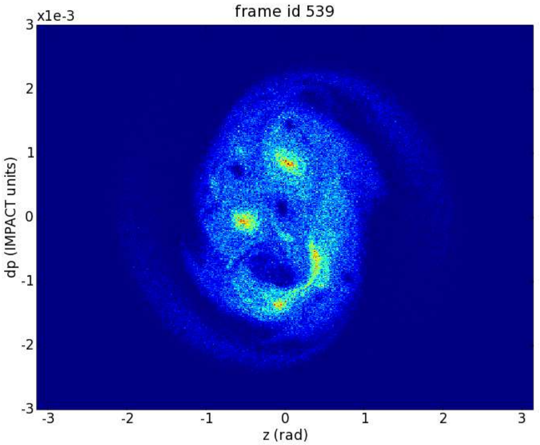
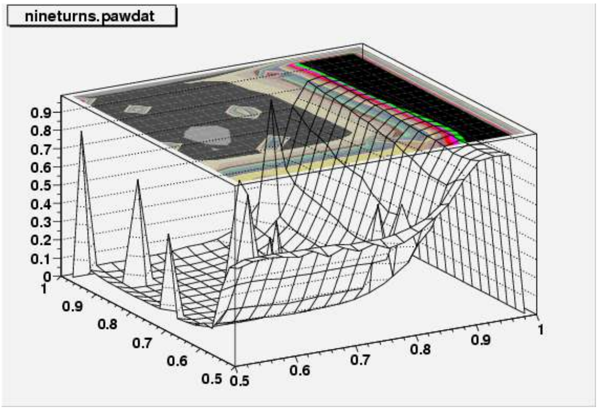
Simulations and studies of collective beam effects at FNAL

ANL Beam and Applications Seminar

Panagiotis Spentzouris, Fermilab





Why study collective effects?

- Increased demand on throughput of particle accelerators results in
  - higher beam currents, which require
    - excellent control of beam loss
    - ➔ multi-particle effects must be included accurately in design and optimization studies

Such effects include space-charge in low energy machines, beam-beam in colliders, wakefields, electron cloud effects, ...

Example: study of space charge effects

- Model behavior of
  - ~10^{12} particles
  - through 100's of beam-line elements
  - 1000's-10000's turns (if circular)
  - 6 degrees of freedom/particle

- Collective effects depend on beam distribution
- Beam distribution affected by
  - external forces
  - collective effects

Συνεργεια

Multi-particle dynamics

- Self consistent solution requires 3D modeling
- Use particle-in-cell (PIC) techniques
  - solve continuous equations on discrete grid
- Typical grid size: 50 x 50 x 150
- Large number of macroparticles (1-10M) required to study beam halo

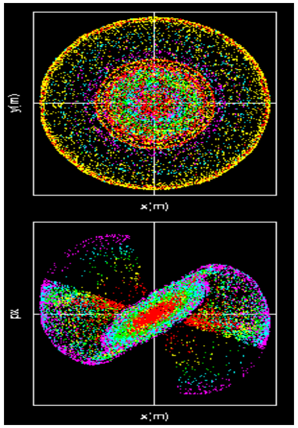
➔Parallel codes utilizing parallel computers are necessary

Συνεργεια

High-fidelity collective effects code development timeline

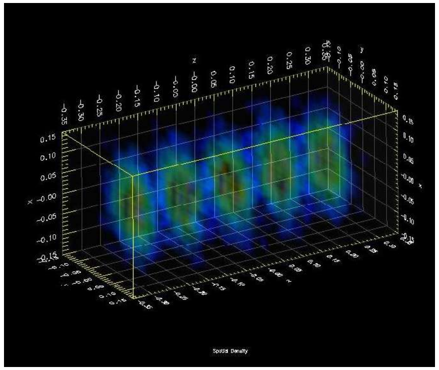
15 years of development utilizing special program funding

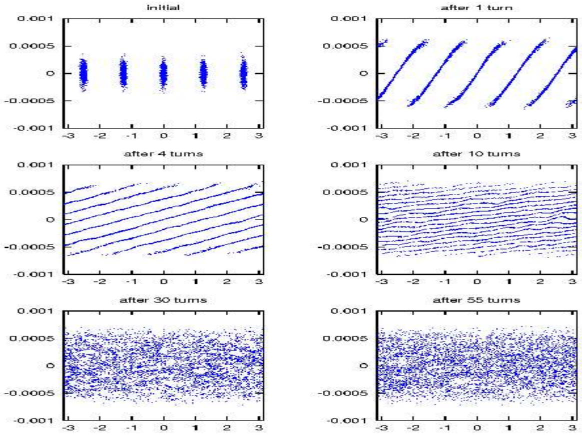
- Early 1990s: LANL-funded 2D PIC code development
- Mid 1990s: DOE Grand Challenge
  - LANL/SLAC/Stanford/UCLA
- 1999: DOE/HENP bridge funding to SciDAC project
  - introducing **FNAL** {space-charge in ionization cooling}



➔ 2001: SciDAC Project. **FNAL is a major contributor**

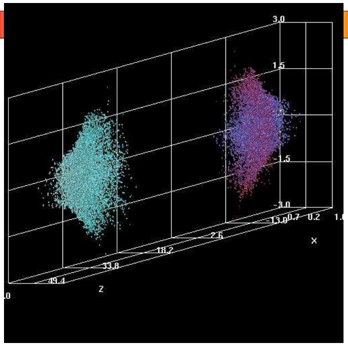
- Modeling of high intensity beams in circular machines
- Beam studies and analysis
- Extensible framework, integrated components



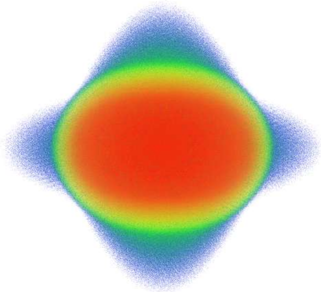


SciDAC Accelerator Science & Technology Collaboration

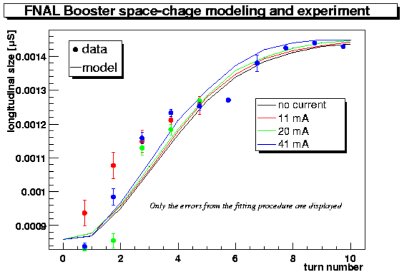
Συνεργεια



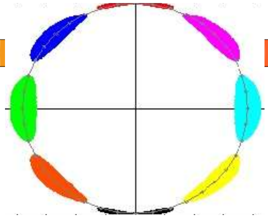
LBNL
Beam-beam modeling, space charge in linacs & rings, parallel Poisson solvers, collisions



UC Davis
Visualization, multi-resolution techniques



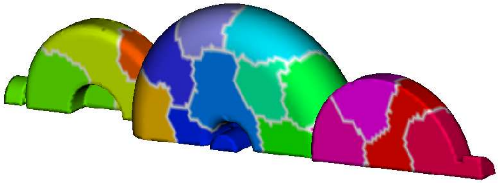
FNAL
Software Integration, Lie methods, space charge in rings, FNAL Booster sim/expt



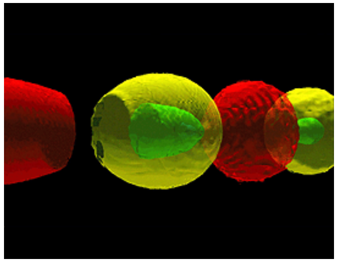
BNL
Wakefield effects, Space charge in rings, BNL Booster simulation

$$M=e^{:f_2:}\, e^{:f_3:}\, e^{:f_4:}\ldots$$
$$N=A^{-1} M A$$

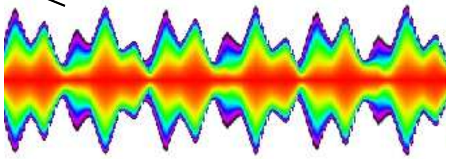
U. Maryland
Lie Methods in Accelerator Physics, MaryLie



SLAC
Electromagnetic component modeling



UCLA
Parallel PIC Frameworks



LANL
High order optics, beam expts, collisions, multi-language support, statistical methods

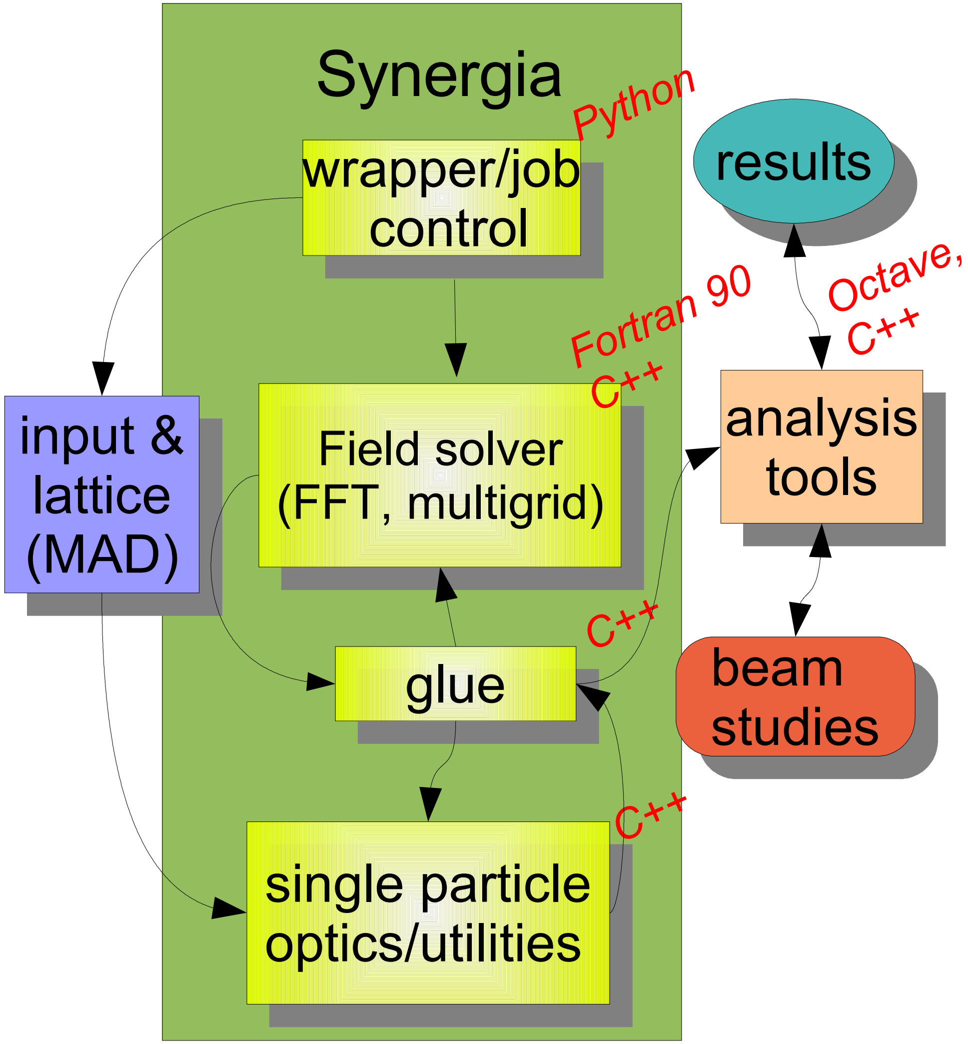
The FNAL Synergia project

Part of US DOE SciDAC program, with objectives:

- Develop accelerator simulation framework capable of 3D collective beam effect modeling, with realistic model parameters, in a time scale relevant for current operations.
  - tightly coupled parallel computing
  - flexible interface & analysis tools
  - re-use/integrate existing physics modules
- Develop necessary tools for modeling future accelerator designs

The Synergia Framework

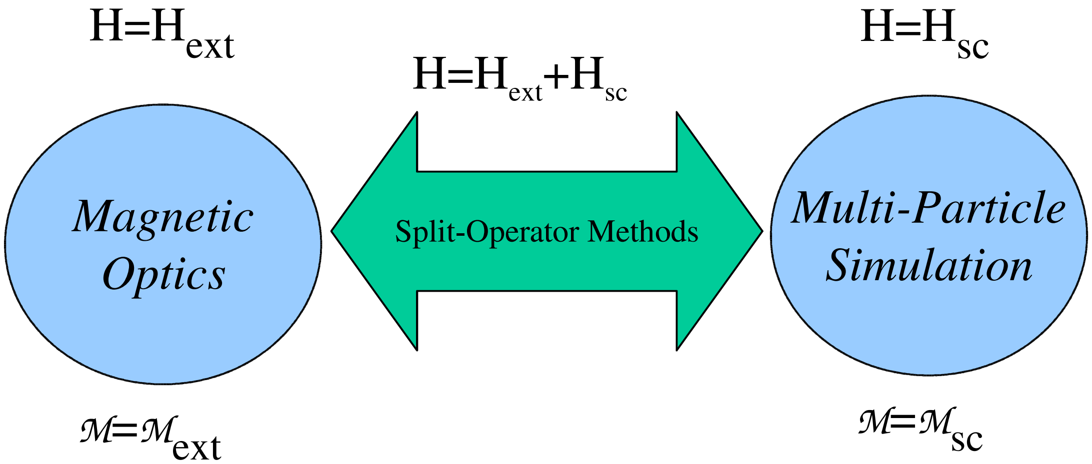
- Encapsulate & extend existing packages, develop new modules
  - single particle optics
    - arbitrary order maps (mxyzptlk, C++)
  - Multi-particle effects
    - Poisson solver: FFT (Impact, F90), multigrid (PETSc libraries, C/C++)
- Physics utilities (Python, C++, Octave)



Collective effects modeling

- Split Operator Method
  - Magnetic optics: efficient particle transport (with "S-codes": Lie maps), rapidly varying forces
  - Multi-particle: computationally expensive, slowly varying forces

minimize number of "expensive" steps



$H=H_{ext}$

$H=H_{ext}+H_{sc}$

$H=H_{sc}$

Magnetic Optics

Split-Operator Methods

Multi-Particle Simulation

$\mathcal{M}=\mathcal{M}_{ext}$

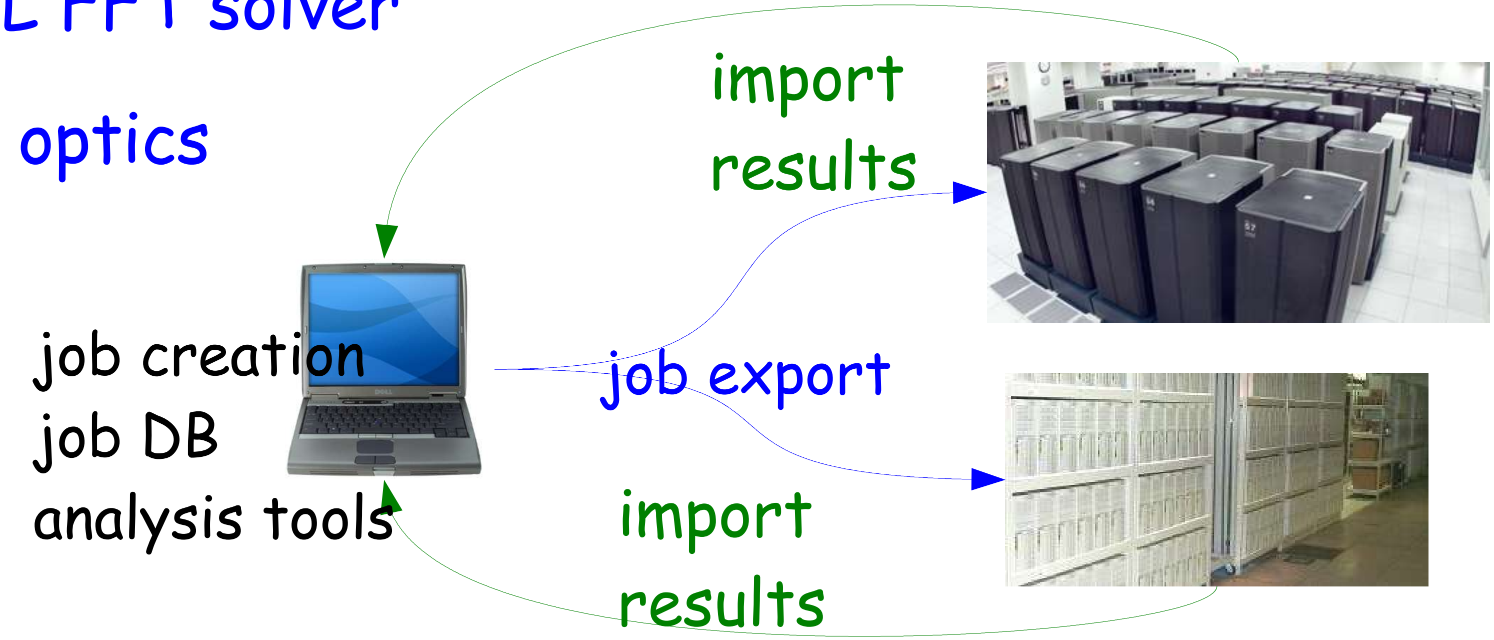
$\mathcal{M}=\mathcal{M}_{sc}$

$$\mathcal{M}(t) = \mathcal{M}_{ext}(t/2)\,\mathcal{M}_{sc}(t)\,\mathcal{M}_{ext}(t/2) + O(t^3)$$

Synergia framework

- Humane user interface & flexible “model building” tools
- Complete job management & portable build systems
- Analysis tools & diagnostics
- Re-use LBNL FFT solver and FNAL AD optics libraries

develop new solvers



job creation
job DB
analysis tools

job export

import results

import results

Synergia framework

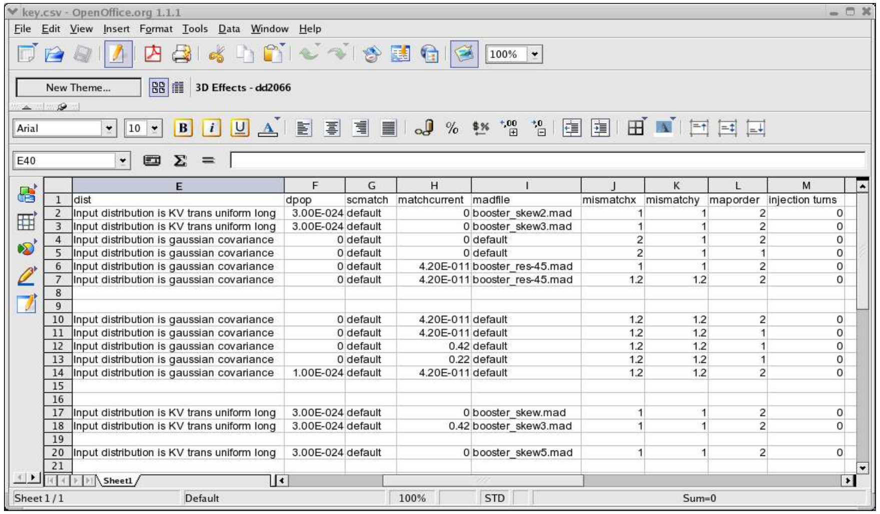
```
mad_file = myopts.get_value("Mfile")
(D_x, D_y) = madcalc.dispersion_initial(mad_file,"bcelinj",
                                        myopts.get_value("energy"))
if myopts.get_value("matchcurrent") != None:
    match_current = myopts.get_value("matchcurrent")
else:
    match_current = ip.current()
[sigma_x,sigma_xprime,r_x,sigma_y,sigma_yprime,r_y] = envelope_match(
    myopts.get_value("emit"), match_current,mad_file)

mismatchx = myopts.get_value("mismatchx")
mismatchy = myopts.get_value("mismatchy")
ip.x_params(sigma = sigma_x * mismatchx, lam = sigma_xprime * pz / mismatchx)
ip.y_params(sigma = sigma_y * mismatchy, lam = sigma_yprime * pz / mismatchy)
```

job creation script

geometry discription in standard (MAD) language

beam generation “matching module”

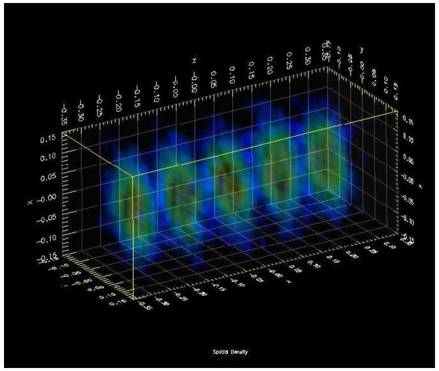


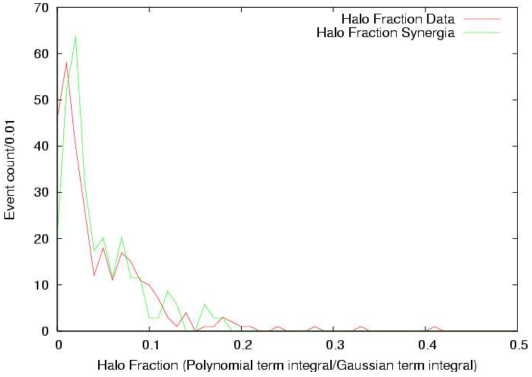
	E	F	G	H	I	J	K	L	M
1	dist	dpop	scmatch	matchcurrent	madfile	mismatchx	mismatchy	maporder	injection turns
2	Input distribution is KV trans uniform long	3.00E-024	default	0	booster_skew2.mad	1	1	2	0
3	Input distribution is KV trans uniform long	3.00E-024	default	0	booster_skew3.mad	1	1	2	0
4	Input distribution is gaussian covariance	0	default	0	default	2	1	2	0
5	Input distribution is gaussian covariance	0	default	0	default	2	1	1	0
6	Input distribution is gaussian covariance	0	default	4.20E-011	booster_res-45.mad	1	1	2	0
7	Input distribution is gaussian covariance	0	default	4.20E-011	booster_res-45.mad	1.2	1.2	2	0
8									
9									
10	Input distribution is gaussian covariance	0	default	4.20E-011	default	1.2	1.2	2	0
11	Input distribution is gaussian covariance	0	default	4.20E-011	default	1.2	1.2	1	0
12	Input distribution is gaussian covariance	0	default	0.42	default	1.2	1.2	1	0
13	Input distribution is gaussian covariance	0	default	0.22	default	1.2	1.2	1	0
14	Input distribution is gaussian covariance	1.00E-024	default	4.20E-011	default	1.2	1.2	2	0
15									
16									
17	Input distribution is KV trans uniform long	3.00E-024	default	0	booster_skew.mad	1	1	2	0
18	Input distribution is KV trans uniform long	3.00E-024	default	0.42	booster_skew3.mad	1	1	2	0
19									
20	Input distribution is KV trans uniform long	3.00E-024	default	0	booster_skew5.mad	1	1	2	0
21									

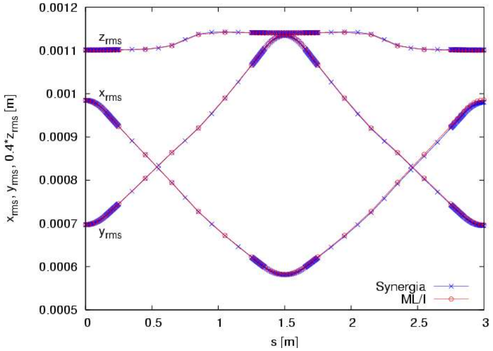
automatic job database

Physics Applications

- 3D space-charge model
  - Multi-bunch capabilities, variety boundary conditions (open, closed, periodic)
  - Tested against other codes and theory
  - Applied to Fermilab Booster modeling







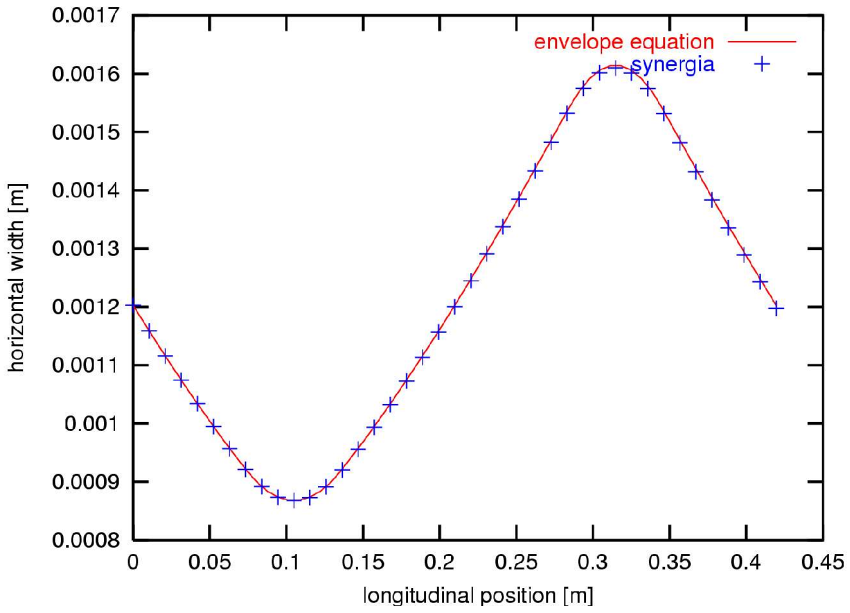
Journal of Computational Physics, Vol. 211, Issue 1, 2005

Model validation tests

0.5 A KV Beam in a FODO channel

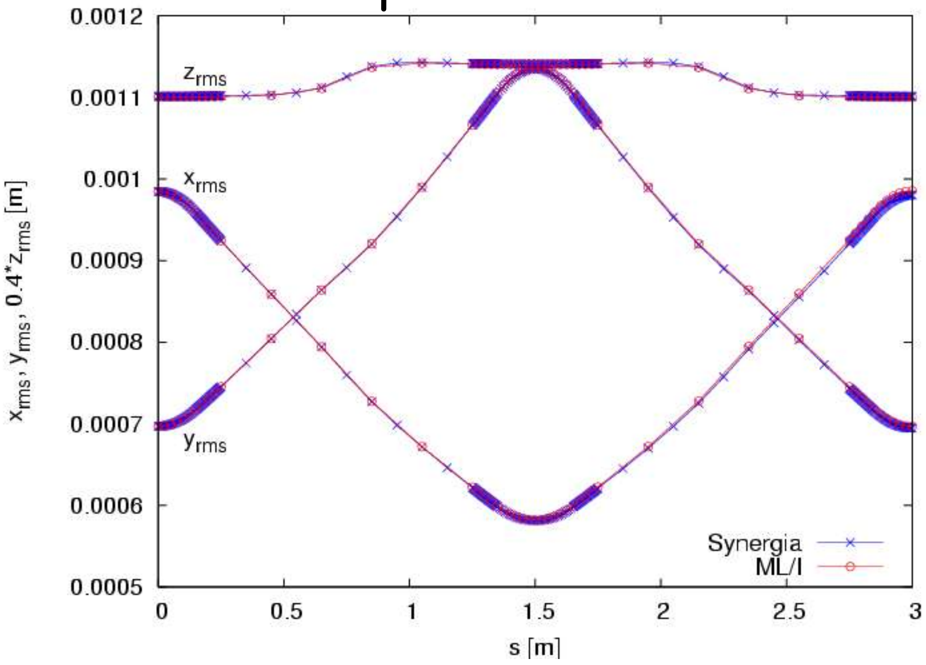
$$\sigma_x'' + K_x\sigma_x - \frac{\epsilon_{\rm rms}^2}{\sigma_x^2} = \frac{\xi}{4(\sigma_x+\sigma_y)}$$

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



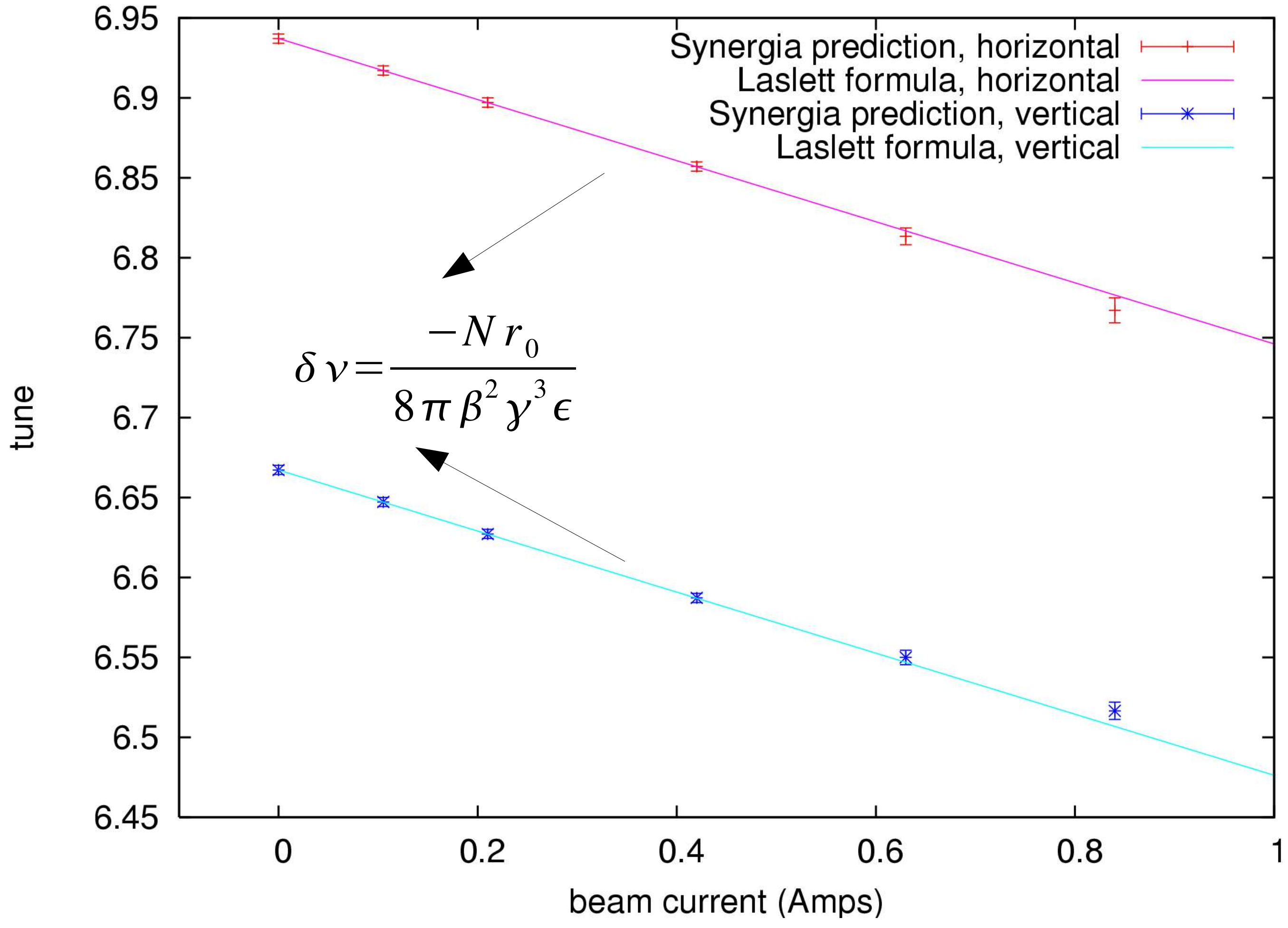
Overall, excellent model-theory & code to code agreement

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



Tune Shifts, compare with Laslett

Particle tunes in a FNAL Booster cell using a KV beam. (open boundary conditions)

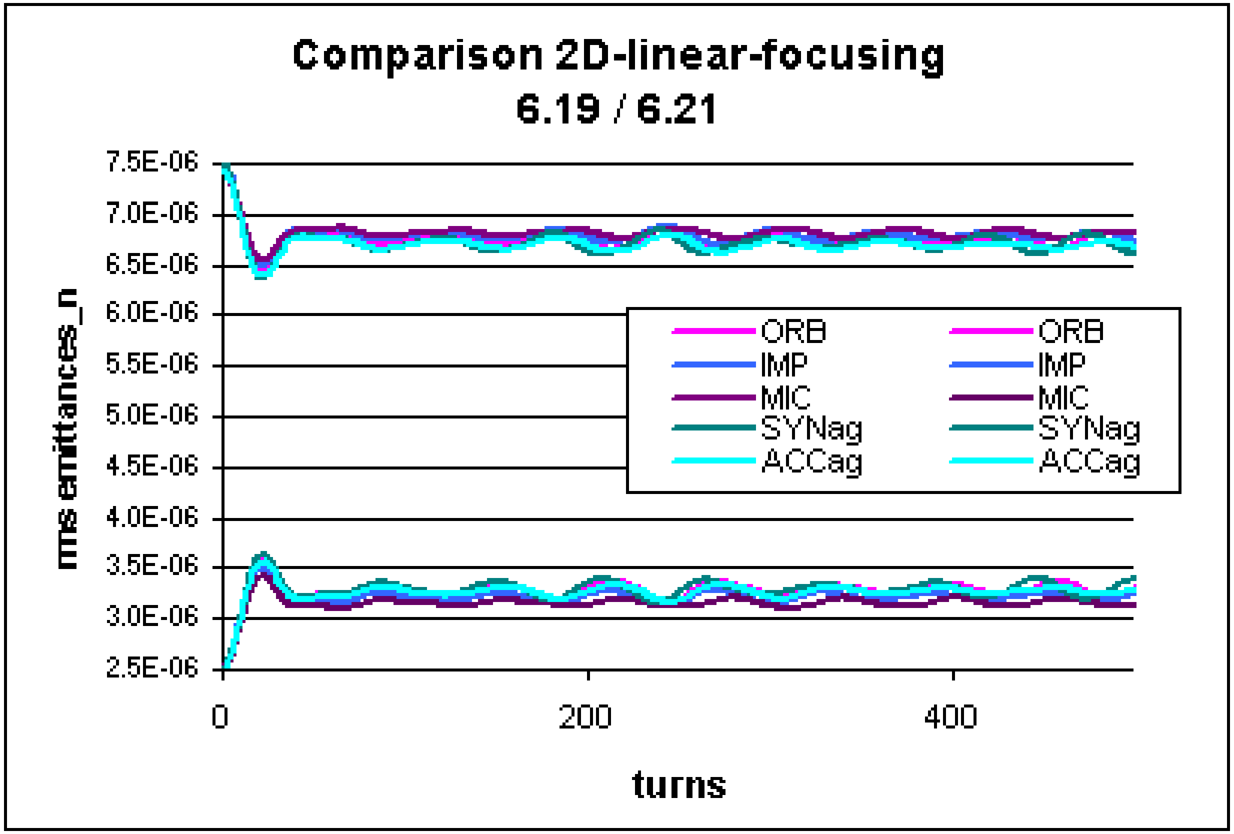


$$\delta\nu = \frac{-N r_0}{8\pi\beta^2\gamma^3\epsilon}$$

CERN PS modeling & benchmarks

Model Montague resonance at the CERN PS (standard simulation candle)

Compare with other codes (Hofmann, et al., PAC05)

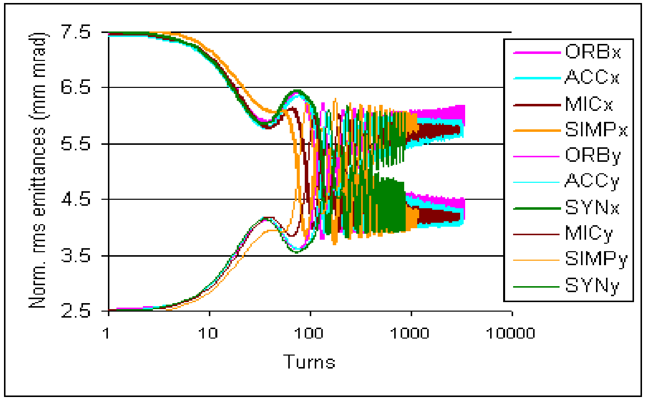


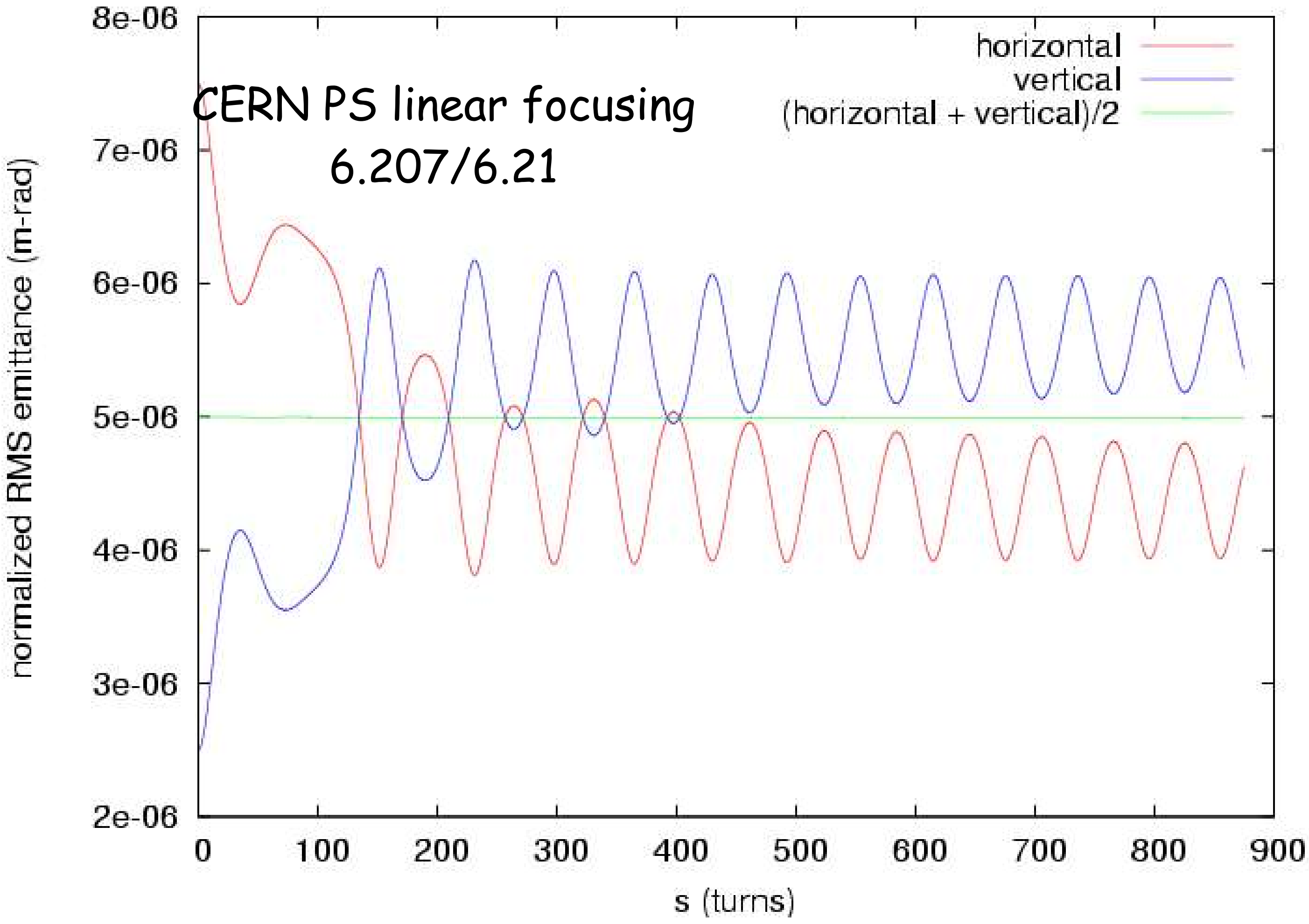
Montague resonance: space charge driven $2Q_x - 2Q_y = 0$ resonance

Numerical stability

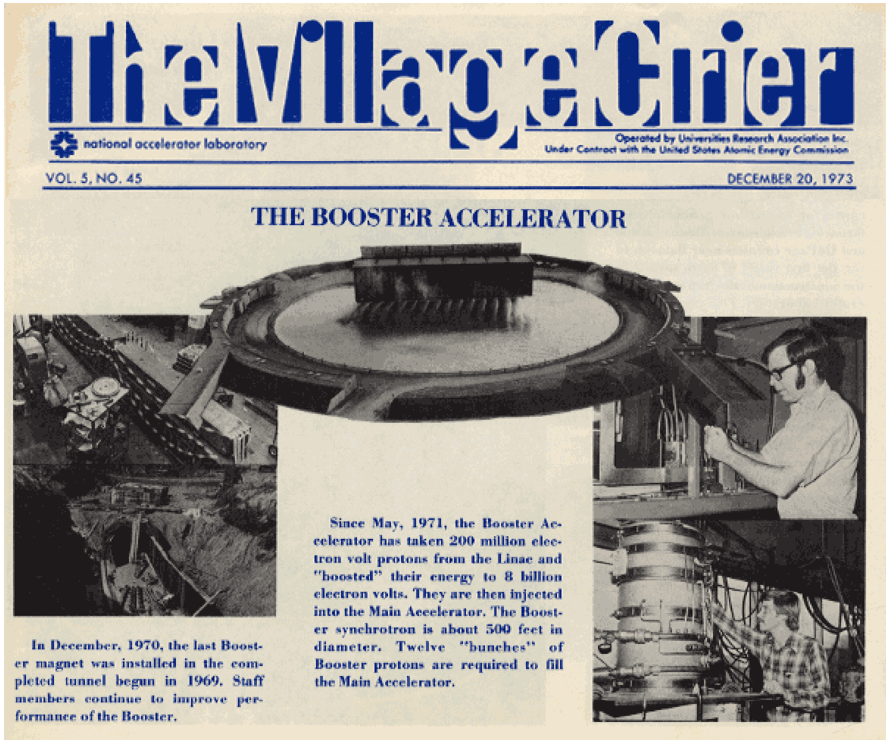
Coupling resonance preserves sum of horizontal and vertical emittance

Most numerically stable implementation in benchmarks!




CERN PS linear focusing 6.207/6.21

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.

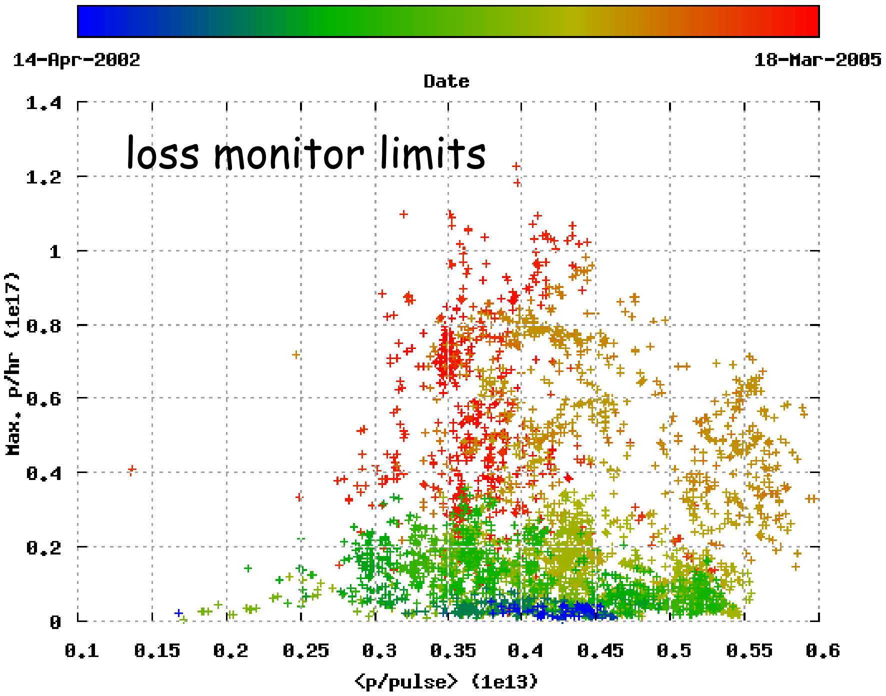
In December, 1970, the last Booster magnet was installed in the completed tunnel begun in 1969. Staff members continue to improve performance of the Booster.

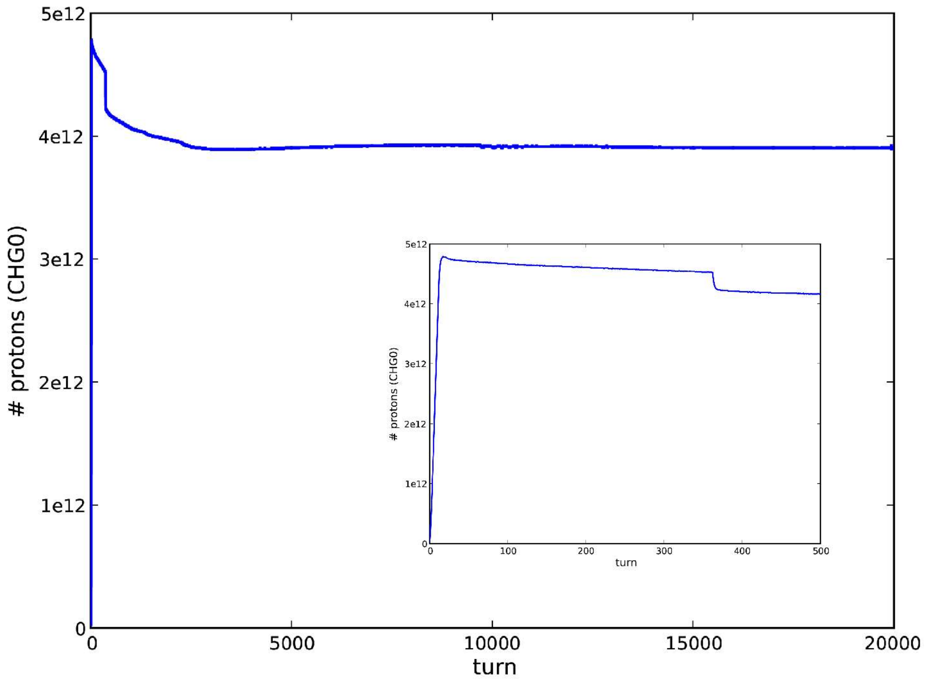
- Rapid cycling, 15 Hz

  400 MeV → 8 GeV
- 24 FOFDOOD cells, 474.2 m long
- RF 37.7 → 52.1 Mhz
- Injection/capture ~ 2 ms
- Multiturn injection, typically 12x35 mA = 420 mA
  - or 4.5E12 ppp @ ~7Hz
- $\nu_h = 6.94$; $\nu_v = 6.66$

FNAL Booster performance

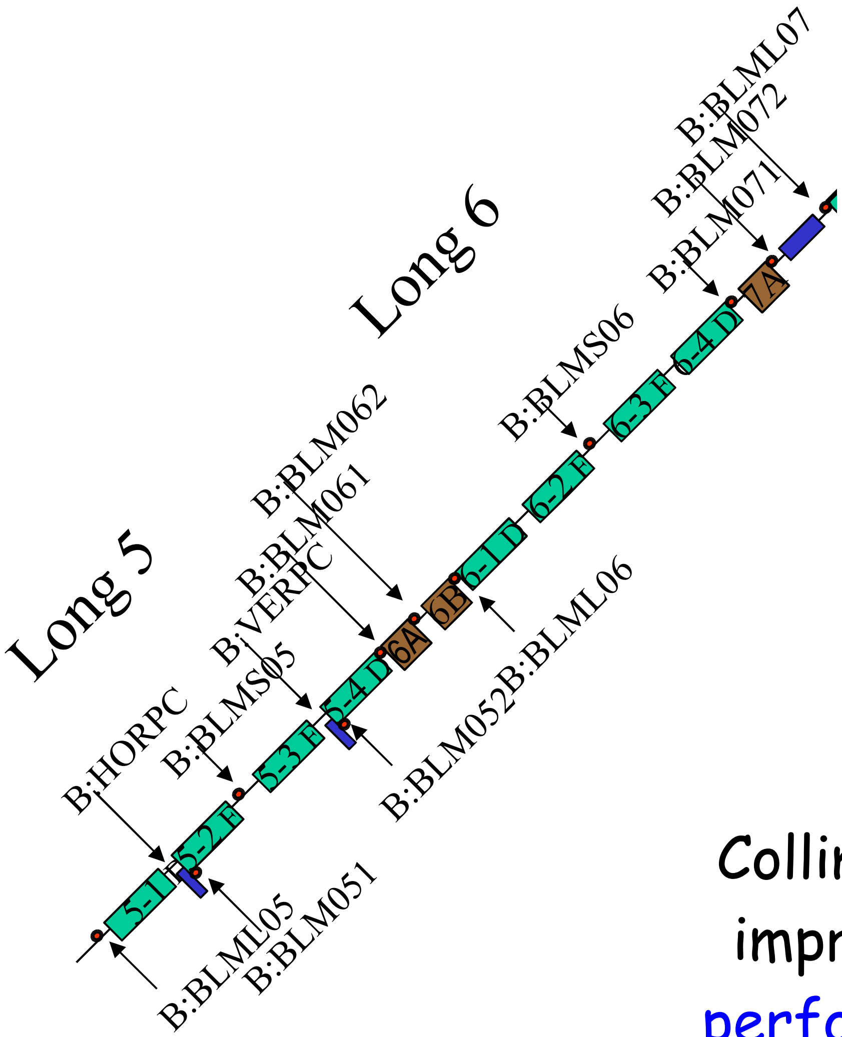
The Booster needs to provide ~5E20 protons/year to serve needs of current FNAL program (emphasis on neutrinos!)

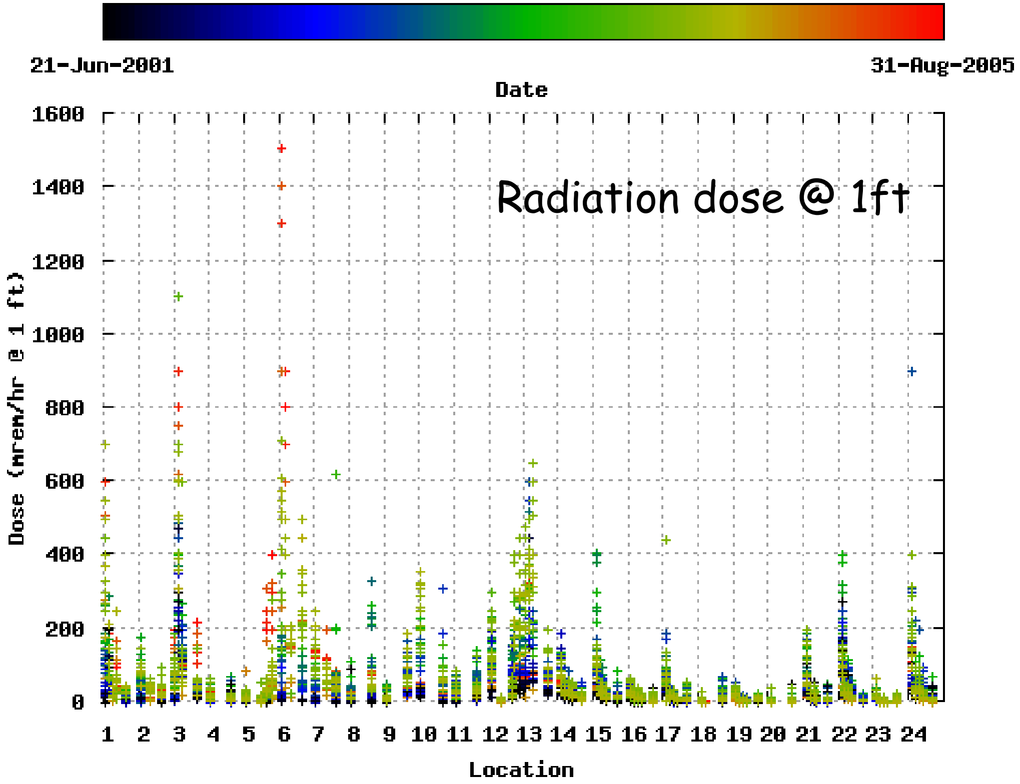




Biggest worry/constraint: damage and activation of tunnel components due to beam loss

Installed collimators improve but not eliminate problem





Radiation dose @ 1ft

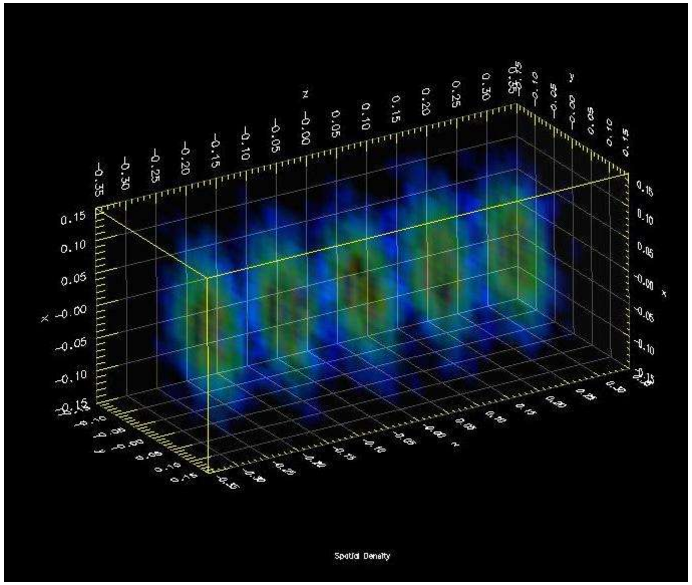
Collimators operational since April '04 improve loss situation, but even their performance depends on beam stability

Συνεργεια

Booster modeling objectives

- Study/quantify development of beam tails
  - for operational parameters
  - with realistic initial conditions
  - compare to beam data
    - understand instrumentation
- Scan parameter space
  - better operational conditions
- Do some physics in the process...

Simulation details

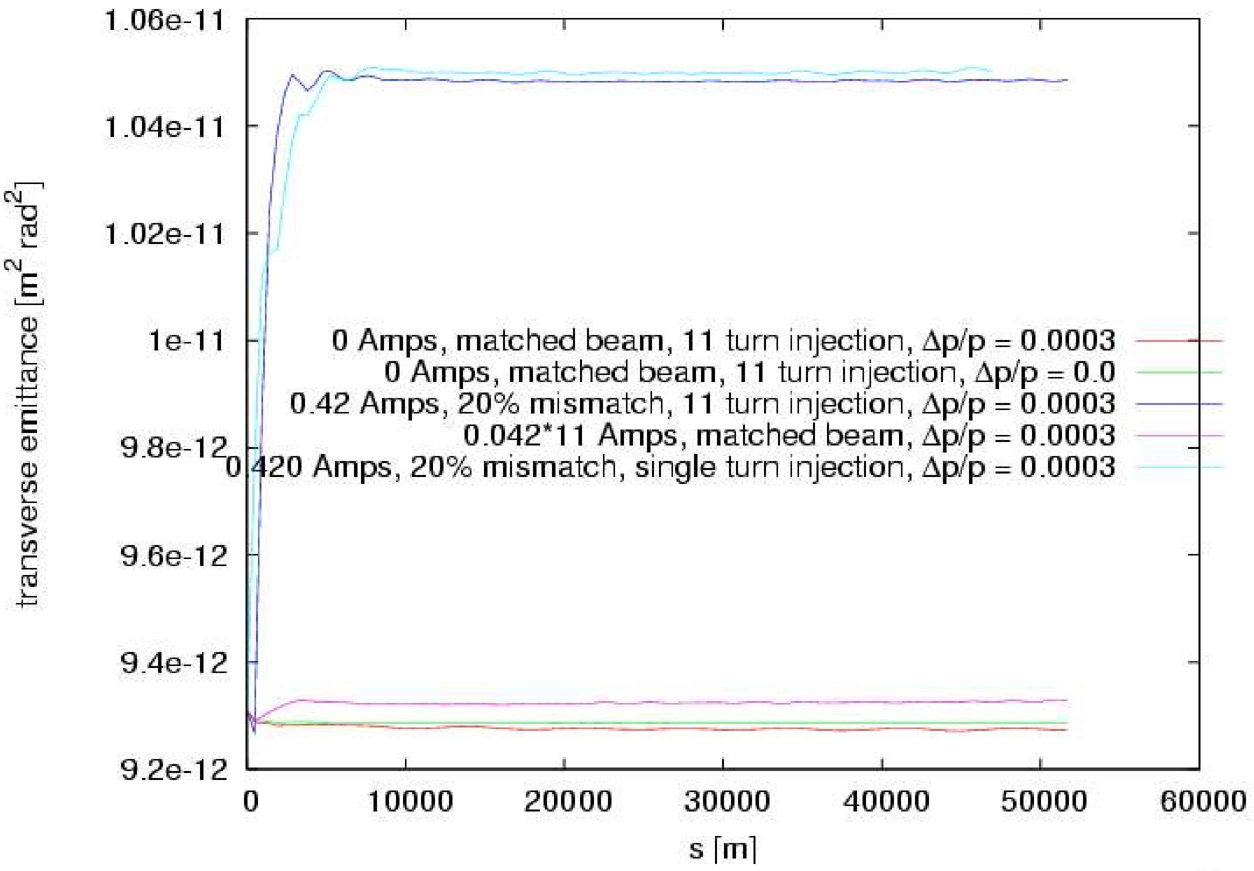


Multi-bunch modeling in 3D

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

- Fully 3D space-charge
- Use 33x33x257 grid and ~ 5,000,000 particles
- boundary conditions
  - longitudinal periodic
  - transverse closed
- Multi-turn injection
- 6-D PhS matched beam generation utilities

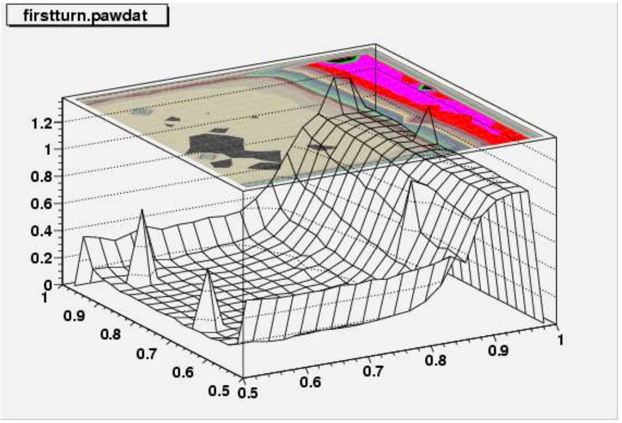
FNAL Booster, coasting beam

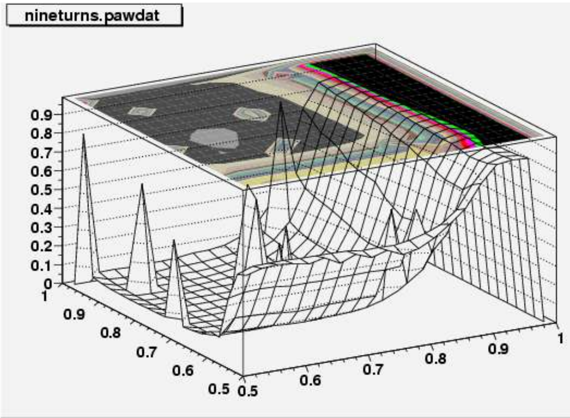


3-D FNAL Booster simulation, using 2nd order maps, with coasting beam. The simulation shows a 12% increase in transverse emittance due to space charge for 20% mismatch. This agrees well with the prediction (13%) from Reiser's free energy model:

$$\frac{\epsilon_f^T}{\epsilon_i^T} = 1 + 4\left[(\mu-1)^2 - (\mu-1)^3\right] + \mathcal{O}((\mu-1)^4),$$

Coherent Space-charge effects





- **Booster coasting beam experiment**
  - use corrector quads to vary horizontal and vertical tunes
  - record beam transmission to locate resonances
  - repeat for different currents
  - Tune shifts extracted from shifted resonance location vs quad current.

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

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

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

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

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

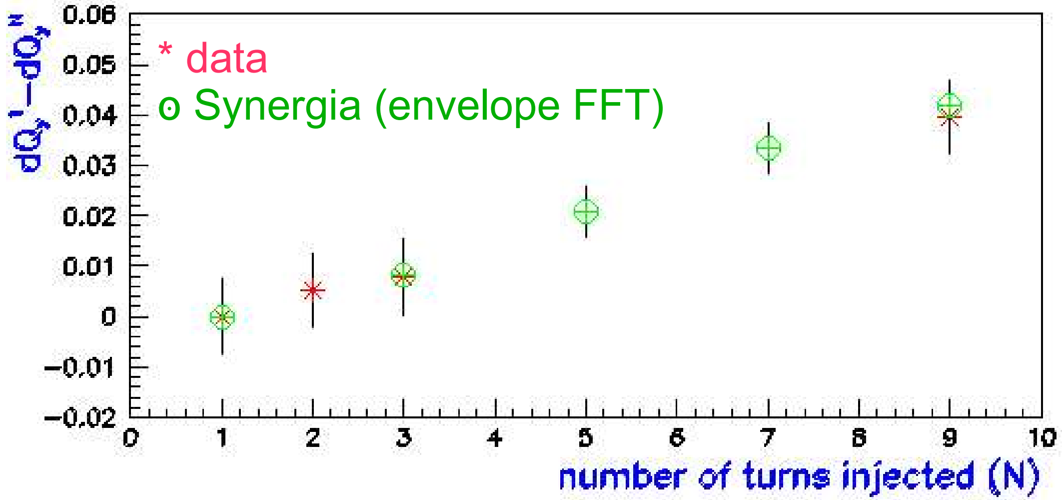
$$B - A: \ 0 = \Delta Q^N_{sc} - \Delta Q^1_{sc} + \frac{dQ}{dI}(\Delta I^N_Q - \Delta I^1_Q)$$

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

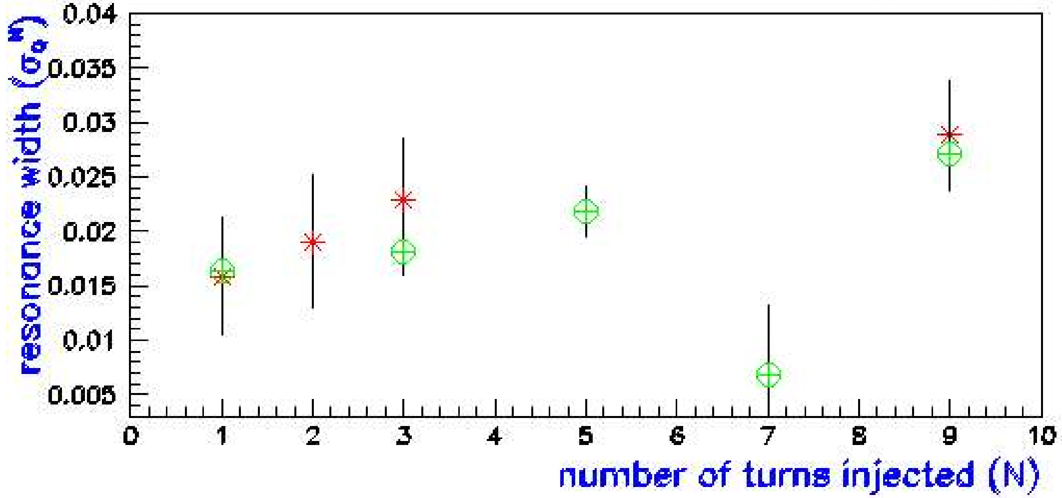
$$\Delta Q^N_{sc} - \Delta Q^1_{sc} = \mathrm{dQ}^1_{(x/y)} - \mathrm{dQ}^N_{(x/y)}$$

Coherent tune shift

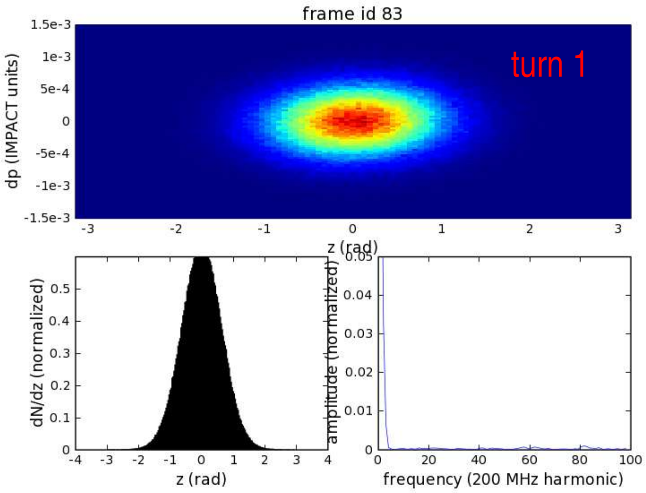
Fit transmission vs tune data and extract location and width of resonance for different currents.

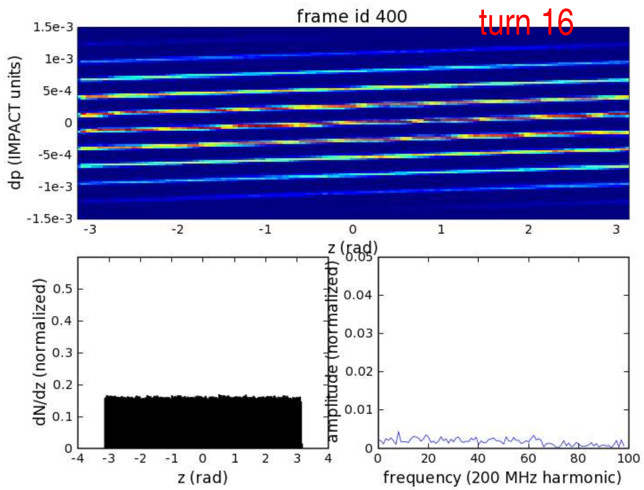


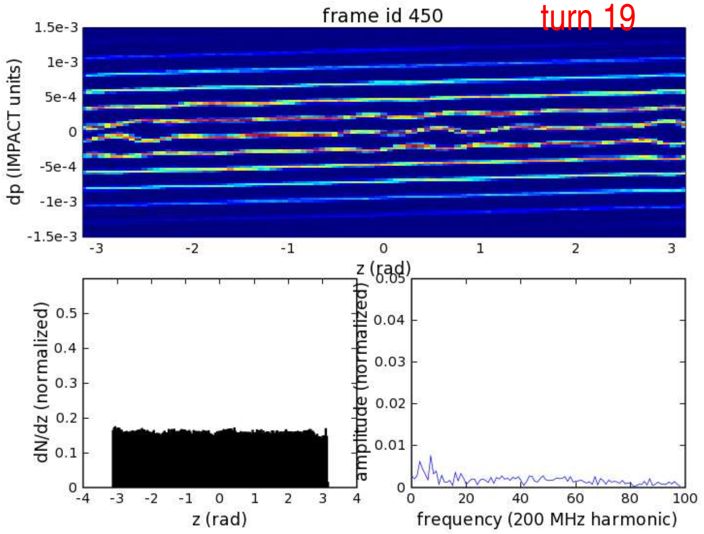
Compare with Synergia: excellent data and simulation agreement

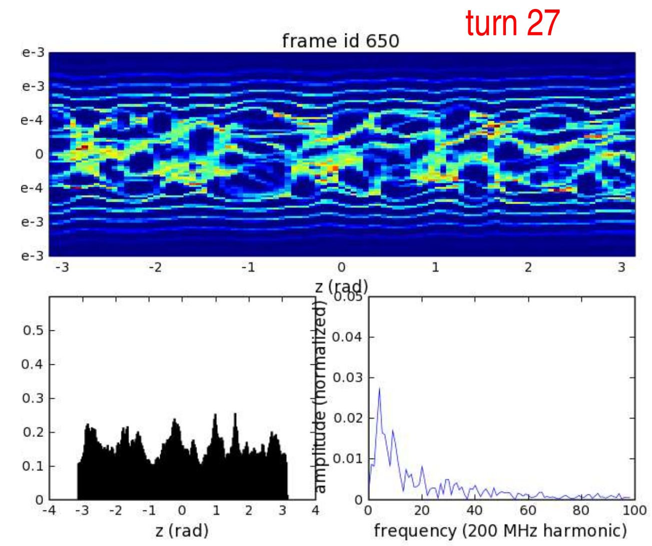


Coherent noise due to space-charge









No RF bunching

Structure appears~10 turns after beam de-coheres.

Effect independent of grid size & initial distribution details, depends on beam current & size of beam pipe

Observation agrees with *I. Hofmann, Part.Accel.34, 1990*

Bunched beam, beam shape studies

IPM detector calibration

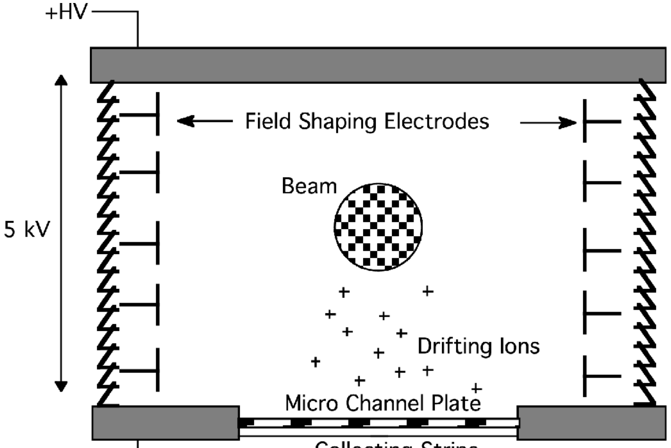
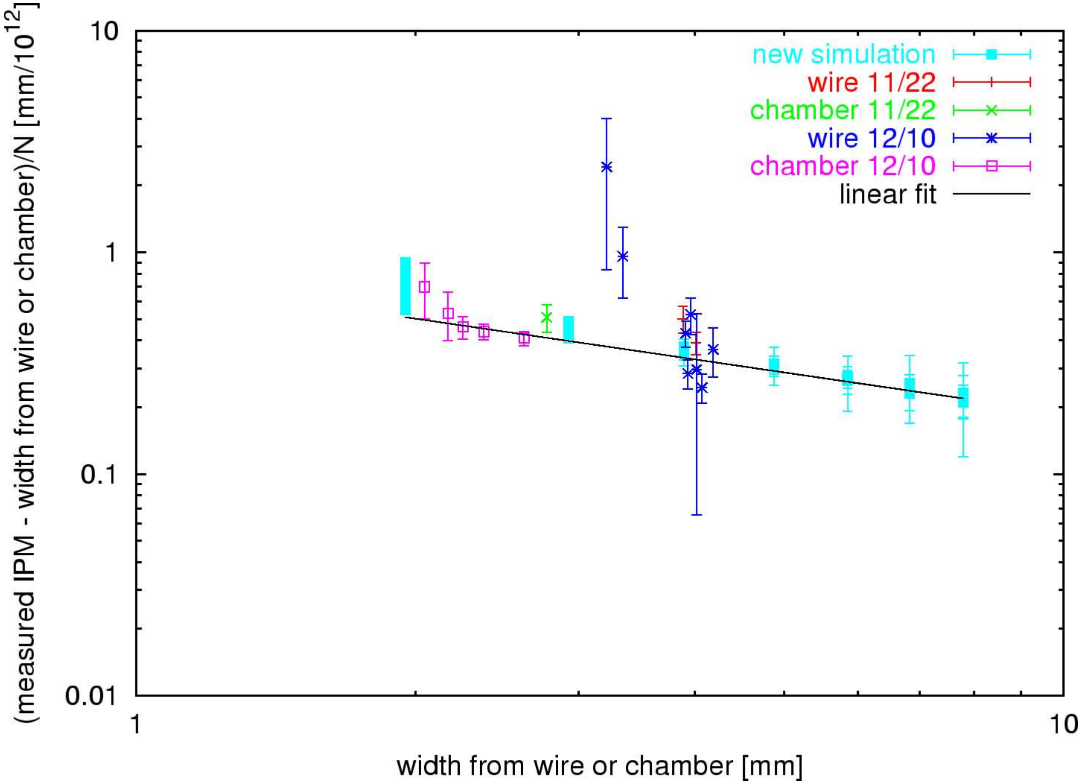


figure 8.6

Ionization Profile Monitor detector provides transverse beam profile measurements/turn. Response depends on beam charge.

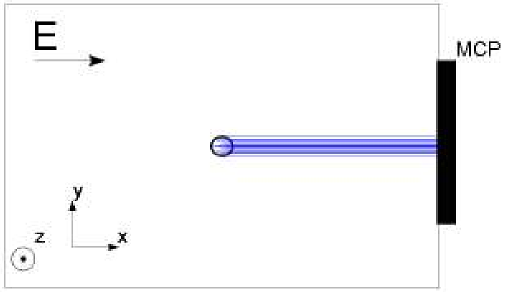
We modeled the IPM response and calibrated the detector against other detectors (wire @ injection and MWPC @ extraction)

J. Amundson, J. Lackey, P. Spentzouris, G. Jungman and L. Spentzouris, ***Phys. Rev. ST Accel. Beams 6:102801, 2003***

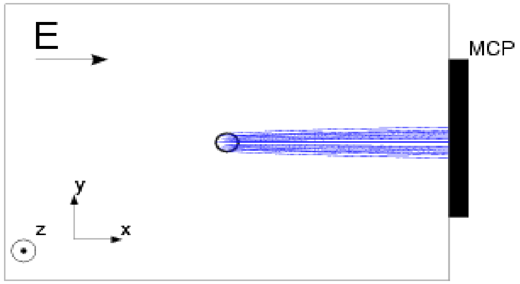


IPM Calibration

IPM response model

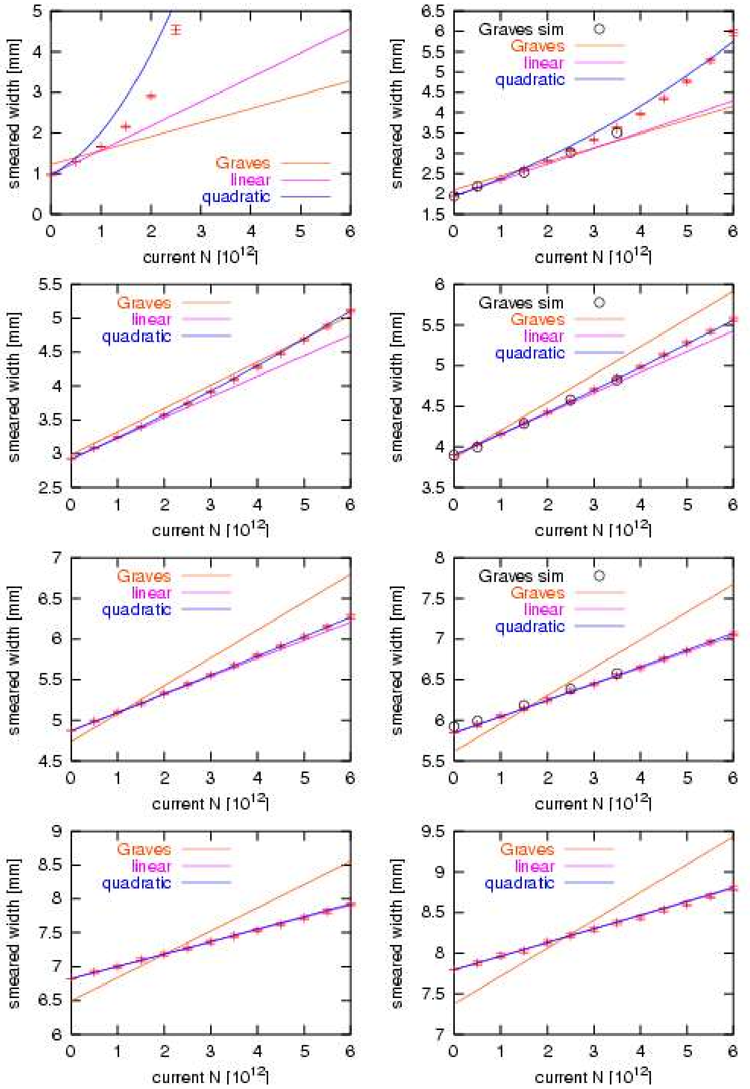


0 beam charge



nominal beam charge

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



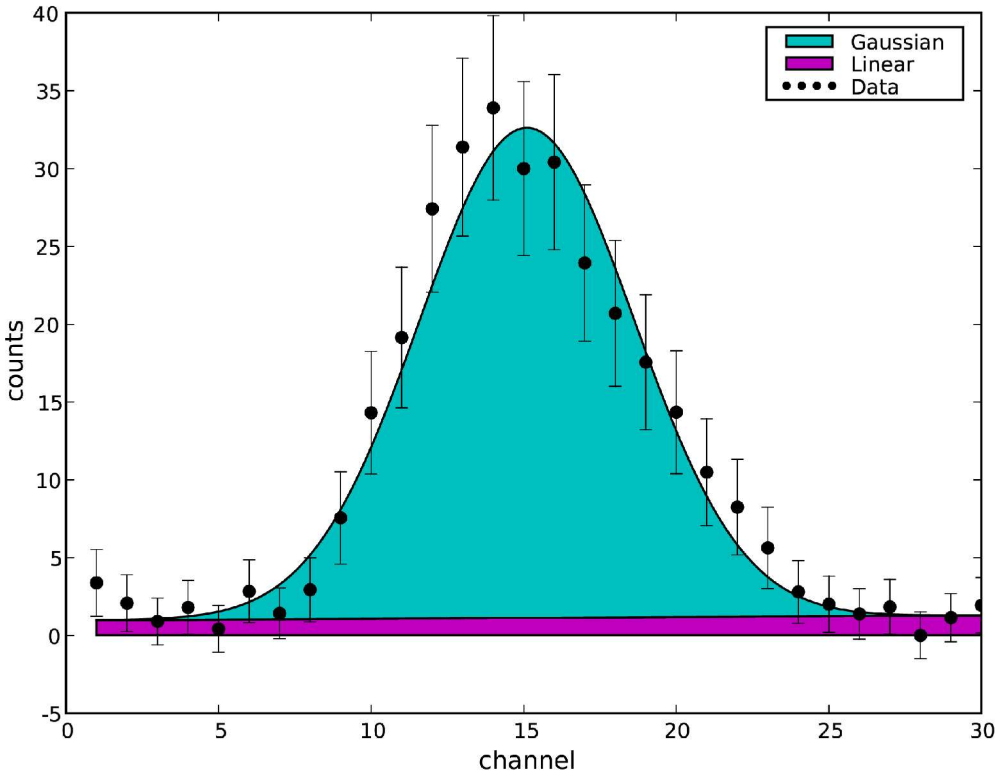
Beam halo

Try to understand tails in beam distribution using beam profile shape analysis.
Define:

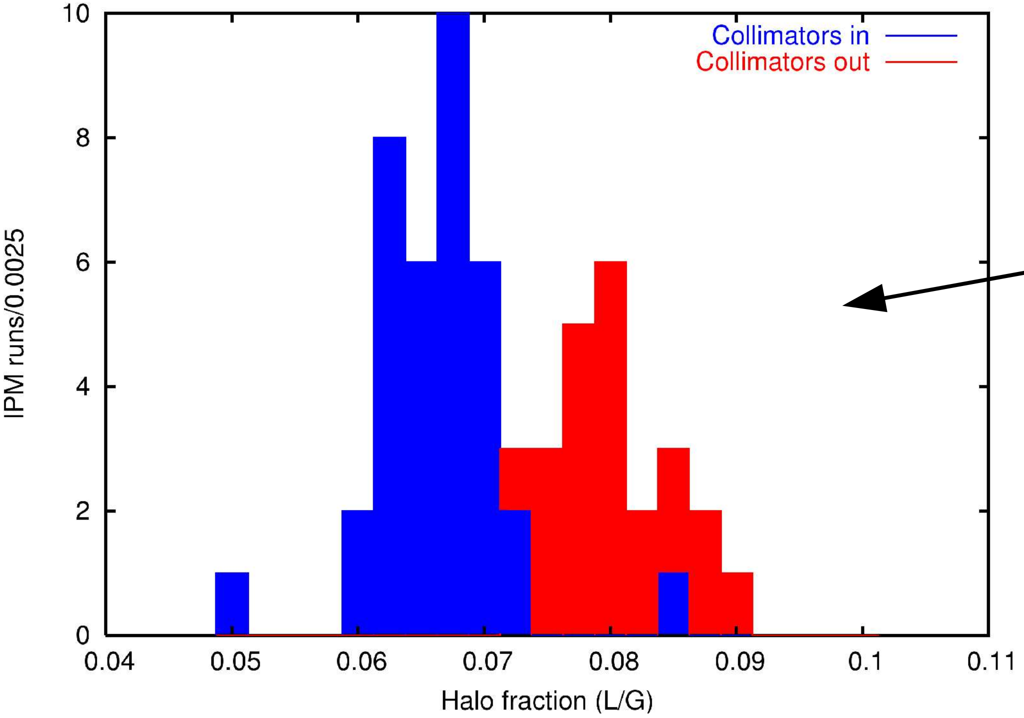
$$L \equiv \int_{detector} \ell(x)dx$$

$$G \equiv \int_{detector} g(x)dx$$

IPM profile showing Gaussian (G) and Linear (L) contributions

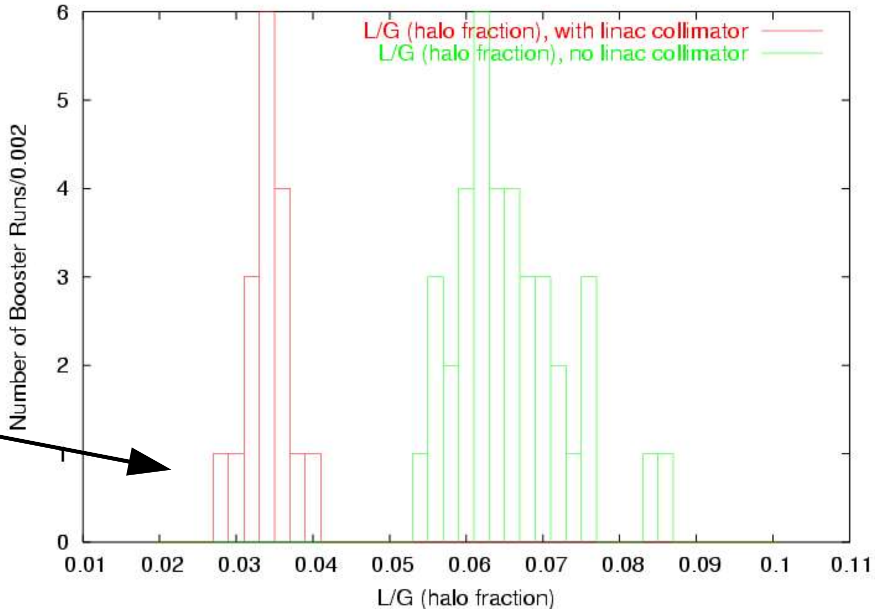


How well does it perform?

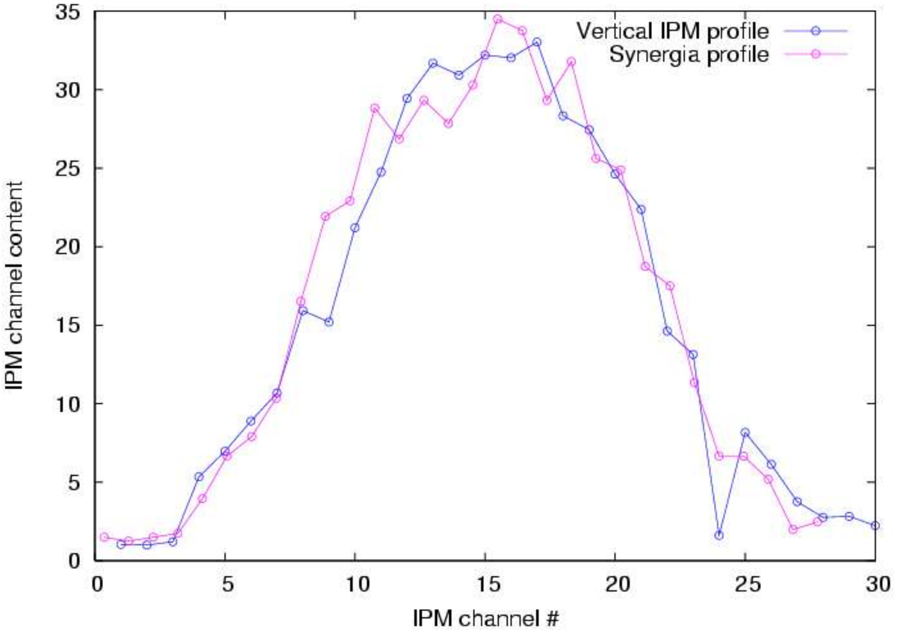


Comparison of L/G measurements with and without Booster collimators, averaging 500 turns before extraction

Comparison of L/G measurements with and without Linac collimator, averaging 500 turns after injection



Model IPM response



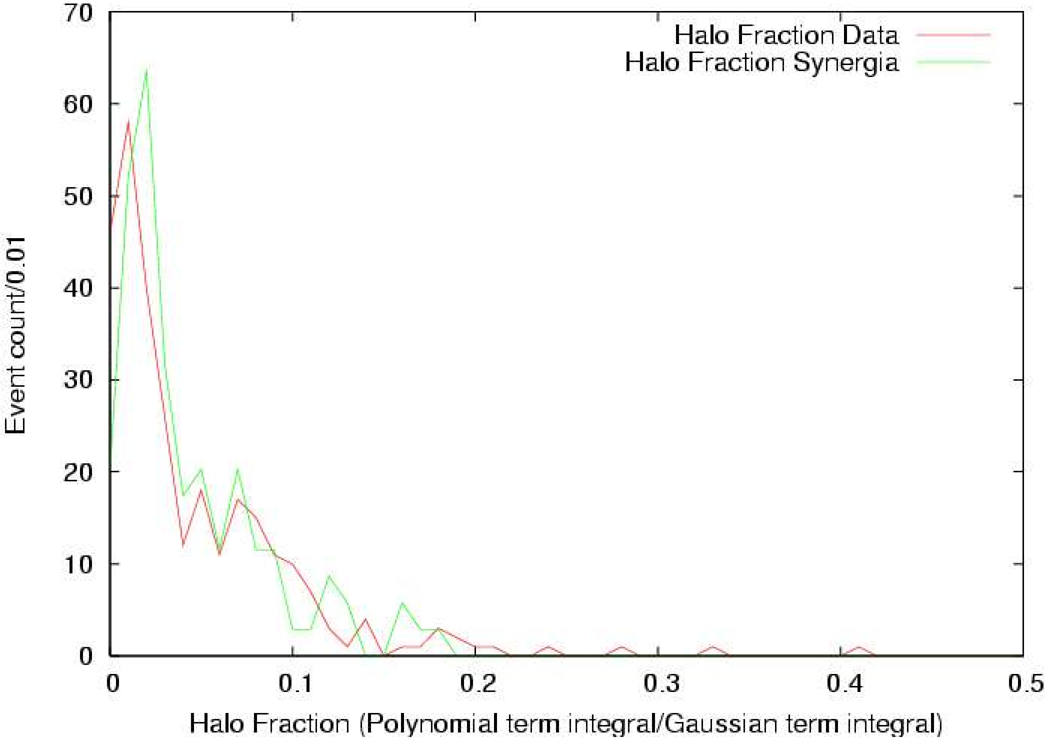
Smeared Synergia vs data profiles

Model Booster beam during injection and capture phase. Measure beam profiles using IPM (using calibration procedure). Model IPM response (apply smearing to simulated beam)

Compare measured IPM profiles and L/G with simulation.

“Halo” comparison results

Compare L/G for first 100 turns:



Data:

mean (L/G) = 0.049 ± 0.0011

Synergia:

mean (L/G) = 0.044 ± 0.0065

(good agreement, but data distribution has a longer tail -more halo-)

Also, IPM smearing is done post-processing (slow)

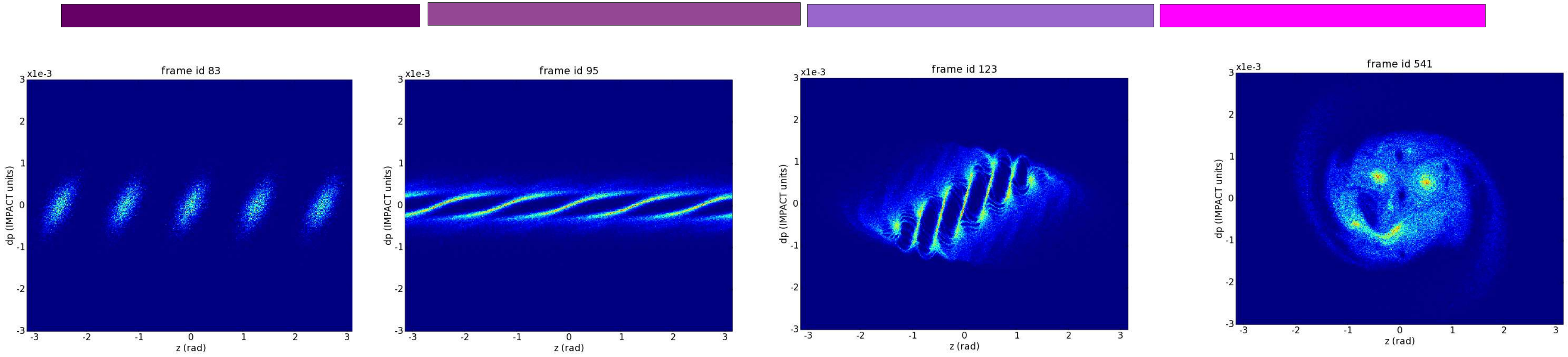
→ use sub-sample of 1M particles

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

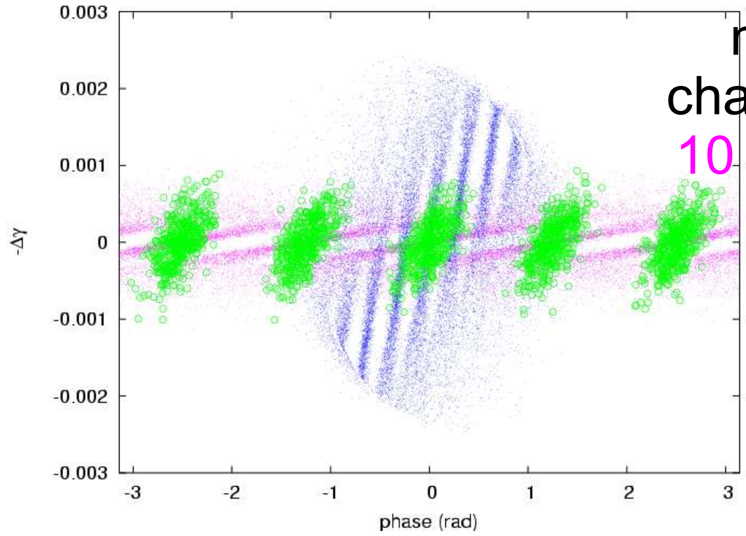
Booster bunched beam

Realistic Booster is very complex: ramping magnets, rf, large momentum spread, nonlinearities (space-charge, ...), coupling between transverse and longitudinal planes.

Longitudinal phase-space: injection, before bunching, start & end bunching

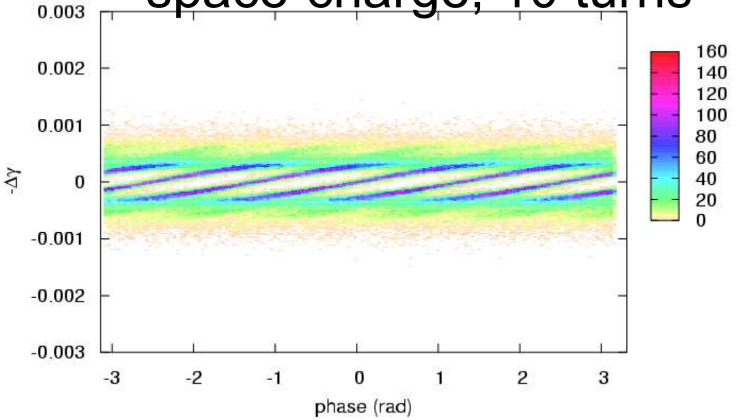


Booster longitudinal phase-space

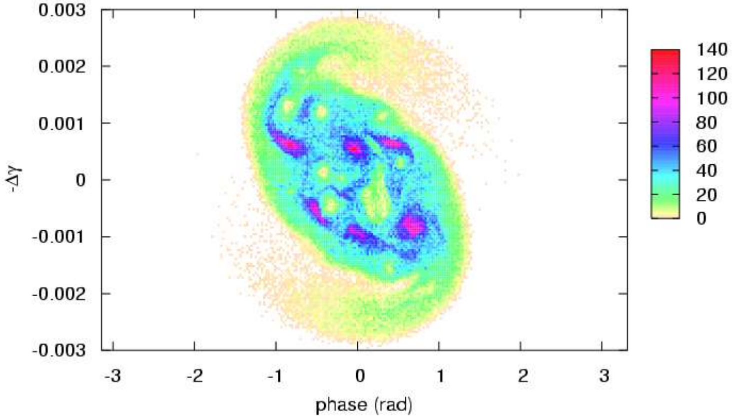


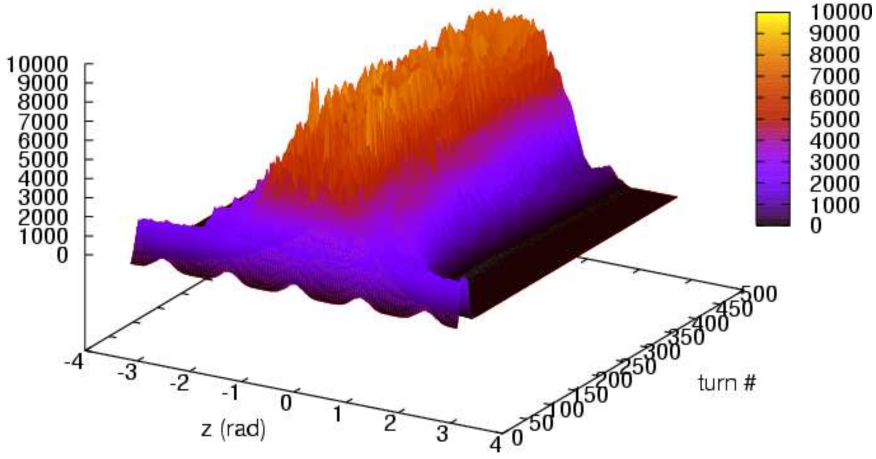
no space charge: 1 turn, 10 turns, 400 turns

space-charge, 10 turns

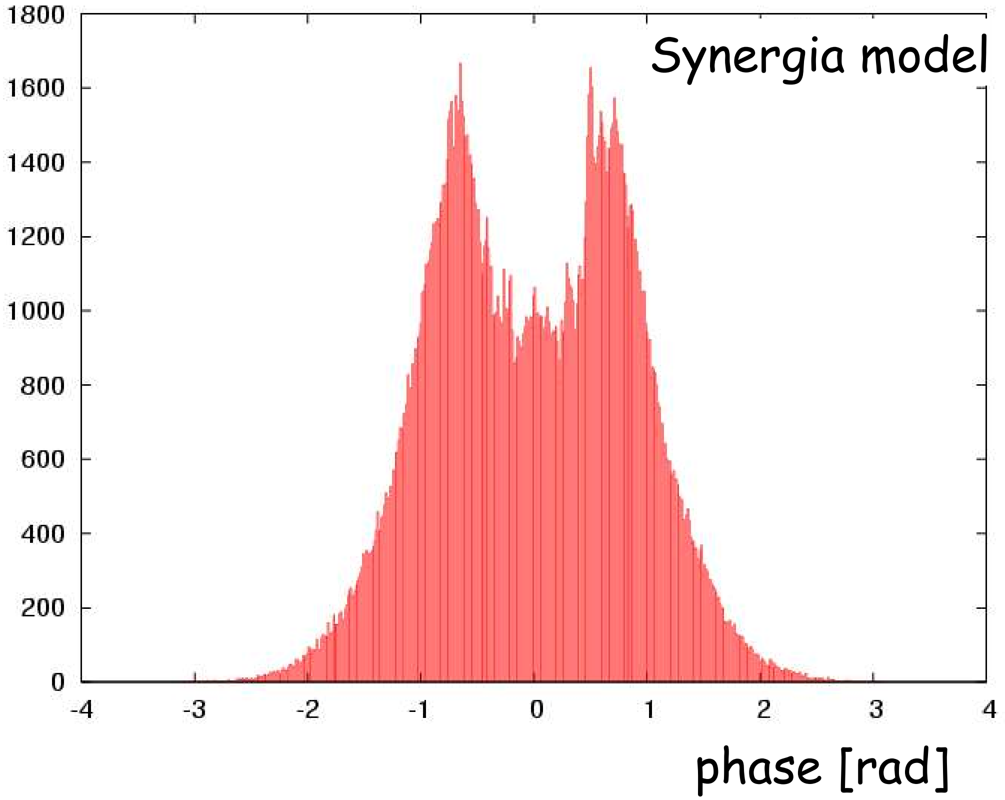


space-charge, 400 turns

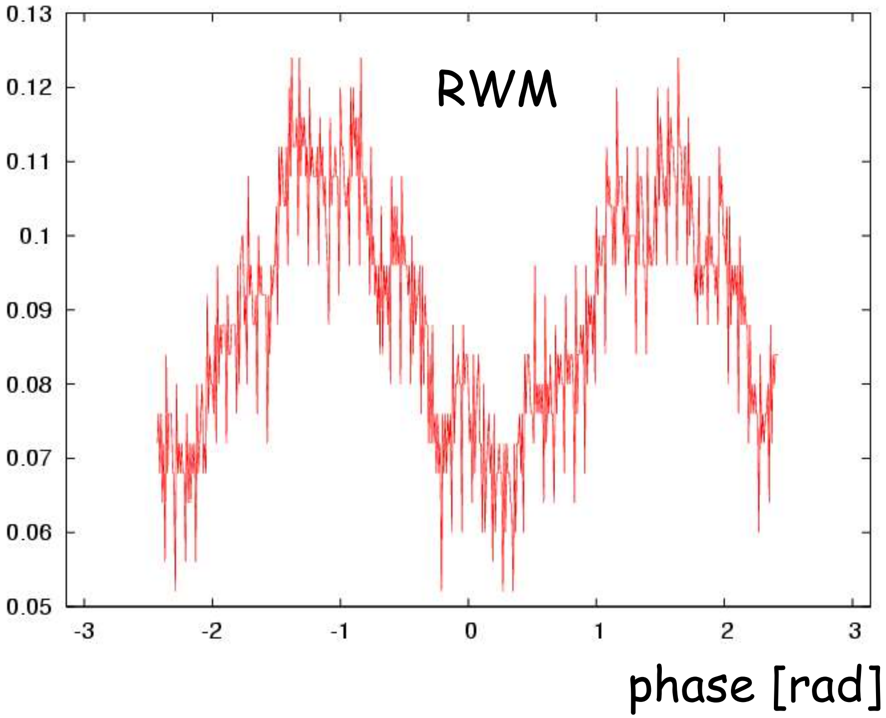




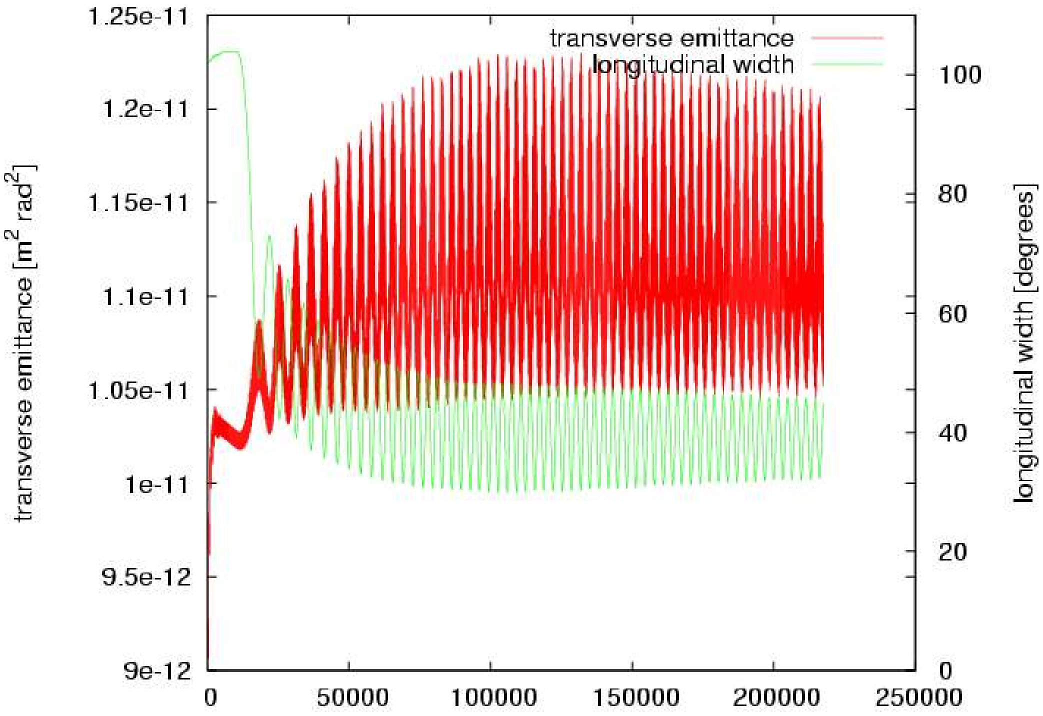
Longitudinal distributions



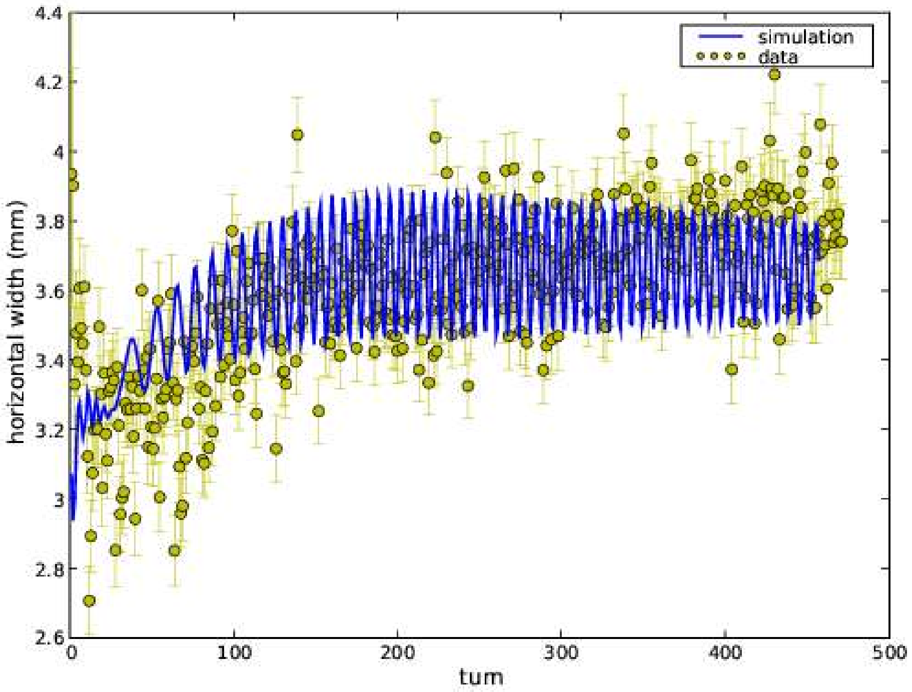
qualitative agreement
with data



Capture not so adiabatic...



transverse emittance couples to longitudinal degrees of freedom

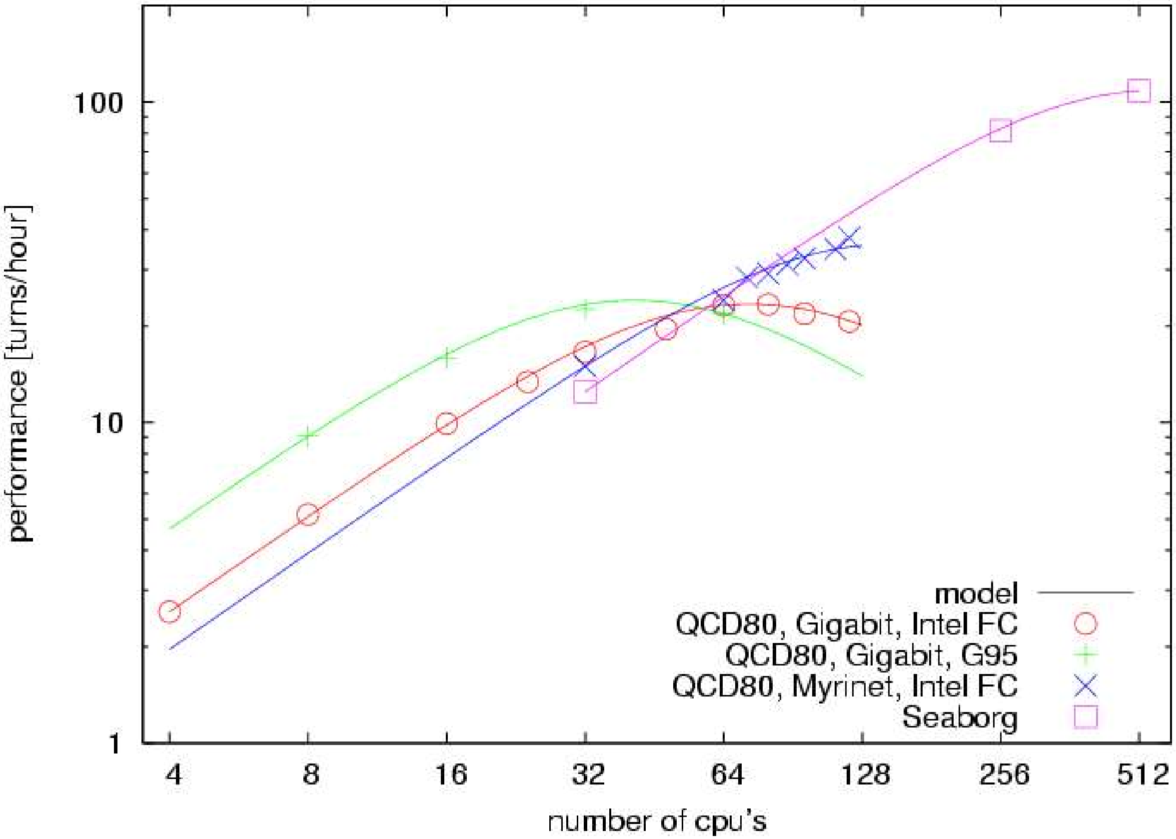


Compare profiles; model consistent with data, but not enough precision in measurement to see details

Συνεργεια

Performance

- Synergia ported to PC clusters with fast networki and to the NERSC supercomputer
- Performance: ~100 FNAL Booster turns/hr on 512 NERSC CPUs, ~50 turns/hr on 64 2GHz Xeons with Infiniband networking.



Performance model:

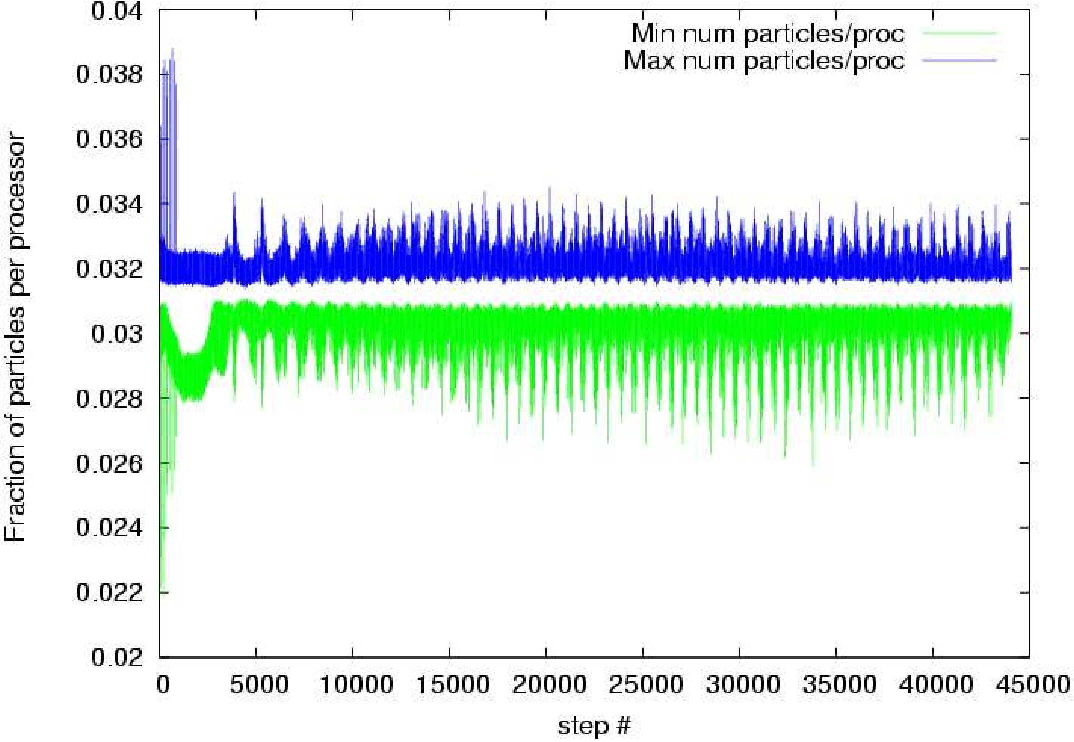
$$t = \frac{A}{N} + B\,N$$

N number of cpu's, 1/A ~ processor speed,
B ~ networking speed

Performance details

- FFT solver: domain decomposition.
  - phase space distributed on computational grid
- Synergia includes particle manager and load balancing algorithm, but
  - ➔ big communication penalty for mismatched beams

load balancing works well, but depending on networking speed it might do more harm than good



Summary

- The Synergia framework provides a flexible accelerator modeling environment
  - user interface, physics utilities, analysis tools
- Space charge module in Synergia enables high-fidelity self consistent modeling
  - Benchmarked against other codes, compared against theoretical predictions
  - Detailed FNAL Booster model implementation

Outlook

- The Synergia framework allows easy interface with “kick” physics modules:
  - impedance effects
  - beam-beam
  - started developing electron cloud
- Physics opportunities:
  - strong-strong beam-beam (Tevatron –in progress--, LHC); NLC damping ring space-charge; MI electron cloud

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