Northern Illinois University

Studies of Electron Cooling for an Electron Ion Collider

Béla Erdélyi

DOE-NP Accelerator R&D PI Meeting
December 2, 2020

The Challenge of Electron Cooling as a Computational Beam Dynamics Problem

- **Electron cooling:** methods to significantly reduce the 6D phase space volume of ion beams.
- Achieved in various ways by co-propagating ions with electrons such that ions experience a dynamical friction force
- Approximate analytical estimates fail due to unwarranted approximations*
- Computationally one of the most difficult beam dynamics problems to tackle at the microscopic level

* Chandrasekhar S 1942 *Principles of Stellar Dynamics* (Chicago, IL: University of Chicago Press)
* Trubnikov B A 1965 Particle interactions in a fully ionized plasma *Rev. Plasma Phys.* **1** 105

Close Encounters and the Dynamical Friction

Simulating the dynamical friction force on ions due to a briefly co-propagating electron beam

George I. Bell [a,*], David L. Bruhwiler [a], Alexei Fedotov [b], Andrey Sobol [a], Richard S. Busby [a], Peter Stoltz [a], Dan T. Abell [a], Peter Messmer [a], Ilan Ben-Zvi [b], Vladimir Litvinenko [b]

[a] Tech-X Corporation, Accelerator Technology, 5621 Arapahoe Avenue, Suite A, Boulder, CO 80303, United States
[b] Brookhaven National Lab, Upton, NY 11973, United States

- Discrepancy between direct numerical simulations and tested analytic formulae.

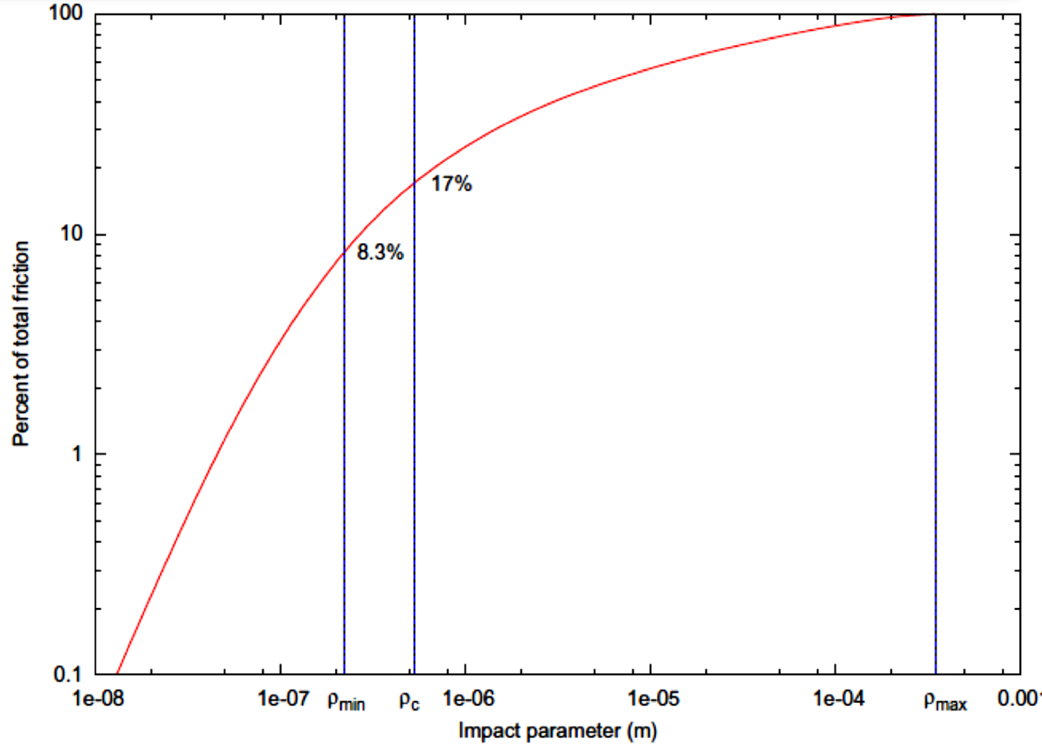


Fig. 6. Cumulative friction by impact parameter. If there are no collisions with impact perimeter less than ρ_c, the dynamical friction will be reduced by 17%.

Bell, G. I., Bruhwiler, D. L., Fedotov, A., Sobol, A., Busby, R. S., Stoltz, P., ... & Litvinenko, V. (2008). Simulating the dynamical friction force on ions due to a briefly co-propagating electron beam. *Journal of Computational Physics*, *227*(19), 8714-8735.

Close Encounters and the Dynamical Friction

Numerical calculation of dynamical friction in electron cooling systems, including magnetic field perturbations and finite time effects

A V Sobol[1,3], D L Bruhwiler[1], G I Bell[1], A Fedotov[2] and V Litvinenko[2]

[1] Tech-X Corporation, 5621 Arapahoe Avenue, Suite A, Boulder, CO 80303, USA

[2] C-A Department Brookhaven National Laboratory, Upton, NY 11973-5000, USA

- The friction force on an ion can significantly deviate from its average due to rare, strong collisions (during a single pass through an electron cooling section).
- Any analytic formula provides a limited view of the full dynamics

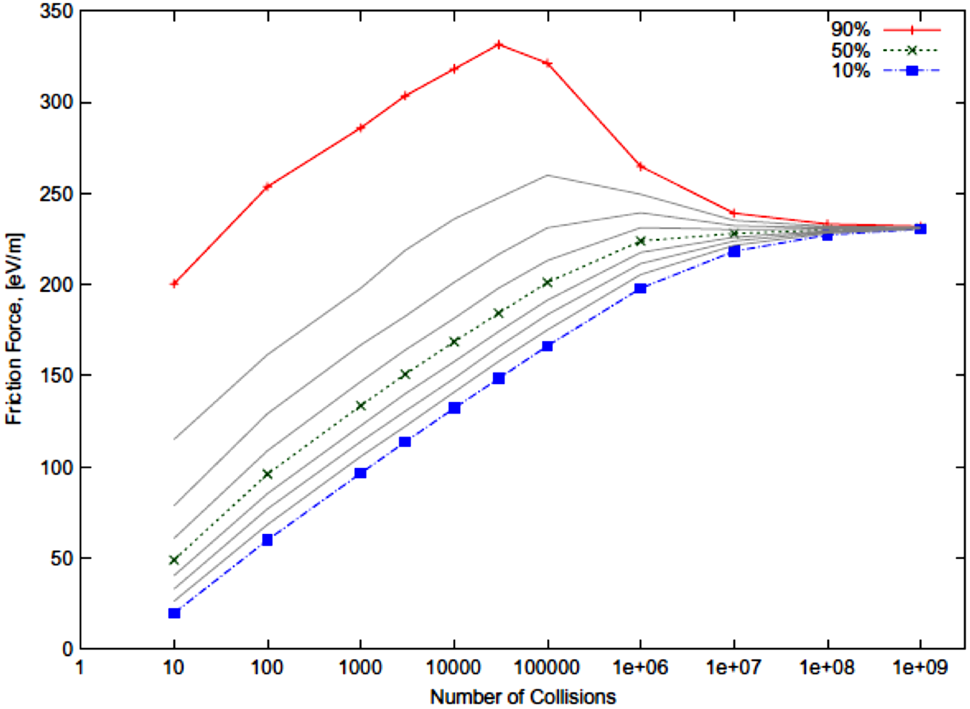


Figure 8. The friction force resulting from a sequence of collisions as an RV. The 10-quantiles (deciles) are plotted as a function of the number of collisions: thick lines are 10%-, 50%- and 90%-quantiles and thin lines are 20%-, 30%-, 40%-, 60%-, 70%- and 80%-quantiles. The 80% confidence interval is very wide unless the number of collisions is extremely large.

Sobol, A. V., Bruhwiler, D. L., Bell, G. I., Fedotov, A., & Litvinenko, V. (2010). Numerical calculation of dynamical friction in electron cooling systems, including magnetic field perturbations and finite time effects. *New Journal of Physics*, *12*(9), 093038.

Collisional Simulations of Electron Cooling

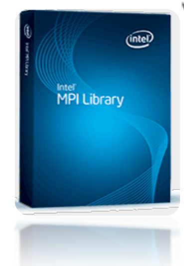
- Accurate description of the cooling dynamics → **high precision microscopic numerical simulations** based on a minimal set of assumptions → Collisional N-Body methods.
- High accuracy leads to **efficiency challenges**:
  - Large particle numbers (but far from statistical limit)
  - Long range pair-wise interaction (both attractive and repelling)
  - Vast spatial and time scales
  - External electromagnetic fields
  - Maintaining symplecticity over long time scales

Main Challenges of an N-Body Solver

- **Efficient Force Computation**
  - ✓ Adaptive hierarchical space decomposition
- **Accurate Time Stepper**
  - ✓ Variable high order, adaptive integrators with automatic steps size and order selection, and dense output
- **Ability to deal with very large N**
  - ✓ Distributed, high performance computing on hybrid architecture supercomputers
- **Ability to deal with long time-scale dynamics**
  - ✓ Symplecticity based on splitting and composition
  - ✗ Time does not parallelize

Particles' High-order Adaptive Dynamics (PHAD)

We developed, and continue to improve, a parallel code (PHAD) based on these new methods that is the first one capable of particle-based simulations of electron cooling and other difficult beam dynamics phenomena with high fidelity, efficiently.



NVIDIA CUDA

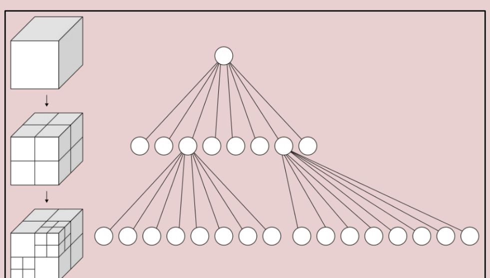
NORTHERN ILLINOIS UNIVERSITY
Center for Research Computing & Data
Division of Research and Innovation Partnerships

NORTHERN ILLINOIS UNIVERSITY
Beam Physics Code Repository
N. Illinois Center for Accelerator & Detector Development
https://www.niu.edu/beam-physics-code/

Efficient, Accurate Collisional Method: PHAD

Force computation $\mathcal{O}(N^2)$

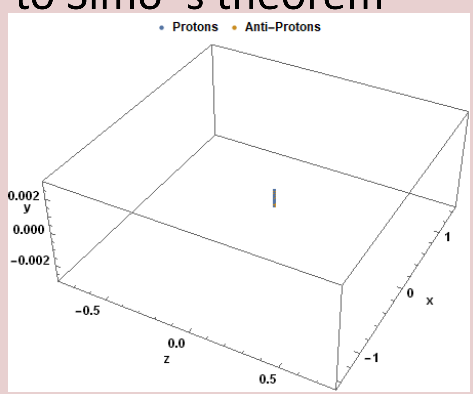
- **Reduced to $\mathcal{O}(N)$ using the FMM**
  - ➢ Adaptive hierarchical space decomposition



https://en.wikipedia.org/wiki/Octree

Accurate and efficient time stepping

- **Developed the Simò Integrator**
  - ➢ Automatic selection of stepsize and order, optimal values according to Simo`'s theorem

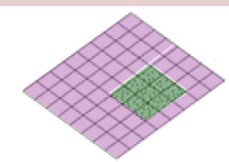


Long time-scale dynamics

- **Strang splitting**
  - ➢ Combine exact and numerical solutions
  - ➢ Maintain symplecticity

$$\frac{d\hat{Y}_j}{dt} = F_i(\hat{Y}, t) = \underbrace{F_j^{[1]}(\hat{Y}, t)}_{S_i} + \underbrace{F_i^{[2]}(\hat{Y}, t)}_{S_i^c}$$

$$\hat{Y}(h) = \phi^{[2]}_{h/2} \circ \phi^{[1]}_{h} \circ \phi^{[2]}_{h/2}(\hat{Y}_0) + \mathcal{O}(h^3)$$

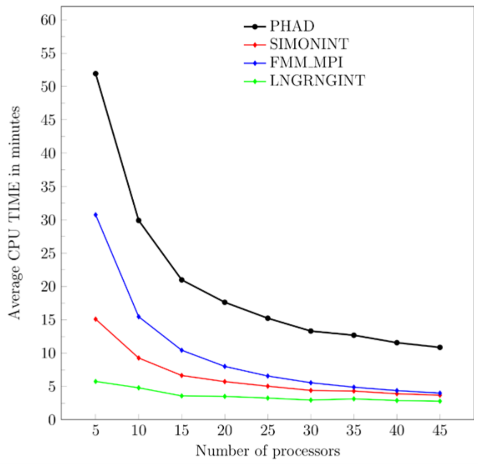


$$\dot{x}_i = \frac{c p_i}{(m_i^2 c^2 + \|p_i\|_2^2)^{1/2}} + 0$$

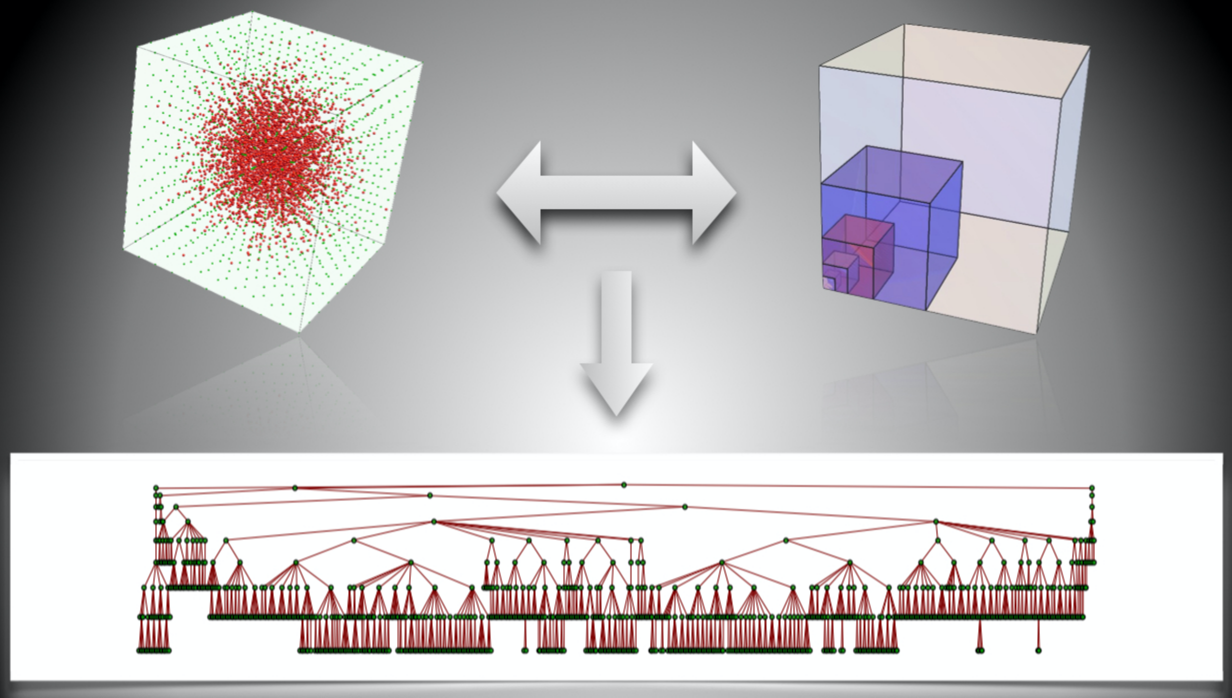
$$\dot{p}_i = \frac{1}{4\pi\epsilon_0} \sum_{\substack{j \in N_i \\ j \neq i}} K(x_i, x_j) + q_i (E + B \times v_i) + \frac{1}{4\pi\epsilon_0} \sum_{j \in N_i^c} K(x_i, x_j)$$

PHAD Features

- Accurate and efficient collisional simulation of charged particle beams in external electromagnetic fields **(minimal assumptions).**
- Fully adaptive both in space and time.
- Numerically symplectic over the long run.
- Best efficiency in reaching an a priori set error level.
- Ability to deal with very large N
  - In addition to the scalable algorithms above, use distributed, high performance computing on hybrid architecture supercomputers



The Fast Multipole Method



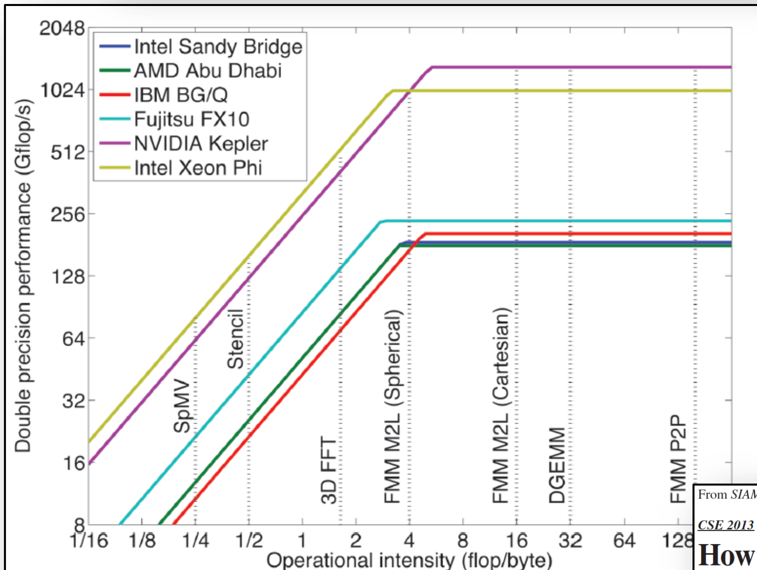
“Best” Algorithms

Comparison of scalable fast methods for long-range interactions

Phys. Rev. E **88**, 063308 – Published 19 December 2013

Axel Arnold, Florian Fahrenberger, Christian Holm, Olaf Lenz, Matthias Bolten, Holger Dachsel, Rene Halver, Ivo Kabadshow, Franz Gähler, Frederik Heber, Julian Iseringhausen, Michael Hofmann, Michael Pippig, Daniel Potts, and Godehard Sutmann

Our findings suggest that, depending on system size and desired accuracy, the FMM- and FFT-based methods are most efficient in performance and stability.

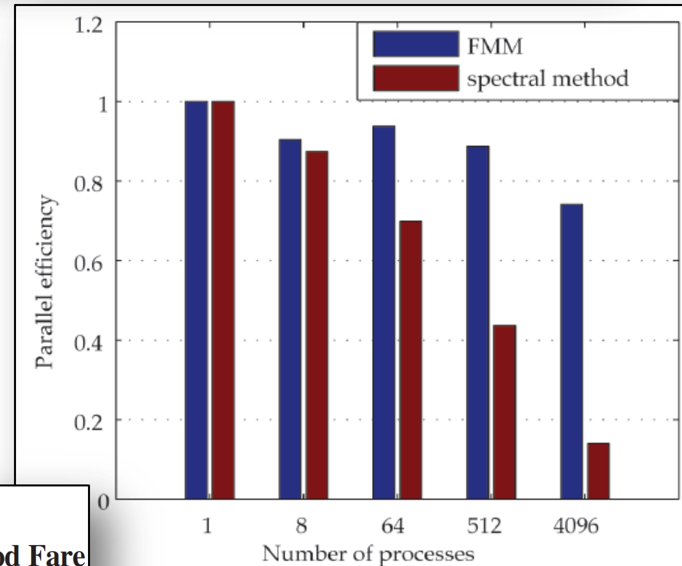


From *SIAM News*, Volume 46, Number 6, July/August 2013

CSE 2013

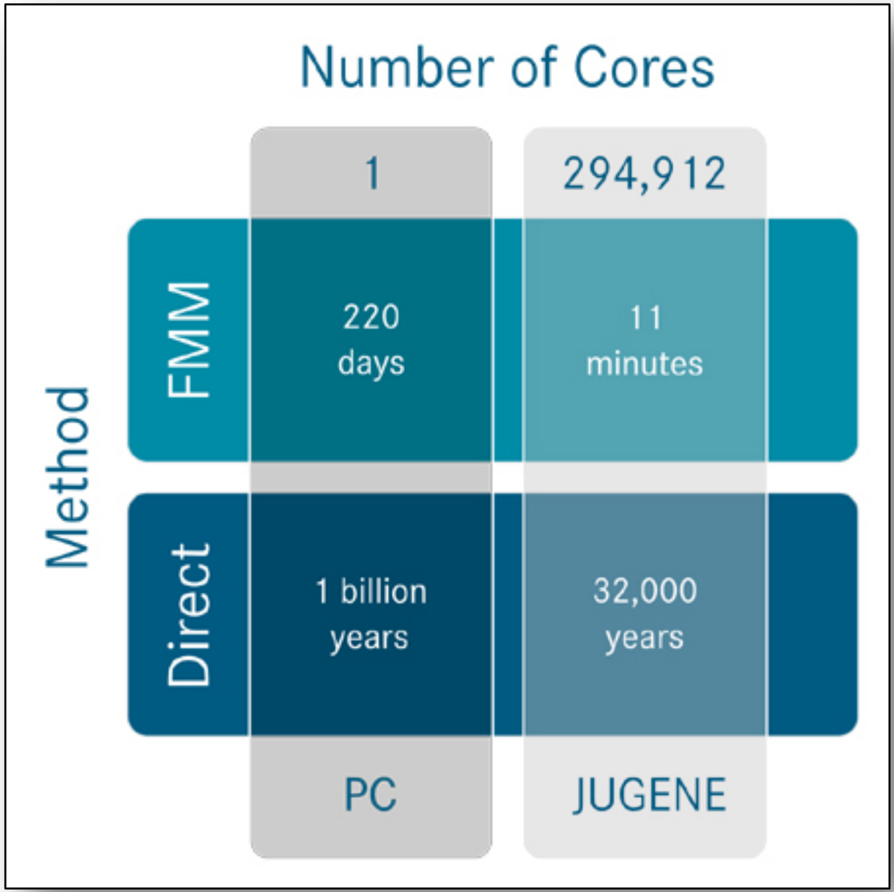
How Will the Fast Multipole Method Fare in the Exascale Era?

By Lorena A. Barba and Rio Yokota



FMM World Record

3,011,561,968,121 particles



Credit: Jülich Supercomputing Centre (JSC)

Electron Cooling Simulations (A. al Marzouk)

- PHAD is first code capable of providing a microscopic description of electron cooling with high fidelity, efficiently:
  - See previous PI meetings for low energy DC and modulator simulations for coherent electron cooling

- **Benchmarking with experiments:**
  - Through collaboration with JLAB and BNL, simulations are being performed for the IMP's experiments
  - JLAB planned to cool ion beams using bunched electron beams → study ERL-based cooler to provide a highly bunched cooling electron beam with energy up to 55 MeV
  - To study such a cooling process, low energy cooling with bunched electron beams experiments were carried out at the storage ring CSRm at IMP in China

ZHANG, Yuhong – JLAB
BENSON, Stephen – JLAB
ZHANG, He – JLAB
WANG, Haipeng – JLAB
ZHAO, He – BNL

IMP Experiment

Xia, Jia-Wen, et al. "The heavy ion cooler-storage-ring project (HIRFL-CSR) at Lanzhou." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 488.1-2 (2002): 11-25.

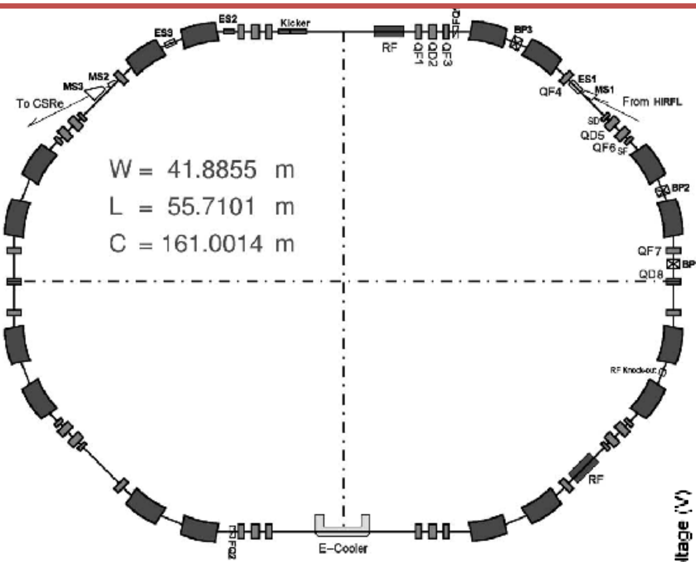


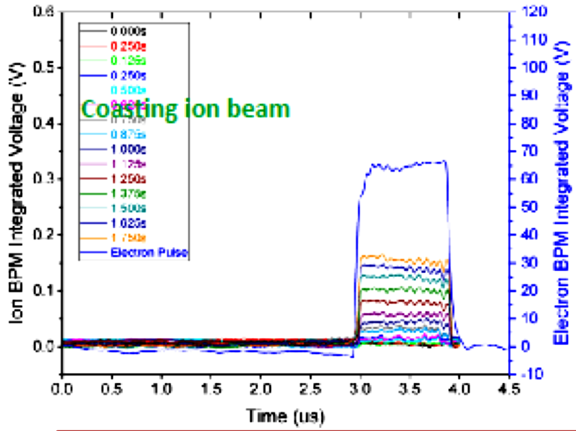
Fig. 4. Lattice layout of CSRm.

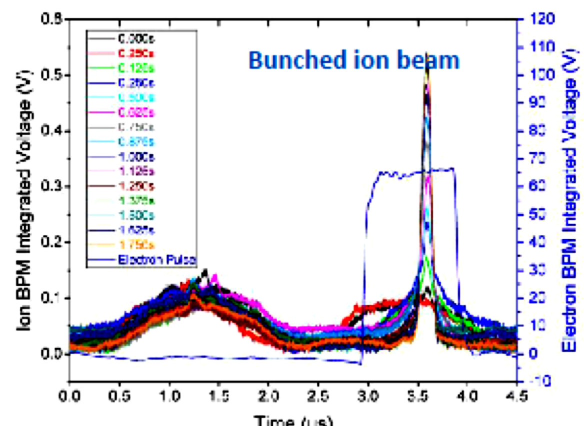
Zhao, H., et al. "Simulation of ion beam cooling with a pulsed electron beam." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 902 (2018): 219-227.

Table 2
Beam parameters in the pulsed electron beam cooling experiment.

Parameter	Coasting beam	Bunched beam
Ion	$^{12}C^{6+}$	$^{12}C^{6+}$
Energy [MeV/u]	7	7
Number of particles	5.0×10^8	1.3×10^8
RMS momentum spread	2×10^{-4}	7×10^{-4}
RMS bunch length [ns]	–	~135
RF voltage [kV]	–	1.2
Harmonic number	–	2
E-beam peak current [mA]	30	65
E-beam diameter [cm]	~3	~2.5
Pulse width [ns]	2000	1000
Rising/falling time [ns]	10	10

The 2nd cooling experiment run (2017)

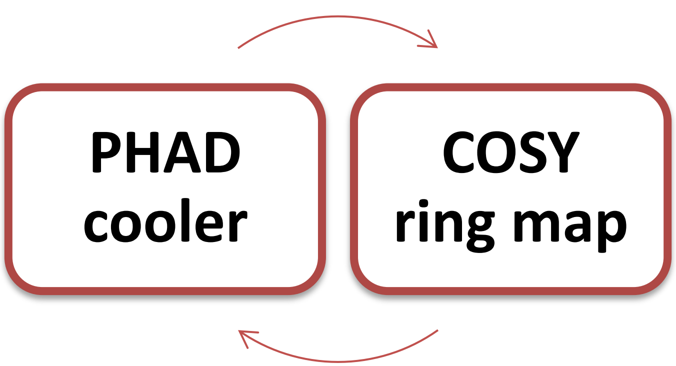




Yuhong Zhang and Haipeng Wang, "Bunched Beam Cooling Experiment." *2018 Accelerator Research & Development PI Meeting*, November 13-14, 2018

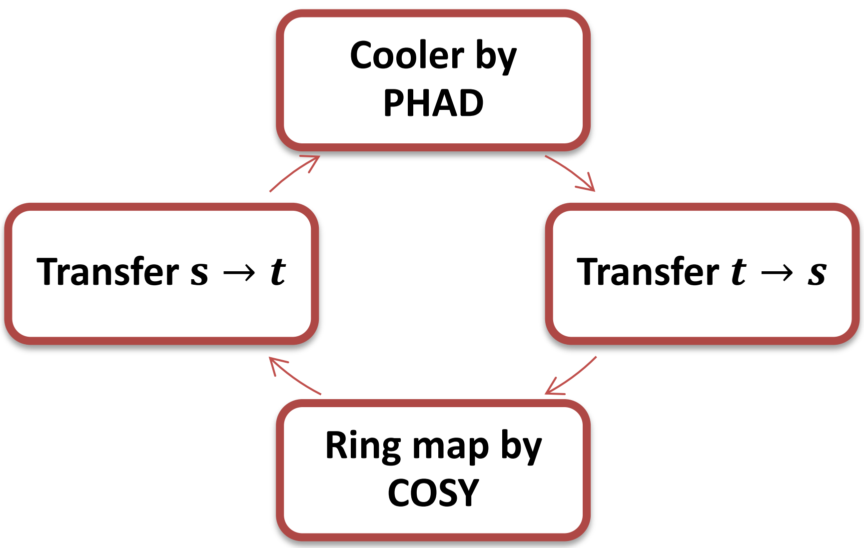
Simulations Progress

- PHAD is an add-on/extension/plugin to **COSY INFINITY**:
  - A general-purpose nonlinear beam dynamics community code based on Differential Algebra
  - Large library of optical elements
  - Transfer maps of elements, and whole systems through composition of maps
- Able to compute **full ring dynamics to high order**



Cooler Edges and Independent Variables

- Ring map is s −based
- PHAD is t −based
- Keep transferring the independent variable between s and t at exit/entrance of the cooler



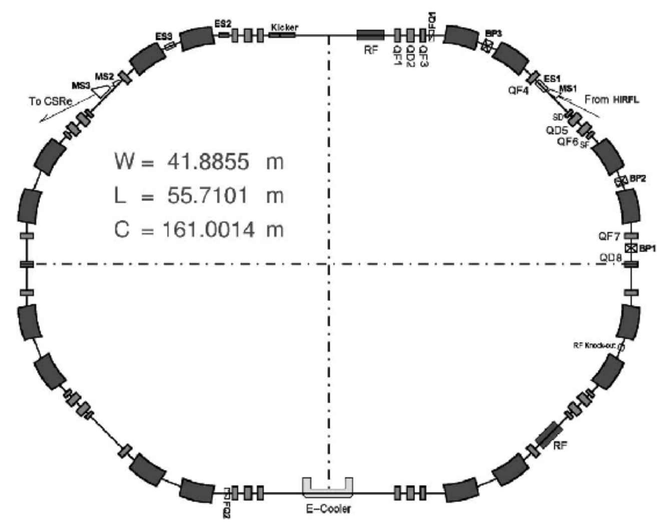
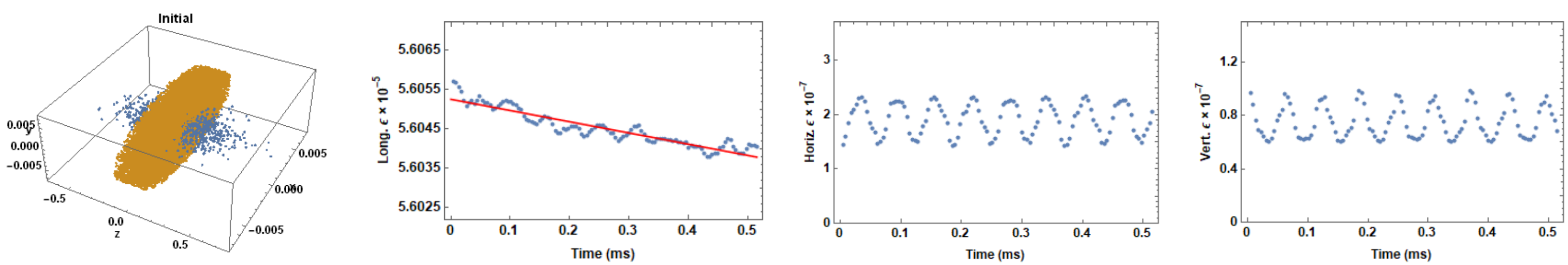


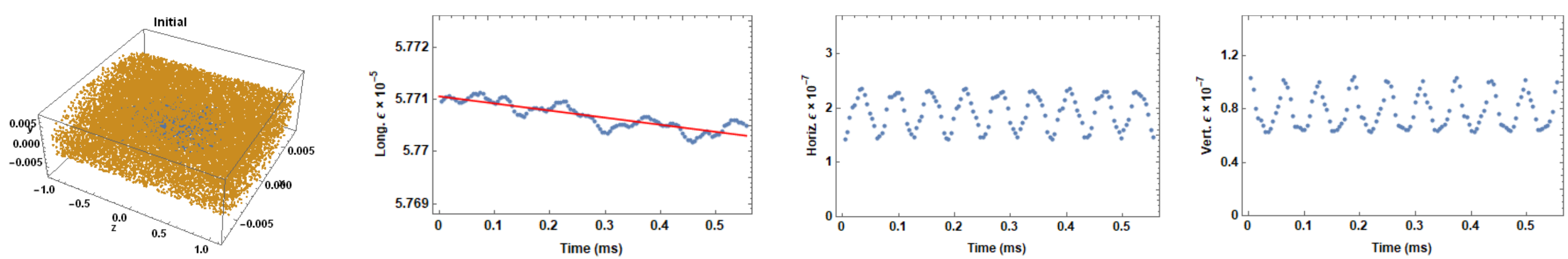
Fig. 4. Lattice layout of CSRm.

Bunched Electron Cooling

- **Fixed ratio:** $I = 65\ mA, \Delta t = 1\ \mu s, N_{ions} = 1.3 \times 10^8 \rightarrow ratio = 3120.75$
- $N_{ions} = 1000 \rightarrow N_e = 3.12 \times 10^6, \sigma_{ions} = 22\ cm, macroe = 200\ electrons \rightarrow \widetilde{N_e} = 15604$
- **Short pulse:** $l_e = 22\ cm \rightarrow I = 83.3\ \mu A, \boldsymbol{\tau^{-1} = 0.5\ s^{-1}}$



- **Long pulse:** $l_e = 2.2\ m \rightarrow I = 8.33\ \mu A, \boldsymbol{\tau^{-1} = 0.24\ s^{-1}}$

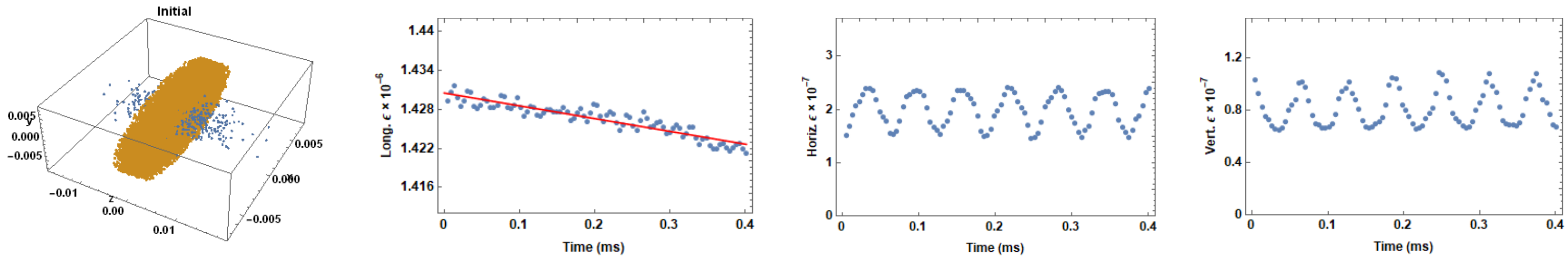


Bunched Electron Cooling – Short Pulse

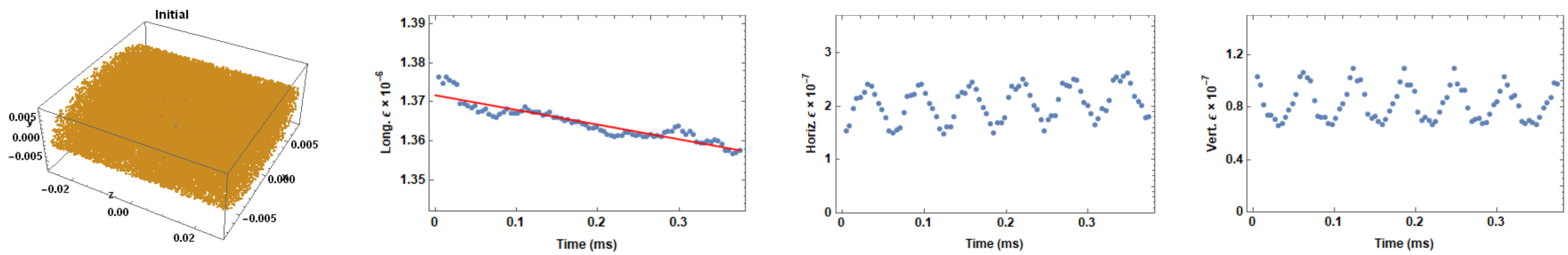
Rate estimate from	$\tau_{\|\|}$ (sec)	$\tau_{\perp}$ (sec)
PHAD Simulation	2	
IMP Experiment	≈ 2	
Analytic **Standard - Spherical**	$v_i < \Delta_e$: 163; $v_i \gg \Delta_e$: 0.2	
Analytic **Standard - Disk**	0.1	0.27
Analytic **Strong Magnetic -Adiabatic**	7.2×10^{-3}	8×10^{-3}
Analytic **Strong Magnetic - Binary Collision**	0.015	0.02
Analytic **Finite magnetic - "Empirical"**	7×10^{-3}	7×10^{-3}

Bunched Electron Cooling – Fixed Current

- **Fixed current:** $I = 15\,mA,\ N_{ions} = 500, \sigma_{ions} = 5.5\,mm$
- **Short pulse:** $l_e = 5.5\,mm \rightarrow N_e = 1.4\times10^7, macroe = 900\ electrons \rightarrow \widetilde{N_e} = 15604,$ $\boldsymbol{\tau^{-1} = 13.8\ s^{-1}}$

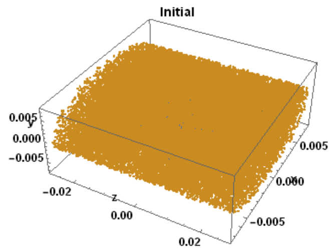


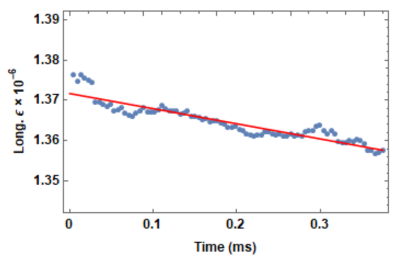
- **Long pulse:** $l_e = 5.5\,cm, \rightarrow N_e = 1.4\times10^8, macroe = 3500\ electrons \rightarrow \widetilde{N_e} =$ $40124, \boldsymbol{\tau^{-1} = 27\ s^{-1}}$

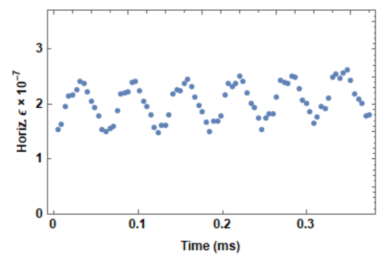


Bunched Electron Cooling – Fixed Length

- **Fixed length:** $l_e = 5.5\ mm,\ N_{ions} = 500, \sigma_{ions} = 5.5\ mm$
- **High current:** $I = 15\ mA \rightarrow N_e = 1.4{\times}10^8, macroe = 3500\ electrons \rightarrow \widetilde{N_e} = 40124,$ $\boldsymbol{\tau^{-1} = 27\ s^{-1}}$

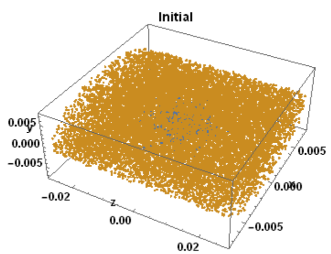


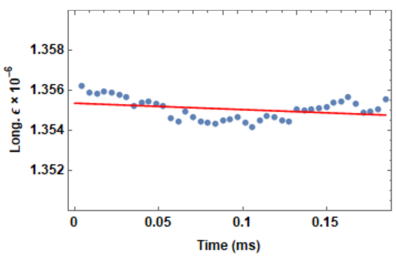


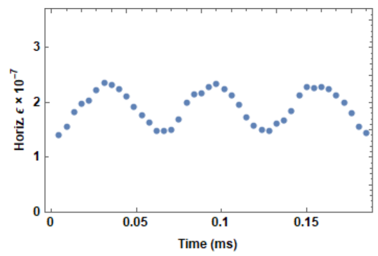


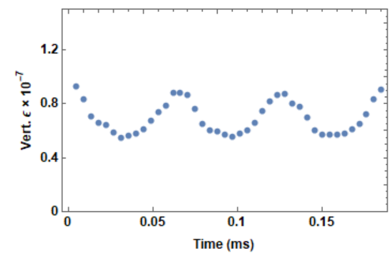
- Fixed length: $l_e = 5.5\ mm,\ N_{ions} = 500, \sigma_{ions} = 5.5\ mm$
- High current: $I = 15\ mA \rightarrow N_e = 1.4{\times}10^8, macroe = 3500\ electrons \rightarrow \widetilde{N_e} = 40124,$ $\tau^{-1} = 27\ s^{-1}$
- Low current: $I = 1.5\ mA \rightarrow N_e = 1.4{\times}10^7, macroe = 900\ electrons \rightarrow \widetilde{N_e} = 15604,$ $\tau^{-1} = 2.4\ s^{-1}$

- **Low current:** $I = 1.5\ mA \rightarrow N_e = 1.4{\times}10^7, macroe = 900\ electrons \rightarrow \widetilde{N_e} = 15604,$ $\boldsymbol{\tau^{-1} = 2.4\ s^{-1}}$









Summary

- The fixed ratio simulations were based on the **cooling of bunched ion beams experiment** (cooling time $\lesssim$ 2 sec) and our **simulations gave similar cooling times,** with slightly longer time for the longer pulse due to very low current.
- **In agreement with experimental results**:
  - For a fixed current, longer pulses have faster cooling.
  - For a fixed length, higher currents have faster cooling.
- **Work in progress**:
  - high energy (relativistic) ion beams.
  - use different e-beam distributions.

Conclusions

- **Computational** **<u>collisional</u>** **beam physics will** play an important part in modeling and simulating electron cooling; designing, operating, and improving current and future particle accelerators and their performance
- **Algorithmic and hardware improvements multiply**, making high fidelity large-scale problems feasible
- **Fundamental algorithms** and methods are general enough to be adaptable/applicable to many other beam dynamics problems and different scientific fields
- Current and next generation **high-performance computing** systems are well matched to these algorithms
- **High-fidelity** *electron cooling simulations based on first principles are now feasible and ongoing*