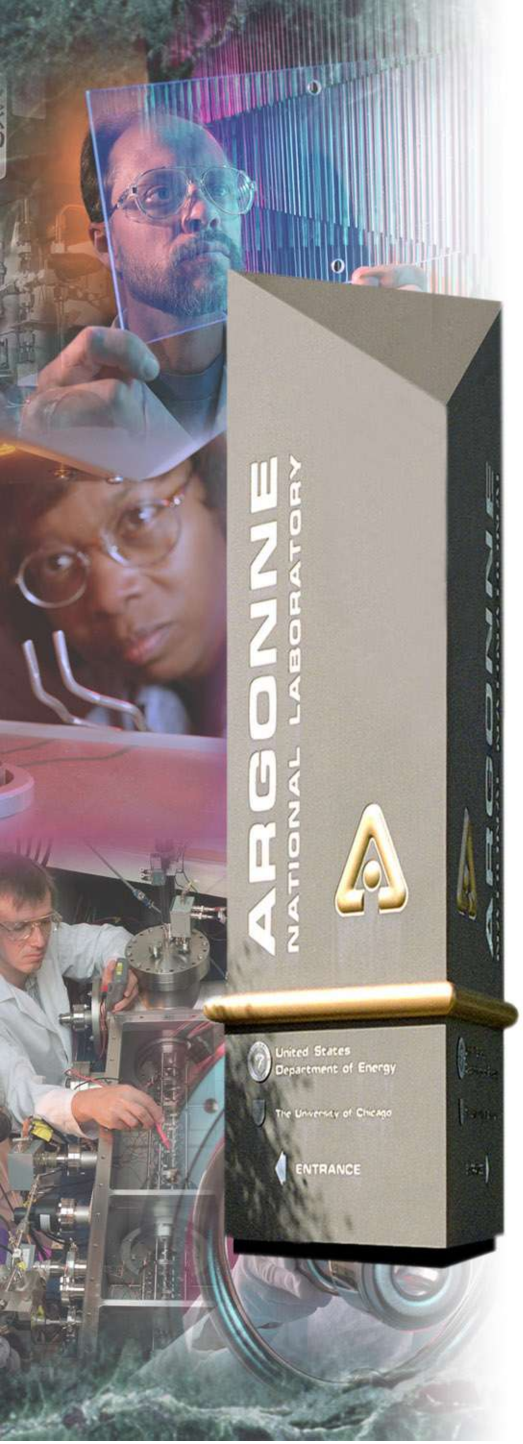


Accelerator Physics Aspects of Crab-Cavity-Based Production of Picosecond X-ray Pulses

Michael Borland
Operations Analysis Group
APS Operations Division

February 17, 2005

Office of Science
U.S. Department of Energy

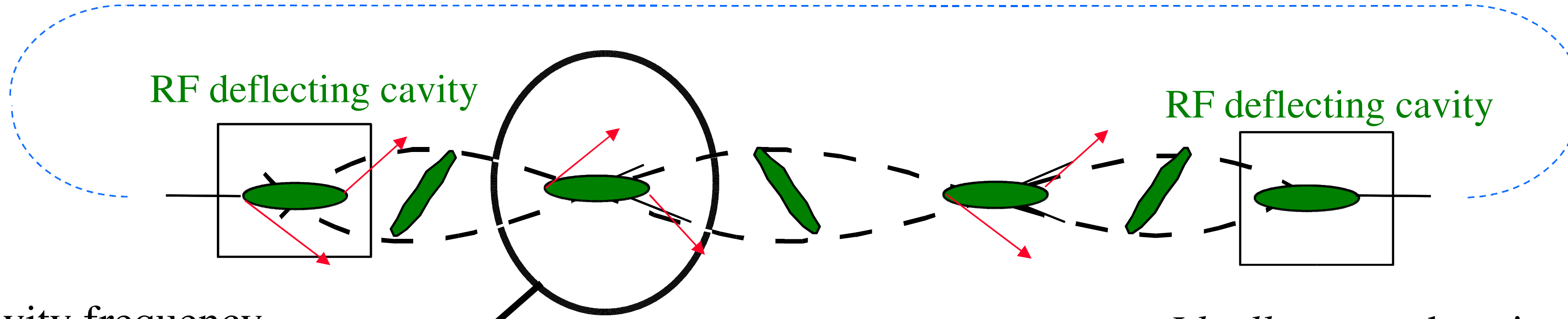
A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Outline

- Review of Zholents' concept
- Basic analysis of compression
- Lattice choices and constraints
- Emittance degradation
- Tolerances
- Lifetime issues
- Photon beam properties
- Optimization of compression

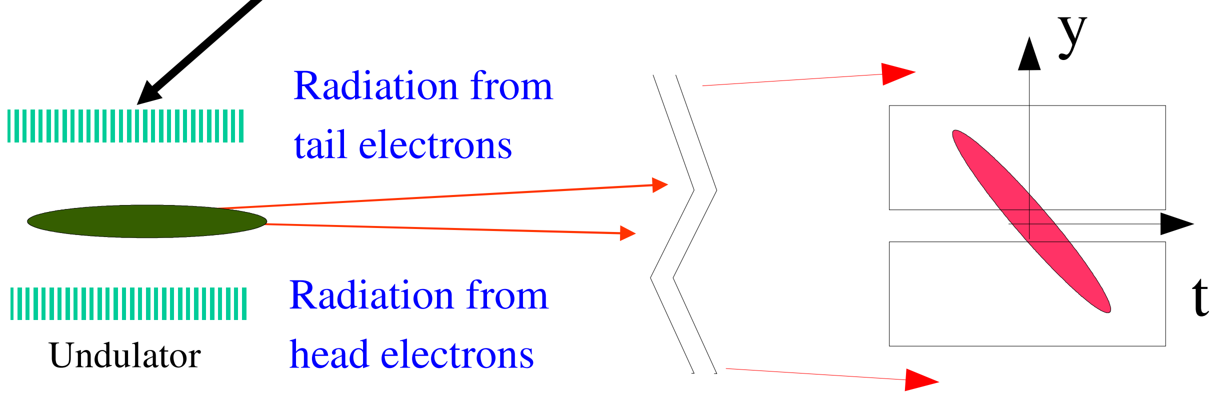
Zholents' Transverse Rf Chirp Concept

(Adapted from A. Zholents' August 30, 2004 presentation at APS Strategic Planning Meeting.)



Cavity frequency is harmonic *h* of ring rf frequency

Ideally, second cavity exactly cancels effect of first



Pulse can be sliced or compressed with asymmetric cut crystal

Compression Analysis

- Assuming everything is linear, the minimum achievable pulse length for a long beamline is

$$\sigma_{t,xray} = \frac{E}{V\omega}\sqrt{\sigma^2_{y',e} + \sigma^2_{y',rad}}$$

Electron beam energy → E

Deflecting rf voltage & frequency → V, ω

Unchirped e-beam divergence (typ. 2~3 μrad) → $\sigma_{y',e}$

Divergence due to undulator (typ. ~5 μrad) → $\sigma_{y',rad}$

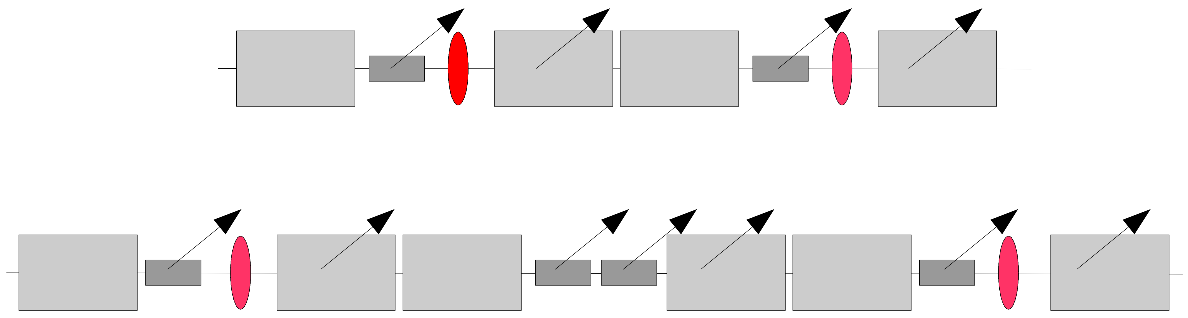
→ For 6 MV, 2800MHz (h=8) deflecting system, get ~0.4 ps!

- This ignores lots of details

Lattice Constraints

- Vertical phase advance
  - Must have n*180 degrees phase advance between the cavities
- Undulator placement
  - Should have about m*180 phase advance from first cavity
  - Otherwise, wastes aperture in the ID
- Vertical beta functions at cavities, IDs
  - May need to be modified to satisfy phase advance conditions
  - Must accommodate ID chamber without reducing the acceptance

Lattice Options

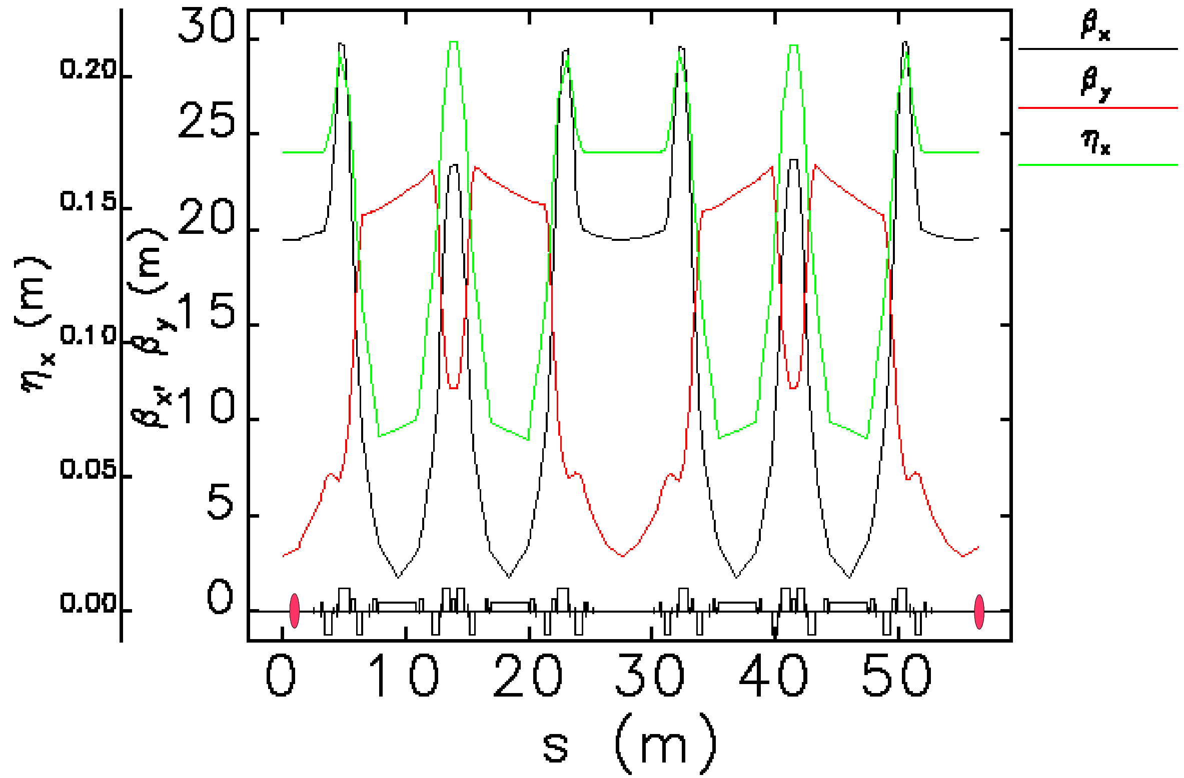


1 sector spacing

1 ID + 1 BM

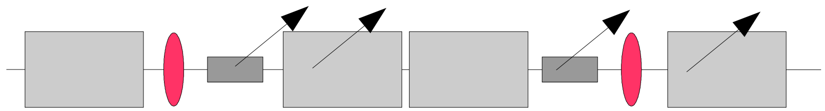
2 sector spacing

3 ID + 2 BM



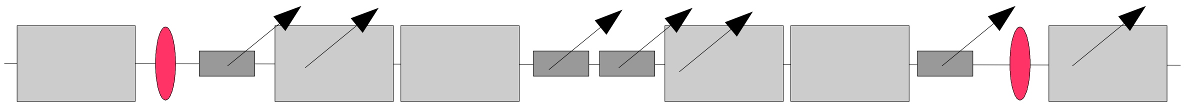
Lattice is nearly indistinguishable from the normal one

Lattice Options



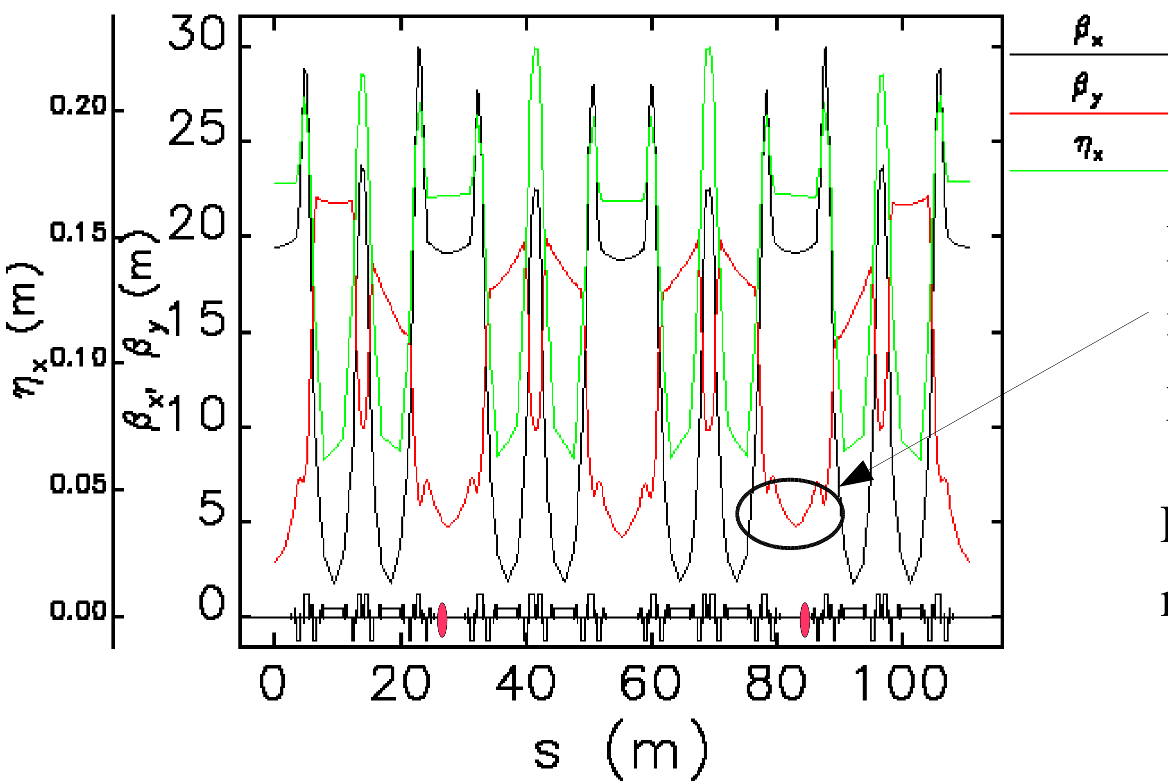
1 sector spacing

2 ID + 1 BM



2 sector spacing

4 ID + 2 BM



Beta function increase required to get the right phase advance

Helps compression by making divergence smaller

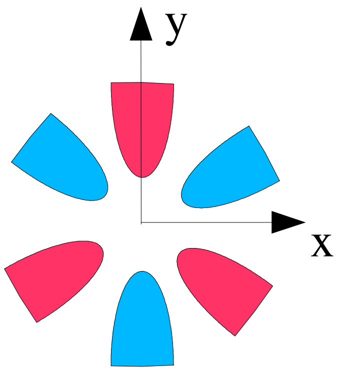
After V. Sajaev, ASD/APG/2004-11

Causes of Emittance Degradation

- Less than total kick cancellation will case emittance increase
- Effects present in a perfect machine
  - Sextupole nonlinearity
  - Chromaticity and beam energy spread
  - Momentum compaction and beam energy spread
- Additional effects in an imperfect machine
  - Lattice errors
  - Lattice coupling between cavities
  - Roll of cavities about beam axis
  - Rf phasing and voltage errors

Sextupole Effects

- Sextupoles are necessary
  - Correct chromatic focusing aberrations
  - Defeat beam instabilities
- Sextupoles have undesirable side-effects
  - Phase advance varies with amplitude
    - Kick cancellation varies with amplitude
    - Vertical emittance increases
  - Horizontal and vertical motion gets coupled
    - Large vertical motion from cavities gets coupled into horizontal
    - Leads to large horizontal emittance growth
- Solution: turn off sextupoles between the cavities



$$B_y = \frac{1}{2} m (x^2 - y^2)$$

$$B_x = m x y$$

Momentum Compaction

- Momentum compaction: the variation in time-of-flight with energy error
- Beam has 0.1% rms energy spread
  - Leads to 51 fs rms time-of-flight spread
  - Equivalent to 0.05 deg rf phase spread for h=8
  - For 6 MV, that means 0.8 μrad added divergence
  - Normal beam divergence is 2.2 urad
  - Adding in quadrature gives 6% emittance growth in a single pass

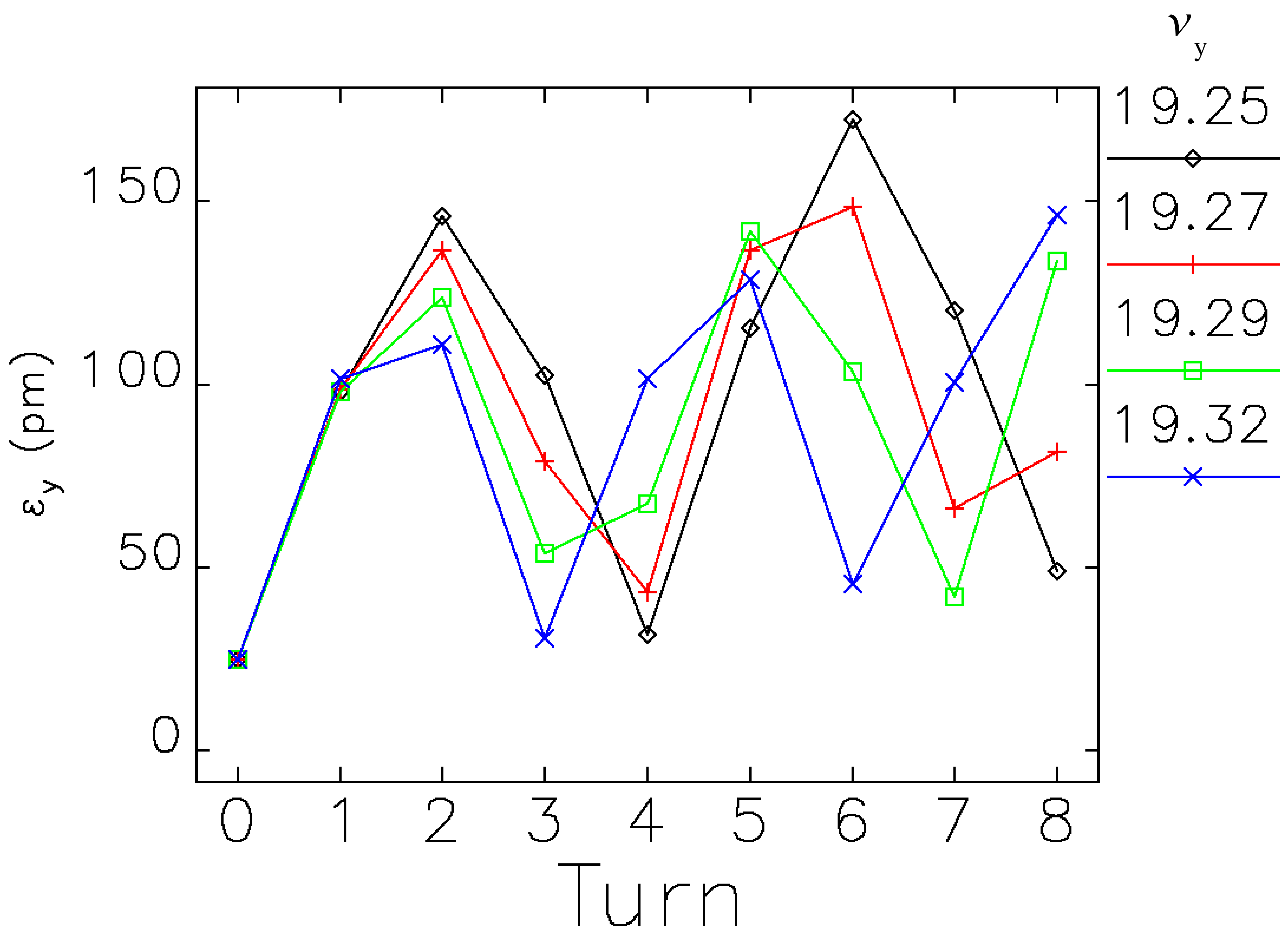
Chromaticity

- Chromaticity: variation in phase advance with energy error
- With interior sextupoles off, very large variation between the cavities
- Beam has 0.1% rms energy spread
  - Results in 0.0022 rms tune spread for propagation between cavities (tune=phase/360 deg)
  - Results in beamsize spread at the second cavity
    - 41 μm for V=6 MV, h=8
    - Nominal beamsize is 11 μm
    - Vertical emittance increases 3.7-fold in a single pass

Prompt Emittance Cancellation

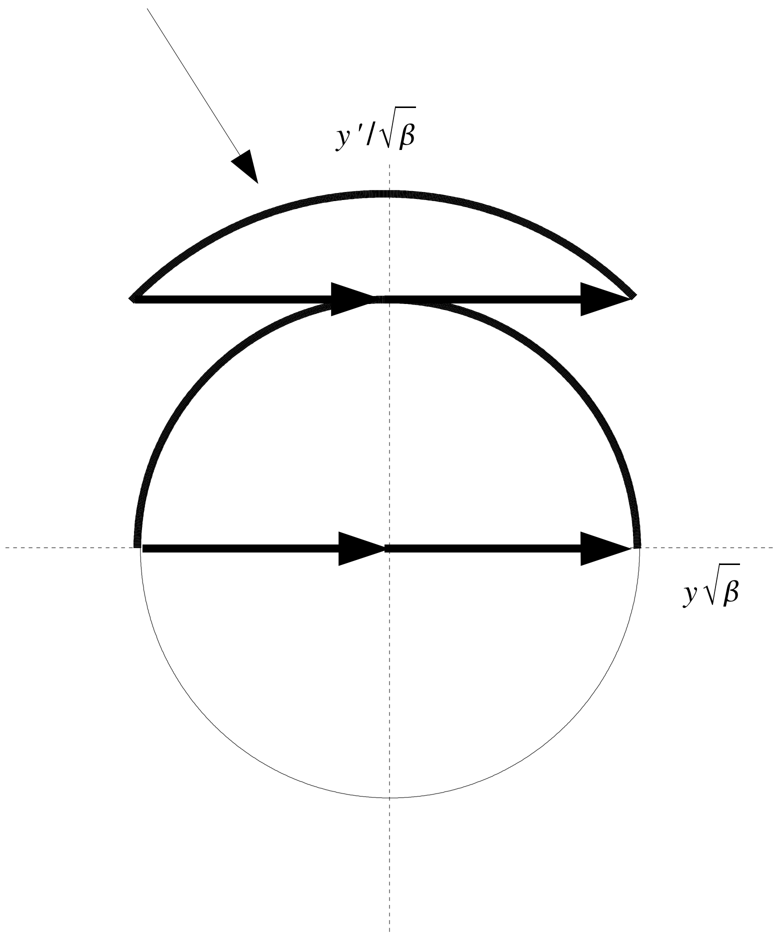
- Particles' slope and position errors are proportional to their momentum deviations
  - Chromaticity gives a position error after the second cavity
  - Momentum compaction gives a slope error
  - Errors turn into betatron oscillations at the vertical tune ν_y=19.27
- Momentum deviation is "roughly" constant over several turns
  - "Same" error is given repeatedly over several turns
  - Using ν_y=19.25, expect "exact" cancellation of the errors from two turns ago
  - Leads to "exact" emittance cancellation in four turns
- Unfortunately things are too rough and not exact enough
  - Emittance degradation builds up

Turn-by-Turn Emittance



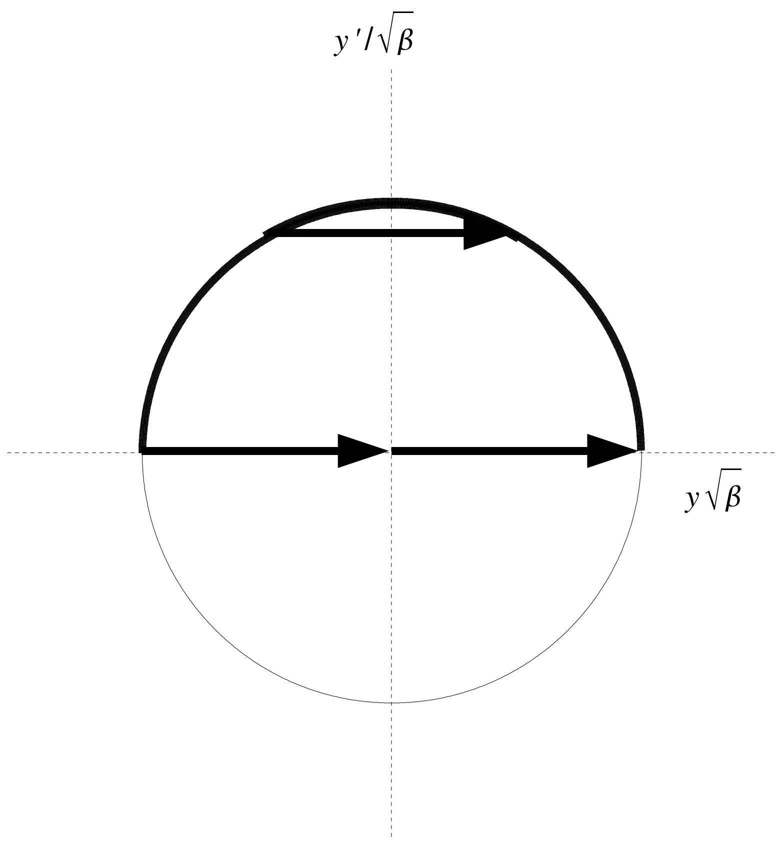
Why Cancellation Occurs

Larger maximum amplitude samples more nonlinearity



Tune of N+0.25

Fewer turns for cancellation means less synchrotron motion, more ideal result

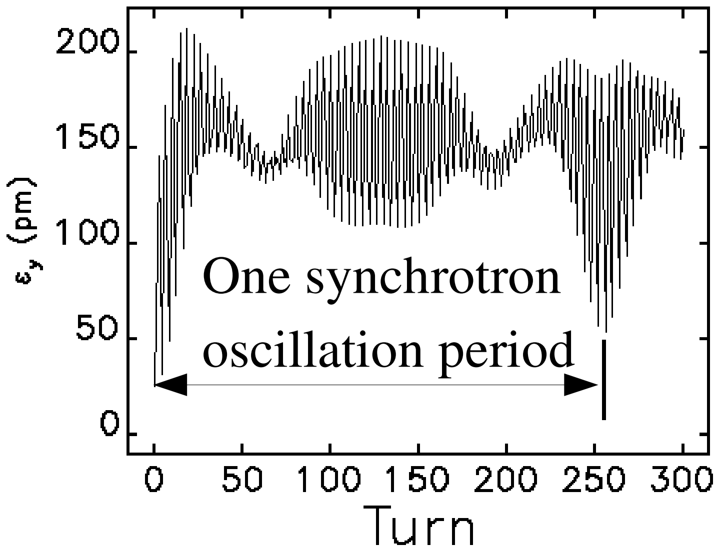


Tune of N+1/3

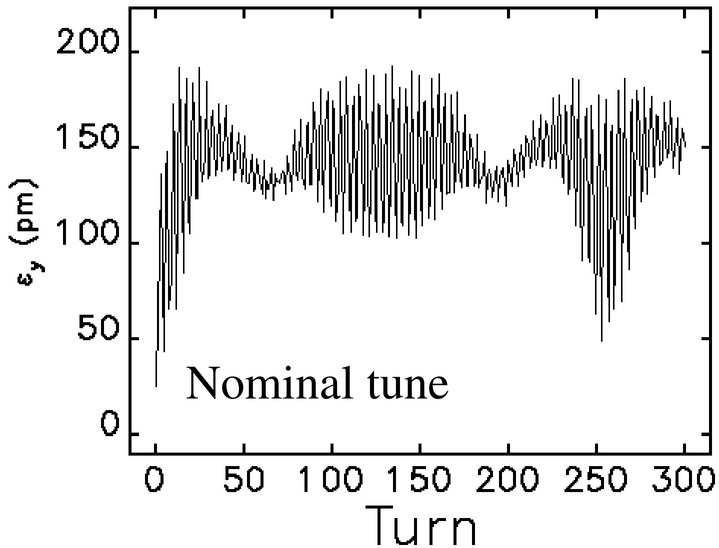
Long-Term Emittance Cancellation

- Simple analysis indicates that emittance degradation should largely cancel
  - After a certain number of turns, and
  - After one synchrotron period
- In reality this can't exactly happen because of
  - Exterior sextupole nonlinearities
  - Quantum excitation
- These spoil the perfect harmonic motion of particles

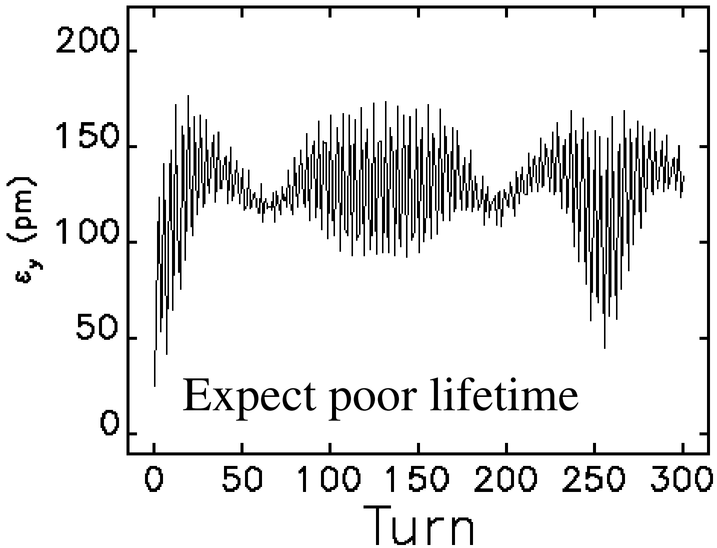
Longer Term Results (No QE)



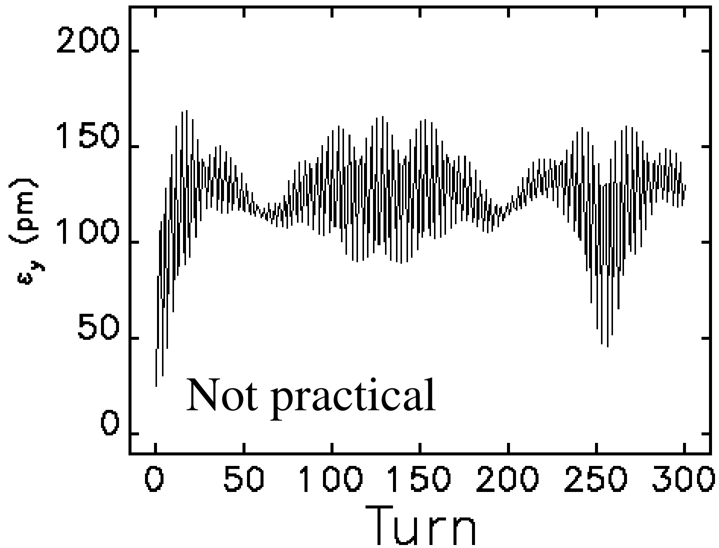
ν_y: 19.25



ν_y: 19.27



ν_y: 19.29

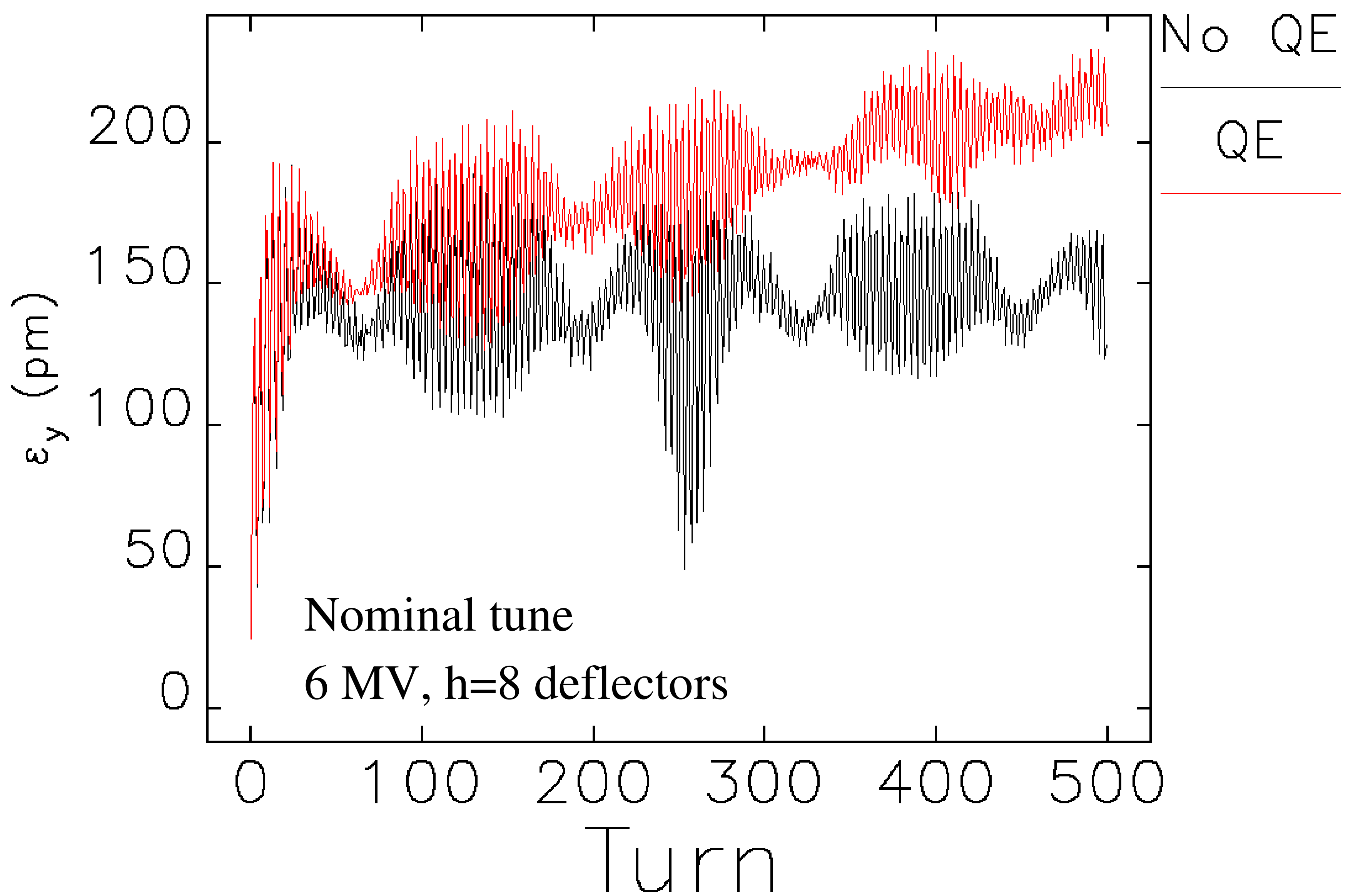


ν_y: 19.32

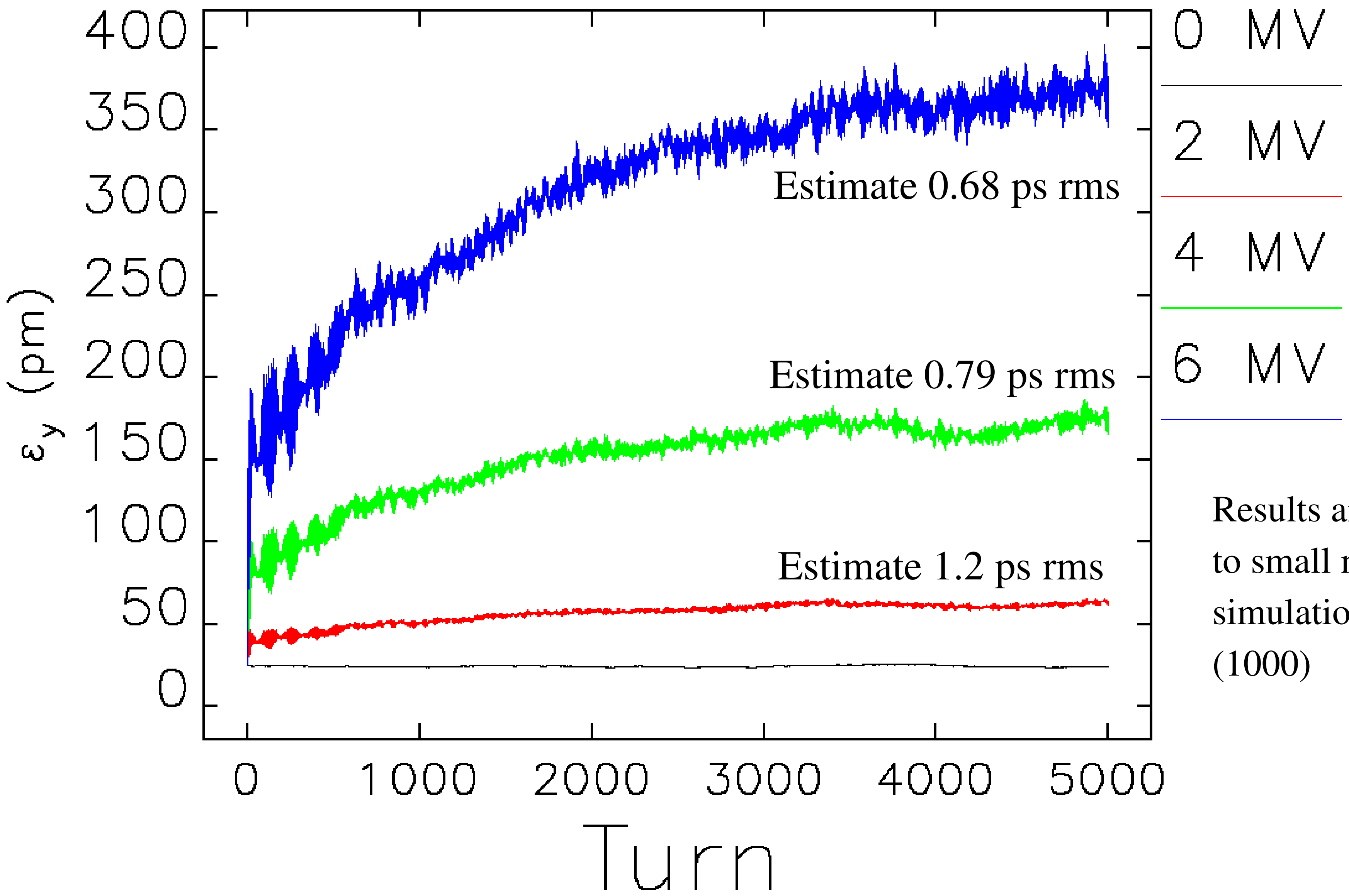
Synchrotron Radiation Effects

- Synchrotron radiation does two things
  - Damps particle oscillations
  - Excites particle amplitudes (quantum excitation)
  - Balance between these gives the beam a certain emittance and momentum spread
- Was assumed that SR was a small effect
  - Emittance growth is very rapid (20 turns)
  - Damping time is very long (~2600 turns)
- Only recently discovered that QE hurts significantly
  - Randomizes particle momenta too quickly
  - Greatly reduces partial cancellation over a synchrotron period

Effect of Quantum Excitation

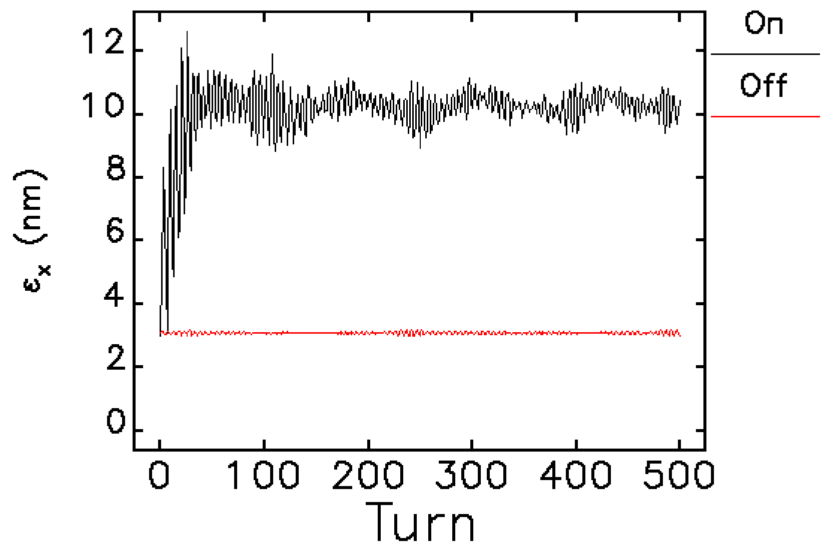


Long-Term Vertical Emittance Growth

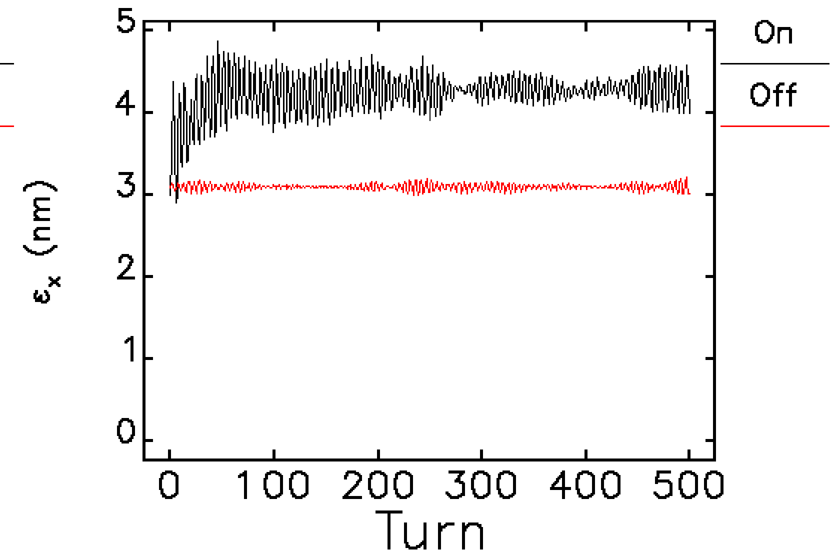


Results are noisy due to small number of simulation particles (1000)

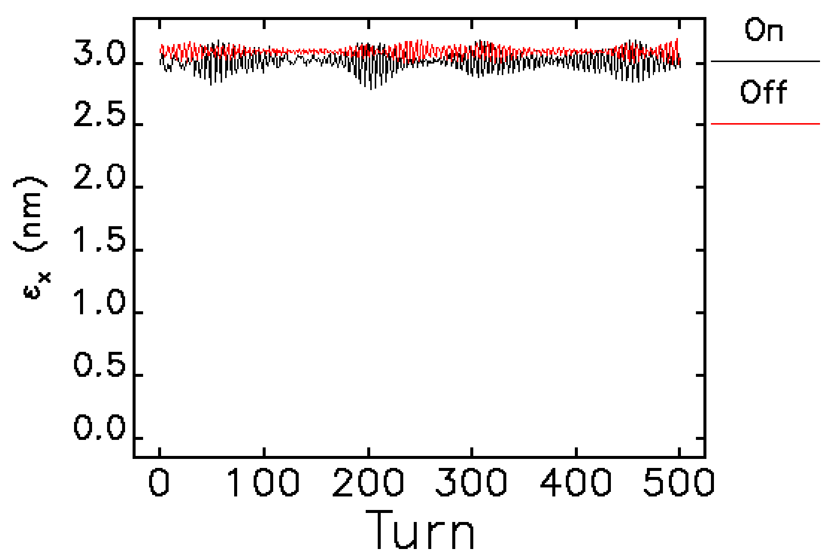
Interior Sextupoles and Horizontal Emittance



6 MV h=8



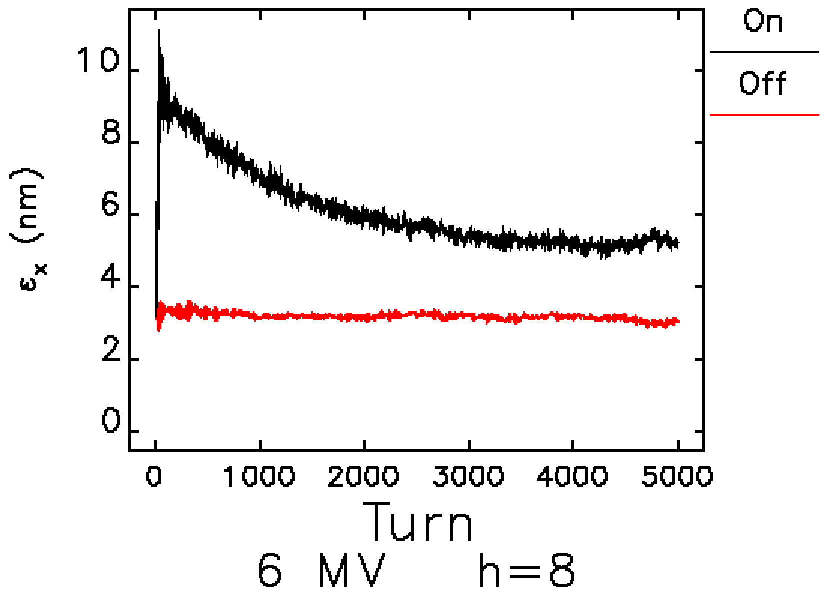
4 MV h=8

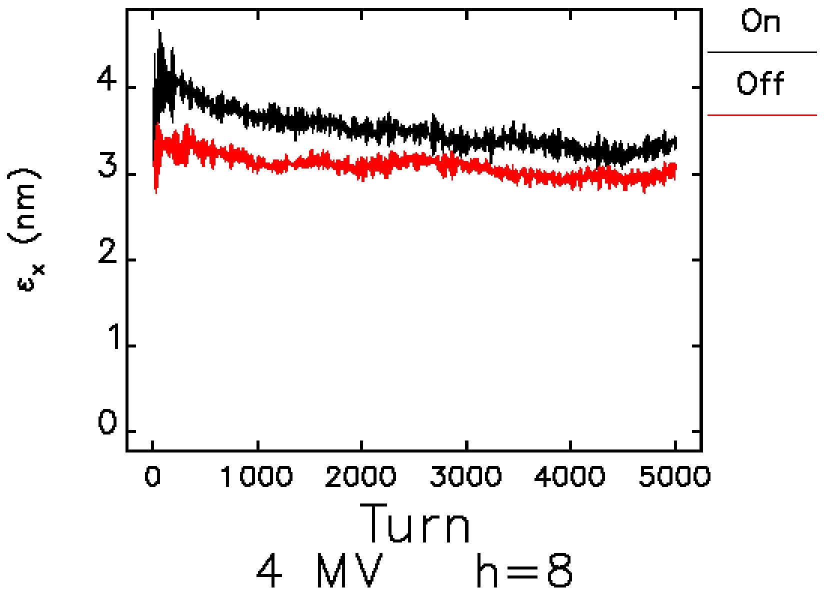


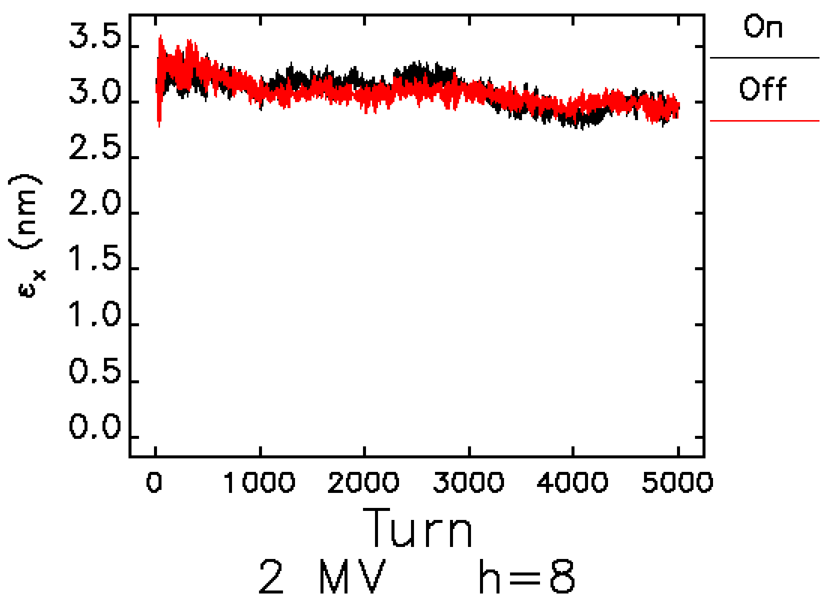
2 MV h=8

Without SR, would conclude that having interior sextupoles limits us to 2 MV

Interior Sextupoles and Horizontal Emittance

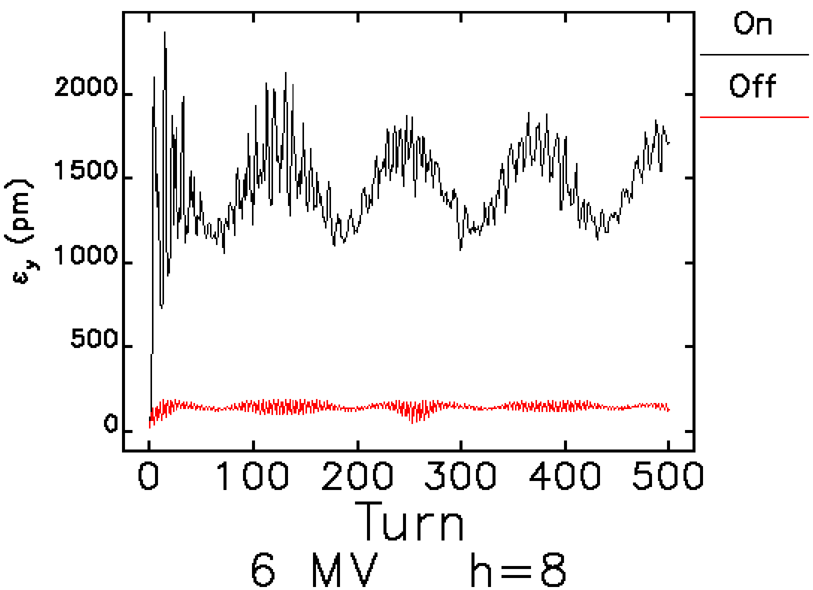


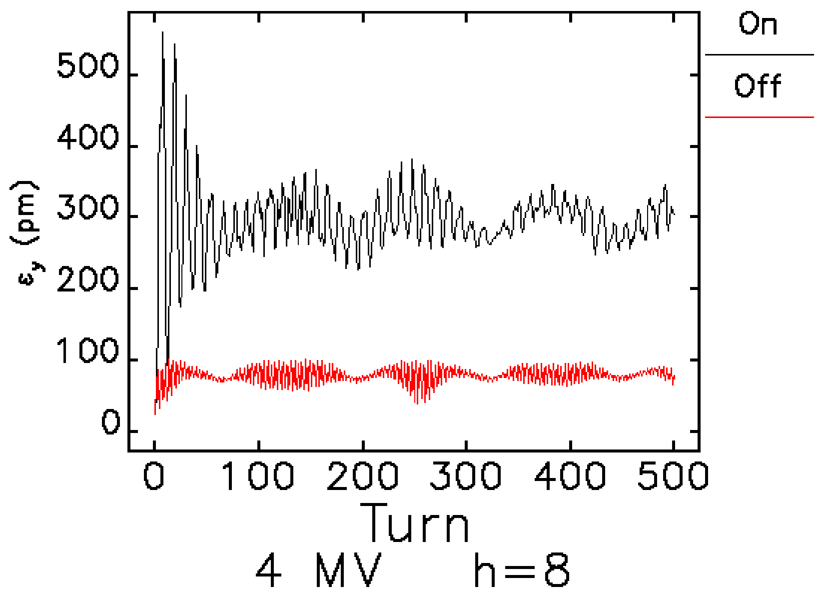


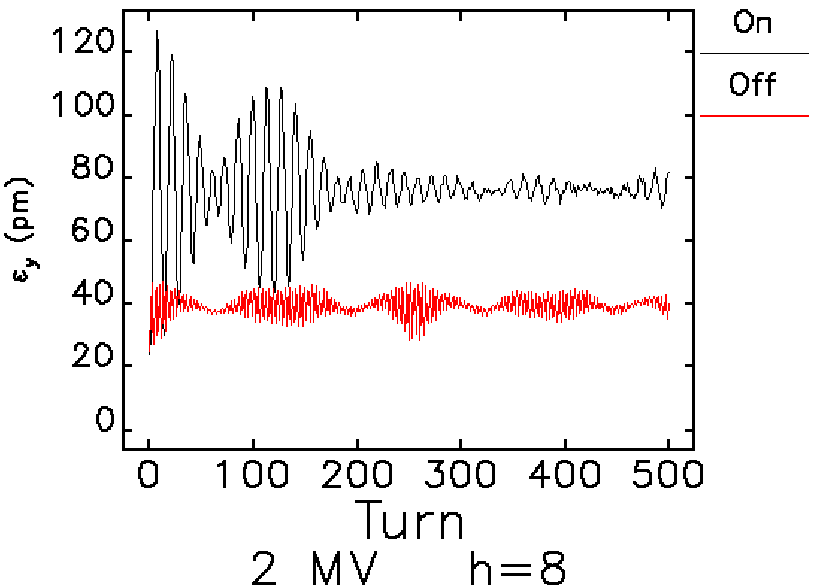


Radiation damping helps sextupole-on case

Interior Sextupoles and Vertical Emittance

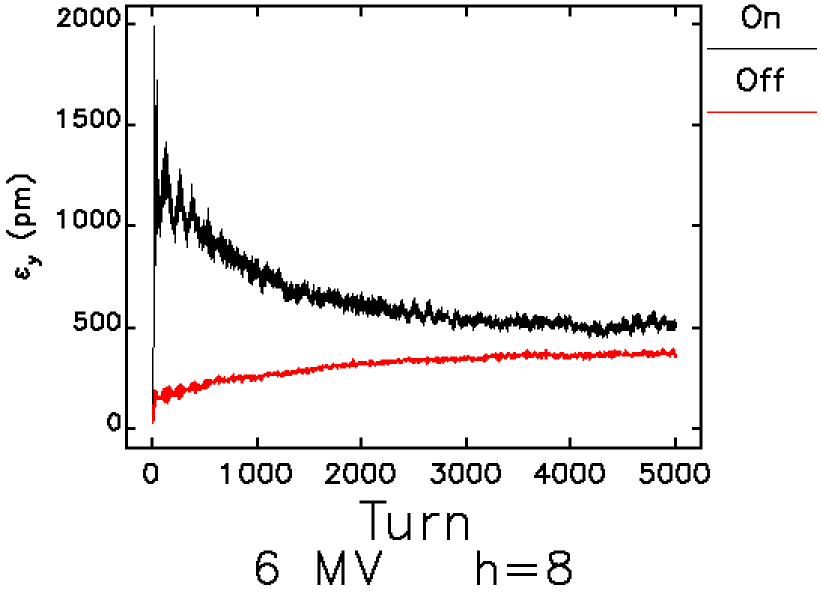


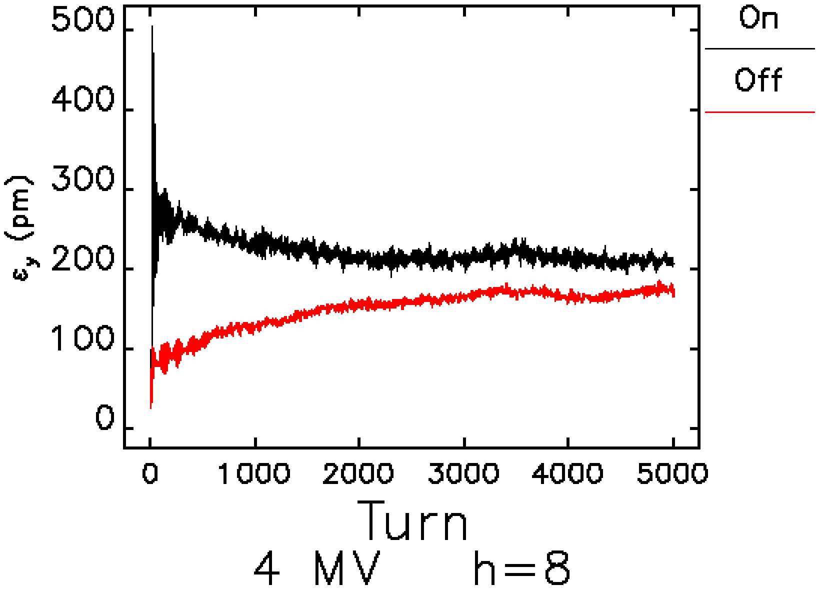


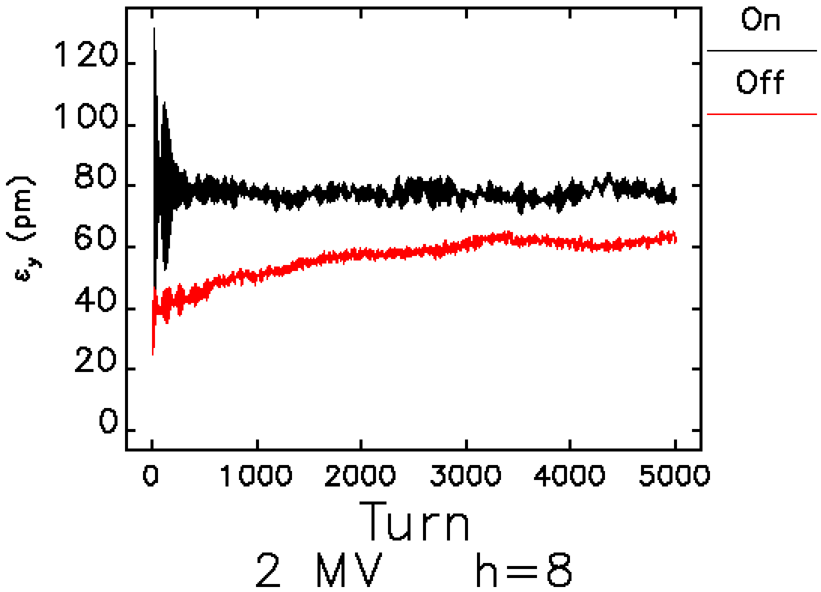


Again, sextupoles-on case looks bad when SR is not included

Interior Sextupoles and Vertical Emittance







Damping helps sextupoles-on case and QE hurts sextupoles-off case

Managing Vertical Emittance Growth

- Keep the voltage low
  - Nominally reduces ability to compress
  - May *help* compression by reducing emittance blowup
- Turn off interior sextupoles
  - Hurts lifetime, but slightly advantageous for V>2 MV
  - Assumed in all subsequent simulations
- Use a one-sector configuration instead of two-sector
  - Should reduce growth two-fold
- Offset ~20 pm of increase by lowering emittance ratio ahead of time[1]

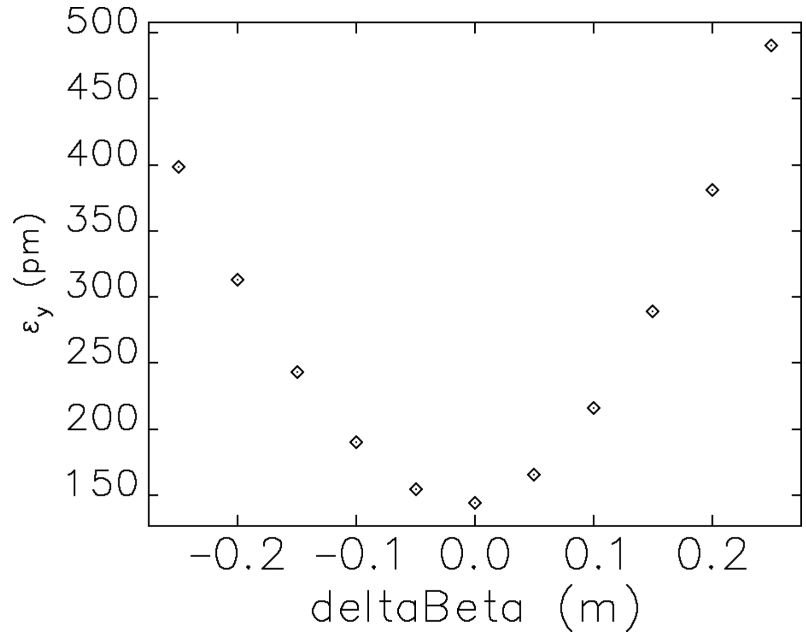
[1] V. Sajaev

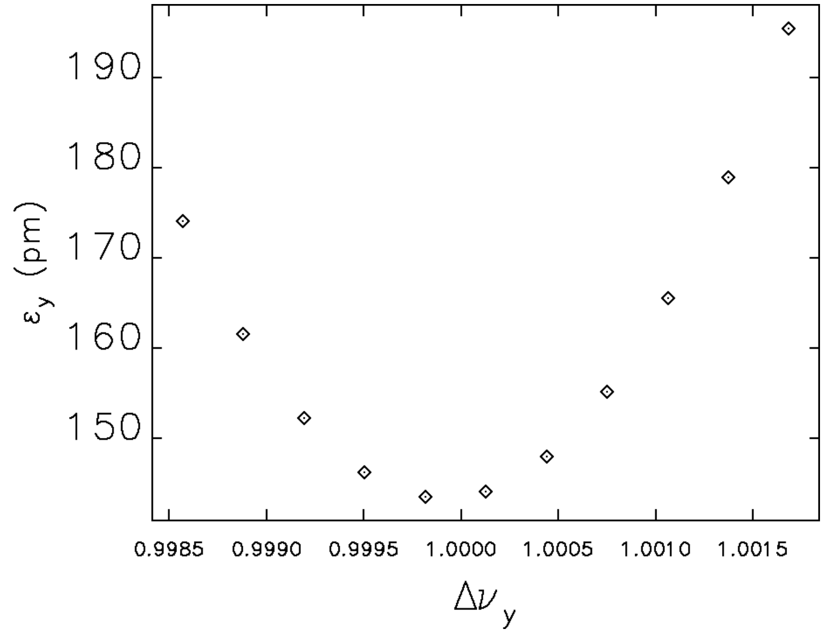
Tolerances and Emittance Degradation

- So far, all calculations assumed a perfect machine
- Tolerances have been estimated for several types of errors
  - To date, didn't include QE effects
  - QE lets us loosen tolerances since we can't preserve the emittance beyond a certain level in any case
- All simulations have
  - Interior sextupoles off
  - 6 MV and h=8

Lattice Errors

- Lattice errors can result in
  - Phase advance errors
  - Beta function errors
- Sources include
  - Beamline steering
  - Power supply drift
  - Misalignments
- Lattice correction gives
  - 1% beta function errors[1]
  - <0.001 tune error[2]



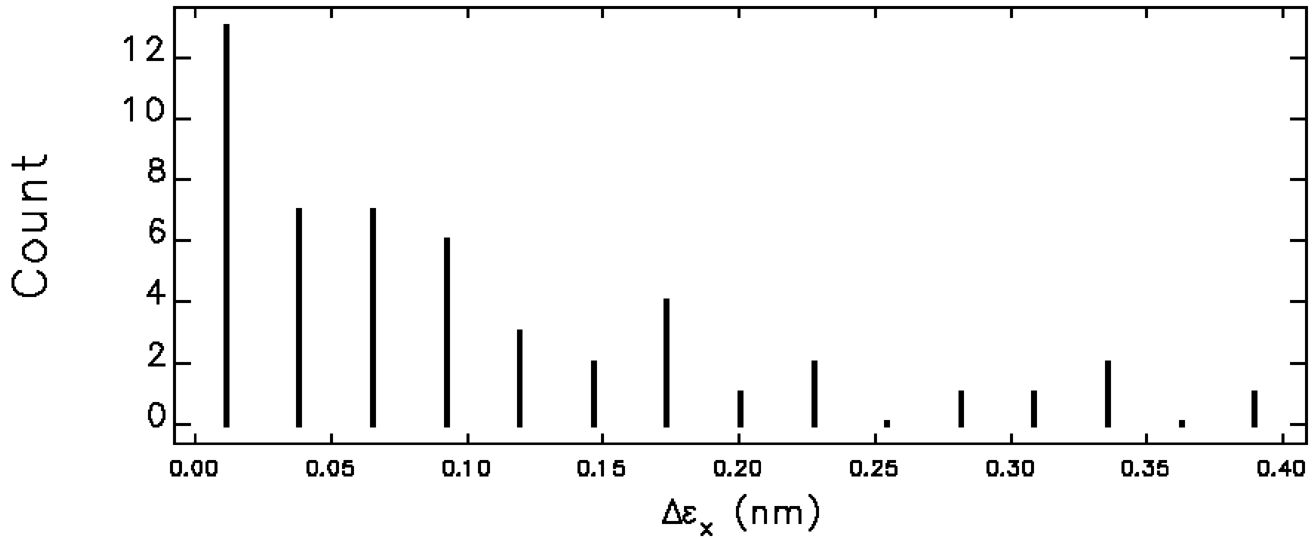


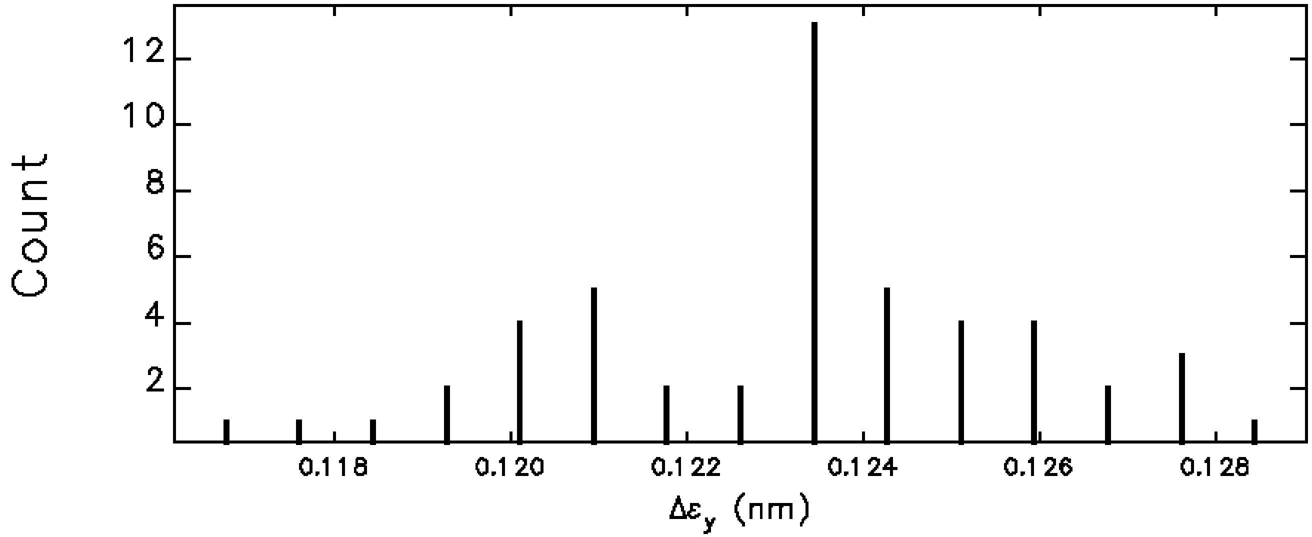
[1]V. Sajaev and L. Emery, EPAC 2002, p. 742

[2]L. Emery

Lattice Coupling Between Cavities

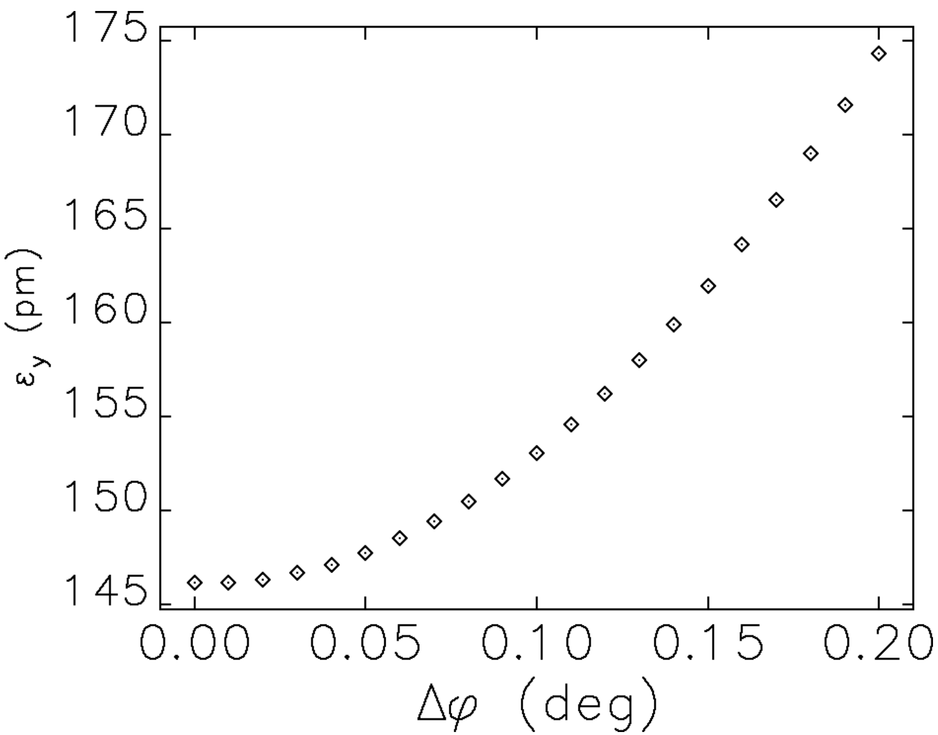
- May have quad and sextupole roll
- Roll is ~0.25 mrad rms[1]
- Didn't simulate with interior sextupoles on





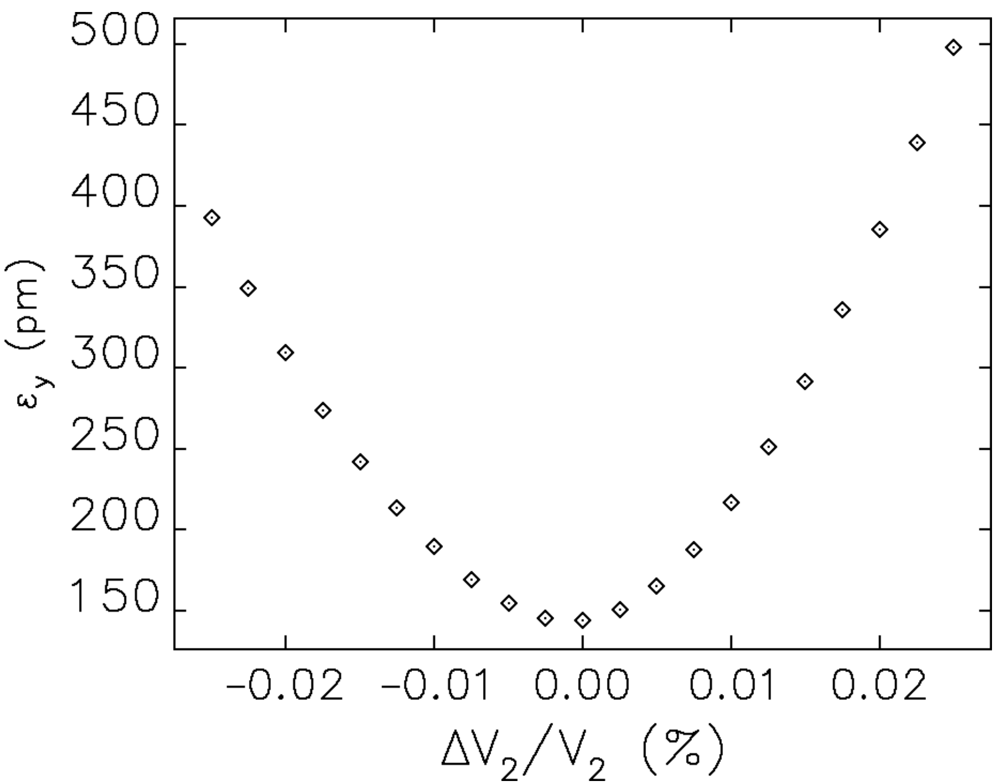
[1]H. Friedsam

Cavity Phase and Voltage



APS *pulsed* S-band systems have ~0.15 deg rms phase jitter[1]

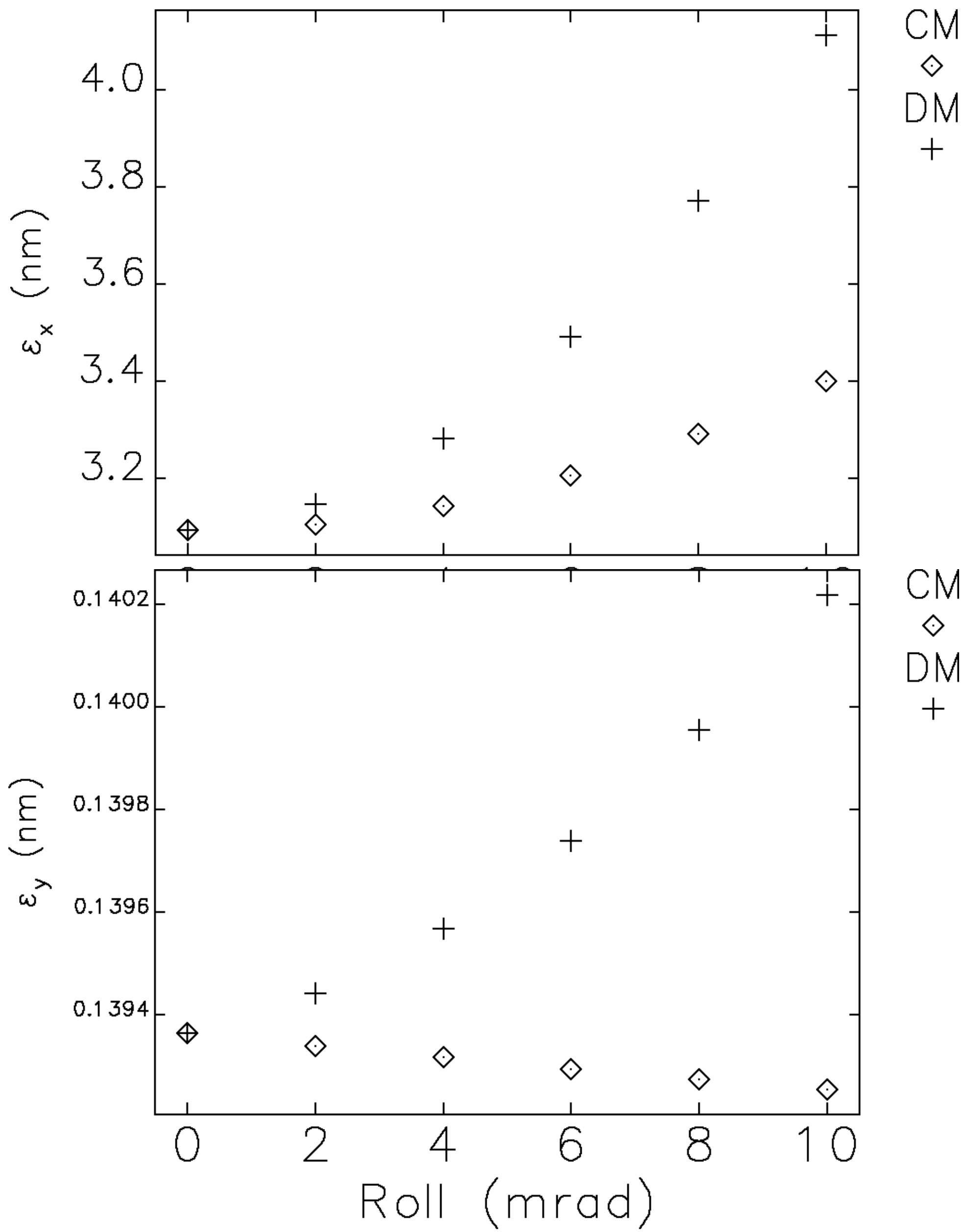
LCLS *pulsed* S-band system assumes 0.1% rms voltage jitter



[1]M. Borland, OAG-TN-2004-019

Cavity Roll

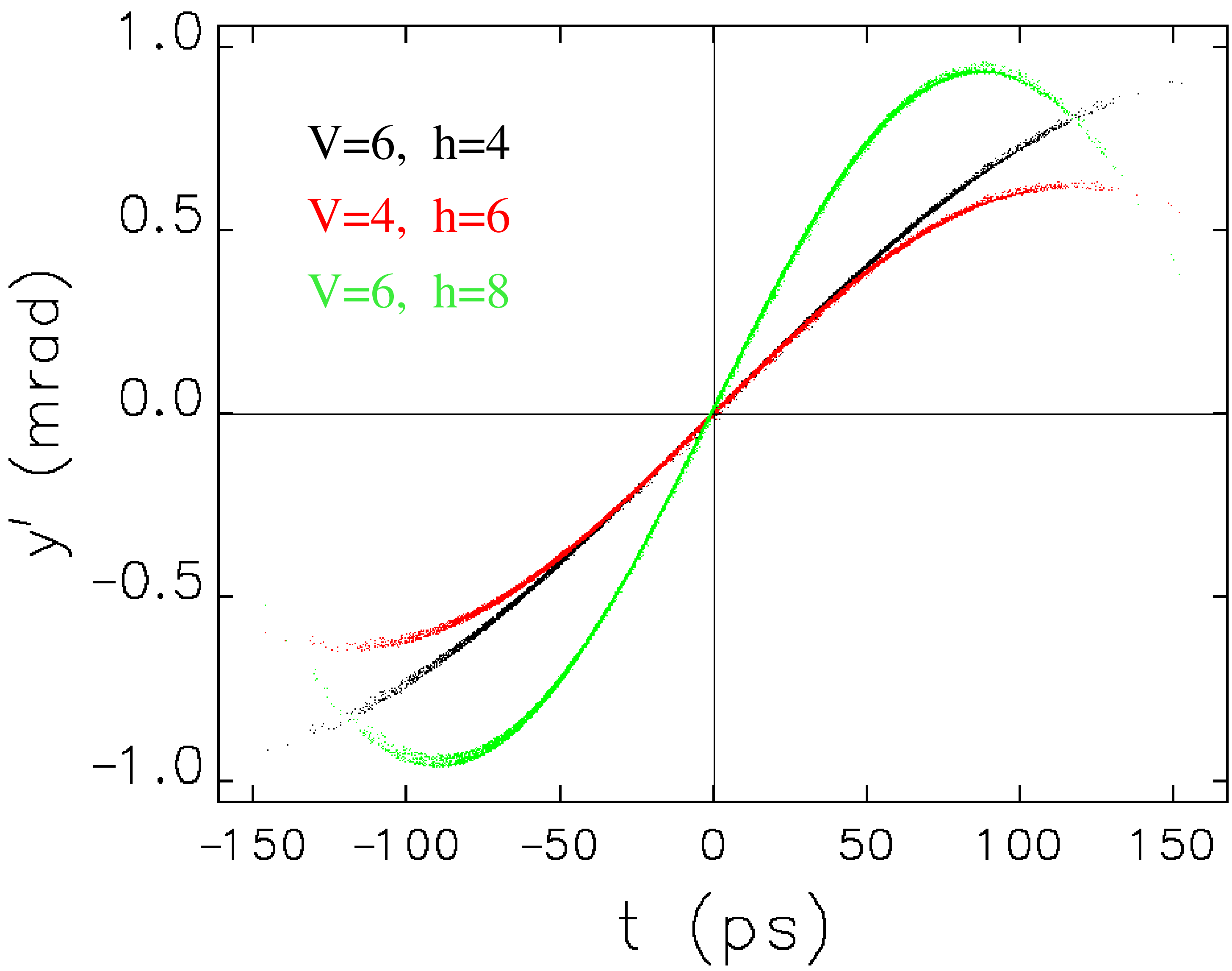
- Cavities may be rolled relative to machine vertical
- General rolls are a combination of
  - Common-mode: rolled in same direction
  - Differential-mode: rolled in opposite directions
- Neither appears to be a problem at ~2 mrad level



Lifetime Limits

- Two concerns with lifetime
  - If chirp is too large, particles may scrape on chamber
  - Large emittance blow-up may contribute to this
  - Need room for ~10σ_y to ensure good lifetime
- ID chamber is the aperture limit
- Cavity center to end of ID chamber is 3.7 m
- At exit of ID chamber, for 6 MV
  - Chirp is +/- 3.2 mm pk-pk
  - If ϵ_y=0.4 nm, get σ_y=49 μm (β_y=6.1m)
  - Allowing +/- 100 μm for orbit, have room for 14σ_y in +/- 4 mm ID chamber
- Lifetime should not be an issue up to ~6.6 MV

Rf Curvature and Frequency Choice



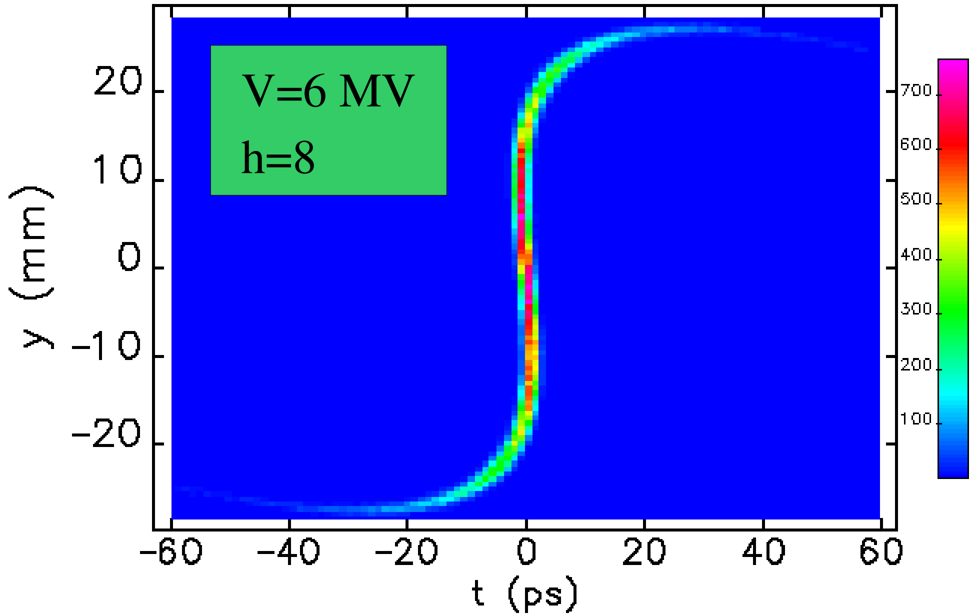
Can get the same compression as long as h*V is constant

Higher V and lower h: more linear chirp and less need for slits

Higher h and lower V: smaller maximum deflection and less lifetime impact

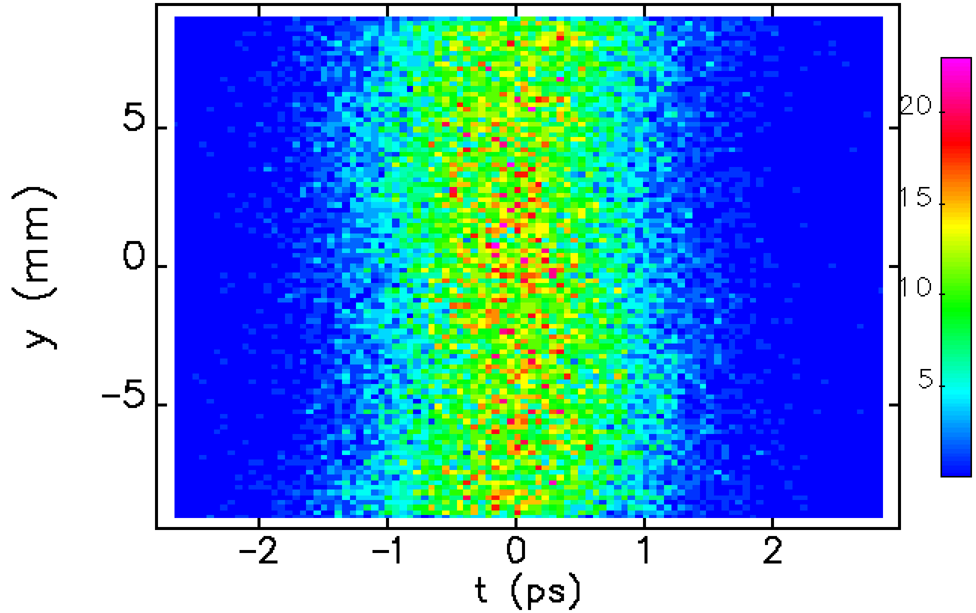
Higher h and higher V: generally shortest pulse achievable

Need for Slits



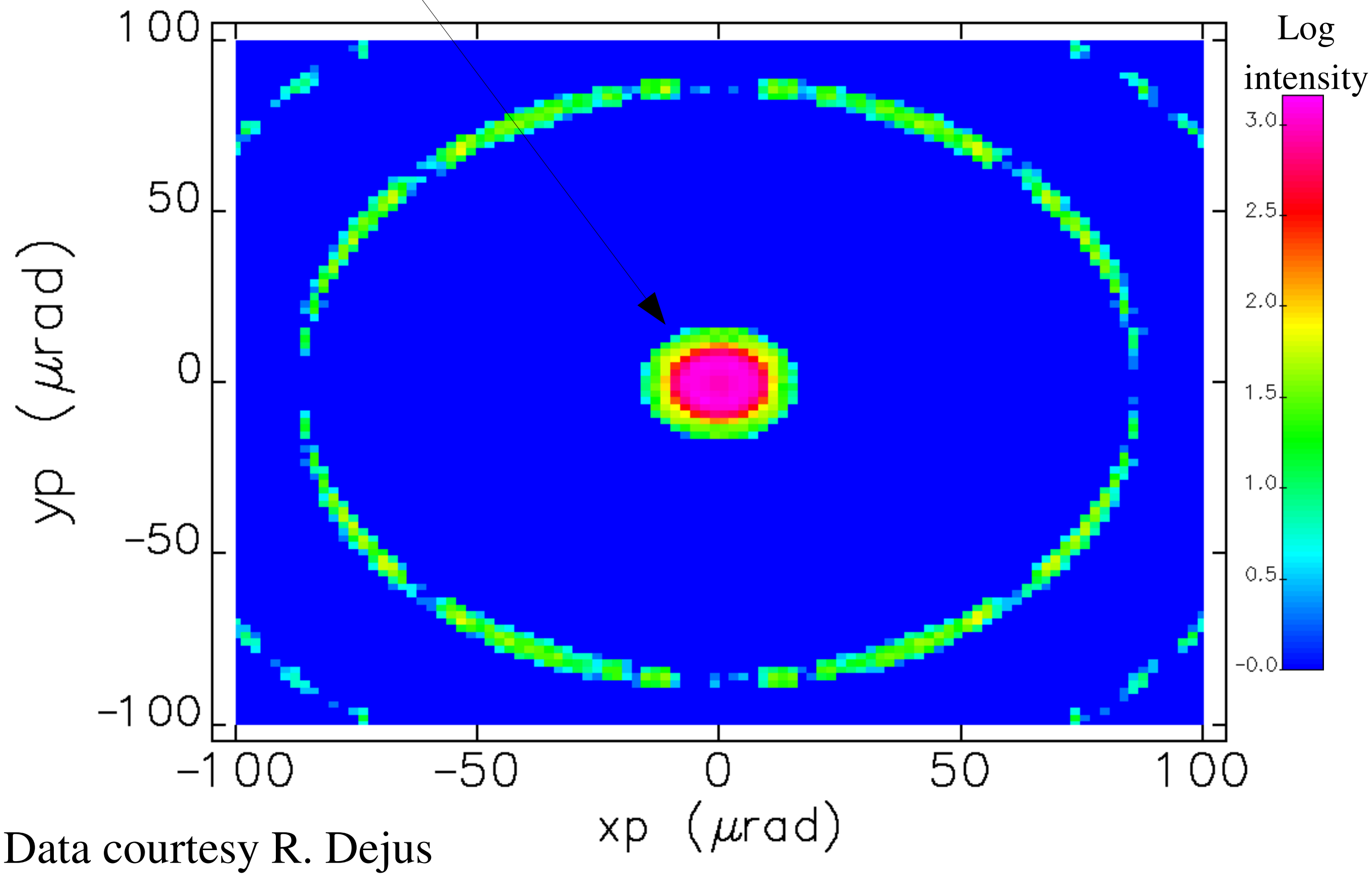
Without slits, rf curvature prevents complete compression

With slits, we lose intensity but get complete compression



Undulator Radiation Pattern

Central cone opening angle ~5 urad rms



Data courtesy R. Dejus

For estimates, use

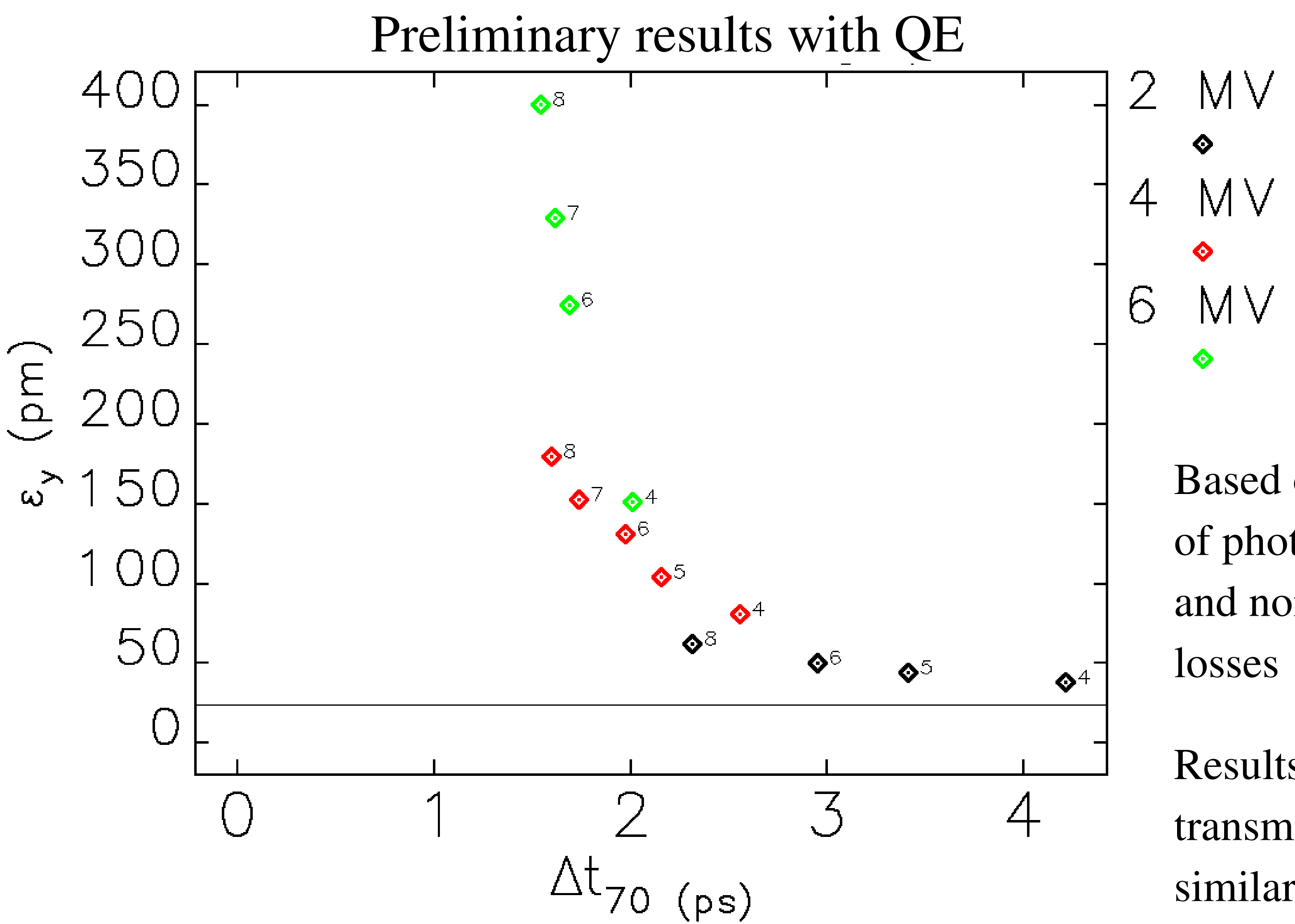
$$\sigma_\theta = \sqrt{\frac{\lambda}{2L}}$$

Simulations use distribution function[1]

$$S(\theta) \approx sinc^2\left(\frac{nN\pi\gamma^2\theta^2}{1+K^2}\right)$$

[1]K.J. Kim, AIP 565 (1989)

Simulation Results for 10 keV, UA



Based on retaining 10% of photons, including slits and nominal 70% optics losses

Results for 5 and 20% total transmission are very similar

Impedance Concerns

- Machine impedance may cause problems
- Vertical impedance checked with tracking (Y.C. Chae)
  - No obvious problems found
  - Needs to be looked at more closely
- Longitudinal impedance not checked
  - Potential well distortion probably not an issue
  - Above the microwave threshold (~7 mA/bunch), increased energy spread will create problems
  - Needs to be checked with simulation

Summary

- Zholents' scheme has been studied quite thoroughly
- Not possible to get ~1 ps FWHM bunches as stated at the 2004 Strategic Planning Meeting
  - Voltage must be higher (4~6 MV not 2 MV)
  - Frequency may be higher (2800 MHz not 1400 MHz)
  - Probably turn off interior sextupoles, harming lifetime
  - Emittance growth is a serious issue
- Tolerances seem manageable
  - Need to revisit tolerances in light of QE discovery
  - Evaluate with interior sextupoles on
- Need to revisit impedance issues