Northern Illinois University

Electron Cooling for an Electron Ion Collider: Computational Methods and Code Development

Béla Erdélyi

DOE-NP Accelerator R&D PI Meeting

October 20, 2017

Main Goals

- Proof of principle **demonstration of electron cooling** with the **first particle-level detailed** simulations (Jones Report:: line 3: High, A)
- **Develop a high-performance code** with these capabilities, and other beam dynamics challenges beyond cooling (Jones Report:: line 4: High, A)
- **Applications** to electron-ion collider (MEIC/LEIC) modeling, design, and optimization (Jones Report:: line 39: High)

Expenditures and Milestones

	FY10+FY11	FY12+FY13	FY14+FY15	FY16+FY17	TOTALS
Funds Allocated	0+56	55+52=107	50+54=104	50+50=100	$367K
Actual Costs to Date	56	107	104	100	$367K

	FY17	FY18
Quarter 1	Shared memory parallelization of FMM data structures and integration with parallel FMM	Electron cooling simulations in the JLEIC pre-booster at injection
Quarter 2	Variable order Picard integrator with automatic step size control parallelization	Electron cooling simulations in the pre-booster at extraction energy
Quarter 3	Binned time step implementation in parallel	Setup the re-circulator ring optics and bunched cooling in COSY
Quarter 4	Parallel PHAD integration, benchmarking and optimizations	Study electron beam dynamics in the re-circulator ring, set maximum useful turn limits

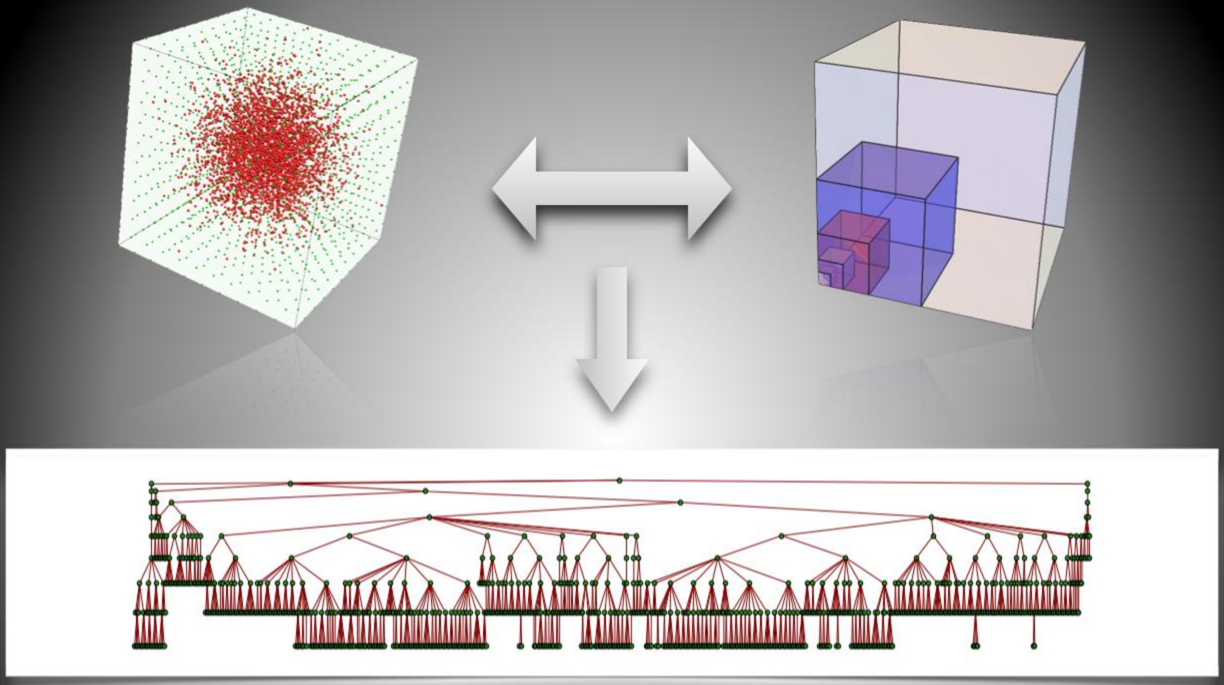
Cooling as an N-Body Problem

- Many **collective beam dynamics** effects can be cast in the form of an N-body problem: space charge, intra-beam scattering, electron cloud, beam-beam, beam-plasma, etc.
- **Electron cooling** is one of the most challenging:
  - Accurate analytical estimates are difficult to come by
  - Large particle numbers, but far from statistical limits
  - Both attractive and repelling forces
  - Close encounters are rare but matter

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**
  - ✗ Time does not parallelize

The Fast Multipole Method



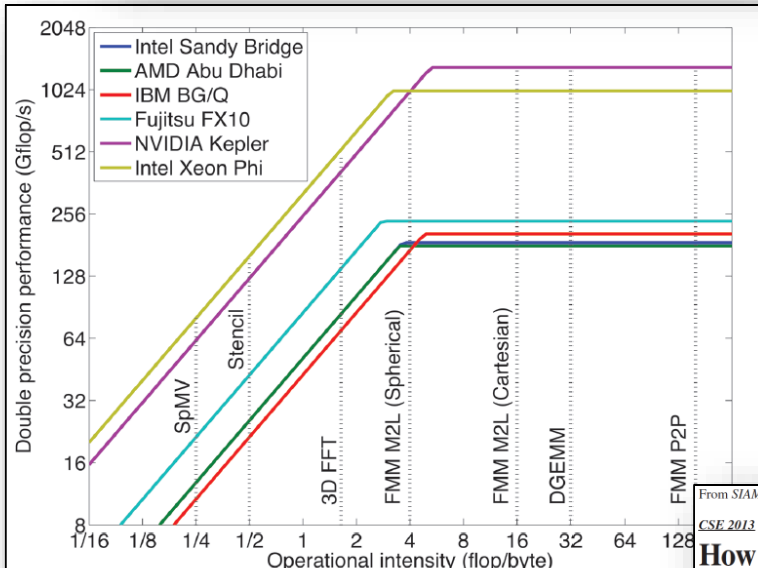
"Best" Algorithms

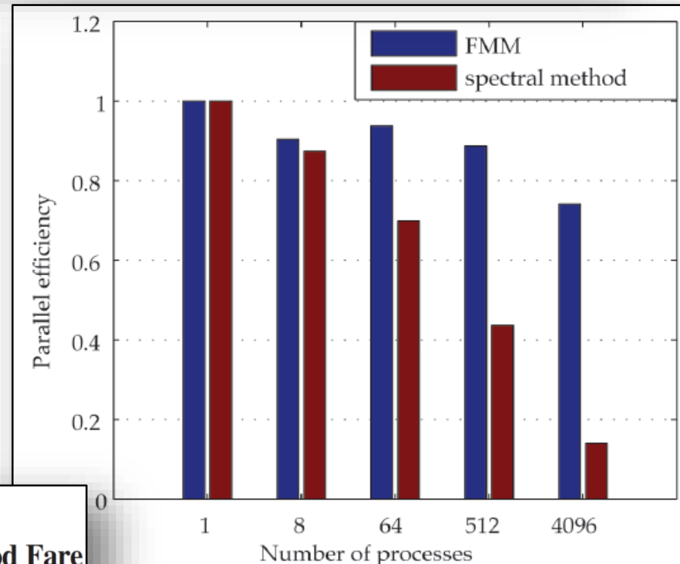
Comparison of scalable fast methods for long-range interactions

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

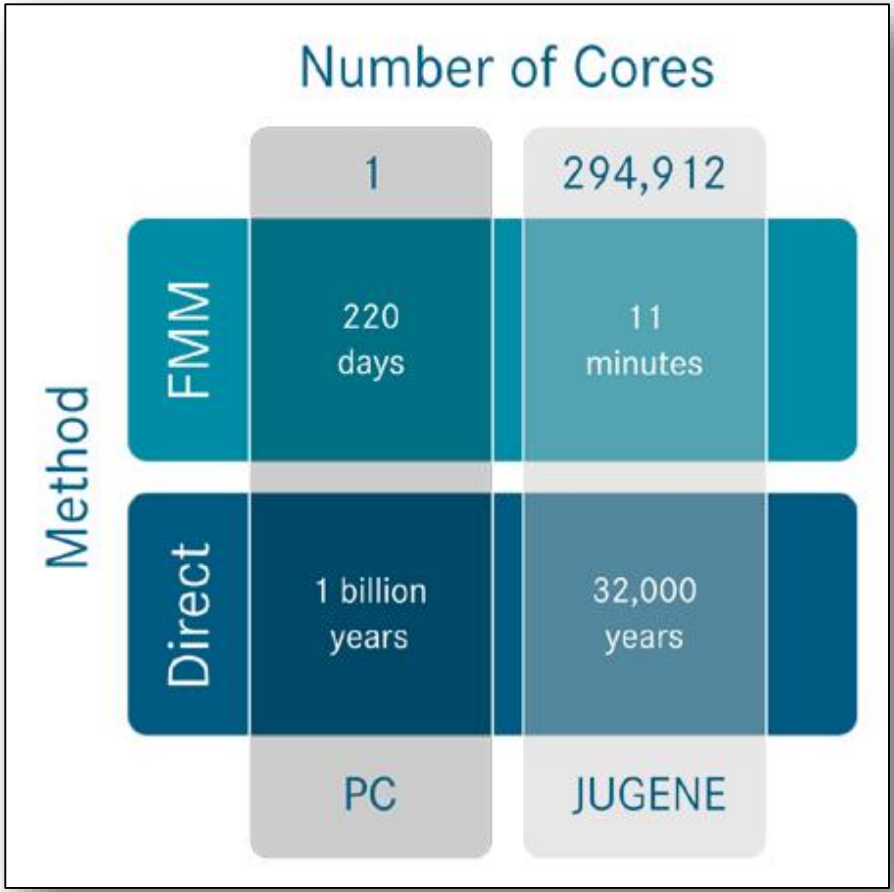
CSE 2013

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)

Picard Integrator

- Picard iterations are used to prove existence and uniqueness of solutions of ODEs
- We implemented it in a Differential Algebraic framework to make it efficient numerically, and variable order to adjust for user requested accuracy
- Not adaptive, hence cannot handle well close encounters and more than one particle species

$$y' = ty^2, y(0) = 1$$

$$y(t) = y(0) + \int_{t_0}^{t} sy(s)^2 ds$$

$$Y_0(t) = 1.$$

$$Y_1(t) = 1 + \int_{t_0}^{t} s(-1)^2 ds = 1 + \frac{1}{2}t^2.$$

$$Y_2(t) = 1 + \int_{t_0}^{t} s(-1 + \frac{1}{2}t^2)^2 ds = 1 + \frac{1}{2}t^2 - \frac{1}{4}t^3 + \frac{1}{24}t^6.$$

$$Y_3(t) = 1 + \int_{t_0}^{t} s(1 + \frac{1}{2}t^2 - \frac{1}{4}t^3 + \frac{1}{24}t^6)^2 ds$$

$$= 1 + \frac{1}{2}t^2 - \frac{1}{4}t^4 + \frac{1}{8}t^6 - \frac{1}{24}t^8 + \frac{1}{96}t^{10} - \frac{1}{576}t^{12} + \frac{1}{8064}t^{14}$$

Particles' High-order Adaptive Dynamics (PHAD)

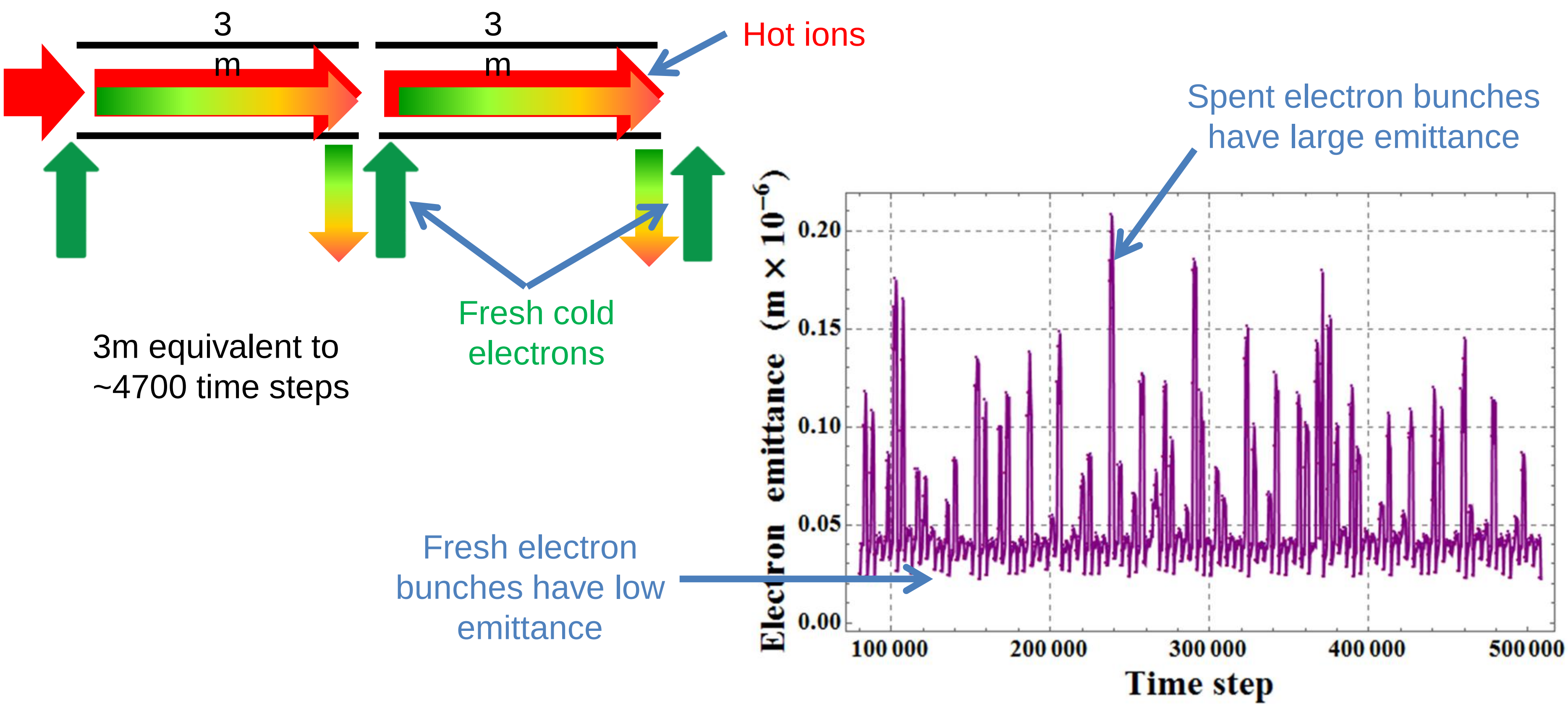
We developed, and continue to improve, a parallel code (PHAD) based on these new methods that will be the first one capable of particle-based simulations of electron cooling and other difficult beam dynamics phenomena with high fidelity, efficiently.

NVIDIA CUDA

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

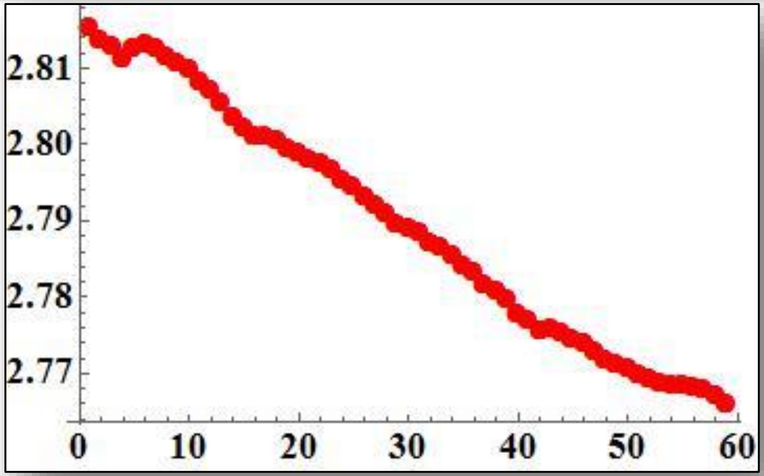
NORTHERN ILLINOIS UNIVERSITY
Beam Physics Code Repository
N. Illinois Center for Accelerator & Detector Development
http://niu.edu/beamphysicscode/

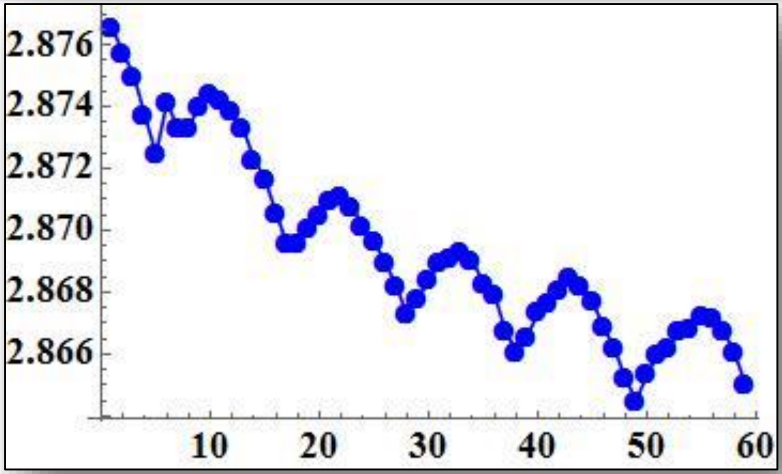
Electron Cooling Simulations

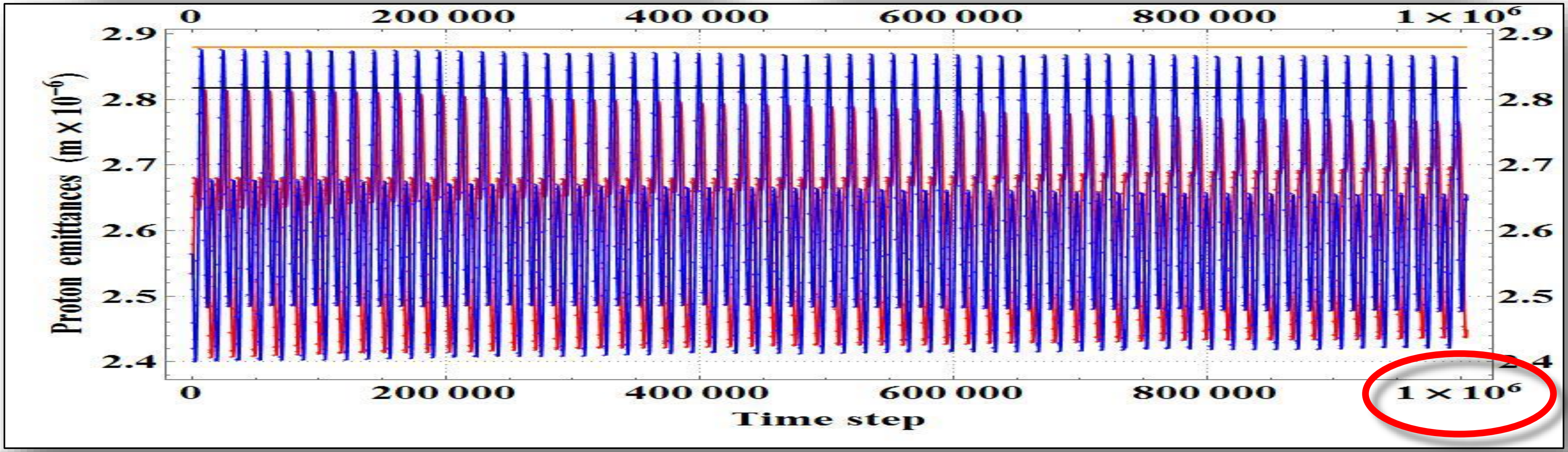


3m equivalent to
~4700 time steps

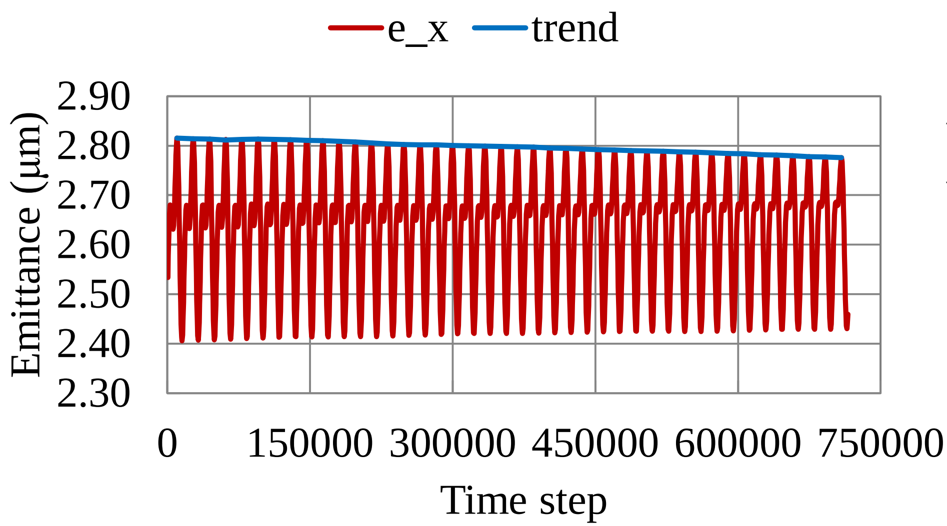
First Particle-Level Cooling Simulation

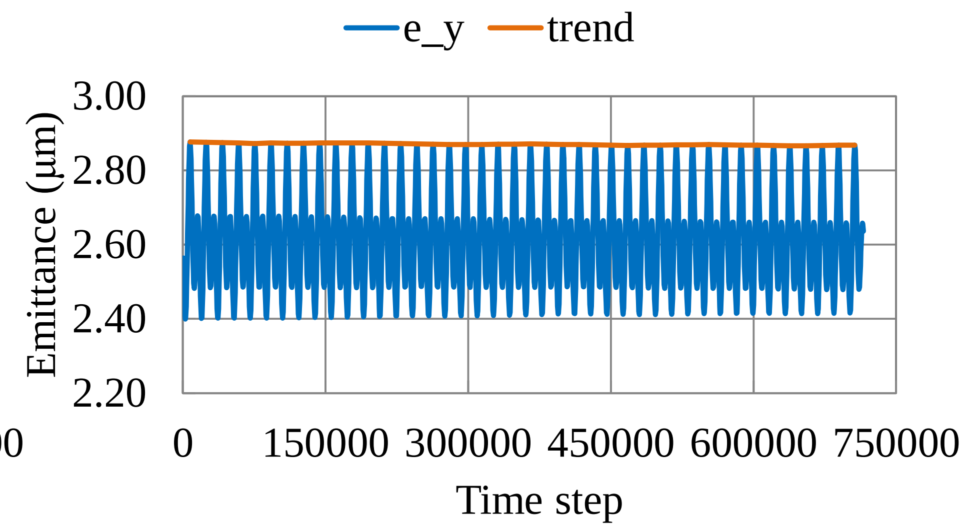






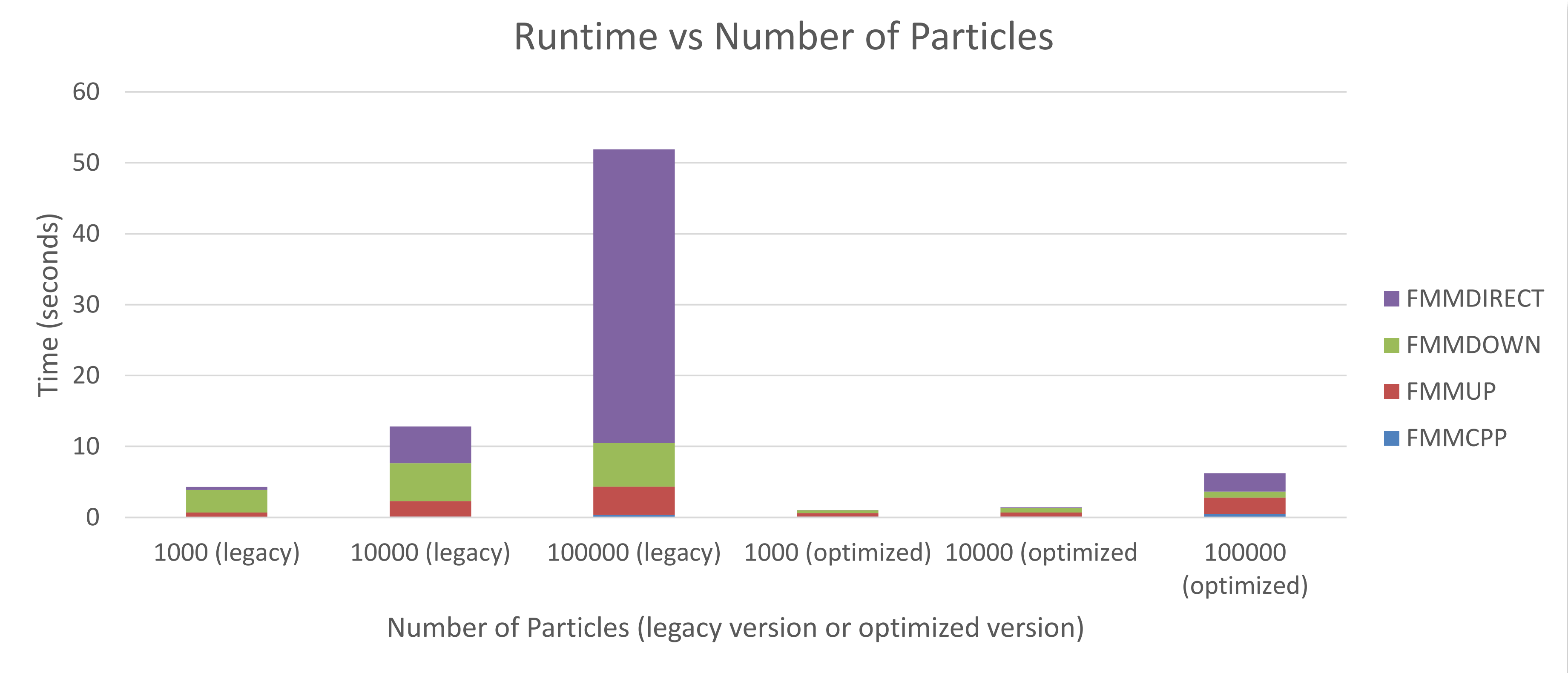
Cooling with Solenoidal Field



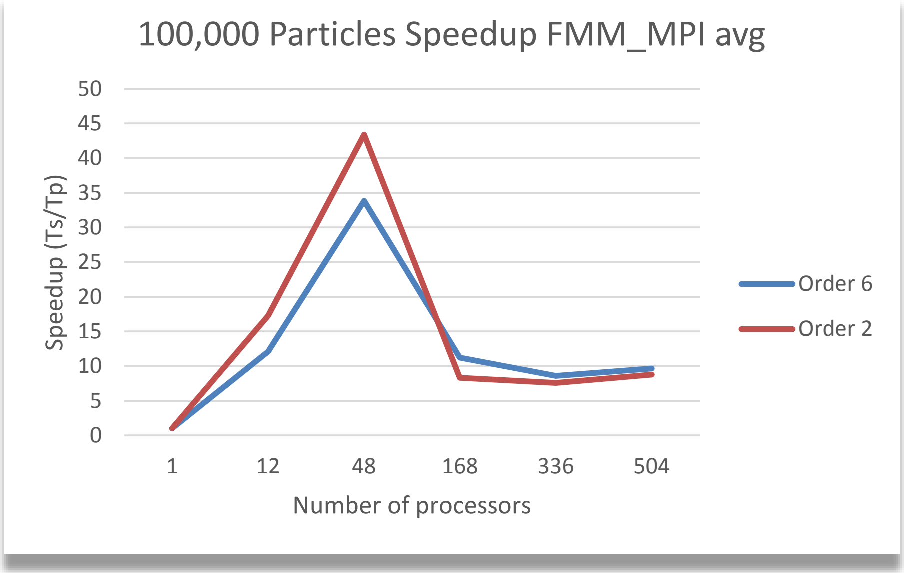


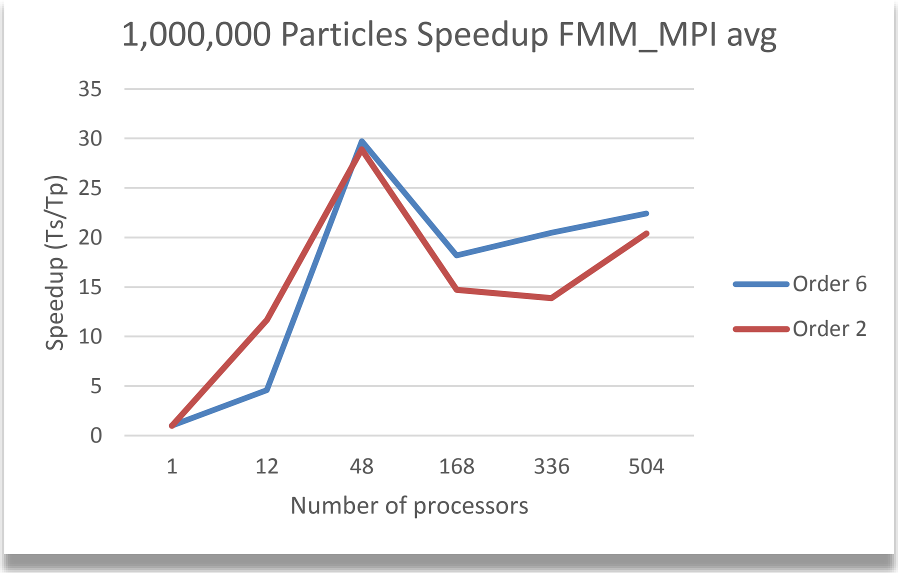
X emittance and Y emittance
decrease faster with time

FMM Parallel Efficiency Improvements



Parallel FMM Speedup (preliminary)





Adaptive, Variable Order Integration

Proposition . *Assume that the function $h \mapsto x(t_m + h)$ is analytic on a disk of radius ρ_m, and that there exists a positive constant M_m such that*

$$|x_m^{[j]}| \approx \frac{M_m}{\rho_m^j}, \qquad \forall j \in \mathbb{N}.$$

Then, if the required accuracy ε tends to 0, the optimal value of h that minimizes the number of operations tends to

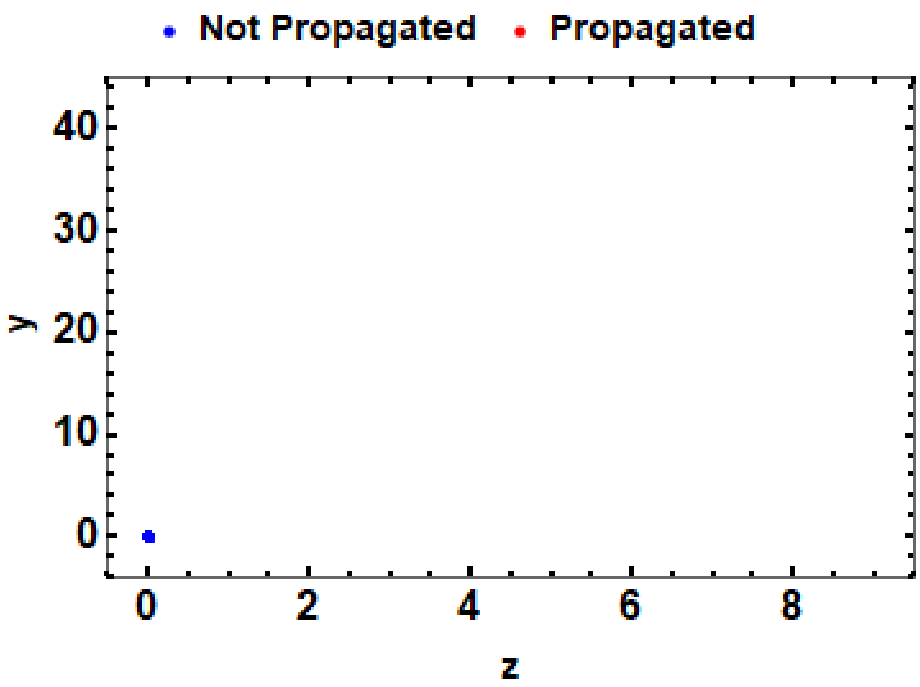
$$h_m = \frac{\rho_m}{e^2},$$

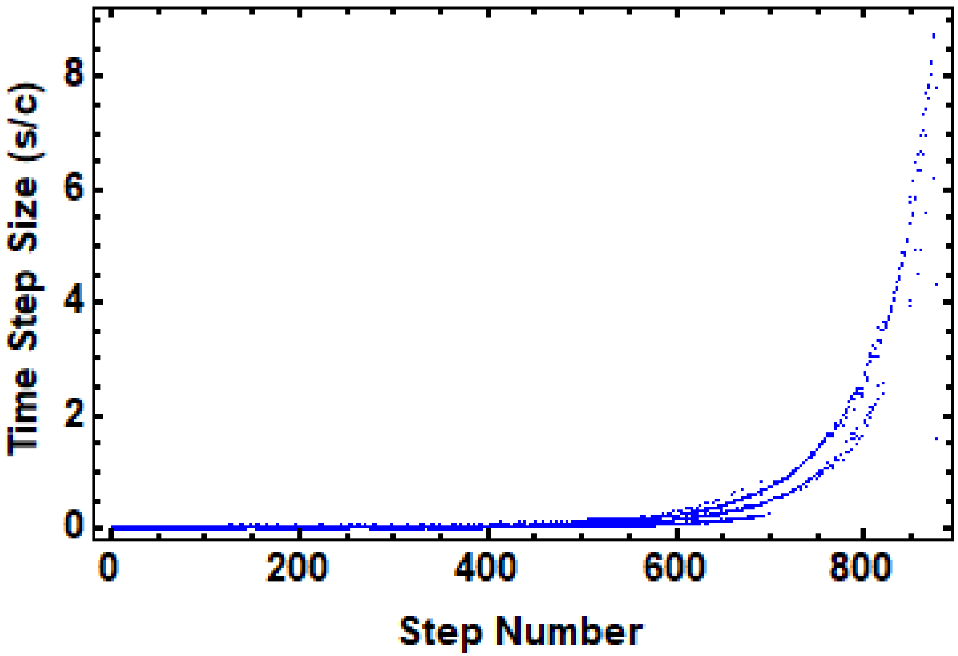
and the optimal order p_m behaves like

$$p_m = -\frac{1}{2} \ln\left(\frac{\varepsilon}{M_m}\right) - 1.$$

Simo (2001)

Low Energy Protons in Electric Field



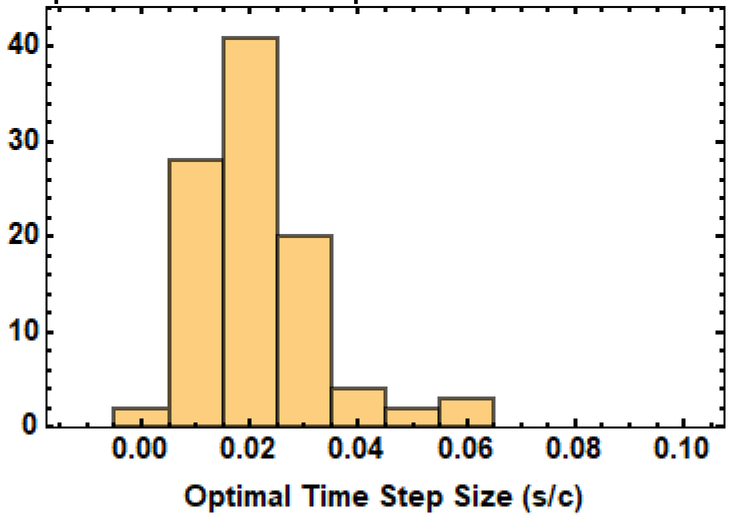


Accuracy setting $\varepsilon = 10^{-12}$

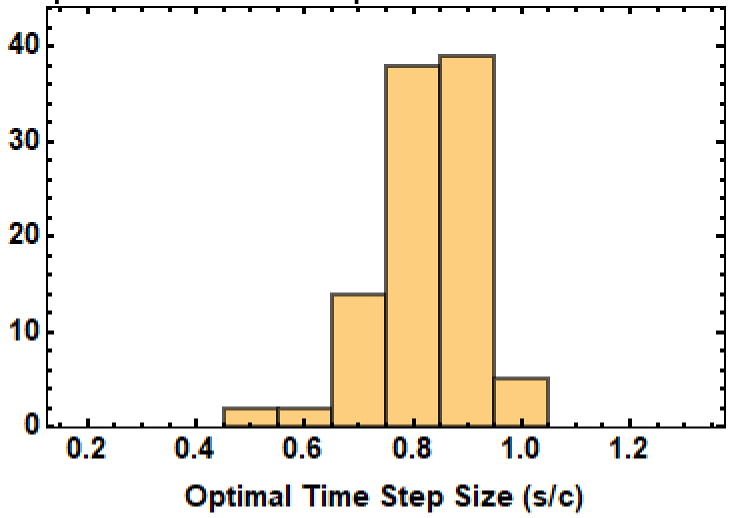
Optimal Time Step Sizes

- Optimal Step sizes at later steps are larger than at earlier steps because the particles move away from each other

- Optimal time step sizes for all particles at step 100

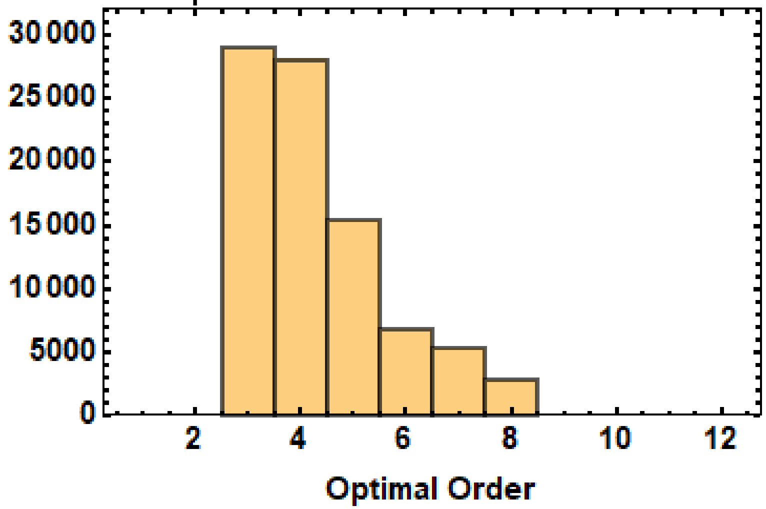


- Optimal time step sizes for all particles at step 700



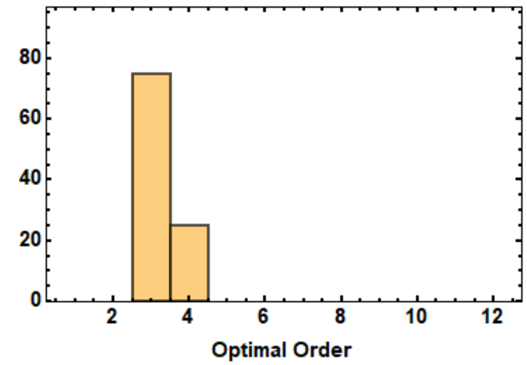
Optimal Orders

- Optimal orders of all particles at all steps

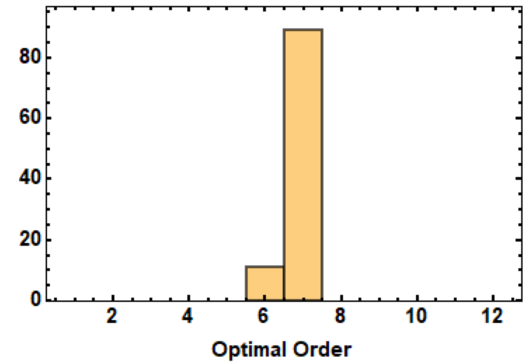


- Orders are varied to achieve the given accuracy efficiently

- Optimal orders of all particles at an early step

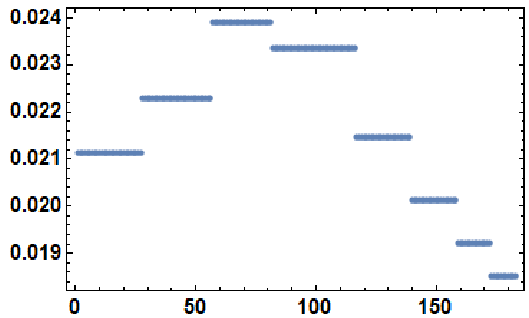


- Optimal orders of all particles at a later step

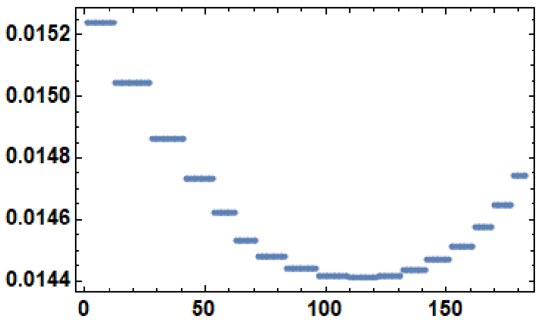


Optimal Time Steps of Some Protons in a High Energy Bunch

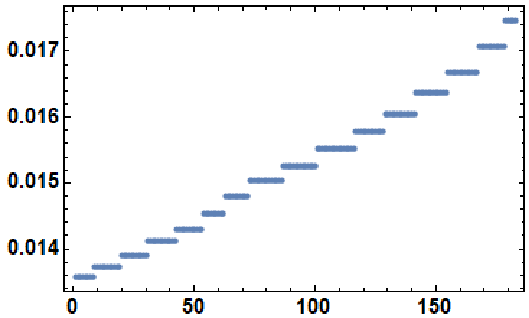
- Particle # 5000



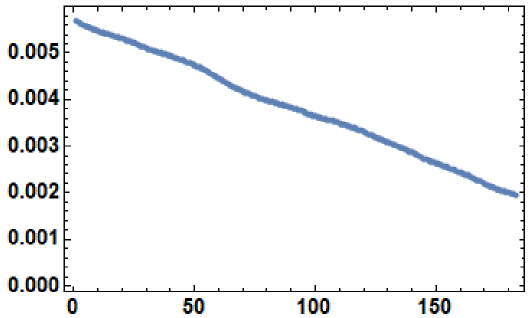
- Particle # 9000



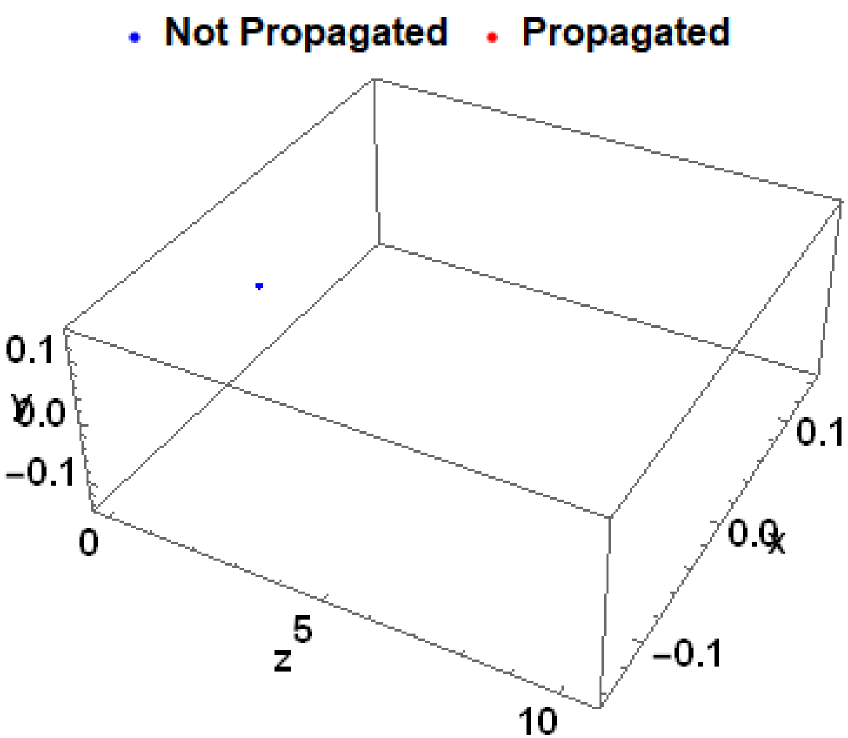
- Particle # 3000

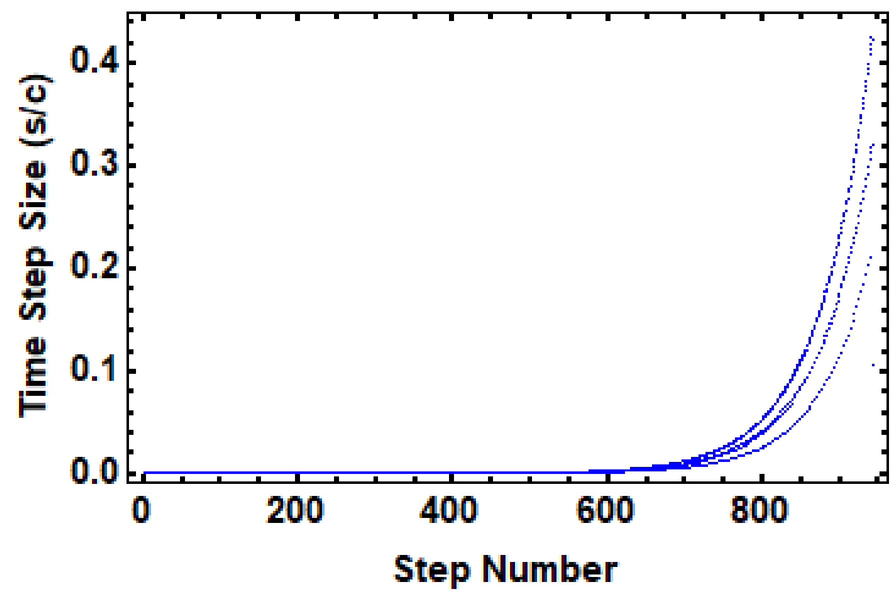


- Particle # 500



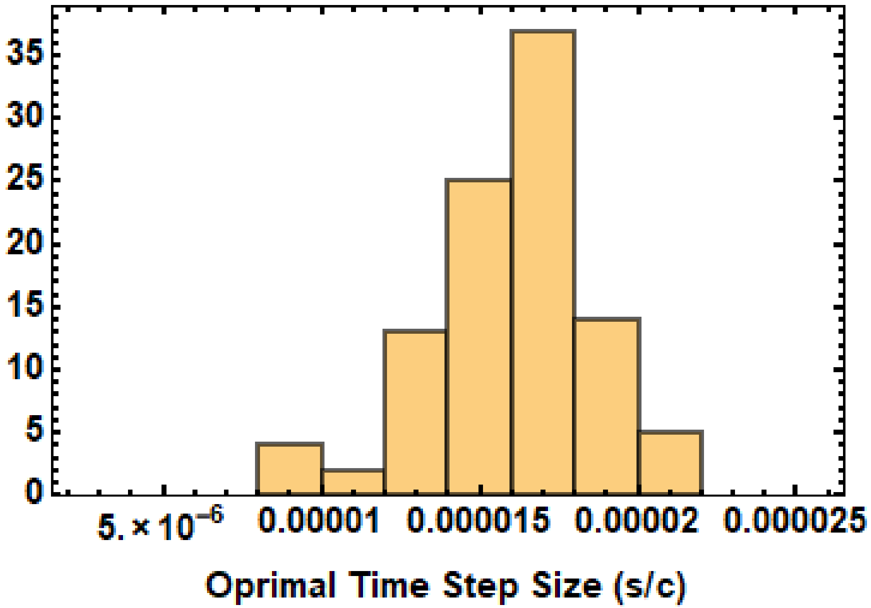
High Energy Lead Ions

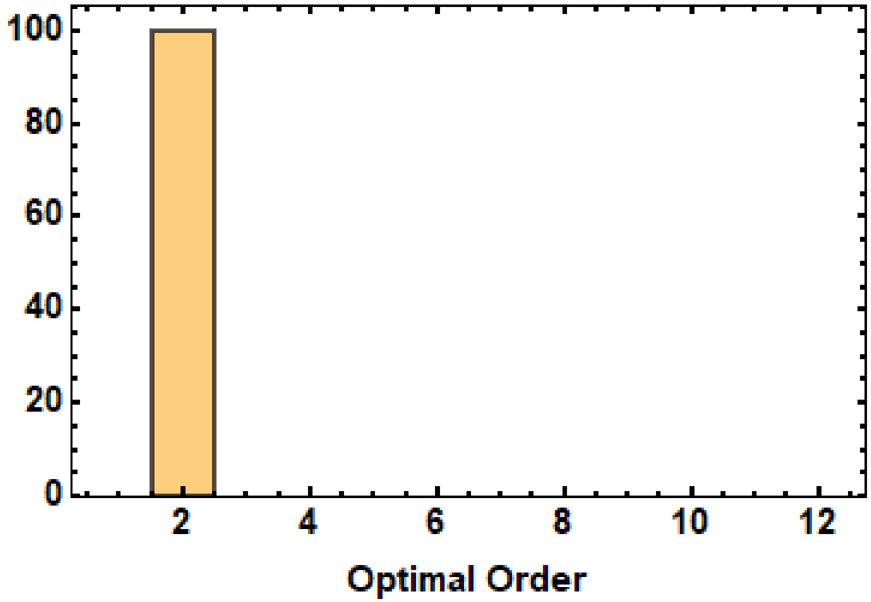




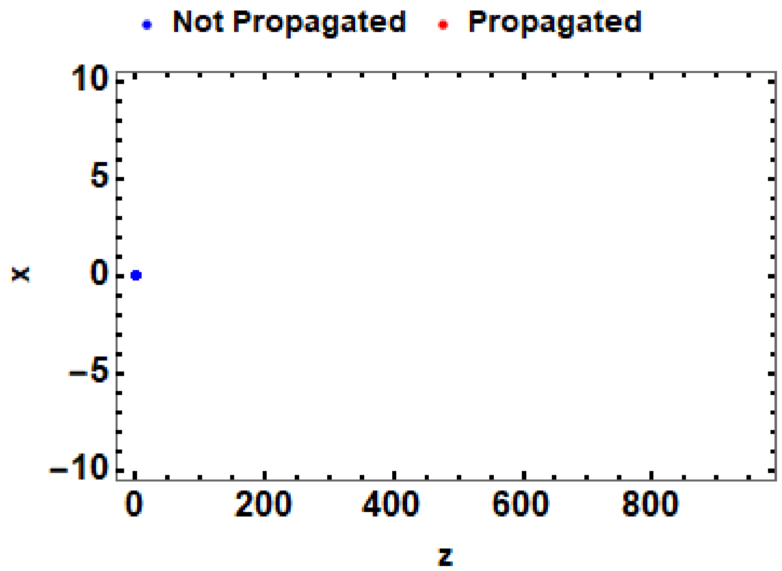
Accuracy setting $\varepsilon = 10^{-5}$

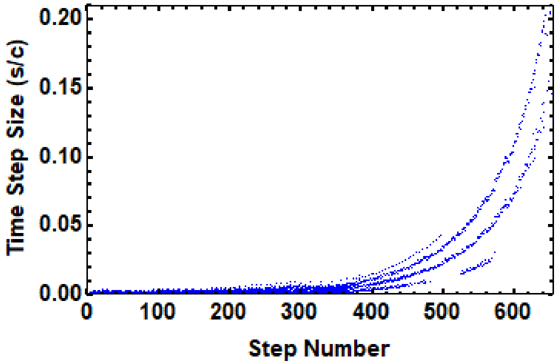
Optimal Time Step Sizes and Orders

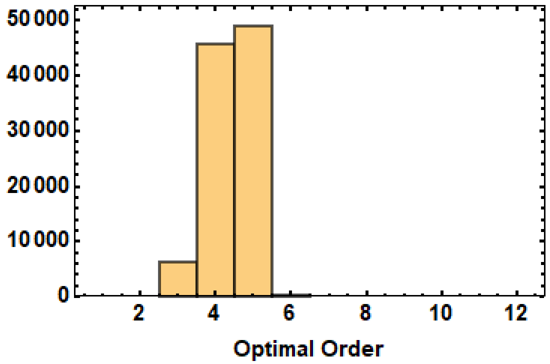




Relativistic Electrons

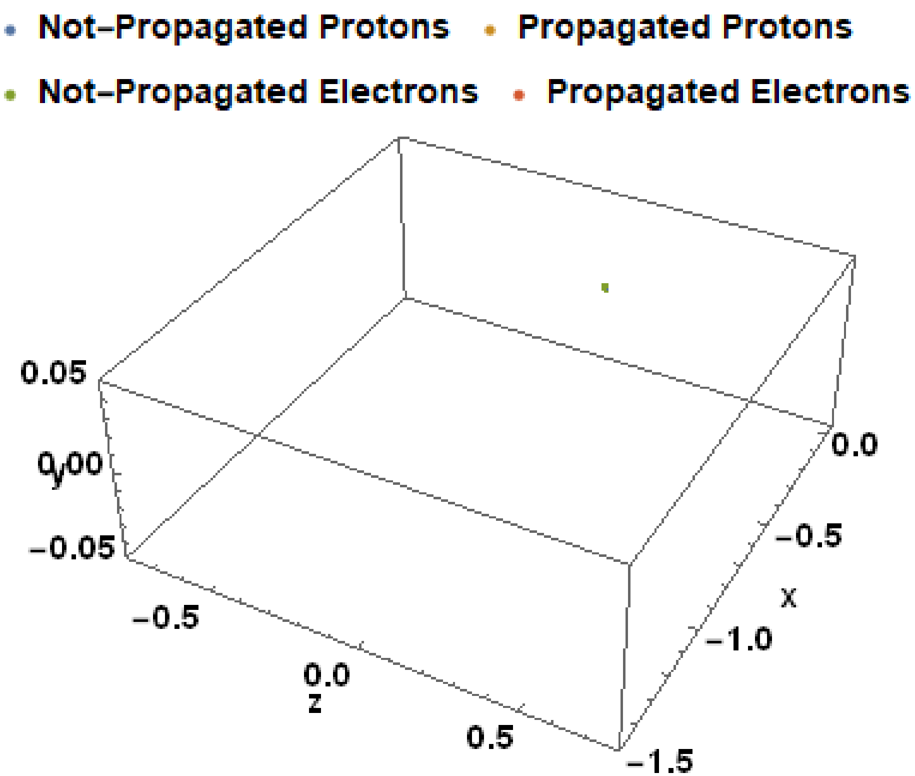


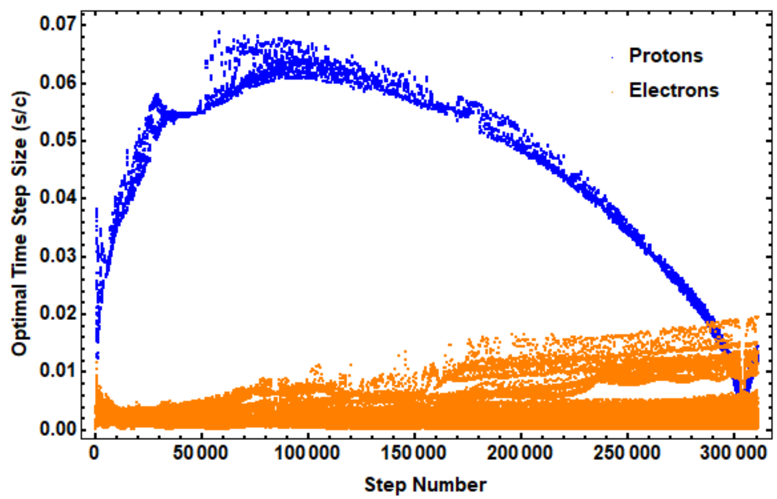




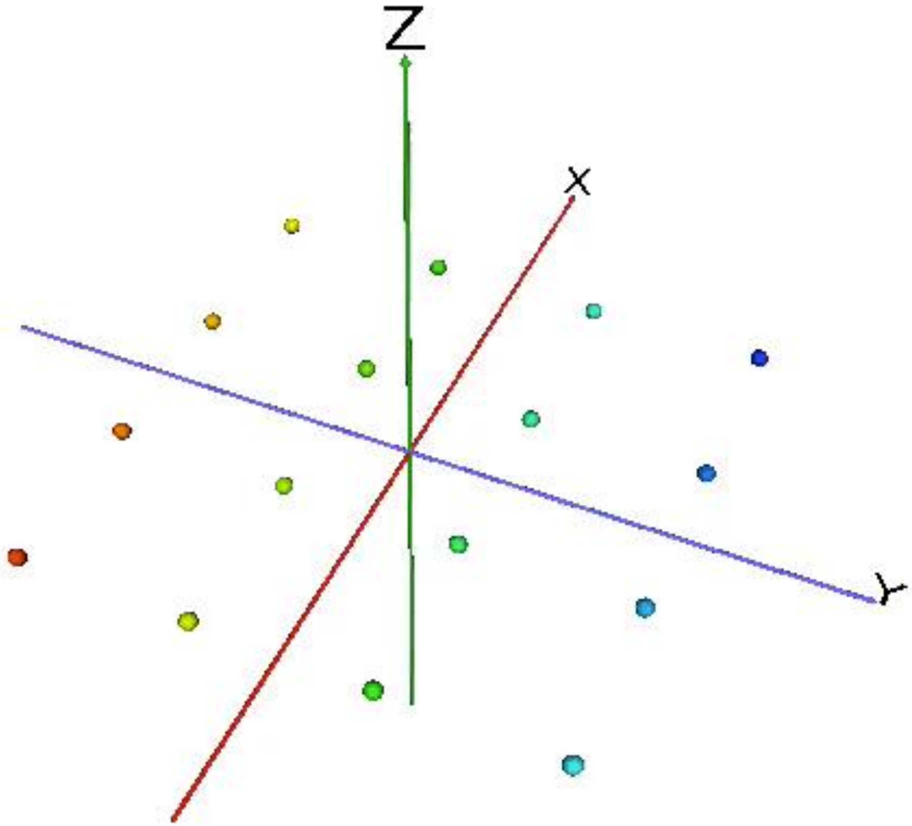
Accuracy setting $\varepsilon = 10^{-16}$

Protons and electrons in magnetic field





Head-On Collisions



Summary and Conclusions

- **Computational beam physics** plays 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
- Entering a new phase of **high fidelity** *electron cooling simulations*