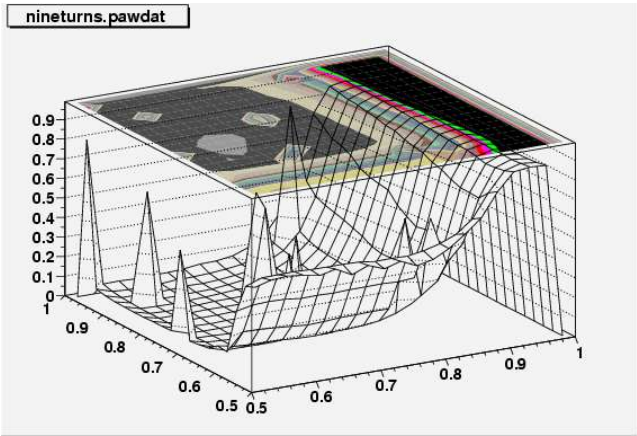
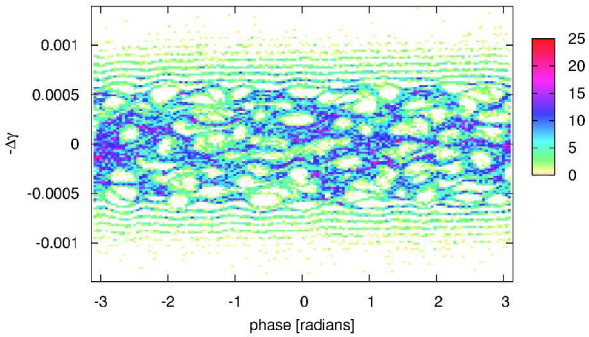
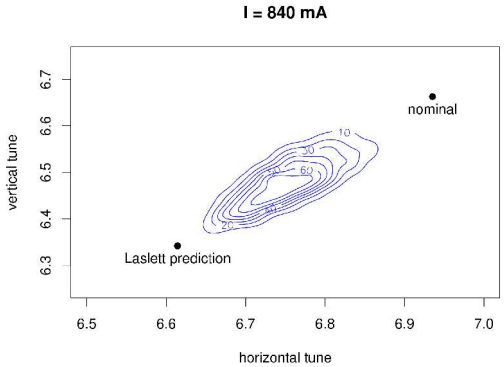
Emittance dilution and halo creation during the first millisecond after injection at the Fermilab Booster

Panagiotis Spentzouris
Fermilab

in collaboration with James Amundson



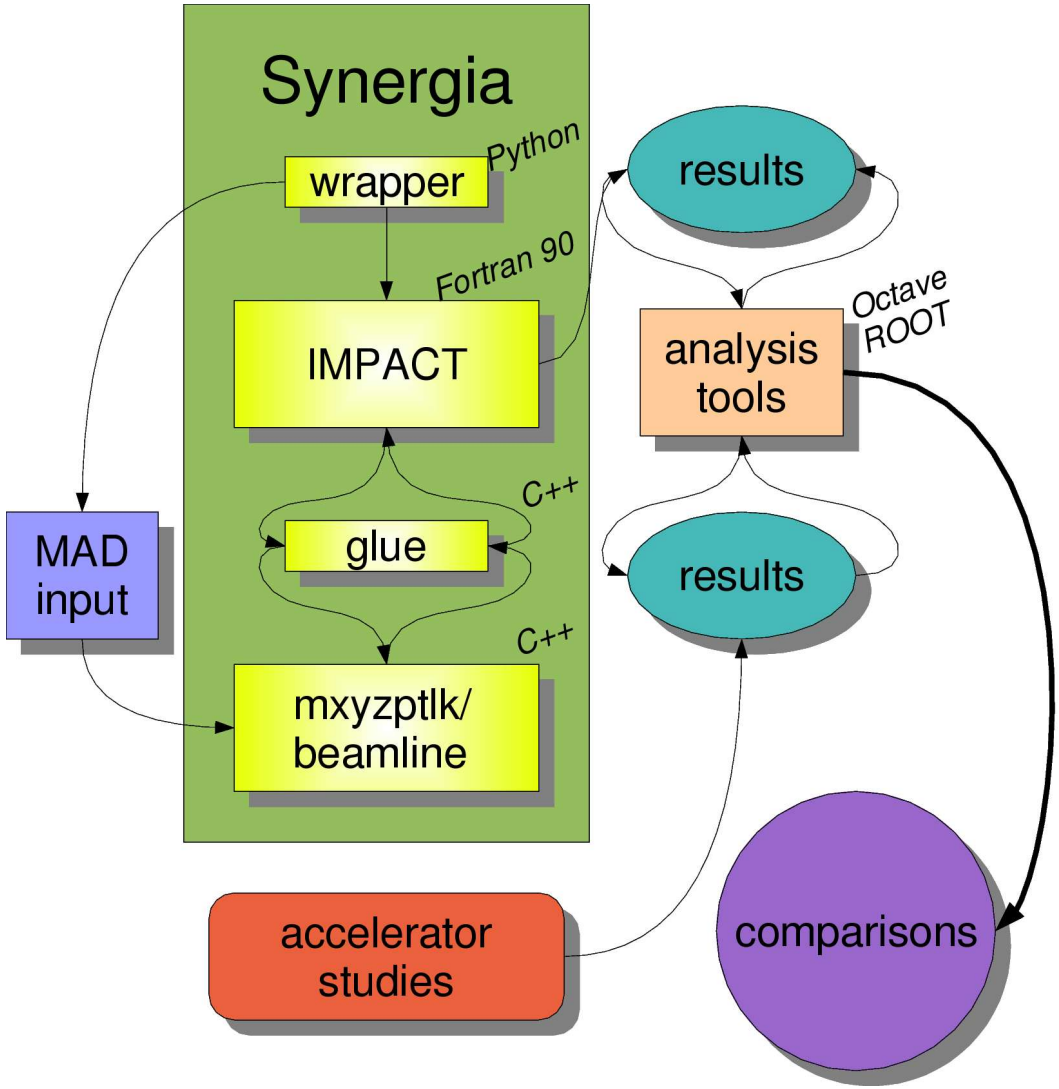




Outline

- *Simulation:* the Synergia framework
  - components, performance
  - “reality” checks/validation
- *Experiment and Simulation comparisons*
  - *FNAL Booster & diagnostics: the IPM detector*
  - *halo formation*
  - coherent tune shift
  - emittance dilution
- Future experiments
  - longitudinal phase space effects
  - transverse plane coupling

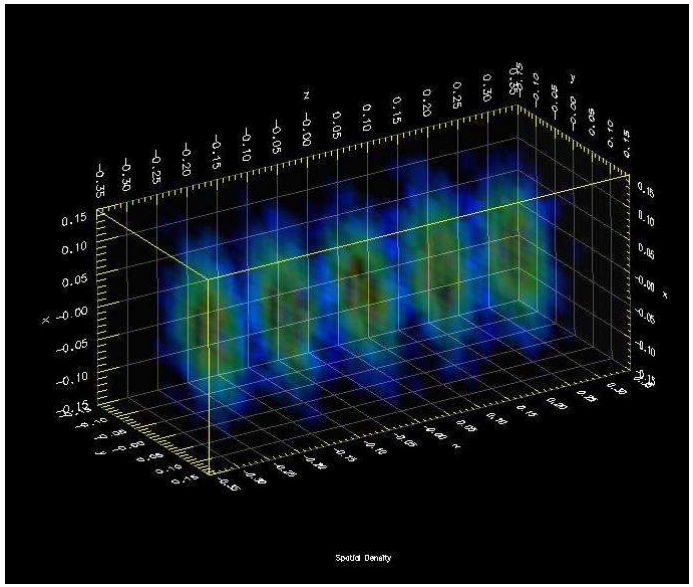
Synergia Overview



- Synergia incorporates & extends IMPACT and mxyzptlk/beamline
- IMPACT
  - program flow, MPI parallelism & space charge
- mxyzptlk/beamline
  - arbitrary-order maps
    - primarily use 2nd-order maps
  - mad parser
- Project funded by SciDAC

http://cepa.fnal.gov/psm/aas/Advanced_Accelerator_Simulation.html

Simulation details



Multi-bunch modeling in 3D

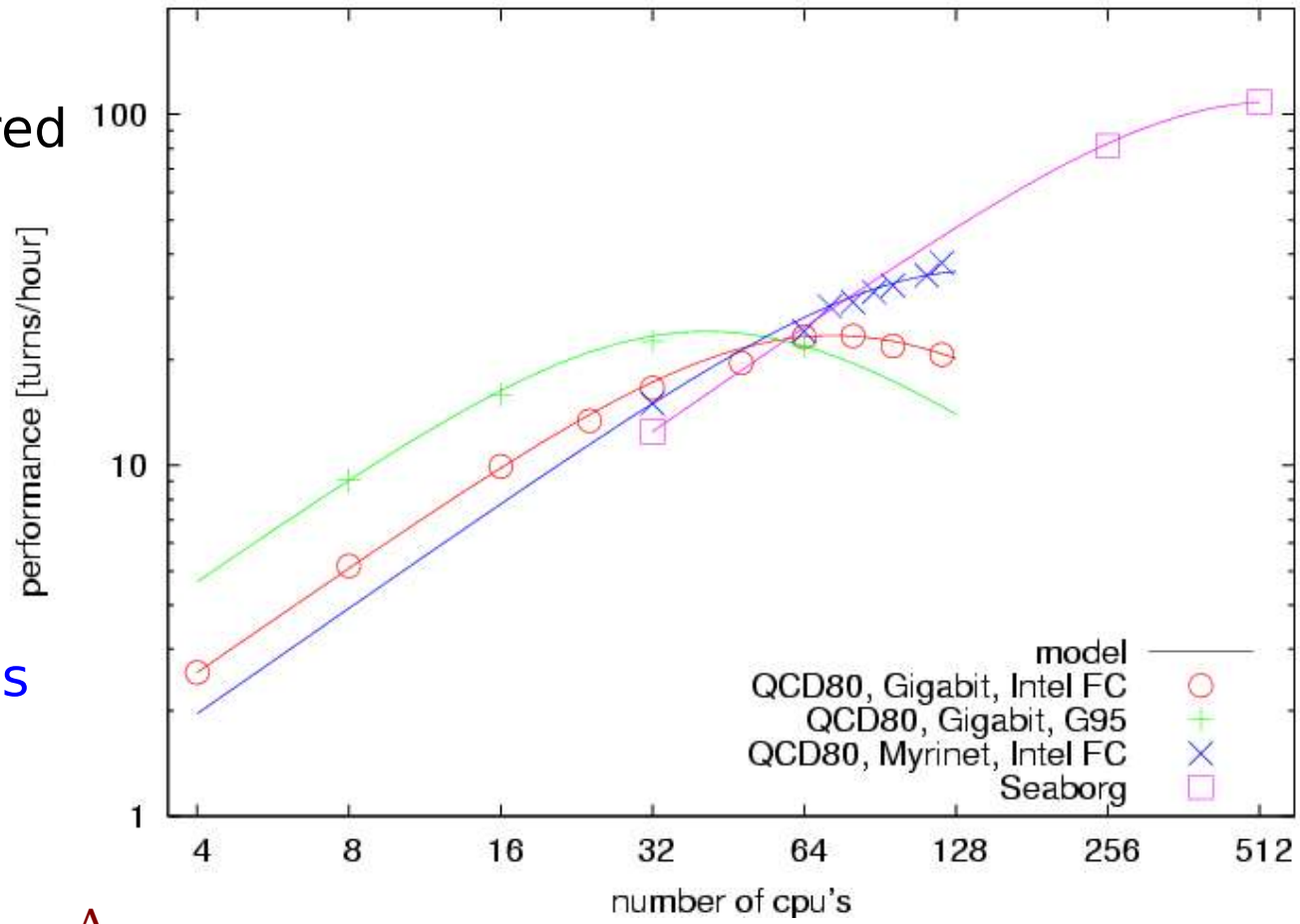
- FNAL Booster simulations follow 5 200 MHz Linac micro-bunches in a 37.8 MHz PhS slice.

- Fully 3D space-charge
- For high-precision simulations use 33x33x257 grid and ~1,000,000 particles
- Periodic boundary conditions – periodic/long beam
- Multi-turn injection
- 6-D PhS matched beam generation utilities

Performance

- parallel computing required
- Code ported to supercomputers (NERSC) and parallel PC clusters
- for a FNAL Booster simulation:

~100 turns/hr on 512 procs



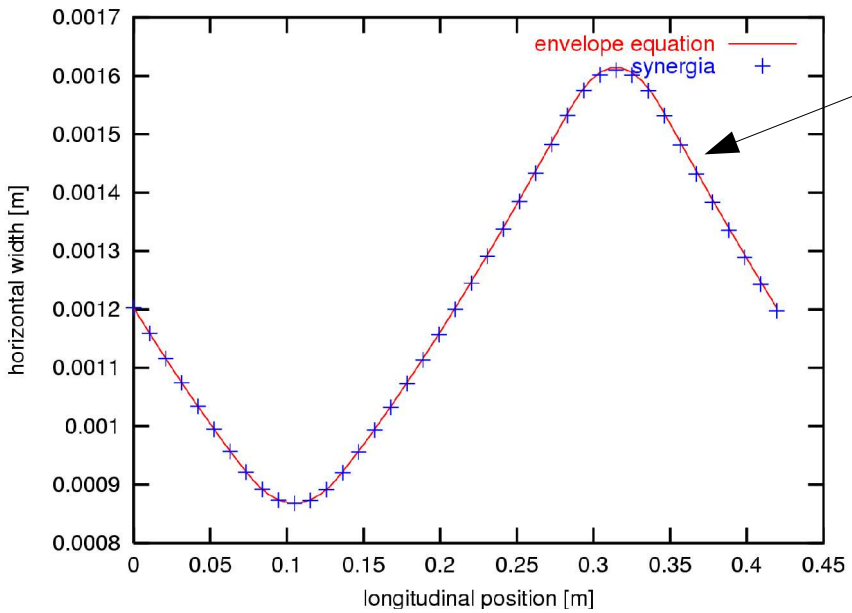
Performance model: $t = \frac{A}{N} + BN$

Model validation tests

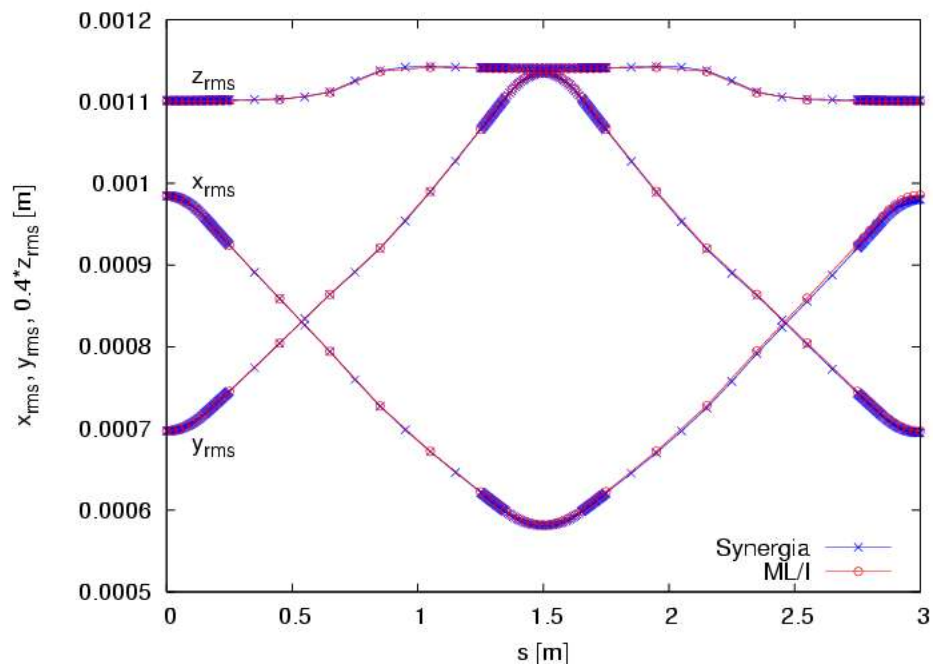
0.5 A KV Beam in a FODO channel

$$\sigma_x'' + K_x\sigma_x - \frac{\epsilon_{\rm rms}^2}{\sigma_x^2} = \frac{\xi}{4(\sigma_x+\sigma_y)}$$

$$\sigma_y'' + K_y\sigma_y - \frac{\epsilon_{\rm rms}^2}{\sigma_y^2} = \frac{\xi}{4(\sigma_x+\sigma_y)},$$



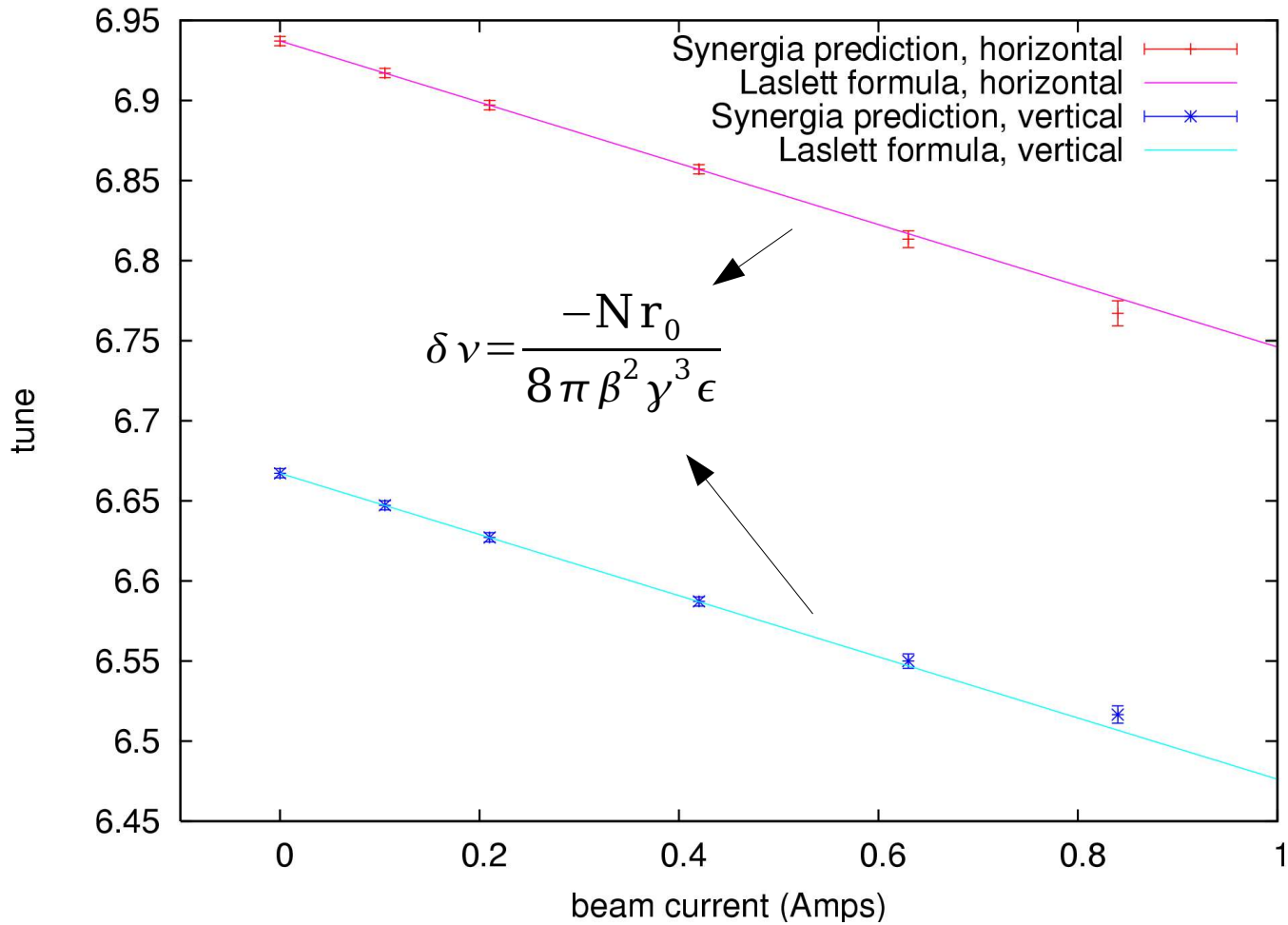
3D cold beam in FODO with rf, comparison with ML/I



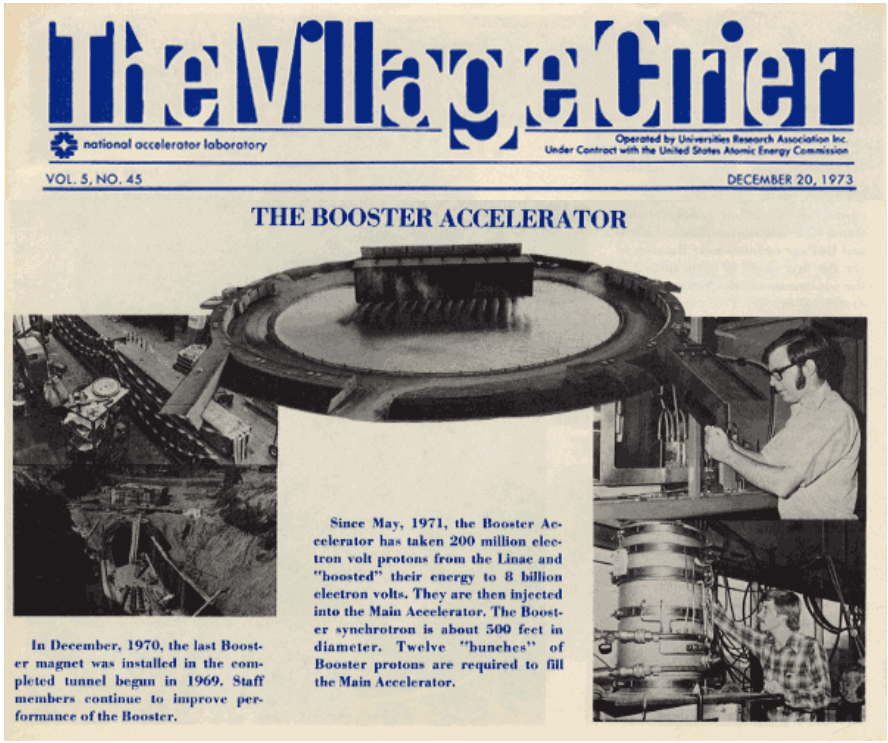
Overall, excellent model-theory & code to code agreement

Tune Shifts, compare with Laslett

Calculate individual particle tunes in the FNAL Booster using a KV beam



The FNAL Booster



The Village Crier

national accelerator laboratory

Operated by Universities Research Association Inc. Under Contract with the United States Atomic Energy Commission

VOL. 5, NO. 45 DECEMBER 20, 1973

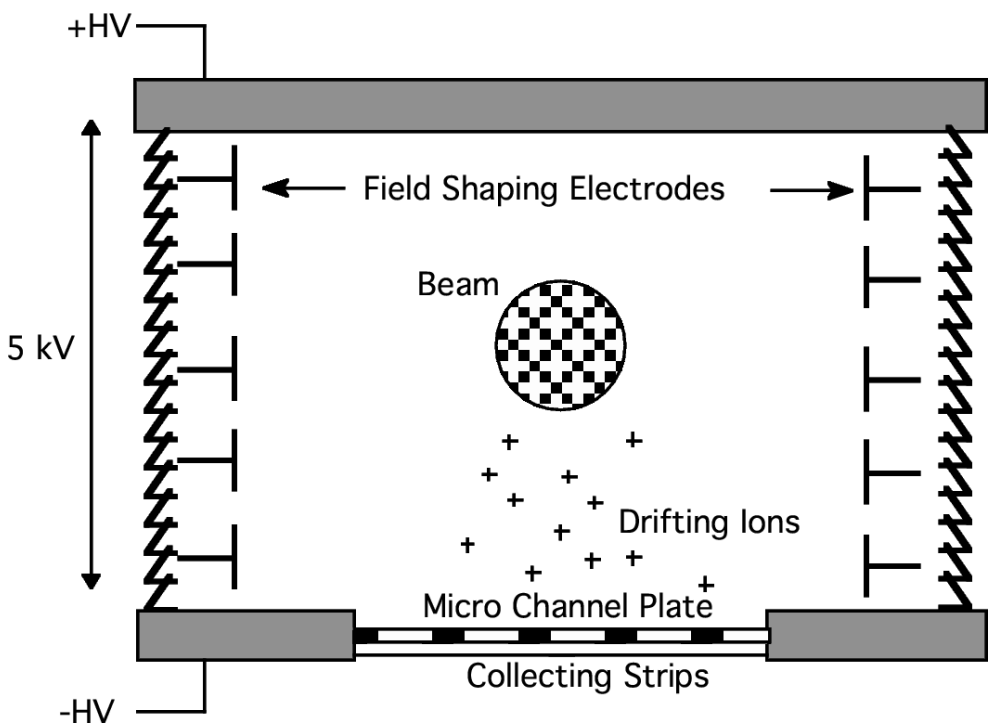
THE BOOSTER ACCELERATOR

Since May, 1971, the Booster Accelerator has taken 200 million electron volt protons from the Linac and "boosted" their energy to 8 billion electron volts. They are then injected into the Main Accelerator. The Booster synchrotron is about 500 feet in diameter. Twelve "bunches" of Booster protons are required to fill the Main Accelerator.

In December, 1970, the last Booster magnet was installed in the completed tunnel begun in 1969. Staff members continue to improve performance of the Booster.

- Rapid cycling, 15 Hz
  400 MeV → 8 GeV
- 24 FOFDOOD cells,
  total length 474.2 m
- RF 37.7 → 52.1 Mhz
- Injection/capture ~ 2 ms
- Multiturn injection, typically
  12x0.035 mA = 0.42 mA
- $\nu_h = 6.94$; $\nu_v = 6.66$
- → here focus on first few hundred turns

Ion Profile Monitor (IPM) Detector

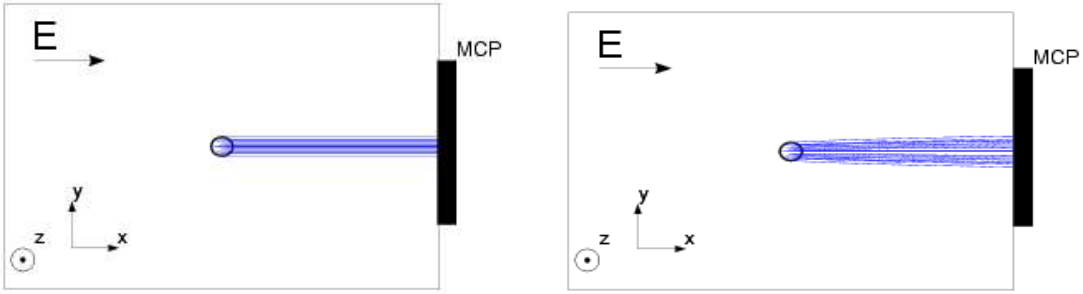


Field generated by beam charge smears measured beam profiles

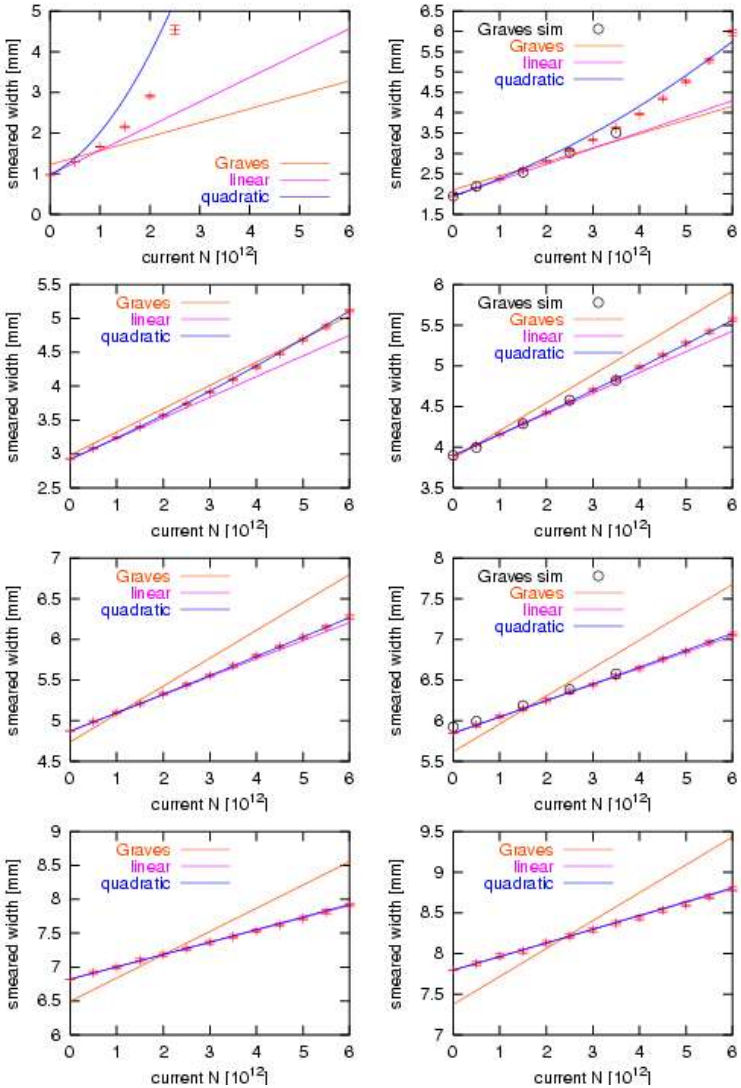
- Turn-by-turn beam profiles in horizontal and vertical planes
- Response affected by beam charge
- We have done detailed theoretical and experimental work on calibration
  Phys. Rev ST AB ***6****:102801, 2003*

IPM Calibration

IPM response model



0 beam charge nominal beam charge

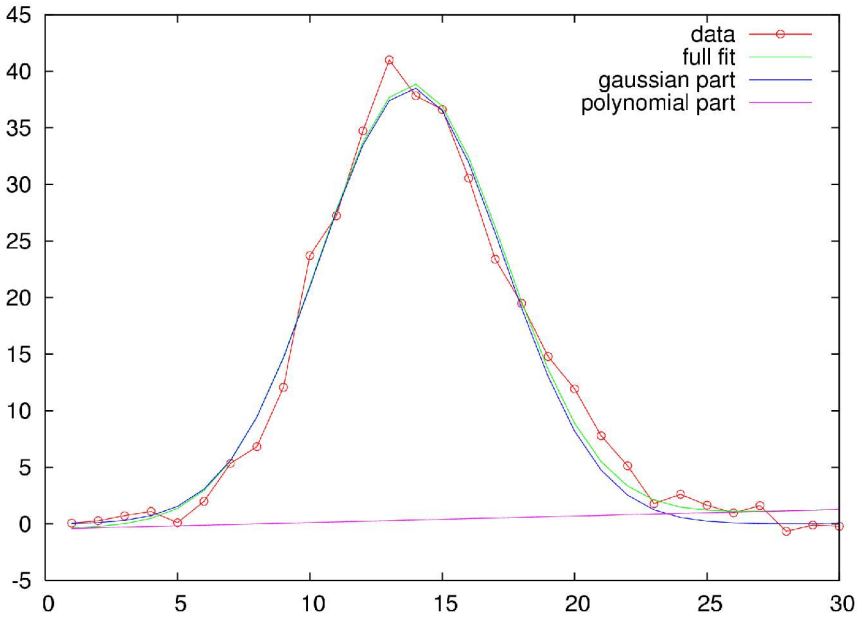


- Model constrained by independent data (@injection and @extraction)
- Calibration provides
  - ➔ correction to measured widths
  - ➔ smearing function for simulated profiles

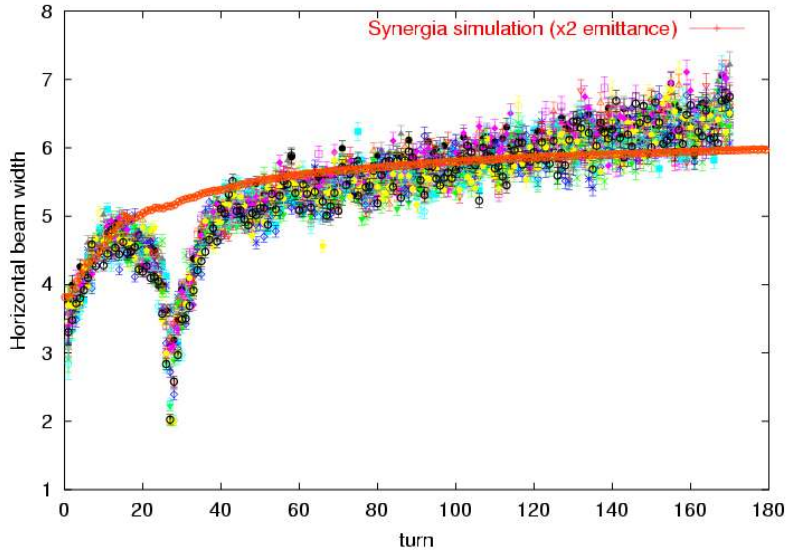
Beam Profiles

IPM profiles fit to Gaussian + linear function

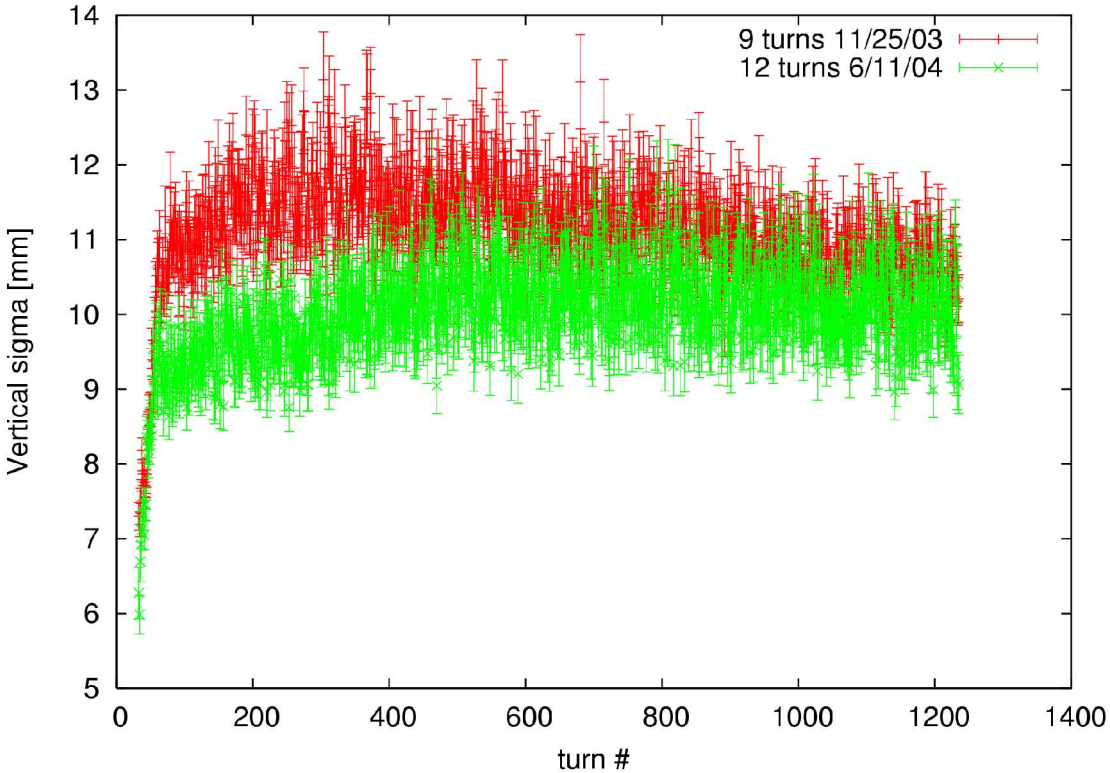
horizontal



For data/simulation comparison of the second moments correct the Gaussian width according to calibration.



Booster Performance



assuming the same emittance:
15% increase in width => ~32% β function change, (fractional tune change of ~0.03)

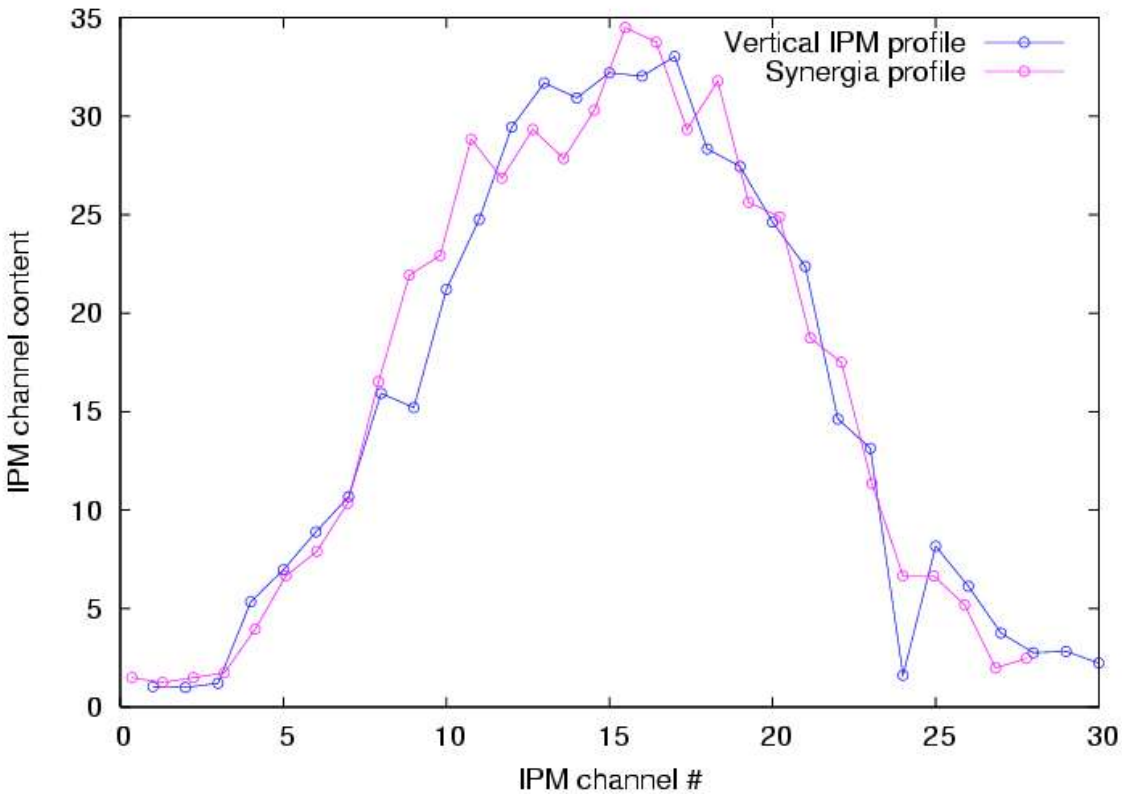
- Booster running better than ever: ~90% efficiency
- Machine & *injected beam* characteristics vary with time.
- Important not to ascribe misalignments, etc to space-charge effects
  - often easier to know *a posteriori*

Simulation beam input

- Matched beam: 6-D Gaussian with
  - 2-component correlation matrix determined by beam optics at injection
  - corrected for finite statistics
  - include space-charge effects in matching
- To study mismatch & chromatic effects
  - change width but keep emittance constant
  - linear lattice but 2nd order maps and $\Delta p/p$

Halo Study

Measured & simulated IPM profiles fit to Gaussian + linear function



$$G \equiv \int (\text{Gaussian term})$$

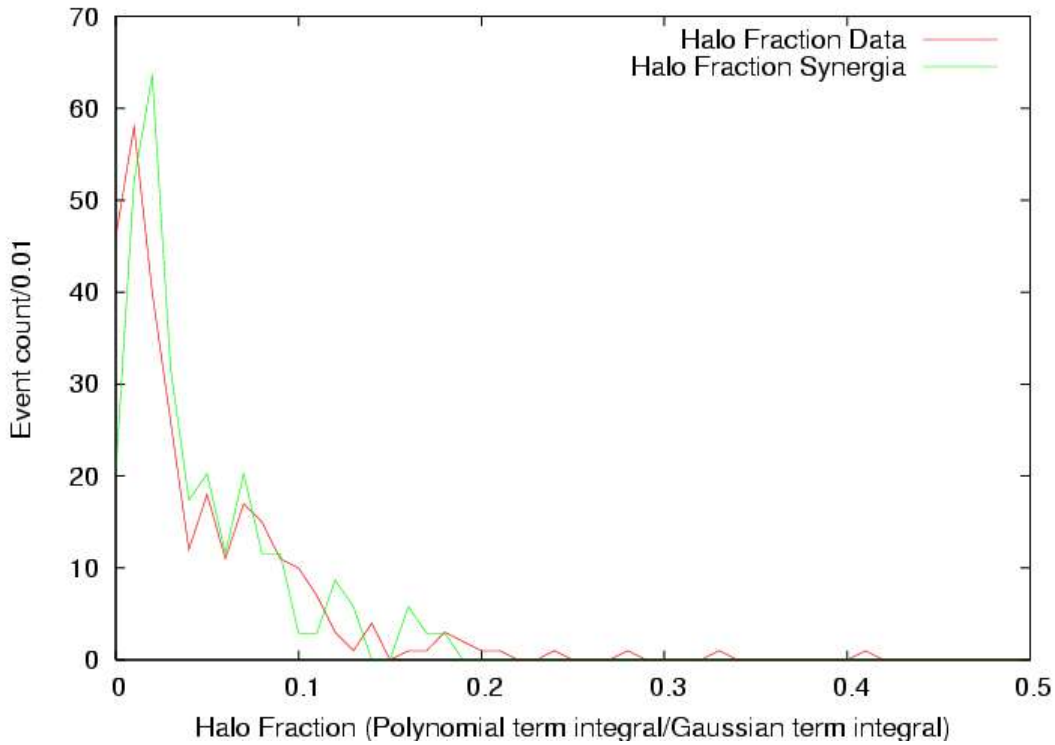
$$L \equiv \int (\text{Linear term})$$

- Smear simulated profiles
- L/G measures non Gaussian fraction (halo).

- Compare data/model

“Halo” comparison results

Compare L/G for first100 turns:



Data:
mean (L/G) = 0.049 ± 0.0011

Synergia:
mean (L/G) = 0.044 ± 0.0065

Note that the data distribution has a longer tail (more halo)

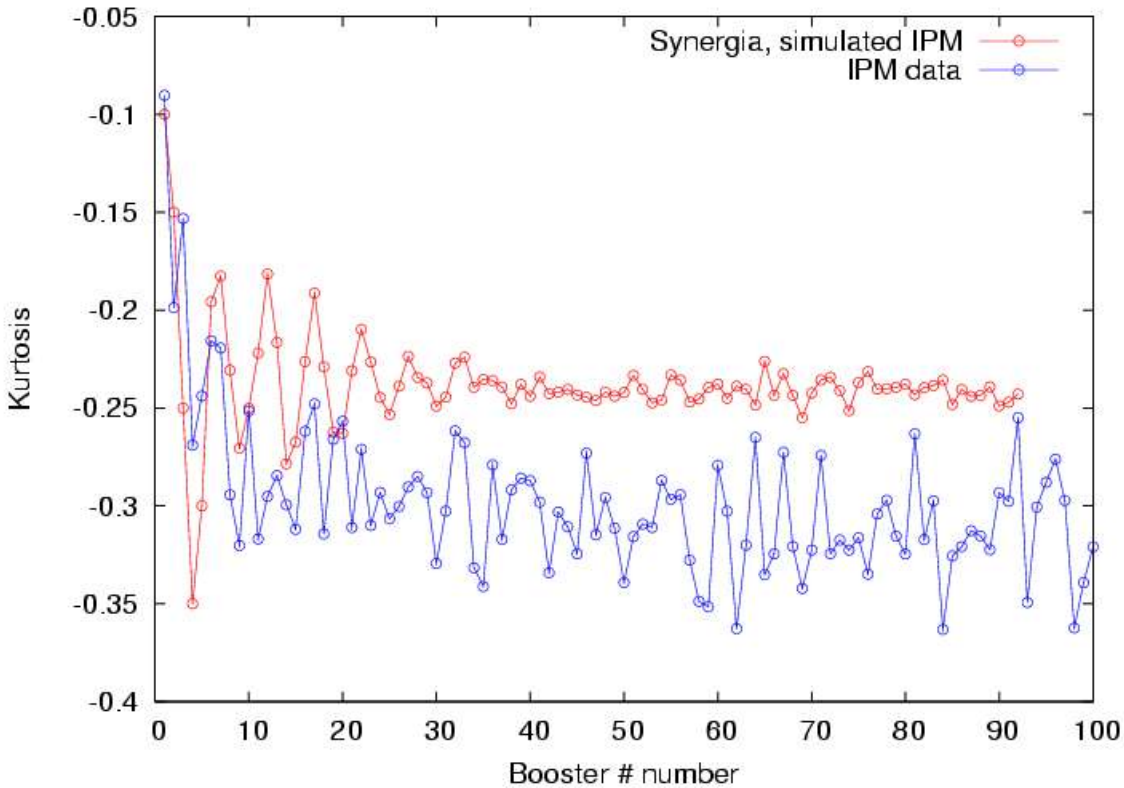
Also, the IPM smearing is done post-processing (slow)
➔ use sub-sample of 1M particles (speed up underway)

For the comparison we modeled a 20% mismatched beam and used 2nd order maps. Both chromatic & space-charge effects are needed to match the data

Halo Formation

Another way to characterize halo is to use kurtosis:

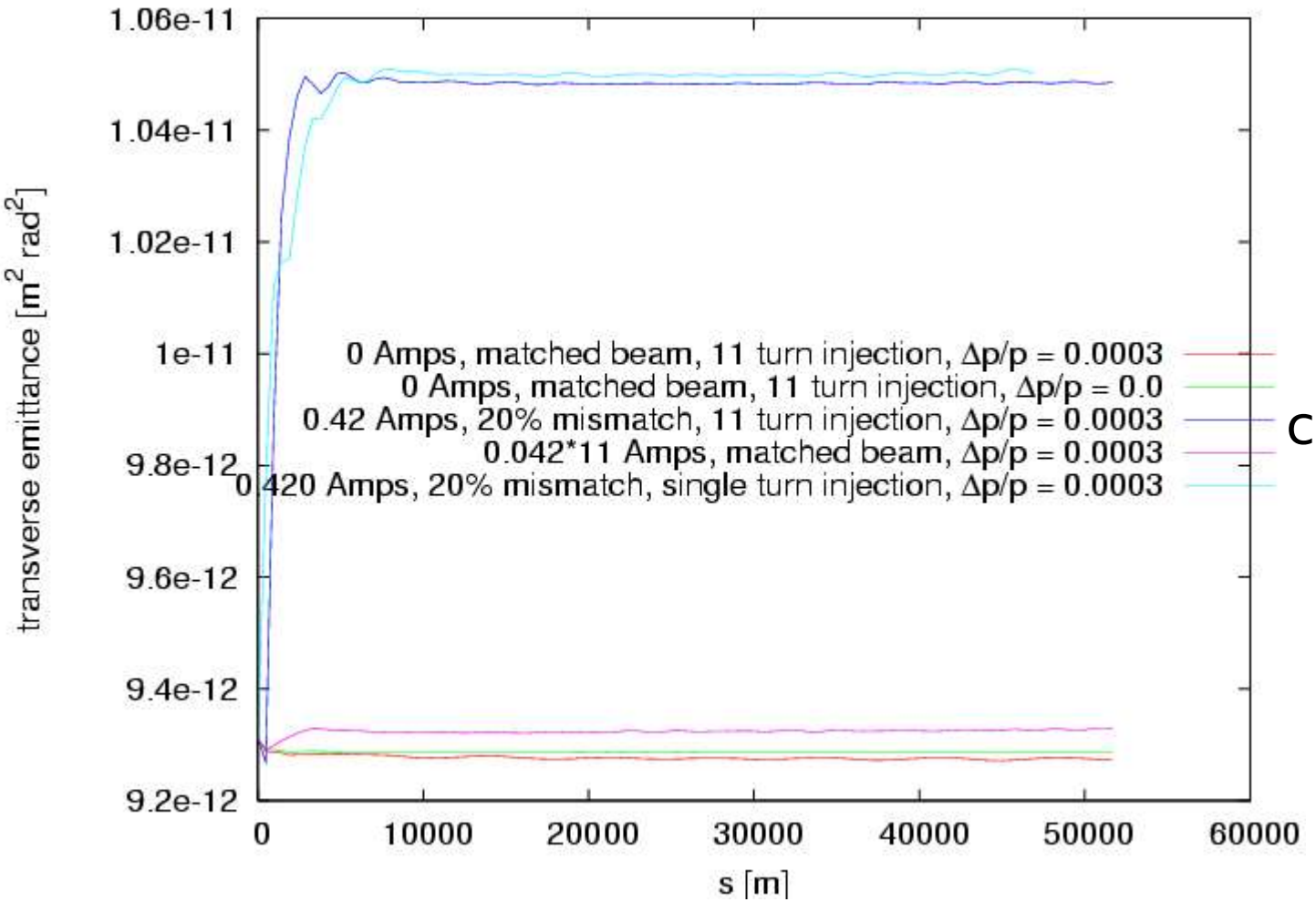
kurtosis $k \equiv \frac{\left\langle (x - \langle x \rangle)^4 \right\rangle}{\left\langle (x - \langle x \rangle)^2 \right\rangle^2} - 3$



Beam profile kurtosis vs turn:

- ➔ Data shows larger deviation from Gaussian shape
- ➔ Beam profiles are platykurtic ("flatter" than Gaussian)

Emittance



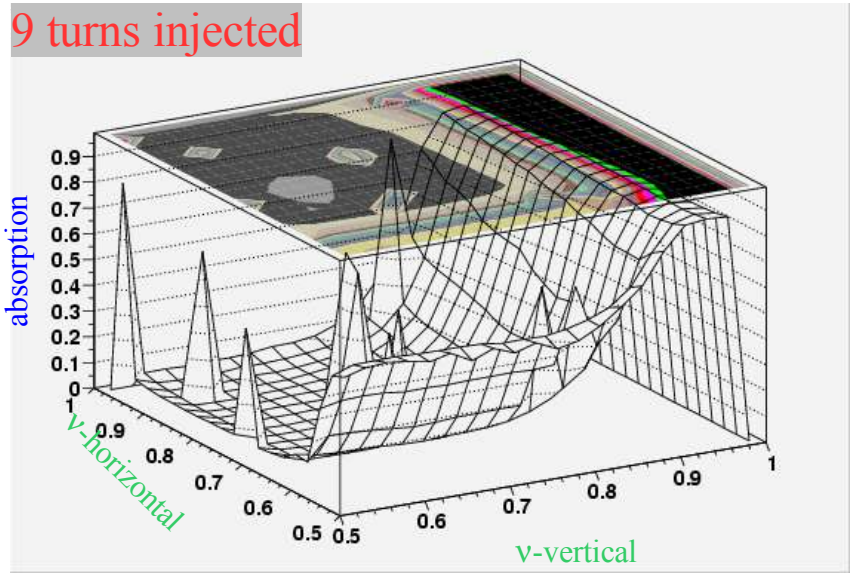
12% emittance increase in first ~20 turns

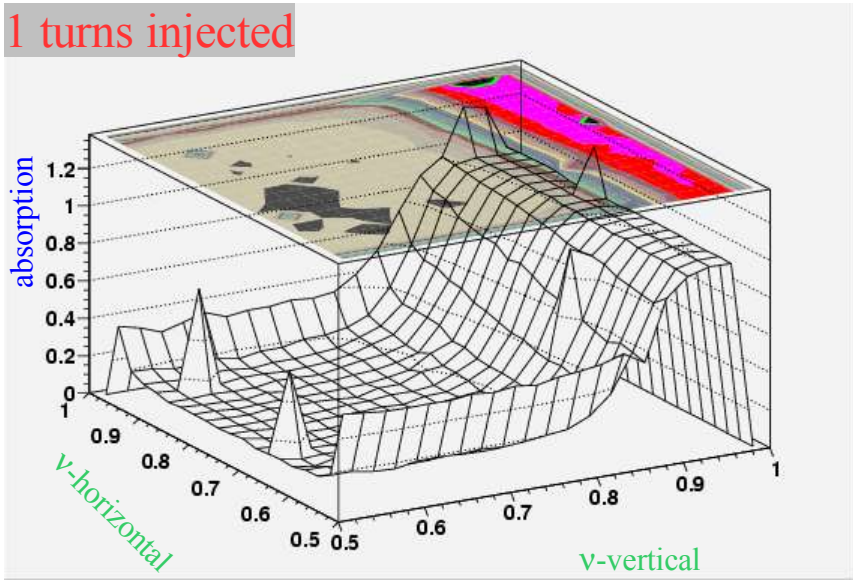
combination of chromatic and space charge effects

Coherent tune study

Measure beam absorption vs intensity, vs machine tune. If space-charge affects envelope tune, quad strength needed to traverse a resonance should vary with intensity.

Data taken Jan '03, with D. McGinnis and B. Pellico





Coherent Tune Comparison

Calculating the relationship between measured tune difference (dQ) and the space-charge tune shift (ΔQ_{sc}):

$$Q = Q_0 + \Delta Q_{sc} + \Delta Q_{quad}$$

$$\Delta Q_{quad} = \frac{dQ}{dI}(\Delta I_{quad})$$

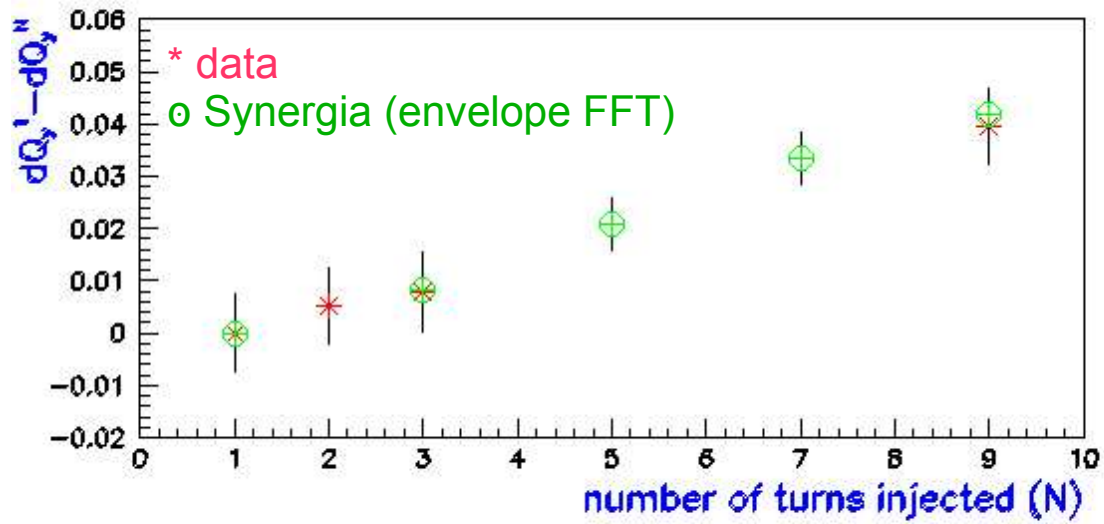
$$A: \ \frac{1}{2} = Q_0 + \Delta Q^1_{sc} + \frac{dQ}{dI}(\Delta I^1_Q)$$

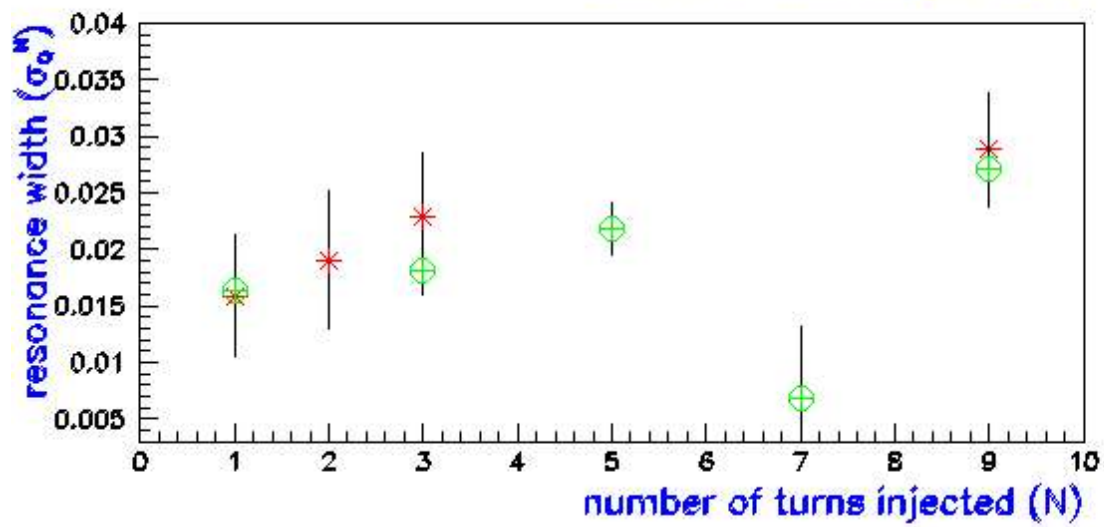
$$B: \ \frac{1}{2} = Q_0 + \Delta Q^N_{sc} + \frac{dQ}{dI}(\Delta I^N_Q)$$

$$B - A: \ 0 = \Delta Q^N_{sc} - \Delta Q^1_{sc} + \frac{dQ}{dI}(\Delta I^N_Q - \Delta I^1_Q)$$

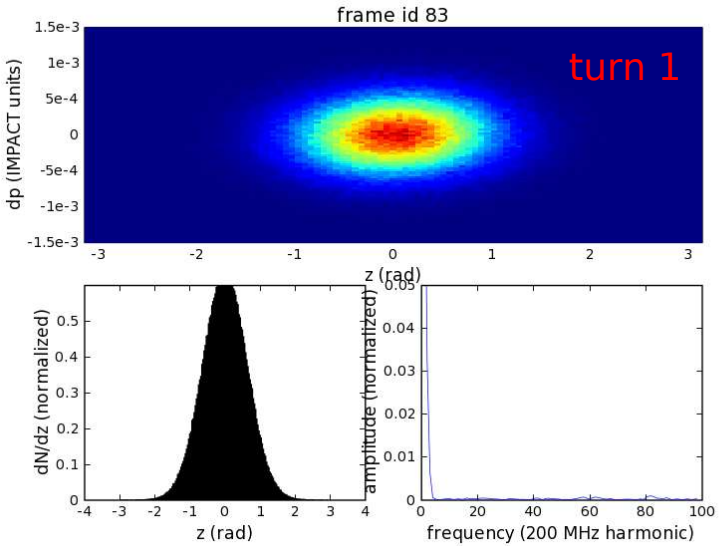
$$\Delta Q^N_{sc} - \Delta Q^1_{sc} = \frac{dQ}{dI}(\Delta I^1_Q - \Delta I^N_Q)$$

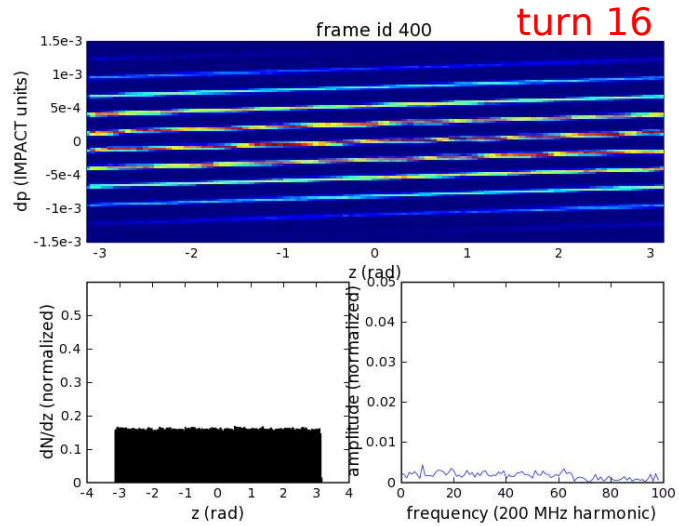
$$\Delta Q^N_{sc} - \Delta Q^1_{sc} = \mathrm{dQ}^1_{(x/y)} - \mathrm{dQ}^N_{(x/y)}$$





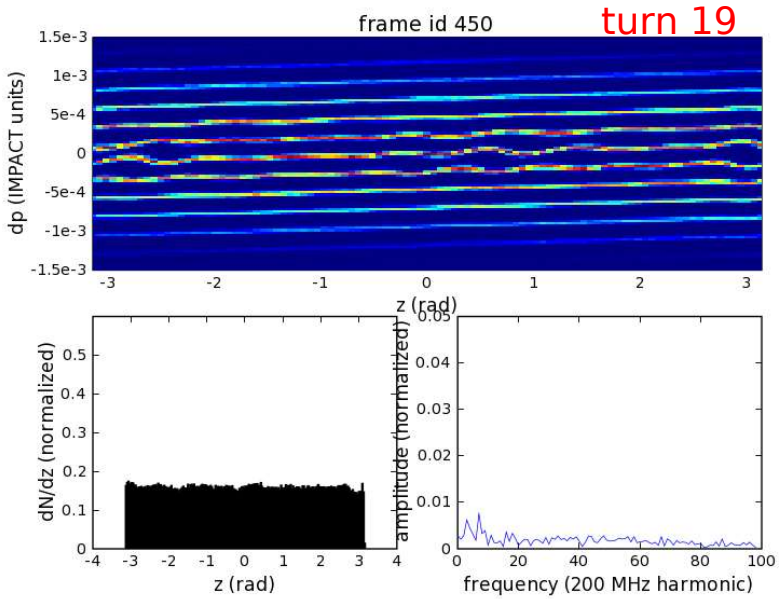
Longitudinal Evolution

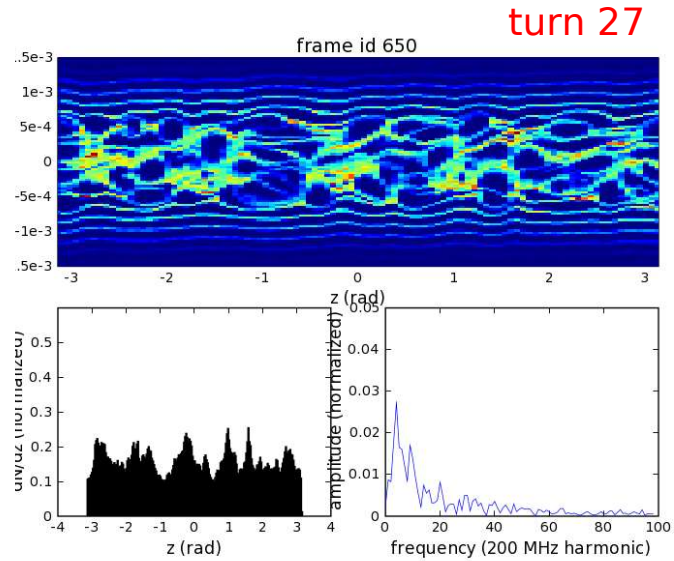




Simulation takes place before RF bunching starts

Structure appears ~10 turns after beam decoheres. interesting effect
➔ need data!

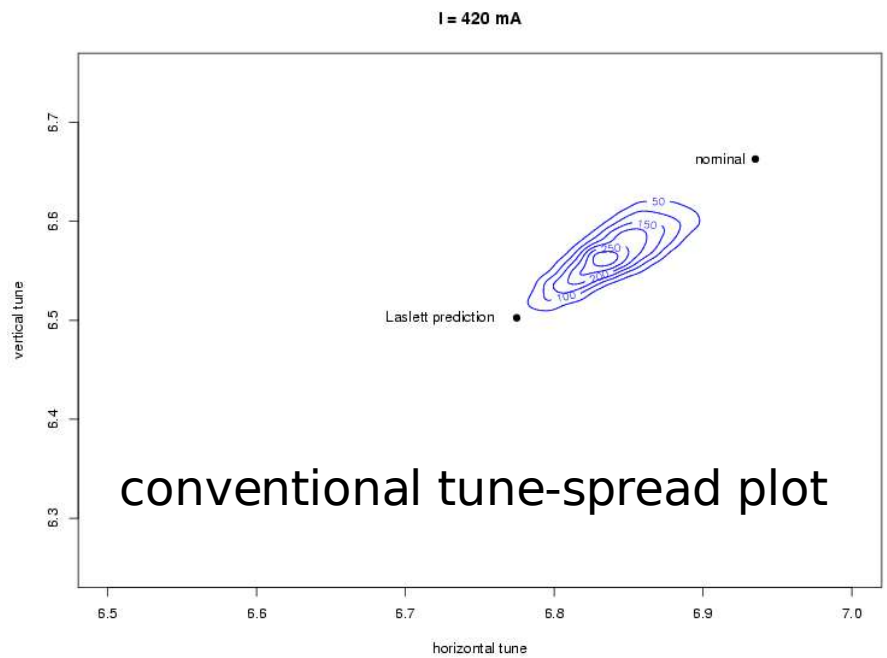




Effect independent of grid size, initial distribution details, and # of macro-particles

Effect depends on beam current.

Frequency spectrum



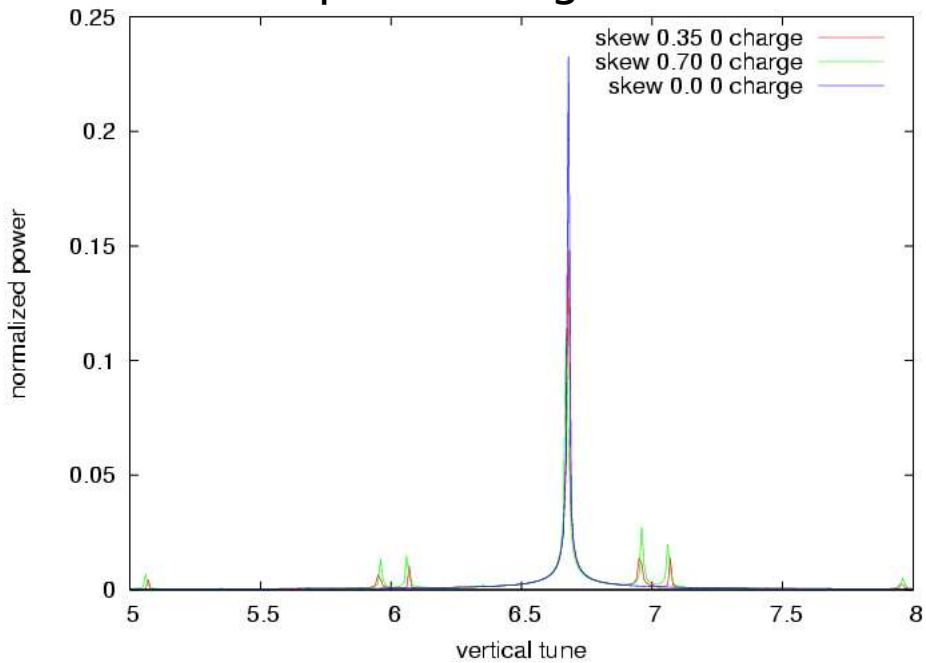
Convention:
take FFT of trajectories
the tune is the frequency with maximum strength
(in a simple case, the only frequency)

A different approach:

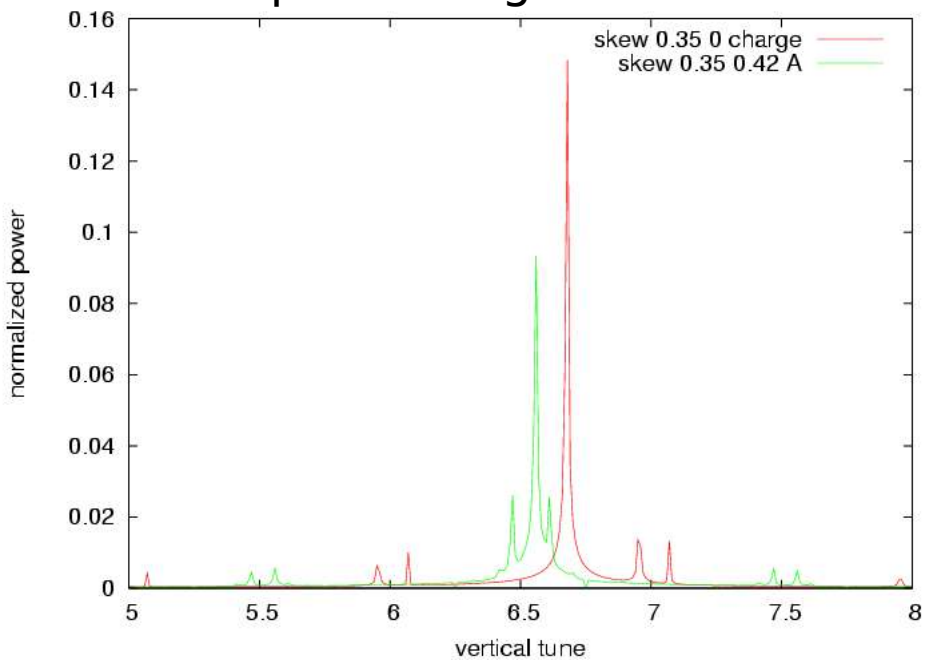
- take FFT of each particle trajectory
- keep the entire curve
- normalize area and make a histogram of all trajectories
- result is normalized frequency “strength” per trajectory

Frequency spectrum with coupling

No space charge



Space charge on



1 skewed quad = total Booster skewed quad strength

- additional structure in frequency spectrum
- doubling the strength and adding space charge effects leads to large losses!

Summary

- The Booster is running with record intensity and efficiency
  - many improvements on conventional physics issues
- Large-scale Synergia simulations indicate collective effects contribute to halo creation, coupled to
  - (Mis)matching
  - Chromatic effects
- Coherent tune shift measurements in good agreement with simulation
- Simulation indicates persistent structure in longitudinal PhS
  - data needed to investigate
- Investigate losses tied to coupling of transverse planes in the presence of space-charge.