Electron Cooling Simulation Based on First Principles

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1 Topic and status

In traditional electron cooling, heavy ions are mixed with co-moving electrons and transfer their thermal energy to the electron beam inside the cooler. This technique is used to compensate the intrabeam scattering [1, 2] effect and/or to reduce the emittance and momentum spread of the ion beam. It plays an important role in modern high current heavy ion colliders, such as the electron-ion collider[3]. Although the theory has been developed decades ago [4, 5, 6] and the DC coolers have been successfully implemented in several accelerators [7, 8], the numerical simulation of electron cooling remains challenging and the available tools are limited. Current simulation tools usually use theoretical and/or empirical formulas to calculate the friction force and the cooling rate [9, 10, 11]. Particle-based simulation has been implemented to track the motion of one or a few ions inside an electron sea and calculate the friction force on the ion [12]. Numerical tricks are used to mitigate the diffusion, so it is not really a first principle-based simulation. Recently, a N-body particle simulation method based on the first principles has been implemented for electron cooling by Prof. Erdelyi's group in the Northern Illinois University [13]. However, their work is new and needs time to be widely accepted by the community. It also needs to be validated and benchmarked, too. The existing tools work well for low energy DC cooler. As the new colliders go to the higher energy region, accelerator physicists have proposed electron coolers with higher energy bunched electron beams [10]. New simulation tools may be needed for the new coolers. A dependable simulation tool based on the first principle will provide a convenient and economical way for electron cooler design and related beam dynamic study.

2 Current and future challenges

The challenges of particle-based simulation come from the following two properties of the electron cooling mechanism. First, electron cooling is a collisional procedure, in which ions transfer energy to the electrons. The simulation of the collision needs accurate electric field calculation and small enough time step size. We cannot use average field of the electrons as we often can do in space charge effect simulations. Second, electron cooling is a slow procedure. During one pass through the cooler, the diffusion effect on an ion may overwhelm the cooling effect. After multiple passes, the random diffusion will be averaged to zero and the cooling effect dominates. This means one has to simulate a relatively long time to let the cooling effect show up. Other issues that needs to be considered include the electron dynamic in such an electron-ion plasma, which can evolve on a faster time scale than the collision process, and the cyclotron frequency for a magnetized electron cooler. Another factor that makes the condition worse is the large number of particles involved in the simulation, which could go above 10^9. The long time, the small step size, the difficulty to parallelize the computation in time, and the large particle

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number make the simulation a challenging task without well-designed algorithms (such as a symplectic particle pusher) and good strategies for code parallelization and optimization.

3 Advances needed to meet challenges

To address the aforementioned challenges, we need to develop a Poisson solver for the field calculation and an integrator to move the particles using a language that supports high efficient computation, such as C++. The fast multipole method is a candidate for the field solver for its efficiency that scales linearly with the particle number and its high accuracy especially for particles close to each other, but other solvers should be investigated. A flexible design will allow easy extension of the field solver to more complex setup. The code needs to be optimized for excellent scalability of parallelization so that it could run on the modern exascale machines with thousands of CPUs and other accelerators such as GPUs. It should also be modularized and then the field solver and the integrator will be reusable for other collective effect simulations. We will seek for an open source license and host the codes on github, which is convenient for both the contributors and the users. Validation and benchmark of the codes should be done with other codes and experimental data.

References

[1] A Piwinski. "Intrabeam scattering". In: (1974).

[2] James D Bjorken and Sekazi K Mtingwa. "Intrabeam scattering". In: *Part. Accel.* 13.FERMILAB-PUB-82-47-THY (1982), pp. 115–143.

[3] A. Arno et al. *An Electron-Ion Collider Study*. Tech. rep. Brookhaven National Laboratory, 2019. URL: https://wiki.bnl.gov/eic/upload/EIC.Design.Study.pdf.

[4] Ya S Derbenev and A N Skrinskij. *The kinetics of electron cooling of beams in heavy particle storage devices*. Tech. rep. Institute of nuclear physics, USSR academy of sciences, Siberian division, 1968.

[5] Yar S Derbenev and A N Skrinsky. "The effect of an accompanying magnetic field on electron cooling". In: *Part. Accel.* 8 (1978), pp. 235–243.

[6] Helmut Poth. "Electron cooling: theory, experiment, application". In: *Physics reports* 196.3-4 (1990), pp. 135–297.

[7] Sergei Nagaitsev, Lionel Prost, and Alexander Shemyakin. "Fermilab 4.3 MeV electron cooler". In: *Journal of Instrumentation* 10.01 (2015), T01001.

[8] V Parkhomchuk and I Ben-Zvi. *Electron cooling for RHIC*. Tech. rep. Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider, 2001.

[9] AO Sidorin et al. "BETACOOL program for simulation of beam dynamics in storage rings". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 558.1 (2006), pp. 325–328.

[10] He Zhang et al. *Multi-stage electron cooling scheme for JLEIC*. Tech. rep. Thomas Jefferson National Accelerator Facility, Newport News, VA (United States), 2018.

[11] He Zhao et al. "Electron cooling of a bunched ion beam in a storage ring". In: *Physical Review Accelerators and Beams* 21.2 (2018), p. 023501.

[12] George I Bell et al. "Simulating the dynamical friction force on ions due to a briefly co-propagating electron beam". In: *Journal of Computational Physics* 227.19 (2008), pp. 8714–8735.

[13] Sumana Abeyratne and Bela Erdelyi. "N-body Code to Demonstrate Electron Cooling". In: *Int. Workshop on Beam Cooling and Related Topics (COOL'15), Newport News, VA, USA, September 28-October 2, 2015*. JACOW, Geneva, Switzerland. 2016, pp. 59–62.