OLD DOMINION UNIVERSITY

IDEA FUSION

Toward Gear-Change and Beam-Beam Simulations with GHOST

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Interdisciplinary Collaboration

Jefferson Lab (CASA) Collaborators:

Vasiliy Morozov, He Zhang, Fanglei Lin, Yves Roblin, Todd Satogata

Old Dominion University (Center for Accelerator Science):

Professors:

Physics: Alexander Godunov

Computer Science: Mohammad Zubair, Desh Ranjan

Graduate students:

Computer Science: Kamesh Arumugam, Ravi Majeti

Physics: Chris Cotnoir, Mark Stefani

Outline

- Motivation and Challenges
  - Importance of beam synchronization
  - Computational requirements and challenges
- GHOST: New Beam-Beam Code
  - Outline
  - Present and future capabilities
  - Proposed implementation for beam synchronization
- Status and Timetable

Motivation: Implication of "Gear Changing"

- Synchronization – highly desirable
  - Smaller magnet movement
  - Smaller RF adjustment

- Detection and polarimetry – highly desirable
  - Cancellation of systematic effects associated with bunch charge and polarization variation – great reduction of systematic errors, sometimes more important than statistics
  - Simplified electron polarimetry – only need average polarization, much easier than bunch-by-bunch measurement

- Dynamics – question
  - Possibility of an instability – needs to be studied (Hirata & Keil 1990; Hao *et al*. 2014)

Computational Requirements

- Perspective: At the current layout of the MEIC
  1 hour of machine operation time ≈ 400 million turns

- Requirements for long-term beam-beam simulations of MEIC
  ① High-order symplectic particle tracking
  ② Speed
  ③ Beam-beam collision
  ④ "Gear changing"

- Our main charge is two-fold:
  - Do it right:
    - High-order symplectic tracking
  - Do it fast:
    - One-turn maps, approximate beam-beam collisions

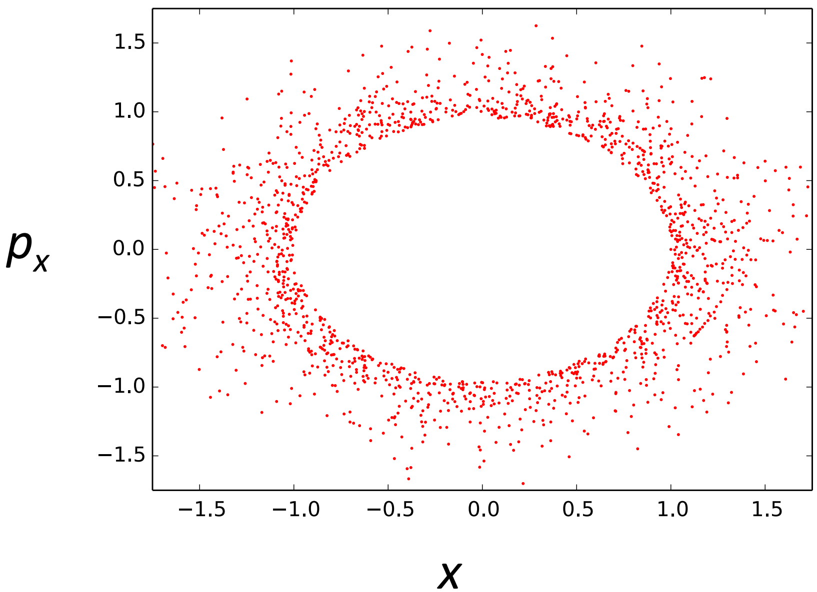
GHOST: Outline

- GHOST: Gpu-accelerated High-Order Symplectic Tracking
- Our philosophy: Resolve computational bottlenecks by
  - Employing Bassetti-Erskine approximation for collisions
  - Implementing the code on a massively-parallel GPU platform
- GPU implementation yields best returns when:
  - The same instruction for multiple data (particle tracking)
  - No communication among threads (particle tracking)
- Two main parts:
  1. Particle tracking
  2. Beam collisions

GHOST: Symplectic Particle Tracking

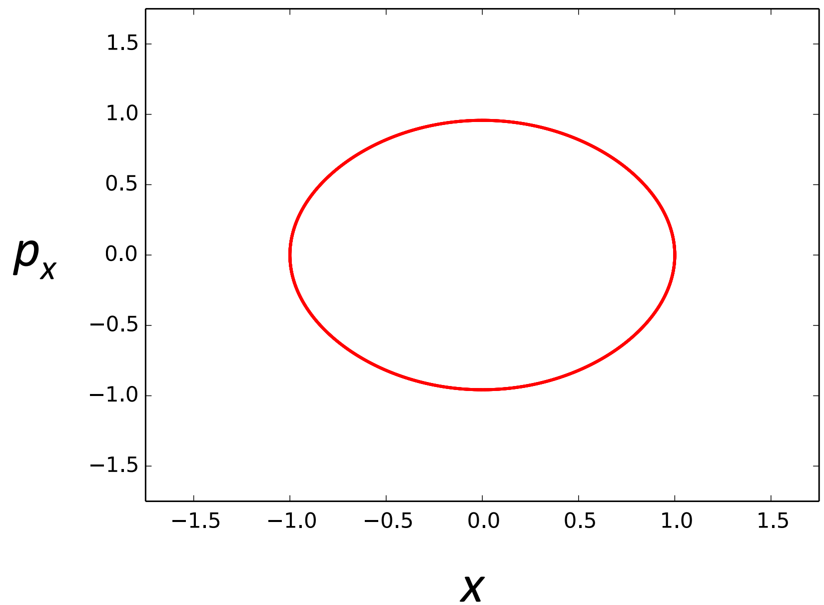
- Symplectic tracking is essential for long-term simulations

Non-Symplетic Tracking
500 000 iterations, 3rd order map



Energy not conserved
Particle will soon be lost

Symplетic Tracking
500 000 iterations, 3rd order map



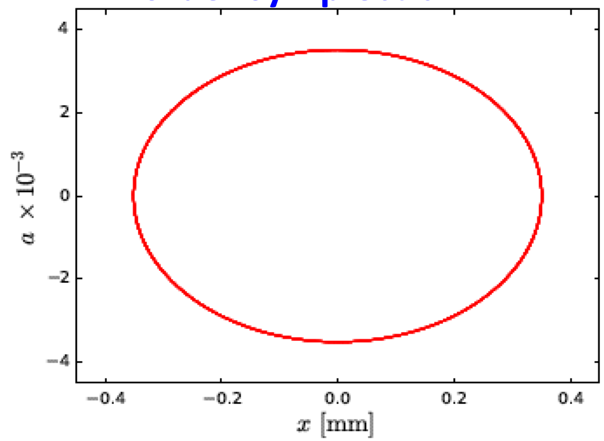
Energy conserved

GHOST: Symplectic Particle Tracking

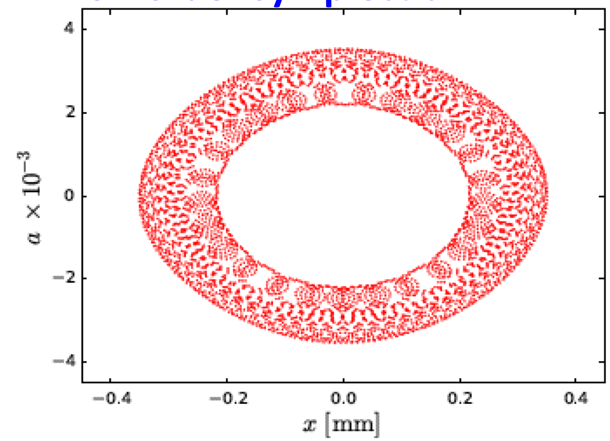
- Higher-order symplecticity reveals more about dynamics

5000 turns

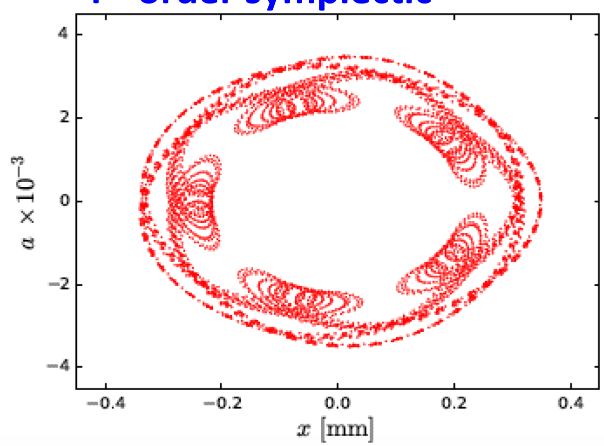
2nd order symplectic



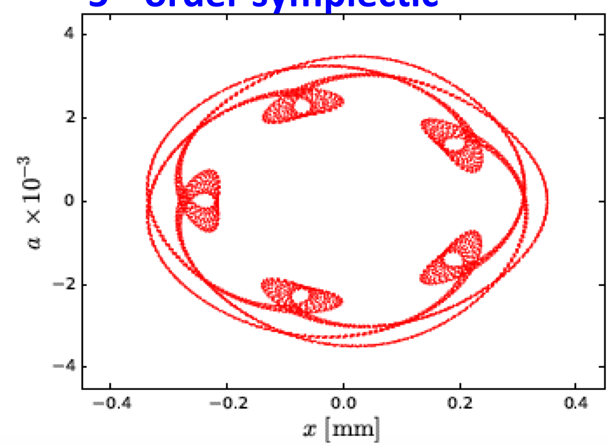
3rd order symplectic



4th order symplectic



5th order symplectic



GHOST: Symplectic Particle Tracking

- Symplectic tracking in GHOST is the same as in COSY Infinity (Makino & Berz 1999)
- Start with a one-turn map

$$x = \sum_{\alpha\beta\gamma\eta\lambda\mu} \mathcal{M}(x|\alpha\beta\gamma\eta\lambda\mu) x^{\alpha} a^{\beta} y^{\gamma} b^{\eta} l^{\lambda} \delta^{\mu}$$

- Symplecticity criterion enforced at each turn

$$(\boldsymbol{q}_f, \boldsymbol{p}_i) = \mathbf{J} \nabla F_2(\boldsymbol{q}_i, \boldsymbol{p}_f) \qquad \mathbf{J} = \begin{bmatrix} 0 & -\mathbf{I} \\ \mathbf{I} & 0 \end{bmatrix}$$

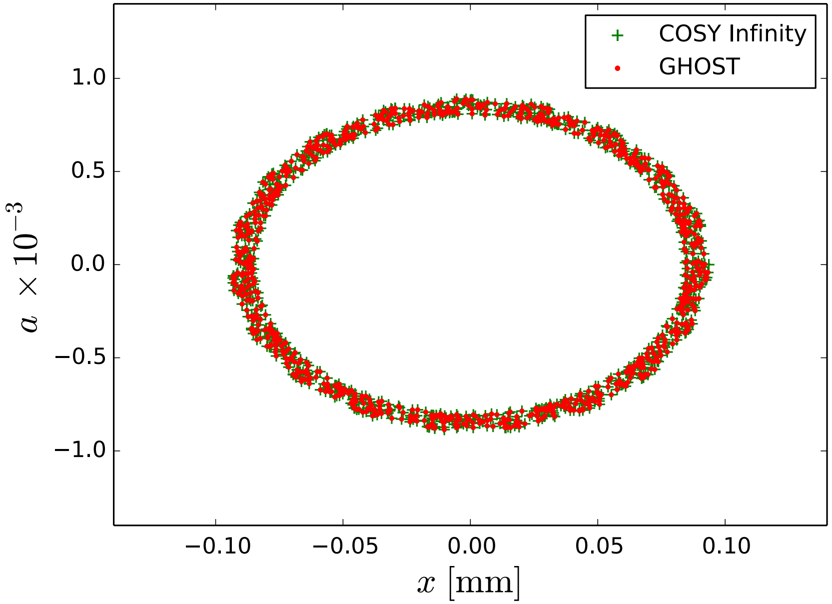
Initial coordinates $(\boldsymbol{q}_i, \boldsymbol{p}_i)$ Final coordinates $(\boldsymbol{q}_f, \boldsymbol{p}_f)$

- Involves solving an implicit set of non-linear equations
  - Introduces a significant computational overhead

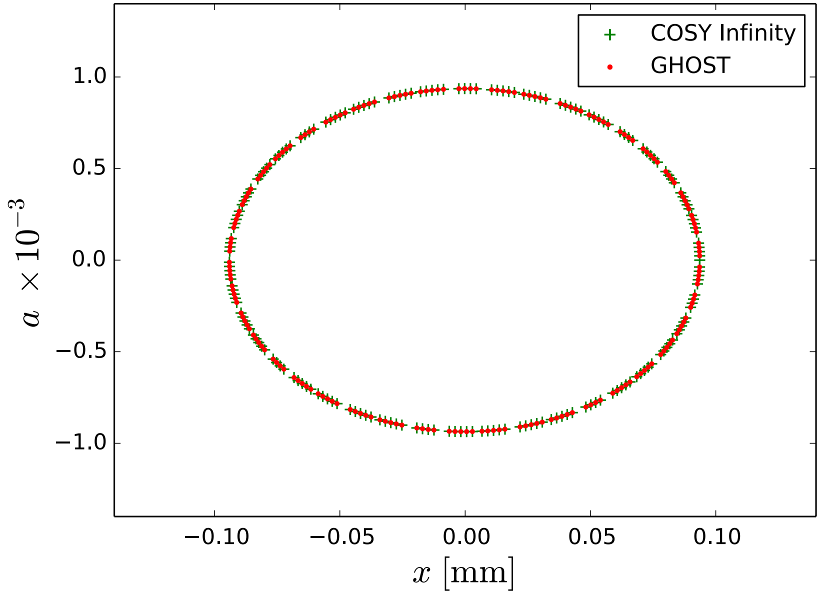
GHOST: Symplectic Particle Tracking

- Symplectic tracking in GHOST is the same as in COSY Infinity (Makino & Berz 1999)

Non-Sympletic Tracking 3rd order map
COSY GHOST 100,000 turns



Sympletic Tracking 3rd order map
COSY GHOST 100,000 turns

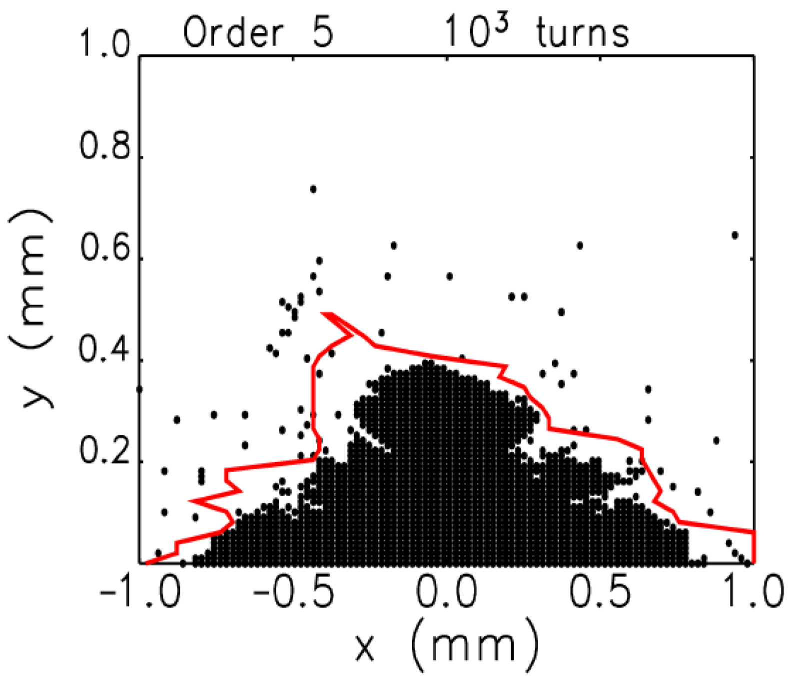


Perfect agreement!

GHOST: Symplectic Particle Tracking

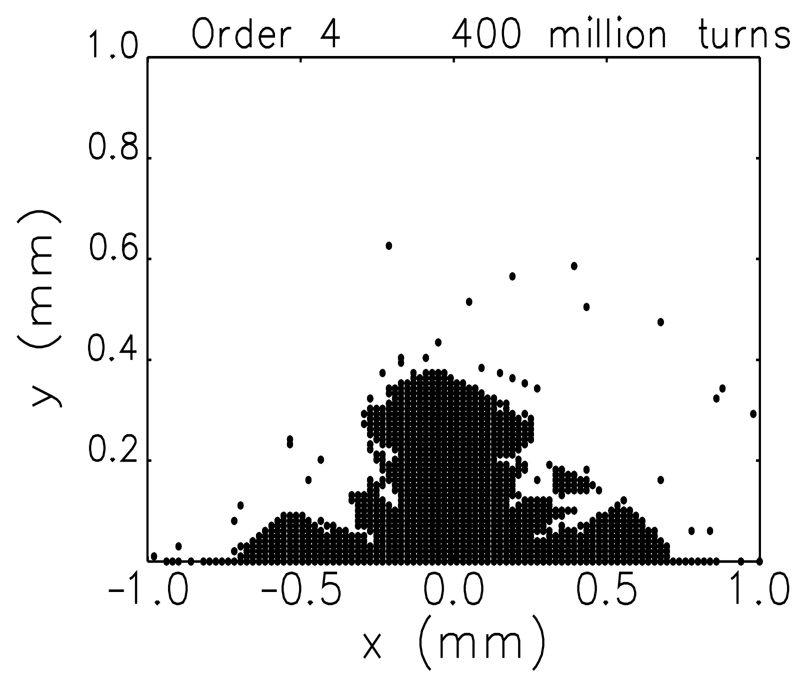
- Dynamic aperture comparison to Elegant (Borland 2000)
- 400 million turn simulation (truly long-term)

GHOST **Elegant** **1,000 turns**



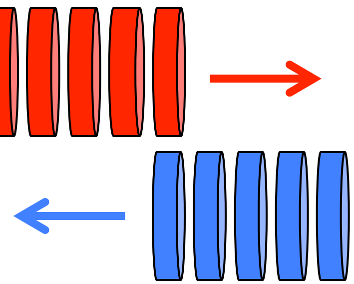
Excellent agreement!

Sympletic Tracking 4th order map



GHOST: Beam Collisions

- Bassetti-Erskine Approximation
  - Beams treated as 2D transverse Gaussian slices
    (Good approximation for the JLEIC)
  - Poisson equation reduces to a complex error function
  - Finite length of beams simulated by using multiple slices

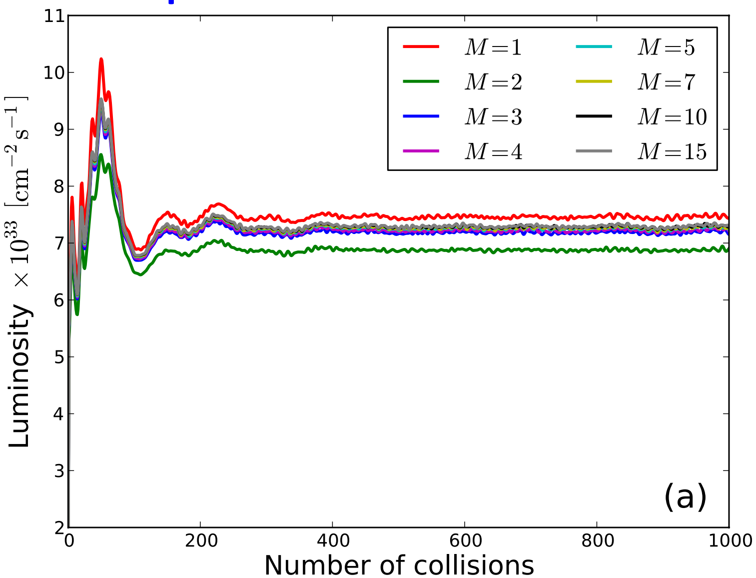


- We generalized a “weak-strong” formalism of Bassetti-Erskine
  - Include “strong-strong” collisions (each beam evolves)
  - Include various beam shapes (original only flat beams)

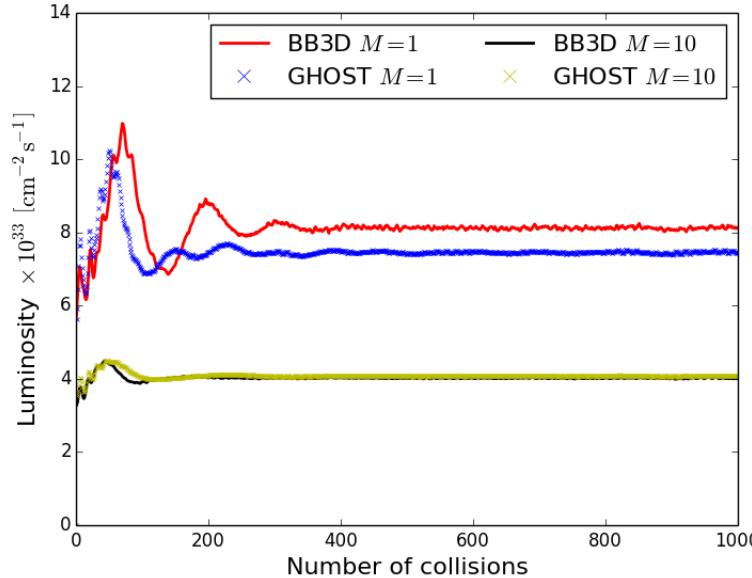
GHOST Benchmarking: Collisions

- Code calibration and benchmarking
  - Convergence with increasing number of slices *M*
  - Comparison to BeamBeam3D (Qiang, Ryne & Furman 2002)

GHOST, 1 cm bunch
40k particles



BeamBeam3D & GHOST, 10 cm bunch
40k particles



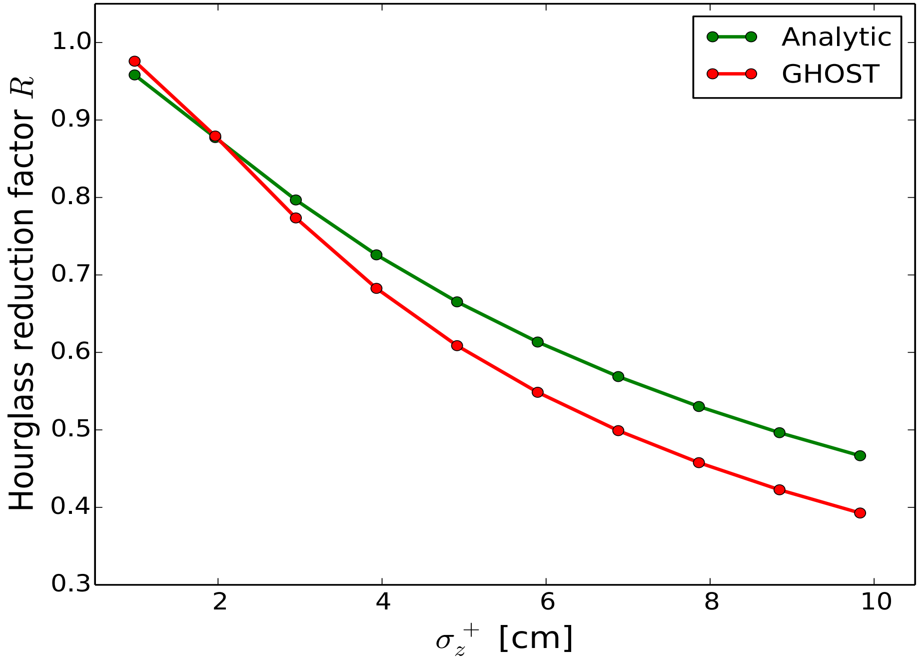
Finite bunch length accurately represented

Excellent agreement with BeamBeam3D

GHOST Benchmarking: Hourglass Effect

- When the bunch length $\sigma_z \approx \beta^*$ at the IP, it experiences a geometric reduction in luminosity – the *hourglass effect* (Furman 1991)

GHOST, 128k particles, 10 slices

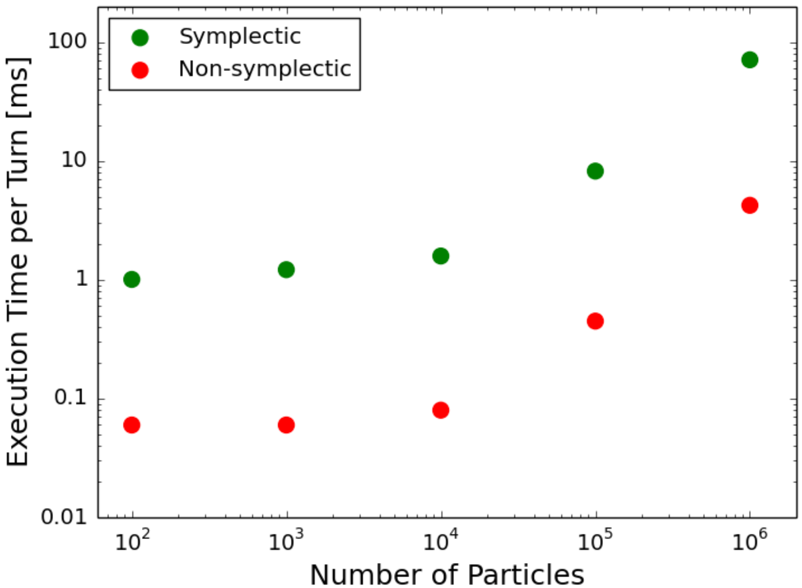


Excellent agreement with theory

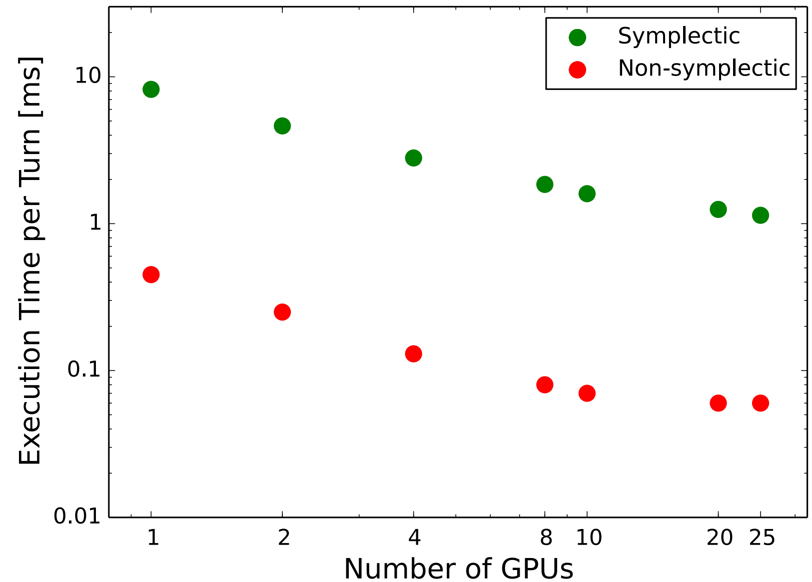
GHOST: GPU Implementation

GHOST: 3rd order tracking

1 GPU, varying # of particles



100k particles, varying # of GPUs



Speedup on 1 GPU over 1 CPU over 280 times

400 million turns in an JLEIC ring for a bunch with 100k particles:
< 7 hr non-symplectic, ~ 4.5 days for symplectic tracking

With each new GPU architecture, performance improves

GHOST: Beam Synchronization

- Gear change requires many collisions per crossing (≈ 3400)
  - The load can be alleviated by implementation on GPUs
  - The information for all bunches stored: huge memory load
  - Now more interesting to CS folks: truly parallel problem

- Prognosis:
  - Gear change is implementable, but will slow the code down
  - Long-term simulations may not be so "long"

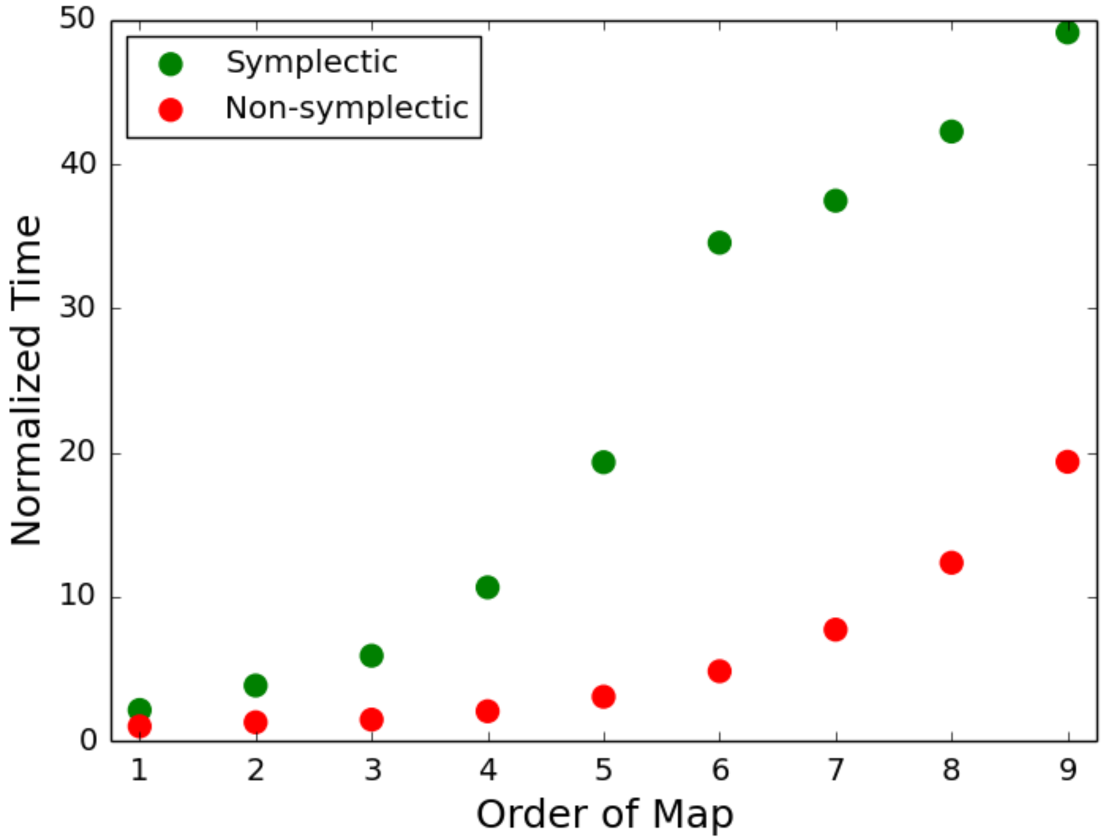
GHOST: Status

- Stage 1: Particle tracking (COMPLETED)
  - High-order, symplectic tracking optimized on GPUs
  - Benchmarked against COSY: Exact match
  - 400 million turn tracking-only simulation completed
  - Submitted for publication (*Phys. Rev. Accel. Beams*)
- Stage 2: Beam collisions (CURRENTLY UNDERWAY)
  - Bassetti-Erskine collision implemented on GPUs
  - Validation, benchmarking and optimization currently underway
  - Single bunch simulations in the summer
  - Multiple bunch simulations by the end of the year
- Stage 3: Other effects to be implemented (YEAR 2 & BEYOND)
  - Other collision methods: fast multipole
  - Space charge, synchrotron radiation, IBS

Backup Slides

GHOST GPU Implementation

GHOST Tracking on 1 GPU



JLEIC Design Parameters Used

Quantity	Unit	e^- beam	p beam
Energy	GeV	5	60
Collision frequency	MHz	750	
Particles per bunch	10^{10}	2.5	0.416
Beam current	A	3.0	0.5
Energy spread	10^{-3}	0.71	0.3
rms bunch length	mm	7.5	10
Horiz. bunch size at IP	μm	23.4	
Vertical bunch size at IP	μm	4.7	
Horiz.1 emit. (norm.)	μm	53.5	0.35
Vertical emit. (norm.)	μm	10.7	0.07
Horizontal β^*	cm	10	
Vertical β^*	cm	2	
Vertical beam-beam tune shift		0.029	0.0145
Damping time	turns	1516 (6.8 ms)	$\approx 2.4 \times 10^6$ ($\approx$ 11000 s)
Synchrotron tune		0.045	0.045
Ring length	m	1340.92	1340.41
Peak luminosity	$cm^{-2}s^{-1}$	0.562×10^{34}	
Reduction (hourglass)		0.957	
Peak luminosity with hourglass effect	$cm^{-2}s^{-1}$	0.538×10^{34}	