Iota Based Experiments: Space-Charge Simulations

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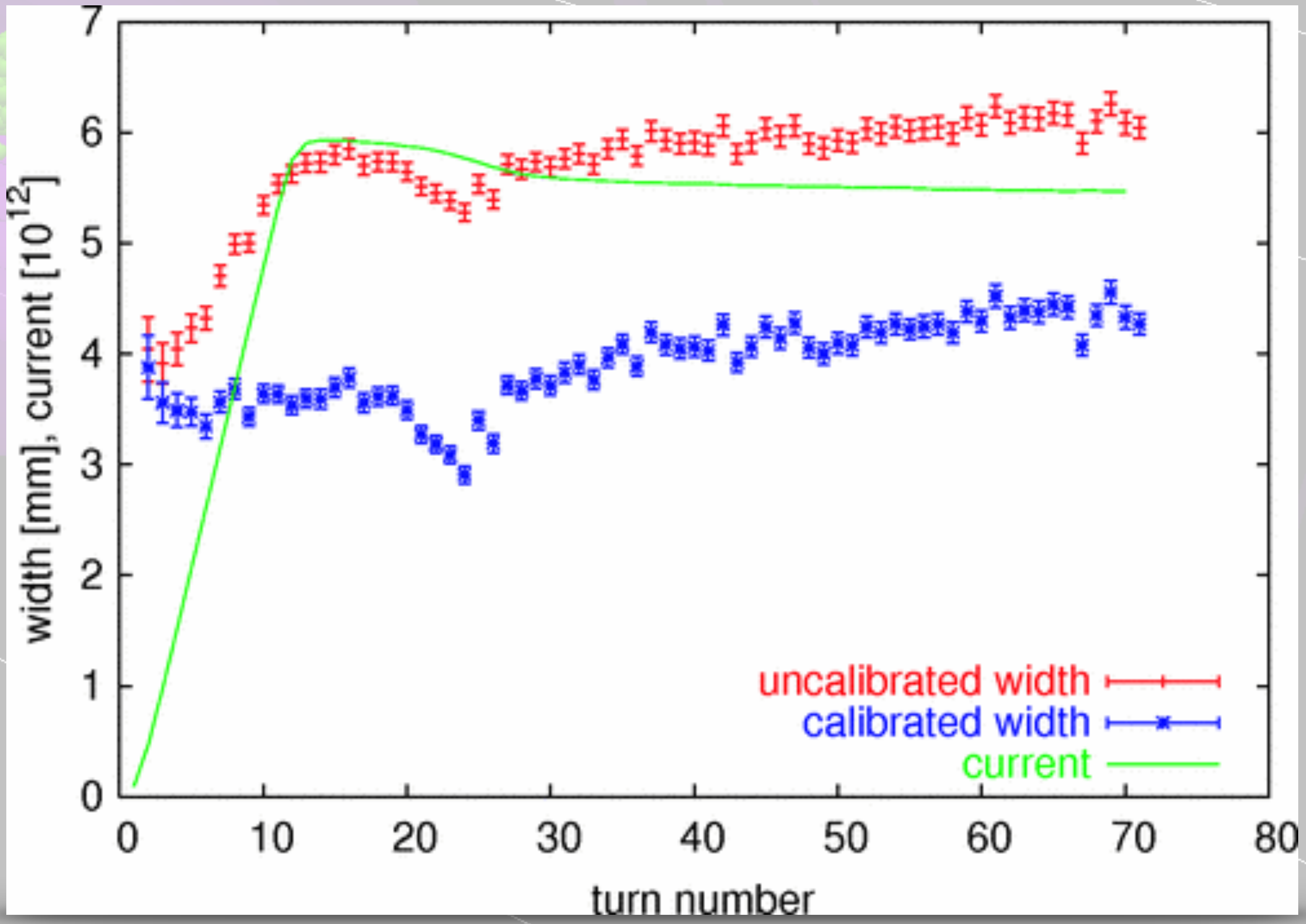
Objectives

- Ultimate goal is to develop and study space-charge mitigation techniques
  - utilization of IOTA special non-linear elements
    - investigate performance for less restrictive configurations than a fully integrable optics system —discussed in Dave's talk— e.g. characterize how "off" you could go with beam shape and still get a positive effect
  - other elements (electron-lens) or even more conventional approaches (using more conventional elements to manipulate the beam)

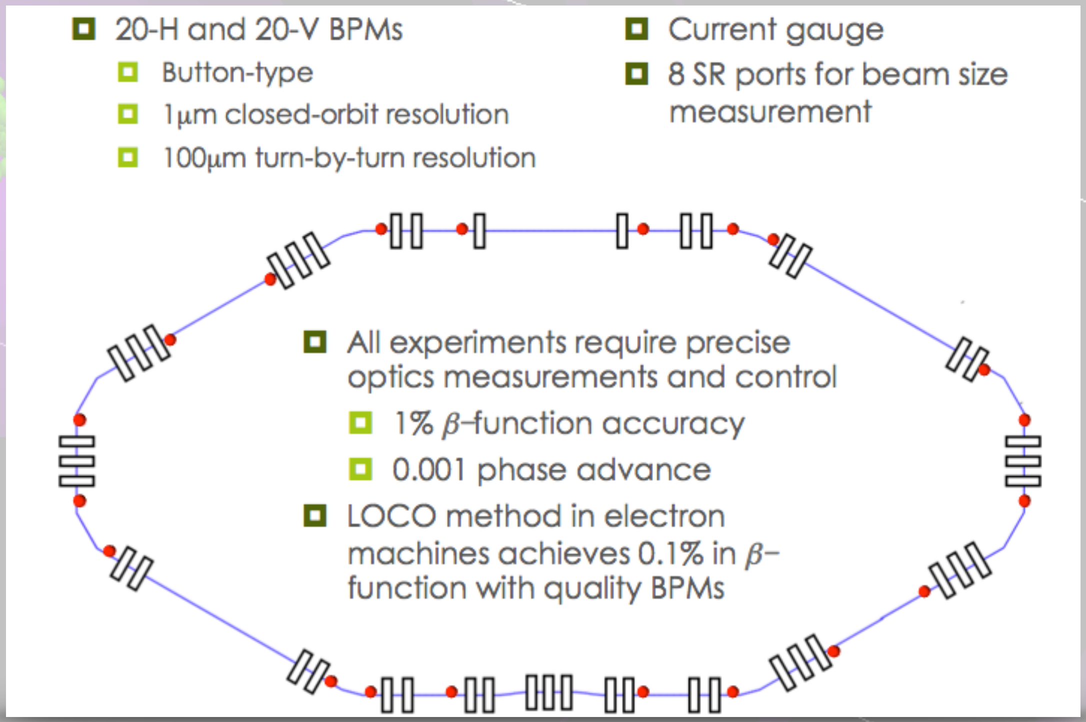
But before we get there…

- Establish the validity of the numerical model
  - with and without space-charge
- Leads to specific requirements for instrumentation and beam
  - types of instrumentation and measurement accuracy
  - beam type, energy, injection parameter control



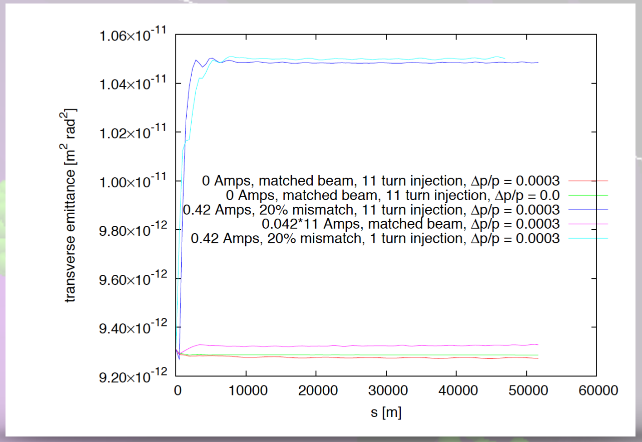
Instrumentation & beam parameters

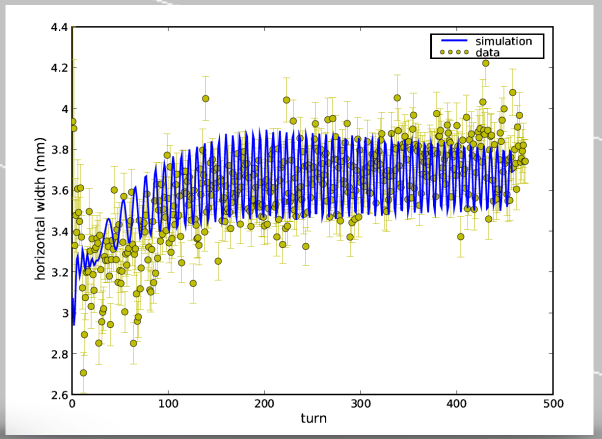
- Turn-by-turn position, profile & current measurements
- Ability to precisely measure beta functions (OK)
- Transverse (more than one location) and longitudinal profiles (OK?)
- Ability to manipulate injected beam (shape, position), vary beam current
- Ability to achieve space-charge tune shift > 0.25
    - high-current low energy protons preferable



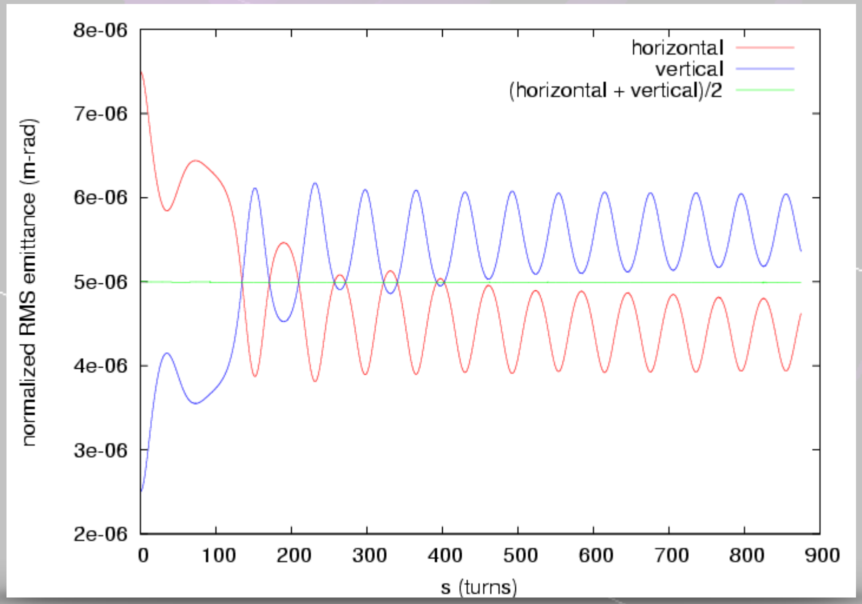
Validation studies

- Build IOTA model (lattice function measurements, apertures); also correctors and non-linear element(s)





- Measure emittance growth for different initial conditions (matching, current, momentum spread; different beam distributions —if possible—) and compare with simulation predictions

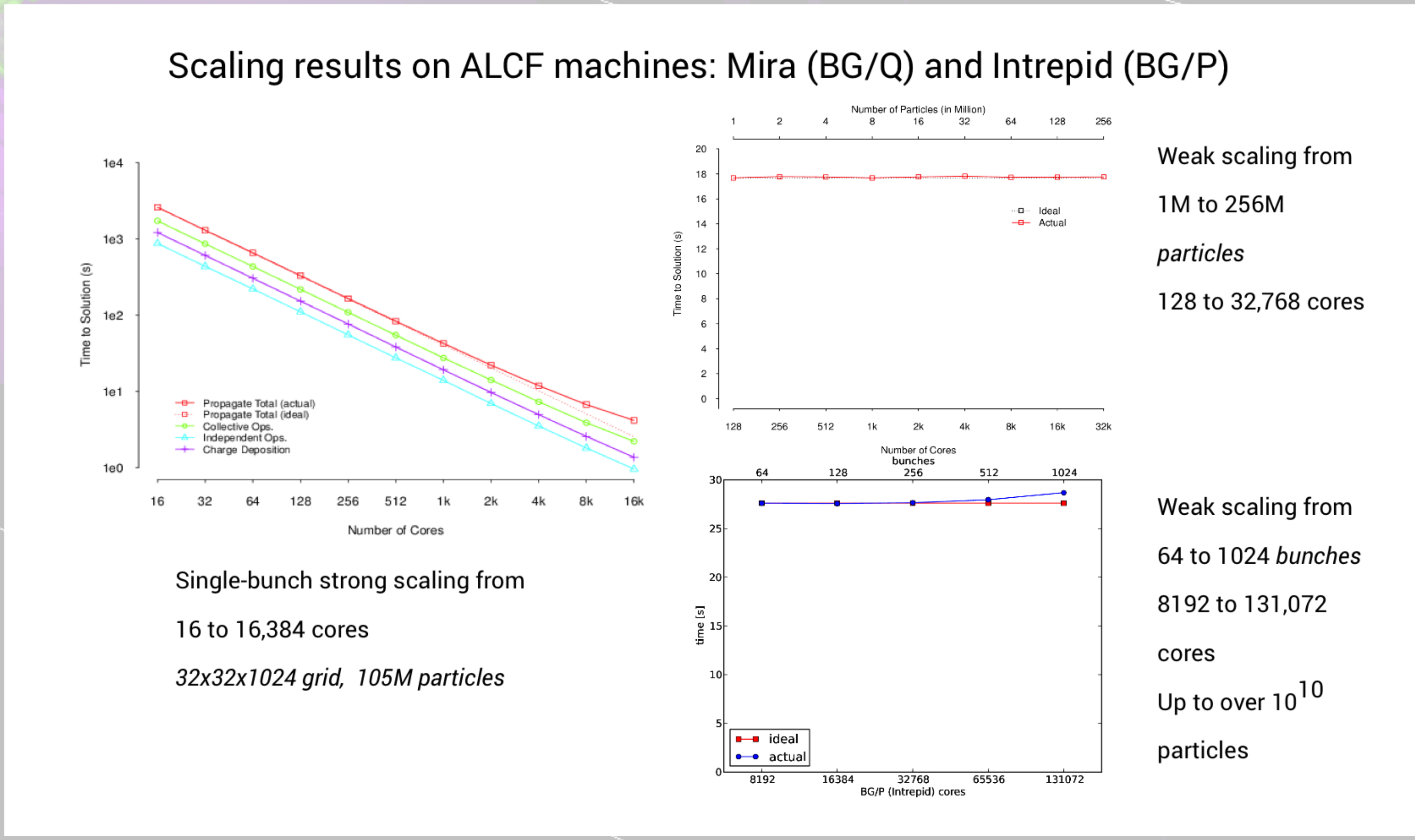


Experiments

- Emittance exchange (Montague resonance, 2Qx-2Qy=0; differentiate from transverse plane coupling) in the presence of space-charge
  - compare with simulation, model and measure transverse plane coupling
- Resonance crossing with and without strong space-charge
  - compare with simulation predictions (beam loss & beam characteristics and time evolution)
- Study behavior of beam (different currents, shapes) with special non-linear optics
  - numerical modeling and measurements

Simulation

- Use the Synergia framework
  - fully 3D PIC solvers
  - parallel
  - allows modeling of billions of macro particles for accurate loss/halo prediction



Synergia

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Fermilab

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The ComPASS Project

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Fermilab

Synergia

- Accelerator simulation package
  - independent-particle physics
    - linear or nonlinear
  - collective effects
    - simple or computationally intensive
  - can go from simple to complex, changing one thing at a time
- Goal: best available physics models
  - *best* may or may not mean *computationally intensive*

https://web.fnal.gov/sites/Synergia/

- Designed for range of computing resources
  - laptops and desktops
  - clusters
  - supercomputers
- Goal: best available computer science for performance
  - significant interaction with computer science community

Personnel

Synergia is developed and maintained by the
Accelerator Simulation group
in Fermilab's
Scientific Computing Division

James Amundson, Paul Lebrun, Qiming Lu, Alex Macridin, Leo Michelotti (CHEF), Chong Shik Park, Panagiotis Spentzouris and Eric Stern

With development contributions from Tech-X: Steve Goldhaber

Physics

- Single-particle physics are provided by CHEF
  - direct symplectic tracking
    - magnets, cavities, drifts, etc.
  - (and/or) arbitrary-order polynomial maps
  - many advanced analysis features
    - nonlinear map analysis, including normal forms
    - lattice functions (multiple definitions)
    - tune and chromaticity calculation and adjustment
    - etc.
- Apertures
- Collective effects (single and multiple bunches)
  - space charge (3D, 2.5D, semi-analytic, multiple boundary conditions)
  - wake fields
    - can accommodate arbitrary wake functions
  - electron cloud
    - proof of principle only

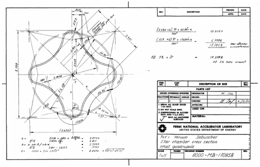
Space charge in Synergia

Variety of boundary conditions and levels of approximation

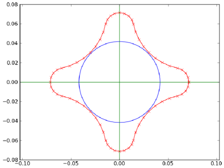
- 3D open transverse boundary conditions
  - Hockney algorithm
  - open or periodic longitudinally
- 3D conducting rectangular transverse boundary
  - periodic longitudinally
- 3D conducting circular transverse boundary
  - periodic longitudinally
- 2.5D open boundary conditions
  - 2D calculation, scaled by density in longitudinal slices
- 2D semi-analytic
  - uses Bassetti-Erskine formula
  - σ_x and σ_y calculated on the fly
- New space charge models can be implemented by the end user

Synergia 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

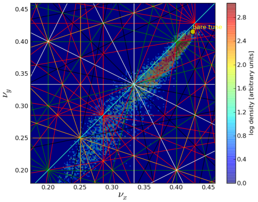


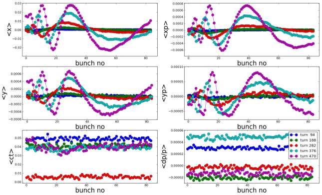
Synergia implementation: detailed, but fast (inscribed circle optimization)

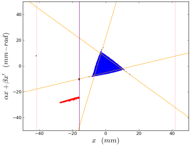
Status

Synergia 2.1 is being used for all production work in our group at Fermilab.

- Fermilab Main Injector
  - space charge, multipoles, detailed apertures, orbit bumps
- Fermilab Booster
  - space charge, wakes, 84 bunches
- Fermilab Debuncher (Mu2e experiment)
  - space charge, ramping, resonant extraction
- Hybrid MPI-OpenMP and MPI-GPU versions







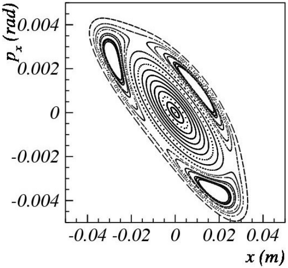
Space charge trapping benchmark

- Space charge trapping benchmark in GSI SIS18
  - http://web-docs.gsi.de/~giuliano/research_activity/trapping_benchmarking/main.html
- Discussed elsewhere at this workshop
- *The aim of the code benchmarking is to confirm the space charge induced trapping of particles in a bunch during long term storage.*

Benchmark step

The fifth step is to benchmark the phase space with test particles when the sextupole is on and in presence of space charge.

Benchmark



Synergia