Long-Term Simulation of Beam-Beam Dynamics with GHOST

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Outline

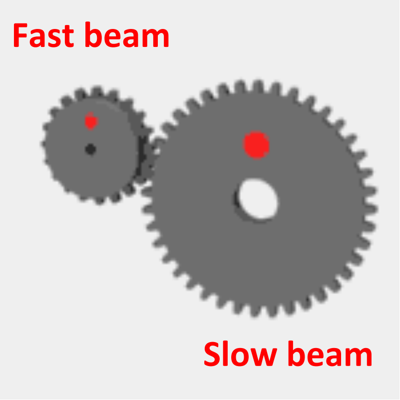
- Motivation and challenges of beam-beam simulations of JLEIC
  - Computational requirements
  - "Gear change" scheme for beam synchronization
- GHOST code development
  - Outline of the implementation (tracking and collision)
  - Simulating "gear change"
- GHOST status report

Computational Requirements

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

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

Implication of "Gear Change"



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

GHOST: Outline

- GHOST: Gpu-accelerated High-Order Symplectic Tracking

  Designed and developed from scratch

- GHOST resolves computational bottlenecks by:
  - Using one-turn maps for particle tracking
  - Employing Bassetti-Erskine approximation for collisions
  - Implementing the code on a massively-parallel GPU platform

- Why GPUs?
  - Ideal for "same instruction for multiple data" (particle tracking)
  - Best when no communication required (tracking; collision)
  - Moore's law still applies to GPUs (no longer for CPUs)

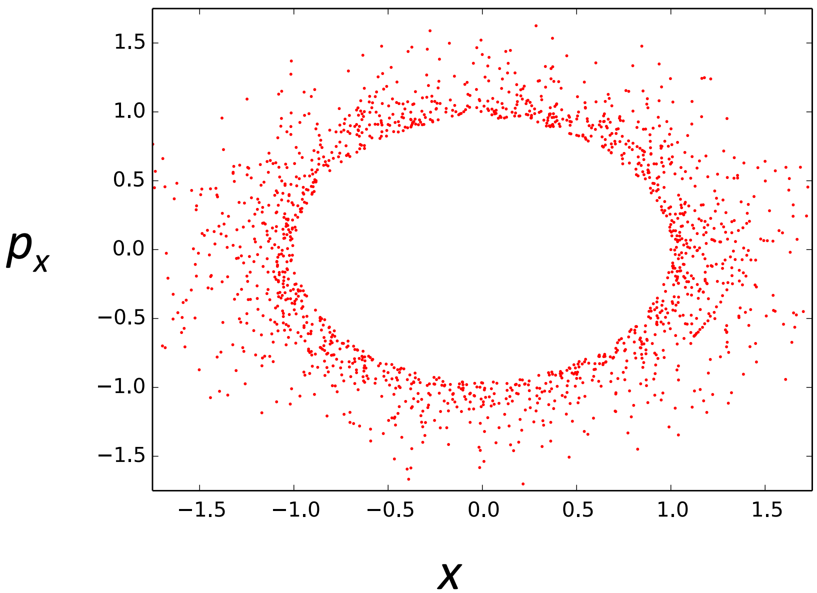
- Two main parts:

  1. Particle tracking
  2. Beam collisions

GHOST: Symplectic Particle Tracking

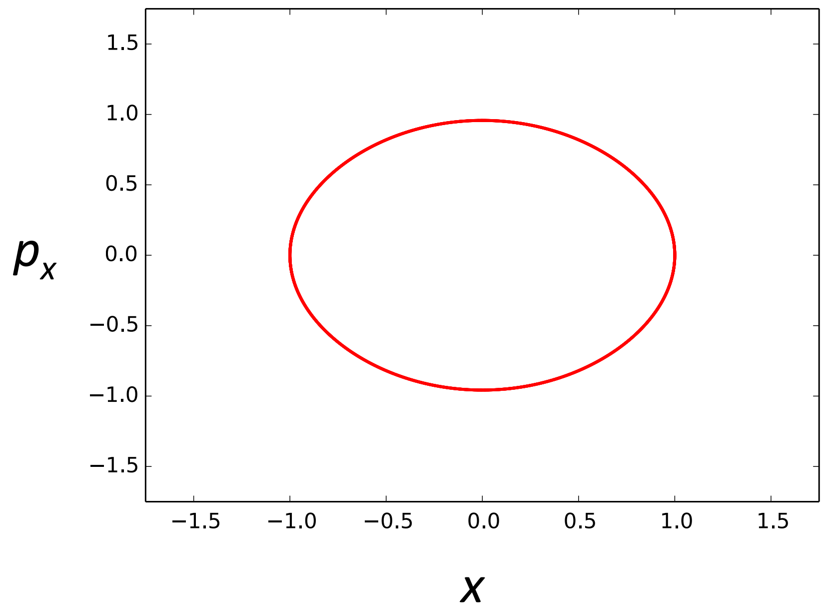
- Symplectic tracking is essential for long-term simulations

Non-Sympletic Tracking
500 000 turns, 3rd order map



Energy is not conserved
Particle will soon be lost

Sympletic Tracking
500 000 turns, 3rd order map

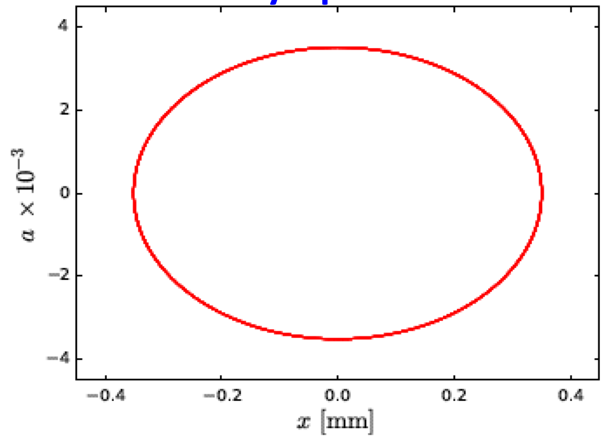


Energy is conserved

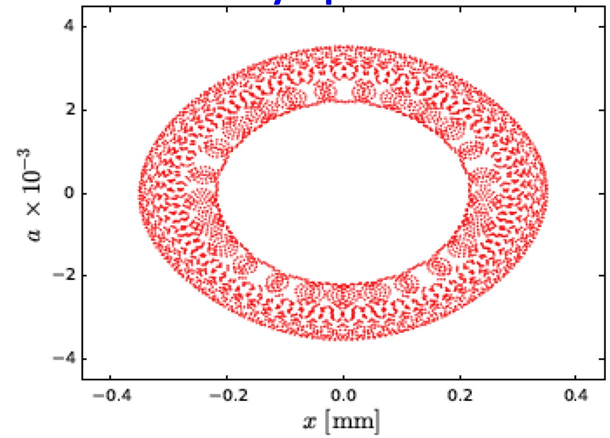
GHOST: Symplectic Particle Tracking

- Higher-order symplecticity reveals more about dynamics

2nd order symplectic

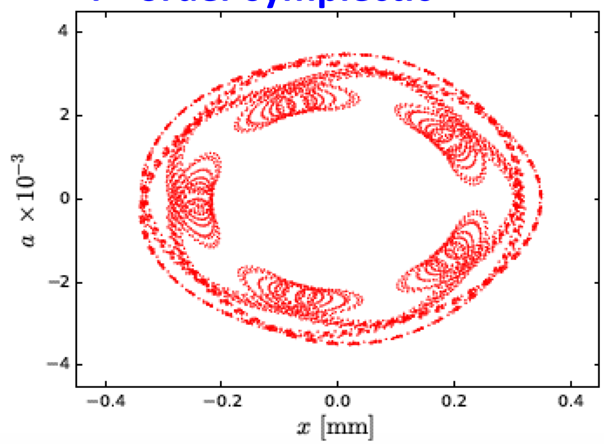


3rd order symplectic

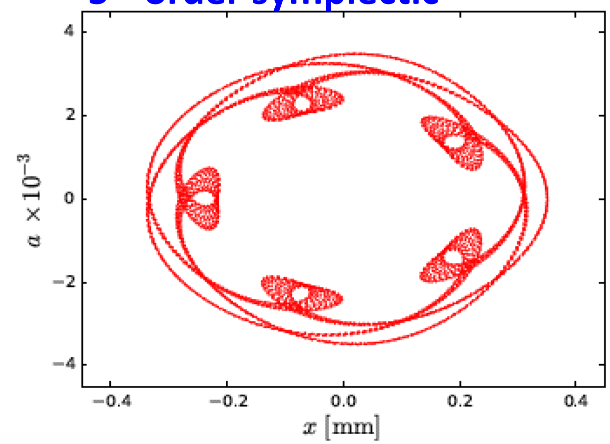


5000 turns

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

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

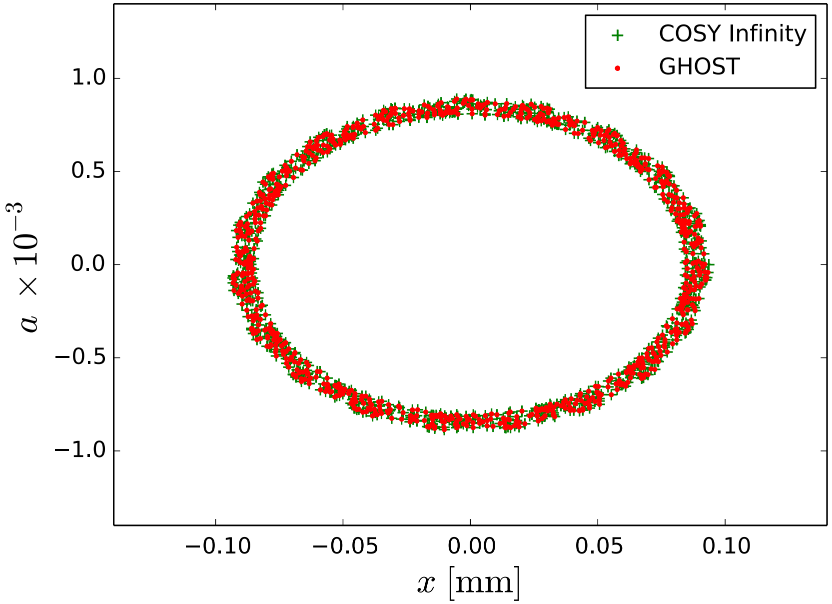
Initial coordinates $(\boldsymbol{q}_i, \boldsymbol{p}_i)$ Final coordinates $(\boldsymbol{q}_f, \boldsymbol{p}_f)$

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

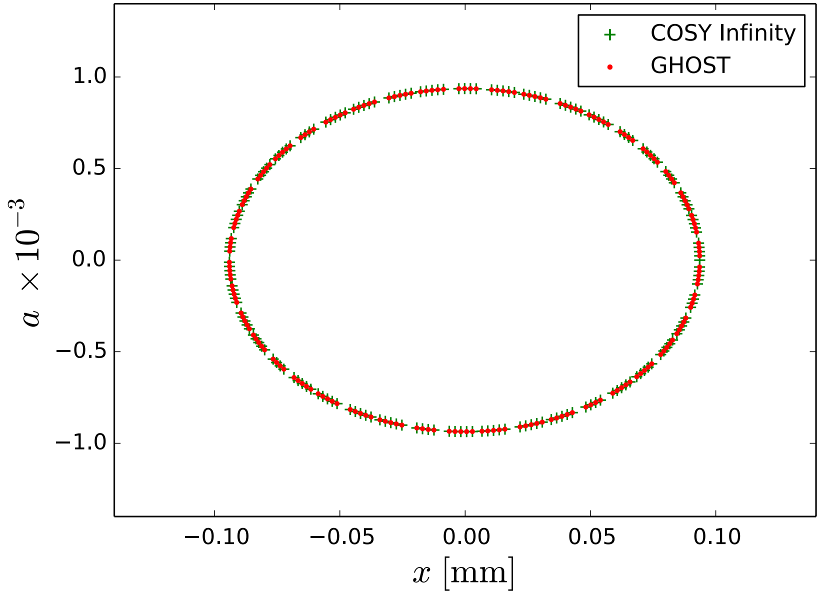
GHOST: Symplectic Particle Tracking

- 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

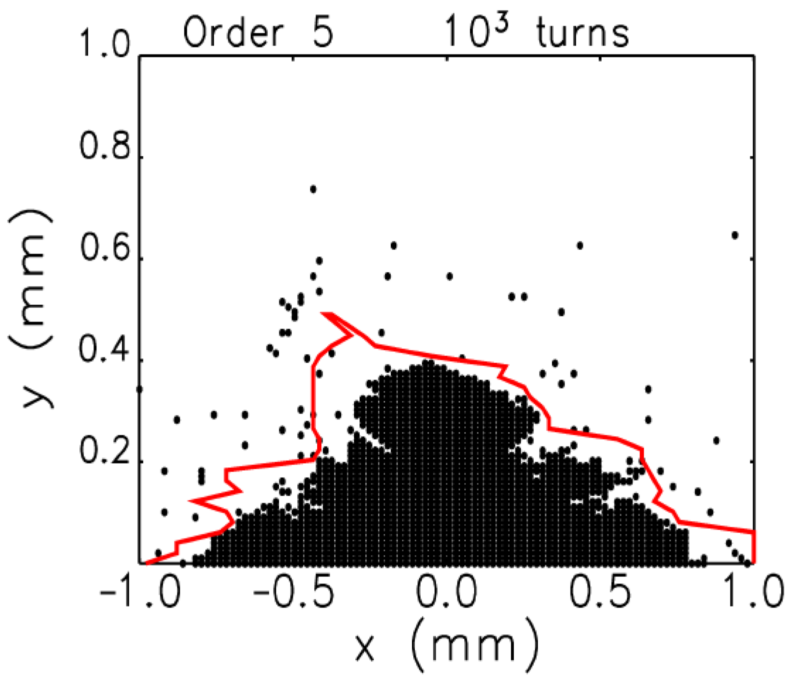


Perfect agreement!

GHOST: Symplectic Particle Tracking

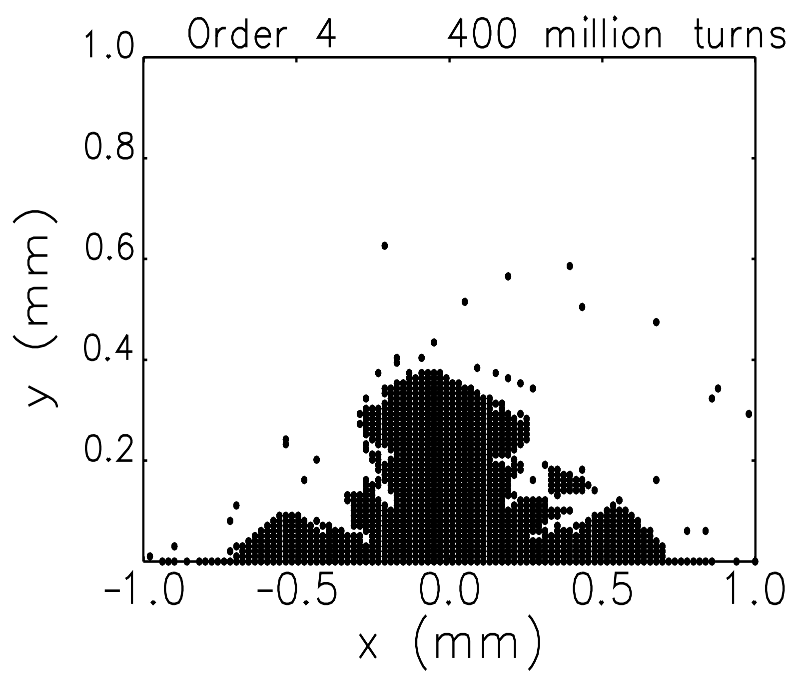
- Dynamic aperture comparison to elegant (Borland 2000)
- 400 million turn simulation (truly long-term)

GHOST **elegant** **1,000 turns**



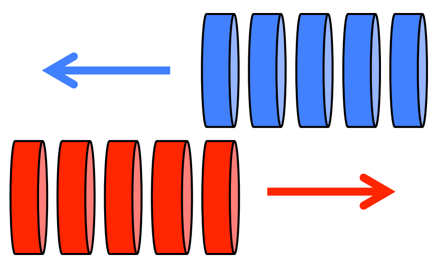
Good agreement

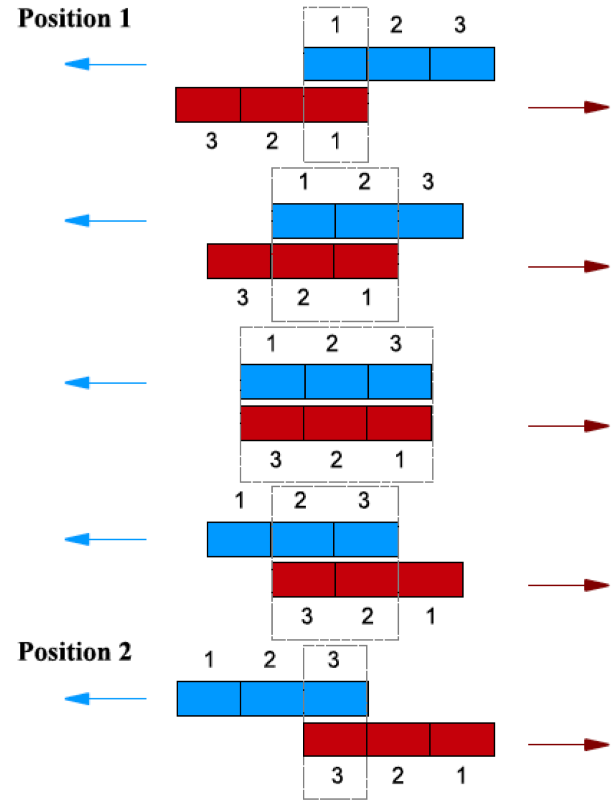
Sympl. 4th order, 400 million turns



GHOST: Beam Collisions

- Bassetti-Erskine approximation
  - Beams as 2D transverse Gaussian slices
  - Poisson equation reduces to a complex error function
  - Finite length of beams simulated by using multiple slices



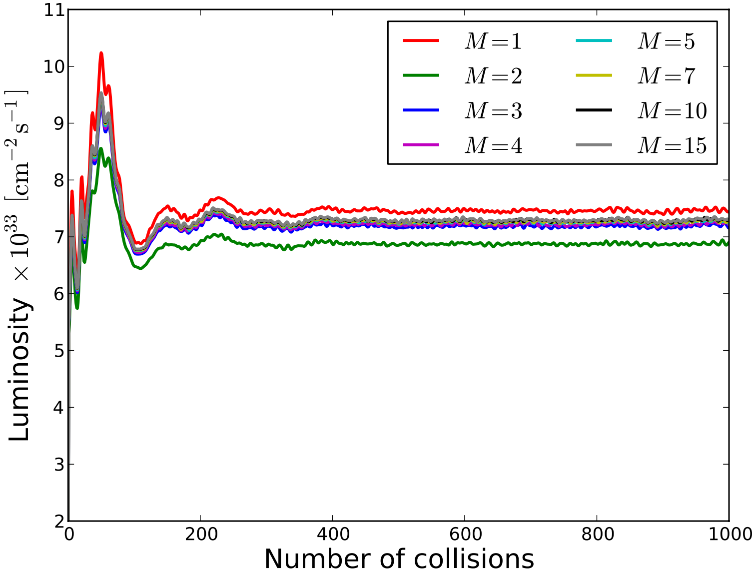


- We generalized a “weak-strong” formalism of Bassetti-Erskine
  - Include “strong-strong” collisions (each beam evolves)
  - Include various beam shapes (originally only flat beams)

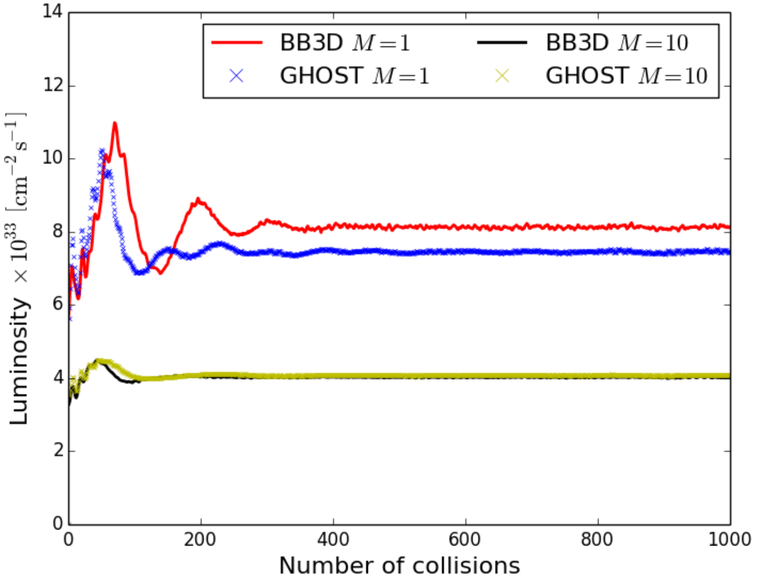
GHOST Benchmarking: Collisions

- 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



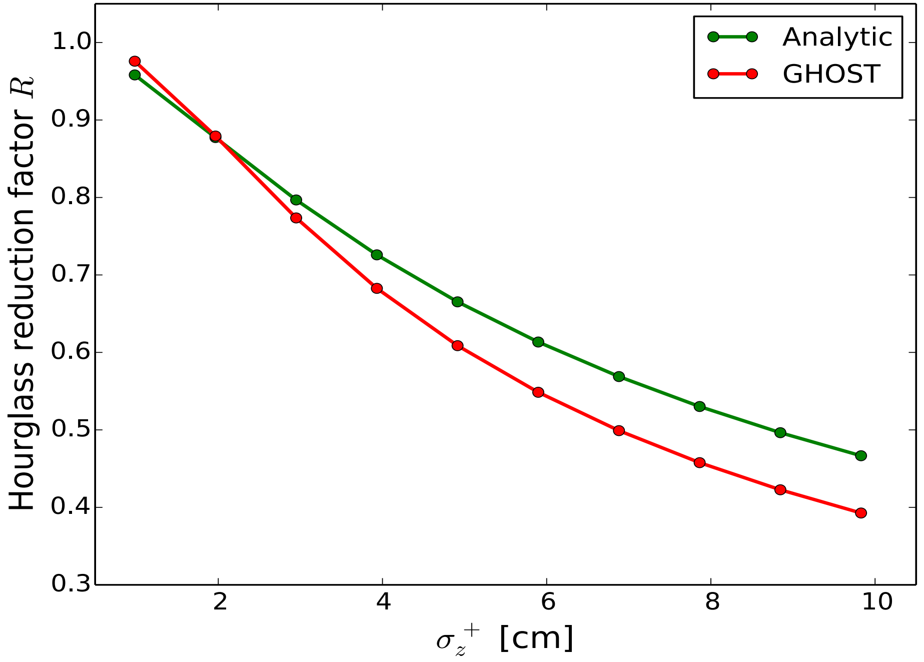
Finite bunch length accurately represented

Good agreement with BeamBeam3D

GHOST Benchmarking: Hourglass Effect

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

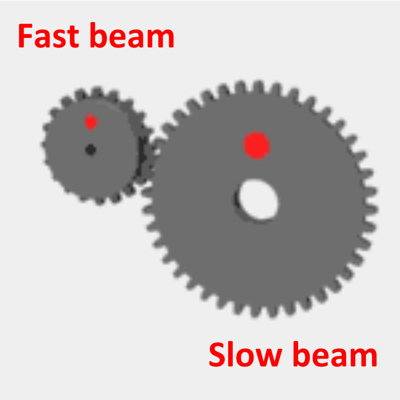
GHOST, 128k particles, 10 slices



Good agreement with theory

“Gear Change” with GHOST: Approach

- “Gear change” provides beam synchronization for JLEIC
  - Collision of beams with different number of bunches (n_1, n_2) in each ring (JLEIC: $n_1 \approx 3420$)
  - If n_1 and n_2 are mutually prime, all combinations of bunches collide
  - Initially: $n_1 = n_2+1$; more flexibility: general n, m

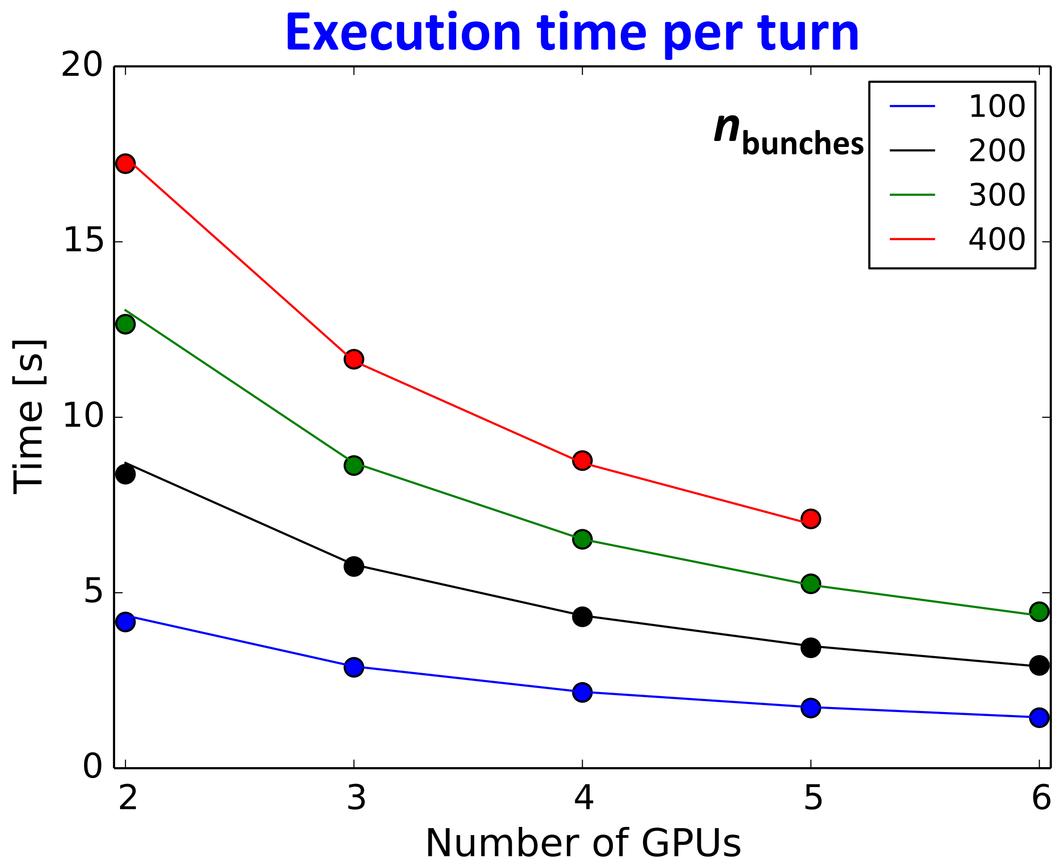


- Broken symmetry: from 1 x 1 to n x (n+1)

- The computational load is alleviated with GPUs
  - n_2 collisions happen concurrently – highly parallelizable
  - information for all bunches is stored – large memory load

- Collide multiple bunch pairs on a predetermined schedule
  - n_{bunch} different pairs collide at each turn – highly parallelizable

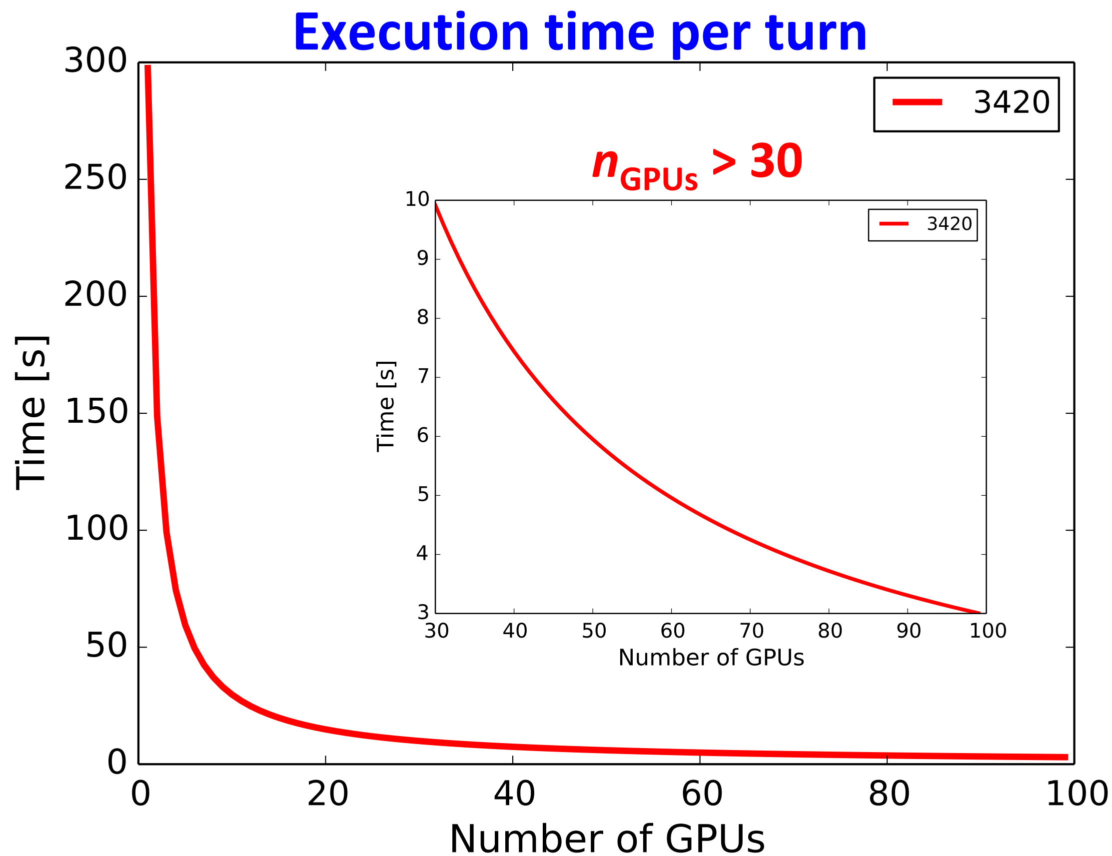
"Gear Change" with GHOST: *n* x (*n*-1)



One turn on K40 GPUs: $$t = 0.087 \frac{n_{\text{bunches}}}{n_{\text{GPUs}}} \text{ sec}$$

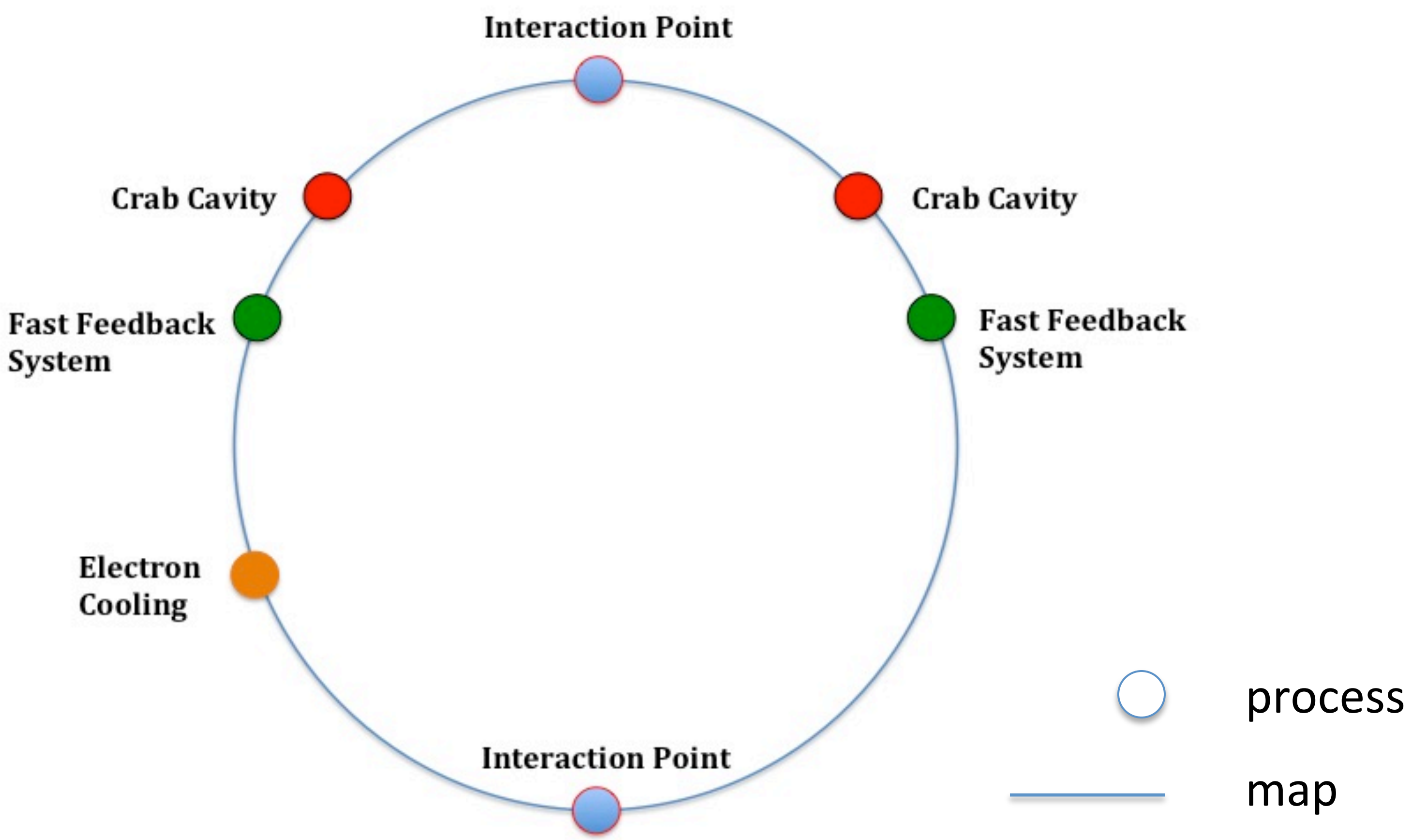
Execution time scales as $1/n_{\text{GPUs}}$

“Gear Change” with GHOST: *n* x (*n*-1)



One turn on K40 GPUs: $$t = 0.087 \frac{n_{\mathrm{bunches}}}{n_{\mathrm{GPUs}}} \text{ sec}$$

Current/Future Efforts: Other Functionalities



GHOST's modular nature allows for flexibility in simulations

GHOST: Status Report

- Stage 1: Particle tracking
  - ☑ High-order, symplectic tracking optimized on GPUs
  - ☑ Benchmarked against COSY: Exact match
  - ☑ 400 million turn tracking-only simulation completed
- Stage 2: Beam collisions and "gear change"
  - ☑ Single-bunch collision implemented on multiple GPUs
  - ☑ *n* x (*n*-1) collision implemented on a multiple GPU (arbitrary *n*)
  - ☑ General *n* x *m* collision implemented on a single GPUs (soon multi-GPU)
- Stage 3: Benchmarking and simulations (underway)
  - Multiple-bunch validation, checking, benchmarking and optimization
  - Systematic simulations of JLEIC and "gear change"
  - Other collision methods: fast multipole
  - Synchrotron radiation, space charge, electron cooling, multiple IPs, IBS

Backup Slides

Benchmarking GHOST

- Benchmarking GHOST with other codes (currently underway)
    1. Systematically compare to BeamBeam3D and Guinea Pig
    2. Conduct convergence studies
    3. Reproduce the hourglass effect for the aggressive JLEIC design

- Gear change simulations
    1. Simulate "gear change" effects for low number of bunches (Reproduce 11-10 as in Hao *et al*. 2014)
    2. Scale up to full JLEIC parameters (3420/3419, 3420/3418, … bunches)

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}	

Speedup

				6Slices	1Turn			
Npart	CPU			GPU			Speedup CPU	
	Tracking	Collision		Tracking	Collision			
1000	0.644896	13.2116		0.644768	15.4794		0.85	
10000	1.02157	129.49		1.04451	17.9388		7.22	
100000	5.86016	1287.17		5.91194	29.8827		43	
1000000	54.5349	12851		54.8268	147.746		86	
				10k Particles		6Slices		
Nturn	CPU			GPU			Speedup CPU	
	Tracking	Collision		Tracking	Collision			
1	1.04202	129.479		1.03523	17.823		7.26	
10	0.953088	131.204		0.96128	17.7718		7.38	
100	0.965376	143.975		0.961472	17.4446		8.25	
1000	0.951872	119.376		0.989312	12.4215		9.61	
				1Million Patricles		1Turn		
Nslices	CPU			GPU			Speedup CPU	
	Tracking	Collision		Tracking	Collision			
1	54.473	2235.67		54.8347	30.738		72	
2	54.4848	4396.9		54.7464	54.4933		81	
3	54.4546	6480.04		54.7209	75.2644		86	
4	54.4835	8612.99		54.8068	99.6275		86	
5	54.5129	10708.2		54.7883	125.001		86	
6	54.4469	12843.6		54.7732	147.913		87	