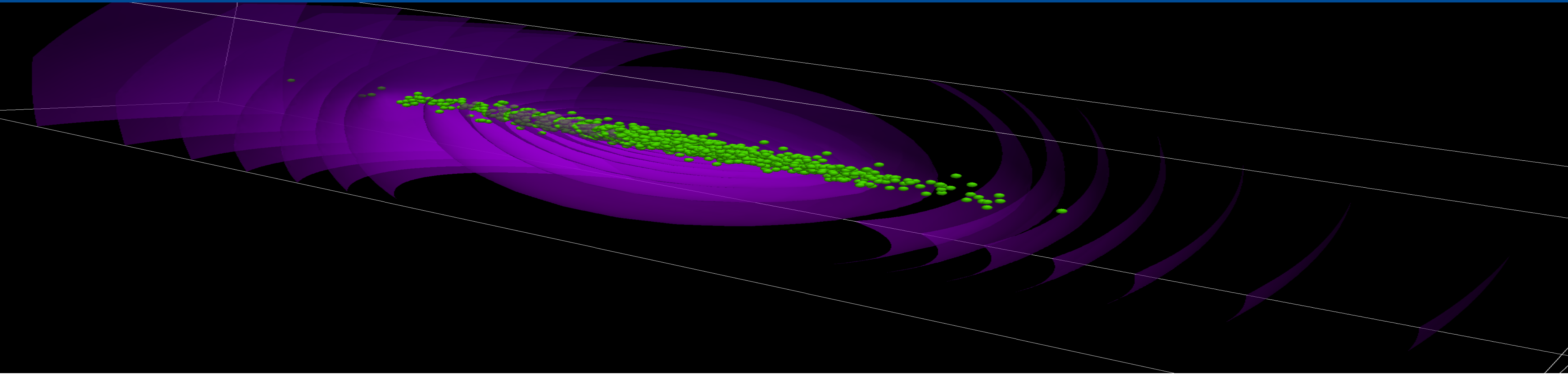


Synergia: a new platform for beam dynamics with multiple bunch interactions

James Amundson

APS April-in-January Meeting

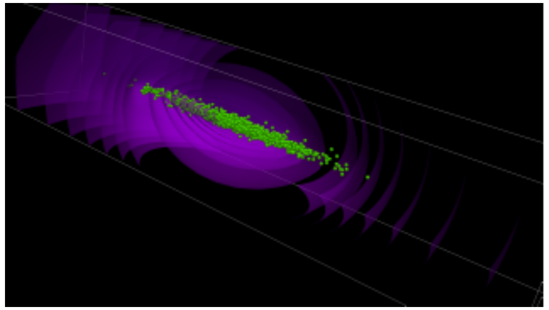
28 January 2017

Synergia

- Synergia is a comprehensive package for beam dynamics
- How comprehensive?
  - Single particle dynamics
  - Single bunch dynamics
  - Multiple-bunch (train) dynamics
  - Dual-train dynamics
    - The newest addition to Synergia

Thanks to Eric Stern (FNAL, Scientific Computing Division) and
Robert Ainsworth (FNAL, Accelerator Division) for their contributions to this talk

Logo soup for breakfast



Synergia: A comprehensive accelerator beam dynamics package

http://web.fnal.gov/sites/synergia/SitePages/Synergia%20Home.aspx

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Accelerator Simulation Group

James Amundson, Qiming Lu, Alexandru Macridin, Leo Michelotti, Chong Shik Park, (Panagiotis Spentzouris), Eric Stern and Timofey Zolkin

ASCR Leadership Computing Challenge

ALCC

Computer time from INCITE and ALCC

U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING

The ComPASS Project
High Performance Computing for Accelerator Design and Optimization
https://sharepoint.fnal.gov/sites/compass/SitePages/Home.aspx

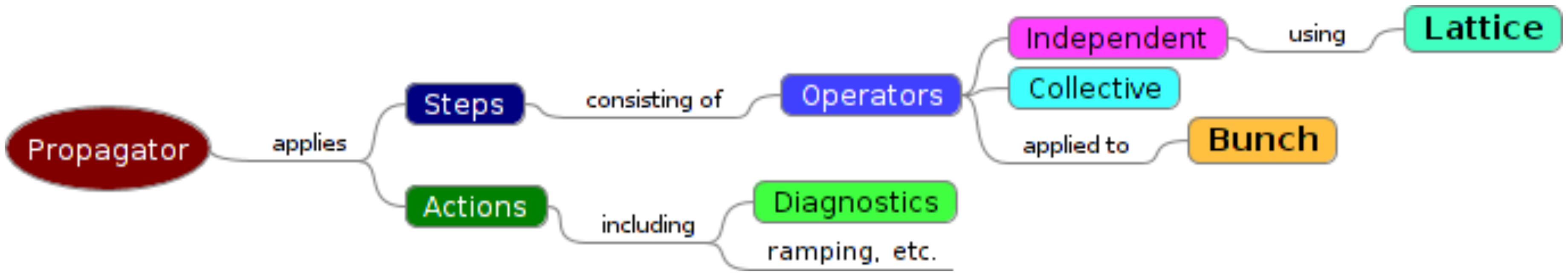
Funded by DOE SciDAC

CAMPA Consortium for Advanced Modeling of Particle Accelerators

Funded by DOE

Synergia concept

- The split-operator method combines external fields (magnets) with internal fields (space charge, wakefields)
  - 1/2-step external fields + full step internal kick + 1/2 step external fields
  - External field calculations (single-particle effects)
    - Trivially parallelizable
  - Internal field calculations (collective effects)
    - Particle-in-cell calculation
- Synergia is a framework based on a generalization of the split operator approach



Computational details

- Synergia simulations are (usually) Python applications
  - Synergia functionality is provided in the form of a library of classes
    - Implementation is entirely C++ with Python bindings
  - Pure C++ applications are also possible
- Synergia allows users to implement run-time logic for ramping, feedback, *etc.*
- Synergia provides examples ranging from a trivial FODO cell to real-world accelerators with realistic running conditions
- Synergia simulations are fully checkpointable
  - Including user-provided classes

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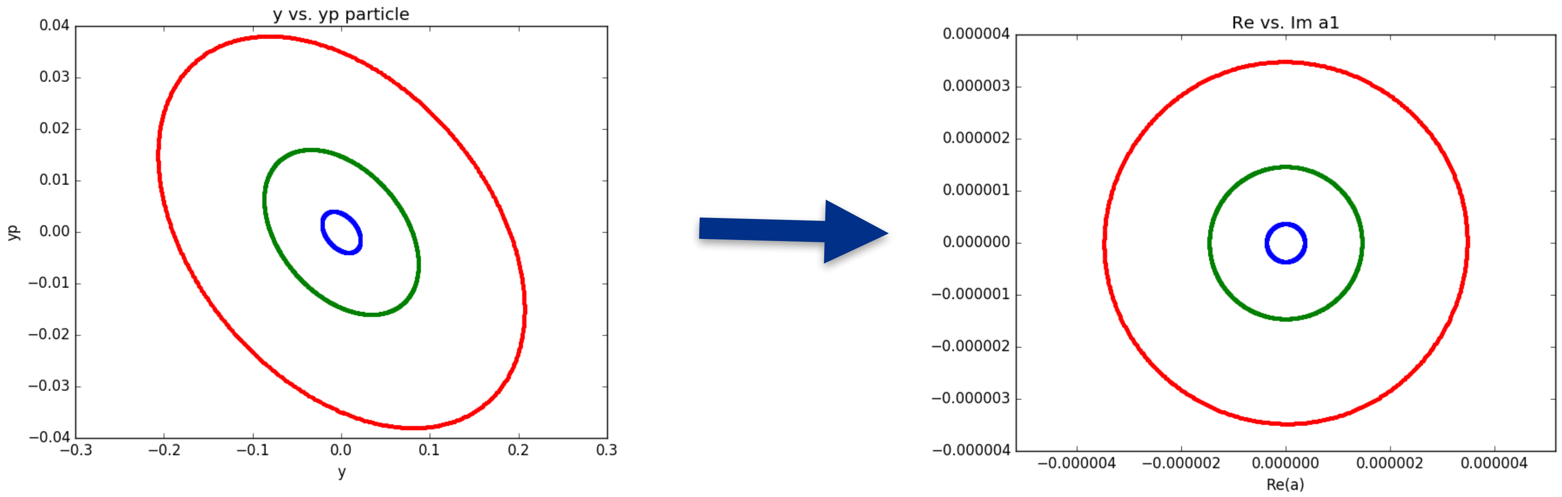
CHEF provides single-particle physics for Synergia

- CHEF is a single-particle beam dynamics library by Leo Michelotti (FNAL)
  - magnets, cavities, drifts, etc.
    - direct symplectic tracking
    - (and/or) arbitrary-order polynomial maps
  - utilizes automatic differentiation
    - same code to do tracking and nonlinear map generation
  - many advanced analysis features
    - nonlinear map analysis, including normal forms
    - lattice functions (multiple definitions)
    - tune and chromaticity calculation and adjustment
    - etc.

Normal form analysis

- Linear case (FODO cell) transforms elliptical Poincare phase space plots to circular action-angle representation



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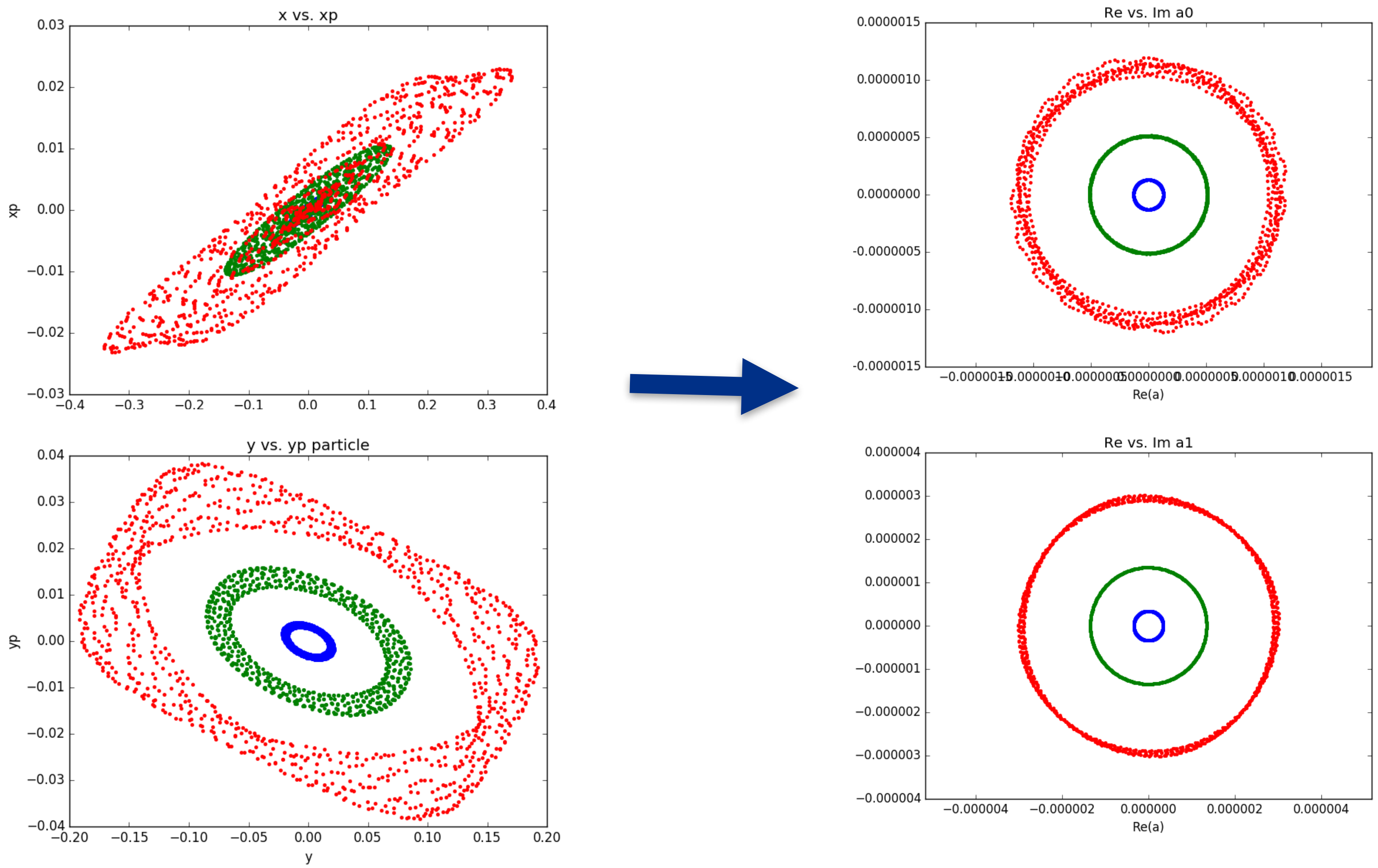
Normal form analysis

- Nonlinear case (includes octupole and skew quadrupole)



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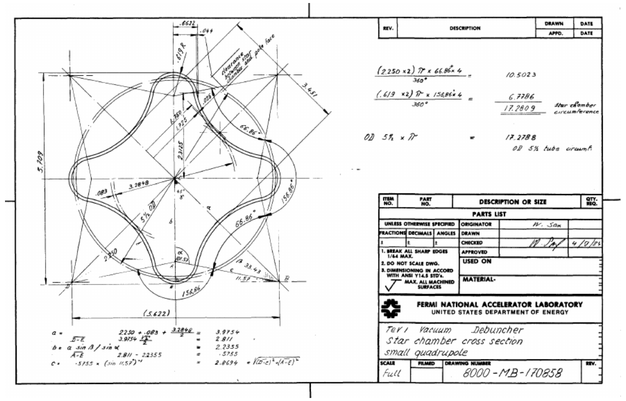
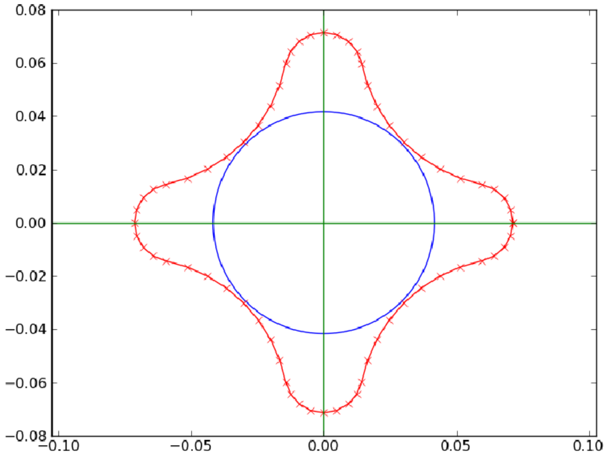
Aperture model

- Apertures can be associated with elements and/or steps
- 2D model
  - could be extended with slices
- Geometric
  - circular
  - elliptical
  - rectangular
  - polygon
  - wire
- Abstract
  - phase space
  - Lambertson
    - removes particles
- New apertures can be implemented by the end user



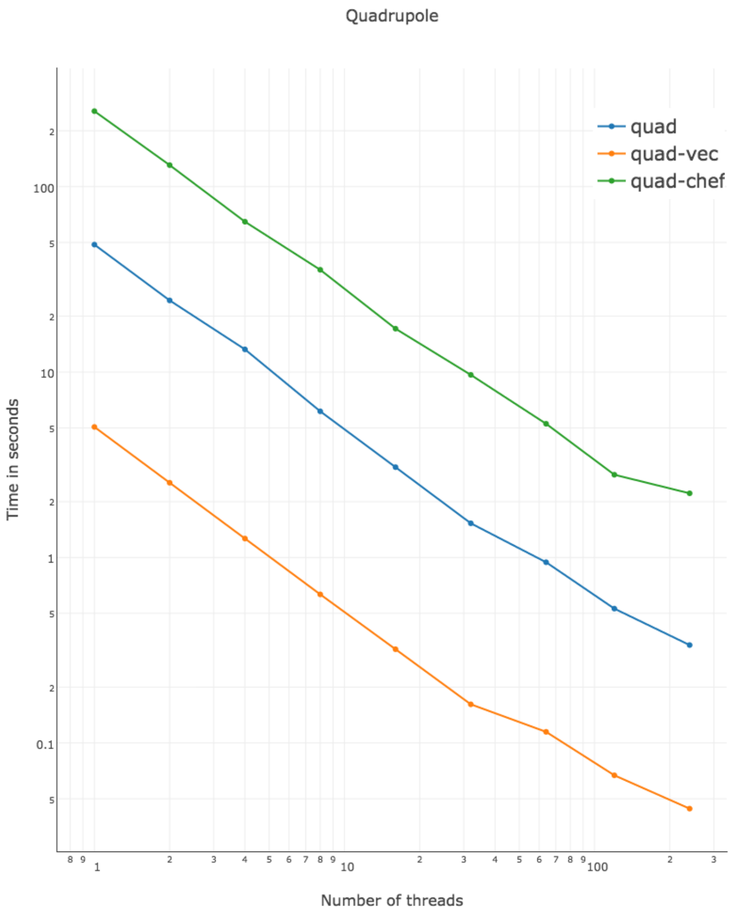
Engineering drawing of FNAL Debuncher quad cross section



Synergia implementation: detailed, but fast (inscribed circle optimization)

Preparing for Exascale (optimizing for Intel Phi)

- libFF is our next-generation single particle implementation
- libFF gives an overall speedup compared to CHEF
- Explicit vectorization gives another overall speedup
  - libFF required for vectorization
- OpenMP allows us to take advantage of all 240 hardware threads
- Overall speedup for quadrupole is 5768x



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Synergia

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  - Single particle dynamics
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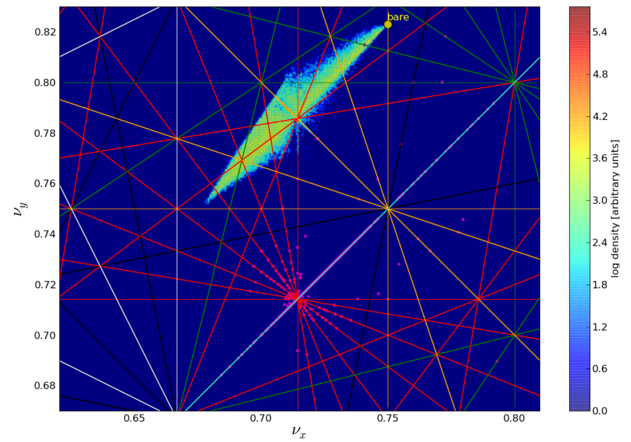
  - Dual-train dynamics
    - The newest addition to Synergia

Collective effects in Synergia

- Collective effects are Synergia's *raison d'etre*
- Single bunch collective effects in Synergia include
  - Wakefields
    - Arbitrary wake functions
  - Space charge
    - Variety of boundary conditions and levels of approximation
    - 3D open transverse boundary conditions
    - 3D conducting rectangular transverse boundary
    - 3D conducting circular transverse boundary
    - 2.5D open boundary conditions
      - 2D calculation, scaled by density in longitudinal slices
    - 2D semi-analytic
      - uses Bassetti-Erskine formula, σx and σy calculated on-the-fly
    - New space charge models can be implemented by the end user

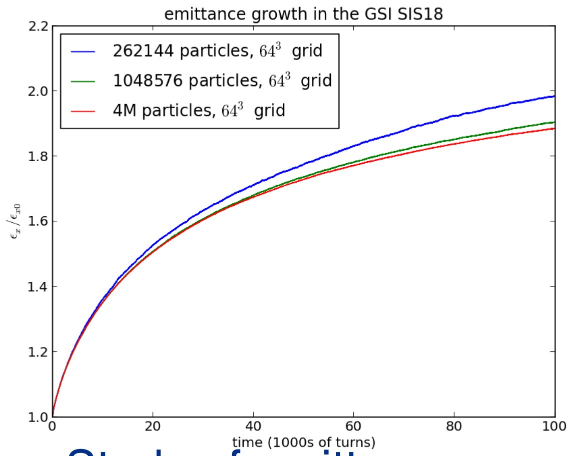
Synergia Single-bunch Space Charge Examples

- Resonant extraction in FNAL Debuncher Ring for Mu2e experiment
  - Ramped nonlinear lattice combined with significant space charge effects



Tune footprint as part of working point scan

- Study emittance growth over 100,000 revolutions in GSI SIS18 accelerator
  - 7,100,000 steps, 4,194,304 particles
  - 29,779,558,400,000 particle-steps
  - 1,238,158,540,800,000 calls to "drift"



Study of emittance growth and statistical noise

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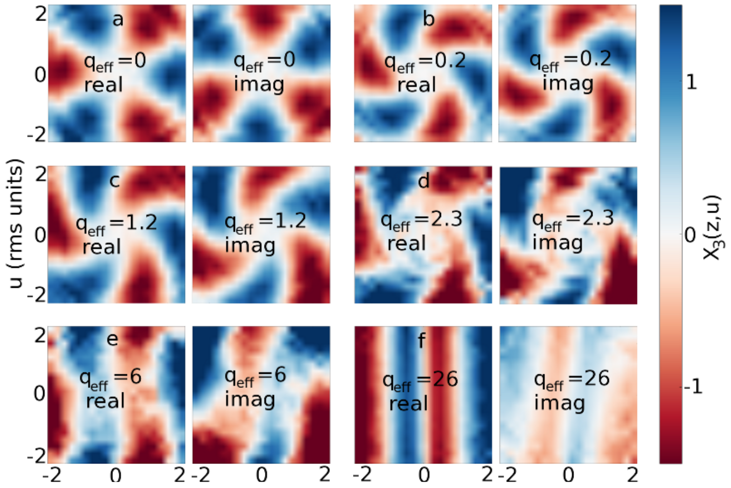
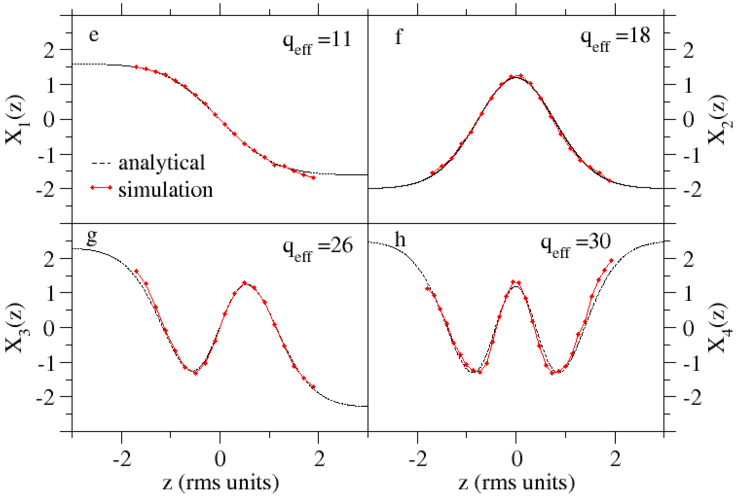
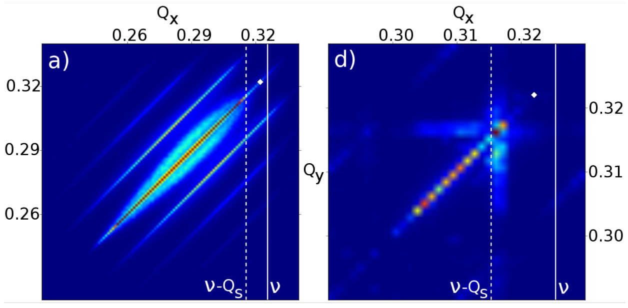
Synergia Single-bunch Space Charge for Theoretical Studies



- Space charge modes provide theoretical framework for space charge studies
  - A. Burov, PRST-AB 12, 044202 (2009), PRST-AB 12, 109901, (2009).
- Difficult to extract modes from noise in realistic simulation
- First use of Dynamic Mode Decomposition (DMD) in Beam Dynamics
  - Macridin, et al., PRST-AB (2015).
- Excellent theory/simulation agreement



- Booster simulations also led to discovery of parametric Landau Damping
  - Macridin, Burov, et. al.
  - Fermilab PUB-16-391-APC-CD



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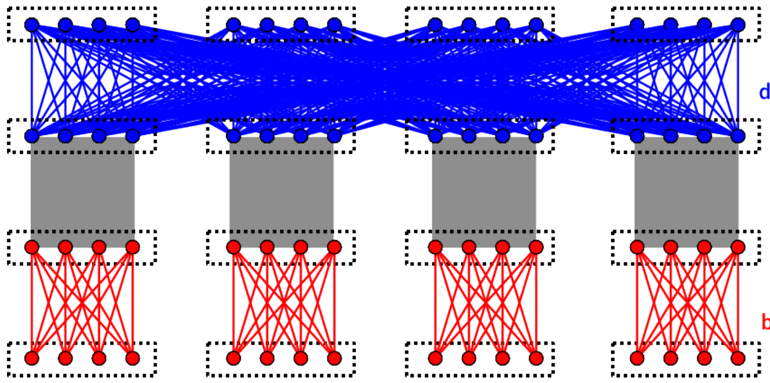
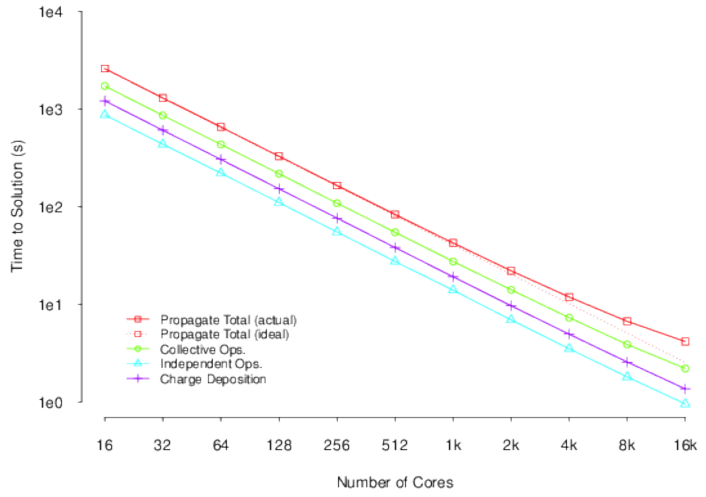
Preparing for Exascale

- Communication avoidance
  - Field solves are a fixed size problem
  - More calculation, less communication
  - Allows scaling in number of particles and/or bunches
  - Can use arbitrary unit size, but one node is usually best



- With communication avoidance, we have achieved strong scaling over ~1000x



Single-bunch strong scaling from 16 to 16,384 cores
32x32x1024 grid, 105M particles

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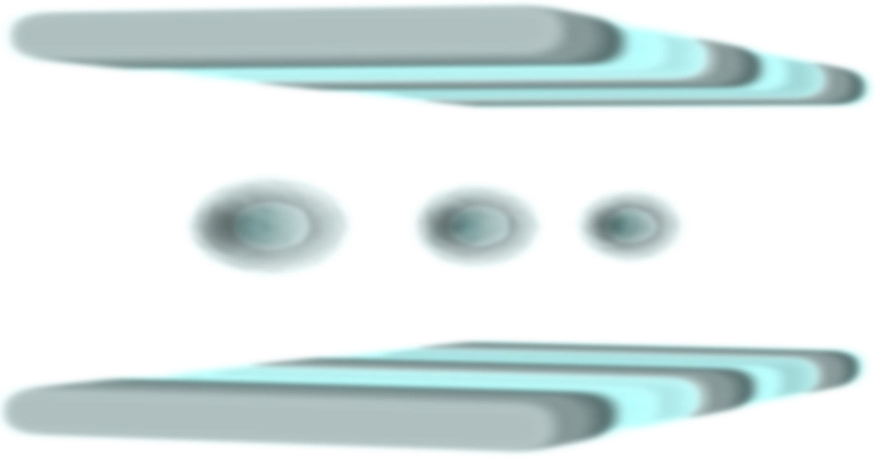
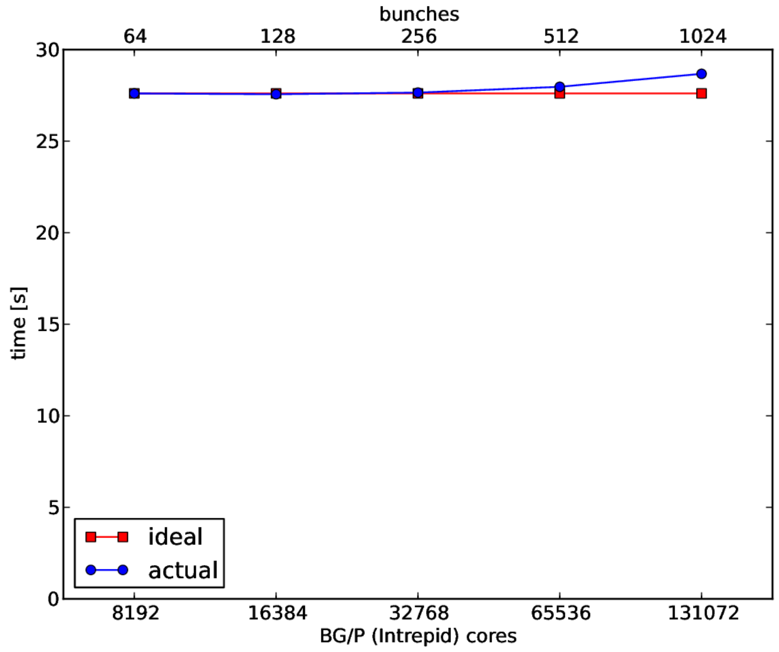
Bunch train dynamics

- Synergia can propagate a *train* of bunches
  - Collective effects can either apply to bunches individually, collectively, or both
  - Space charge is in the first category
  - Wakefields are in the last category
- Bunch train simulations can be very large
  - Synergia shows excellent weak scaling



ALCF's Intrepid
Weak scaling from 64 to 1024 *bunches*
8192 to 131,072 cores; up to over 10^{10} particles



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Synergia Bunch Train with Wakefields Example

experiment

4 x 10^{10} p per bunch $\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times (0.06\, m^{-1}, 0.025\, m^{-1})$

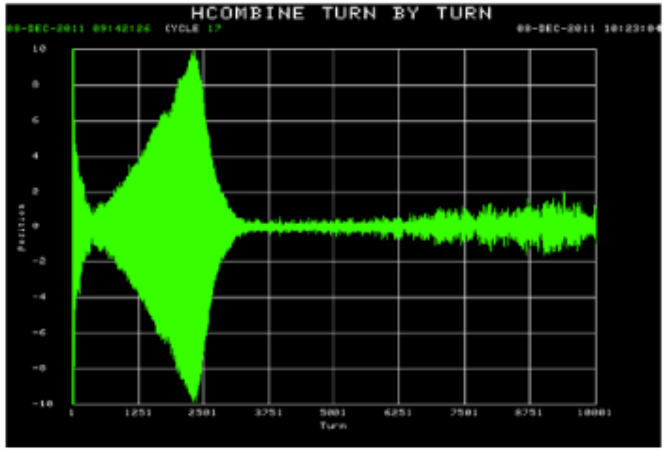
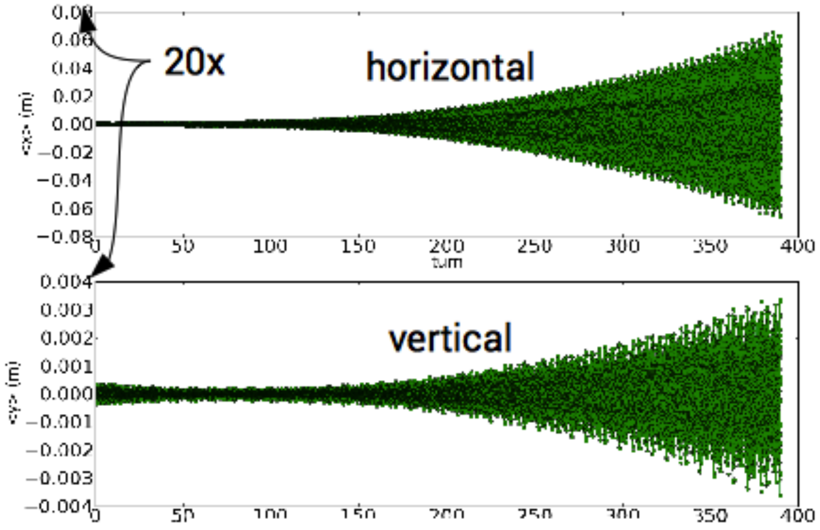


Figure 1: Combined TBT signal from HBPMs (arbitrary units) at $N_p = 4{\cdot}10^{12}$ after coupling correction.

simulation

5 x 10^{10} p per bunch $\left(\frac{\omega_{\xi x}}{\beta c}, \frac{\omega_{\xi y}}{\beta c}\right) = 2\pi \times (0.023\, m^{-1}, 0.023\, m^{-1})$



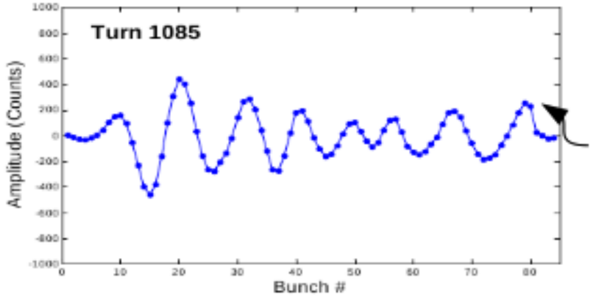
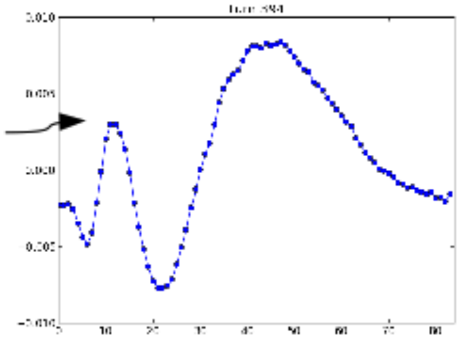


Figure 3: Bunch-by-bunch horizontal positions at the onset of horizontal instability

bunch-to-bunch coupling effect



qualitative agreement

- Synergia qualitatively reproduces an observed instability in the Fermilab Booster
- The wakefields are large and complicated due to the presence of exposed laminations
- Simulating an entire bunch train was critical
  - Instability only occurs in simulations of at least 14 bunches

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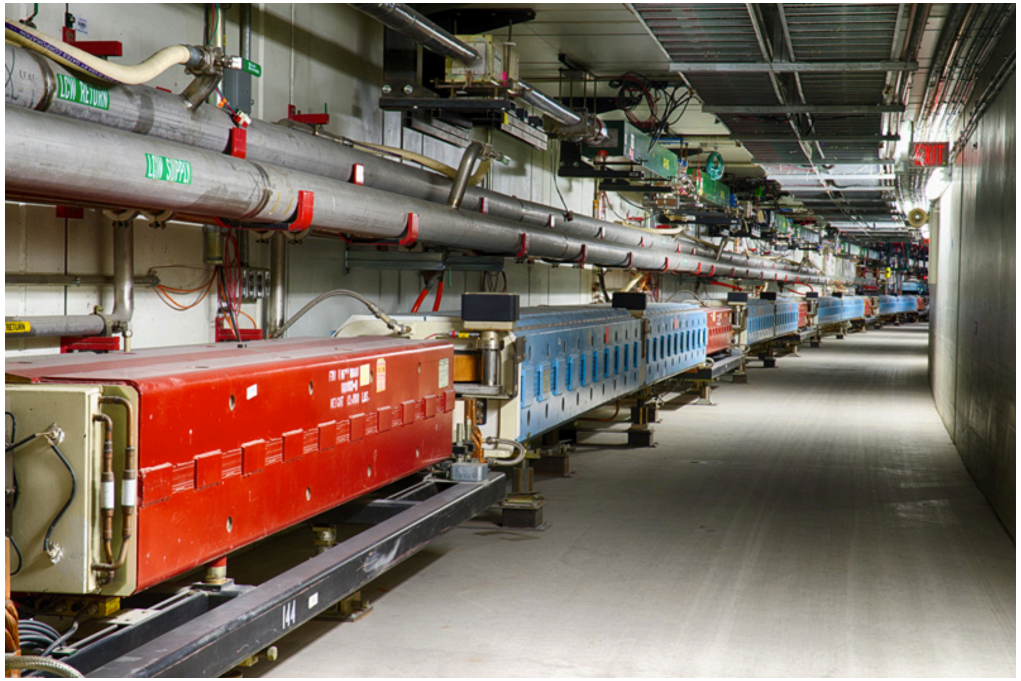
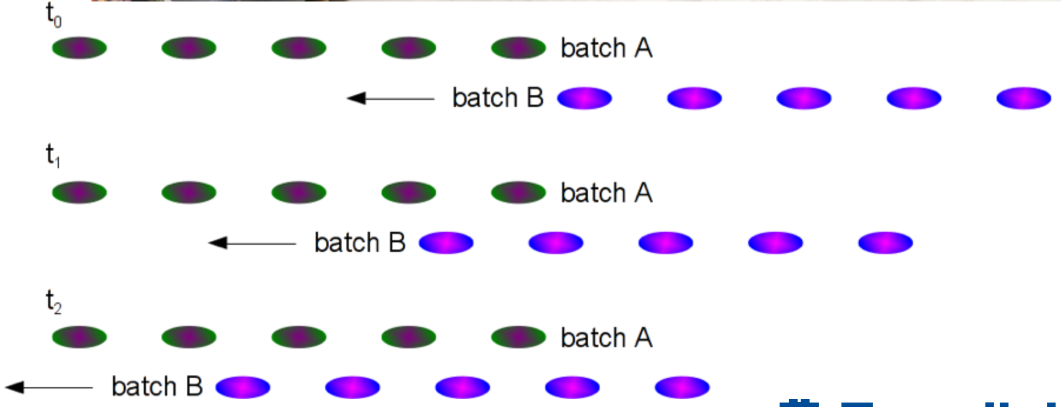
Motivation: Slip Stacking in the Fermilab Recycler and Main Injector

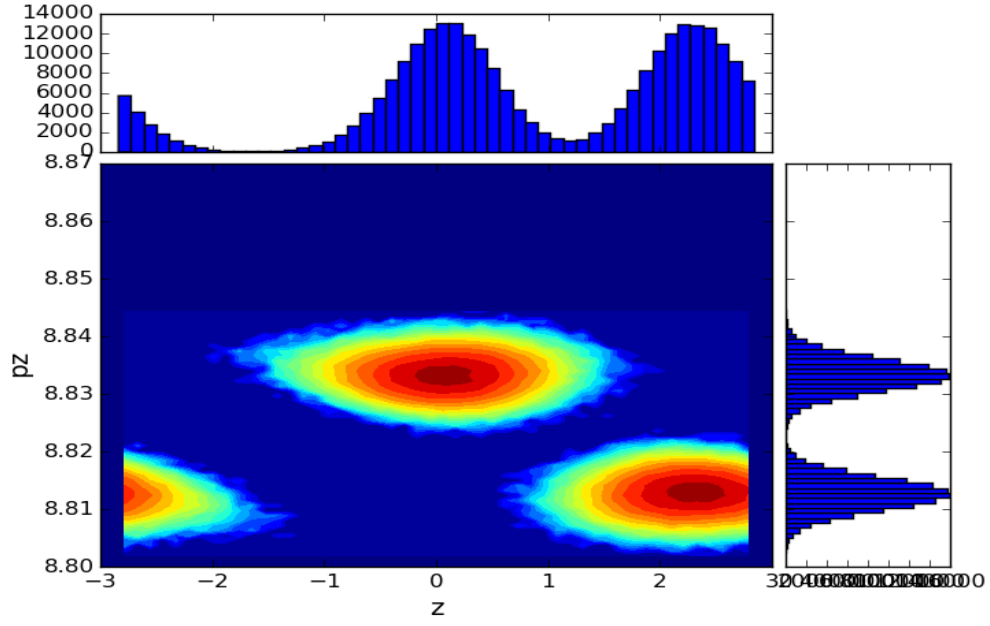
- The Fermilab Recycler and Main Injector are the two largest components of the current Fermilab accelerator complex
- Slip stacking
  - Used to create high-intensity beams
  - Pairs of bunches combined
  - First approximation: periodic boundary conditions to mimic other pairs
  - Realistic simulations will include O(500) pairs
  - Non-trivial structure observed in operation
- Truly a leadership class computing problem.
- Work in progress!



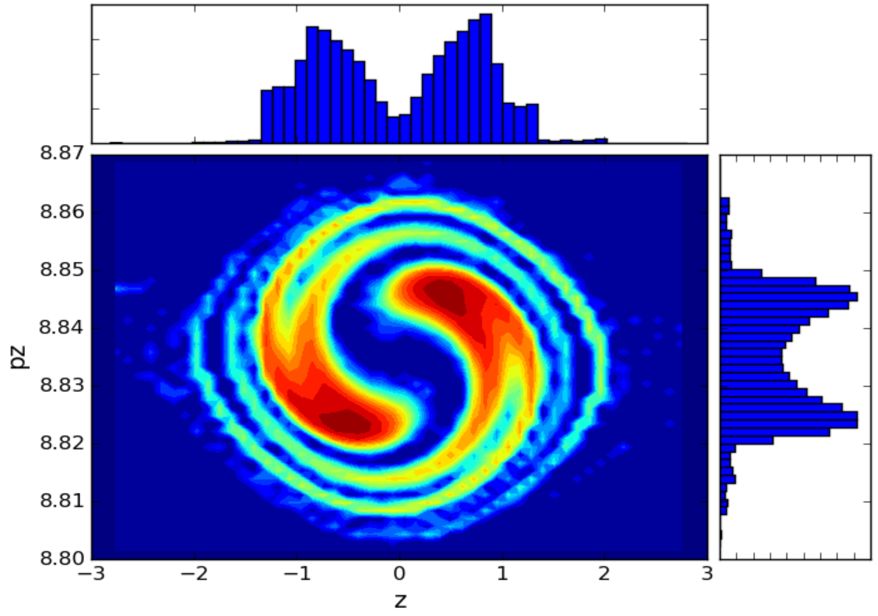


First attempt at slip stacking

- Periodic boundary conditions to simulate infinite, uniform stream of bunches
- Captures some of the physics
- Plots show longitudinal phase space



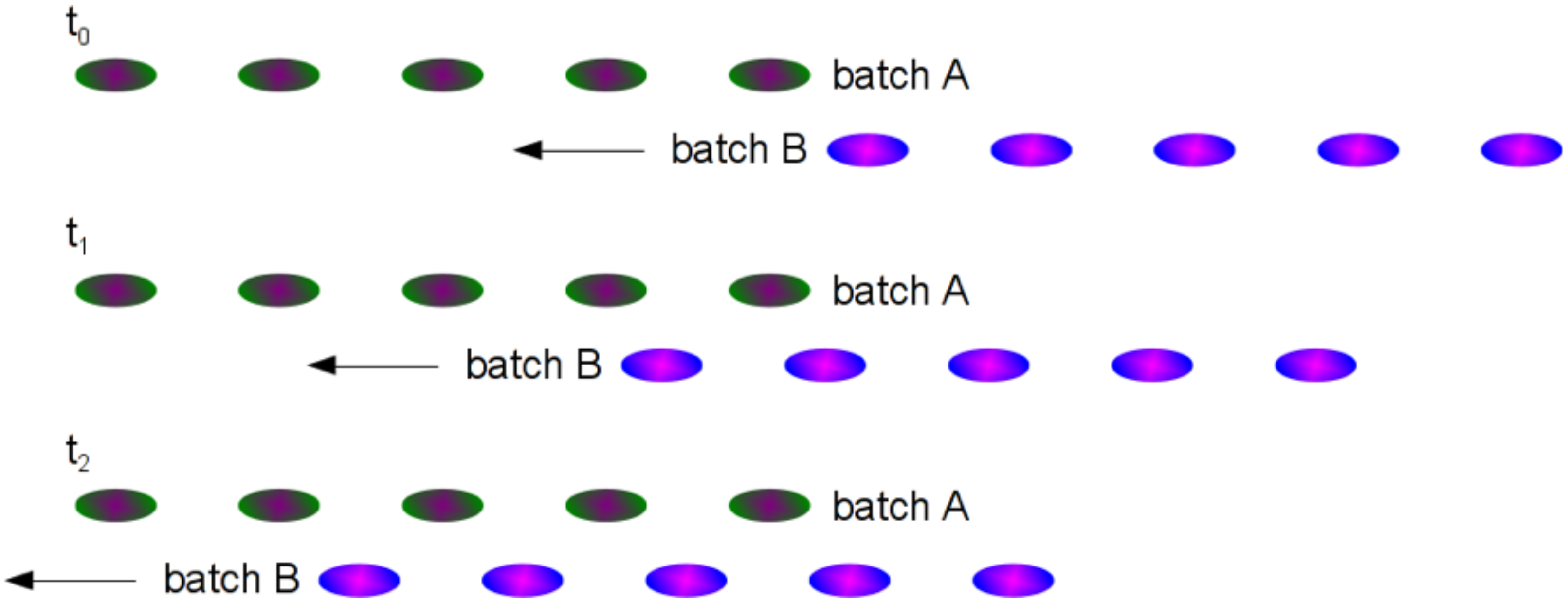
slipping phase



capture phase

Dual-train propagation in Synergia

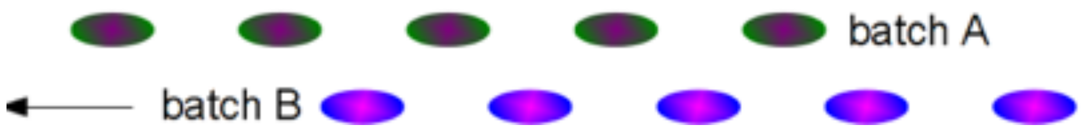
- In order to properly simulate the physics of two slipping trains of particles we have extended the Synergia propagation model to include dual-train propgation
  - Model could also be used for electron cloud-beam dynamics
  - Model could also be used for beam-beam dynamics
    - *Neither yet implemented*
- Simulations include two trains with relative motion



Dual-train Space Charge

First, note that the trains are typically well-separated in phase space, but strongly overlapping in physical space

- Bunches are well-separated longitudinally within a train

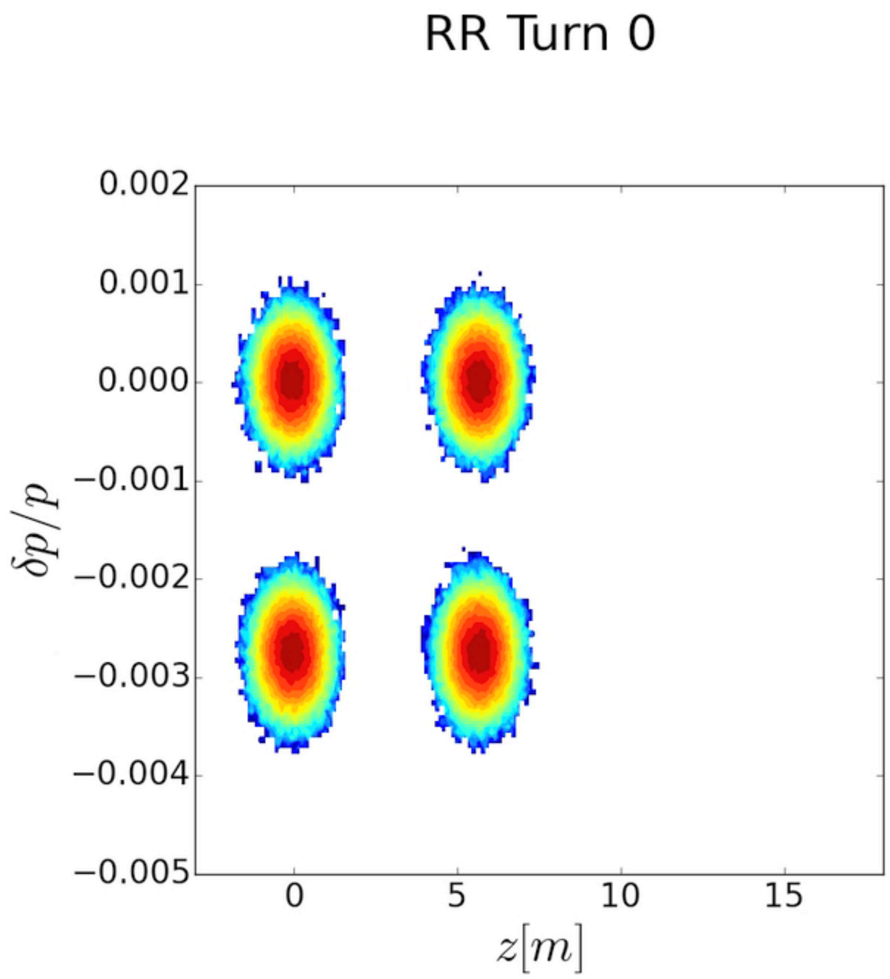


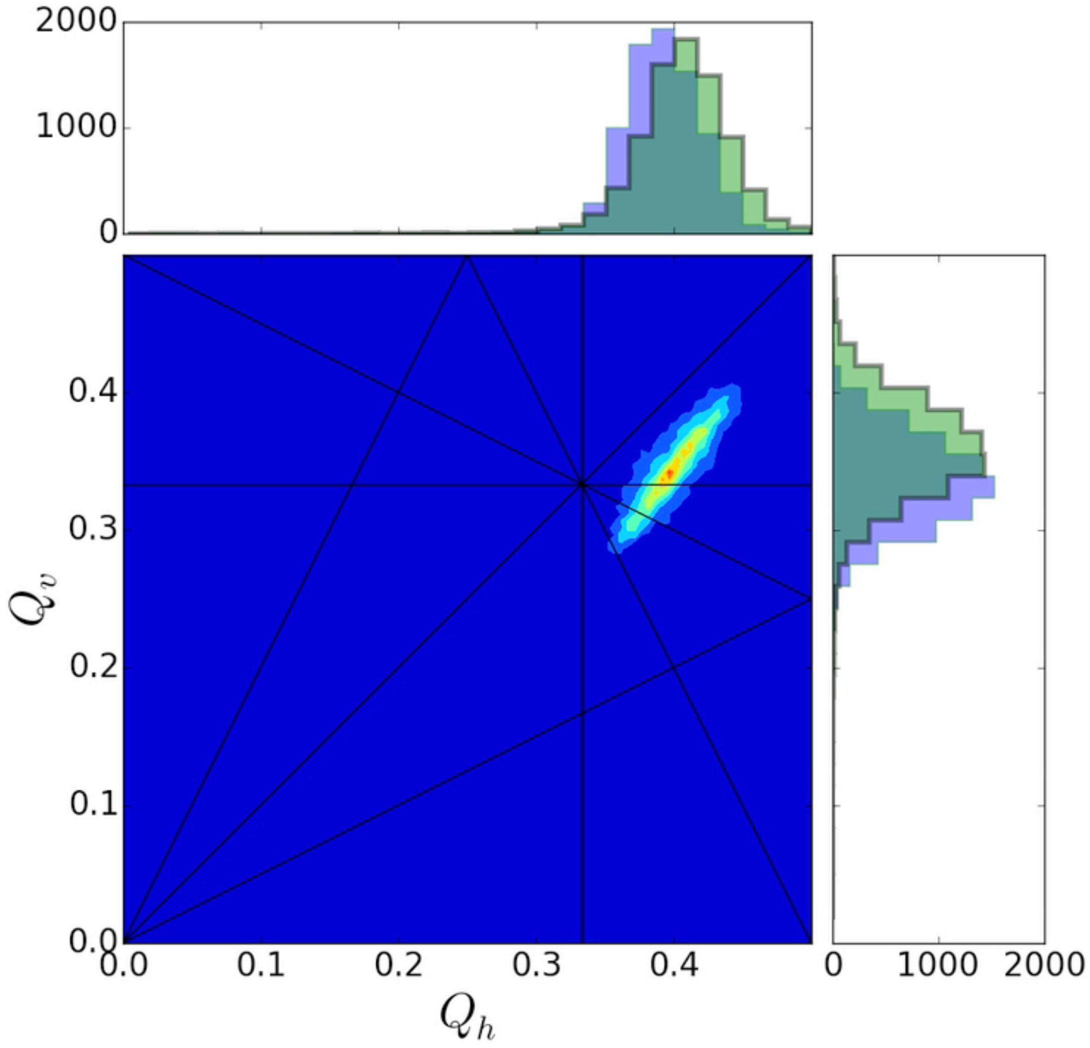
Space charge algorithm for dual-train propagation: use superposition

1. Calculate internal space charge for each bunch, saving fields
2. Find overlapping bunches
   - Each primary bunch (batch A) will have 0-2 overlaps with bunches from batch B
     - If bunches are evenly spaced, which they are here, but Synergia also allows uneven spacing
3. For each overlapping pair, exchange fields and kick particles due to other bunch's field
   - alternate odd/even bunches to avoid contention

First Synergia Results with Dual-train Space Charge

Slip portion of slip stacking for 2x2 bunches
in the Fermilab Recycler under realistic conditions





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Conclusions

- Synergia is a comprehensive framework for beam dynamics simulations.
  - Single-particle physics
  - Single-bunch physics
  - Bunch-train physics
  - Dual-train physics
- We are expanding Synergia to meet the needs of the accelerator community while also preparing for Exascale computing.