Simulation Studies of the Interplay Between Space-Charge and Impedance Effects for Project X

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Overview

- The Main Injector is crucial for future Fermilab projects
- Toward a comprehensive and unified simulation package for next-generation Fermilab accelerators: Synergia
  - Nonlinear optics
  - Resistive wall
  - Space charge
  - ...and beyond
- Results of some preliminary simulations

Disclaimers

- “for Project X” is being used in a completely non-official sense
  - a disadvantage of being optimistic when asked to give a talk title

Toward a comprehensive and unified simulation package for next-generation Fermilab accelerators

- Virtually all current proposals for future experiments at Fermilab involve higher intensity beams than ever before
- Collective effects limit machine intensities
  - Simulations of collective effects are more important than ever before
    - Interplay between multiple collective effects also becomes more important
      - requires an integrated simulation package
  - Simulation technology has advanced to better take advantage of (massively) parallel machines than ever before
    - Very complex simulations are now possible

The Fermilab Main Injector

- Commissioned 1999
- Initial E 8 GeV
- Max E 120 GeV
- L = 3.3 km
- Harmonic number 588

The Main Injector beam pipe

From a simulator's perspective, the F117 Stealth Fighter is ideal:it doesn't even really look like an airplane, but it was constructed with an easy-to-simulate geometry

In contrast, the Main Injector beam pipe is a challenge to simulators: 12.3 cm wide by 5.31 cm high (5.08 cm high under vacuum), it isn't even exactly elliptical.

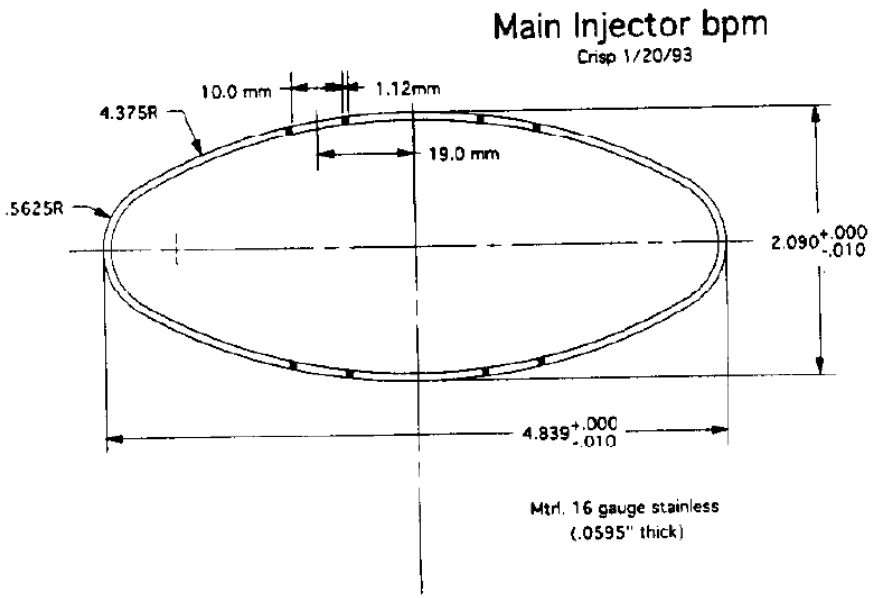
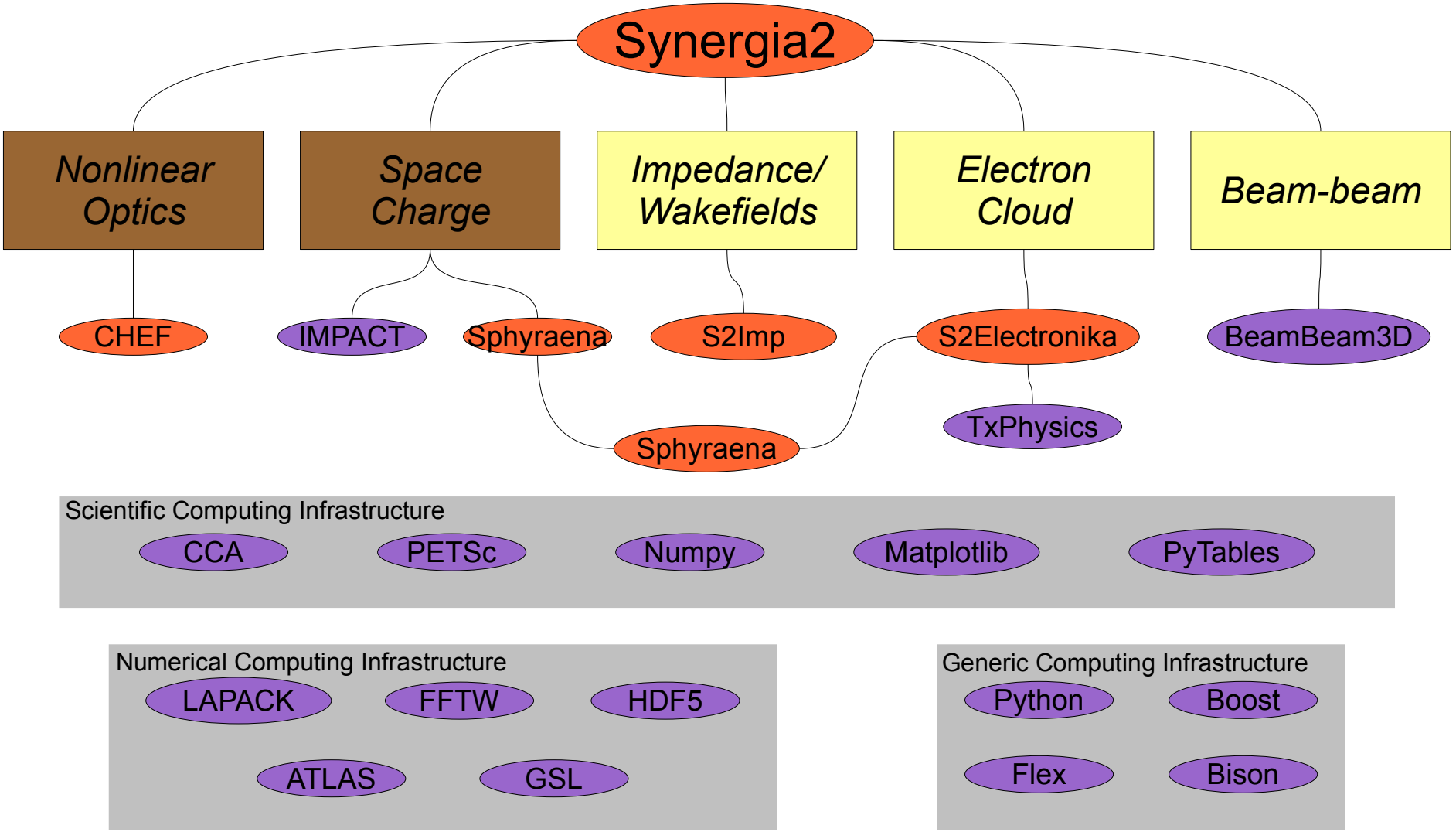


Figure 1: Geometry of Main Injector Beampipe and Beam Position Monitor.

Tools and experience from simulating other portions of the Fermilab accelerator complex

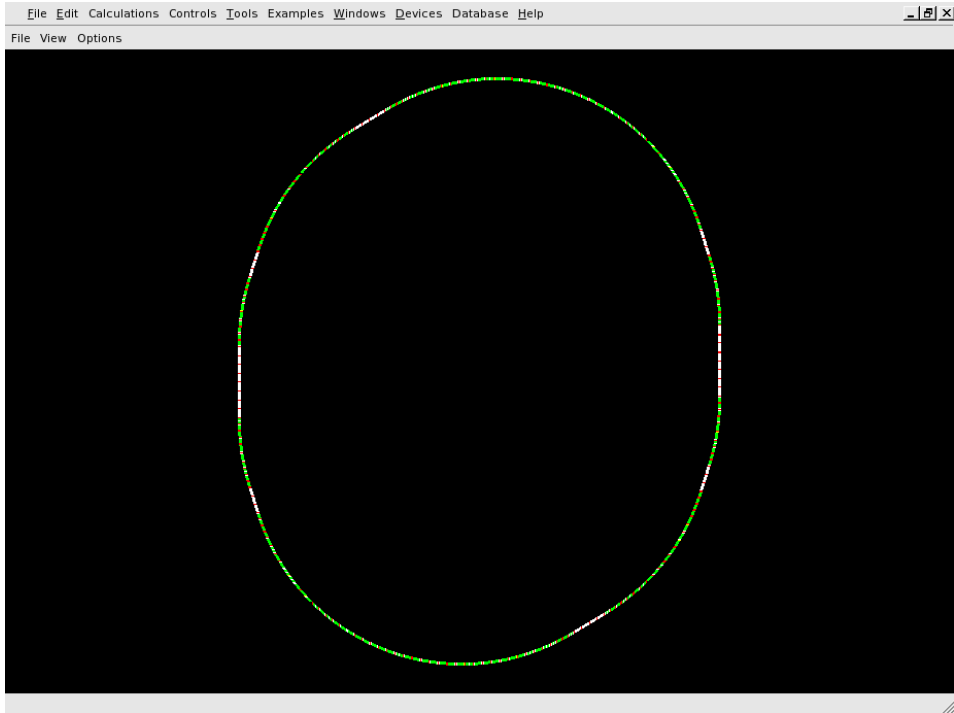
- We are embarking on Main Injector simulations utilizing tools developed for and tested with other Fermilab machines
- From lower energy: space charge
  - Extensively studied in Booster using Synergia
    - see Spentzouris, et al., HB2006, etc.
- From higher energy: resistive wall
  - Studied using BeamBeam3D with resistive wall module developed at Fermilab
    - Now integrated into Synergia



Synergia2 framework development includes multiple advanced accelerator physics topics. Development is aided by relying on both internally- (orange) and externally- (magenta) developed state-of-the-art packages. New physics modules (yellow) are currently under development.

Single-particle tracking: CHEF

- 6D Particle tracking code
  - Arbitrary-order maps
  - Individual particle (non-map) tracking available
    - particularly useful for longitudinal dynamics in beam capture when accurate description of entire bucket is necessary
  - Accepts MAD(8) and XSIF
    - MADX in development
  - Provides a GUI



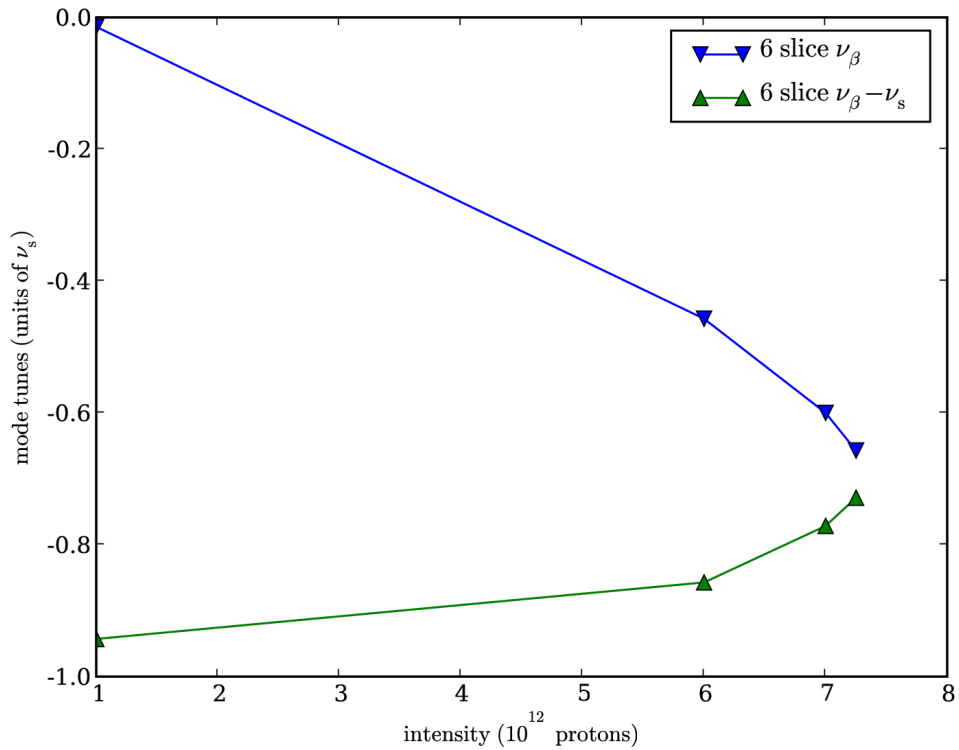
Resistive Wall Impedance Module

- Developed for BeamBeam3D simulations of Tevatron
- Dipole component of resistive-wall wakefields
- Longitudinal charge density is calculated using 3D PIC and cloud-in-cell slices
- Kicks are applied to each particle from all earlier slices

$$\frac{\Delta\vec{p}_\perp}{p} = \frac{2}{\pi b^3}\sqrt{\frac{c}{\sigma}}\frac{N_i<\vec{r}_i>}{\beta\gamma}\frac{L}{\sqrt{z_i}} = W_0 L <\vec{r}>$$

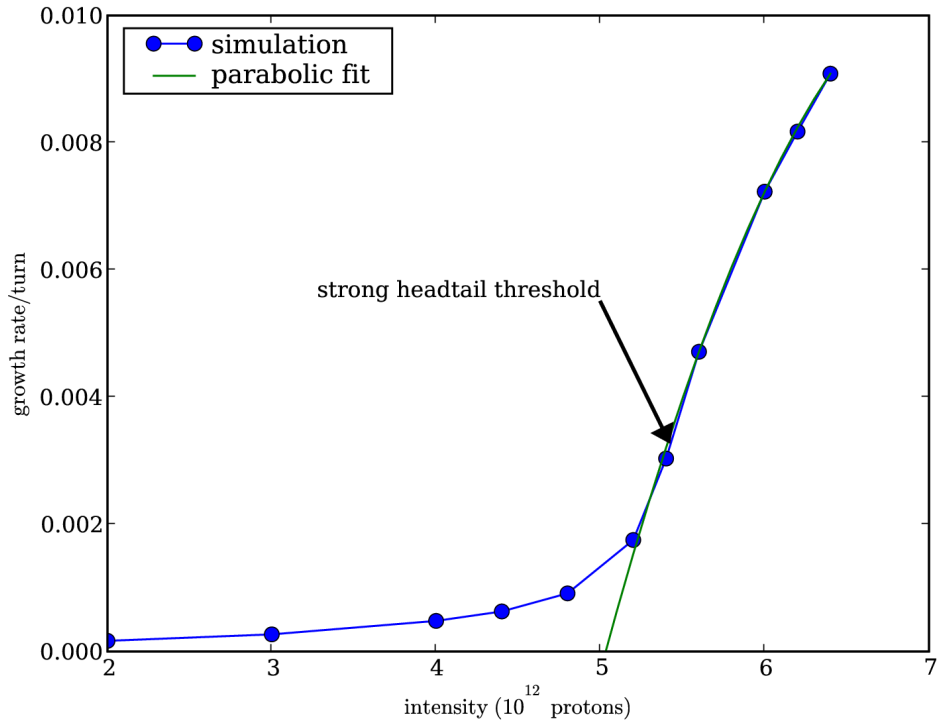
RW Validation Studies

Tevatron study of synchro-betatron modes

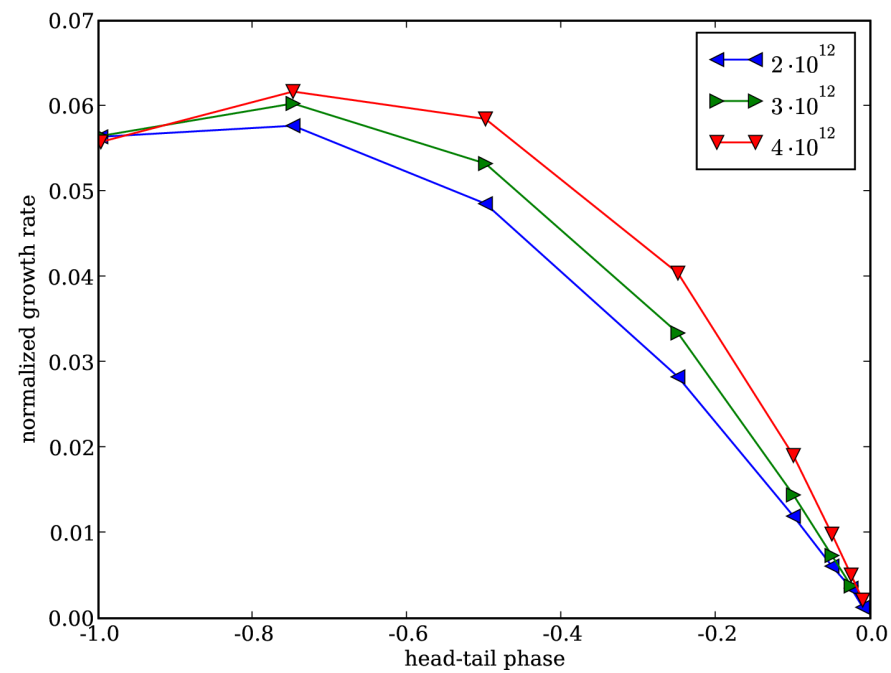


Evolution of the base tune and lower synchro-betatron mode frequencies as a function of beam intensity showing the two modes coming to a common frequency due to impedance.
The vertical scale is in units of the synchrotron tune.

RW Validation Studies



Growth rate of dipole motion as a function of intensity, showing predicted parabolic dependence after the onset of the strong head-tail instability

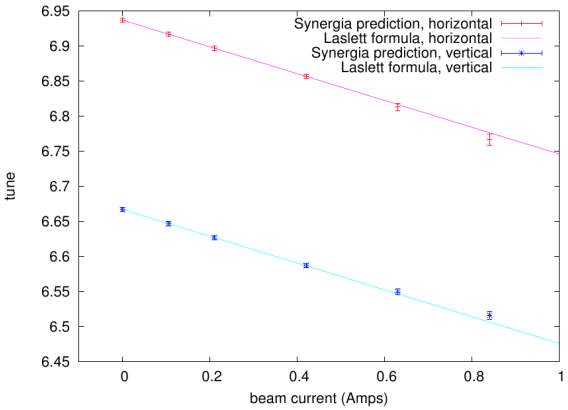


Growth rate as a function of head-tail phase, showing predicted linear growth near 0 and near-universality near -1

See Chao, "Physics of Collective Beam Instabilities in High Energy Accelerators", Chapter 6

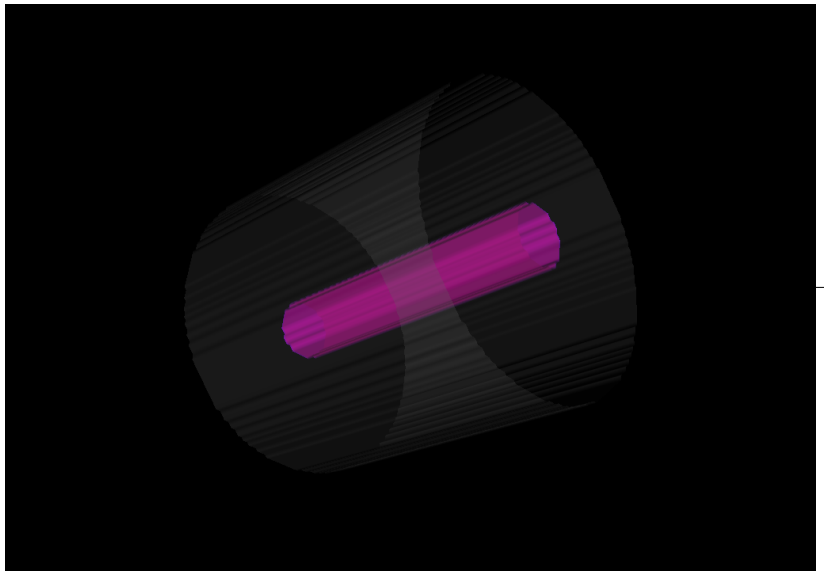
Space charge module

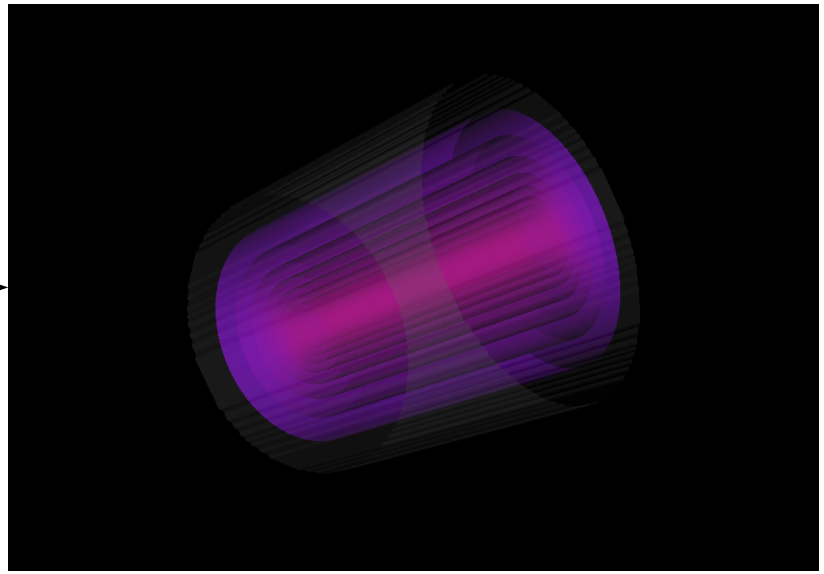
- Extensively validated vs. theory, Fermilab Booster studies, other codes...
- New 3D solver suite, Sphyraena
  - Arbitrary number of loosely-coupled bunches
    - previous strongly-coupled Synergia implementation does not scale past a few bunches
  - Open boundary conditions
  - Conducting circular pipe
  - Finite Difference solver
    - Arbitrary BCs possible
    - First multigrid version too slow for production
    - Progress being made on non-MG version



Sphyraena validation

- Straightforward approach is to test on analytically solvable problems, e.g., (non-)uniform conducting cylinder
  - High degree of symmetry makes for poor tests
    - also makes for solvable problem

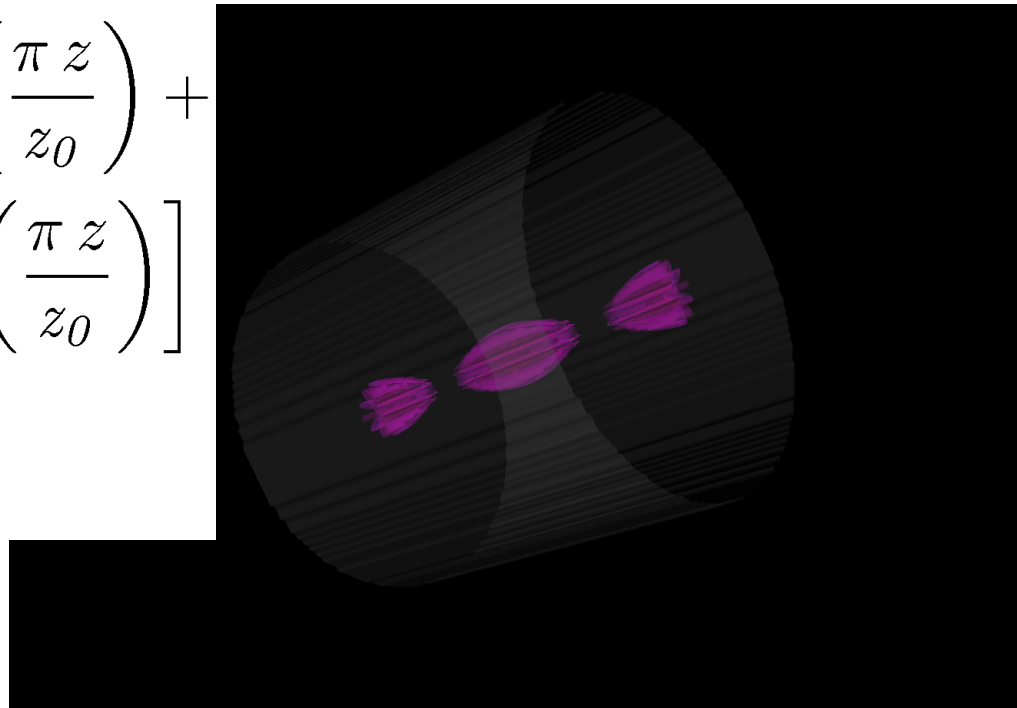




Sphyraena validation, cont.

- Better test: take a non-trivial charge density

$$\rho(r,\theta,z) =$$
$$\Big[\Big(\big(18\,{r_0}^2 - 14\,r^2\big)\,\sin^2(3\,\theta) +$$
$$\big(18\,r^2 - 18\,{r_0}^2\big)\,\cos^2(3\,\theta)\Big)\,\cos^2\left(\frac{\pi\,z}{z_0}\right)\,{z_0}^2 +$$
$$\big(2\,\pi^2\,r^4 - 2\,\pi^2\,r^2\,{r_0}^2\big)\,\sin^2(3\,\theta)\,\sin^2\left(\frac{\pi\,z}{z_0}\right) +$$
$$\big(2\,\pi^2\,r^2\,{r_0}^2 - 2\,\pi^2\,r^4\big)\,\sin^2(3\,\theta)\,\cos^2\left(\frac{\pi\,z}{z_0}\right)\Big]$$
$$\Big/\,\big(r^2\,{r_0}^2\,{z_0}^2\big)$$

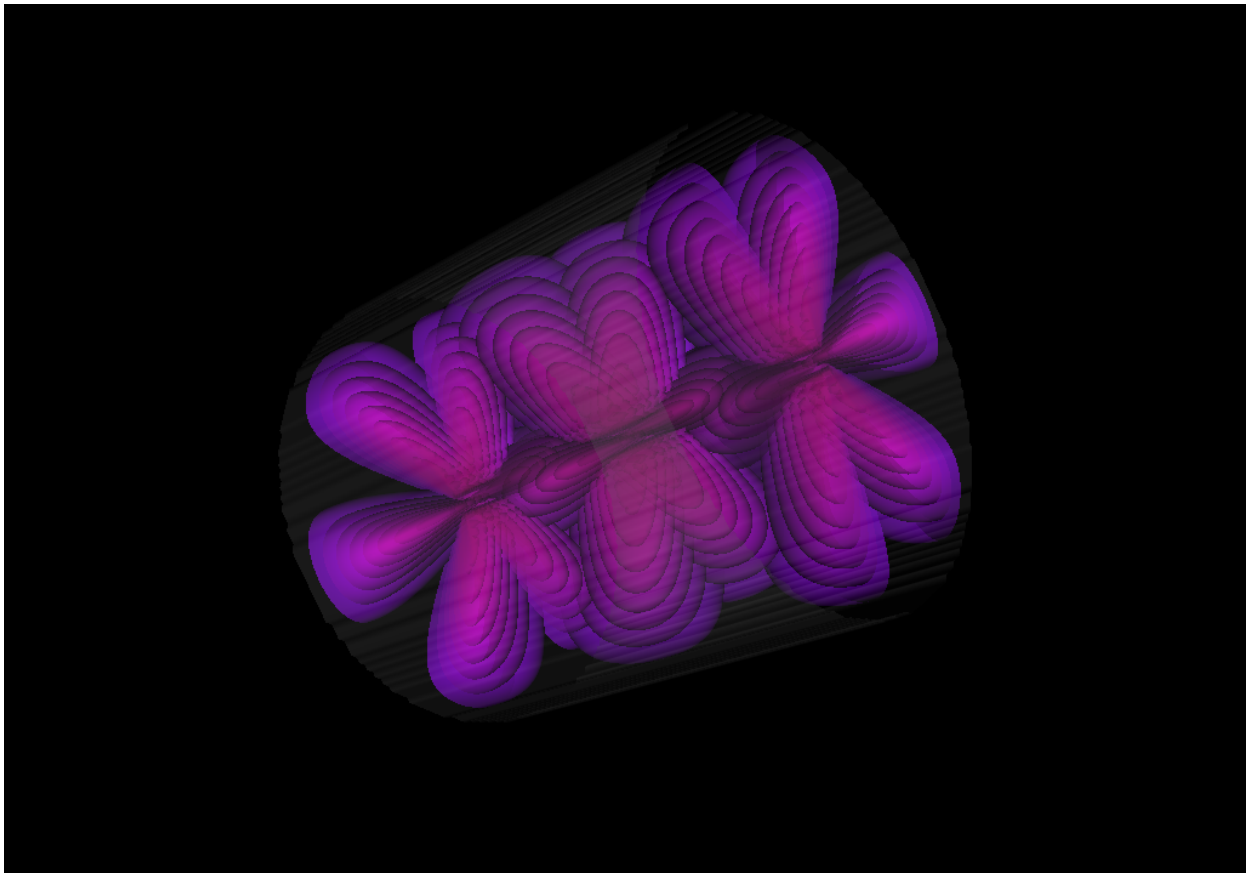


Sphyraena tests, cont.

- ... and produce a test in all coordinates

$$\phi(r,\theta,z) = \left(1 - \frac{r^2}{r_0^2}\right)\sin^2(3\theta)\cos^2\left(\pi\frac{z}{z_0}\right)$$

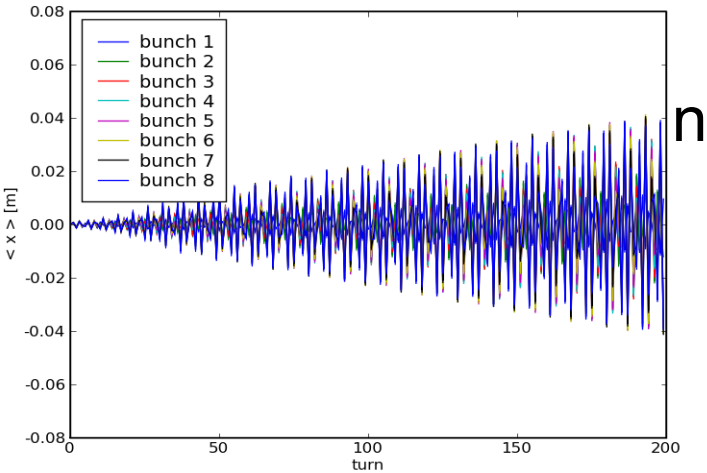
Procedure may be easily extended to any boundaries described by analytical expressions



Simulations of Main Injector Resistive Wall instability before acceleration

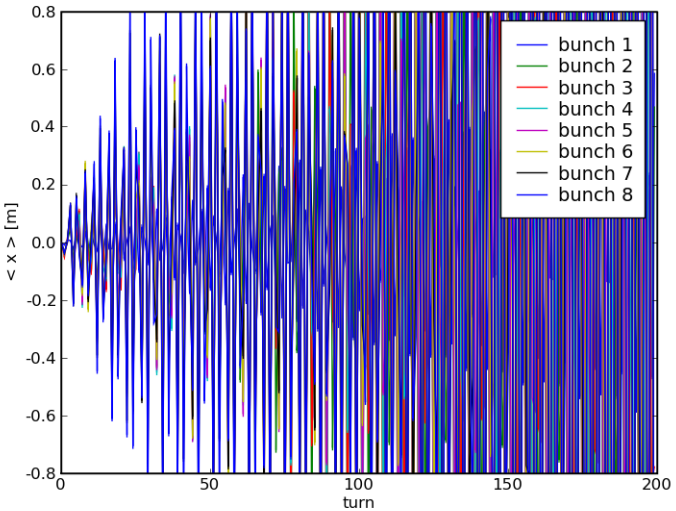
- 8.9 GeV
- 0.75m rms longitudinal bunch size
- 6e10 protons/bunch, 10x, 100x
- 8 consecutive bunches for a total of 524288 macroparticles
- 0.26 mm-mr x and y rms emittance
- x offset 1 mm
- Space charge: 32x32x32 grid
  - circular pipe (mean radius)
- Resistive wall: 32 longitudinal slices
  - x and y radius taken to be pipe w/2, h/2

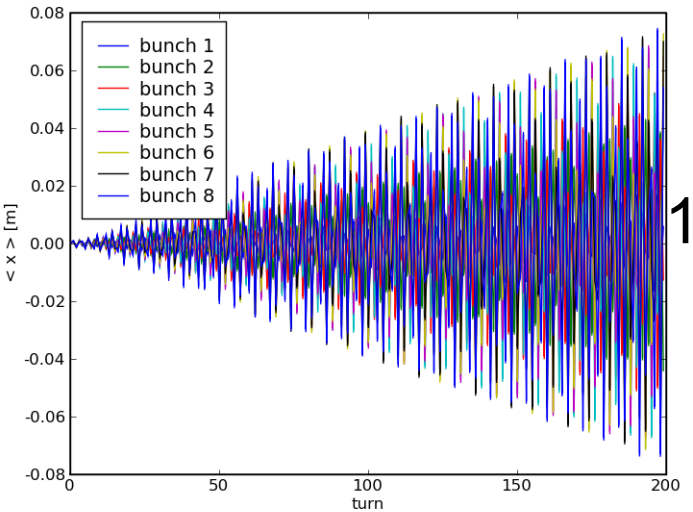
Uncontrolled beam position oscillation and emittance growth



nominal intensity

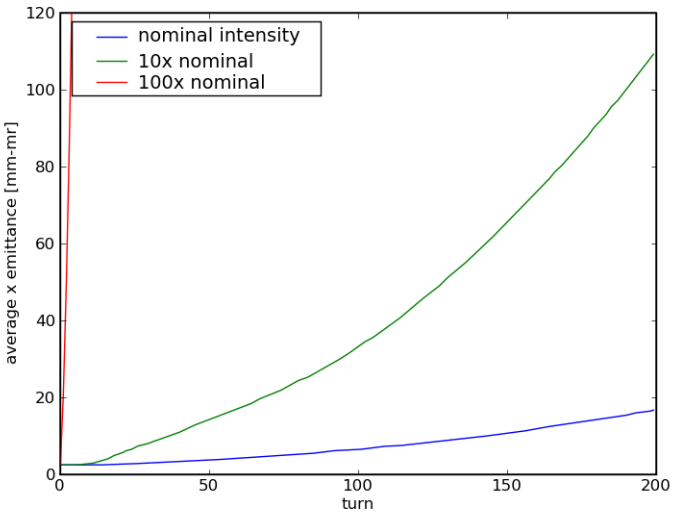
100x intensity





10x intensity

emittance growth



Next steps

- Model the Main Injector methods for avoiding resistive wall instability
  - active damper system
    - Synergia's python-driven simulations especially well suited for this sort of problem
- Move on to other portions of the Main Injector cycle
  - transition region is probably the most interesting

Conclusions

- We have begun the process of simulating the Main Injector with multiple coherent effects
  - Resistive wall
  - Space charge
- Synergia has been extended for this capability
  - will be extended further to include electron cloud effects
- Many opportunities and challenges for new simulations