Numerical Simulations of Space Charge Compensation with Electron Lenses

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IOTA/Fast Collaboration Meeting

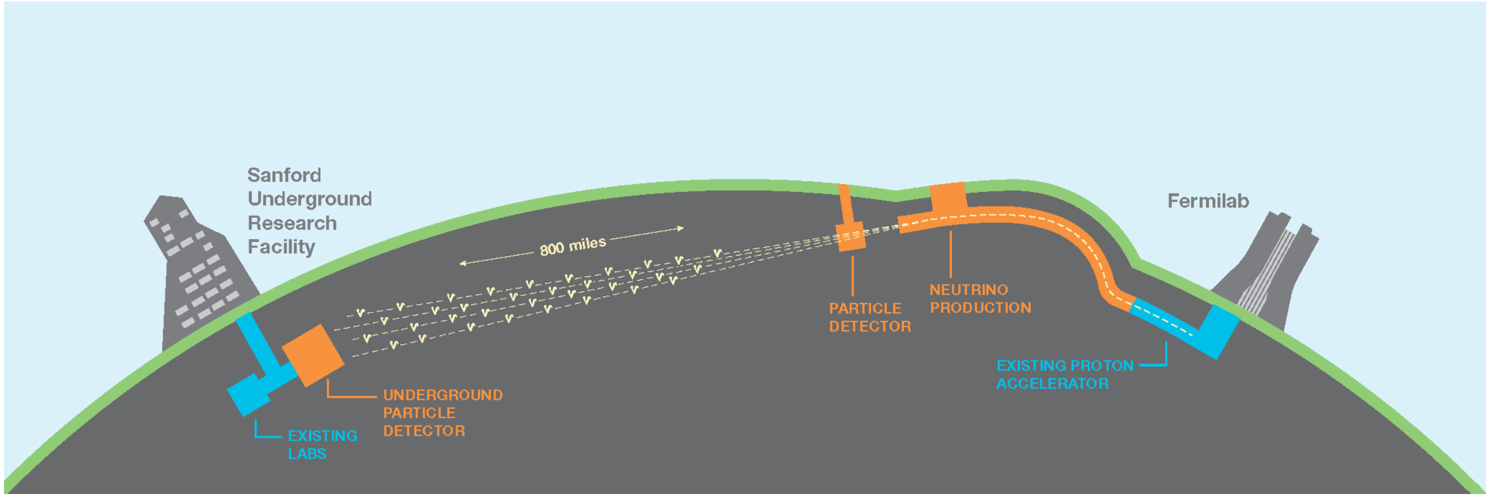
09 May 2018

What am I talking about

- Why do we need to increase intensity?
- What are the problems that result from higher intensity?
- What are electron lenses and why would we use them?
- About Synergia
- Toy model simulations
- Outlook

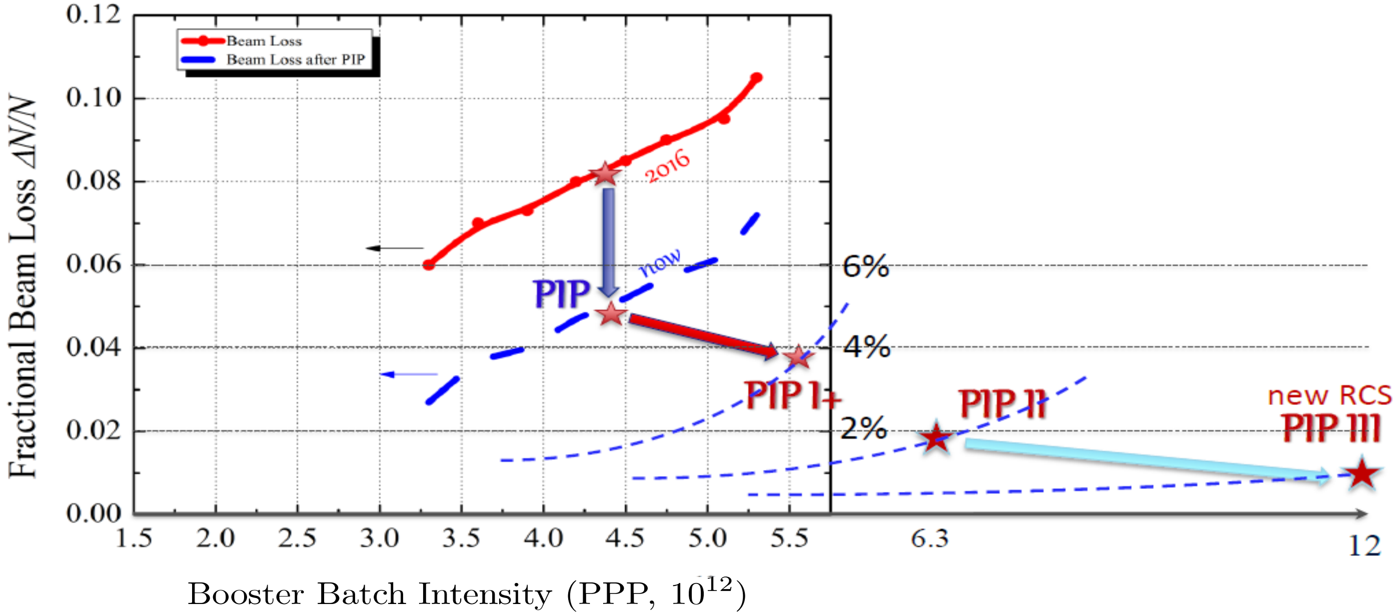
Beam power must increase

In order to get a decent neutrino event rate at the DUNE experiment, beam power on target must go up. This will be through a combination of increasing rep rate and protons/pulse through the injector chain.



Problems with increased protons/pulse

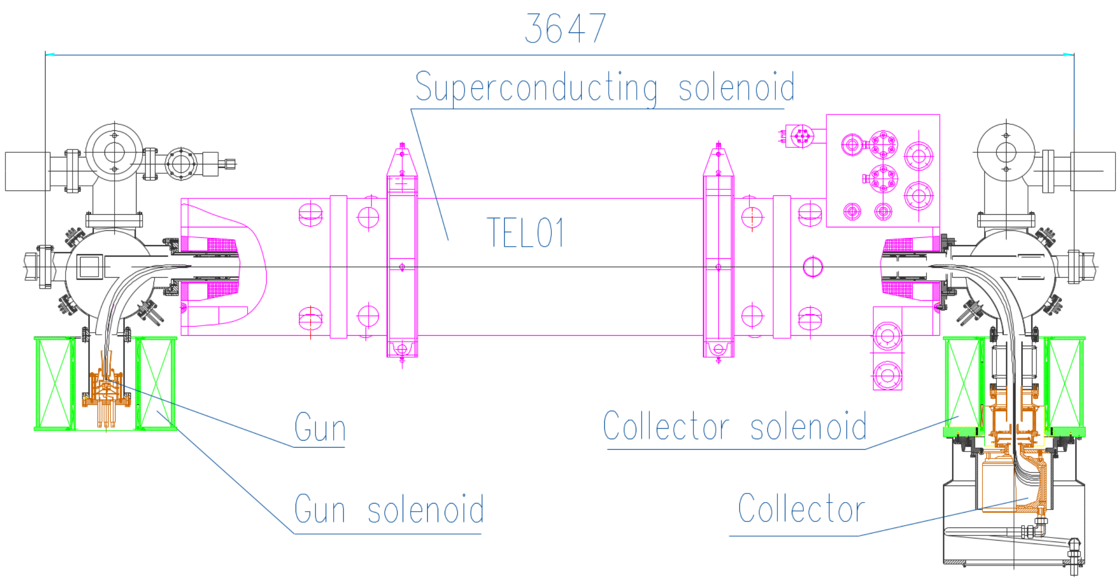
Losses need to be below 1 W/m, but they scale as the bunch charge. To boost power, we need to reduce losses.



Credit: Shiltsev, Pellico, et al.

For PIP-III, bunch charge will go up by factor of 3 while losses would need to be reduced by a factor of 5.

Electron lenses



- Electron lenses have been successfully used for many years
- Transverse profile can be selected
- Strength is able to be controlled in time
- Technology and costs well understood

Fermilab

What does electron lens do

For round Gaussian beam bunches and electron distribution:

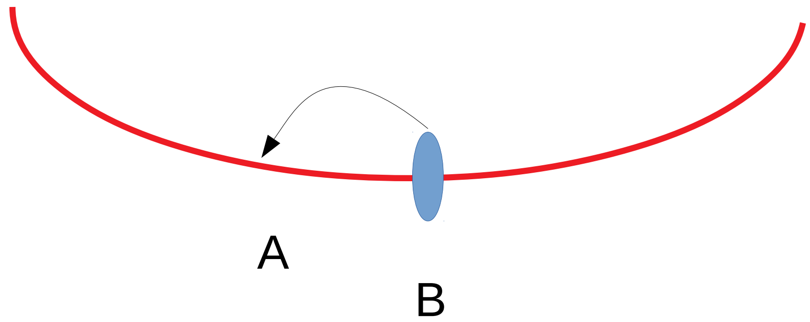
$$\frac{\Delta p_{\mathrm{sc}}}{p} = \frac{2 I_p L_{\mathsf{arc}} r_p}{e \beta_p^3 \gamma_p^3 c} \left(1 - e^{-\frac{r^2}{2\sigma^2}}\right) \frac{1}{r}$$

$$\frac{\Delta p_{\mathrm{el}}}{p} = -\frac{2 I_e L_{\mathsf{el}} r_p (1 \pm \beta_e \beta_p)}{e \beta_e \beta_p \gamma_p c} \left(1 - e^{-\frac{r^2}{2\sigma^2}}\right) \frac{1}{r}$$

$$\begin{cases} + & e \text{ opposite proton} \\ - & e \text{ with proton} \end{cases}$$

I_p	proton beam current	I_e	electron lens current
L_{arc}	length of accelerator arc	L_{el}	length of electron lens
β_p	proton beam velocity	β_e	electron beam velocity
γ_p	proton beam Lorentz factor		
r_p	classical proton radius	σ	RMS radius

Plan to study SC and electron lens effects



- Particle-in-cell simulations to investigate electron lens
- Simplified 12-fold superperiodic model to begin with
- Space charge tune shift approaching unity
- Add effects one-by-one
- Vary number of electron lenses
- Evaluate based primarily on emittance (RMS , 99.9%), secondarily on tune footprint

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. Magnetic elements all agree with MAD-X.
- 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)

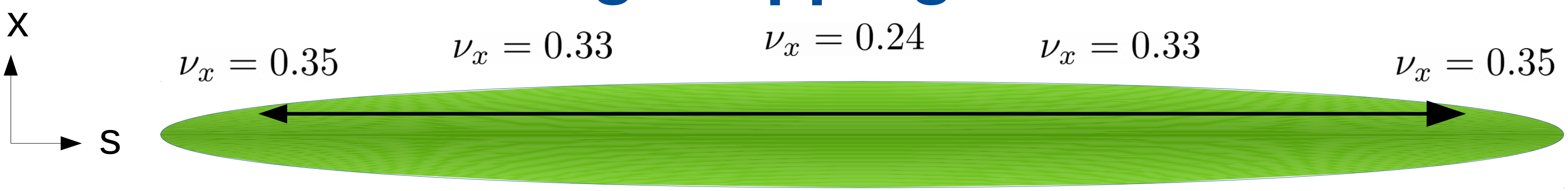
Synergia is actively being used to simulate all the Fermilab machines:

- 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 21, 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

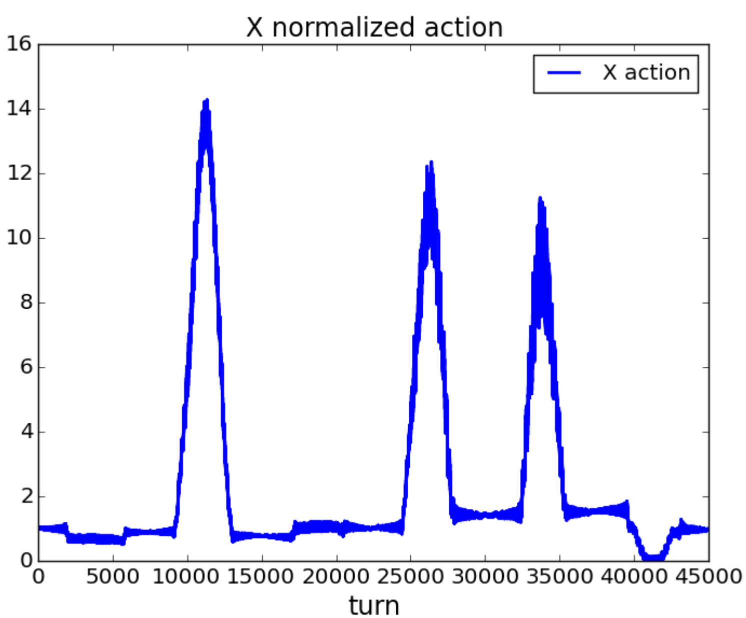
GSI Benchmarking: trapping



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

One synchrotron period is 15000 turns

Synergia



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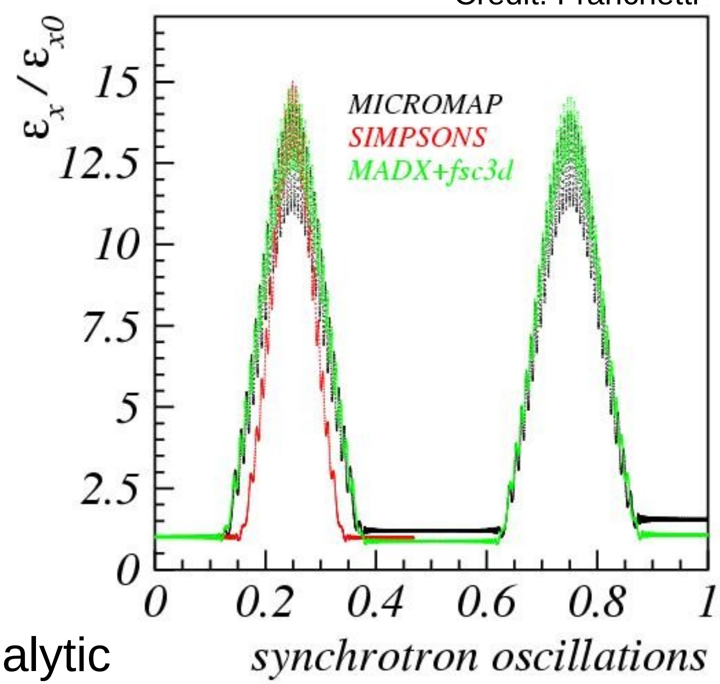
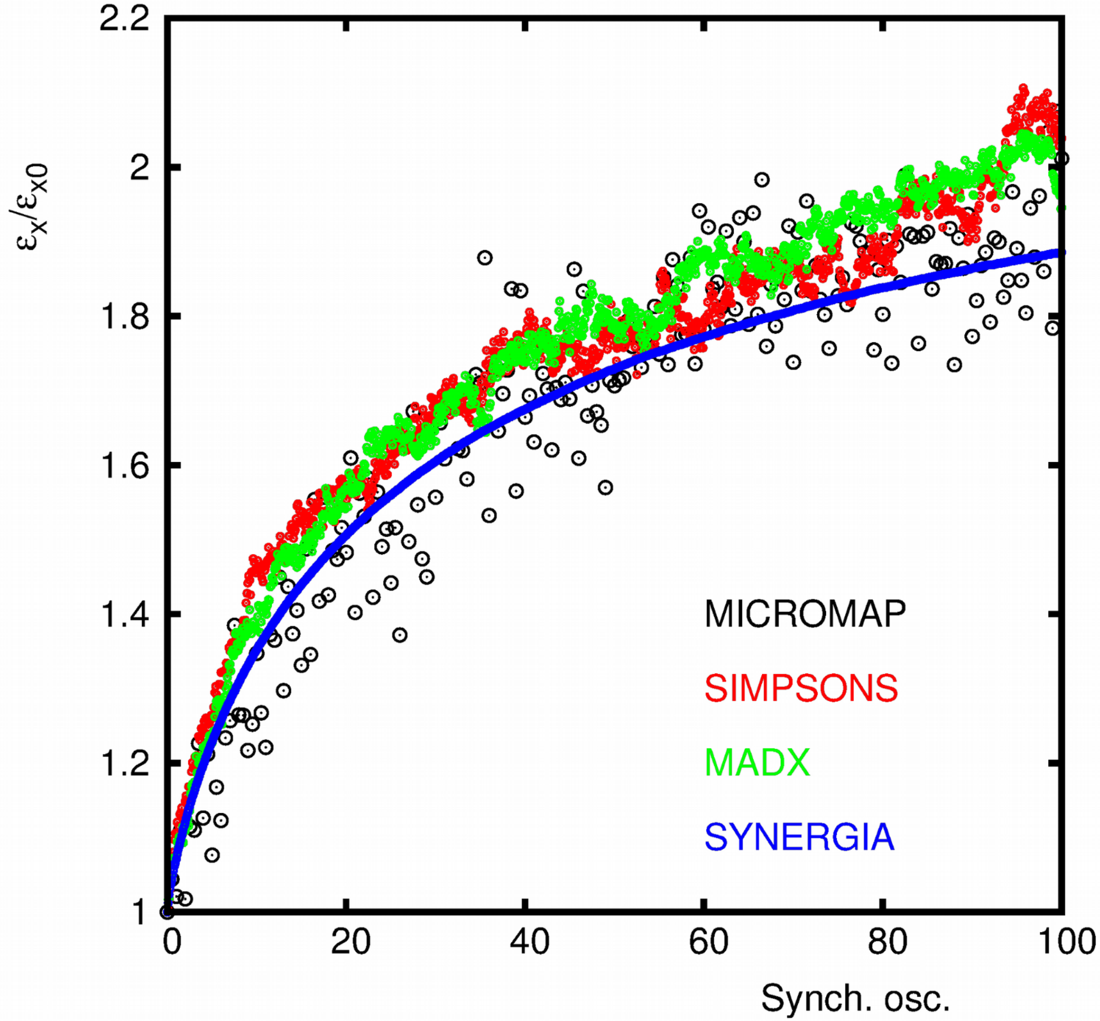
Credit: Franchetti



Emittance growth matches other codes and analytic expectations

GSI Benchmarking: emittance growth



The trapping benchmark shows that Synergia correctly integrates transverse and longitudinal dynamics with space charge. The PIC based amittance growth simulation is smooth, does not become unstable over the long term and falls well within the range of other calculations. The synchrotron period is 1000 turns.

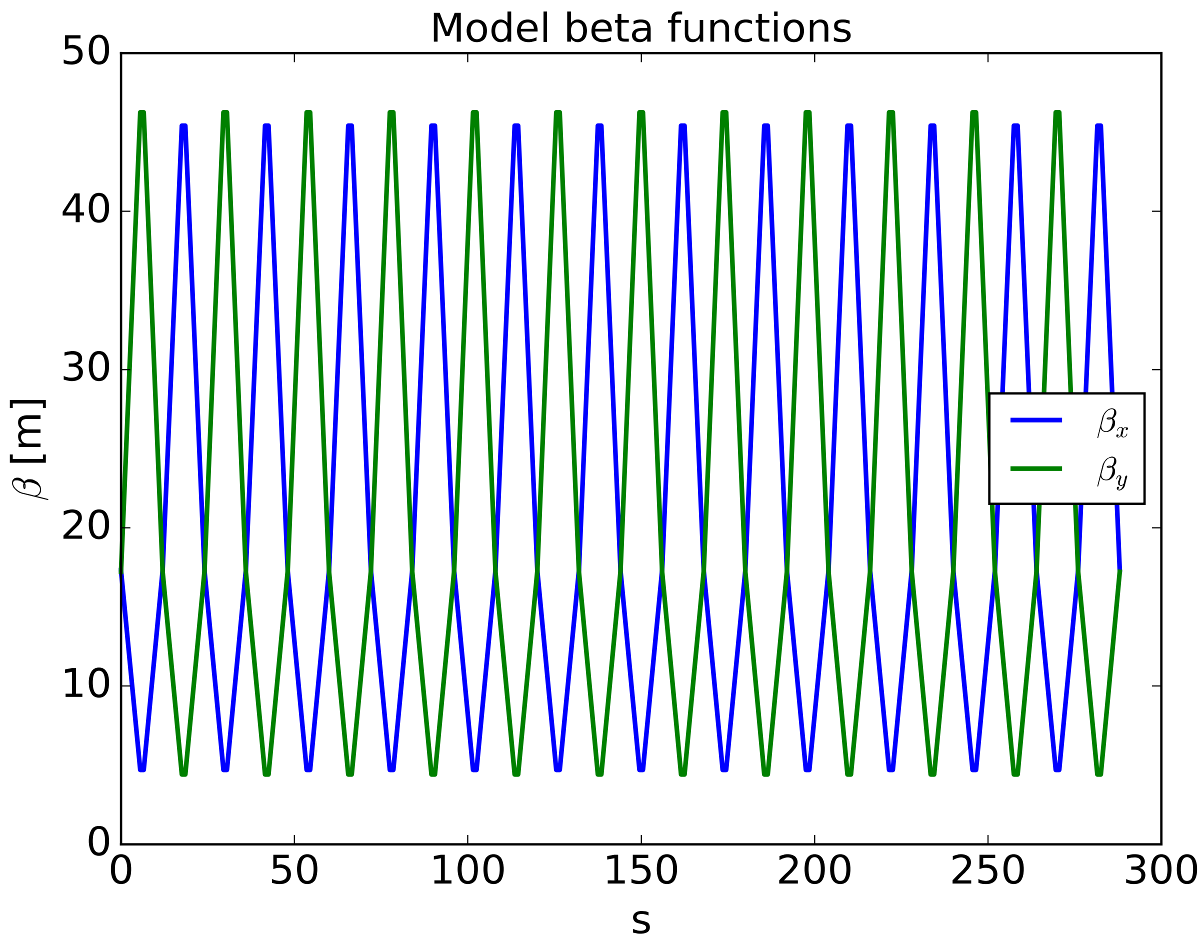
Credit: Schmidt

Two toy lattice models

- Simulate toy FODO lattice with no bends
- 12 periodic uncoupled FODO cells / 1% quadrupole error
- 24 electron lenses placed where beta functions are equal

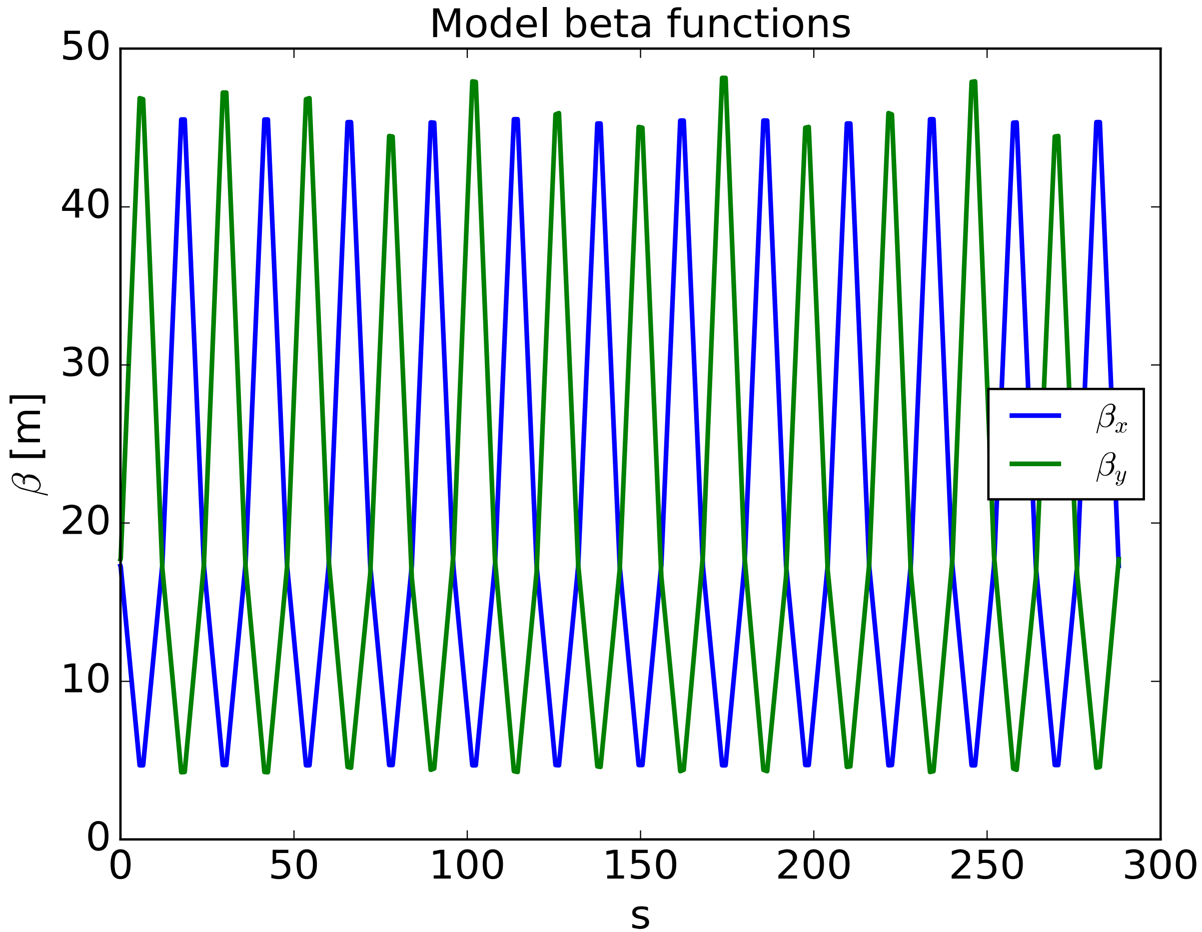
Parameter	**Value**	**unit**
length	288.0	m
beam kinetic energy	0.8	GeV
RF frequency	43.814	MHz
slip factor	-0.291186	
x, y chromaticity	-5.68, -5.97	
total RF voltage	6.287	MV
bunch charge	2×10^{11}	e
RMS bunch length	0.5	m
RMS bunch $\Delta p/p$ spread	0.00288	
x, y emittance	1.0005	mm-mrad
β_x, β_y at lens	17.28, 17.27	m
x, y tunes	3.72, 3.84	
synchrotron tune	1/13	

Lattice functions for the perfect toy model



Lattice functions for the 1% quad error toy model

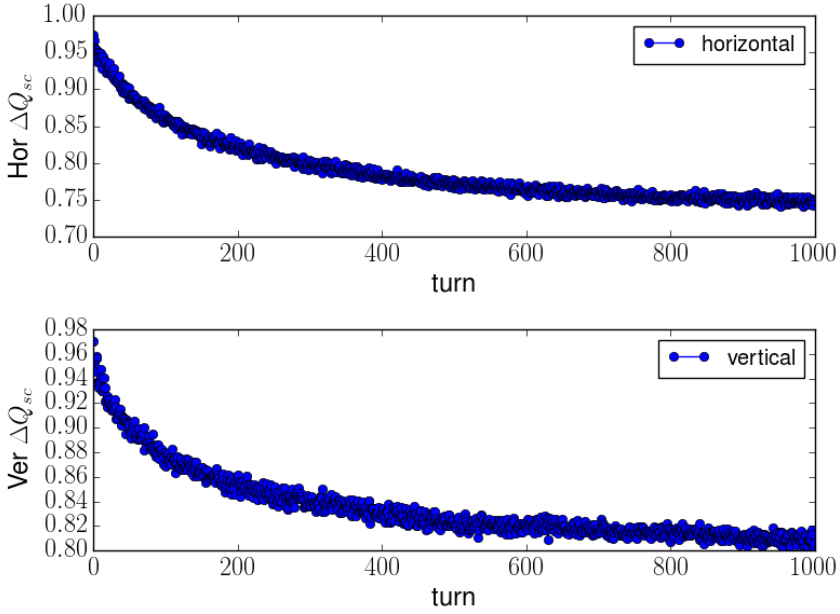
1% strength error in 1 defocussing quad
Tune circuits adjusted proportionally to restore tune



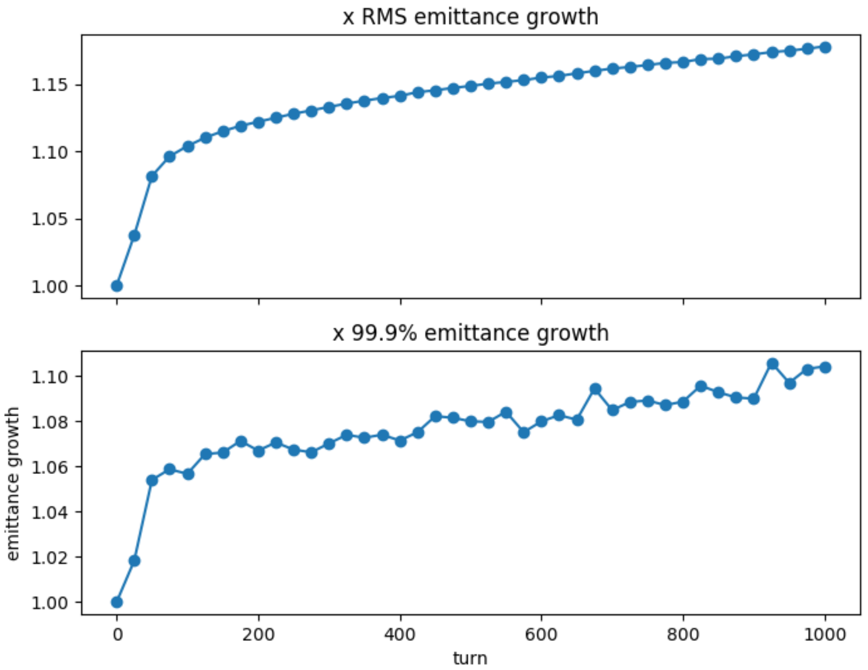
Perfect lattice run (no electron lens)

1000 turns   1M macro-particles   72 space charge kicks/turn

$$\frac{1}{4\pi}\oint K_{\rm sc}(s)\beta_x(s)ds$$



Tune shifts from electric field derivatives

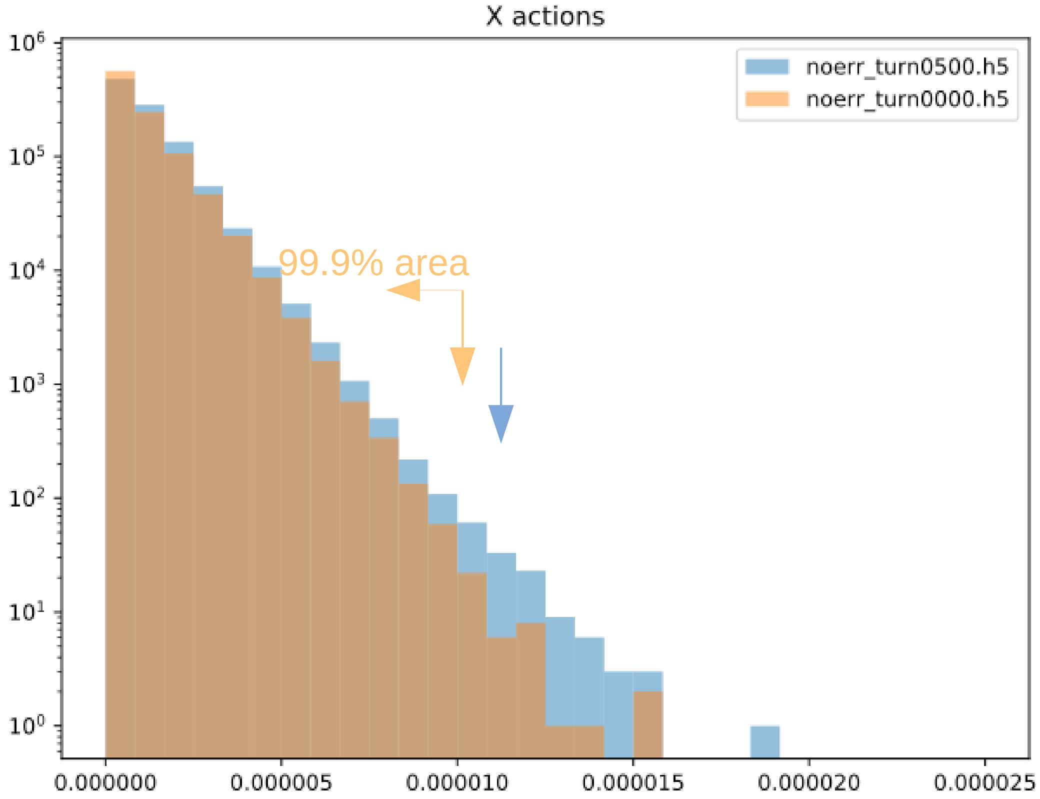


Emittance growths

RMS growth: 17%, 99.9% growth: 10%

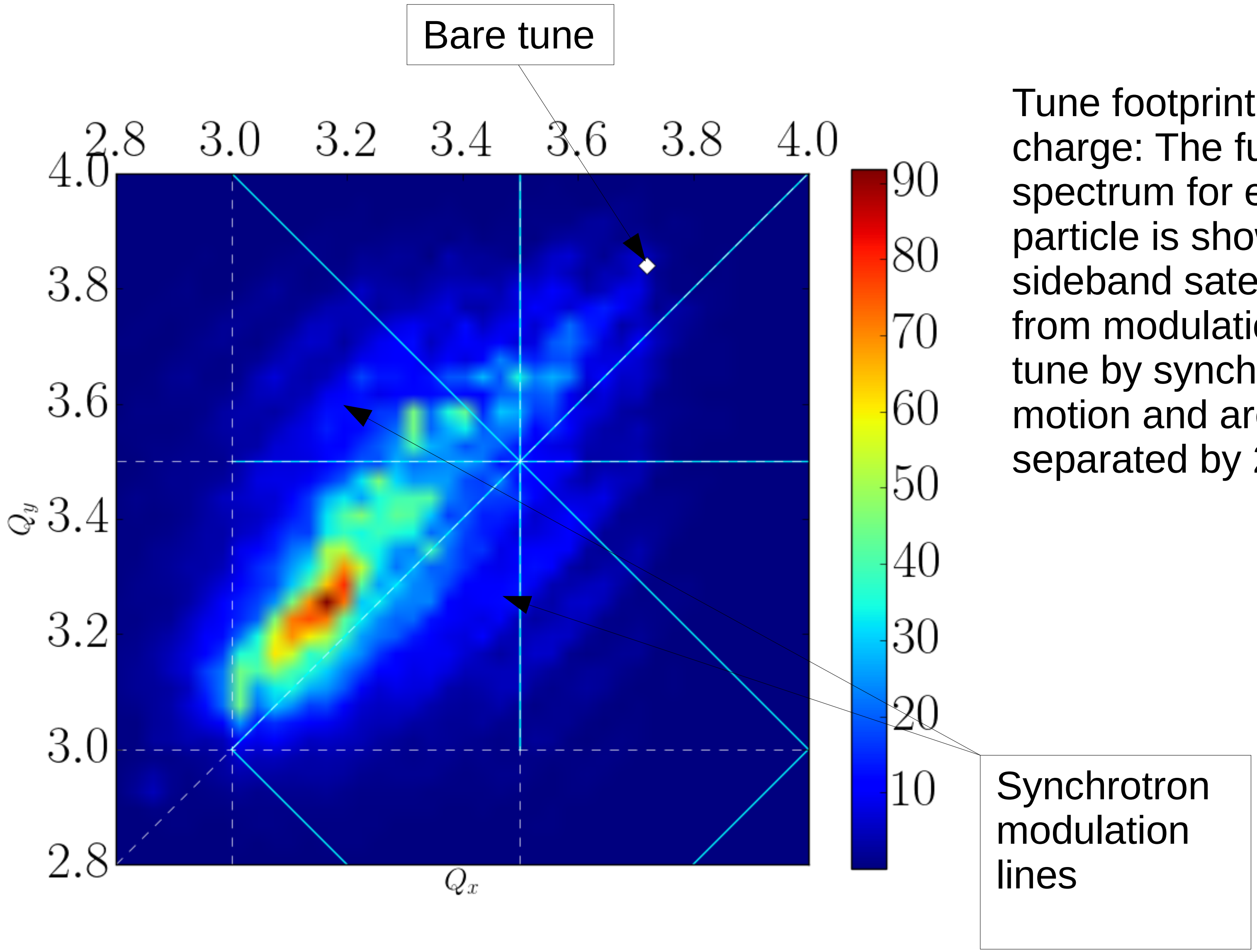
What is 99.9% emittance?

$$\text{particle action} = \frac{x^2 + (\alpha x + \beta x')^2}{2\beta}$$



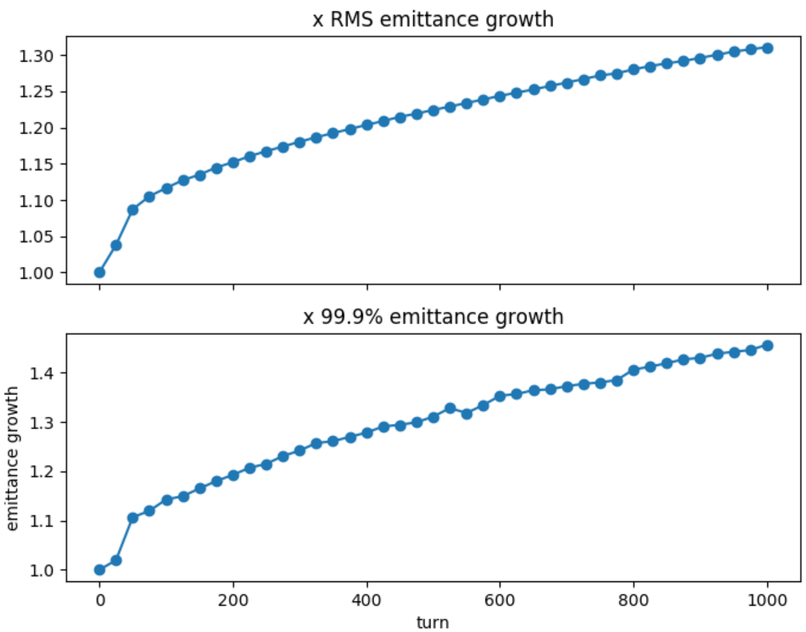
Histogram of particle actions

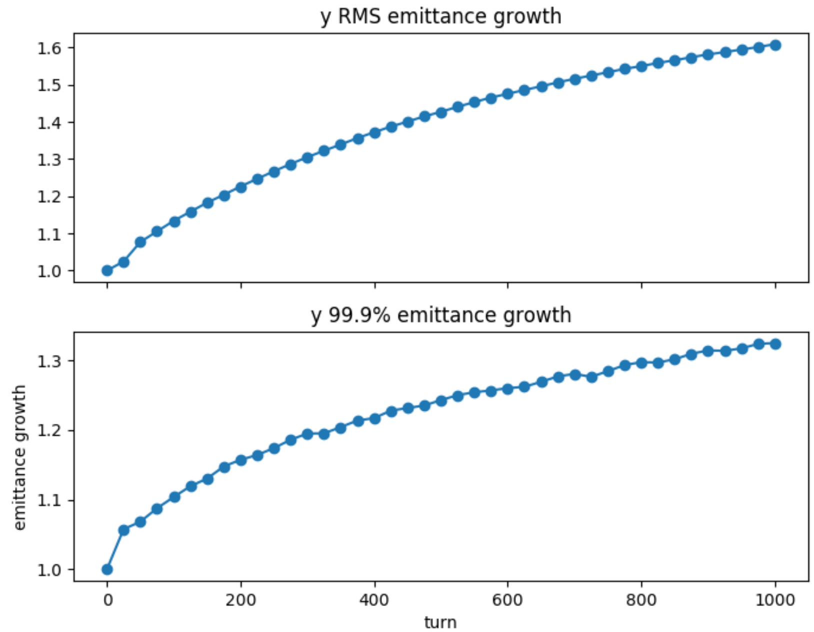
Perfect lattice tune footprint (no lens)



Tune footprint with space charge: The full spectrum for each particle is shown. The sideband satellites arise from modulation of the tune by synchrotron motion and are separated by 2Qs.

Lattice with 1% error in quad





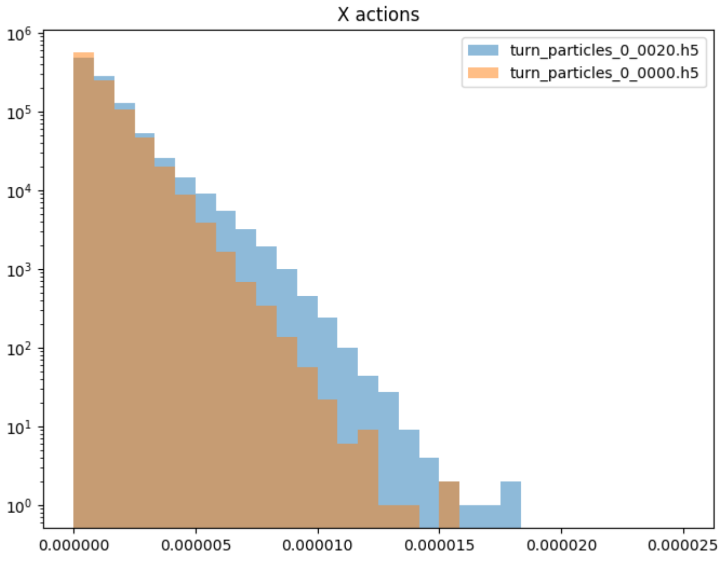
X Emittance growth

RMS growth: 30%
99.9% growth: 45%

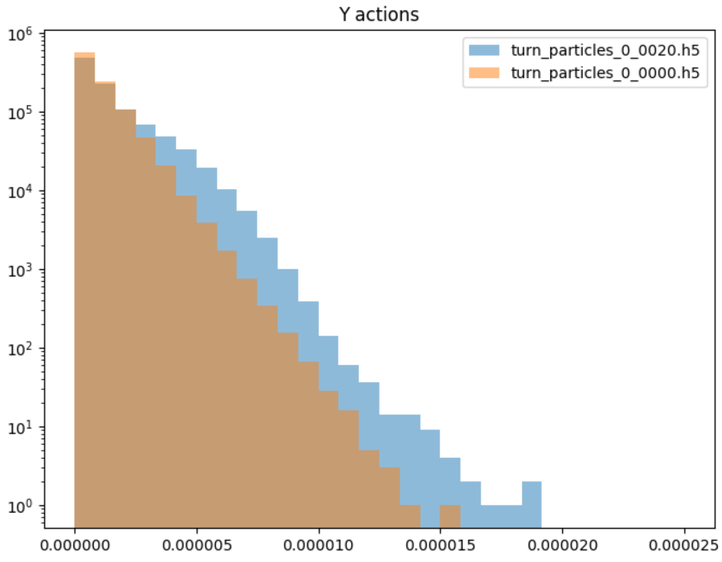
Y Emittance growth

RMS growth: 40%
99.9% growth: 30%

Emittance Distributions for error lattice



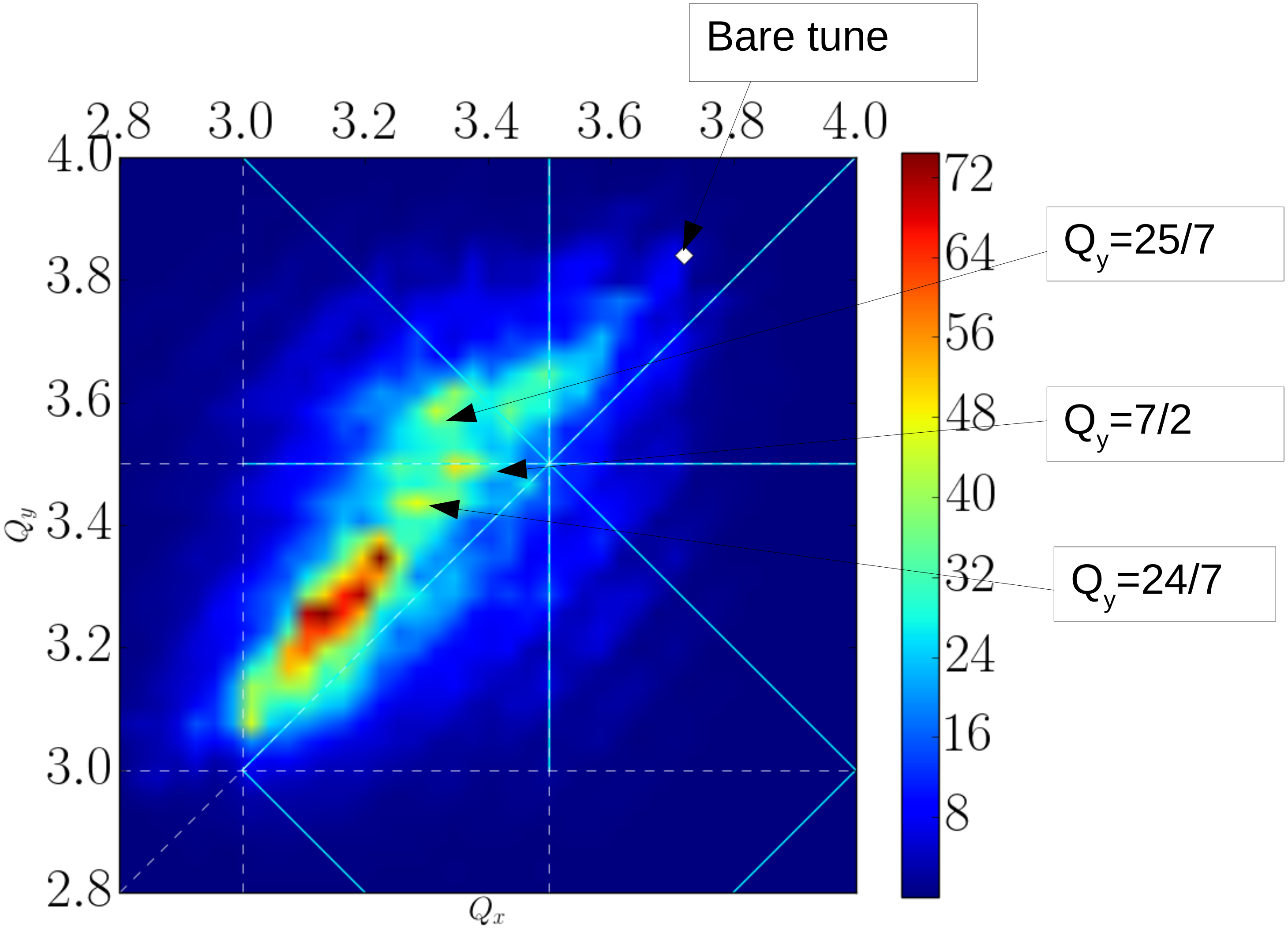
x actions



y actions

The significant emittance growth is due to particles increasing action throughout the entire action range.

Tune footprint for error lattice (no lens)



Outlook

- We have begun a program of systematic studies of space charge effects at record high intensities corresponding to a tune shift approaching unity using the Synergia particle-in-cell code for simulation.
- Starting with a ideal lattice, we will reveal the effects of lattice imperfections and optimal tunes using the RMS and 99.9% emittance growth as a proxy for particle loss.
- Electron lenses will be introduced. The effects of incomplete coverage of the ring as well as longitudinal and transverse profile mismatches will be studied.
- Lee-Teng summer intern doing these simulations this summer

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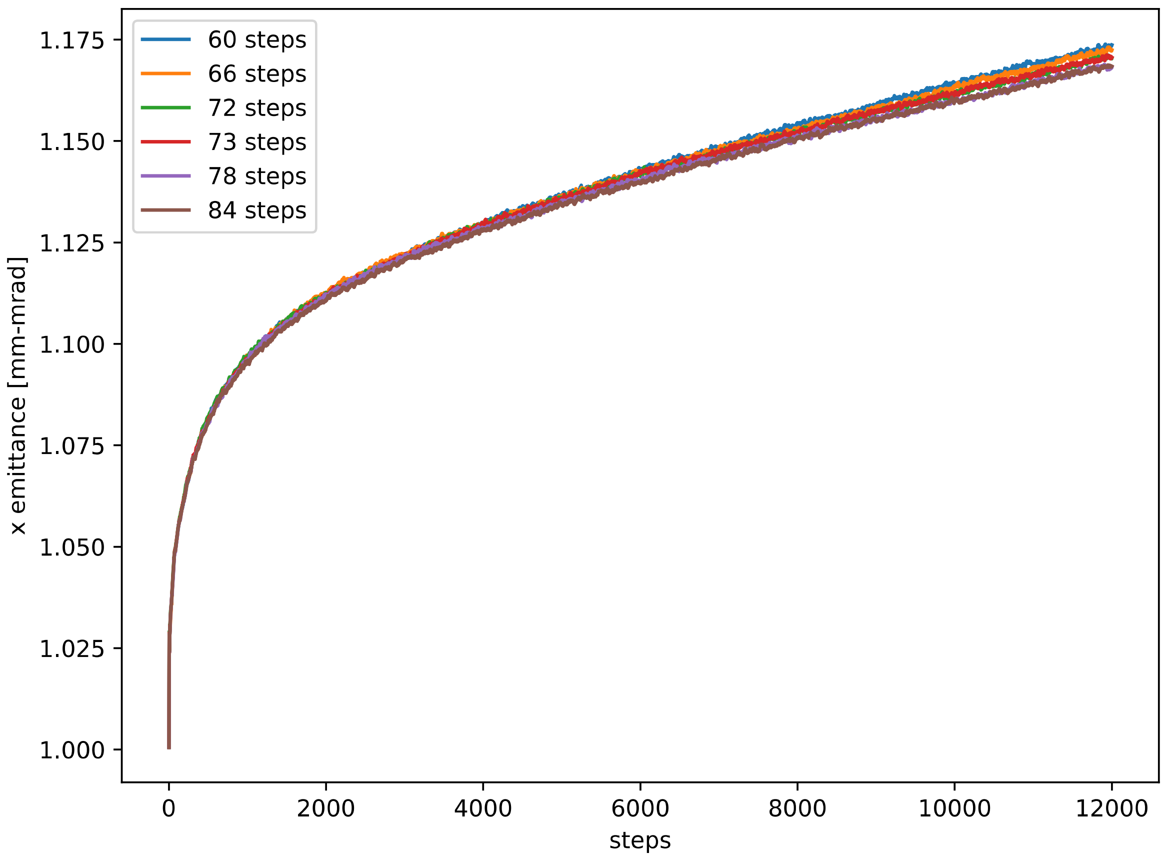
Emittance distribution with error element

Backup slides

Dependence on number of space charge steps



GSI Benchmarking Effort

Space Charge trapping benchmark in GSI SIS18

`http://web-docs.gsi.de/~giuliano/research_activity/trapping_benchmarking/main.html`

The aim of the code benchmarking is to confirm the space charge induced trapping of particles in a bunch during long term storage.

Began ~2003 to explain CERN PS experimental results:

Space charge and octupole driven resonance trapping observed at the CERN Proton Synchrotron, G. Franchetti and I. Hofmann, M. Giovannozzi, M. Martini, and E. Metral, PRST-AB **6**, 124201 (2003)

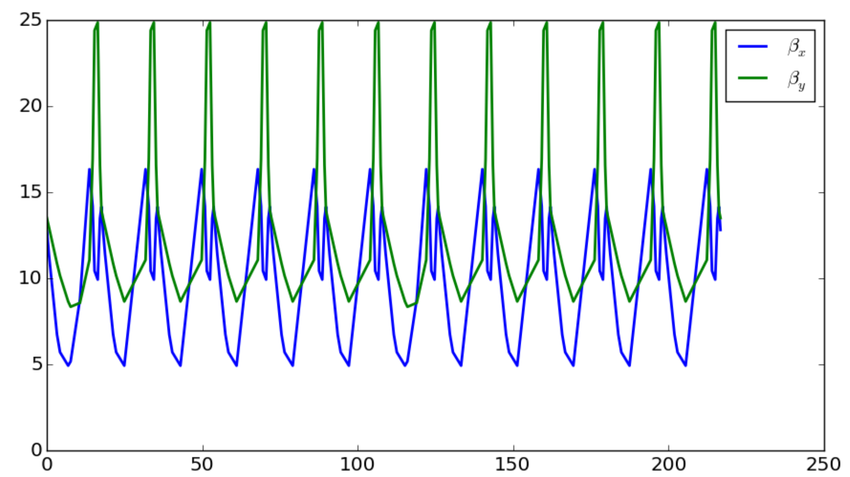
My goal is to demonstrate the beam dynamics and space charge simulation capabilities in Synergia.

- Space charge trapping is demonstrates interplay between beam optics and space charge
- Long term tracking demonstrates the stability of the calculation

Benchmark basics

Based on a simplified 12 cell SIS18 lattice

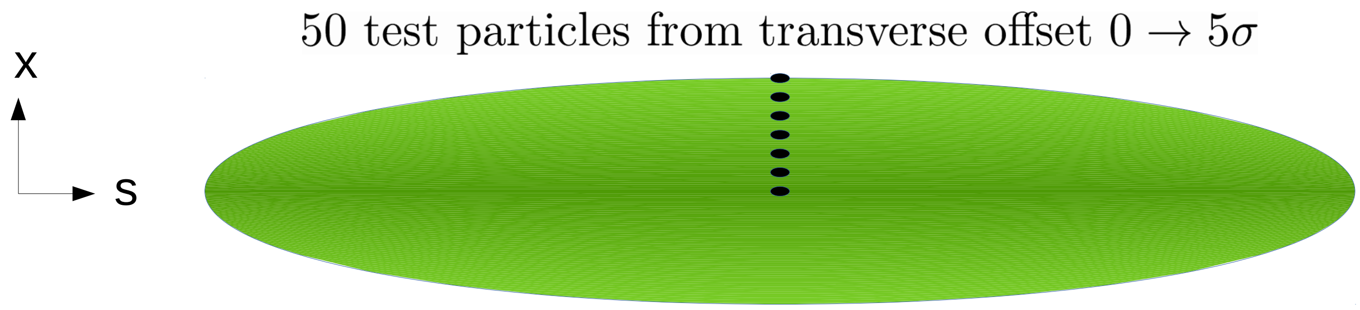
length	216.72 m
momentum	0.147 *GeV/c*
Beam σ_x	6.34 mm
Beam σ_y	5.60 mm
Beam σ_z	38.87 m
Q_x	4.338, 4.3504 or 4.3604
Q_y	3.200
Q_s	1/15000 or 1/1000
Δq_x (SC)	0.1



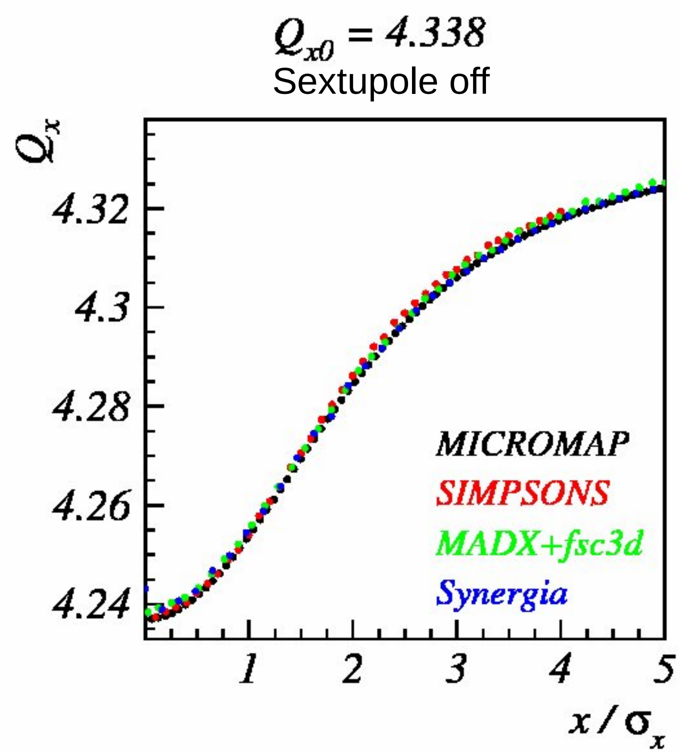
Sextupole may be energized to excite 3rd order resonance

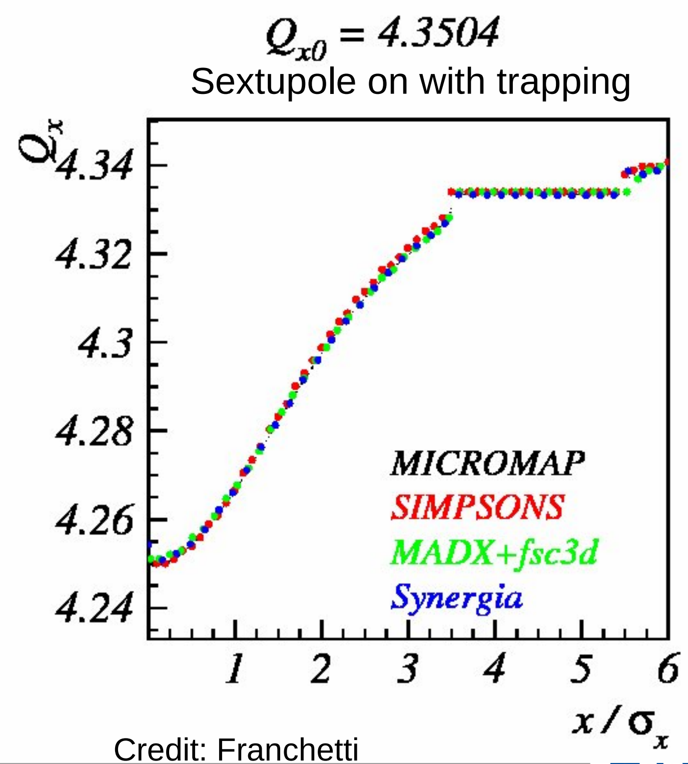
The long bunch is a good candidate for the 2.5D space charge solver

Steps 1-5 establishing dynamics



Propagate 1024 turns, calculate the tune of each test particle

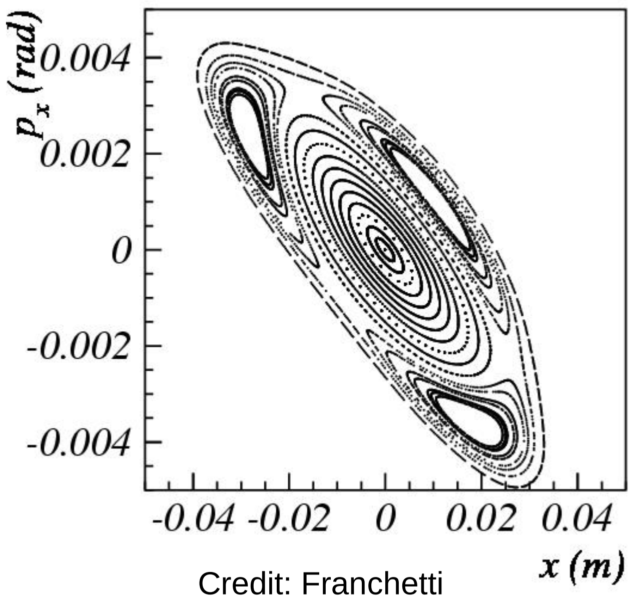




Credit: Franchetti

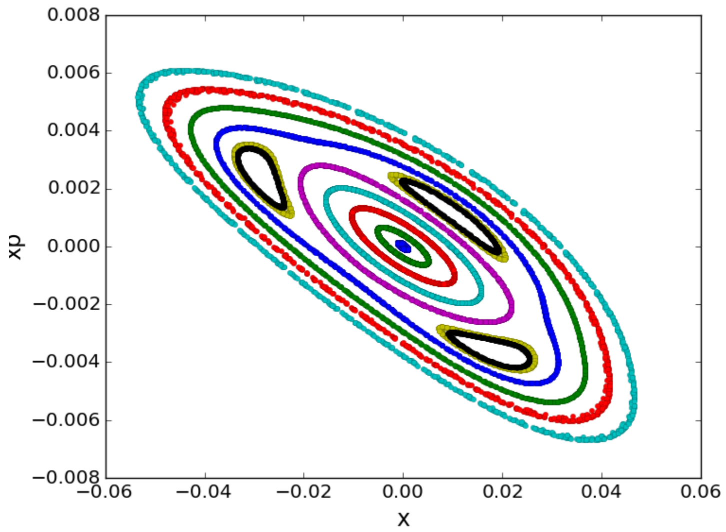
Phase Space of the Trapped Particles

Micromap



Credit: Franchetti

Synergia



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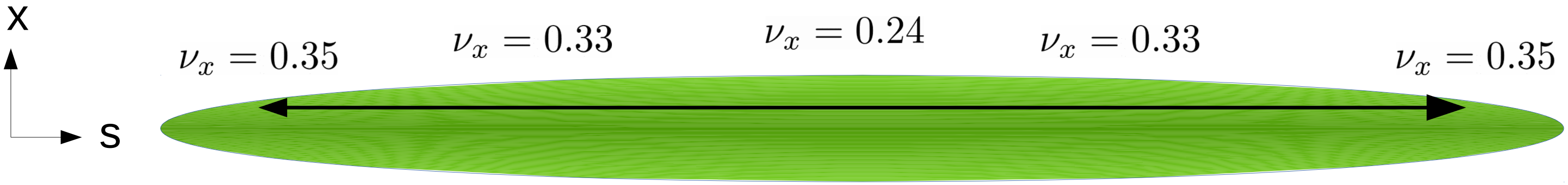
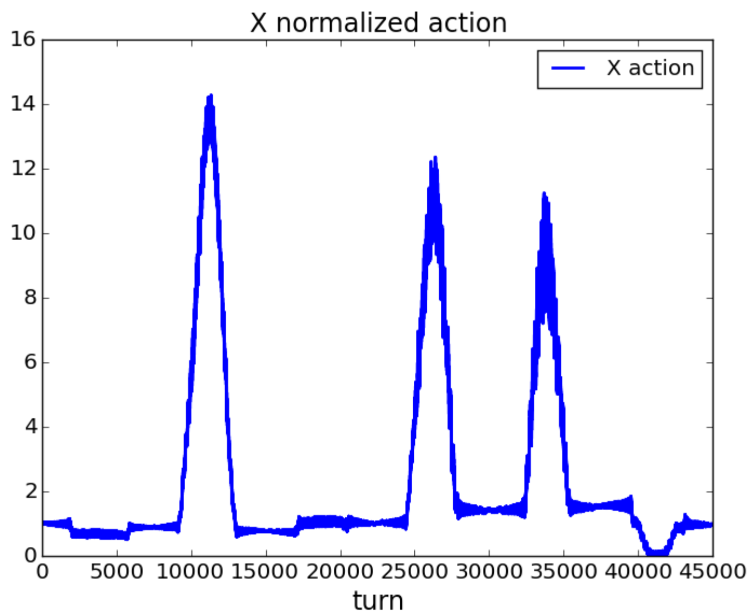
Step 6: long term tracking resonance trapping



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

One synchrotron period is 15000 turns

Synergia



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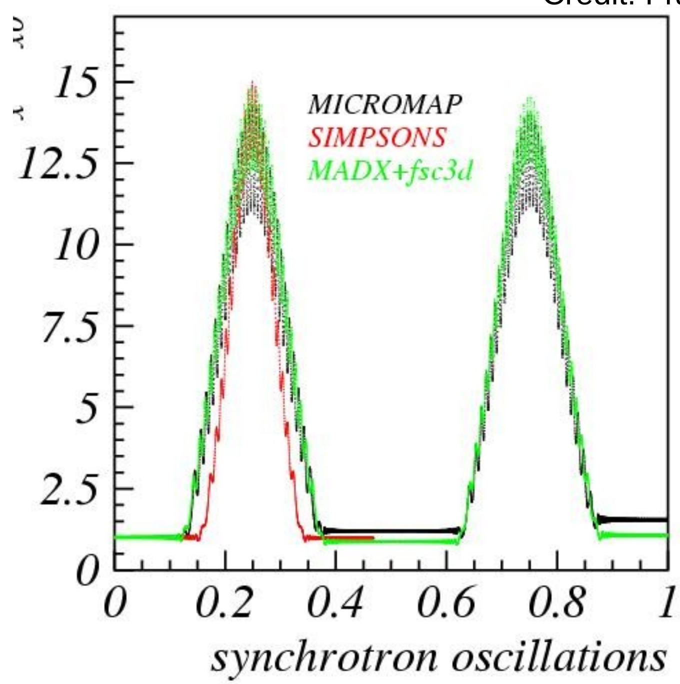
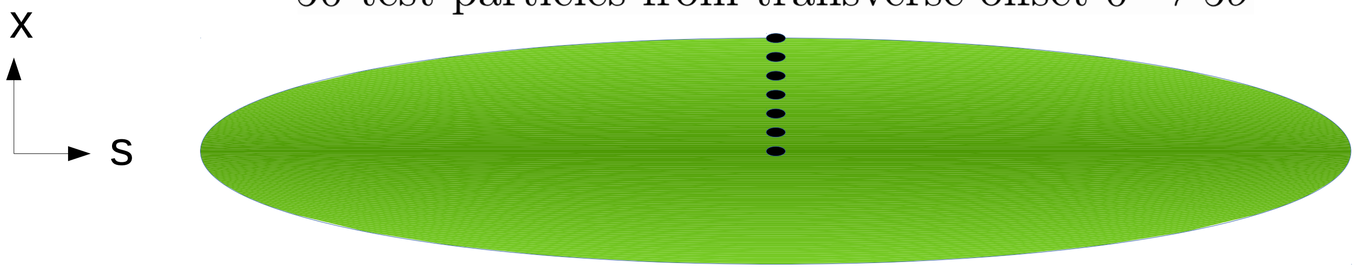
Credit: Franchetti



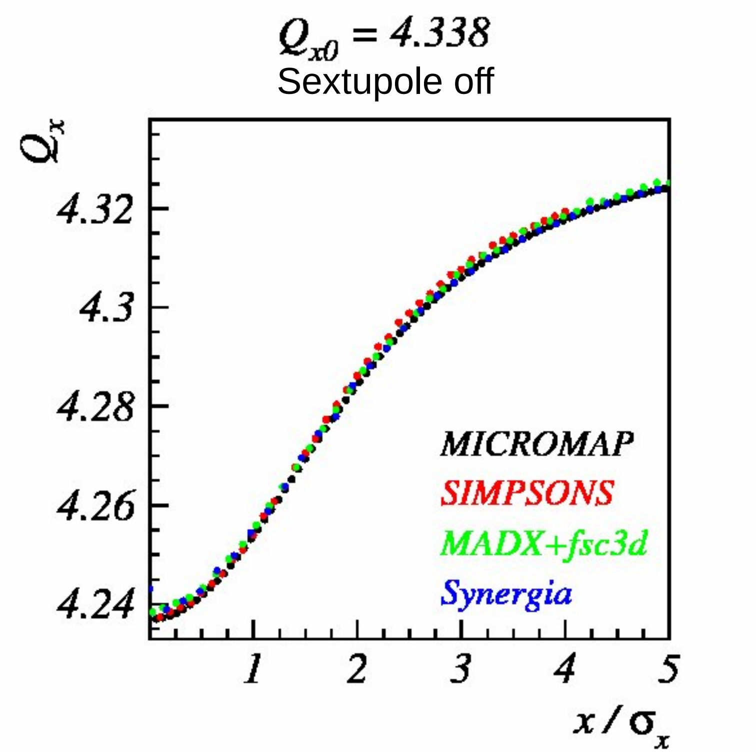
Emittance growth is the same in PIC code

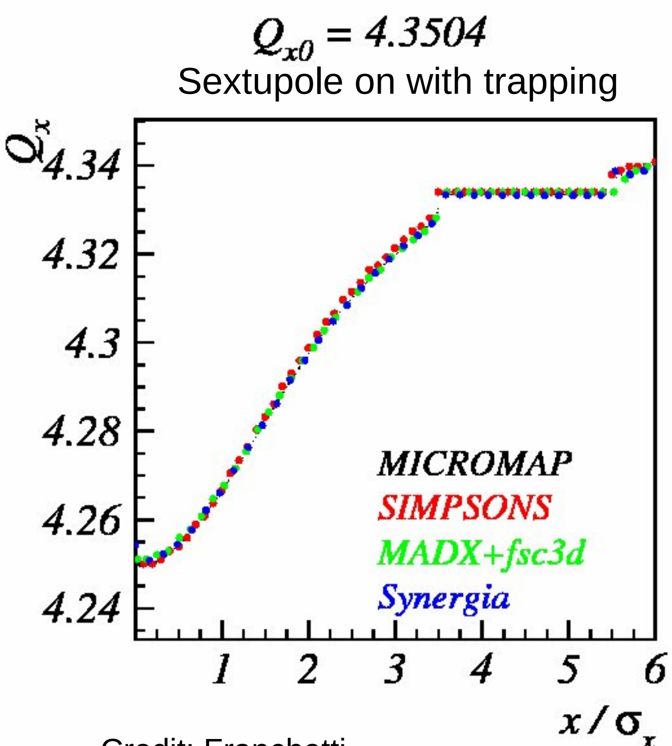
Steps 1-5 establishing dynamics

50 test particles from transverse offset $0 \rightarrow 5\sigma$



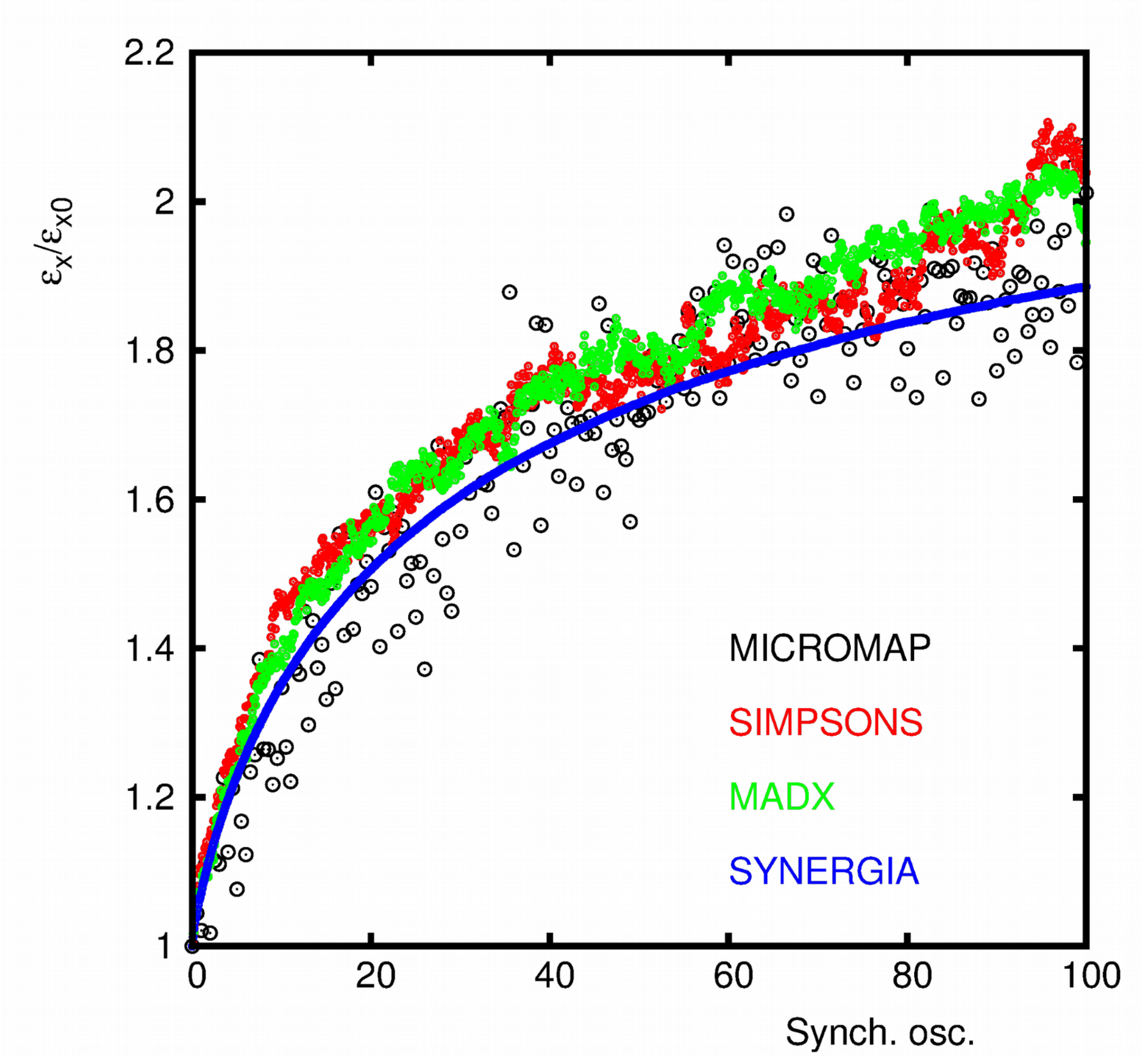
Propagate 1024 turns, calculate the tune of each test particle





Credit: Franchetti

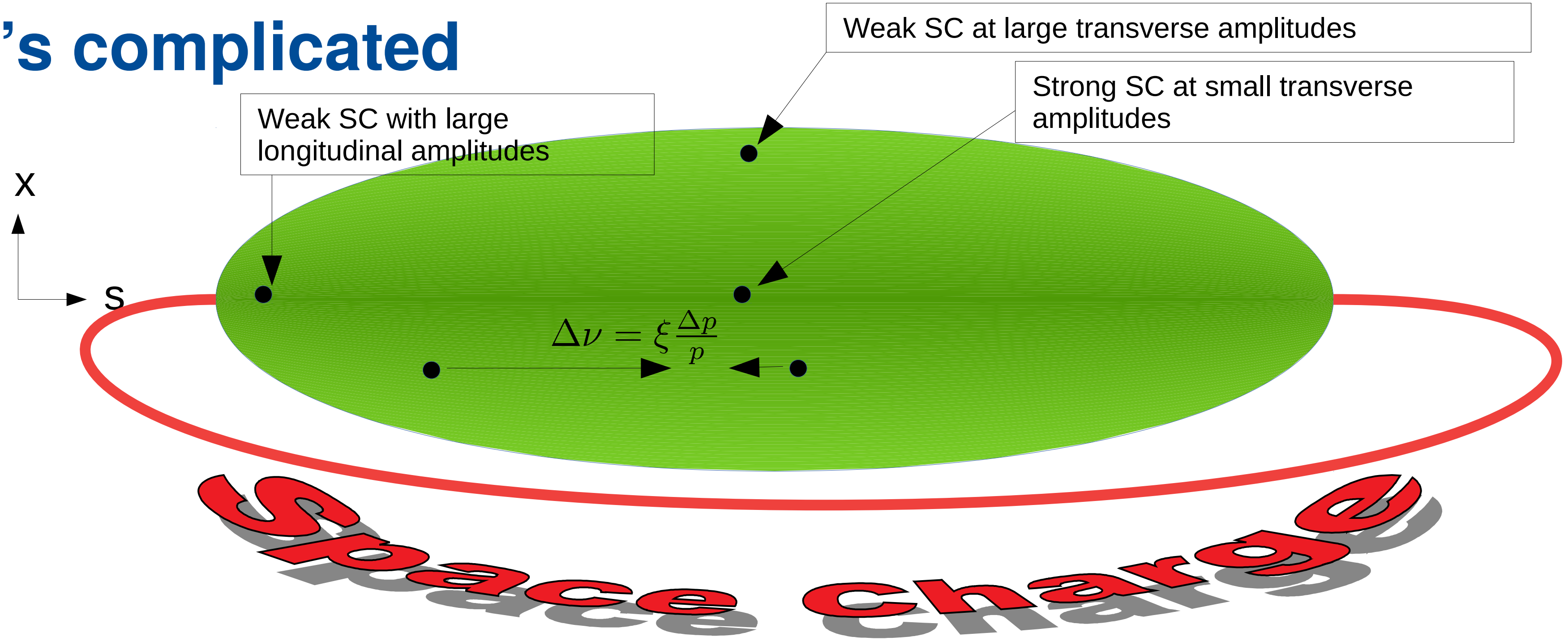
Step 9: Long term tracking and emittance increase



The Synergia PIC based simulation is smooth, does not become unstable over the long term and falls well within the range of other calculations.

Credit: Schmidt

It’s complicated



- Particles experience different space charge forces in different parts of the bunch.
- Space charge happens over the entire ring but there will be only a few electron lenses which break symmetry and may drive resonances.
- Chromaticity contributes a spread of tunes.

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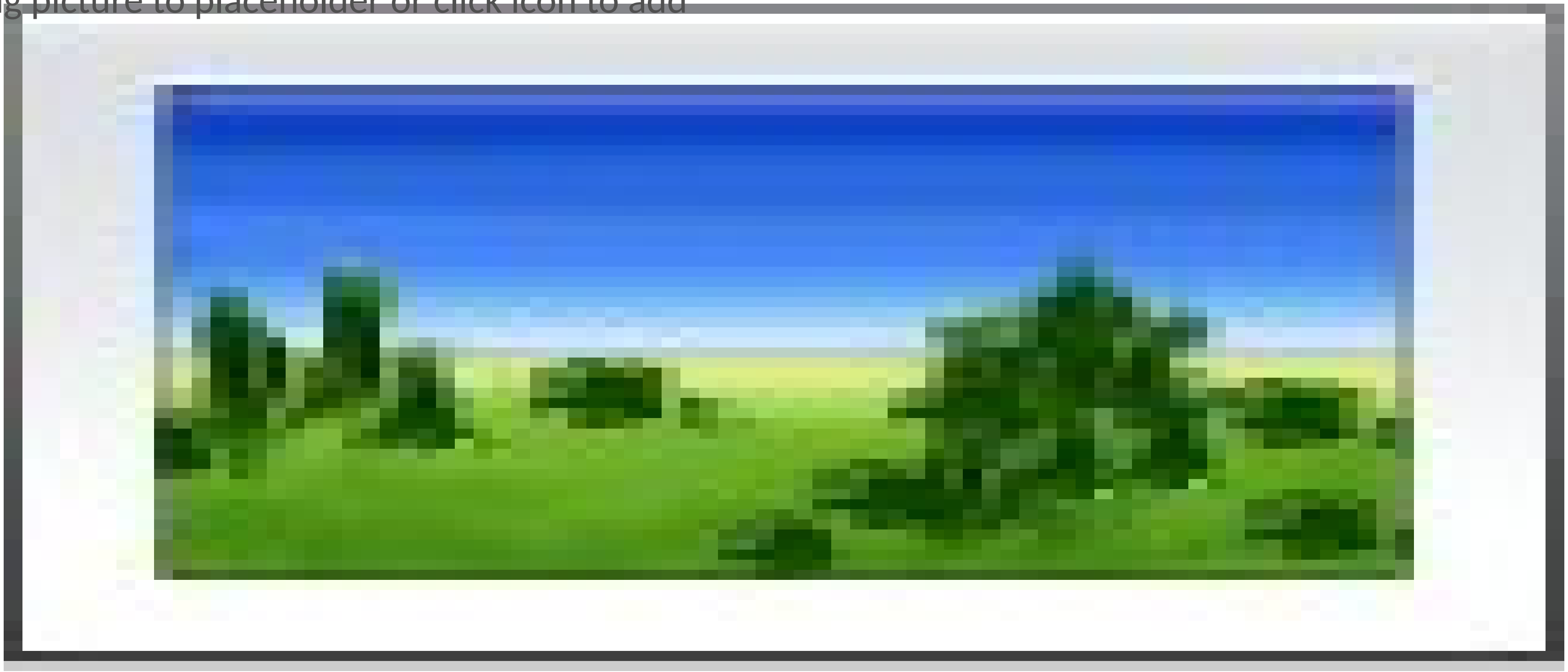

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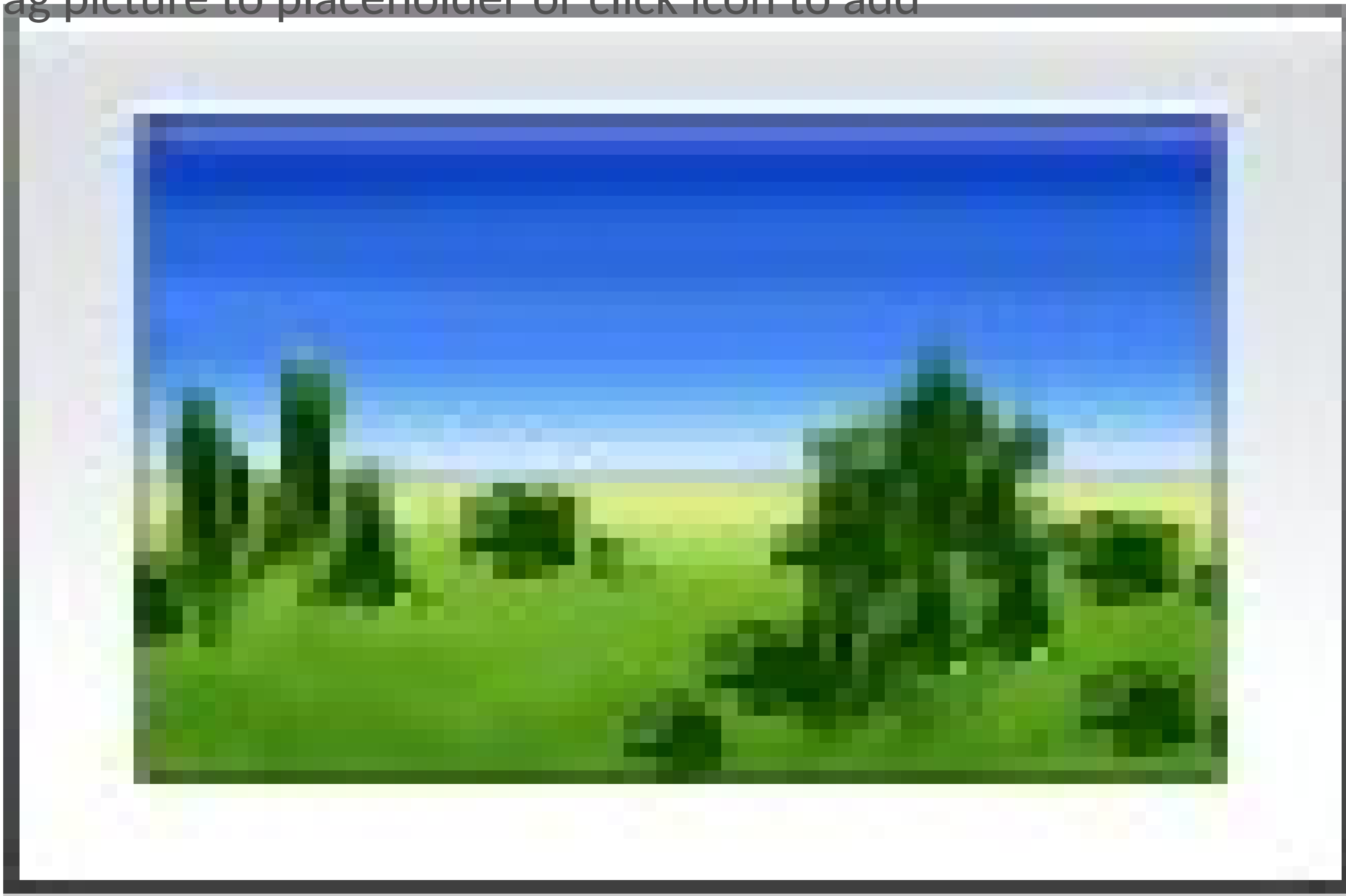

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