FULLY 3D BEAM MULTIPLE BEAM DYNAMICS PROCESSES SIMULATION FOR THE TEVATRON*

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Outline

- Motivation
- Lifetrac simulation
- BeamBeam3d simulation
- Results
- Conclusion

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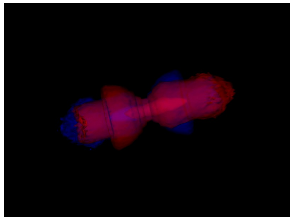
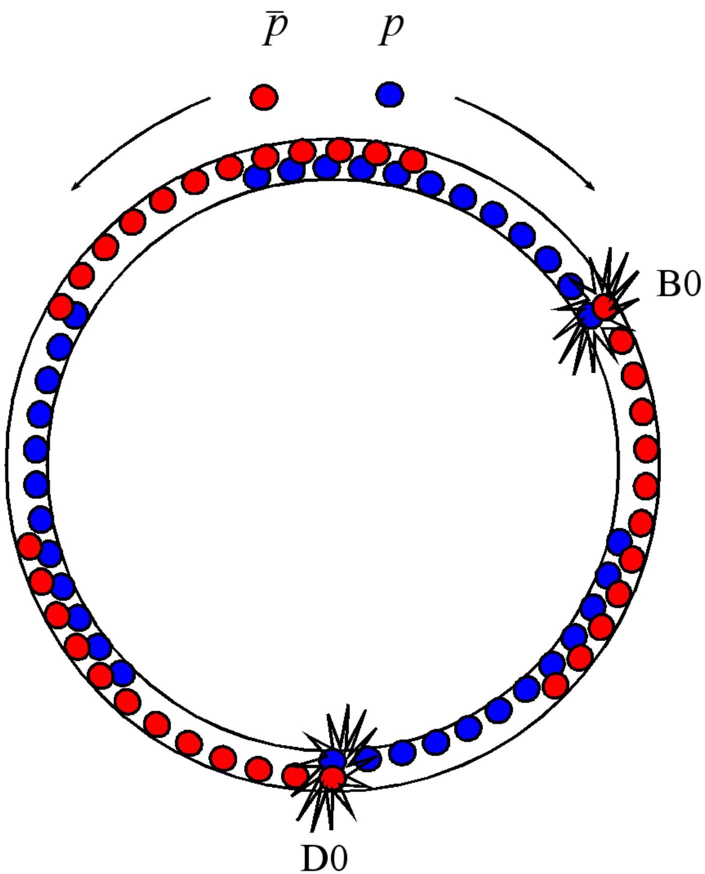
* work supported by U.S. Department of Energy



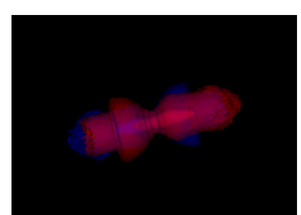
Motivation: The Tevatron is a Complicated Machine

Schematic of Tevatron bunches in the ring



- Coupled H-V motion
- Helical orbit
- Beam-Beam interactions
  - proton couples to antiproton
  - head couples to tail
- Machine impedance
  - couples longitudinal to transverse
- Chromaticity
  - excites instabilities

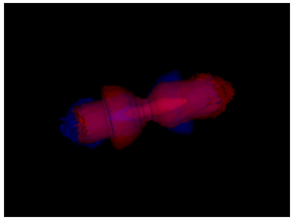
For detailed understanding, numeric simulation seems to way to go.



Lifetrac: weak-strong simulation

(A. Valishev, D. Shatilov)

- Weak-strong beam-beam force calculation based on moments
- Noise and diffusion
- 6-D coupled optics
- Helical orbit
- Chromaticity
- Bunch collision pattern

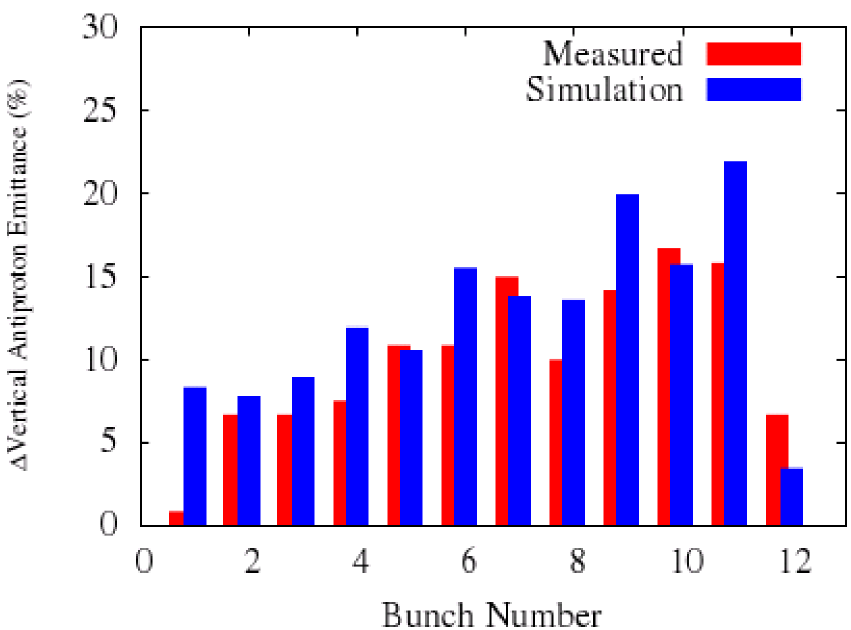


Lifetrac successes

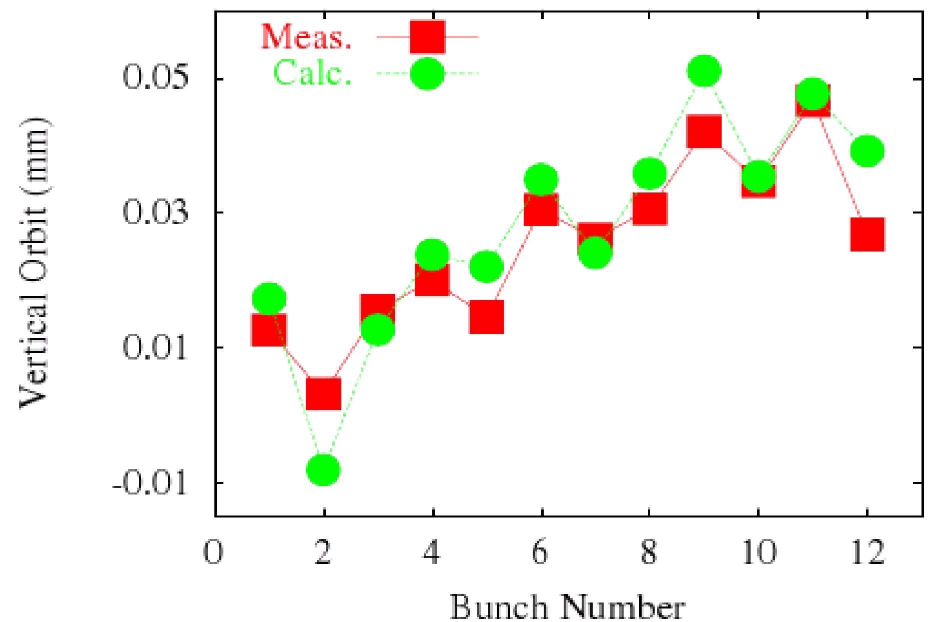
Lifetrac is very fast!

10^7 simulated turns/day on a small cluster

Antiproton emittance growth

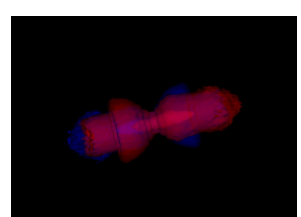


Antiproton bunch offset



Many beam lifetime issues have been addressed with lifetrac:

A. Valishev, Simulation of Beam-Beam Effects and Tevatron Experience, EPAC08

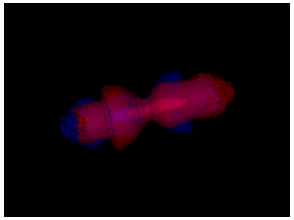


The Tevatron keeps getting better:

Proton and entiproton beam intensities are within of factor of 3 of each other.

Beam-beam tune shift is approximately equal

A strong-strong calculation is indicated.



Enhanced BeamBeam3d* code

Parallel, particle-in-cell Poisson Beam-Beam force calculation.

Coupled XY maps

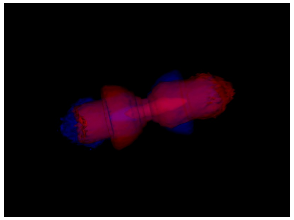
Independent bunch tracking for two beams

Helical trajectory, full collision pattern

Resistive wall impedance model

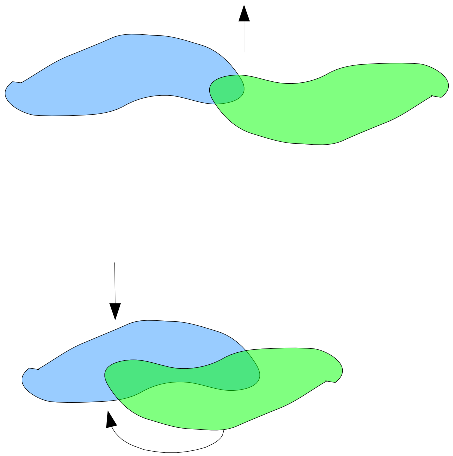
Chromaticity

* Original code by J. Qiang, LBNL

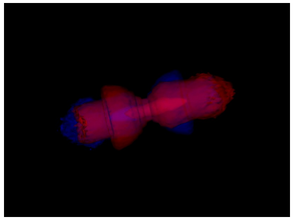


Validation of the Beam-Beam model

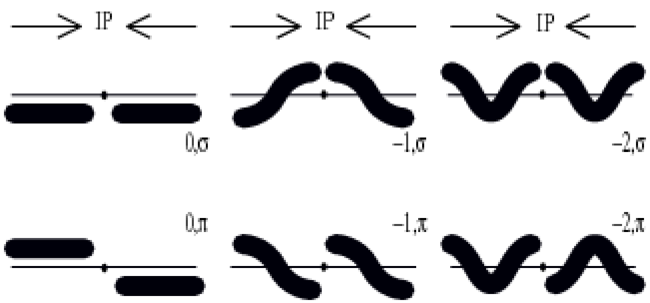
VEPP-2M 500 MeV e^+e^- collider synchrobetatron mode evolution measurement



Synchro-betatron modes are coupled oscillations where the head of a beam bunch couples to the tail mediated by beam-beam interactions with bunches from another beam.

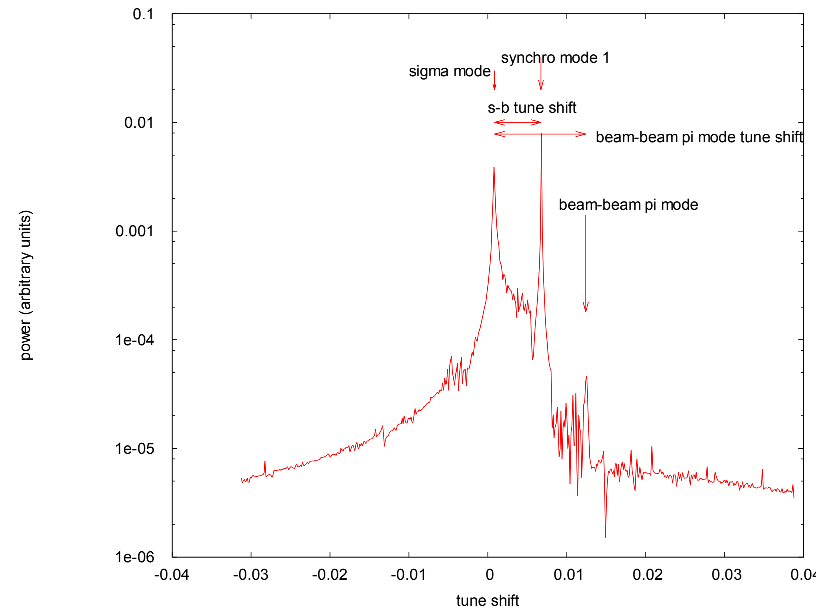


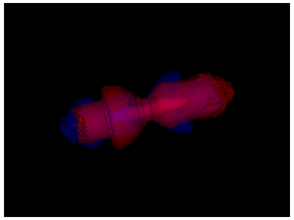
Spectroscopy of synchro-betatron modes



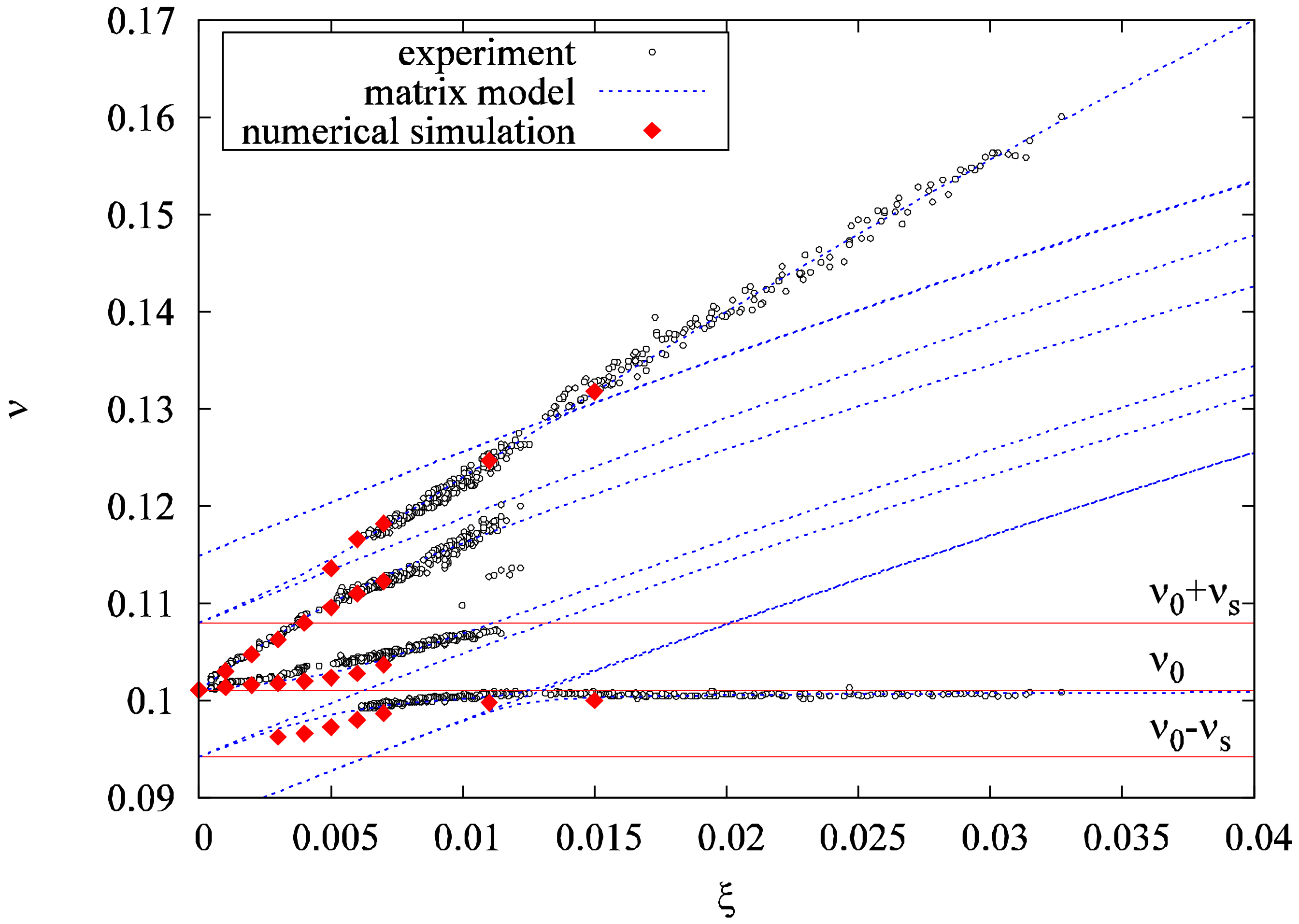
Beam-beam parameter: $\xi = \frac{N_e r_e}{4 \pi \gamma \epsilon}$

Example run with modes

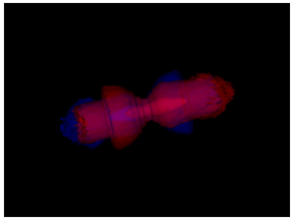




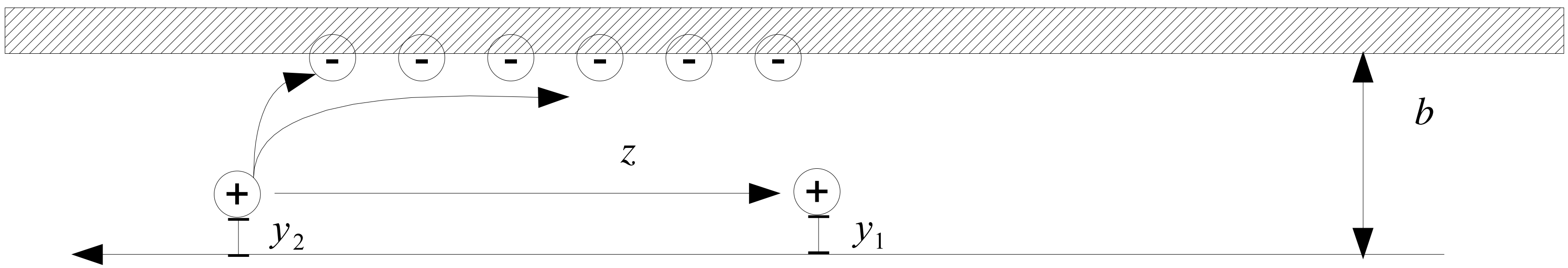
Simulation results vs. experiment, BeamBeam3d, Stern, Valishev*



*I.N.~Nesterenko, et al.Phys.Rev.E, 65, 056502 (2002)



Dipole resistive wall impedance model

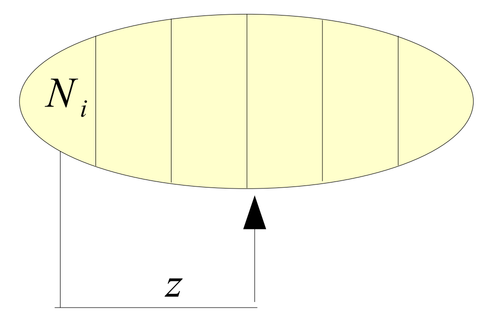


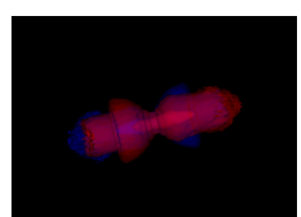
A. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators

A charged particle traveling through a pipe with finite conductivity walls induces opposite signed charges on the walls, leaving behind a wake field which affects succeeding charges.

kick

$$W = \left(\frac{2}{\pi b^3}\right)\sqrt{\frac{4\pi\epsilon_0 c}{\sigma}}\,\frac{L}{z^{1/2}} \qquad \Delta y_2' = \frac{N_i r_p}{\beta\gamma} W y_1$$





Test impedance simulations with understood instabilities

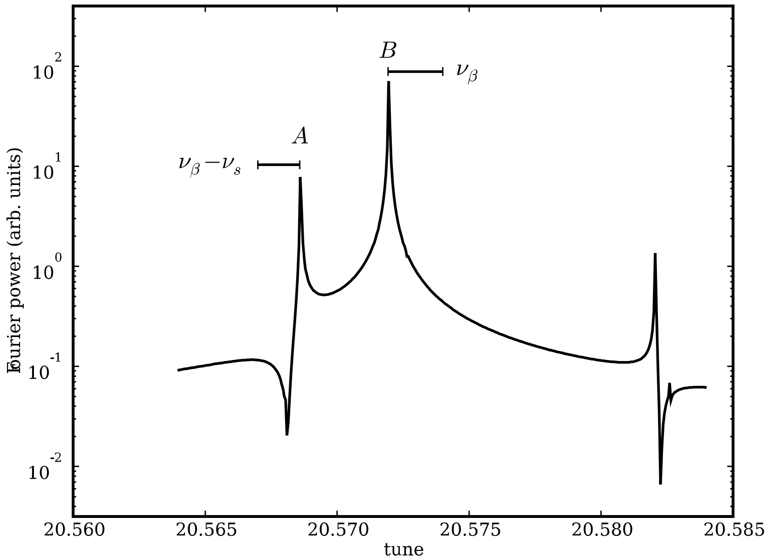
Strong head-tail

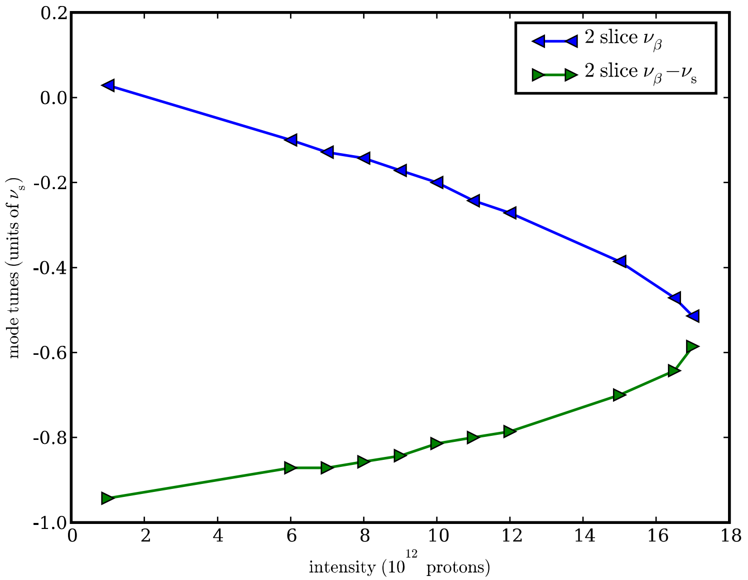
airbag distribution
two-slice model, fixed 20 cm separation
150 GeV
3 cm pipe

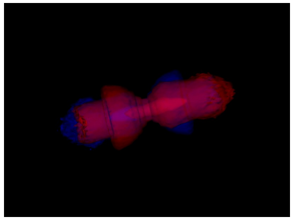
Stable motion when

$$\frac{\pi N r_0 W_0 L}{4(2\pi)^2 \gamma \nu_\beta \nu_s} < 2$$

$$N < \sim 16.7 \cdot 10^{12}$$

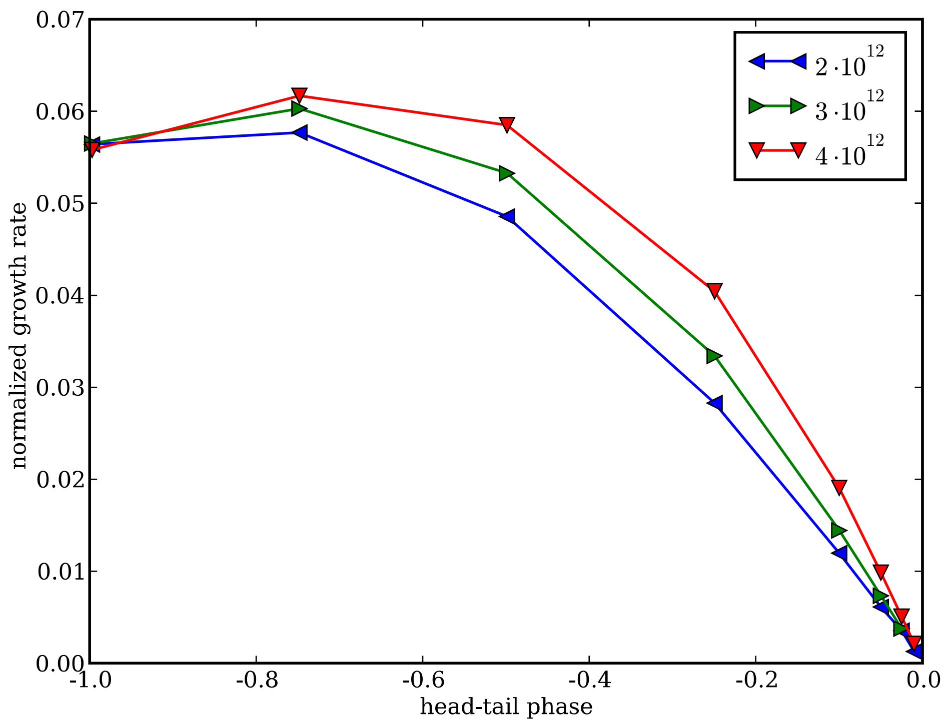






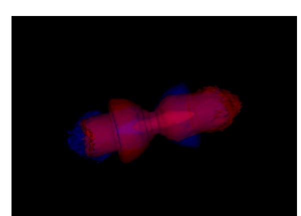
Test impedance simulations with understood instabilities

Weak head-tail



$$\text{head-tail phase} \stackrel{\text{def}}{=} \chi = \frac{\xi \omega_\beta \hat{z}}{c\,\eta} = \frac{2\pi \xi Q_\beta \hat{z}}{L\,\eta}$$

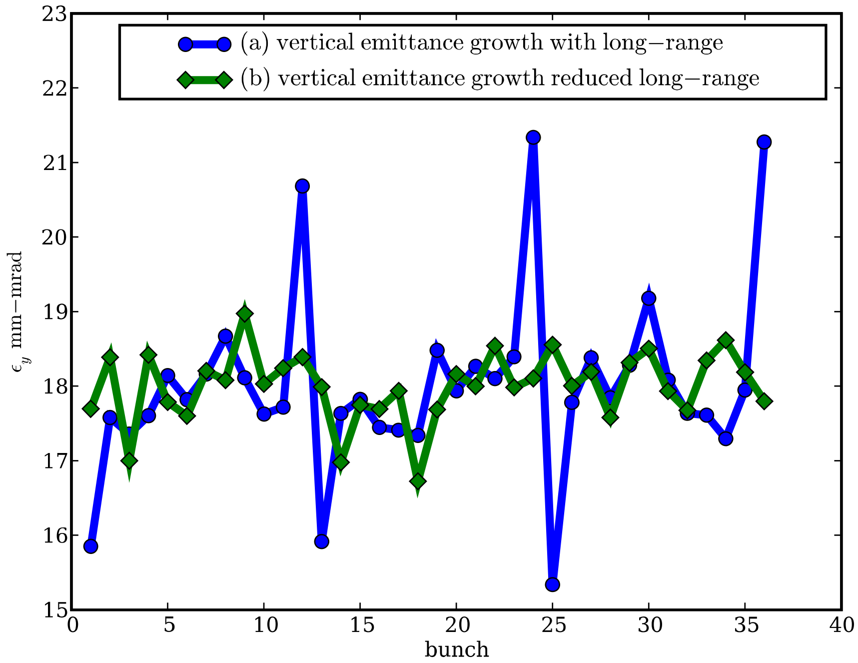
The curves for different intensities start out linearly near 0 and follow a near-universal curve when normalized by geometric and intensity factors.



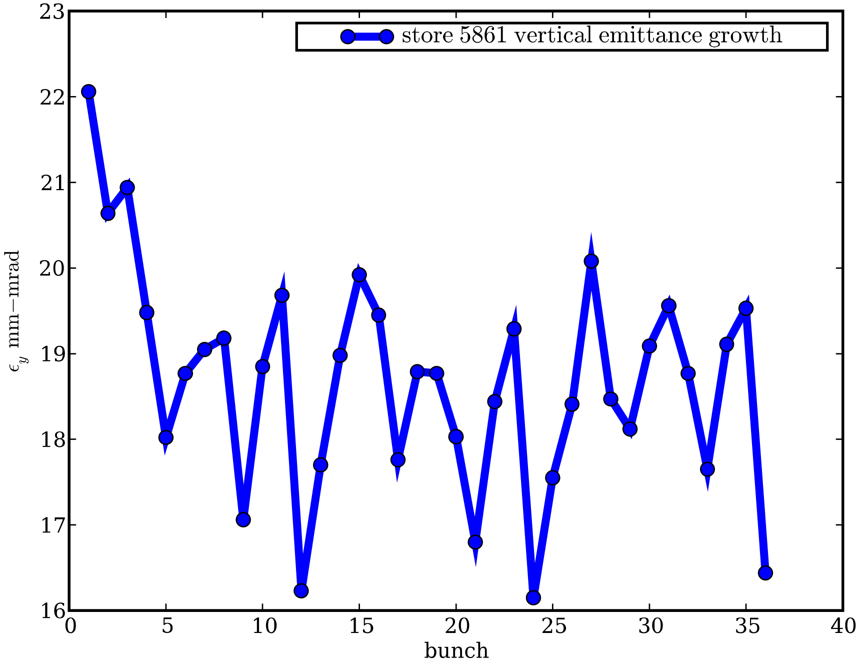
The processes are validated: let's simulate!

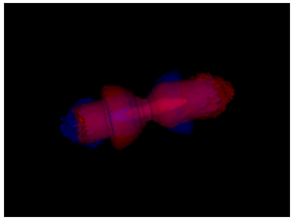
Strong-strong simulation can look at the proton bunches

Simulated vertical emittance growth 50000 turns



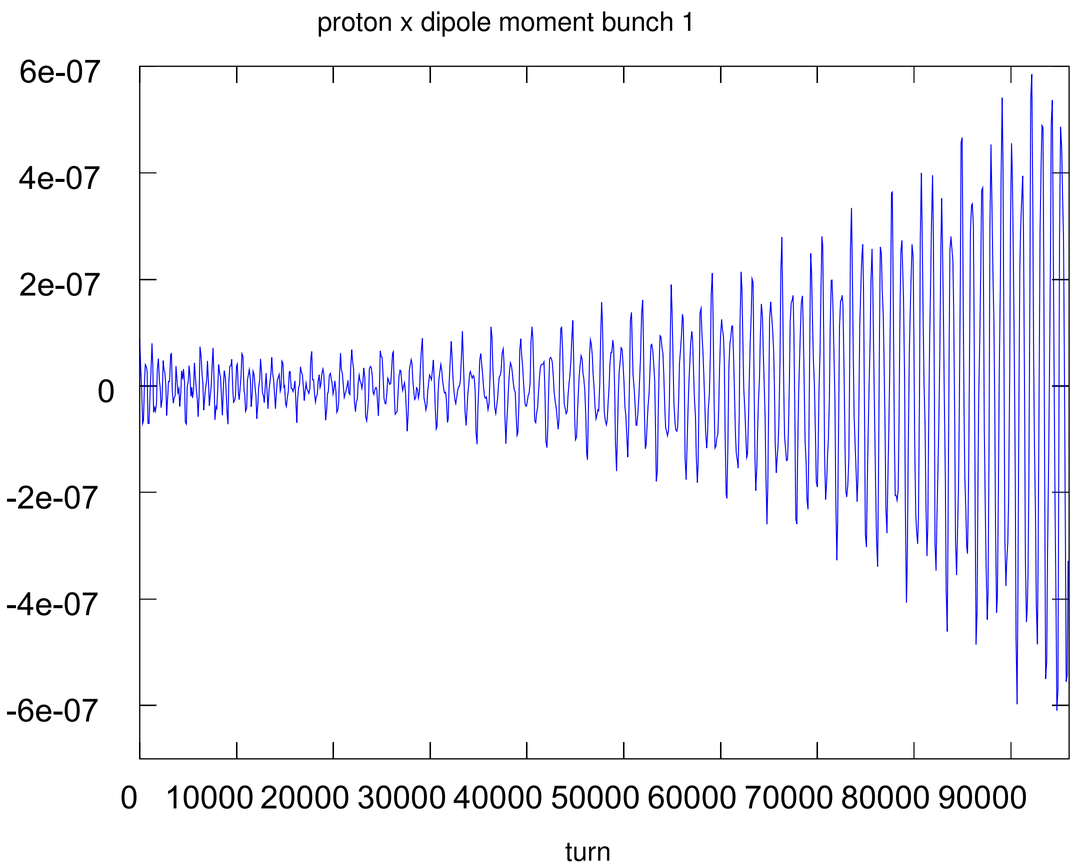
Measured vertical emittance growth (15 min)

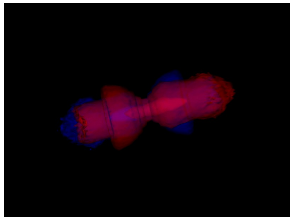




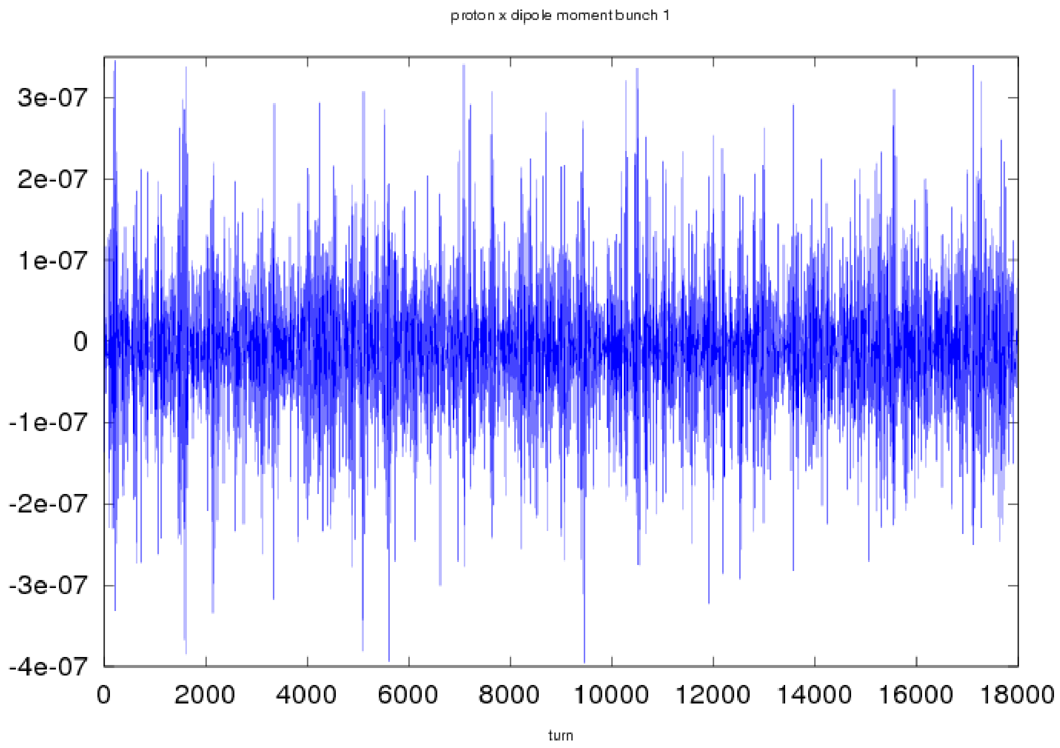
Operational Instabilities

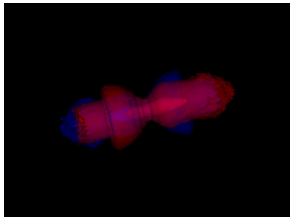
With the current proton levels in the Tevatron, it is susceptible to head-tail instabilities.





After antiprotons are in the machine and head-on collisions are initiated, Landau damping keeps the beam stable.





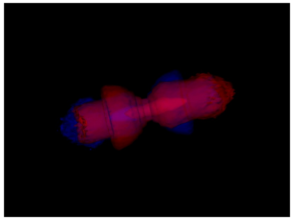
Tevatron Setup Dance

Before beams are brought into collision, they are separated.
Beam-Beam effect is reduced.

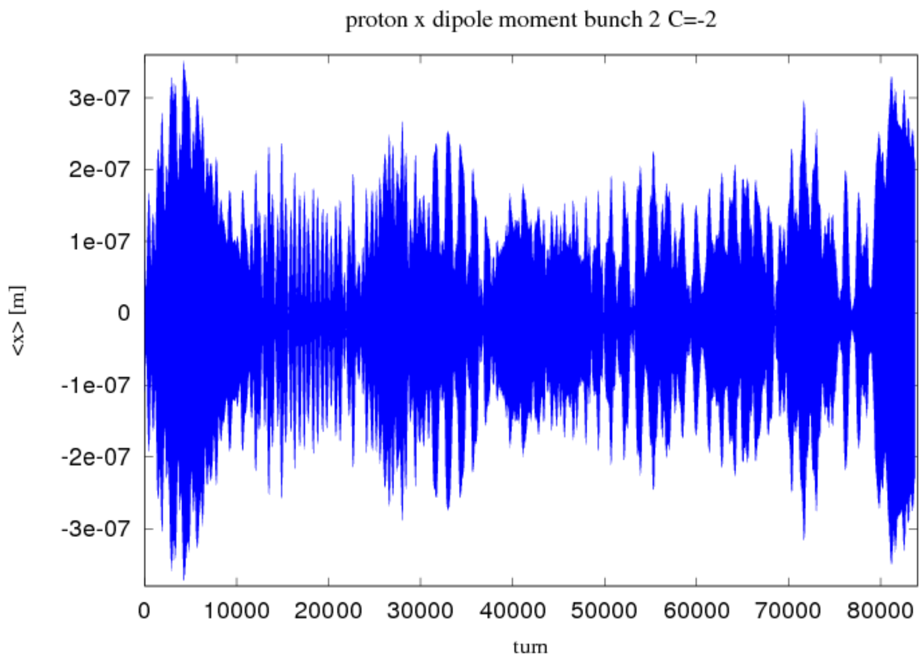
To mitigate head-tail instability, chromaticity is set to large positive value.

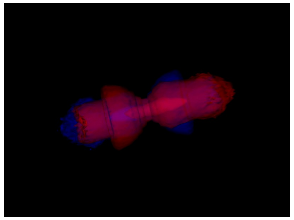
Large chromaticity induces detrimental beam losses.

How low can chromaticity be lowered with reduced Beam-Beam?

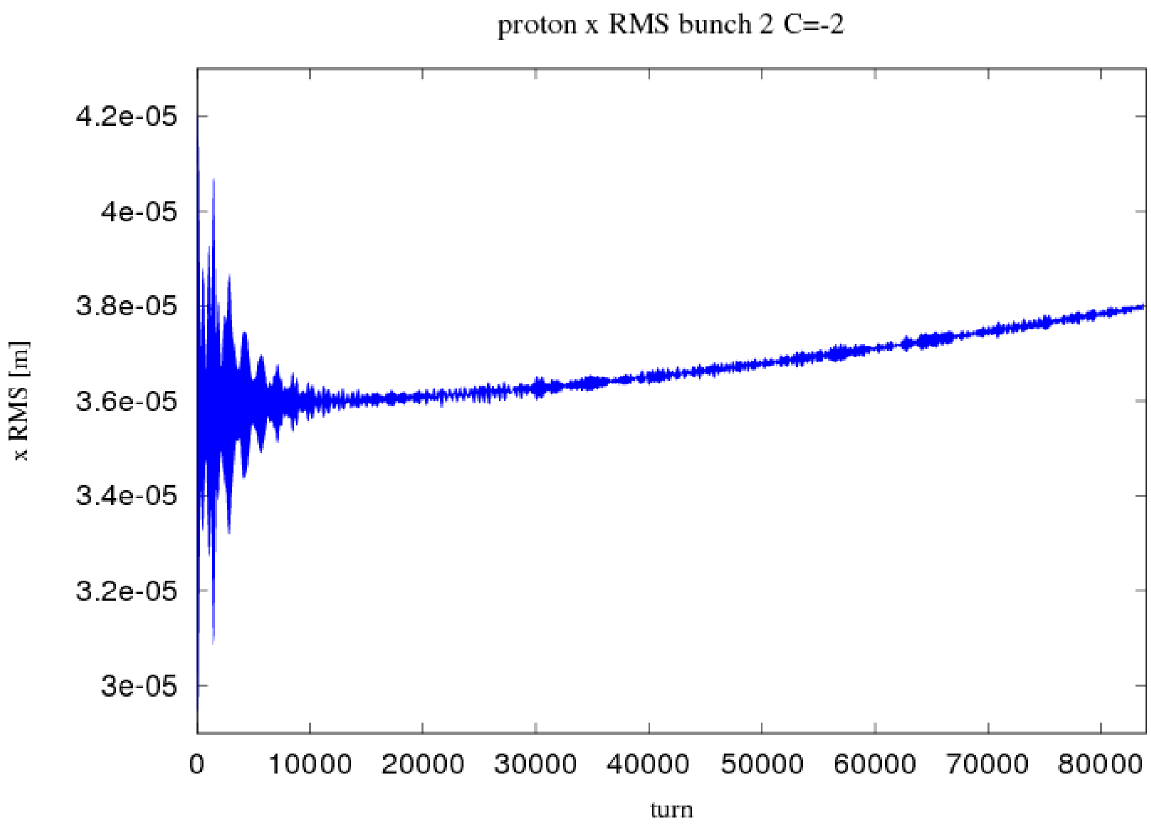


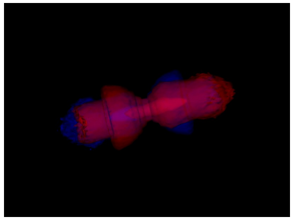
How well does Beam-Beam in separated beams overcome instability?



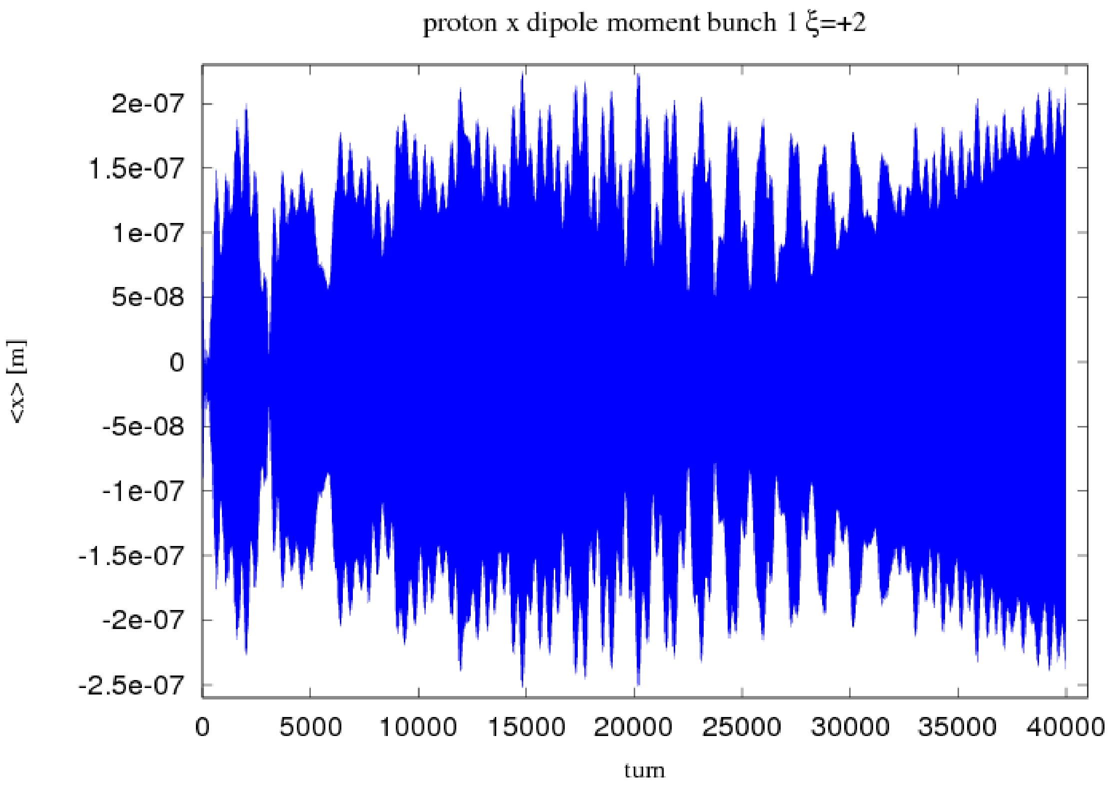


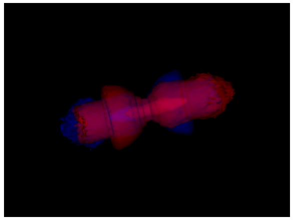
The RMS width is growing. Is this a quadrupole mode instability?



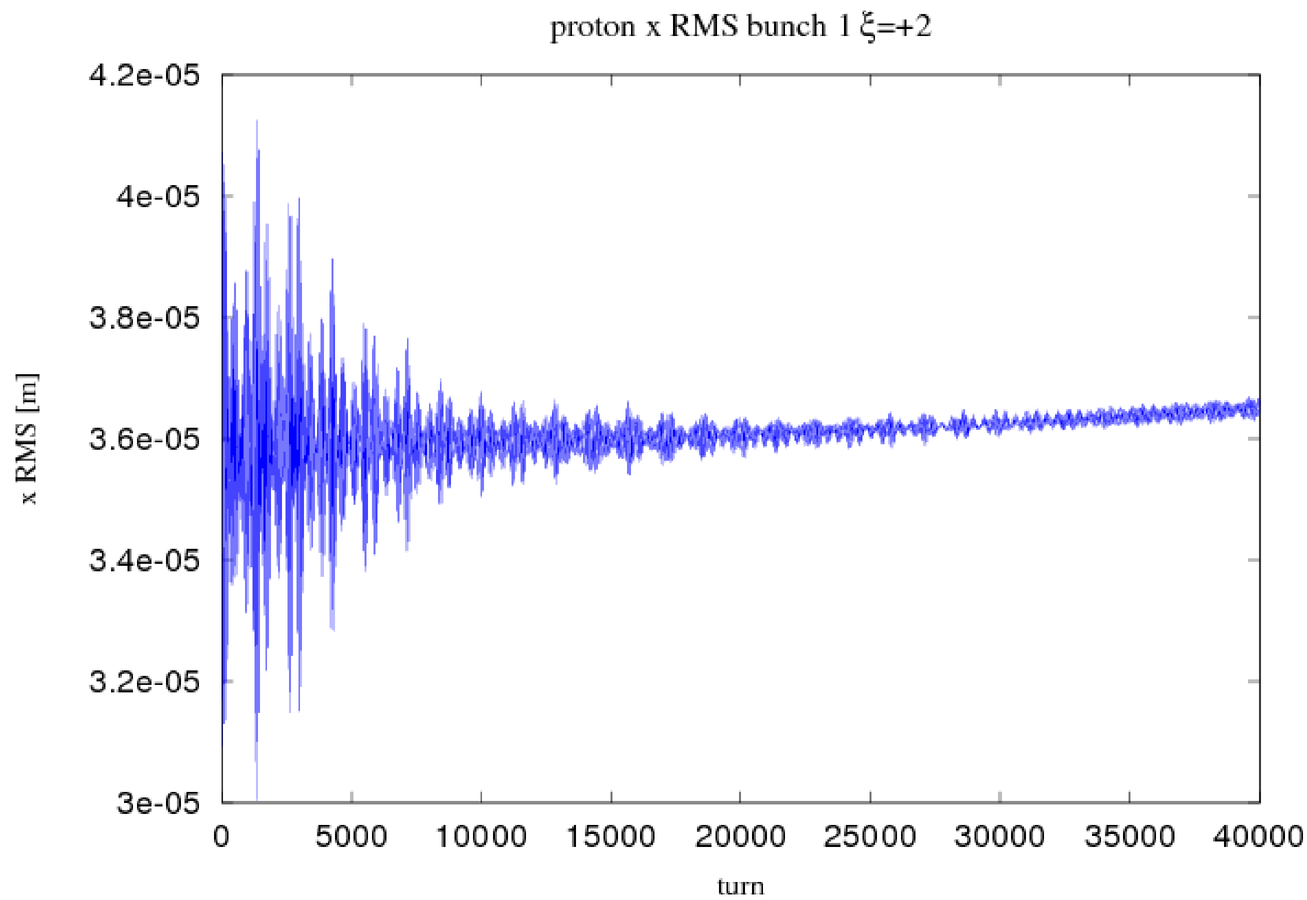


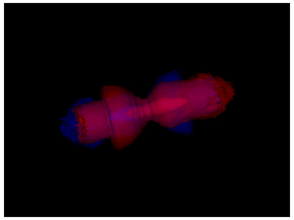
Running with positive chromaticity



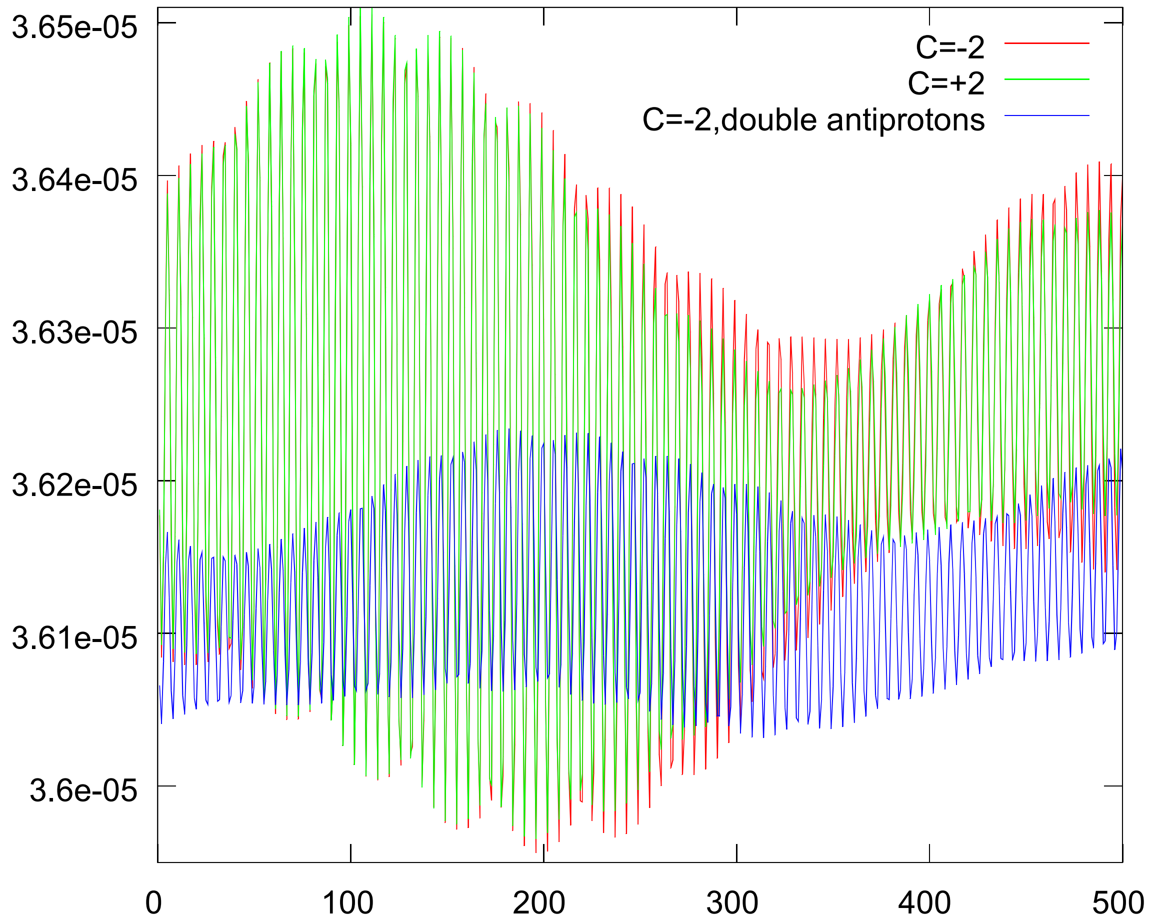


Still some quadrupole growth at C=+2

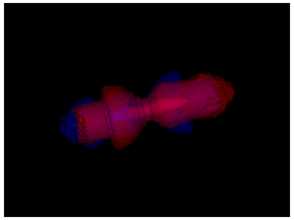




RMS growth for three cases



Currently, Tevatron running with C=+6



Conclusions

- The comprehensive simulation of the Tevatron including measured machine optics and beam orbits, beam-beam effects, chromaticity, resistive wall impedance, and multiple bunch tracking reproduces observed idiosyncratic Tevatron behavior and hints of new interesting behavior.
- Simulations of different operating conditions can guide machine physicists in planning operating parameters and understanding the complicated interaction of multiple effects.
- The execution time of the simulations needs to be improved so that they can address issues faster with more completeness.