the bunched beam cooler will be used to compensate the IBS effect of the coasting ion beam. There are two ways in BETACOOL to model a coasting beam. One way is to put the sample particles on one crass section of the beam. Using such a model, the ion beam can only see a slice of the electron beam. So it works well for DC cooling when the electron beam is homogenous longitudinally. But for bunched electron beam, this model neglects the effect of the variance of the electron distribution. The other way is to put the sample particles all along the ring. The circumference of the MEIC collider ring is more than 2000 m, while the rms length of the electron bunch is only around 2 cm. In such a case, if the number of the ion sample is not large enough for an accurate calculation of the cooling rate. Even if the number of the ion sample is large enough, the calculation efficiency will be bad, since most of the ions do not see the electrons and the time cost on them are wasted. To avoid the above dilemma, we decide to only sample the coasting ion beam around the electron bunch, as shown in Fig. 2. A duty factor is defined as D = L_s/L_d, where L_s is the length of the sample area and L_d is the distance between two electron bunch. The cooling rate of the whole coasting ion beam is calculated as the multiplication of the cooling rate of the sample area and the duty factor. This model assumes the cooling effect is distributed evenly among the ions by diffusion. The electron bunch profile could be taken into account using this model.

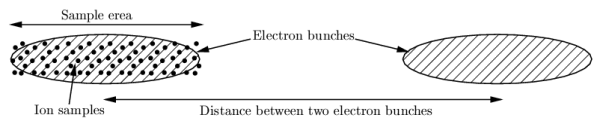

Figure 2: Model of ion beam cooled by electron bunch.

ELECTRON COOLING DYNAMICS

There are two methods in BETACOOL to simulate the evolution of the ion beam emittance during the electron cooling process: the RMS dynamics method and the model beam method. Both of them are implemented in the new program. Using the RMS dynamics method, one assumes the ion beam maintains the Gaussian distribution during the cooling process. For a given time t_i, the total emittance change rate $1/\tau$, as the summation of the IBS expansion rate and the electron cooling rate, can be calculated. Then at the next time t_{i+1} the emittance is calculated as $\varepsilon_{i+1} = \varepsilon_i \cdot e^{dt/\tau}$, where $dt = t_{i+1} - t_i$, and ε_i and ε_{i+1} are the emittances at the respective time. Using the model beam method, one creates a group of ions as the sample of the ion beam at the initial time. IBS effect is treated as a random kick to each ion, which leads to a change of the momentum. Friction force of electron cooling also changes the momentum. Besides these two effects, each ion also makes a random phase advance from time t_i to t_{i+1}. In this way, one can simulate the evolution of the ion beam distribution during the electron cooling process. For example, under a strong electron cooling effect the ion distribution often deviates from Gaussian, which has been observed in experiments, because the center of the ion beam obtains stronger cooling effect than the edge. In such a case, the model beam method is preferred. For more details about these two models, please refer to [3].

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BENCHMARK

The new program has been benchmarked with BETACOOL for typical scenarios of MEIC. A few examples are given in the following. In all the figures, the results of BETACOOL are represented by lines, while the results of the new program are represented by dots.

In Fig. 3 we compare the emittance expansion due to the IBS effect during one hour for (a) the coasting proton beam in the booster ring at 800 MeV and (b) the bunched proton beam in the collider ring at 30 GeV. In Fig. 4 we compare the emittance shrink due to electron cooling in the booster ring (a, b) for coasting proton beam with DC cooler and in the collider ring (c, d) for bunched proton beam with bunched beam cooler. RMS dynamics method is used in a and c, while model beam method is used in b and d. The cooling rate is calculated by the Monte Carlo method in a, and by single particle method in c. In Fig. 5, we compare the emittance evolution under both the IBS effect and the electron cooling effect, which is simulated using RMS dynamic method. The subfigure a shows the cooling process with the DC cooler in the booster ring for the coasting proton beam at 800 MeV. The subfigure b shows the equilibrium between the IBS effect and the electron cooling effect with bunched beam cooler in the collider ring for the bunched proton beam at 100 GeV.

In all the cases, the two programs agree very well. To compare the efficiency of the two programs, we use the same step size and the same total steps to simulate the same number of particles in the last two simulations shown in Fig. 5. For the DC cooling in the booster ring, Fig. 5a, it costs 133 seconds using the new program, or 3060 seconds using BETACOOL. For the bunched beam cooling in the collider ring, Fig. 5b, it costs 31 seconds using the new program, or 422 seconds using

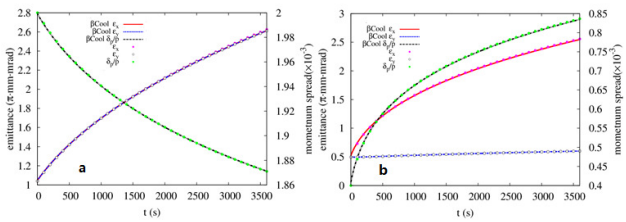

Figure 3: Emittance expansion due to IBS effect.

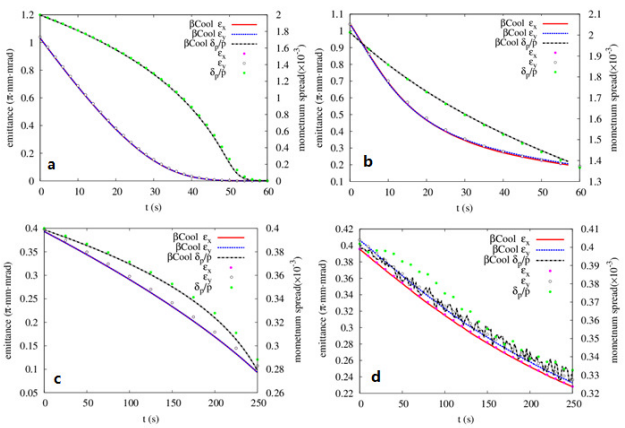

Figure 4: Emittance shrink due to electron cooling.

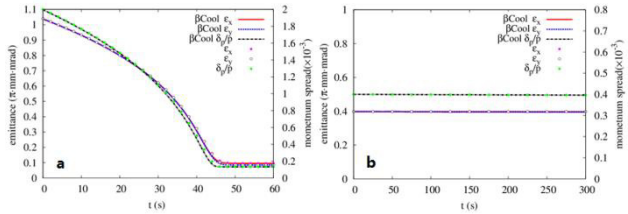

Figure 5: Emittance evolution under both the IBS effect and the electron cooling effect.

BETACOOL. The efficiency has been improved for more than ten times without any parallelization. To be fair, we want to point out that BETACOOL plots the emittance evolution curve during simulation, while the new program only dump out the data. All the plots have to be done by users.

SUMMARY

A new program has been developed to simulate the evolution of the macroscopic beam parameters under the intrabeam scattering (IBS) effect and/or electron cooling. A serial version of the program has been finished and benchmarked with BETACOOL for typical scenarios in MEIC electron cooling design. The results of the two programs agree very well. Computation efficiency has been improved significantly by avoiding redundant computation. The new program brings more flexibility to better fulfil the requirements of MEIC on electron cooling simulations. Now with moderate effort, we can integrate new models into simulations. We have actively implemented the new program in MEIC electron cooler design. At the same time we keep polishing the algorithm and the code. A multiple thread version of the program is under construction, for which one can reasonably expect a further improvements on efficiency.

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