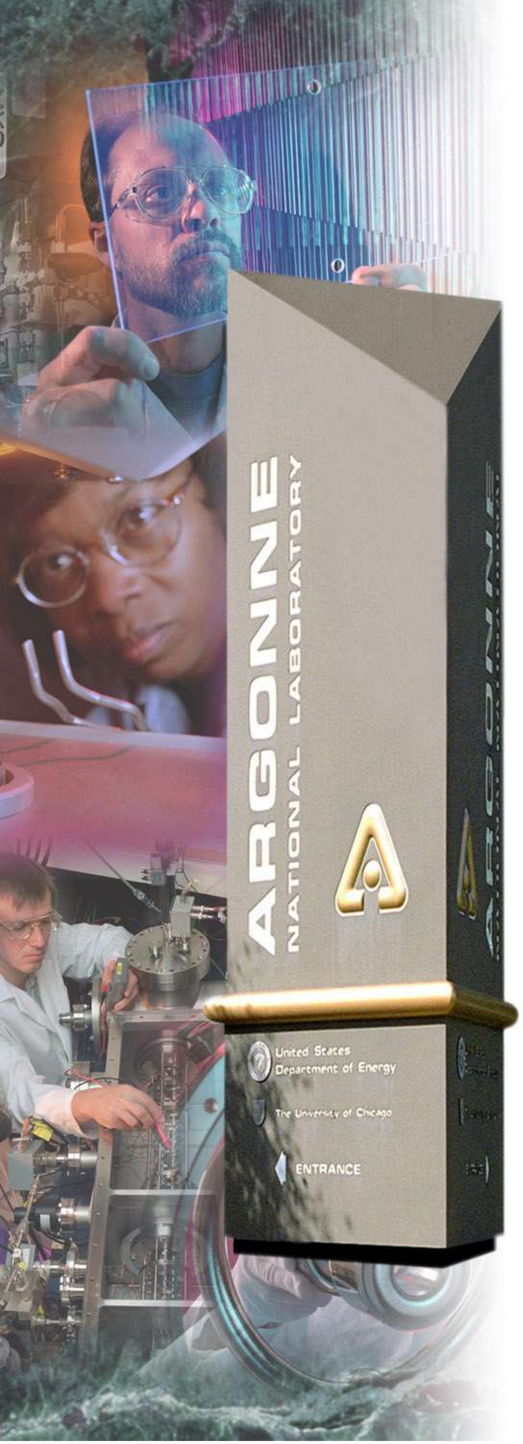

Accelerator Physics Aspects of Crab-Cavity-Based Production of Picosecond X-ray Pulses

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Office of Science
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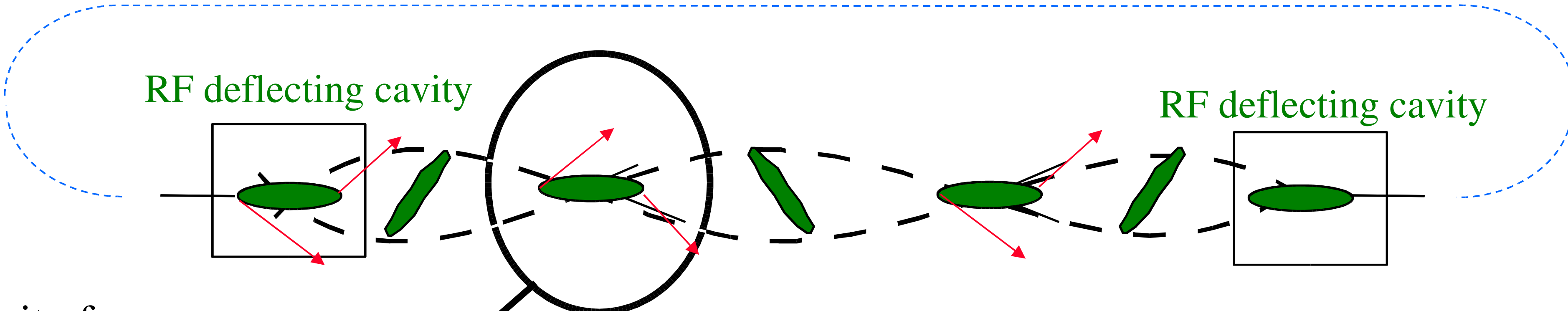
Outline

- Review of Zholents' concept
- Basic analysis of compression
- Simulation code and methods
- Lattice options and constraints
- Lifetime issues
- Emittance degradation mechanisms
- Error sensitivities
- Photon beam properties
- Optimization of compression

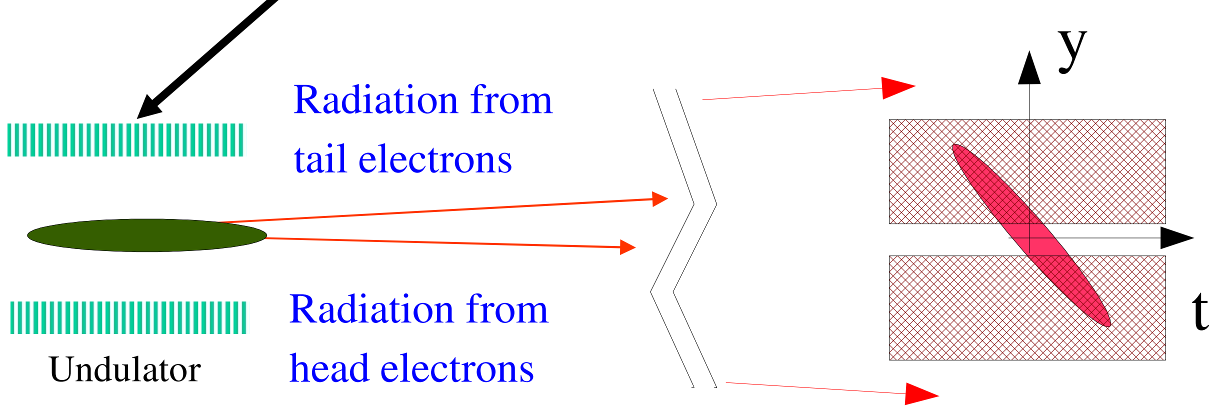
Zholents' Transverse Rf Chirp Concept

(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 if phase advance is n*180 degrees



Pulse can be sliced or compressed with asymmetric cut crystal

Compression Analysis

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

Electron beam energy

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

Deflecting rf voltage & frequency

Unchirped e-beam divergence (typ. 2~3 μrad)

Divergence due to undulator (typ. ~5 μrad)

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

- Normal APS bunch is 40 ps rms

Simulation Code and Methods

- We used **elegant**[1] for all simulations
- Modeled lattice with
  - First-order bending magnets (ρ=38m)
  - Canonically-integrated quadrupoles and sextupoles
- Modeled deflecting cavity with RFTM110 element
  - Zero-length TM110 cavity
  - 6th order radial expansion of electric and magnetic fields
- When included, synchrotron radiation modeled with a lumped element (SREFFECTS)
  - Gives correct damping rates and equilibrium properties

[1]M. Borland, APS LS-287, Sept. 2000.

Simulation and Bunch Lengthening

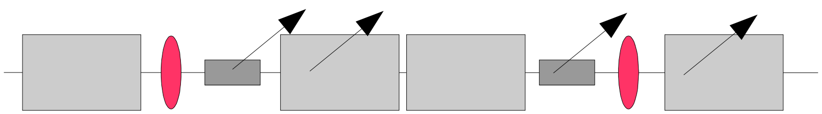
- APS has significant (~2x) bunch lengthening due to potential well distortion[1]
- This can be modeled using **elegant** and an impedance model[2]
- This is *extremely* CPU-intensive, so we used another technique
  - Reduce the simulated rf voltage to lengthen the bunch
- The coherent synchrotron tune is wrong, but
  - The incoherent synchrotron tune is about right
  - I.e., single particle longitudinal dynamics is about right

[1]Y.C. Chae, PAC 2001, 1491 (2001)
[2]Y.C. Chae, PAC 2003, 3017 (2003)

Lattice Constraints

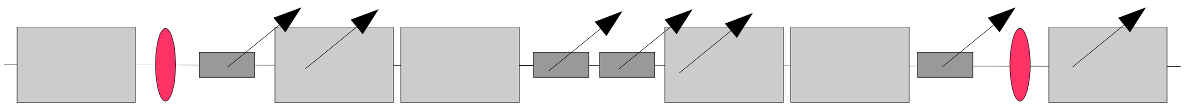
- Vertical phase advance
  - Must have n*180 degrees phase advance between the cavities
- Undulator placement
  - Should have about m*180 phase advance from first cavity
  - Otherwise, wastes aperture in the ID
- Vertical beta functions at cavities, IDs
  - May need to be modified to satisfy phase advance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

Lattice Options



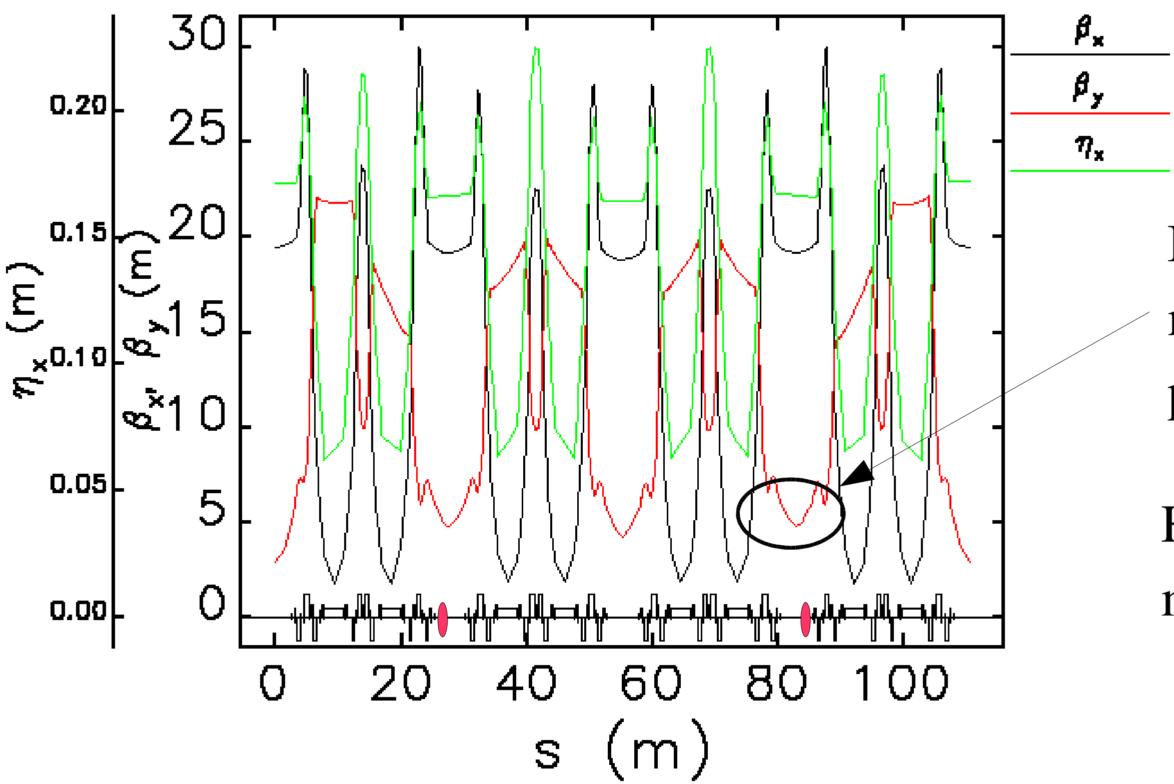
1 sector spacing

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

Lifetime Issues

- The maximum angular deflection seen by any particle is V/E
- We can preserve lifetime by requiring

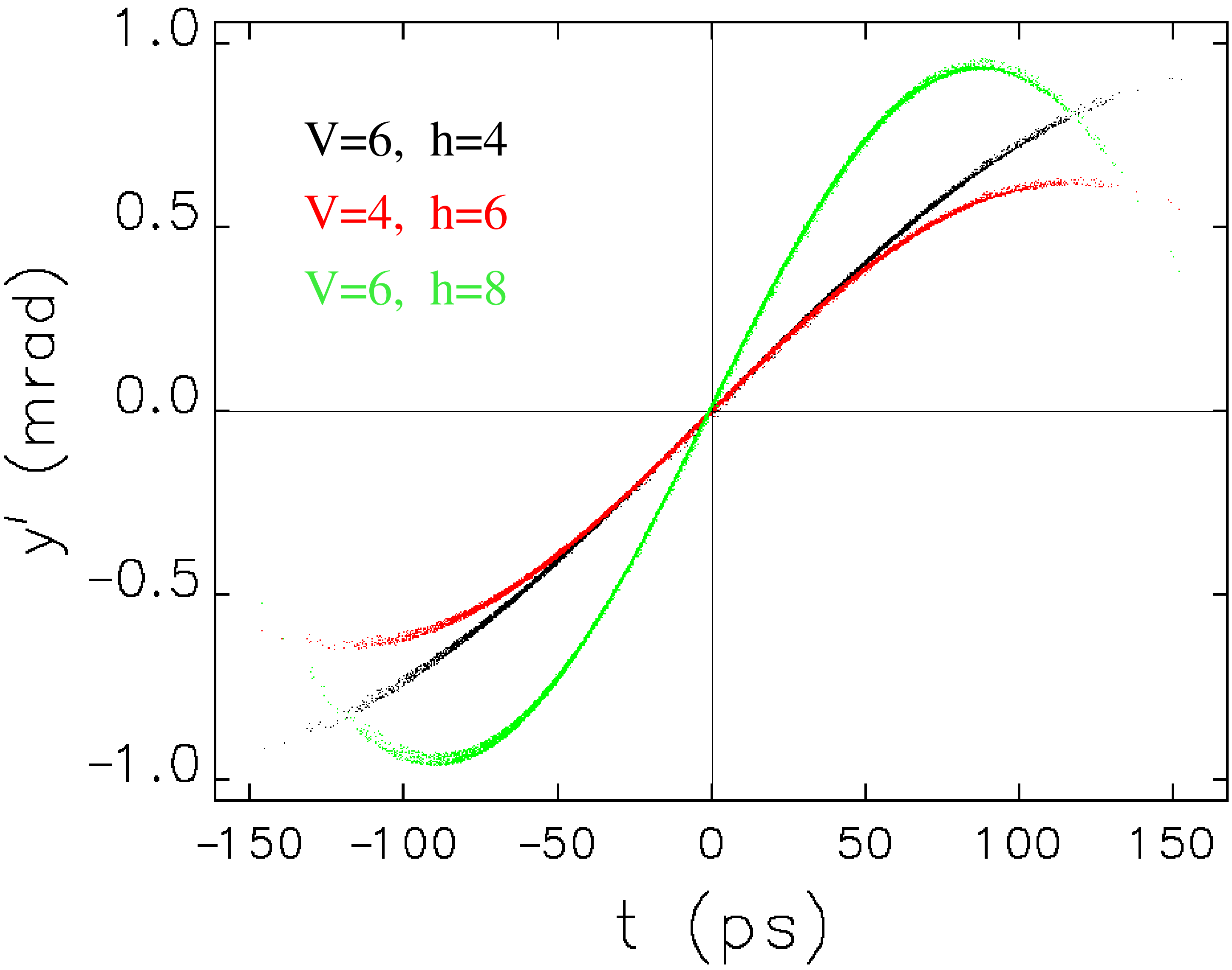
$$\frac{DV}{E} + 10\sigma_{y,\text{slice}} \le A$$

- With A=±4mm aperture and D=3.7m cavity-to-aperture distance, V<7.2 MV gives 10σ aperture
- We need hV=48MV to get 0.4 ps rms
- Must get large hV via h instead of V
  - h=8 is practical limit for power sources[2]
  - 6 MV may be possible for super-conducting system[1]

[1]G. Waldschmidt

[2]D. Horan

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 maximum V: shortest pulse, acceptable lifetime

Causes of Emittance Degradation

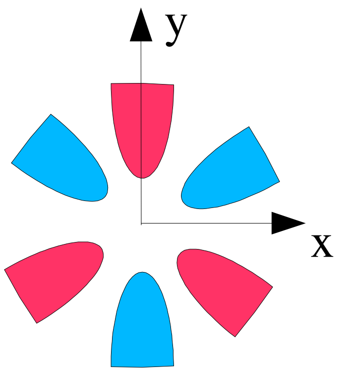
- Less than total kick cancellation will cause emittance increase
- Effects present in a perfect machine
  - Momentum compaction and beam energy spread
  - Sextupole nonlinearity
  - Chromaticity and beam energy spread
- Additional effects in an imperfect machine
  - Lattice errors
  - Lattice coupling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

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

Sextupole Effects

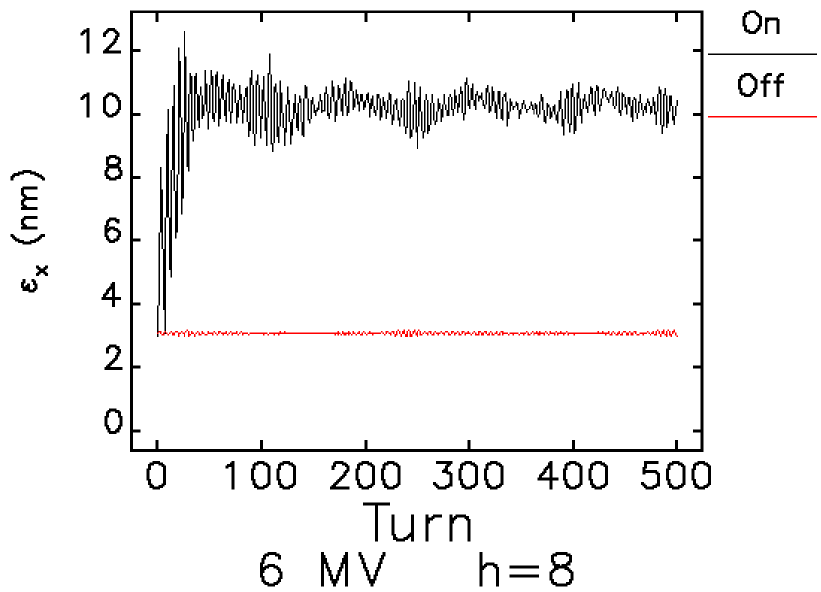
- Sextupoles are necessary
  - Correct chromatic focusing aberrations
  - Defeat beam instabilities
- Sextupoles have undesirable side-effects
  - Phase advance varies with amplitude
    - Kick cancellation varies with amplitude
    - Vertical emittance increases
  - Horizontal and vertical motion gets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

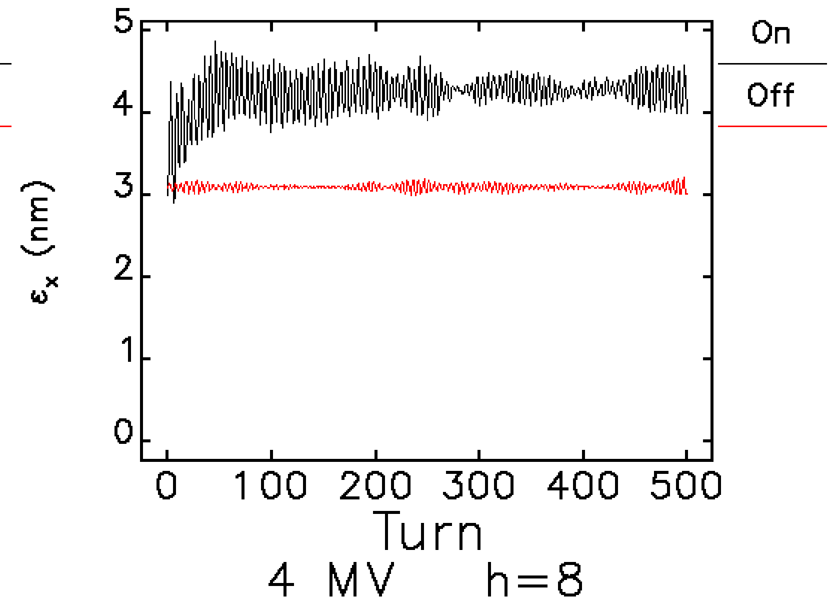


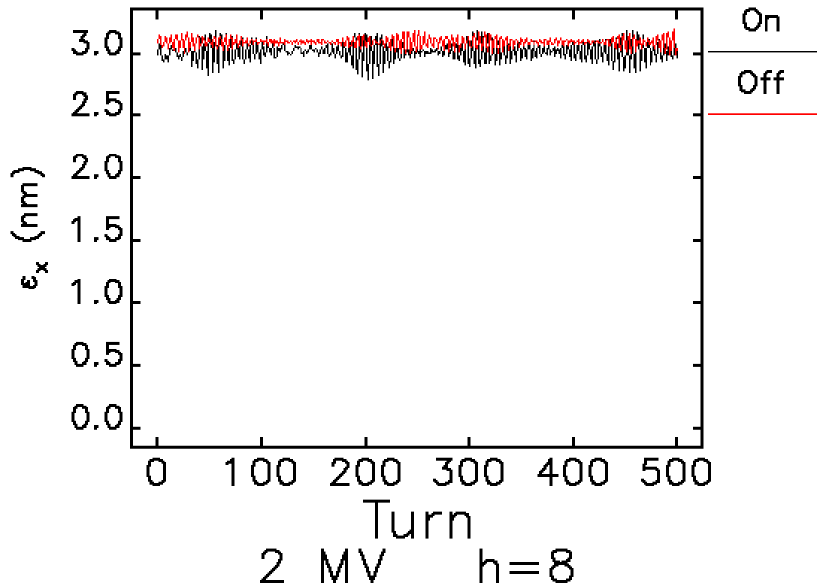
$$B_y = \frac{1}{2} m (x^2 - y^2)$$

$$B_x = m x y$$

Interior Sextupoles and Horizontal Emittance

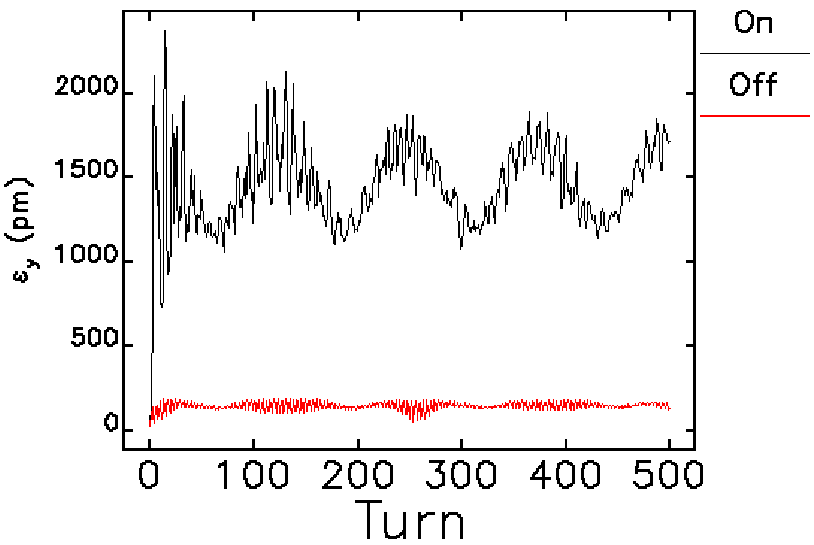




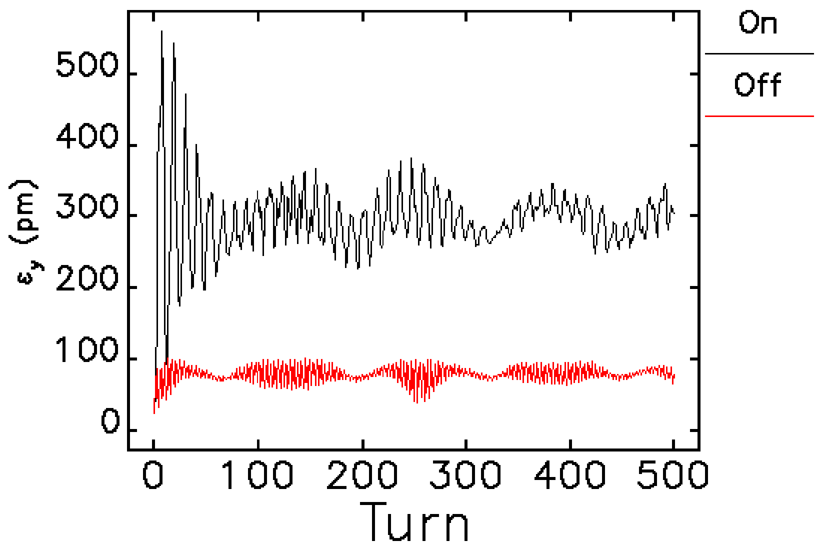


Based on simulations without synchrotron radiation, would conclude that having interior sextupoles on *at normal values* limits us to 2 MV

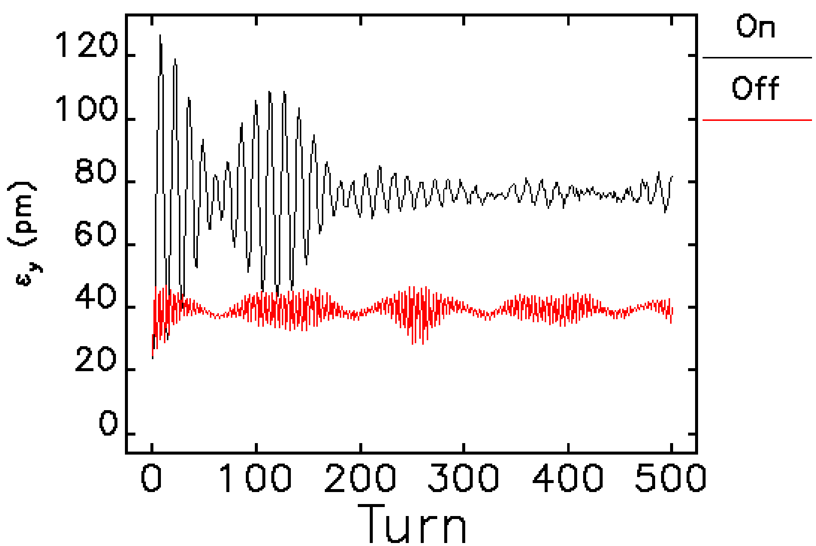
Interior Sextupoles and Vertical Emittance



6 MV h=8



4 MV h=8



2 MV h=8

Again, sextupoles-on case looks *much* worse

This conclusion will be revised later!

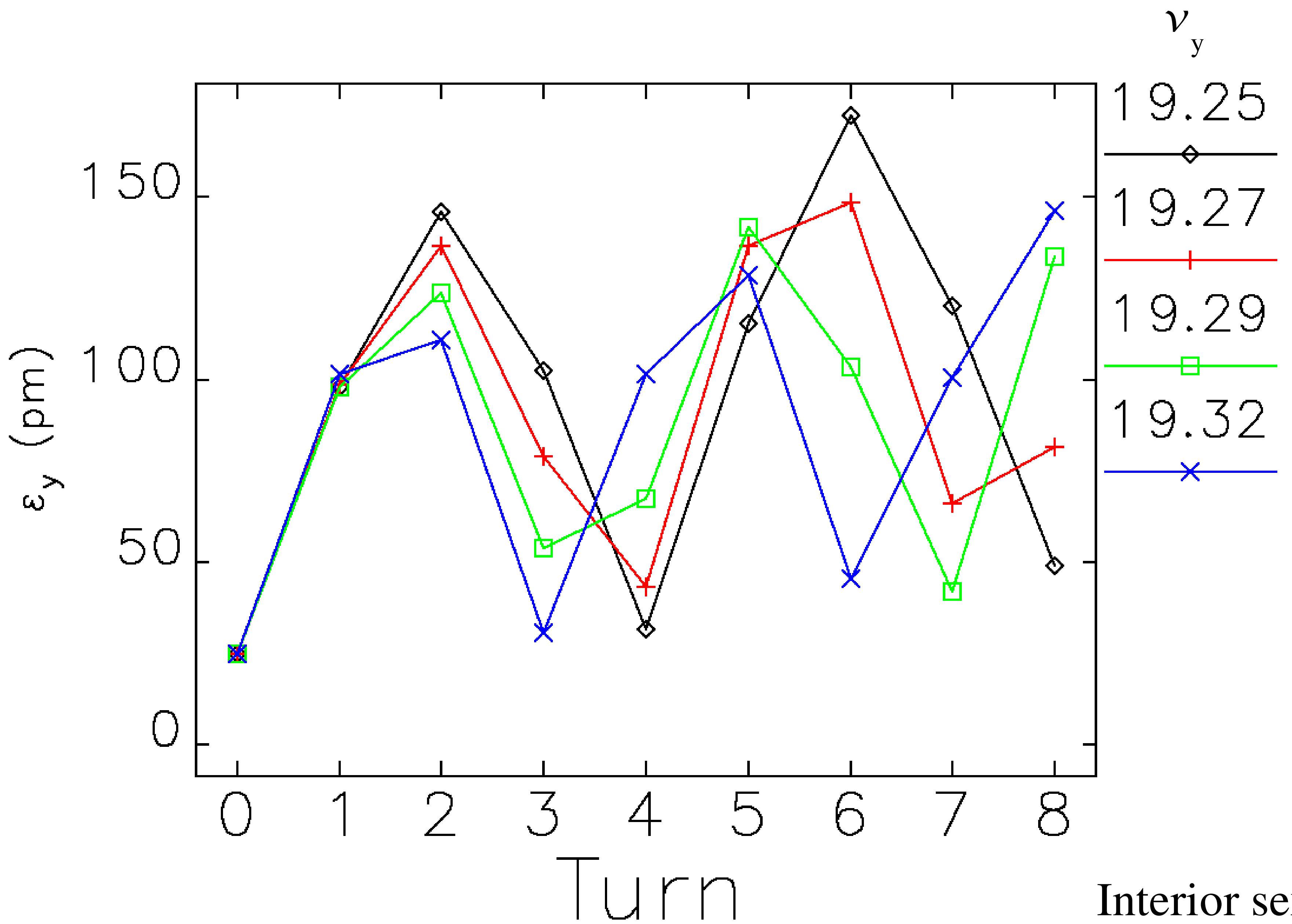
Chromaticity

- 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

Does Emittance Degradation Add Up?

- 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 momentum deviation changes too fast
  - Emittance degradation still builds up, but is limited

Turn-by-Turn Emittance

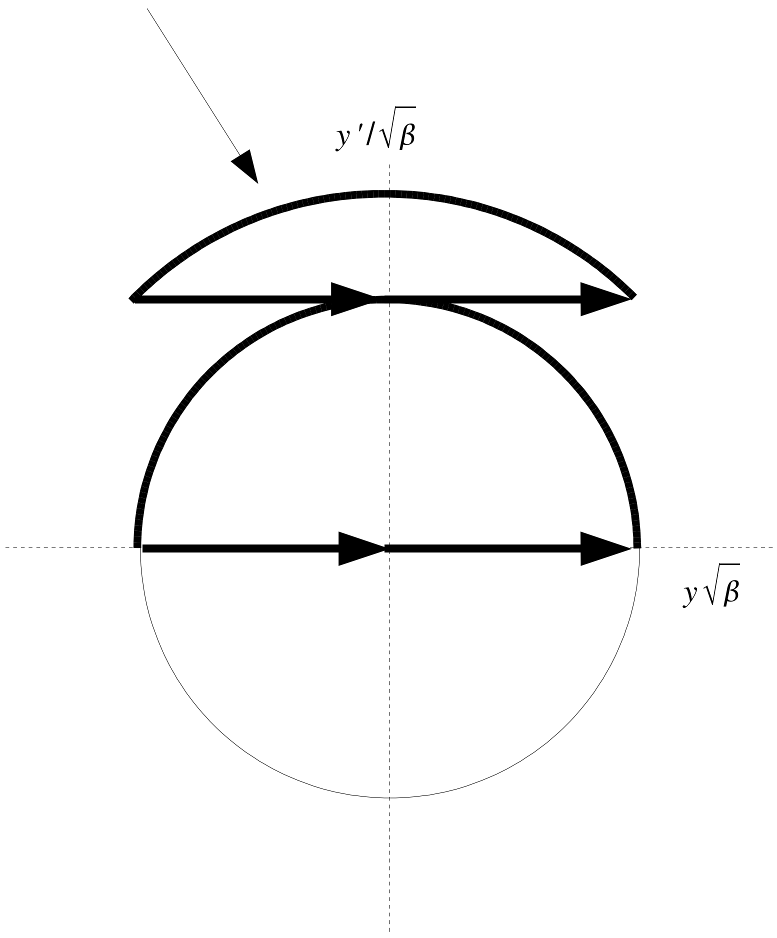


Interior sext. off

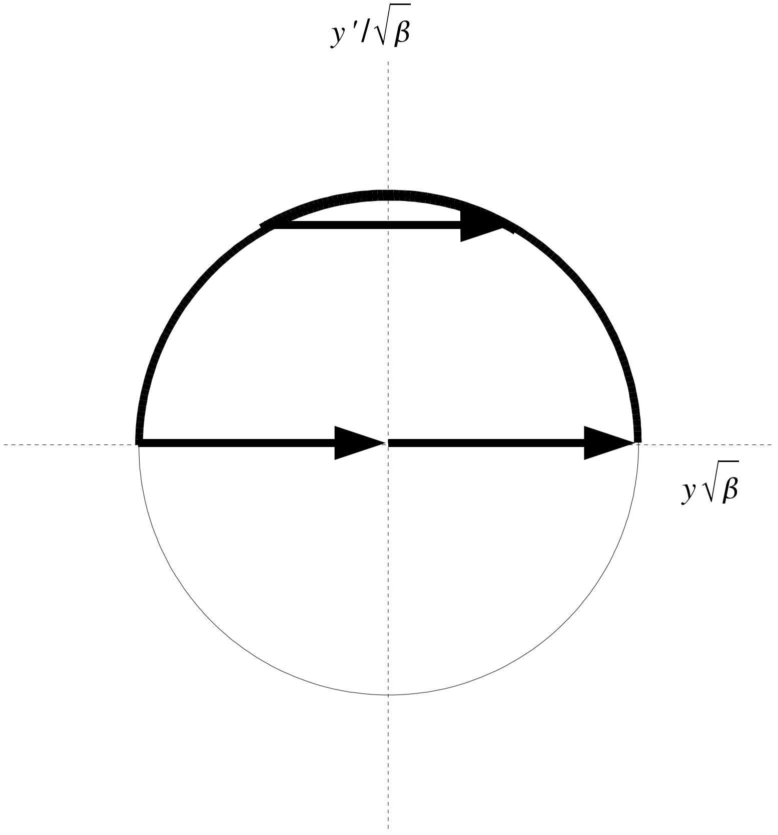
Why Cancellation Occurs

Larger maximum amplitude samples more nonlinearity

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



Tune of N+0.25



Tune of N+1/3

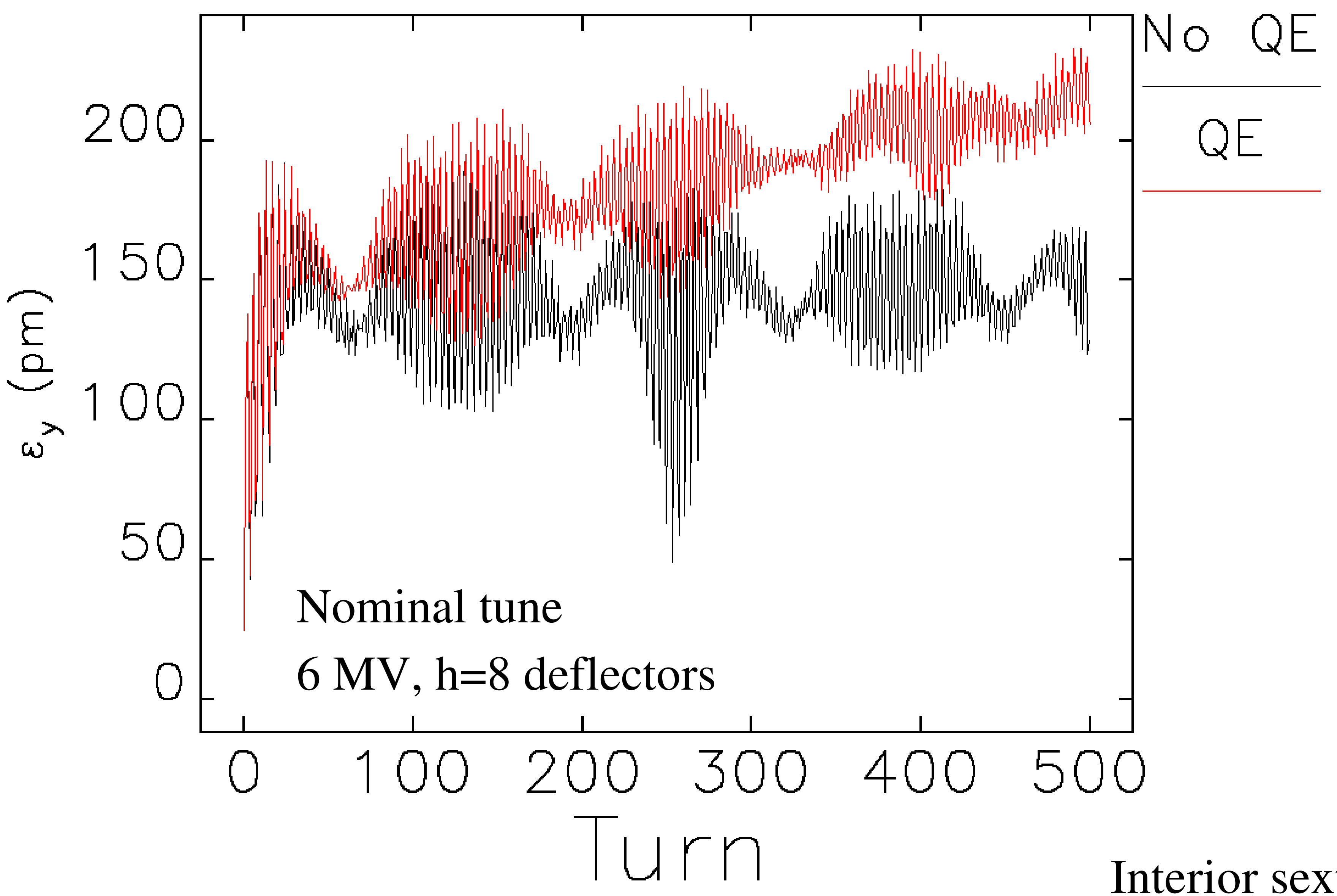
Long-Term Emittance Cancellation

- Ideally, emittance degradation should largely cancel after one synchrotron period
  - Chromaticity- and momentum-compaction-related kick errors are proportional to the momentum offset
- In reality this can't exactly happen because of
  - Exterior sextupole nonlinearities
  - Quantum excitation
- These spoil the perfect harmonic motion of particles

Synchrotron Radiation Effects

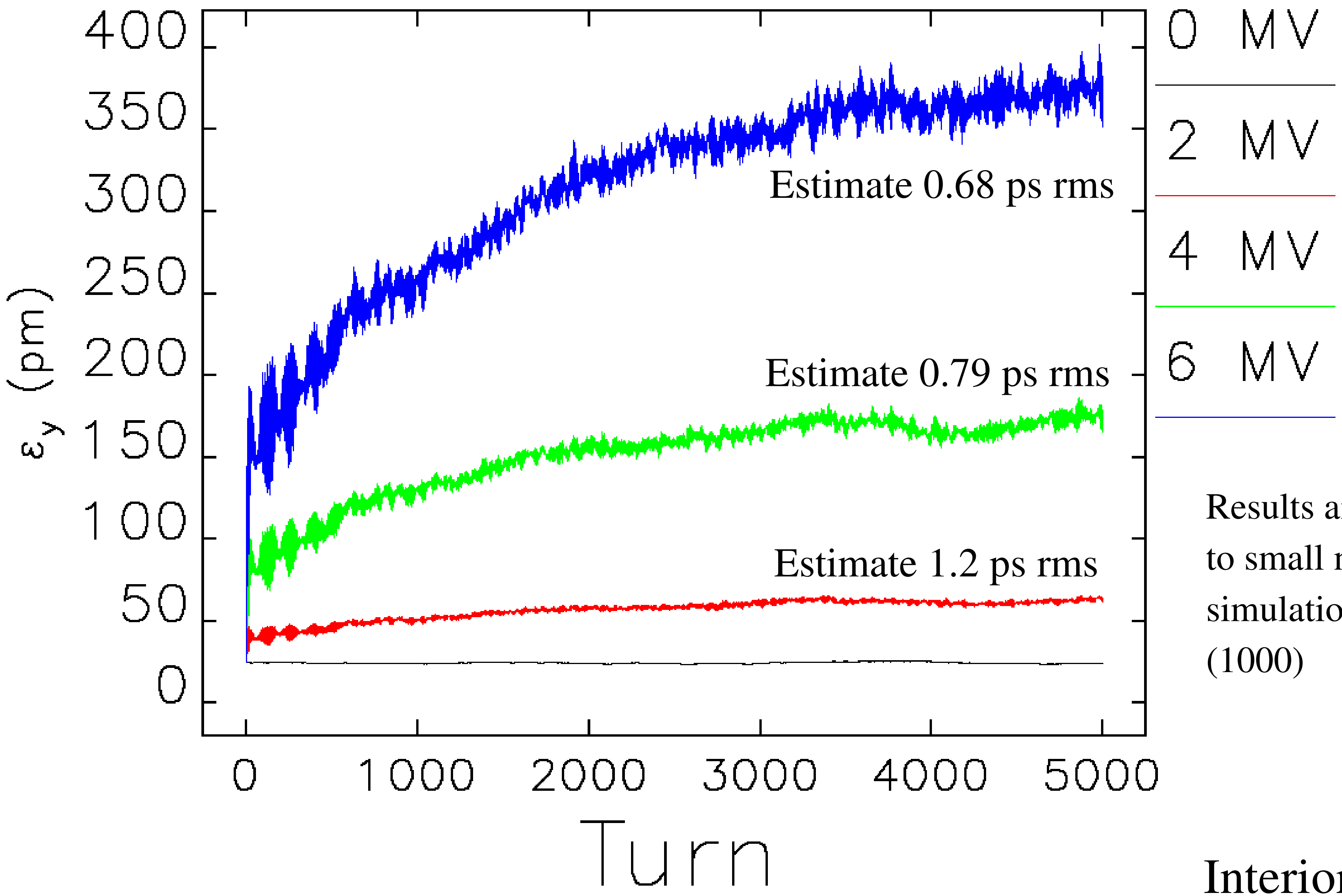
- Synchrotron radiation does two things
  - Damps particle oscillations
  - Excites particle amplitudes (quantum excitation)
- Seemed reasonable to assume that SR was a small effect
  - Emittance growth is very rapid (few turns)
  - Damping time is long (~2600 turns)
- Discovered that with interior sextupoles off, QE hurts significantly
  - Randomizes particle momenta too quickly
  - Greatly reduces partial cancellation over a synchrotron period

Effect of Quantum Excitation



Interior sext. off

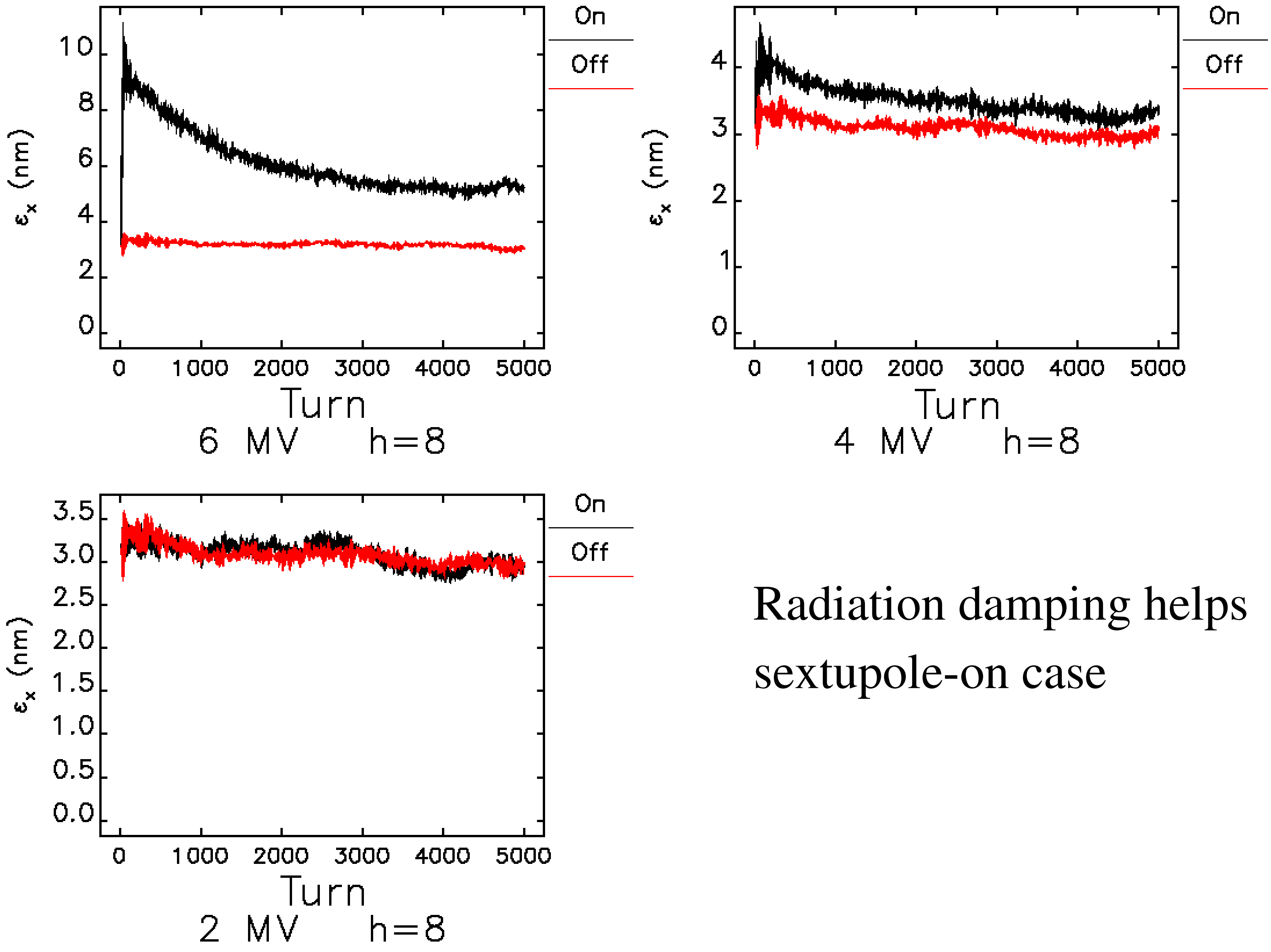
Long-Term Vertical Emittance Growth



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

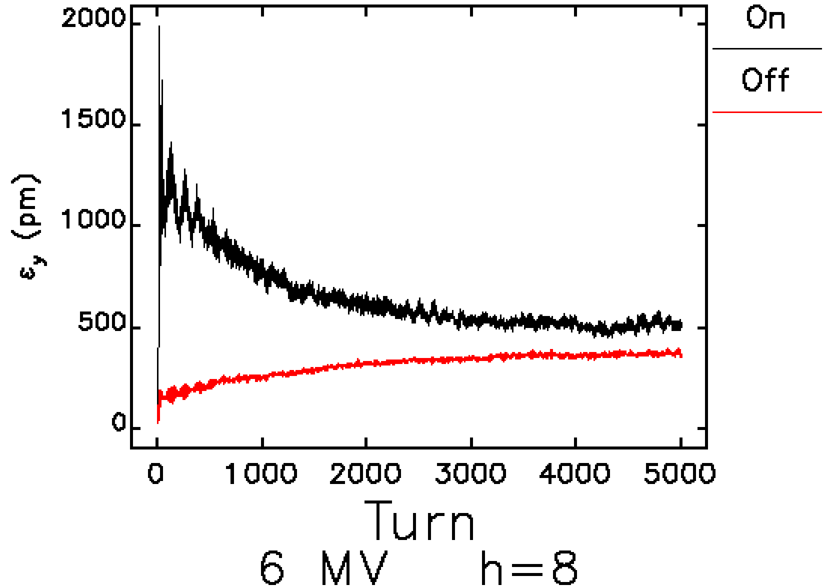
Interior sext. off

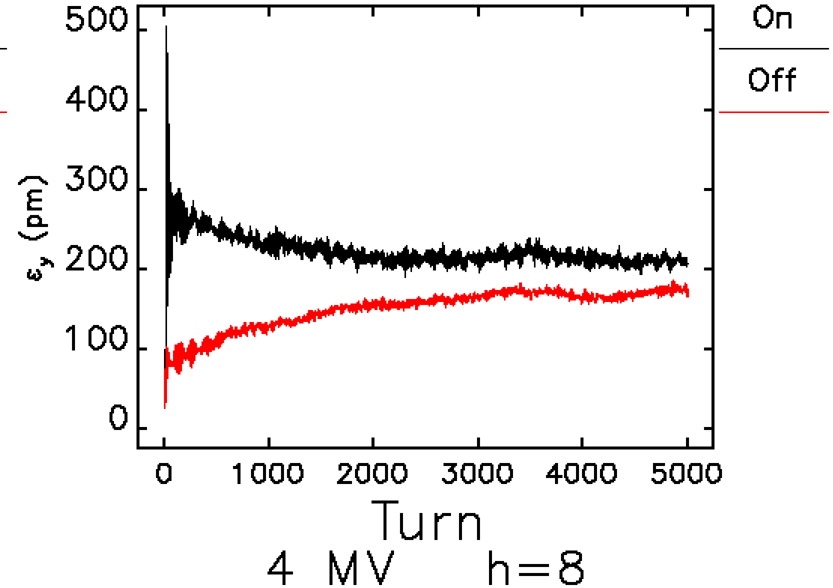
Interior Sextupoles and Horizontal Emittance

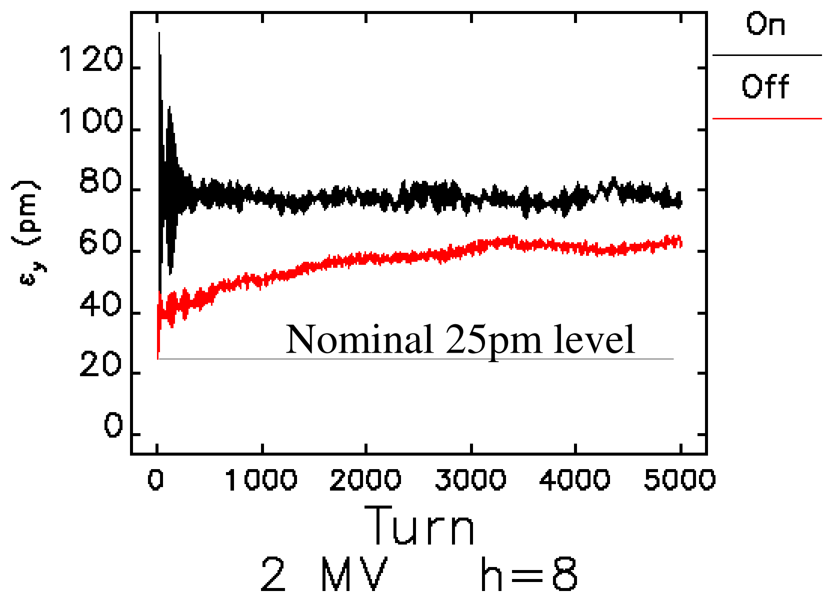


Radiation damping helps sextupole-on case

Interior Sextupoles and Vertical Emittance







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

Fortunately there's another option

Optimizing Sextupoles

- Can directly minimize vertical and horizontal emittance[1]
  - Allow **elegant** to vary the interior sextupoles
  - APS has individual supplies for each sextupole
- Important factors in making this work[2]
  - Use lattice with lower vertical beta functions
  - Zero chromaticity between cavities
  - Don't let sextupoles change too much
- If these are not respected, the dynamic aperture is tiny
- Sajaev's solution is used in all subsequent simulations

[1] M. Borland, OAG-TN-2005-007

[2] V. Sajaev, ASD/APG/2005-06

Optimized Sextupoles

- Opens possibility to increase the number of sectors that could benefit from the compression scheme

Number of sectors	Vertical emittance
2	70 pm
3	59 pm
4	41 pm

- Number of sectors limited by dynamic aperture reduction
- Improvement comes from reducing coupling. Tune shift with amplitude increases.
- Can also make the starting vertical emittance smaller (as small as 8 pm) instead of starting with nominal 25 pm

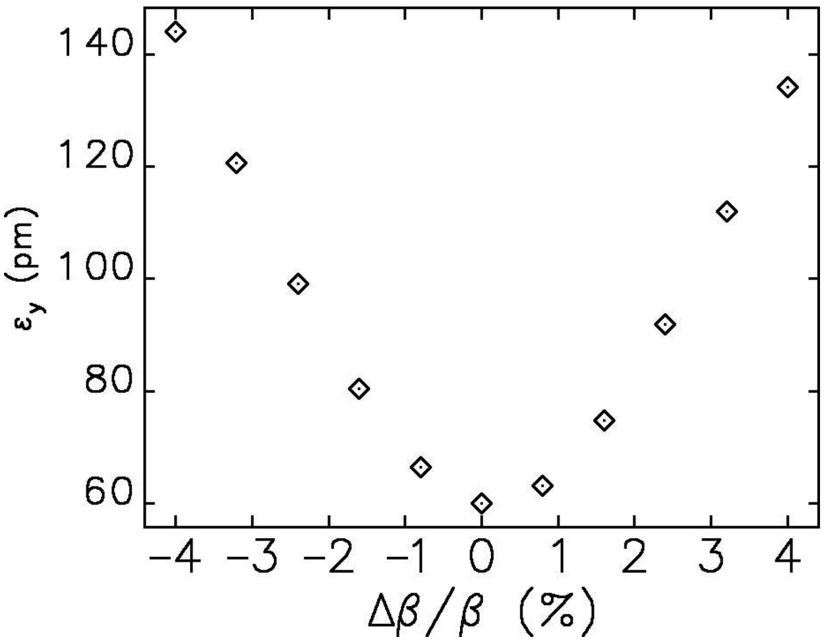
Content courtesy V. Sajaev, APS.

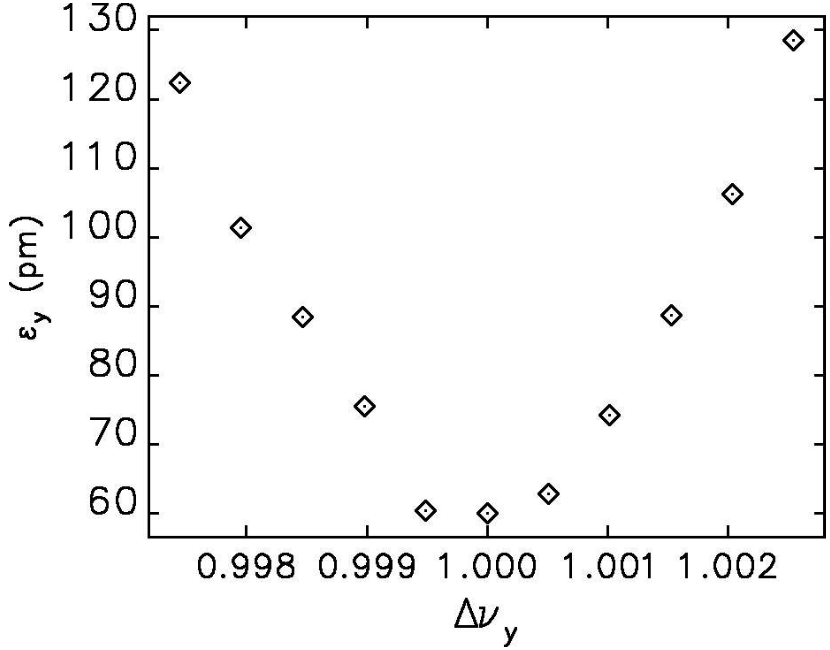
Error Sensitivities

- So far, all calculations assumed a perfect machine
- Sensitivities have been estimated for several types of *static* error
- Assumed 6 MV and h=8
- Simulations include QE effects and damping
  - In simulations, effects are turned on instantaneously and so produce a transient
  - Damping reduces emittance degradation
  - This implies that dynamic errors will have stronger effects

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]



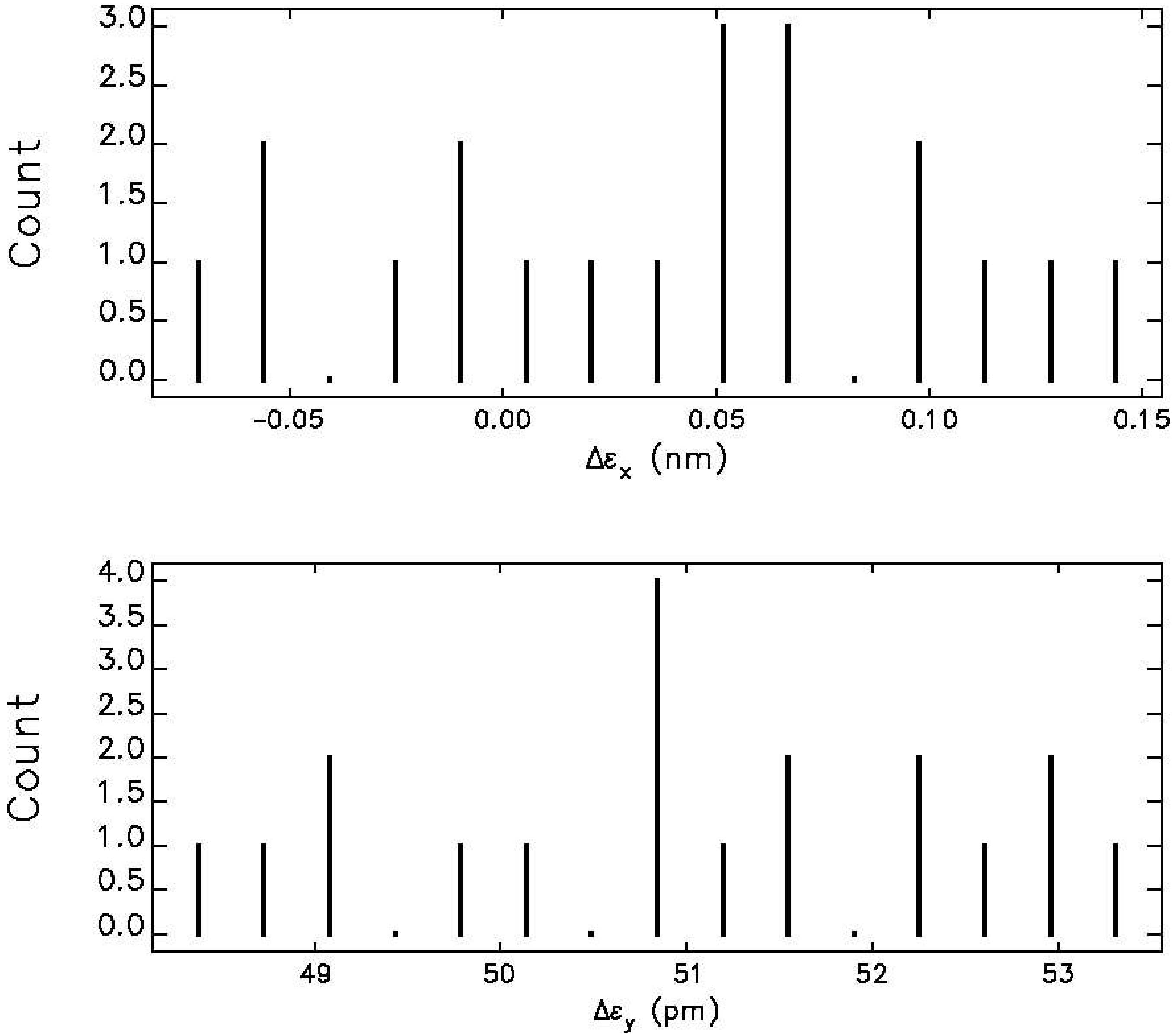


[1]V. Sajaev and L. Emery, EPAC 2002, p. 742

[2]L. Emery

Lattice Coupling Between Cavities

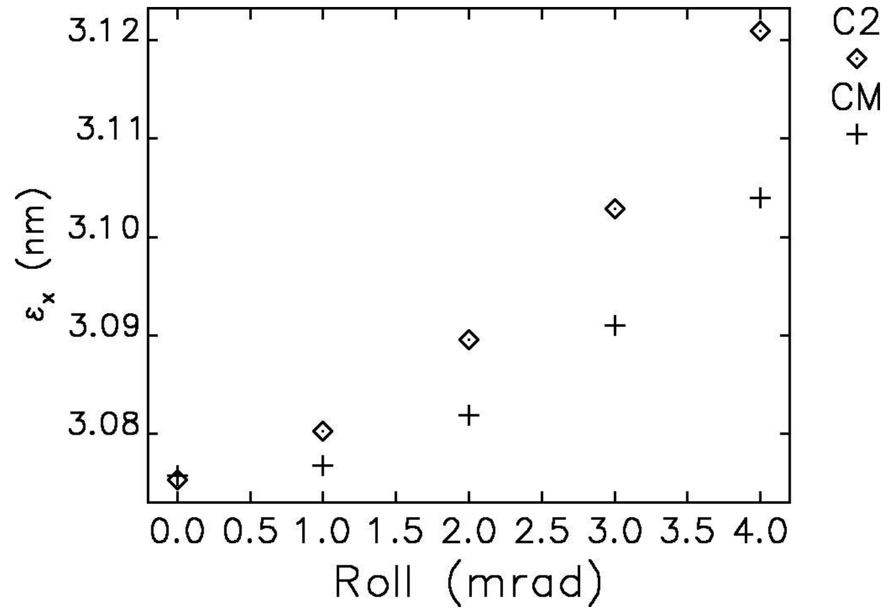
- May have quad and sextupole roll
- Roll is ~0.25 mrad rms[1]
- Performed random roll simulations with 20 seeds
- No coupling correction was employed

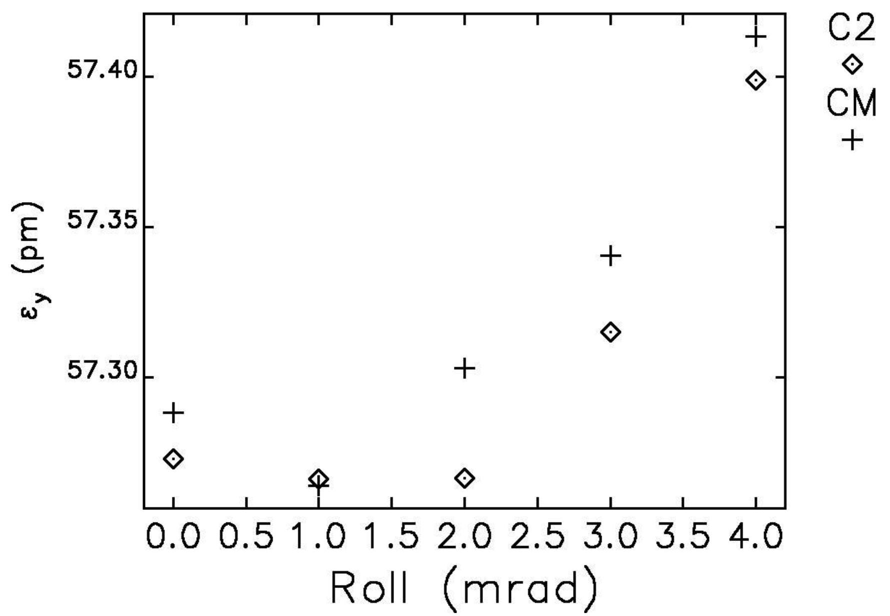


[1]H. Friedsam

Cavity Roll

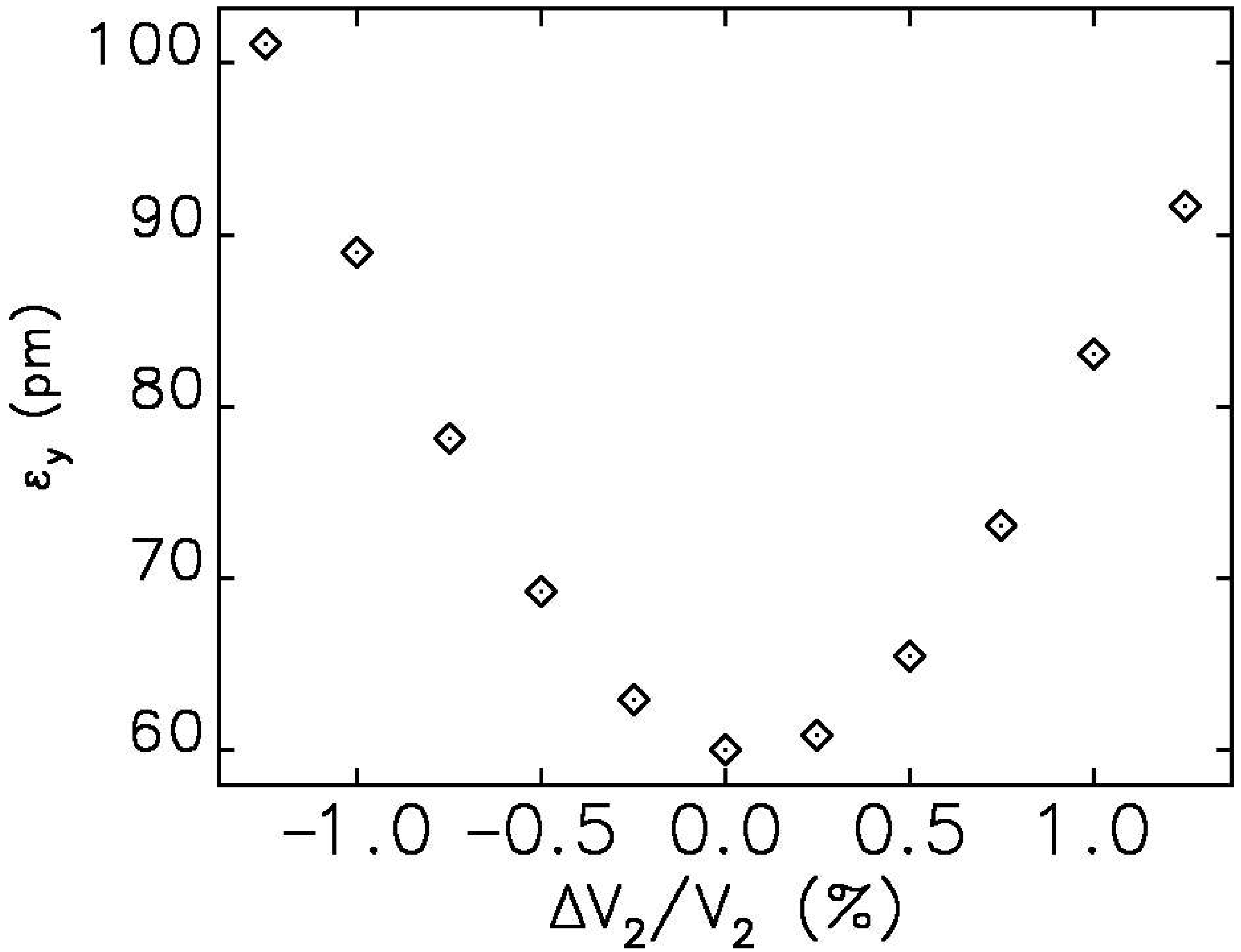
- Cavities may be rolled relative to machine vertical
- Simulated two cases
  - Cavities rolled the same amount (CM)
  - 2nd cavity only rolled (C2)
- Neither is a problem at few mrad level





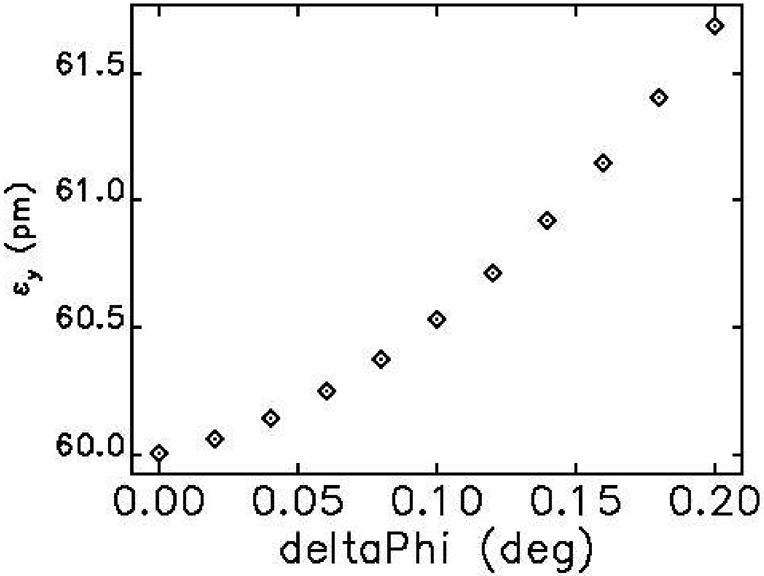
Intercavity Voltage Error

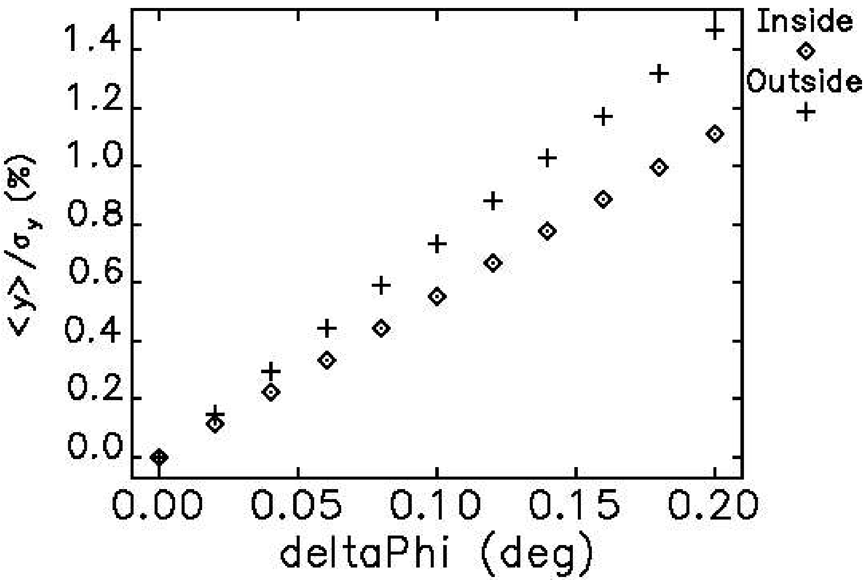
- Imparted errors to one of the cavities
- LCLS *pulsed* S-band system requires <0.1% rms voltage jitter[1]

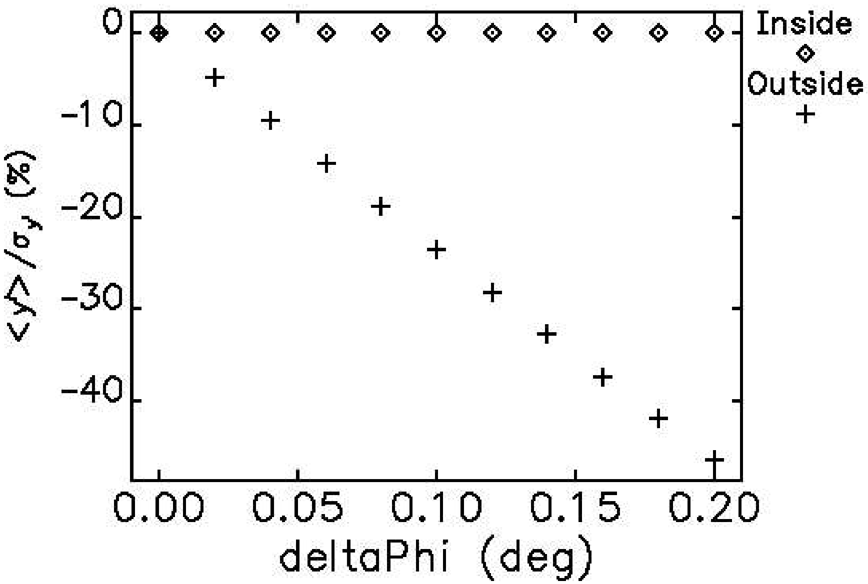


[1]LCLS Design Study Report, SLAC R-521 (1998).

Intercavity Phase Error







SLAC *pulsed* S-band systems have <0.1 deg rms phase jitter[1]

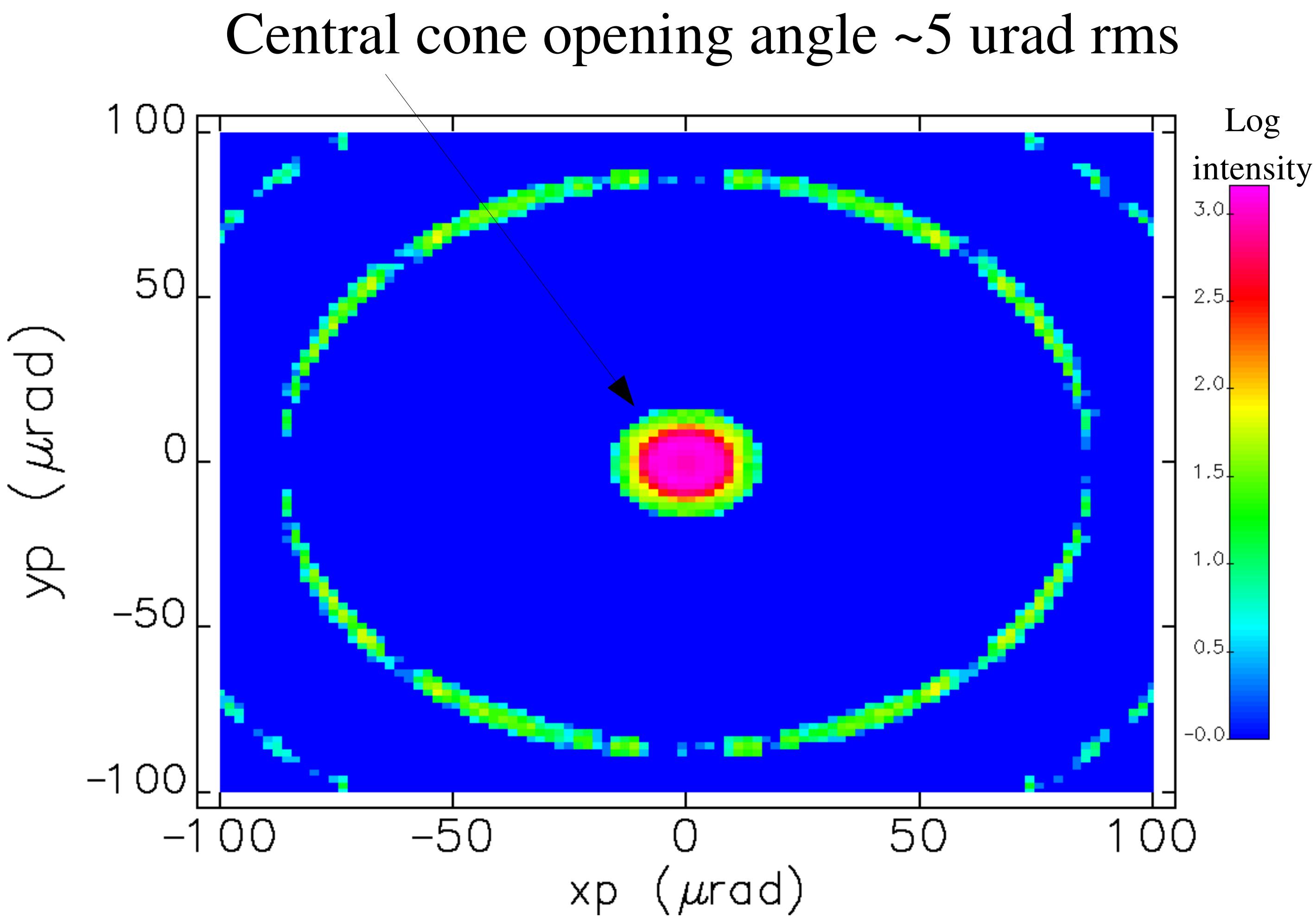
Most difficult issue is orbit disturbance outside the inter-cavity region.

[1]R. Akre et al., SLAC PUB 9421.

Compression Simulation

- Start by tracking 1000 electrons for 10,000 turns to ensure we are well into equilibrium condition
- Form last 100 turns' data into “beam” of 100,000 electrons
- Track this for 10 turns and save phase space on each turn
- Generate one photon for each electron by adding samples from the distribution function
- Use **elegant** to optimize compression through system consisting of
  - Drift (30 m)
  - Vertical slits
  - “Compression matrix” (unit matrix except for variable R_{53})
  - Vary R_{53} to minimize time-spread of central 70% of photons
- Repeat optimization for various slit spacings

Undulator Radiation Pattern



Data courtesy R. Dejus

For estimates, use

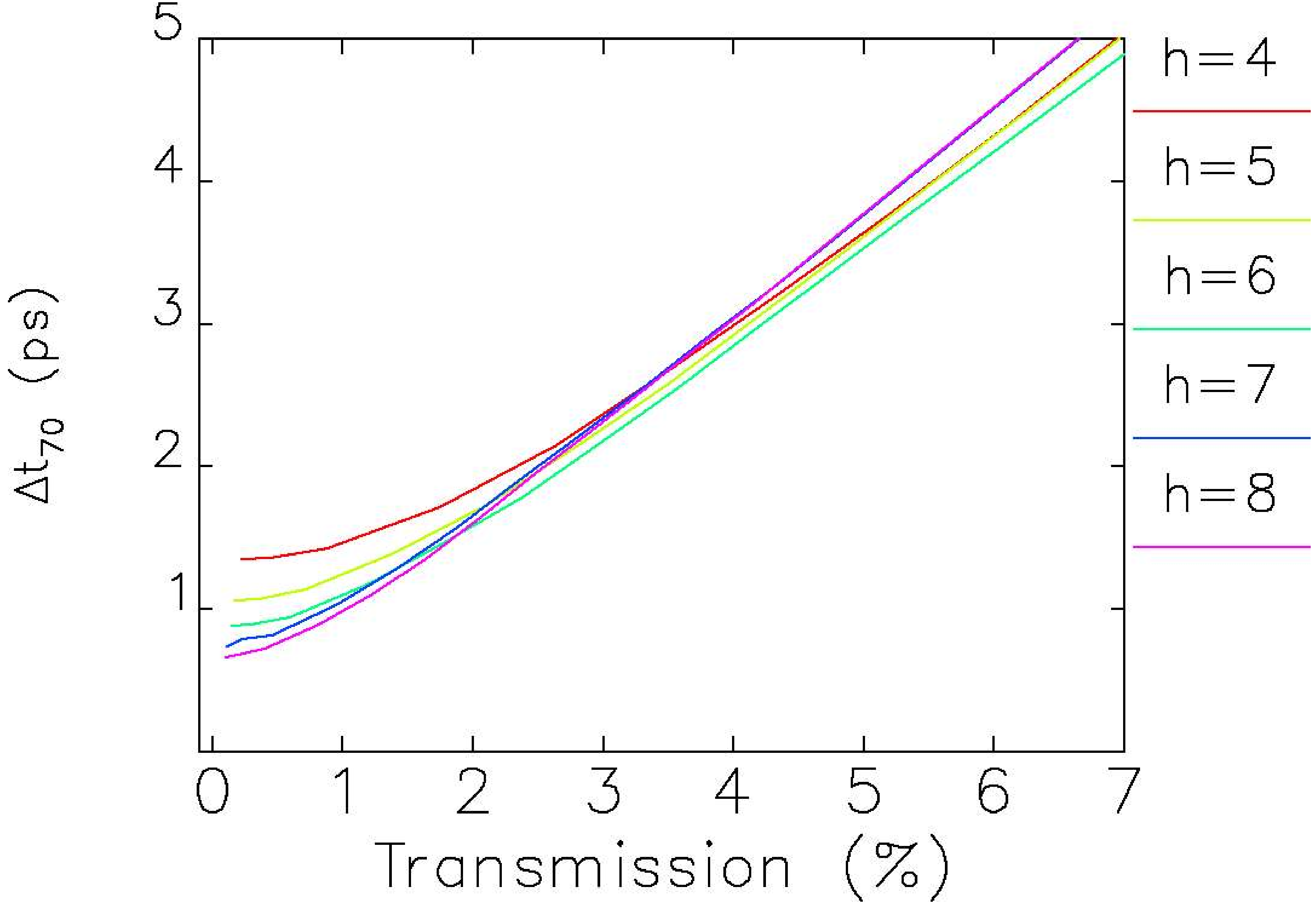
$$\sigma_\theta = \sqrt{\frac{\lambda}{2L}}$$

Simulations use distribution function[1]

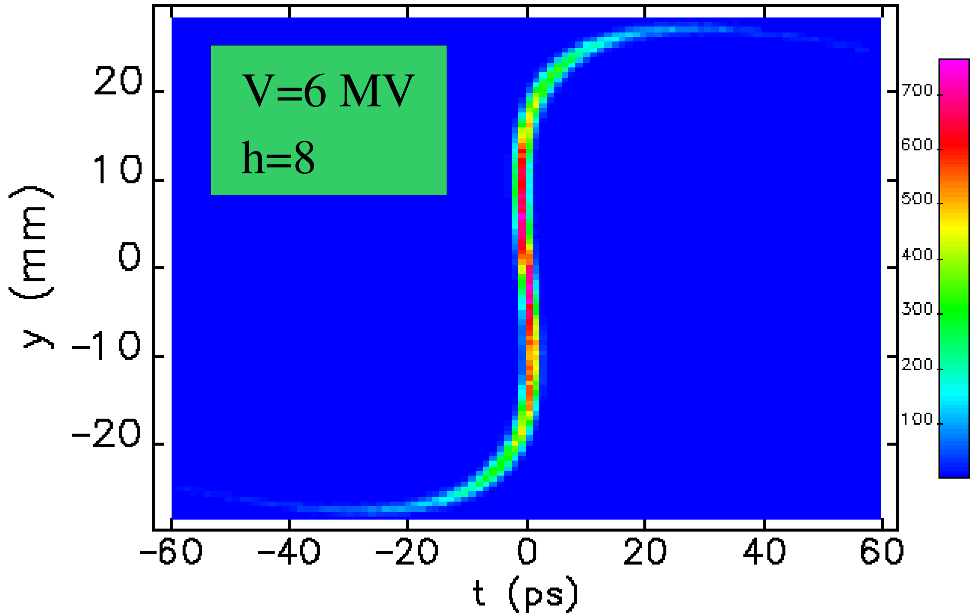
$$S(\theta) \approx sinc^2\left(\frac{n N \pi \gamma^2 \theta^2}{1+K^2}\right)$$

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

Slicing Results for 10 keV, UA

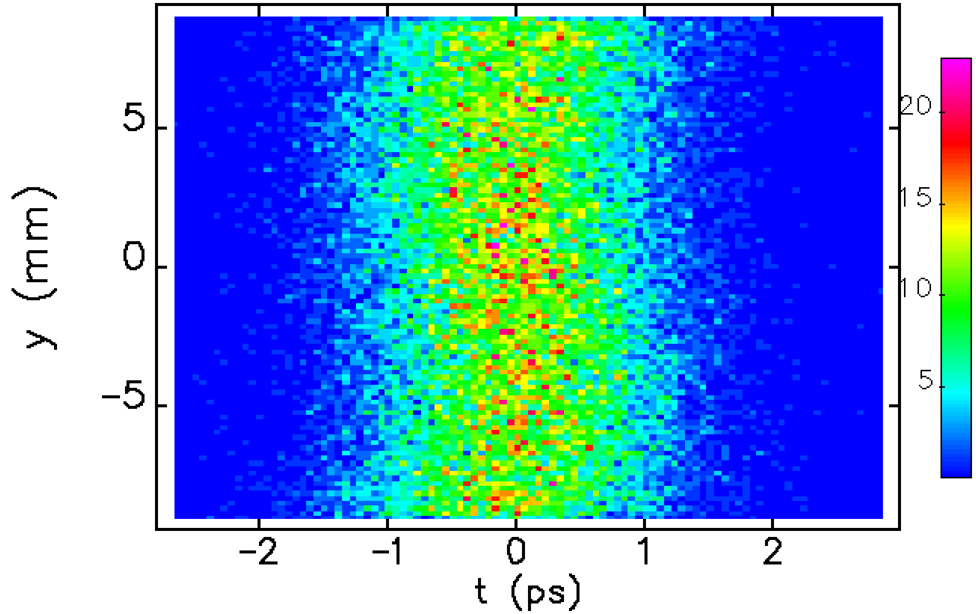


Need for Slits with Compression

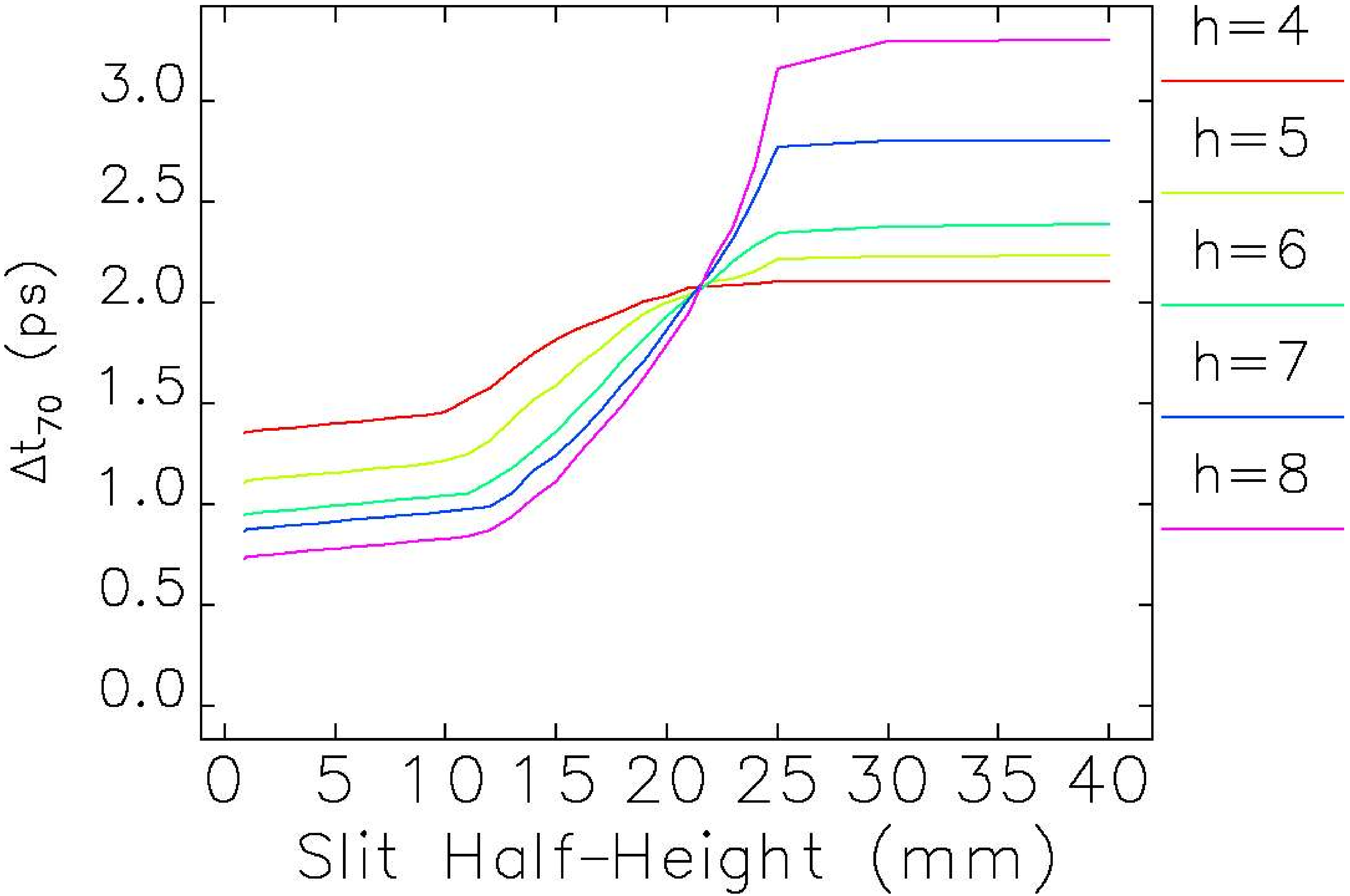


Without slits, rf curvature prevents complete compression

With slits, we lose intensity but get complete compression

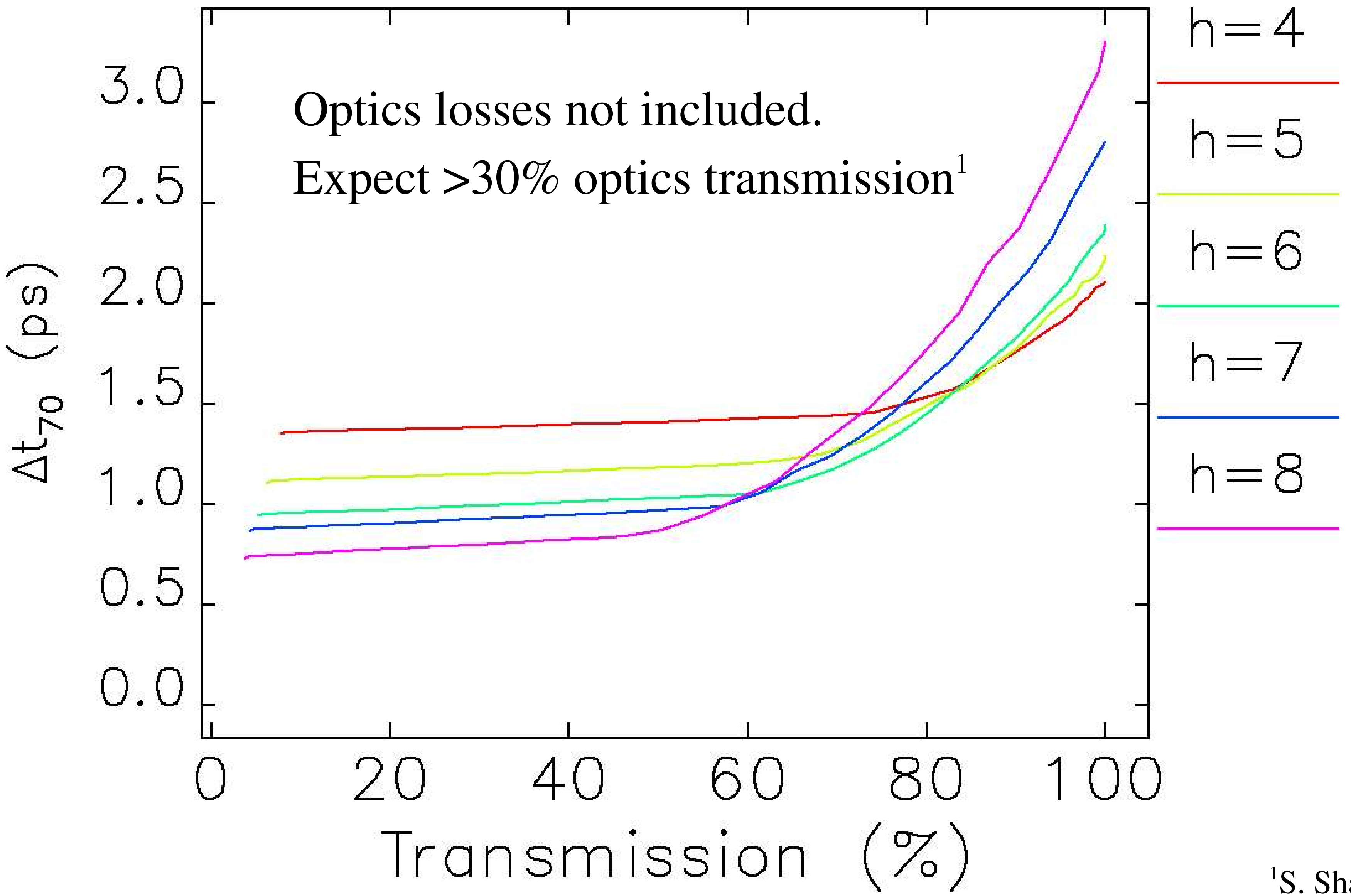


Compression Results for 10 keV, UA[1]



[1]3.3cm period, 2.4m length

Compression Results for 10 keV, UA



[1]S. Shastri

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 will make the bunch non-gaussian
  - Not expected to be a problem
- Cavity LOM/HOMs will be important

Summary

- Zholents' scheme as applied to APS has been studied extensively
- Tolerances mostly manageable
  - Rf phase tolerance will be the hardest
  - Didn't simulate dynamic errors
- Need to revisit impedance issues
- Need to look at stability of the delivered pulses
  - Pointing
  - Arrival time and duration jitter
- Picosecond x-ray pulses appear feasible with 50~70% transmission through slits