Large-Scale Simulation of the FNAL Booster and Comparison with Experiment

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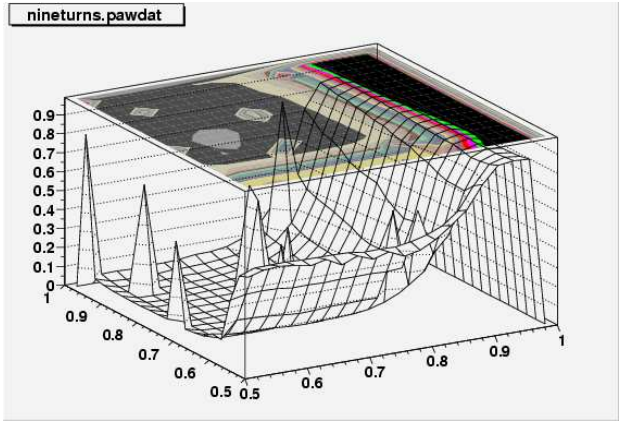
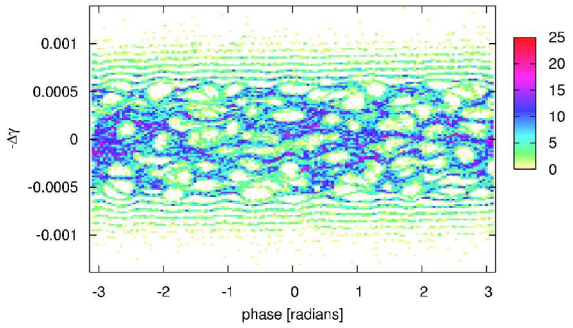
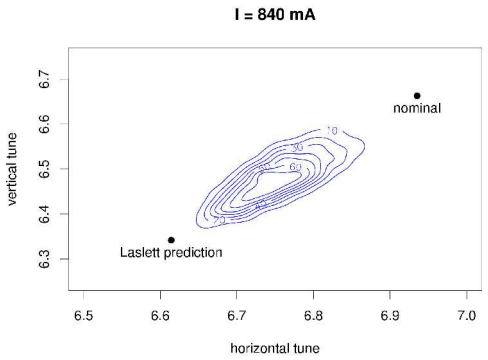
Fermilab

Συνεργεια

in collaboration with Panagiotis Spentzouris



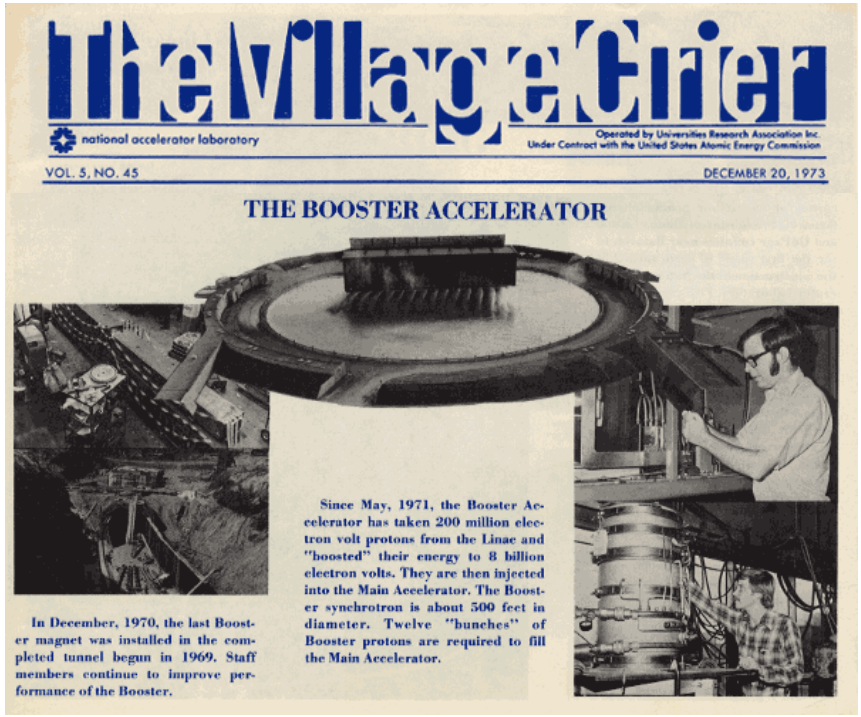




Experiment and Simulation

- *Experiment:* The FNAL Booster
  - halo/collimator studies
- *Simulation:* Synergia
  - halo
  - particle tune spread
- *Experiment and Simulation*
  - coherent tune study and simulation

The FNAL Booster



the Village Crier

national accelerator laboratory

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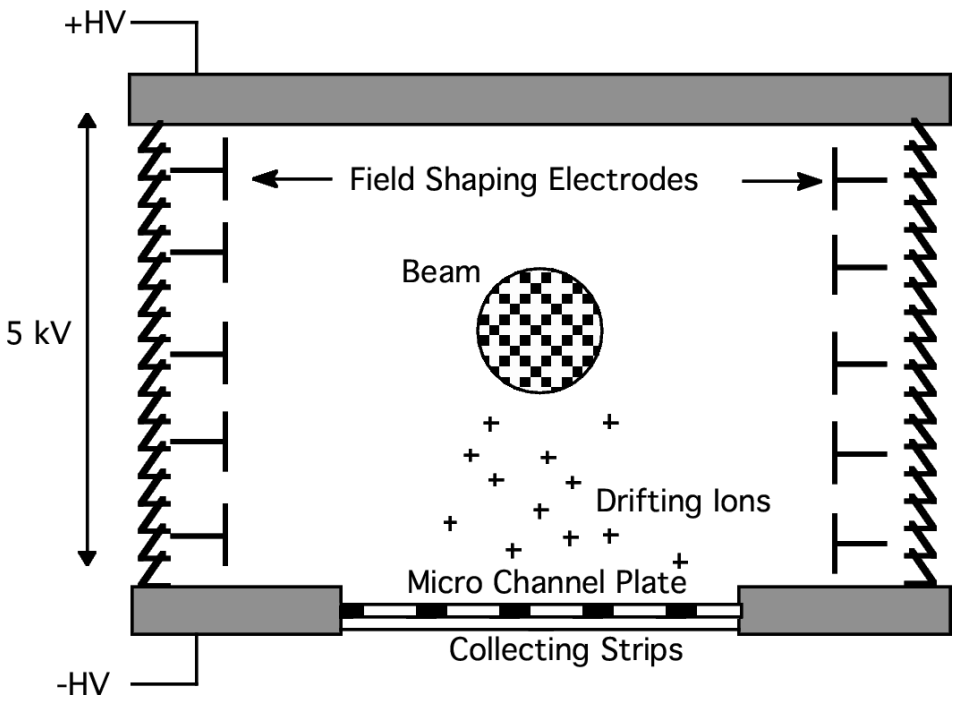
THE BOOSTER ACCELERATOR

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/bunching
  ~ 2 ms
- Multiturn injection, typically
  12x0.035 mA = 0.42 mA
- $\nu_h = 6.94$
  $\nu_v = 6.66$

Ion Profile Monitor (IPM) Data

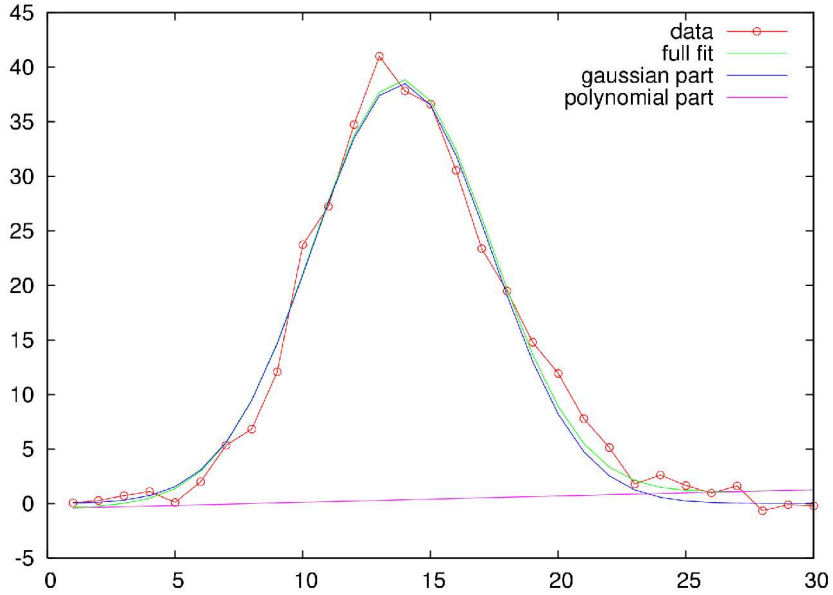


- Turn-by-turn beam profiles in horizontal and vertical planes
- We have done detailed theoretical and experimental work on callibration *Phys. Rev ST AB* ***6****:102801, 2003*

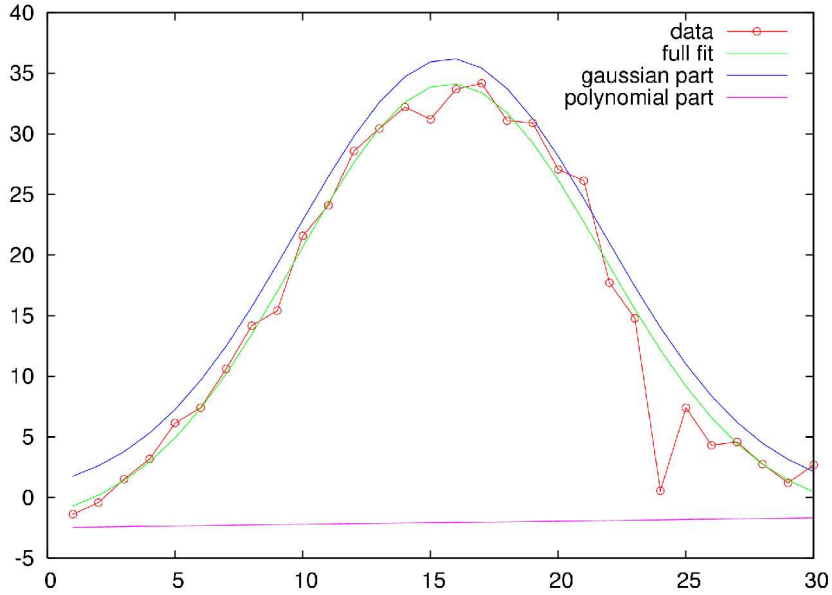
Beam Profiles

IPM profiles fit to Gaussian + linear function

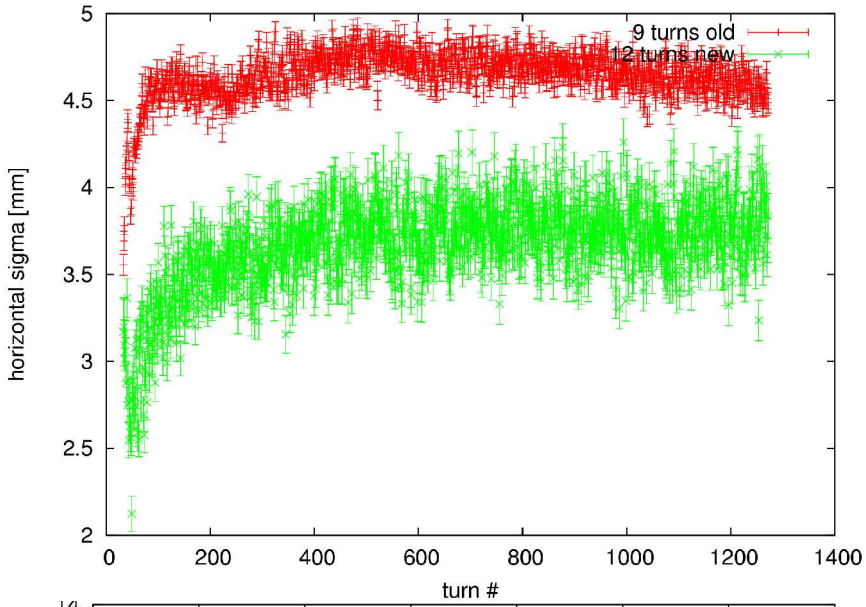
horizontal

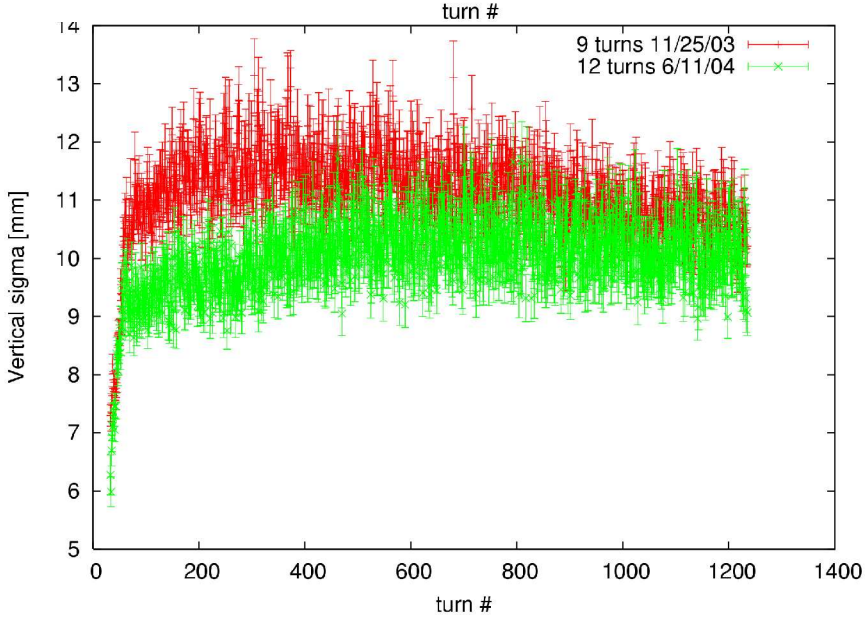


vertical



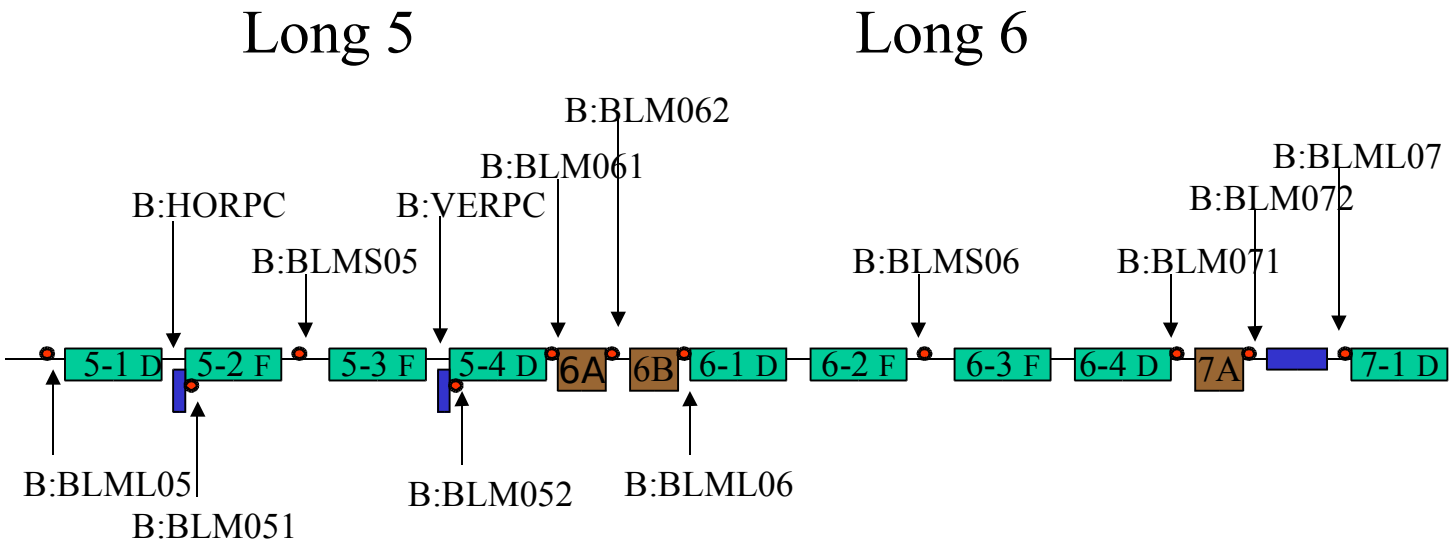
Booster Performance





- Booster currently running better than ever before: ~90% efficiency
- Machine and *injected beam* vary with time
  - In a working machine, things get fixed
- Important not to ascribe things like misalignments to space-charge effects
  - often easier to know *a posteriori*

Collimators



B:S5PCH - upstream mini-straight of Period 5
B:S5PCV - downstream mini-straight of Period 5
6A - upstream end of Long 6
6B - downstream end of Long 6
7A – upstream end of Long 7

The beam is bumped, with bump affecting the beam ~2.5-4.5 ms in the cycle

Collimator Study

- The Booster collimators are designed to safely remove halo particles
- Study: assign the non-Gaussian portion of the beam profile to halo
  - halo with and without collimators
  - halo before and after “bump”
  - reduce effects of run-to-run variations by averaging over five runs each

Collimator Study, continued

IPM profiles fit to Gaussian + linear function

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

$$L \equiv \int (\text{linear part})$$

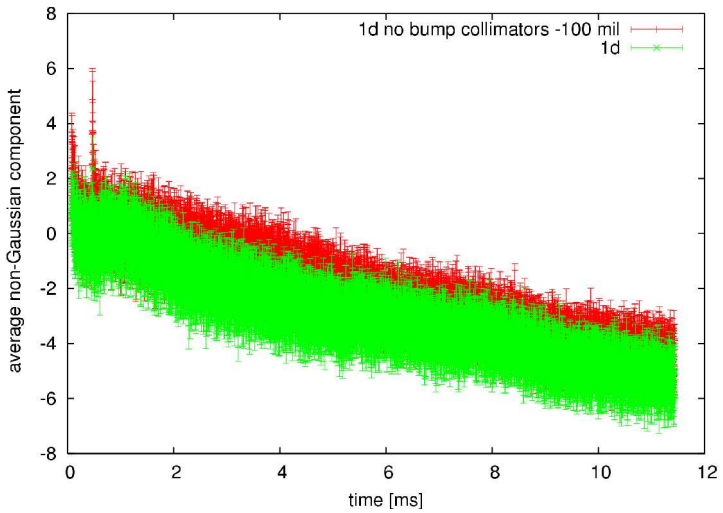
typical measured values in study:

$$L/G \simeq (10-20)\%$$

$$\Delta \equiv L_{\text{no collimator}} - L_{\text{with collimator}}$$

non-zero delta would show that collimators are removing halo

Collimator study results



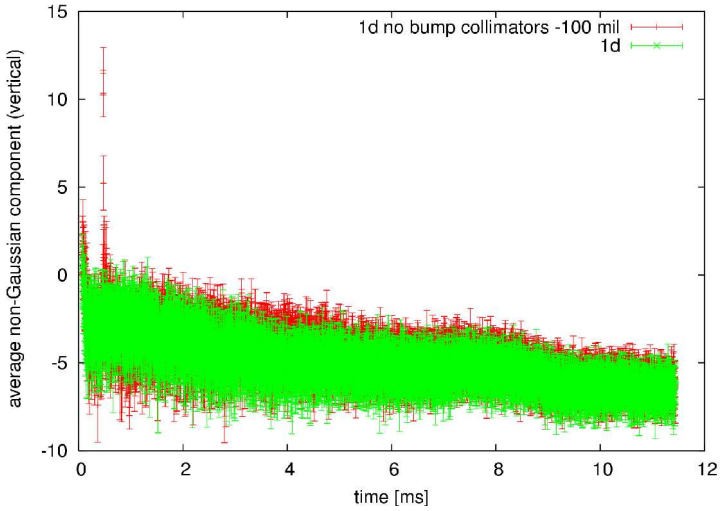
Average over 100 turns:
before bump (turns 100-200)
after bump (turns 5100 -5200)

Horizontal plane

before bump: $\Delta = 0.2699 \pm 0.0411$

after bump: $\Delta = 0.4505 \pm 0.0399$

$\Delta/L \sim (5\text{-}10)\%$



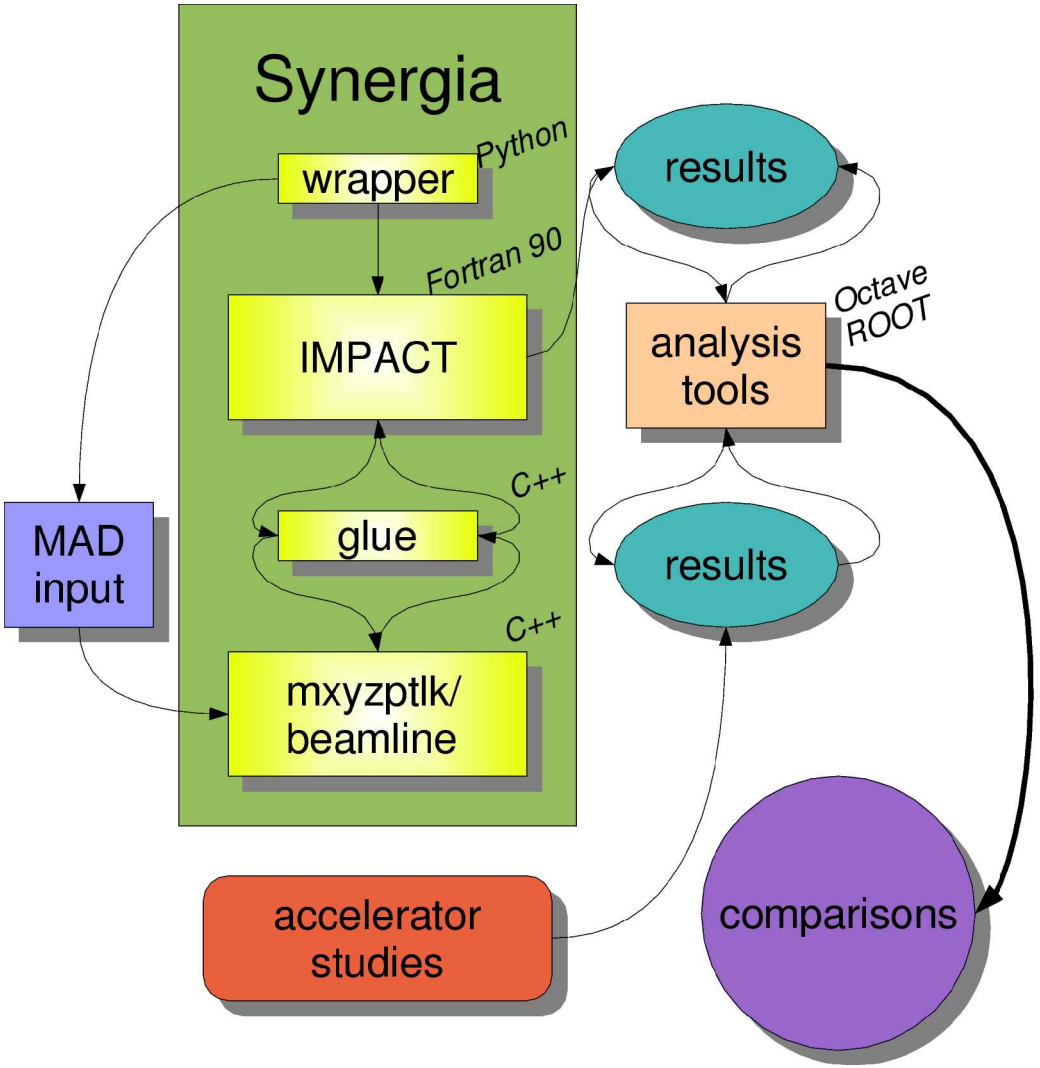
Vertical plane

before bump: $\Delta = 0.6270 \pm 0.2105$

after bump: $\Delta = 0.3978 \pm 0.0989$

$\Delta/L \sim (8\text{-}12)\%$

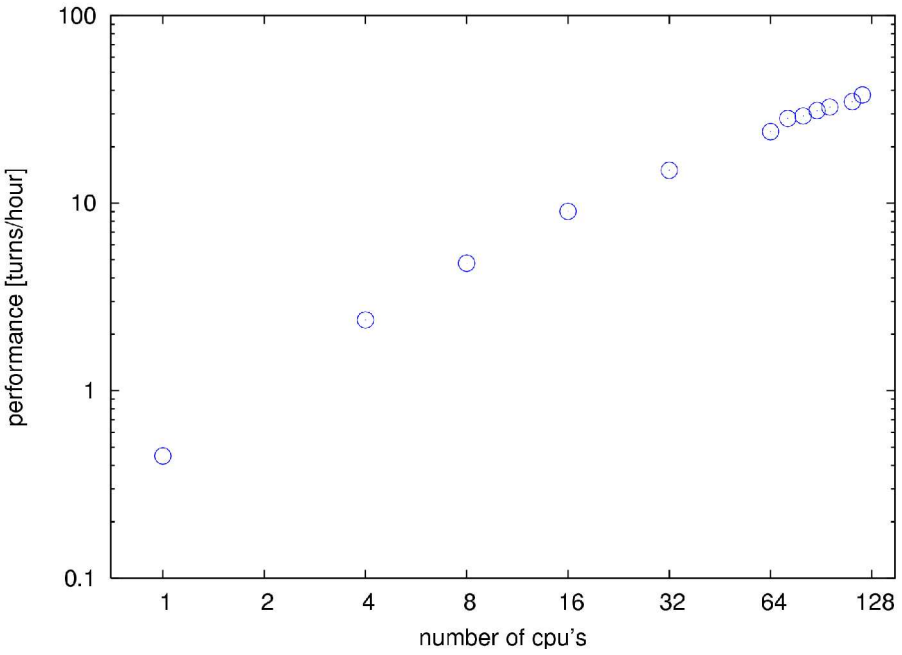
Synergia Overview



- Synergia is a combination of IMPACT, mxyzptlk/beamline, glue code and a wrapper
- IMPACT
  - program flow
  - space charge
- mxyzptlk/beamline
  - mad parser
  - arbitrary-order maps
    - We use primarily 2nd-order maps

Simulation details

Performance on FNAL's old QCD cluster (QCD80)

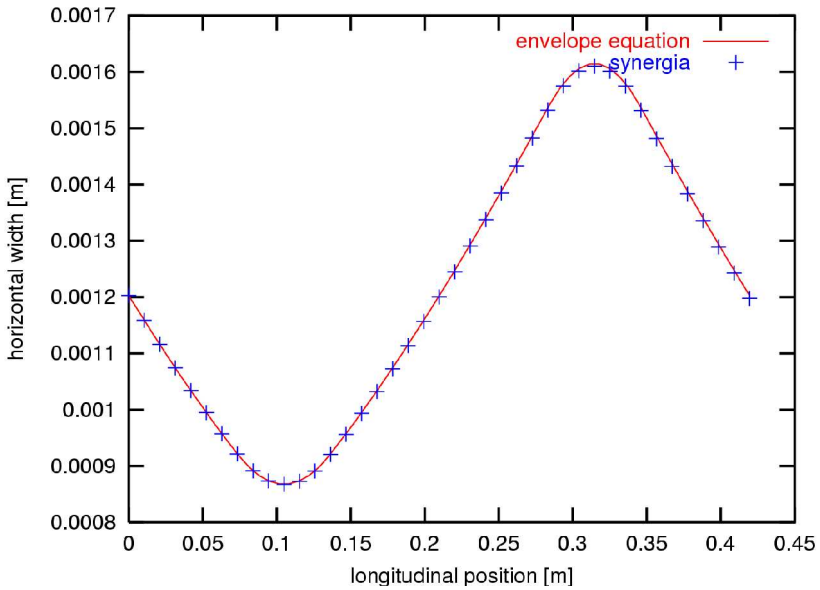


700 MHz PIII, Myrinet

- For high-precision simulations we use 33x33x257 grid and ~1,000,000 particles
- Periodic boundary conditions – periodic/long beam
- Requires a parallel machine
- Multi-turn injection is optional

Comparison with Envelope Equations

0.5 A KV Beam in a FODO channel

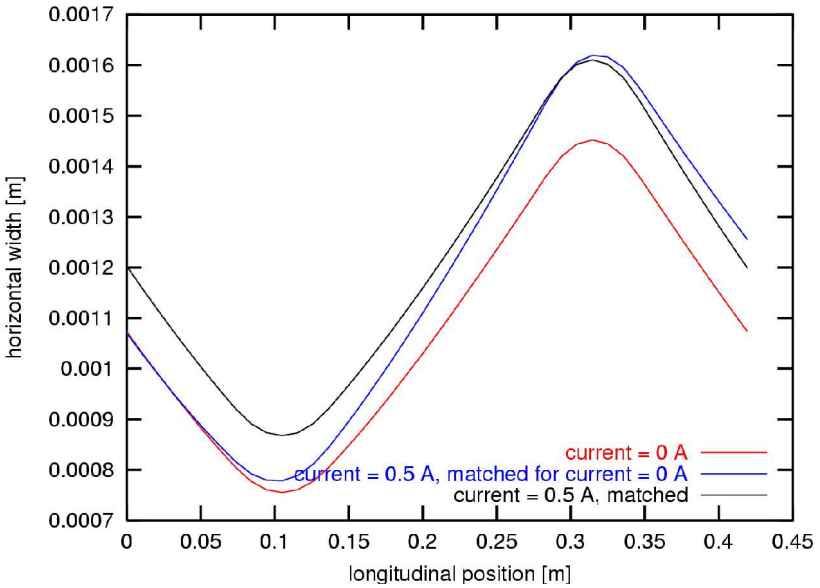


$$\sigma_x'' + K_x\sigma_x - \frac{\epsilon_{\rm rms}^2}{\sigma_x^2} = \frac{\xi}{4(\sigma_x+\sigma_y)}$$

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

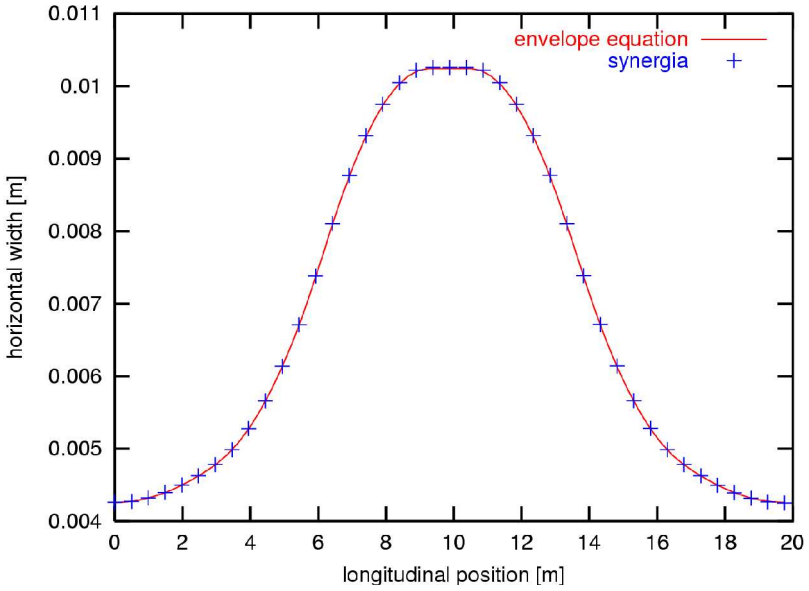
excellent model-theory agreement

results with and without current show the size of the space-charge effect

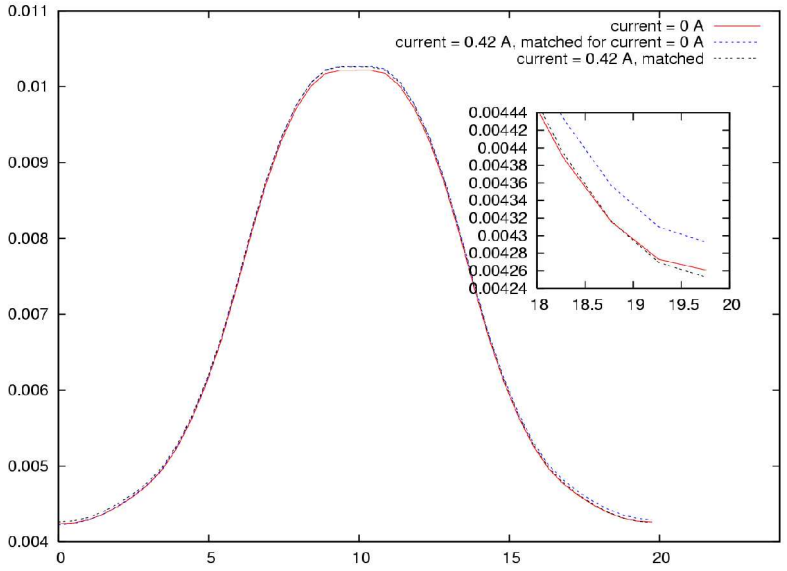


Envelope Equations 2

0.42 A Gaussian Beam in a Booster cell



Booster lattice consists of 24 cells

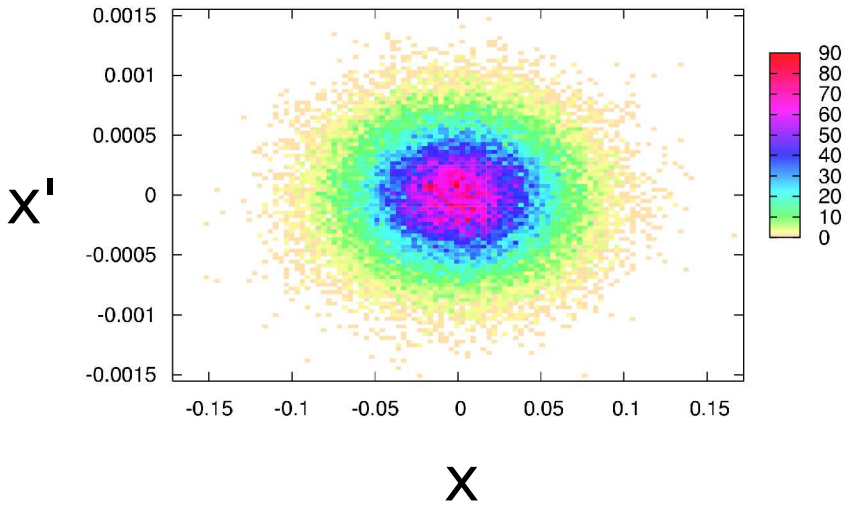


results with and without current show the size of the space-charge effect *in a single cell*

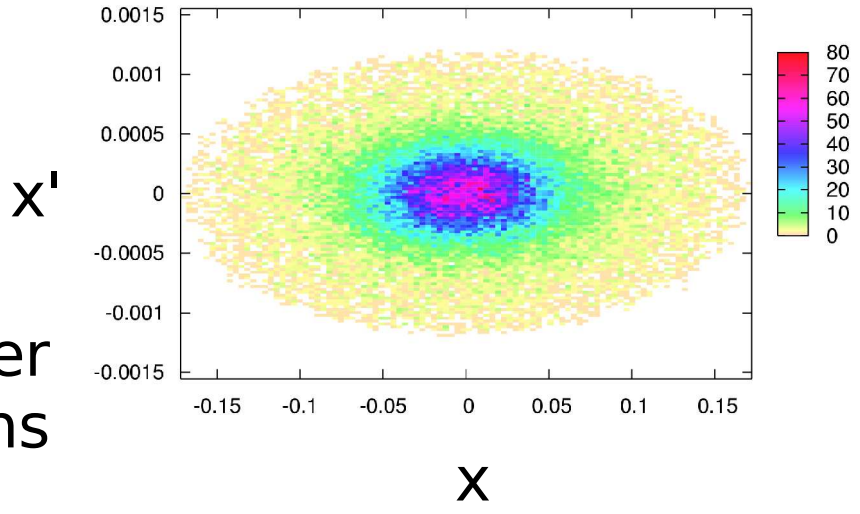
Halo Formation

Inject beam with 20% mismatch in both transverse planes

beam is adjusted so that width increases by 20%, but emittance stays constant

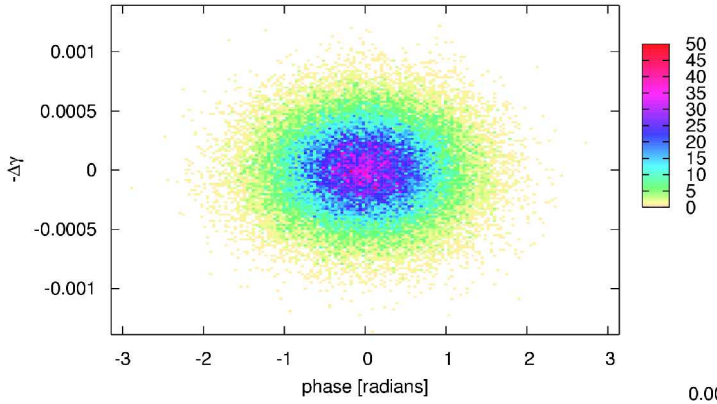


Initial horizontal phase-space profile



Phase-space profile after 100 turns

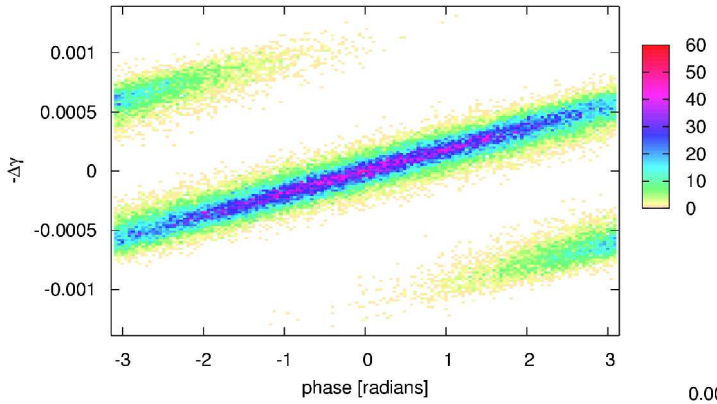
Longitudinal Evolution



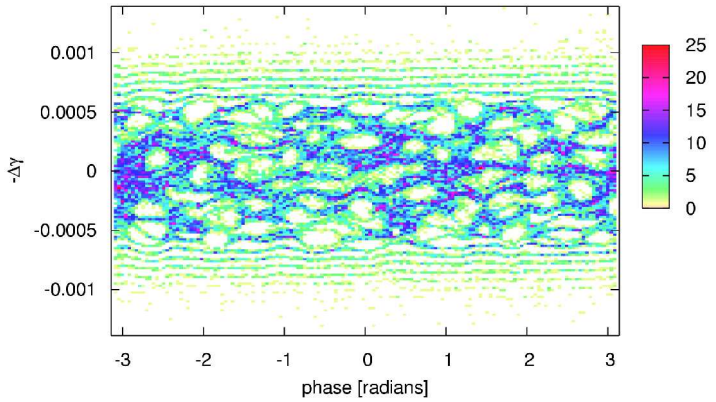
initial longitudinal phase space

simulation takes place before RF bunching starts

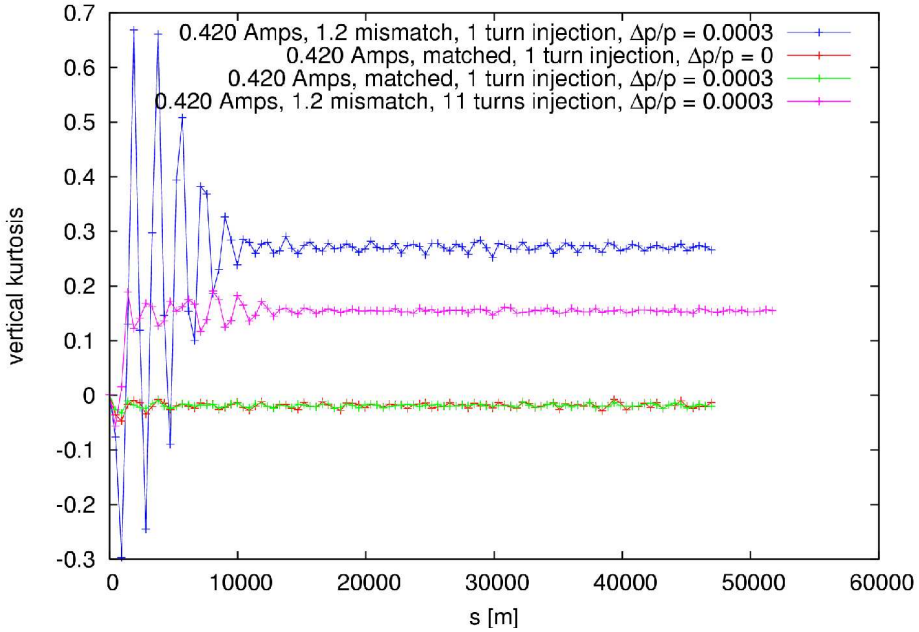
bunches start to merge after a few turns



longitudinal distribution is “uniform” for majority of simulation



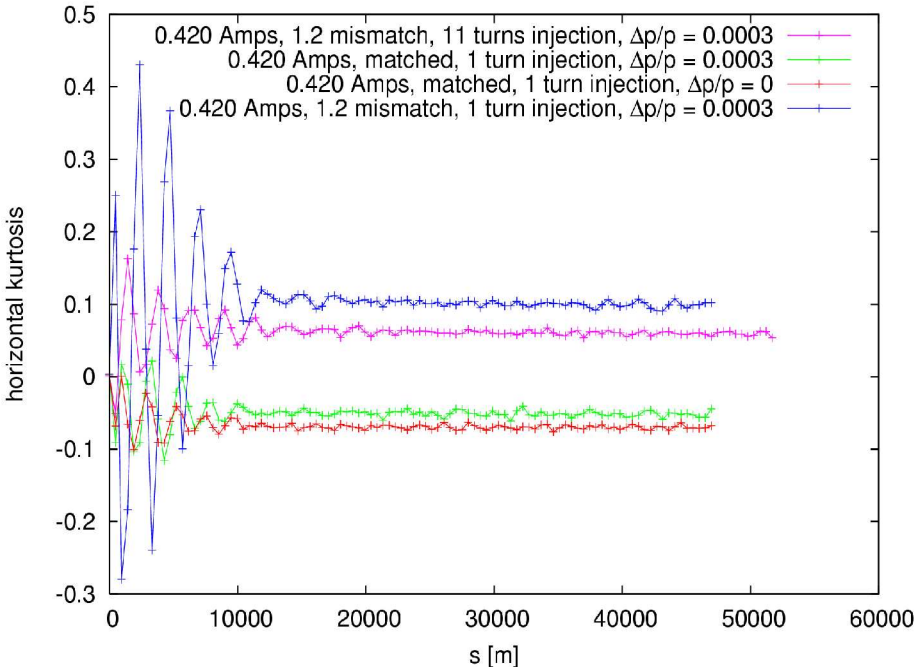
Quantitative Halo Formation



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

vertical

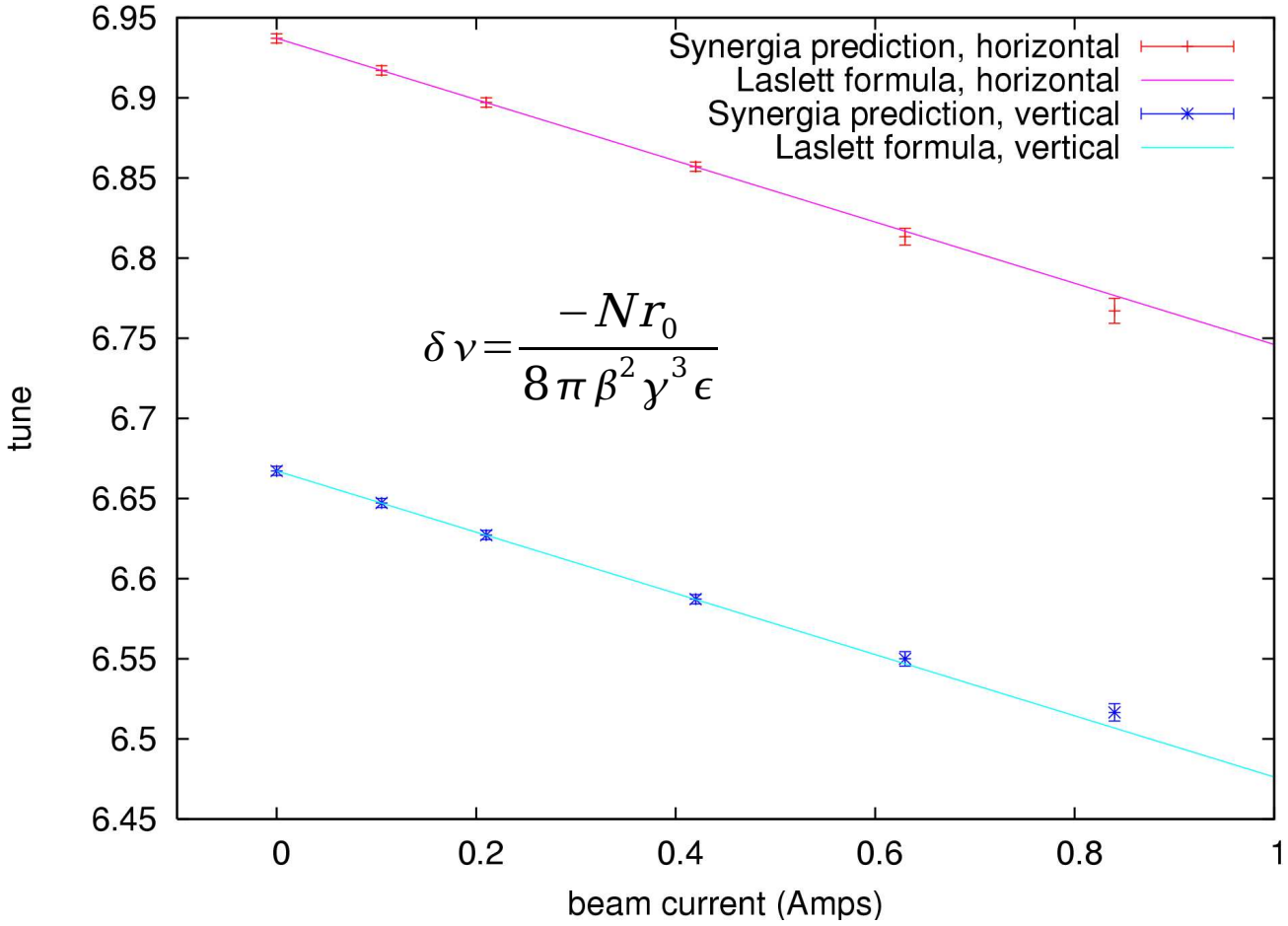
Comparison of vertical and horizontal measurements shows that chromaticity plays a substantial role in halo formation as well as space-charge



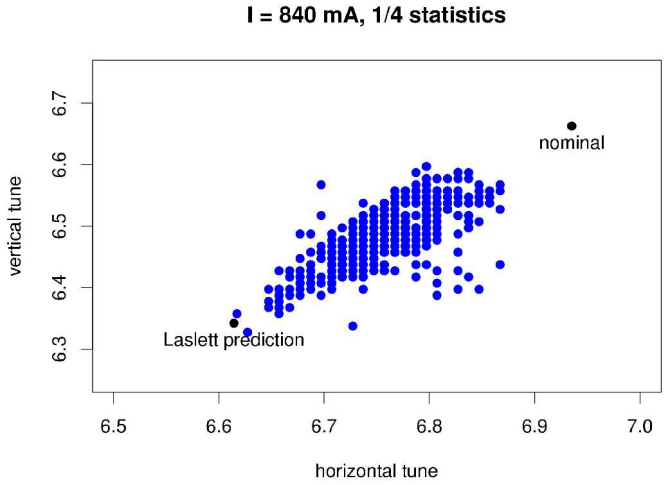
horizontal

Tune Shifts

Calculate individual particle tunes in the Booster using a KV beam

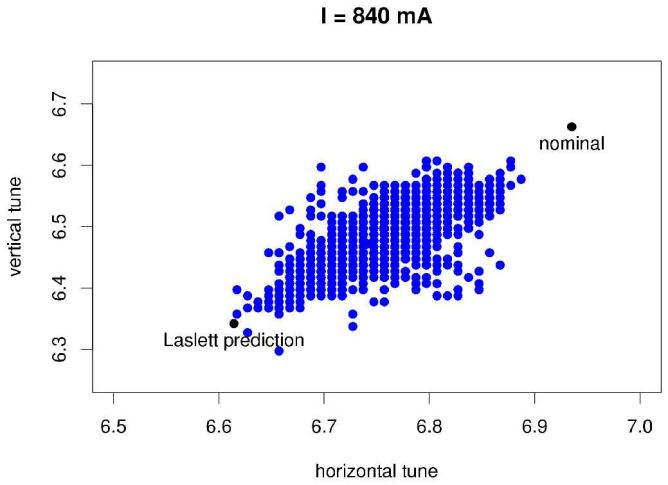


Tune Footprint



Calculate individual particle tunes in the Booster using a Gaussian beam

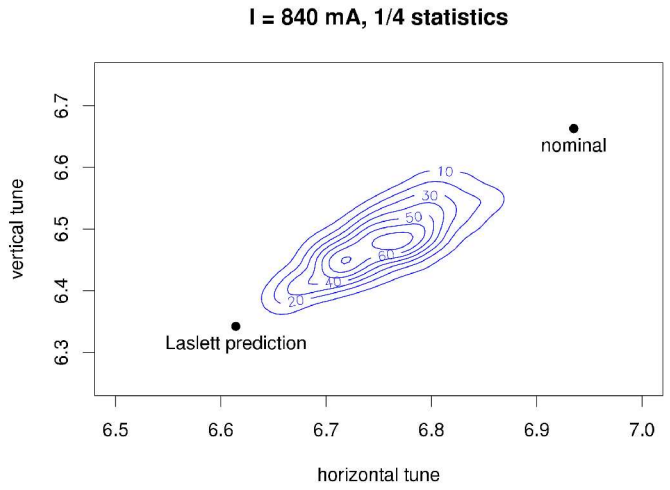
2x typical Booster current to emphasize effect



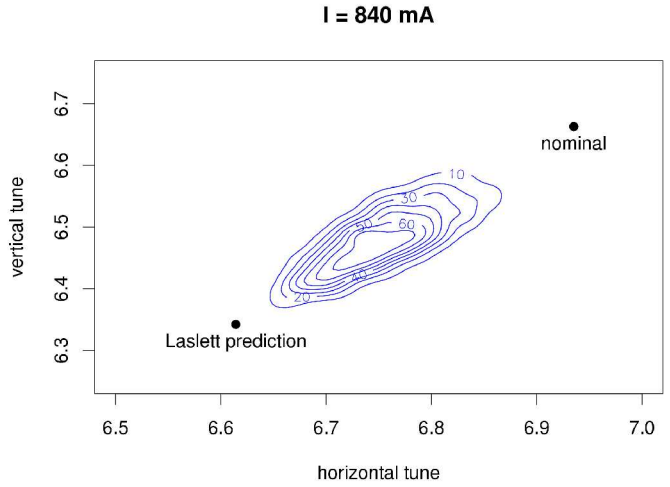
Laslett formula is really upper bound $\delta\nu = \frac{-Nr_0}{4\pi\beta^2\gamma^3\epsilon}$

Scatter plot is misleading. The two plots on the left differ only in statistics.

Better Tune Footprint



Contour plot is more robust

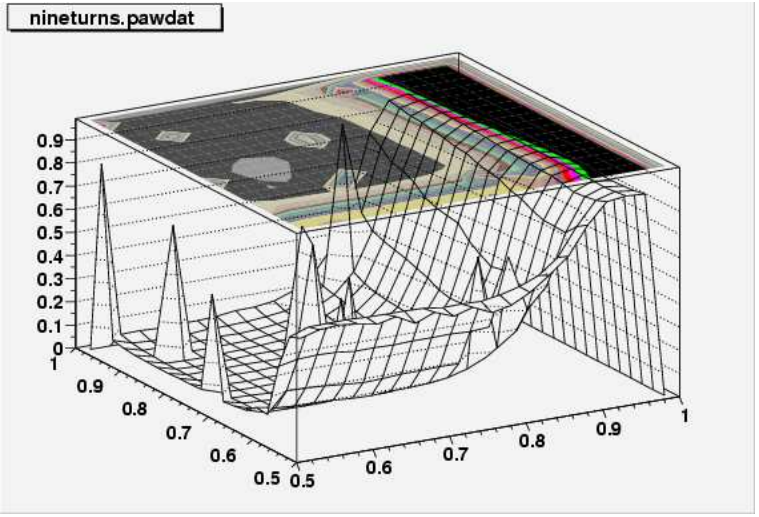


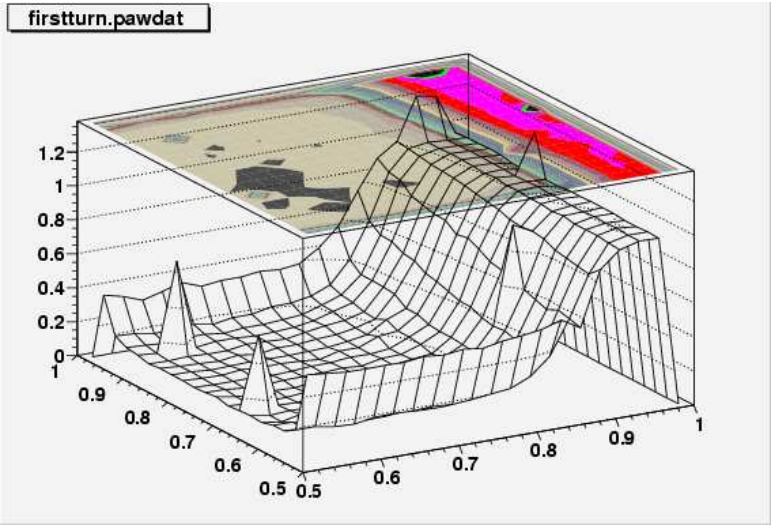
Extent of distribution is significantly less than indicated by scatter plot

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 ($\mathrm{d}Q$) and the space-charge tune shift (ΔQ_{sc}):

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

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

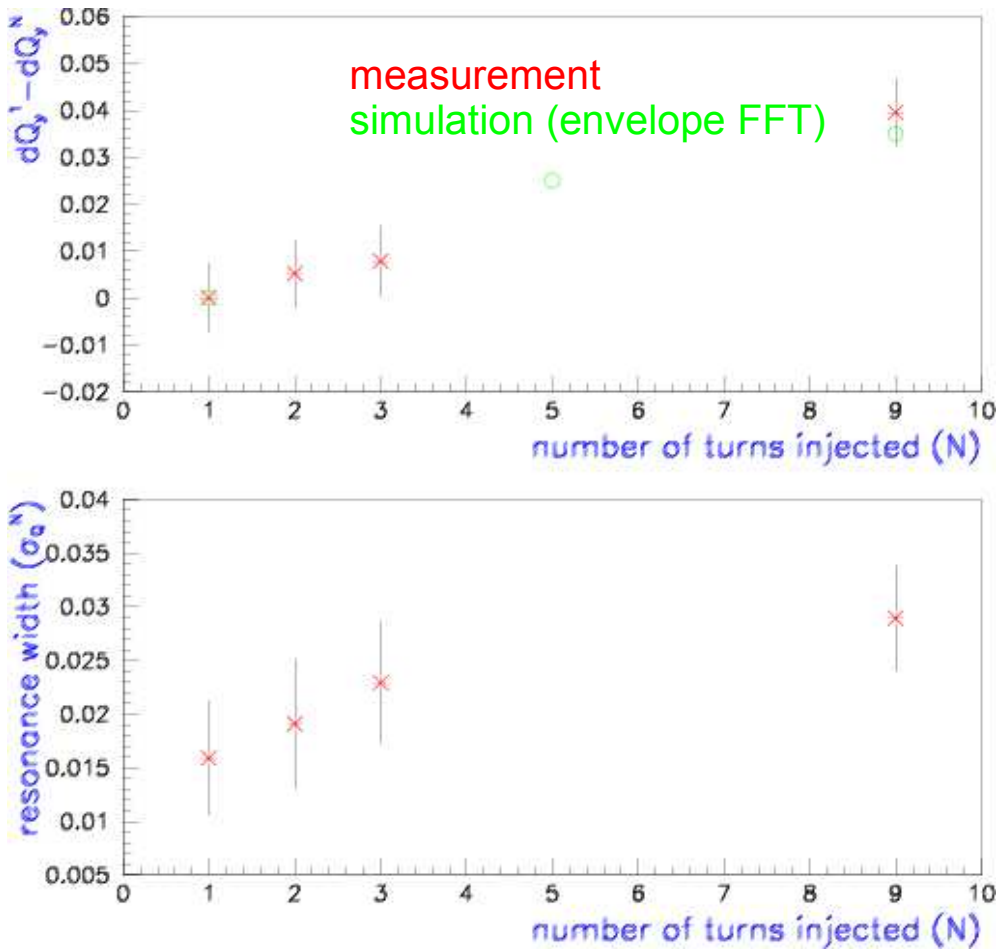
$$A: \ \frac{1}{2} = Q_0 + \Delta Q_{sc}^1 + \frac{dQ}{dI}(\Delta I_Q^1)$$

$$B: \ \frac{1}{2} = Q_0 + \Delta Q_{sc}^N + \frac{dQ}{dI}(\Delta I_Q^N)$$

$$B - A: \ 0 = \Delta Q_{sc}^N - \Delta Q_{sc}^1 + \frac{dQ}{dI}(\Delta I_Q^N - \Delta I_Q^1)$$

$$\Delta Q_{sc}^N - \Delta Q_{sc}^1 = \frac{dQ}{dI}(\Delta I_Q^1 - \Delta I_Q^N)$$

$$\Delta Q_{sc}^N - \Delta Q_{sc}^1 = \mathrm{d}Q_{(x/y)}^1 - \mathrm{d}Q_{(x/y)}^N$$



Conclusions

- The Booster is a working machine
  - Working conditions need to be separated from study conditions
- Large-scale simulations using Synergia show collective effects
  - (Mis)matching very important
  - Chromaticity important, too
- Theory-experiment comparison good where applicable
- Future
  - Simulations of longer time scales
    - investigate losses
  - Studies of resonant behavior