Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

PIC Simulation of Space Charge Compensation by Electron Lens

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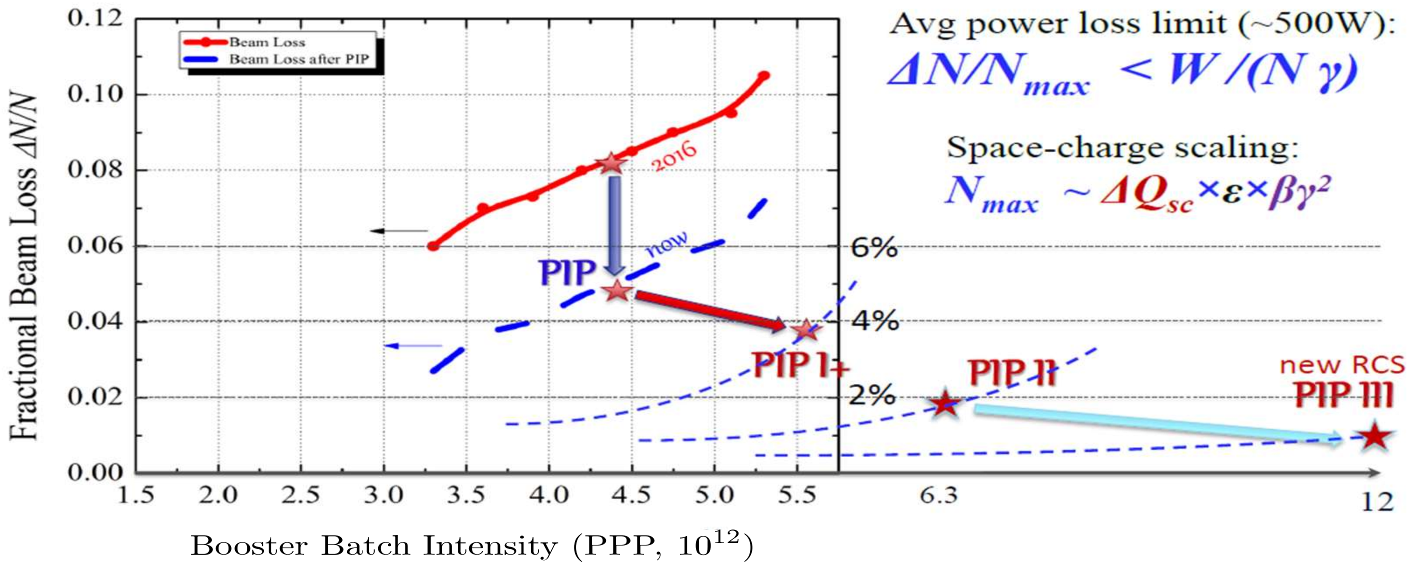
FAST/IOTA Collaboration Meeting 2019

11 June 2019

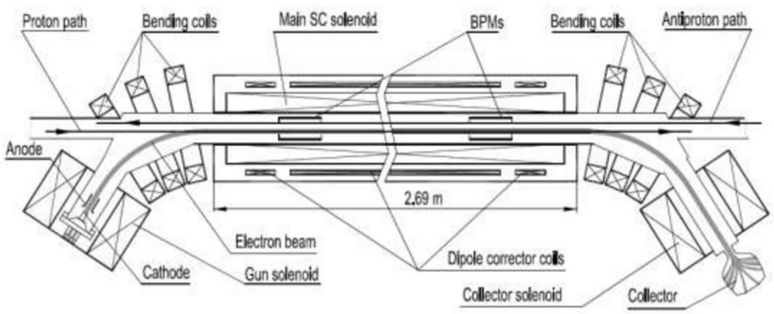
Outline

- Motivation for Space Charge Compensation
- Compensation Evaluation Plan
- Space Charge Simulation Codes
- Compensation Results Ideal Lens
- Compensation Results “Realistic” Lens
- Future Plans and Summary

Strong need for space charge compensation



Electron Lens Force



$$F(r)_{\mathrm{SC}} = \frac{2 I_p r_p}{e \beta_p^3 \gamma_p^3 c} \left(1 - e^{-\frac{r^2}{2\sigma^2}}\right) \frac{1}{r}$$

$$F(r)_{\mathrm{lens}} = -\frac{2 I_e r_p (1 + \beta_e \beta_p)}{e \beta_e \beta_p^2 \gamma_p c} \left(1 - e^{-\frac{r^2}{2\sigma^2}}\right) \frac{1}{r}$$

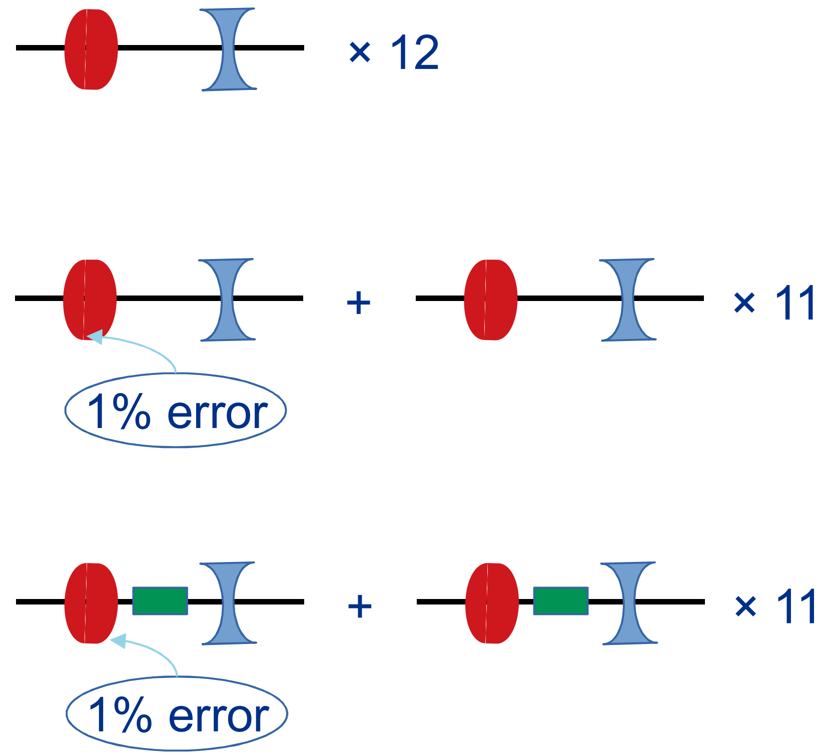
I_p	proton current
I_e	electron current
σ	RMS electron radius
β_e	electron v/c (opposite direction from p)
β_p	proton v/c
γ_p	proton relativistic factor
r_p	classical proton radius

Evaluation Plan

Ideal FODO

FODO with lattice error

FODO with lattice error and 12 lenses



Focusing

Defocusing

Electron lens

ΔQ_{SC} = -0.9

Initially, avoid complications from bends

Space Charge Simulators (1)

Synergia

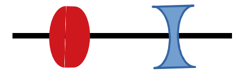
- Combine beam optics and collective effects.
- Thin electron lens element with longitudinal modulation added.
- Developed at Fermilab in the SCD organization.
- PIC fully 3D SC, able to efficiently run millions of macro-particles to reduce statistical noise. All runs performed with 16M macro-particles.
- Macro-particle charge distribution is deposited on a grid. Laplace equation is solved numerically to get potential. Electric field is applied as the space charge kick.
- GSI Space Charge Benchmarking
  - F. Schmidt , *et al.*, Code Benchmarking for Long-Term Tracking and Adaptive Algorithms, doi:10.18429/JACoW-HB2016-WEAM1X01
- Landau Damping of Modes
  - A. Macridin, *et al.*, Simulation of transverse modes with their intrinsic Landau damping for bunched beams in the presence of space charge, PRSTAB **18**, 074401 (2015)

Space Charge Simulators (2)

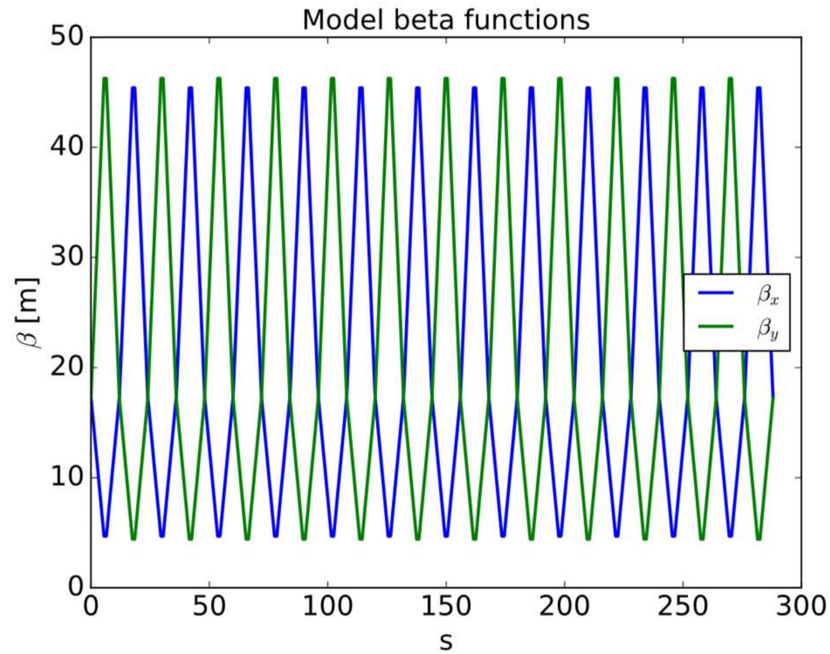
MAD-X SC

- Independent space charge calculations.
- MAD-X space charge upgraded to deal with large space charge.
- Small number of macro-particles (5000), susceptible to statistical effects.
- Beam ∑ matrix calculated by halo-suppressing fitting procedure once/turn.
- ∑ matrix propagated along lattice.
- Space charge kick calculated using the Bassetti-Erskine formula extended for symplecticity with the RMS shape determined by the previously calculated ∑ matrix.

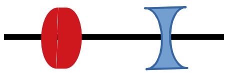
Ideal Lattice


× 12

Parameter	Value	unit
length	288.0	m
beam kinetic energy	0.8	GeV
RF frequency	43.814	MHz
slip factor	-0.291186	
x, y chromaticity	-5.68, -5.97	
total RF voltage	6.287	MV
β_x, β_y at lens	17.28, 17.27	m
x, y tunes	3.72, 3.84	
synchrotron tune	1/13	
RMS bunch radius	4.15	mm
RMS bunch length	0.5	m
RMS bunch $\Delta p/p$ spread	0.00288	
x, y emittance	1.0005e-6	m.rad
bunch charge	2e11	e
SC tune shift	-0.9	

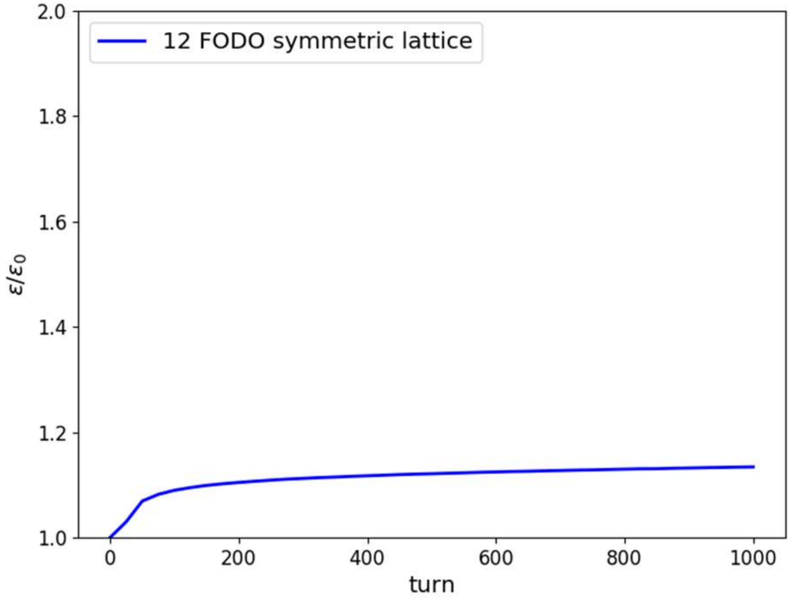


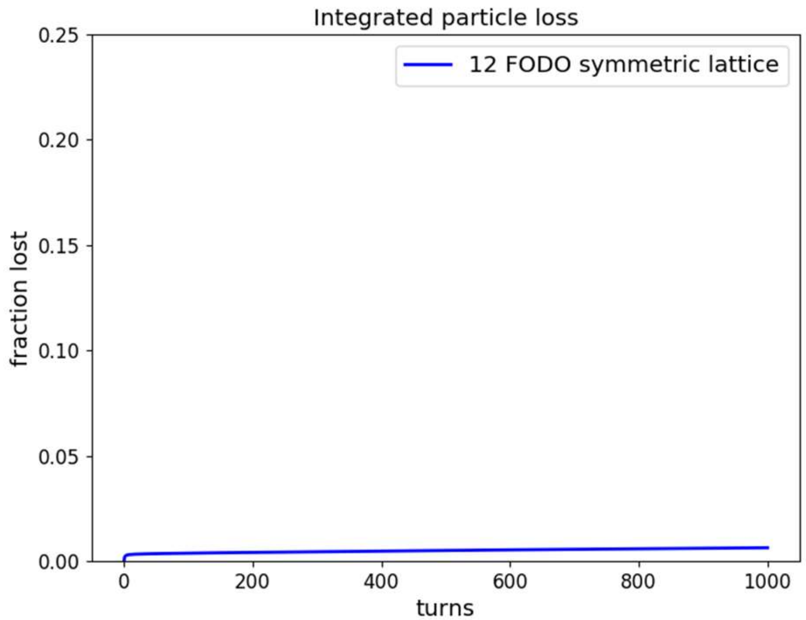
Ideal Lattice (not so bad)



RMS x emittance growth

4 sigma aperture loss

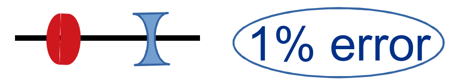


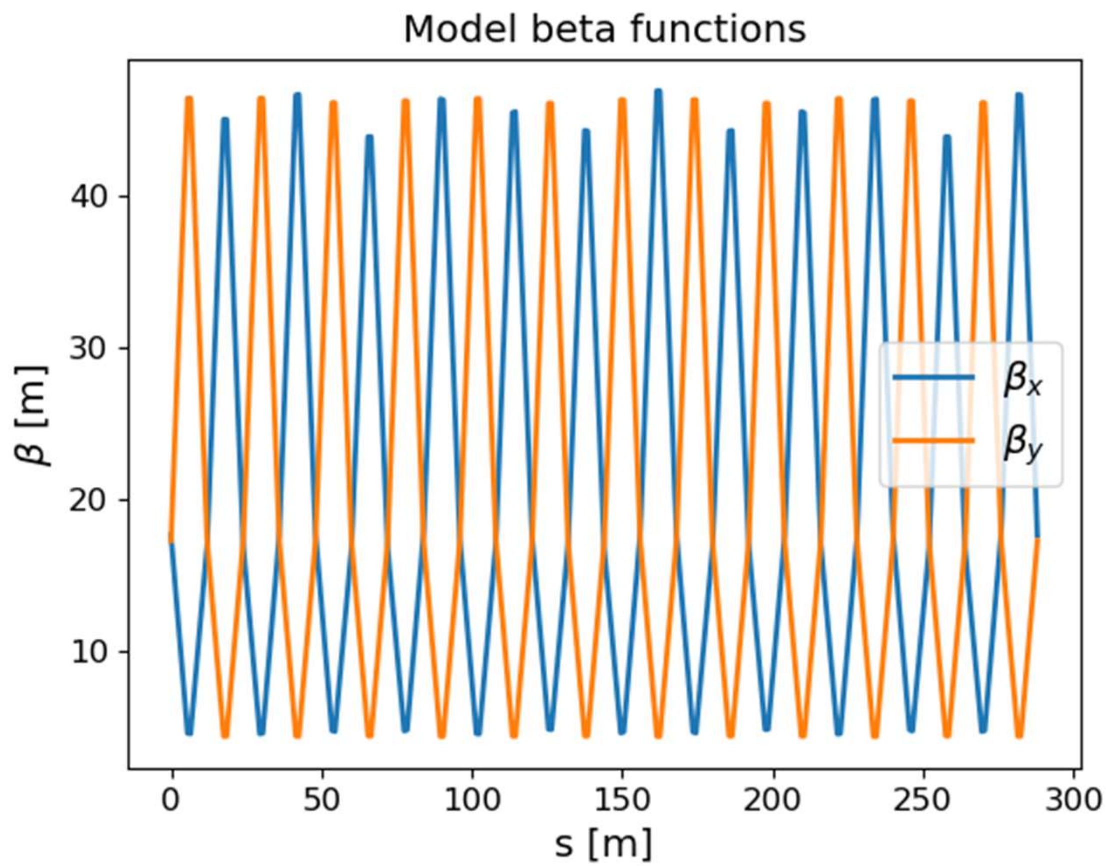


13% emittance growth

0.6% particle loss

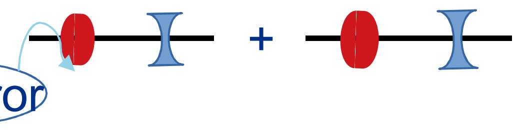
Lattice with 1% element error





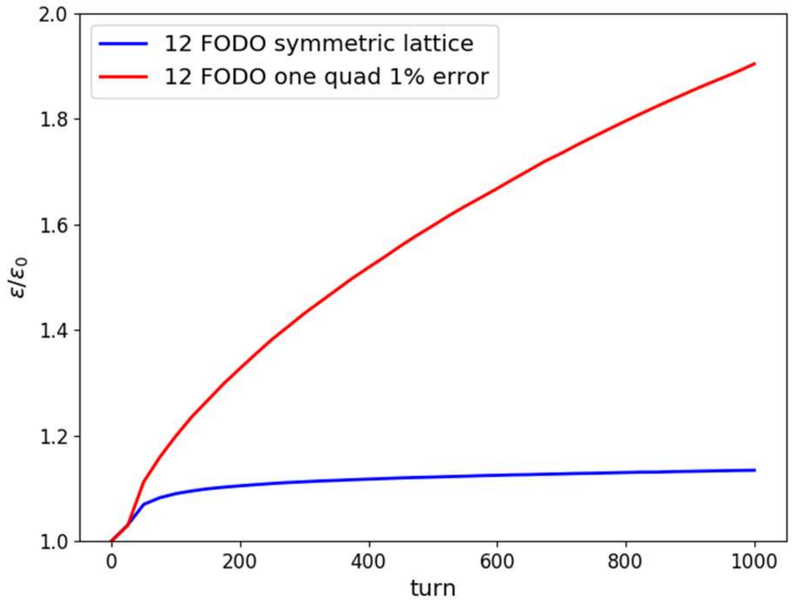
The lattice functions are not obviously terrible but…

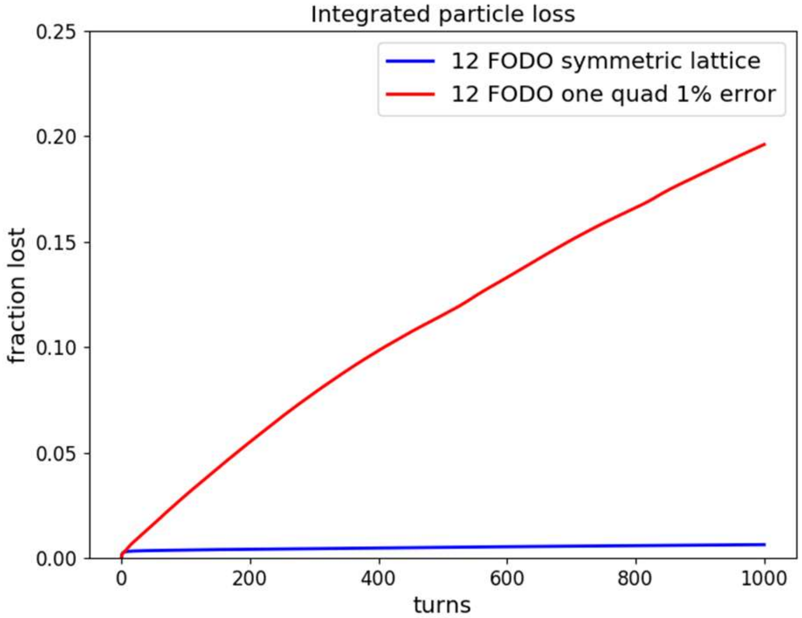
Lattice with 1% element error



RMS x emittance growth

4 sigma aperture loss





91% emittance growth with lattice error

19% particle loss with lattice error

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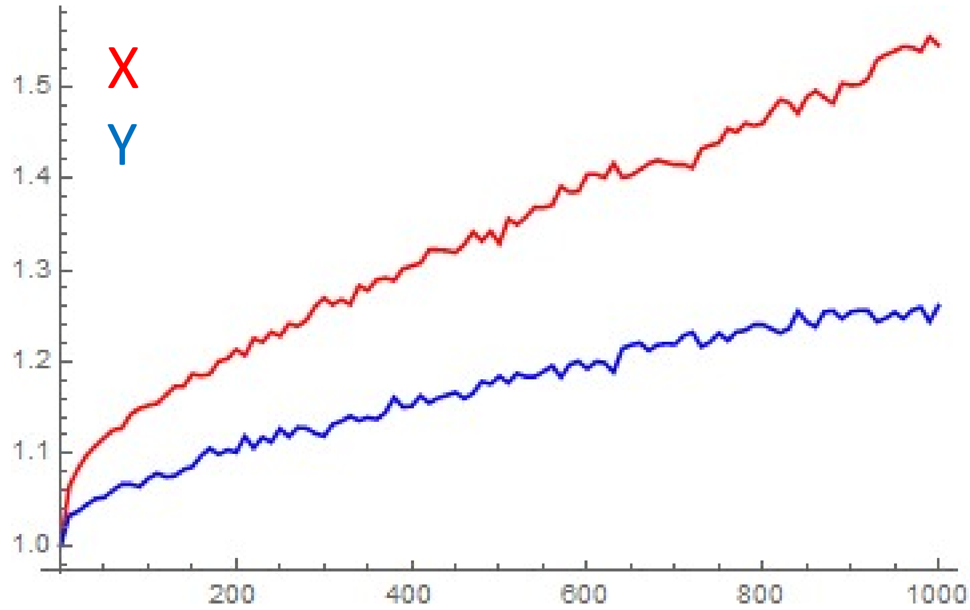
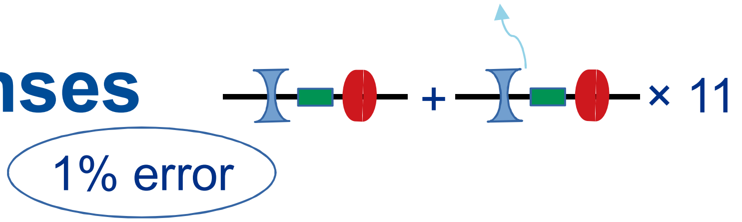
MAD-X SC result with 1% lattice error



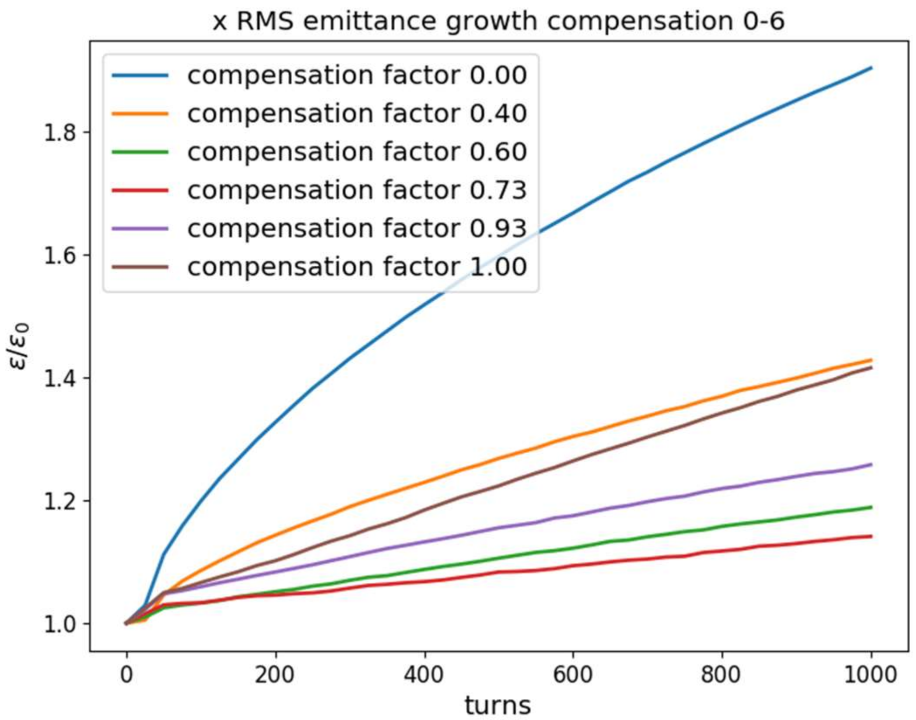
RMS emittance growth

- 50% x RMS emittance growth roughly consistent with Synergia's 90%.

Add 12 ideal compensating lenses



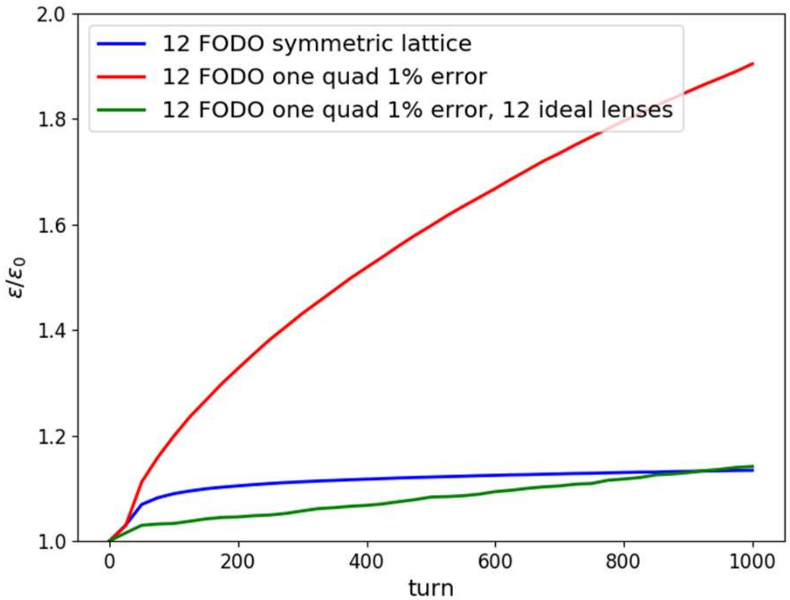
The simulation adds space charge kicks at 72 locations. We can simulate a mathematically perfect compensating lens by adding the same space charge kick multiplied by a negative factor at 12 locations 111° phase advance separation. "Maxwell's Daemon"



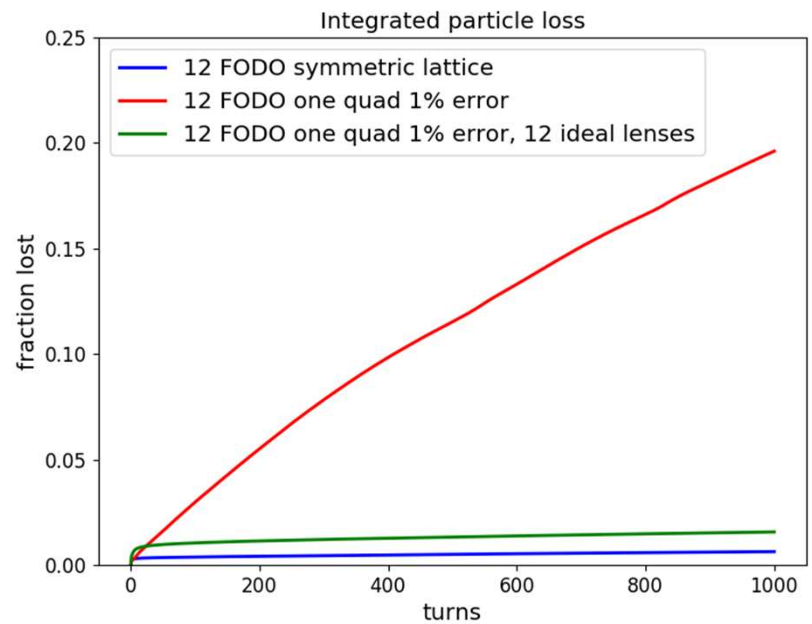
Best compensation occurs at a factor of 0.73 resulting in emittance growth of 14%

12 Ideal Compensating Lenses

RMS x emittance growth



4 sigma aperture loss

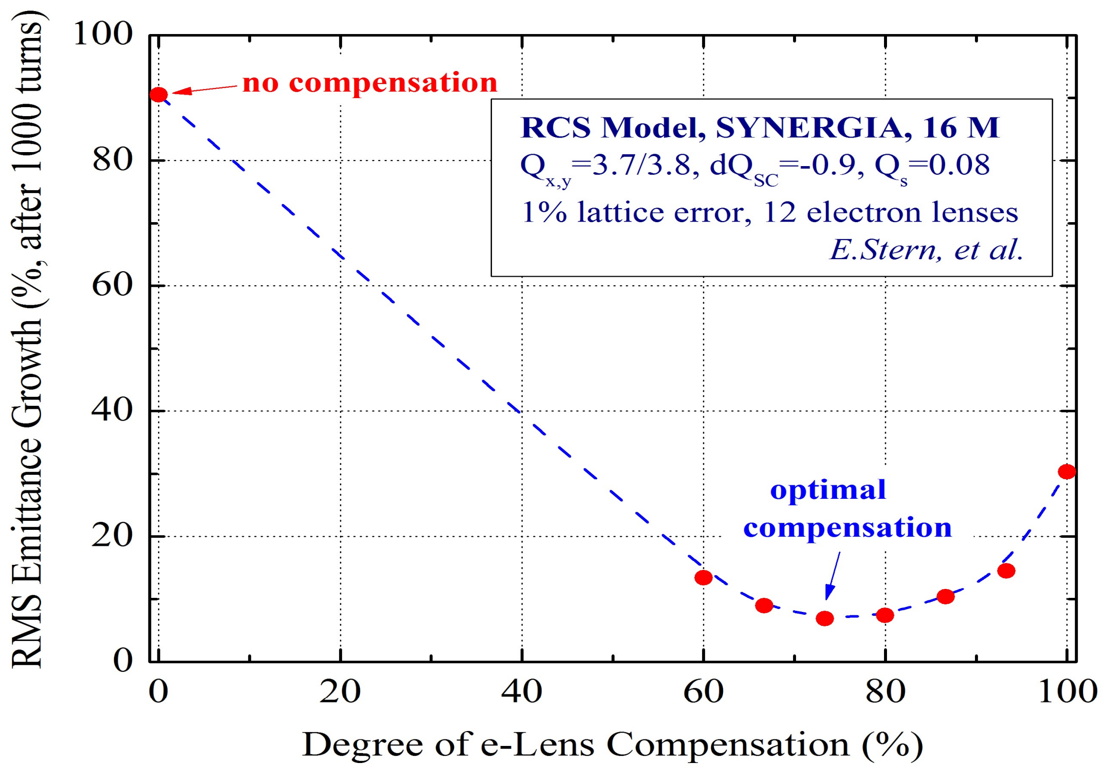


14% emittance growth with lattice error and 12 ideal lenses

1.5% particle loss with lattice error and 12 ideal lenses

Fermilab

Optimal comp



12 more realistic lenses (1)

Lenses implemented as thin kicks at 12 locations located where $\beta_x = \beta_y$.

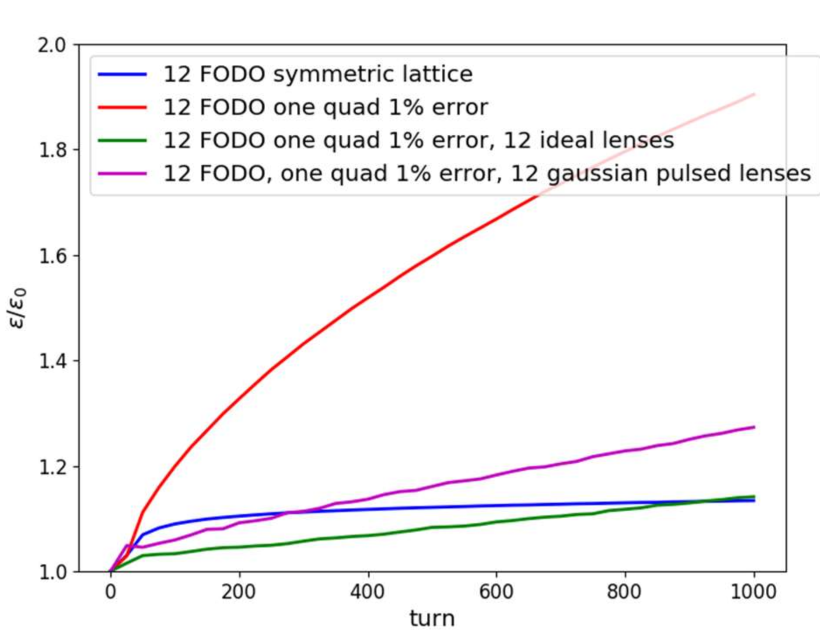
Multiple options for lens profile:

- Lens σ fixed, current fixed
- Lens σ tracks beam σ, current fixed
- Lens σ fixed, current pulsed gaussian to match beam longitudinal density
- Lens σ tracks beam σ, current pulsed gaussian to match bunch longitudinal density

12 more realistic lenses (2)

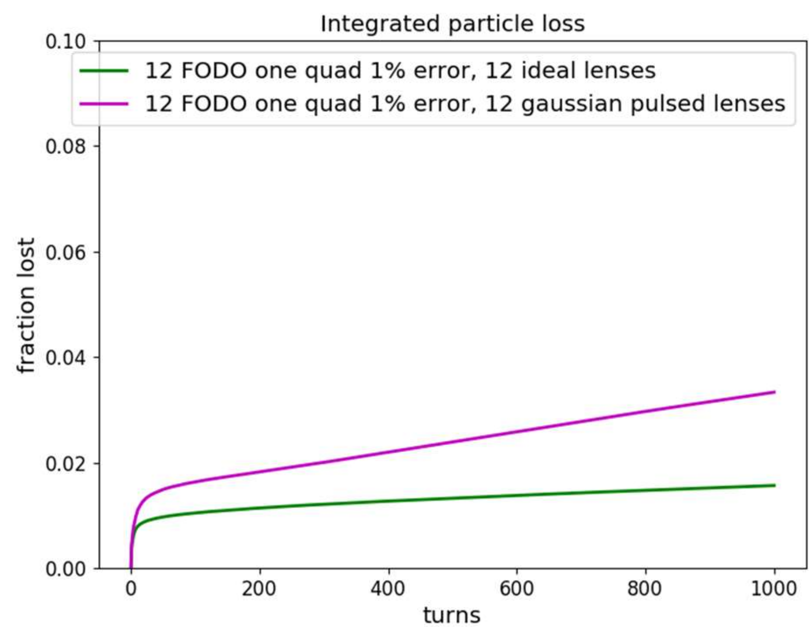
Best compensation occurs when the transverse gaussian profile is fixed to match the beam initial RMS and is pulsed to match the longitudinal bunch density. Optimal compensation strength about 67%

RMS x emittance growth



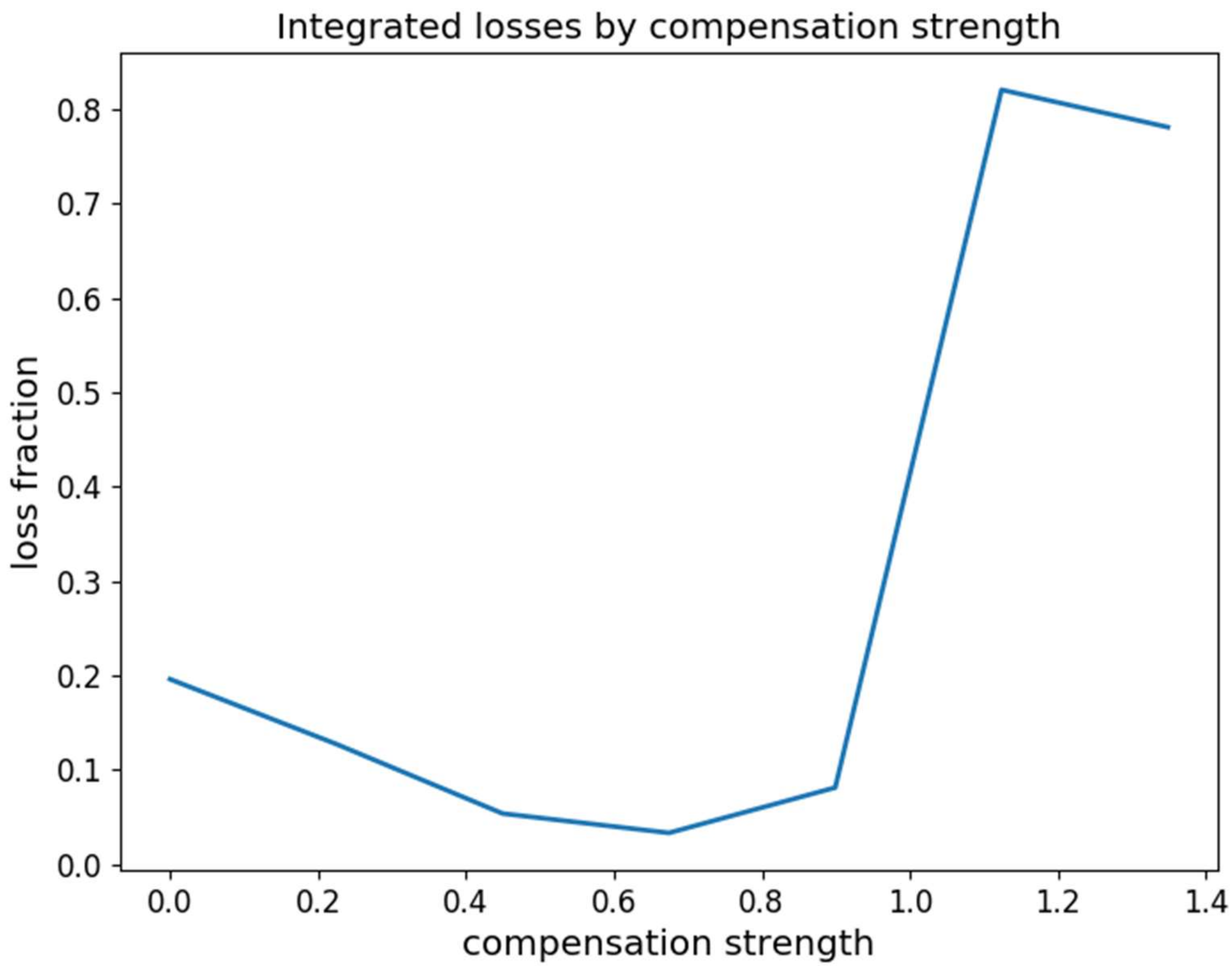
27% emittance growth

4 sigma aperture loss

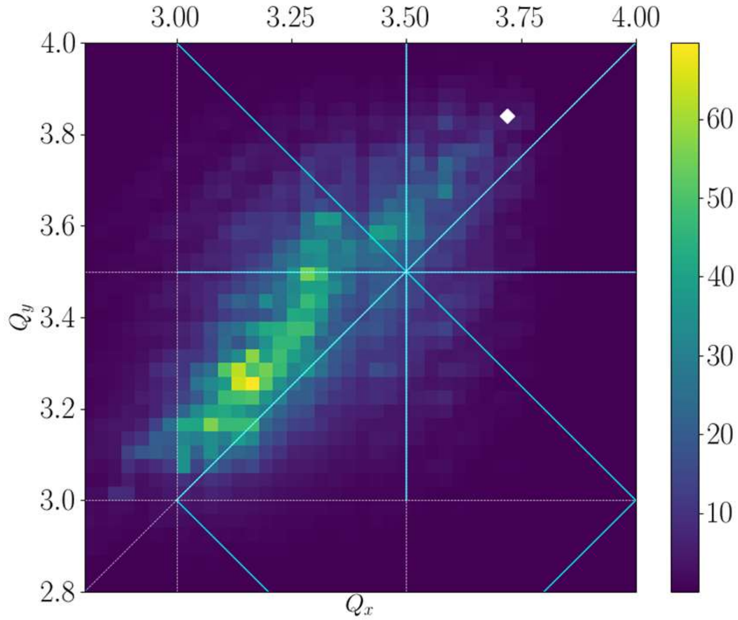


3.3% particle loss

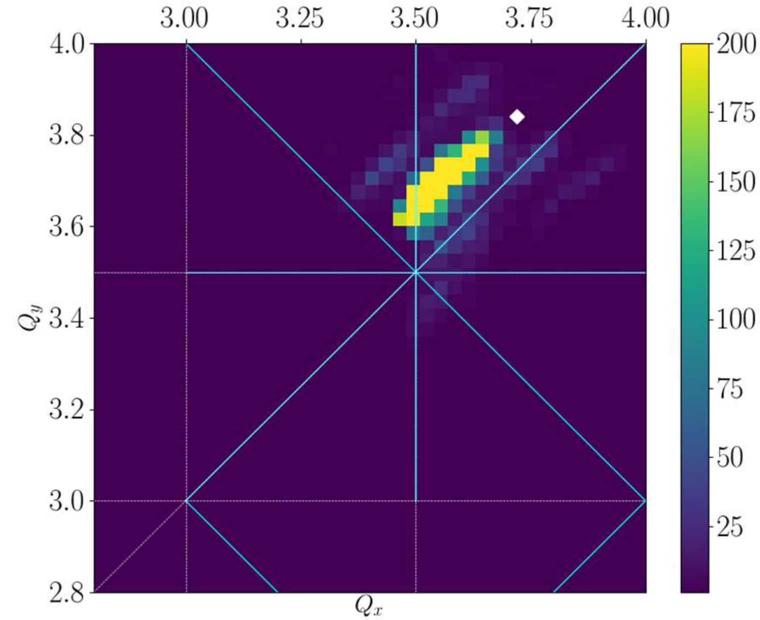
Realistic lens optimal compensation strength



Tune footprints

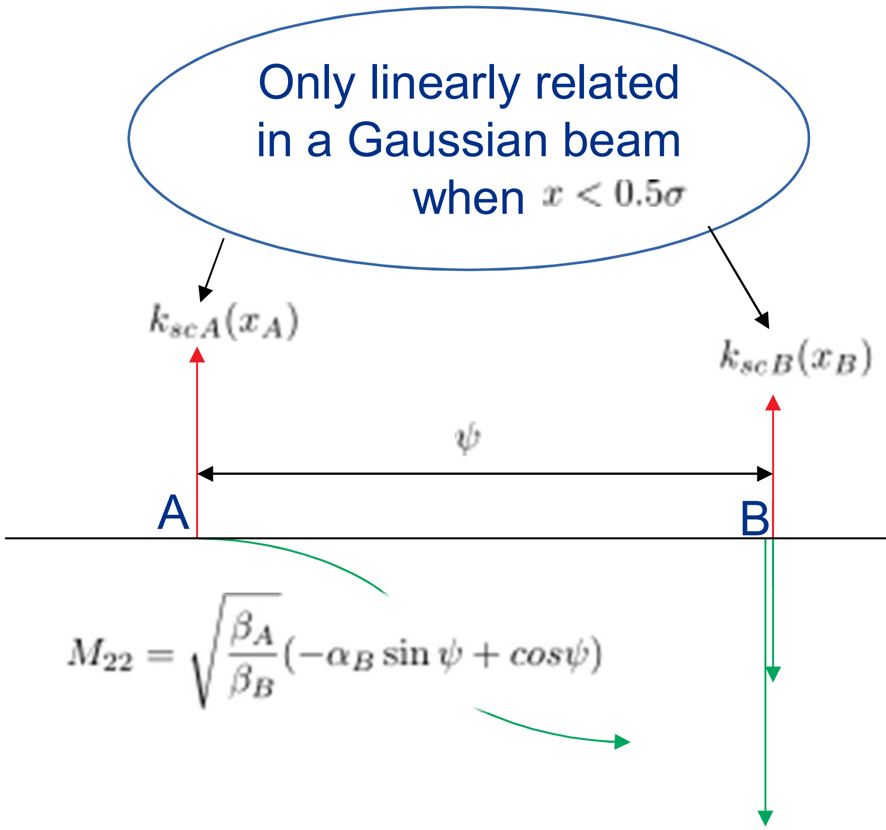


No compensation

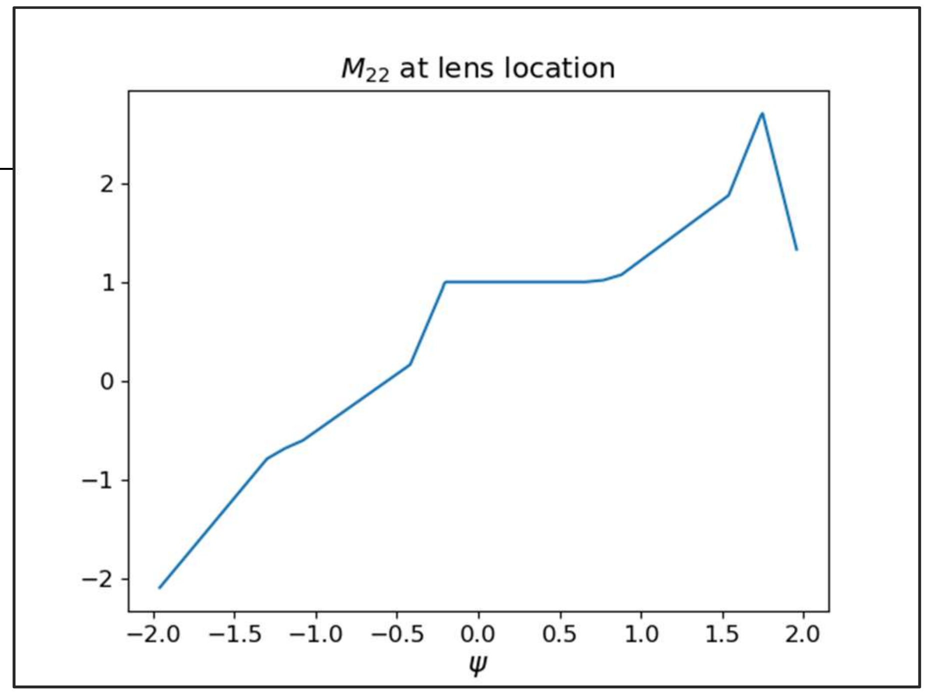


Optimal pulsed gaussian lens compensation

A word about lens separation



$$M_{22} = \sqrt{\frac{\beta_A}{\beta_B}}(-\alpha_B \sin\psi + cos\psi)$$



Future plans

- Different beam distributions may be more amenable to compensation
  - Longitudinally flat
  - Transversely uniform
- Lens might work better in a region where α is small
- More realistic lattice including dipoles, dispersion, chromaticity
- Interplay between impedance and space charge

Summary

- We trust Synergia's space charge simulation at high space charge because of it's successful simulation of Landau damping.
- 16M particles tracked for statistical noise reduction in calculations of emittance growth and losses.
- Extremely high tune spread simulated.
- Lattice errors are a major contributor to space charge generated beam effects.
- Placement of a sufficient number of electron lenses can substantially ameliorate space charge effects.

Backup

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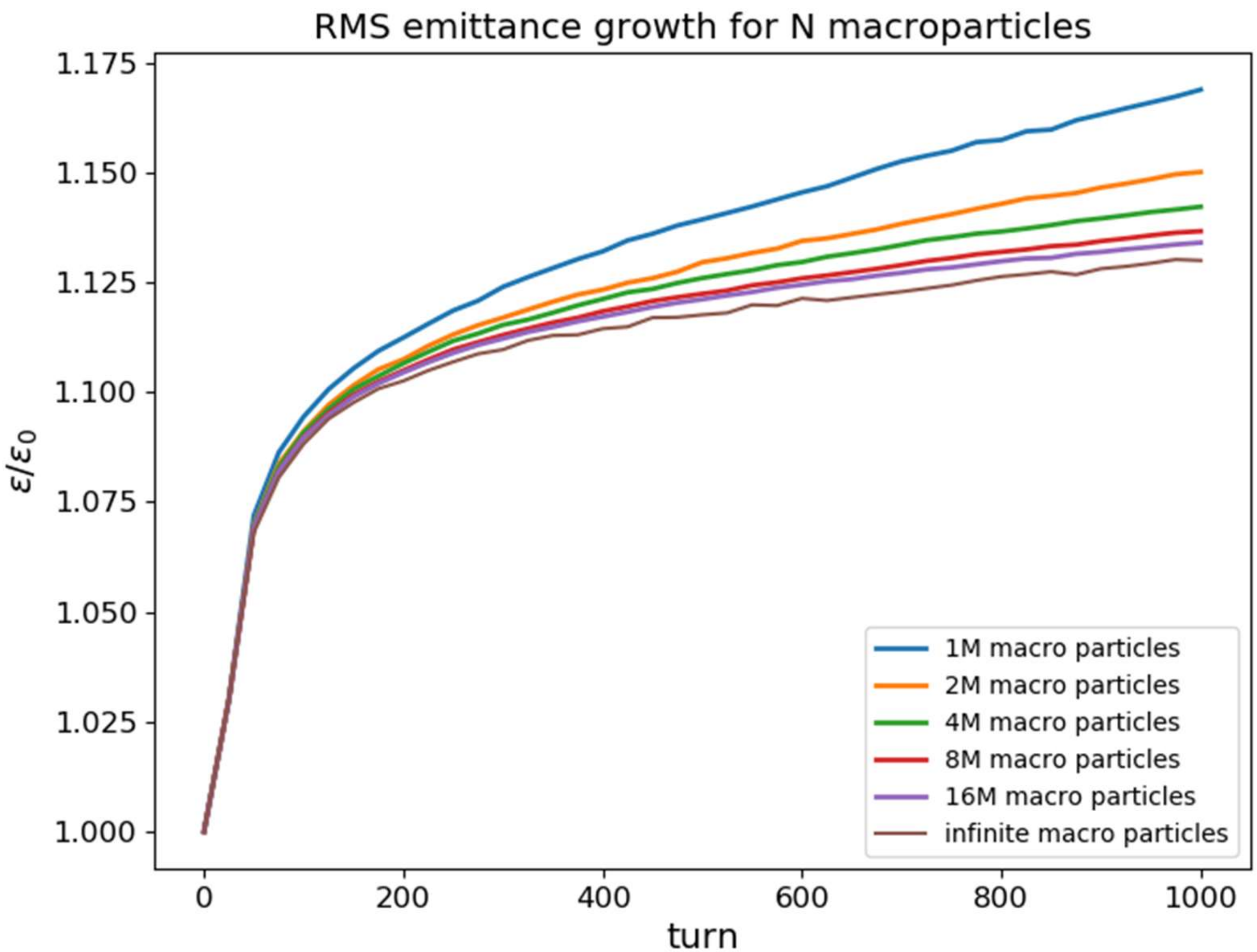
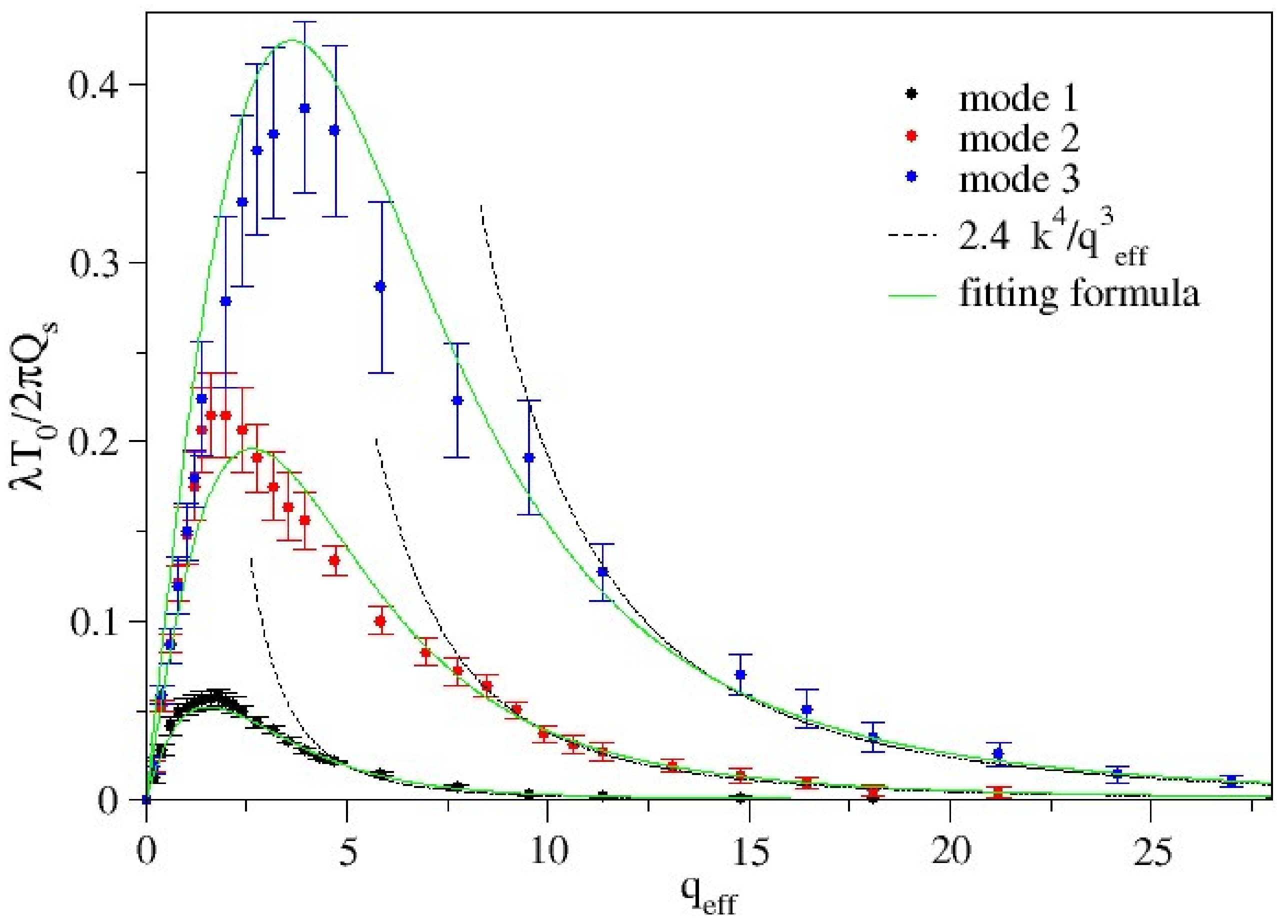
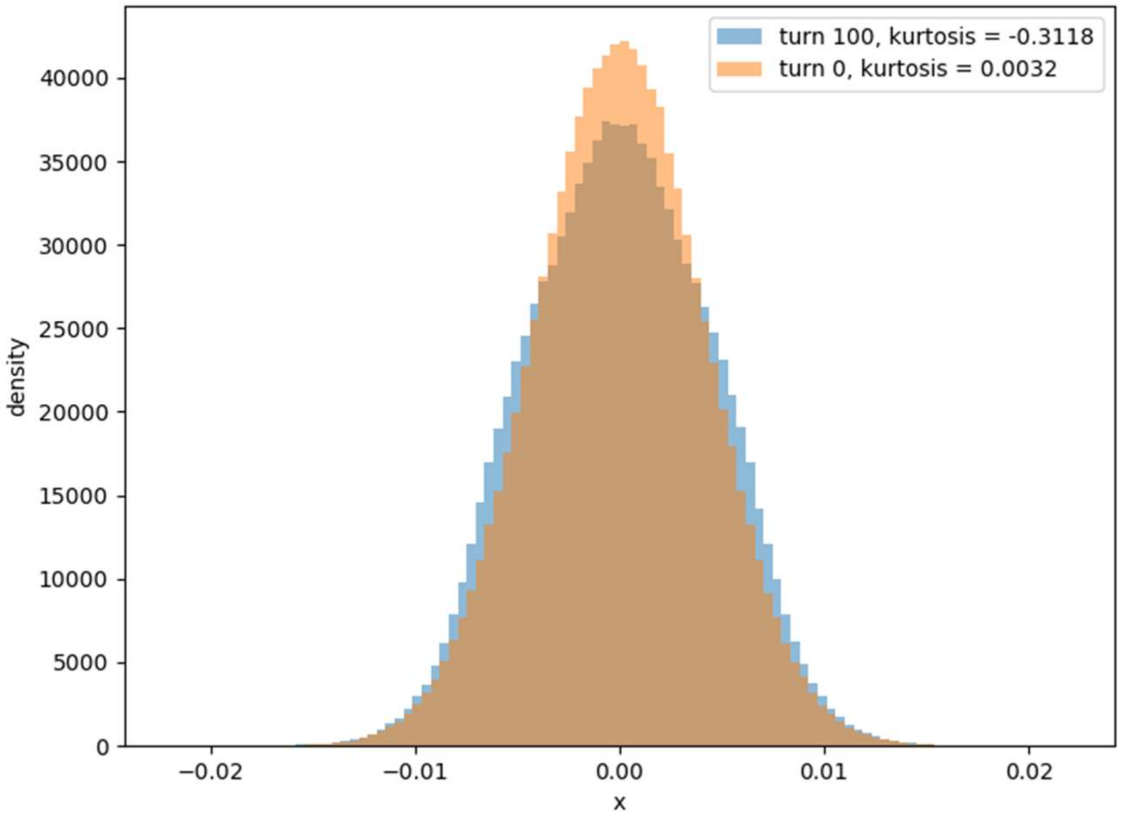
Sensitivity to the number of macro-particles



Landau damping



What's going on with initial emittance growth?



Synergia overview

Self-consistent 6D Particle-in-cell accelerator simulation code

- Specifically designed to simulate combined beam optics and collective effects (space charge and impedance).
- All the usual magnetic elements, RF cavities. Includes detailed septa and apertures for extraction and loss studies
- Now includes electron lens element as a thin lens with longitudinal modulation.
- Collective operations included with beam transport symplectically using the split-operator method.
- PIC space charge solvers available: 2.5D, 3D open boundary, rectangular conducting wall. Semi-analytic: 2D Bassetti-Erskine and linear KV solver.
- Space charge validated with GSI space charge benchmark
- Detailed impedance using a wake functions calculated for particular geometry/composition.
- Multiple bunch beams to investigate coherent bunch modes.
- One or two co-propagating bunch trains.

Synergia overview (cont)

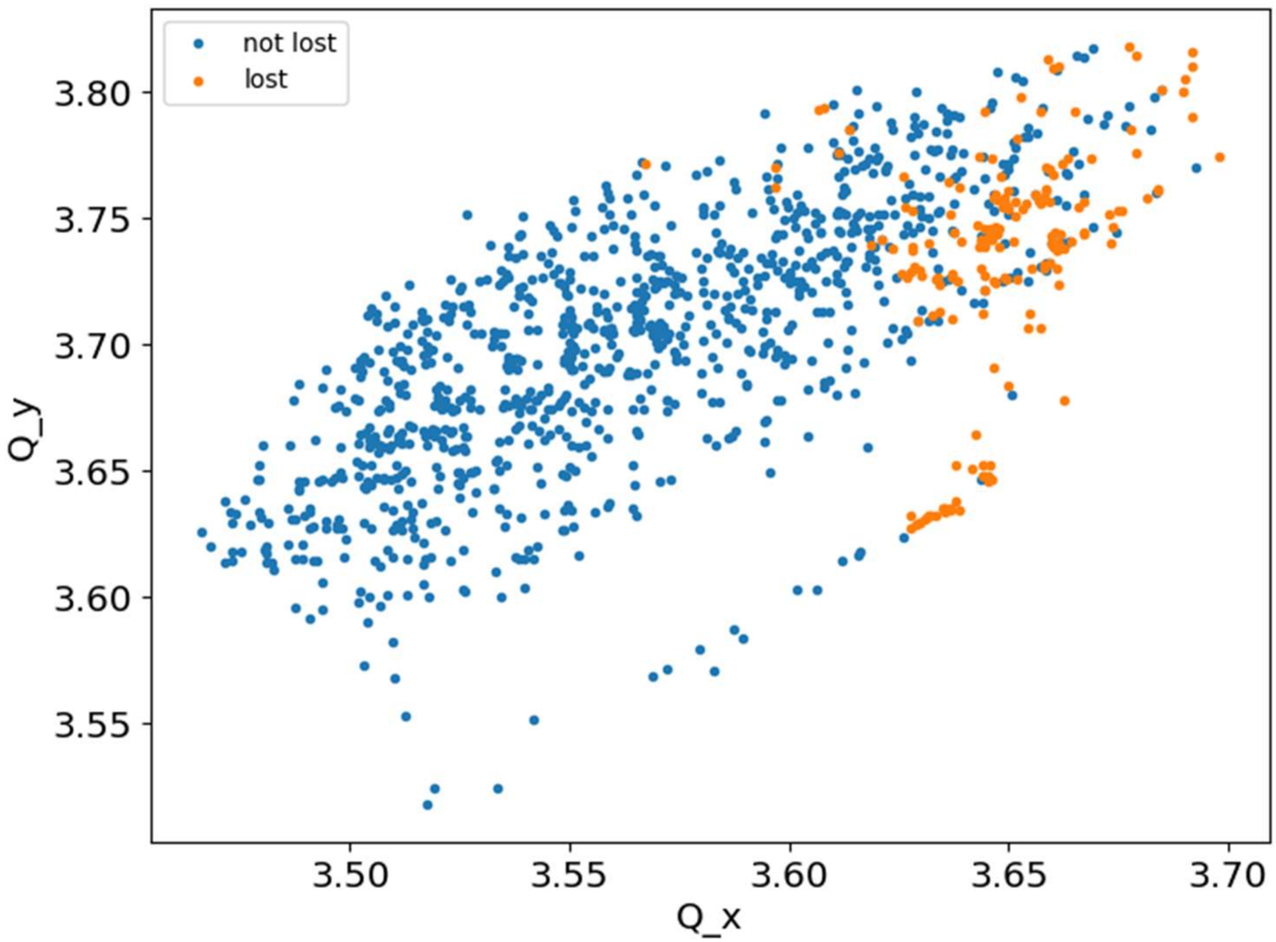
Synergia is actively being used to simulate all the Fermilab machines:

- Fermilab Recycler: Effect of slip-stacking and space charge on losses and evaluation of new operational conditions for optimized running with PIP-II (higher intensity and rep-rate).
- Fermilab Recycler bunch recapture in 2.5 MHz cavities.
- Fermilab Main Injector evaluation of better transition crossing schemes at high rep rates and longitudinal phase space area.
- IOTA propagation with the nonlinear element and understanding effects impacting integrability.
- Landau damping: Alexandru Macridin, *et al*, Parametric Landau Damping of Space Charge Modes, Phys. Rev. Accel. Beams <u>21</u>, 011004
- RCS replacement for the Booster with integrable optics.

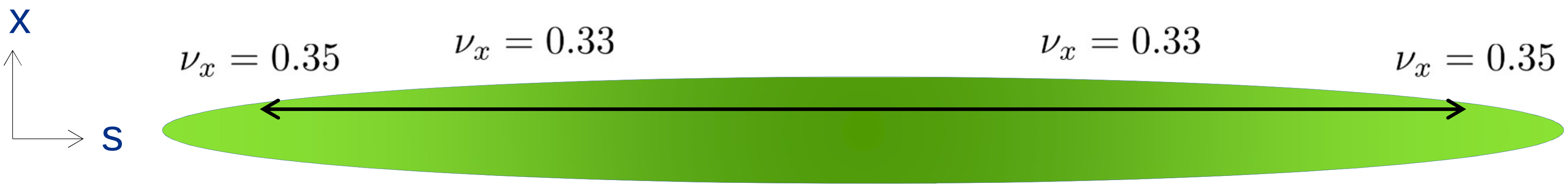
We specialize in multi-bunch, multi-beam, RF manipulation studies.

Note from Monday: includes longitudinal dynamics

Lost particle tunes



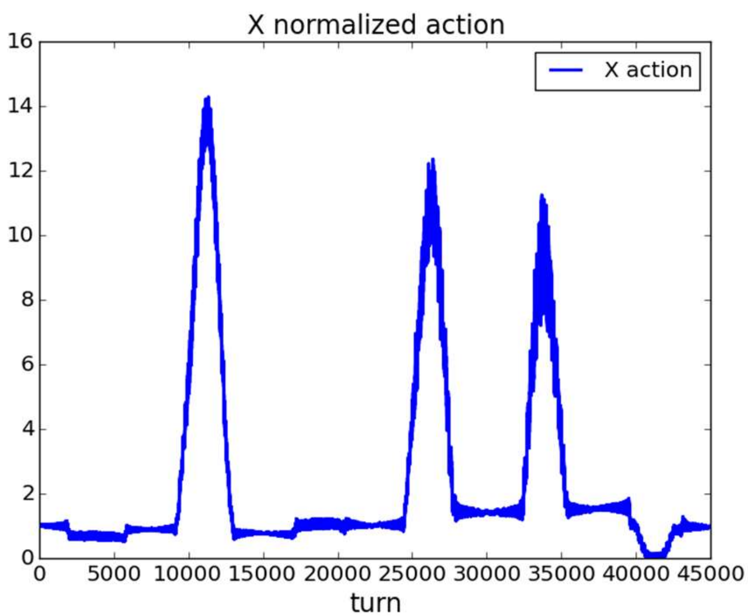
GSI Benchmarking: trapping



Off-axis particle moves through region where space charge tune shift traps it

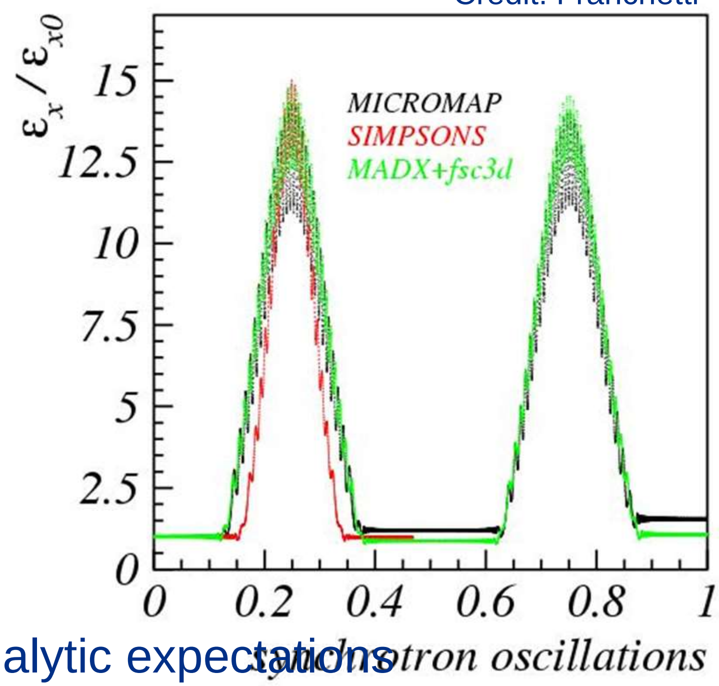
One synchrotron period is 15000 turns

Synergia



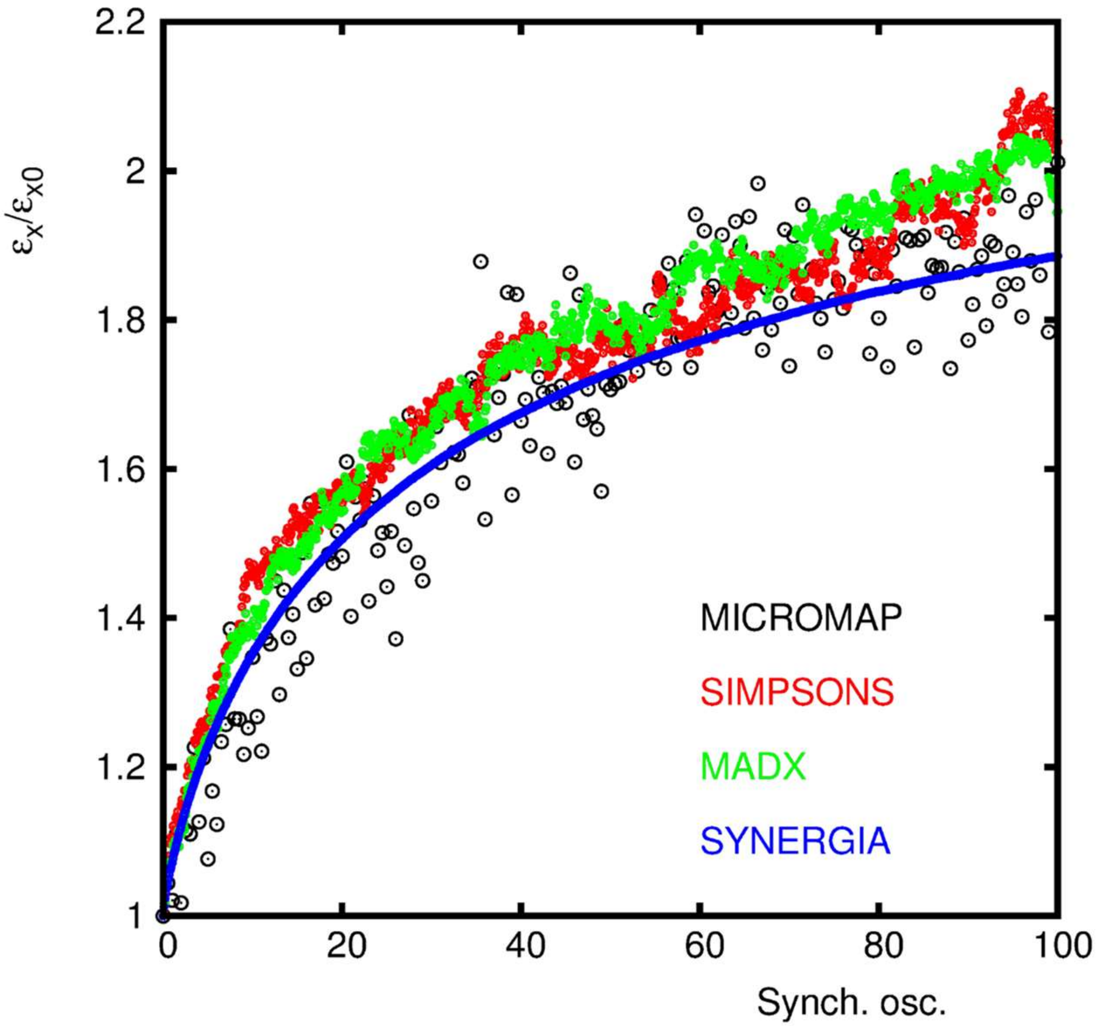
others

Credit: Franchetti



Emittance growth matches other codes and analytic expectations

GSI Benchmarking: emittance growth



The trapping benchmark shows tha

Credit: Schmidt

Fermilab

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Collaborations / Partnerships / Members 28pt Bold
Logos shown are examples

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