DEVELOPMENT OF THE ELECTRON COOLING SIMULATION PROGRAM FOR JLEIC*

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Abstract

In the 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 collision at the collider ring. A new electron cooling process simulation program has been developed to fulfill the requirements of the JLEIC electron cooler design. The new program allows the users to calculate the electron cooling rate and simulate the cooling process with either DC or bunched electron beam to cool either coasting or bunched ion beam. It has been benchmarked with BETACOOL in aspect of accuracy and efficiency. In typical electron cooling process of JLEIC, the two programs agree very well and we have seen a significant improvement of computational speed using the new one. Being adaptive to the modern multicore hardware makes it possible to further enhance the efficiency for computationally intensive problems. The new program is being actively used in the electron cooling study and cooler design for JLEIC. We will present our models and some simulation results in this paper..

JLEIC 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. 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 collisions.

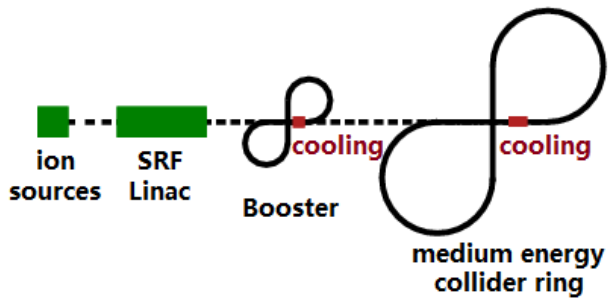

Figure 1: Components of JLEIC ion complex.

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 JLEIC electron cooling system. BETACOOL 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.

The goal of this new simulation program 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: 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.

IBS AND ELECTRON COOLING RATE

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

* Work supported by the Department of Energy, Laboratory Directed Research and Development Funding, under Contract No.-DE-AC05 06OR23177.
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ISBN 978-3-95450-147-2

the ion beam profile and lattice parameters. [4-7] Here we choose Martini model [5] for the IBS rate calculation for JLEIC. 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.

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 JLEIC 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. Coasting ion beam is sometimes modelled as ions on one cross section of the beam [3] under the assumption that the coasting beam is homogeneous in the ring. Such a model works well for DC cooling. But it ignores the variance of the longitudinal electron distribution for bunched electron beam, since the sample ions can only see a slice of the electron beam. Another way is to put the sample ions all along the ring. [3] The circumference of the JLEIC collider ring is more than 2000 m, while the rms length of the electron bunch is only around 2 cm. For JLEIC collider ring, it is not efficient to put the ions all around the ring, since most of the ions do not see the electrons. Assuming all the electron bunches are identical, one only needs to 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.

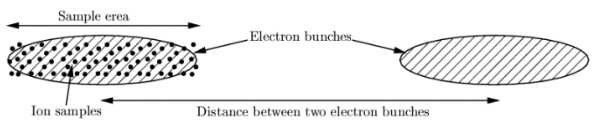

Figure 2: Model of ion beam cooled by electron bunch.

ELECTRON COOLING DYNAMICS

The evolution of the ion beam under the IBS effect and/or electron cooling effect is simulated by a four-step procedure, which can be described as follows: (1) initialize the computational environment; (2) create the sample ions, (3) calculate the IBS rate and the electron cooling rate, and (4) update the beam parameters, such as emittance, momentum spread, and/or bunch length, update the sample ions, and repeat from (3).

Two methods in BETACOOL for electron cooling dynamic simulation, the RMS dynamics method and the model beam method, fit into the four-step procedure. Using the RMS dynamics method, one assumes the ion beam maintains the Gaussian distribution during the cooling process. In step (2), the sample ions with Gaussian distribution is created according the given beam parameters. In step (3), the total emittance change rate $1/\tau$, as the summation of the IBS expansion rate and the electron cooling rate, is calculated. In step (4) the new emittance after cooling is calculated as $\varepsilon_{i+1} = \varepsilon_i \cdot e^{dt/\tau}$, where dt is the time step, ε_{i+1} and ε_i are emittances at the end and the beginning of the step. Then new sample ions are created according to the new beam parameters. Using the model beam method, one creates a group of ions as the sample of the ion beam at the step (2). IBS rate and/or the cooling rate are/is calculated in step (3). In step (4), the 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 during the time interval. Once the 6D coordinates of the sample ions are updated, the new beam parameters can be calculated. Using the model beam method, 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].

BENCHMARK

The new program has been benchmarked with BETACOOL for typical scenarios of JLEIC. 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 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.

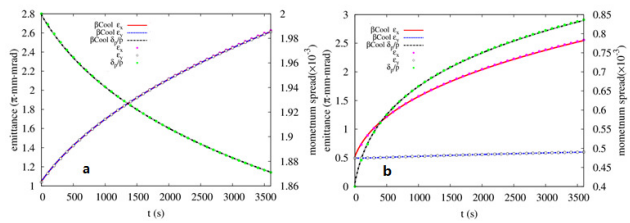

Figure 3: Emittance expansion due to IBS effect.

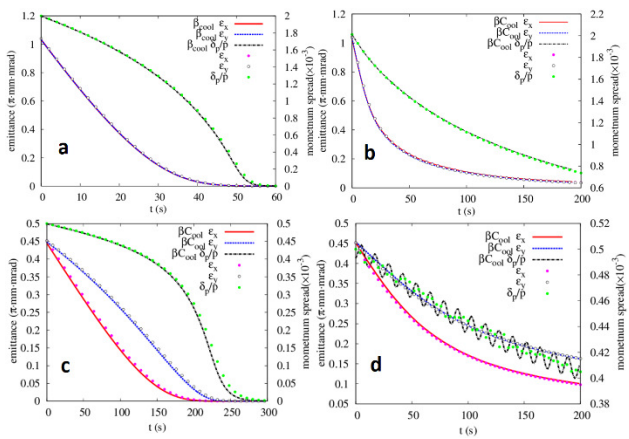

Figure 4: Emittance shrink due to electron cooling.

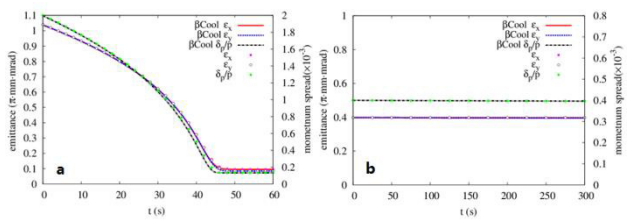

Figure 5: Emittance evolution under both the IBS effect and the electron cooling effect.

PARALLELIZATION

The program is adaptive to the shared memory systems such as a GPGPU (General Purpose Graphic Processing Unit) or a multiple-core CPU. The parallelization is based on thrust, a parallel algorithm library, which supports CUDA, TBB (Threading Building Blocks) and OpenMP. [8] Without changing the source code, the program can be compiled for the aforesaid three platforms with proper respective compiler options. We have tested the program on a desktop PC with AMD Phenom TM II X4 840t processor running at 2.9 GHz and NVidia GTX 660 ti GPU. For IBS rate computation with 100x100x100 grid, it takes 62 seconds using only the CPU and 7.8 seconds using both the CPU and the GPU, which is eight times faster. For electron cooling rate computation with 200,000 sample ions, it takes 0.15 seconds using only the CPU and 0.03 seconds using both the CPU and the GPU, which is five times faster.

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. The program has been benchmarked with BETACOOL for both accuracy and efficiency on typical scenarios in JLEIC 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 JLEIC on electron cooling simulations. A multiple thread version of the program for shared-memory platform has been developed. A factor of five of efficiency improvement has been observed for IBS and electron cooling rate calculation in the test case. The improvement of efficiency raises the feasibility of more sophisticated model in electron cooling simulation.

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ISBN 978-3-95450-147-2