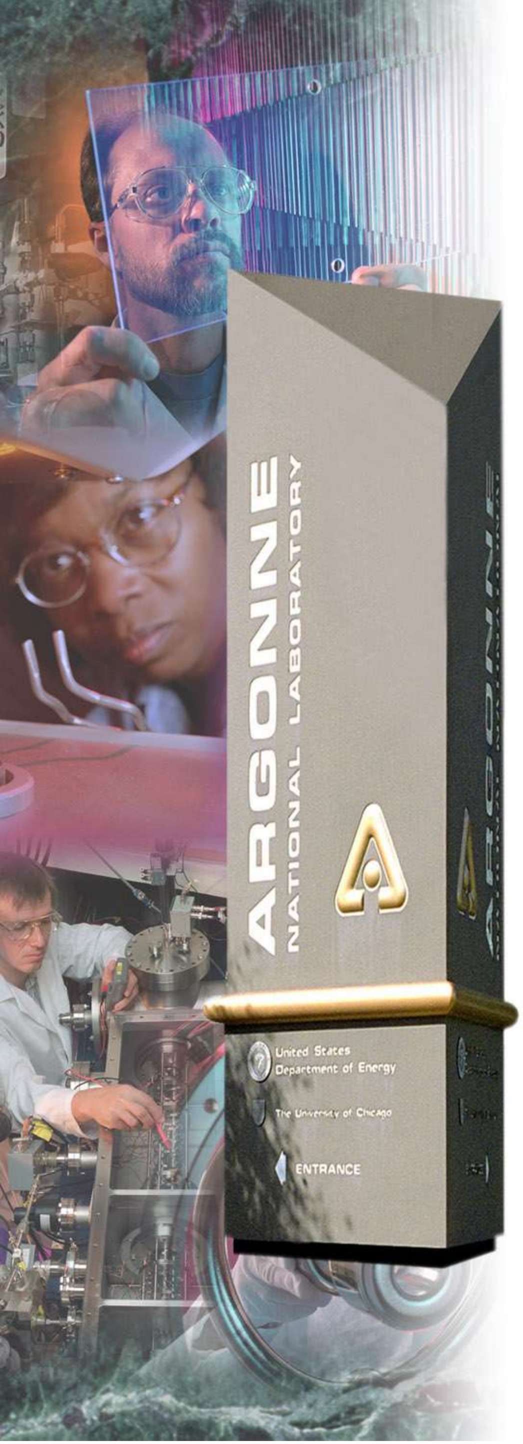

Accelerator Physics Aspects of Crab-Cavity-Based Production of Picosecond X-ray Pulses

Michael Borland
Operations Analysis Group
APS Operations Division

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Office of Science
U.S. Department of Energy

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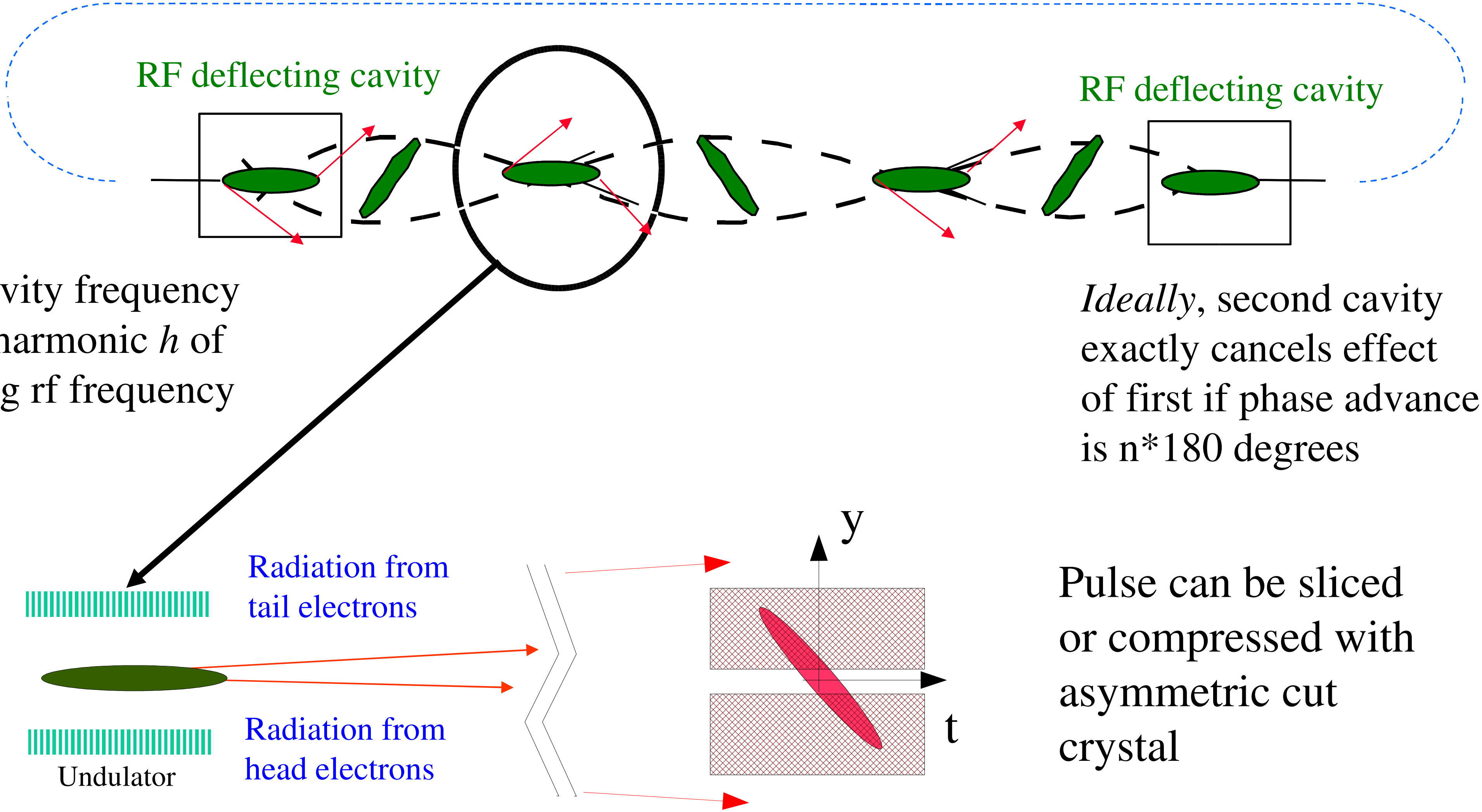
Outline

- 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
- Pulsed option

Zholents' Transverse Rf Chirp Concept

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



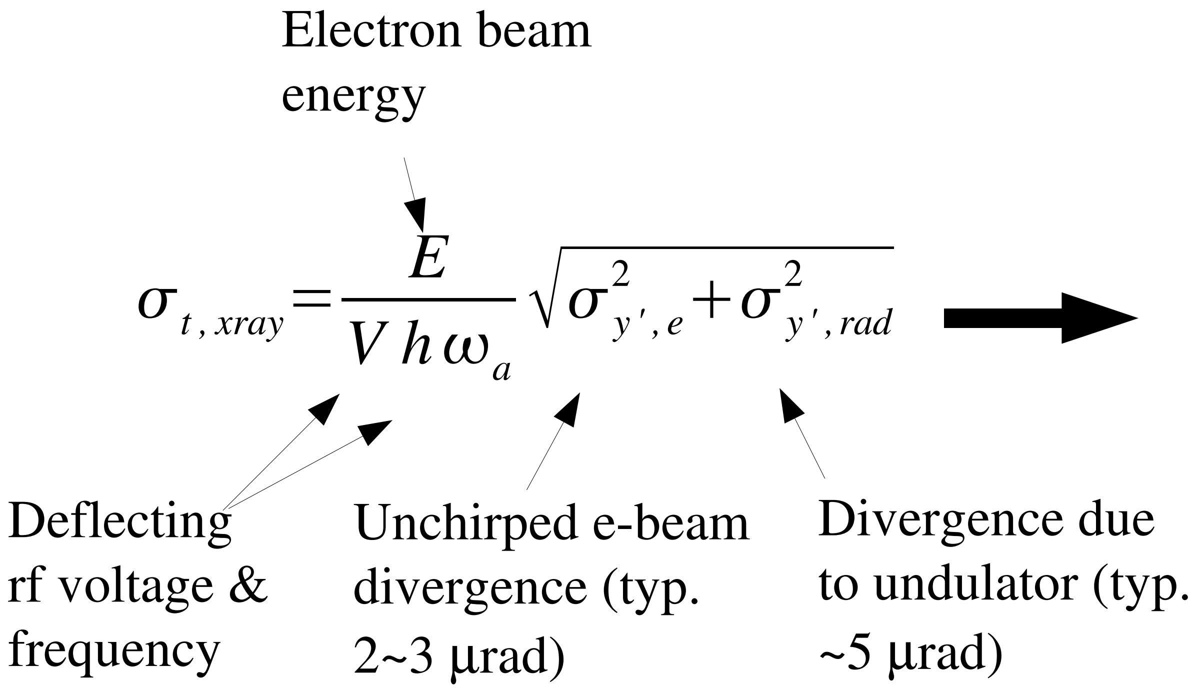
Cavity frequency is harmonic *h* of ring rf frequency

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

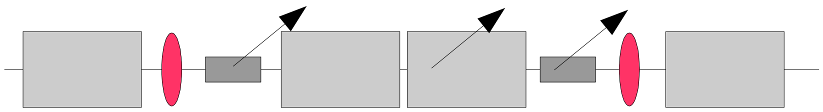
[1] M. Borland, APS LS-287, Sept. 2000.

Simulation and Bunch Lengthening

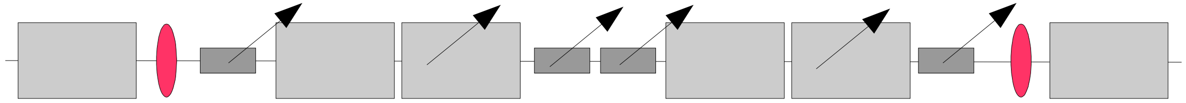
- APS has significant (~2x) bunch lengthening due to potential well distortion[1]
- This can be modeled using **elegant** and an impedance model[2]
- This is *extremely* CPU-intensive, so we used another technique
  - Reduce the simulated rf voltage to lengthen the bunch
- The coherent synchrotron tune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

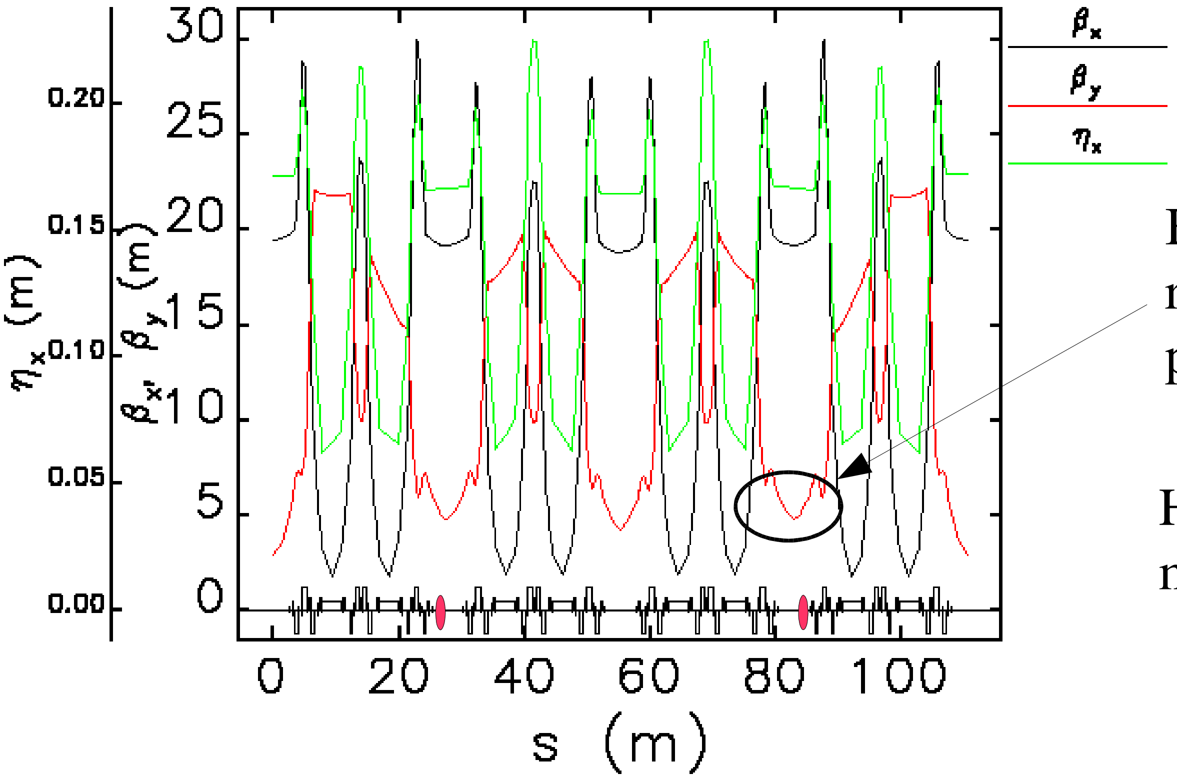
Lattice Options



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

Lifetime Issues

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

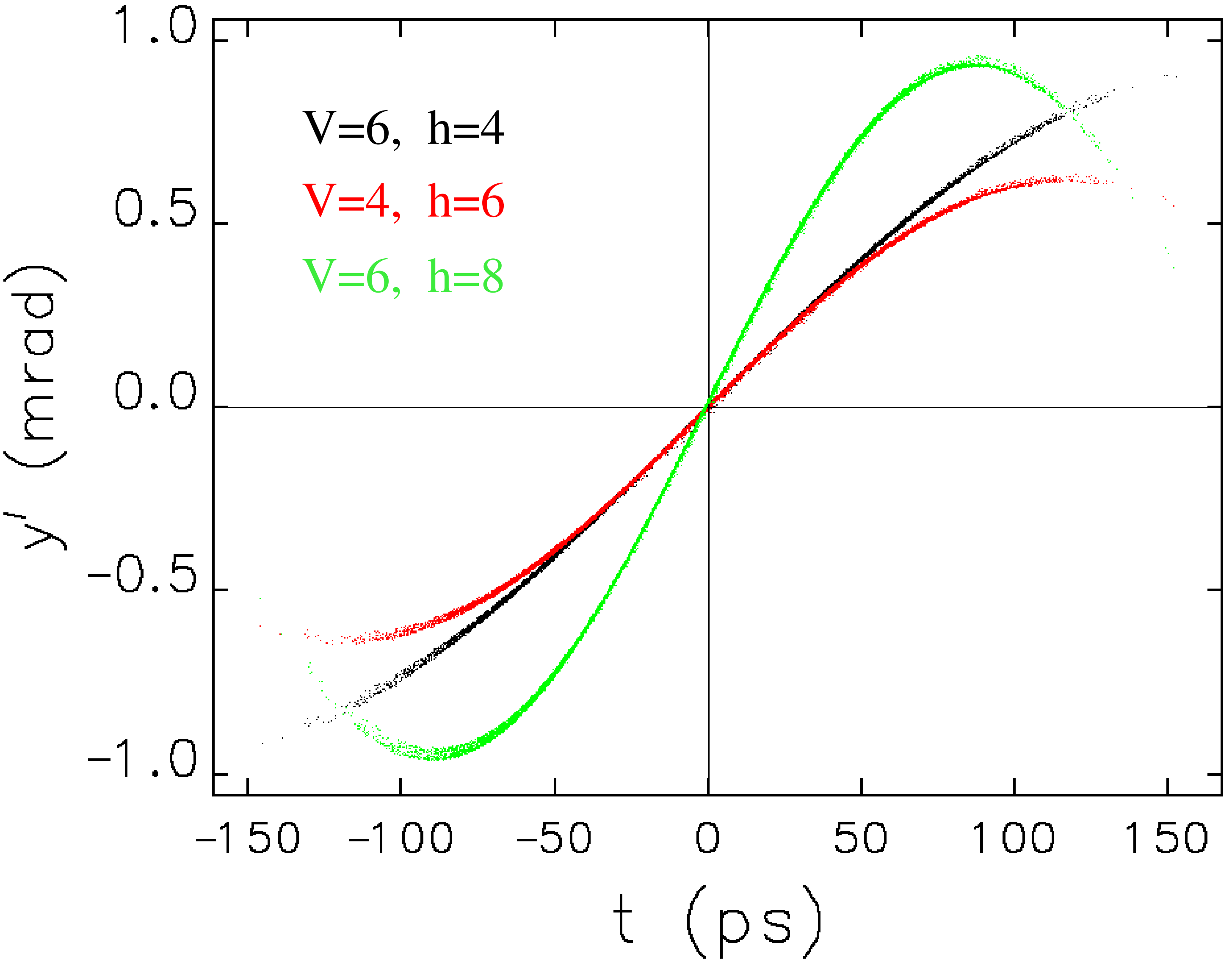
$$\frac{DV}{E} + 10\sigma_{y,\mathrm{slice}} \le A$$

- 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

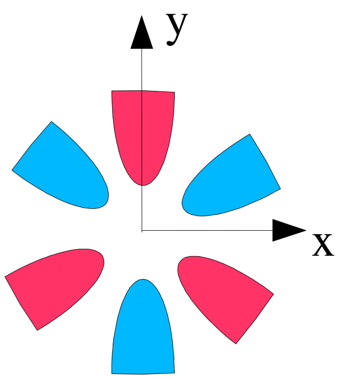
- Less than total kick cancellation will cause emittance increase
- Effects present in a perfect machine
  - Momentum compaction and beam energy spread
  - Sextupole nonlinearity
  - Chromaticity and beam energy spread
- Additional effects in an imperfect machine
  - Lattice errors
  - Lattice coupling 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

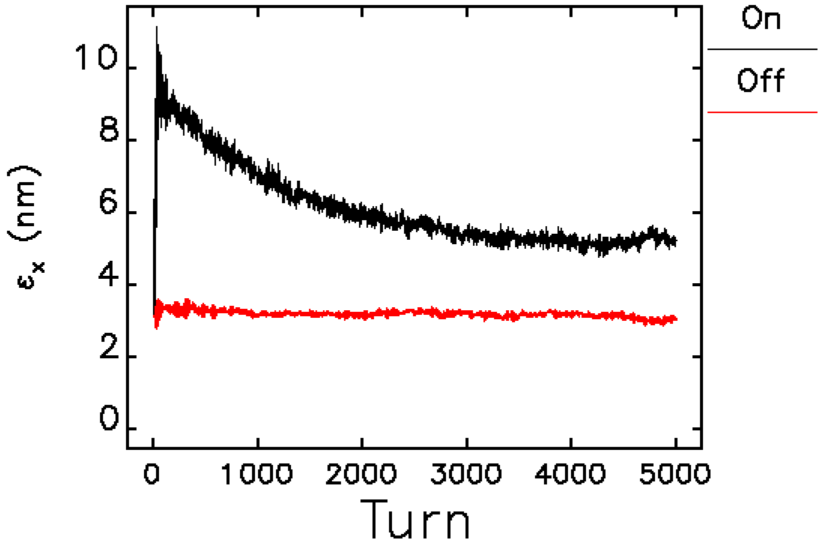
- Sextupoles are necessary
  - Correct chromatic focusing aberrations
  - Defeat beam instabilities
- Sextupoles have undesirable side-effects
  - Phase advance varies with amplitude
    - Kick cancellation varies with amplitude
    - Vertical emittance increases
  - Horizontal and vertical motion gets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



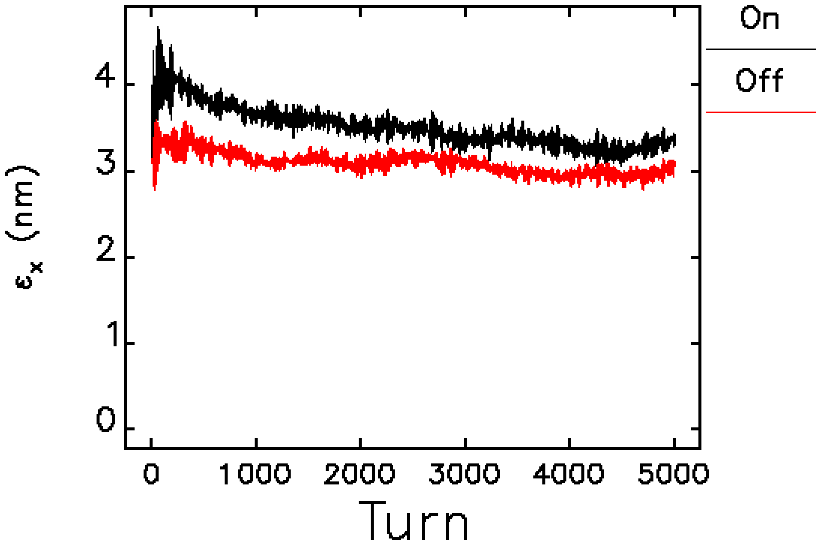
$$B_y = \frac{1}{2} m (x^2 - y^2)$$

$$B_x = m x y$$

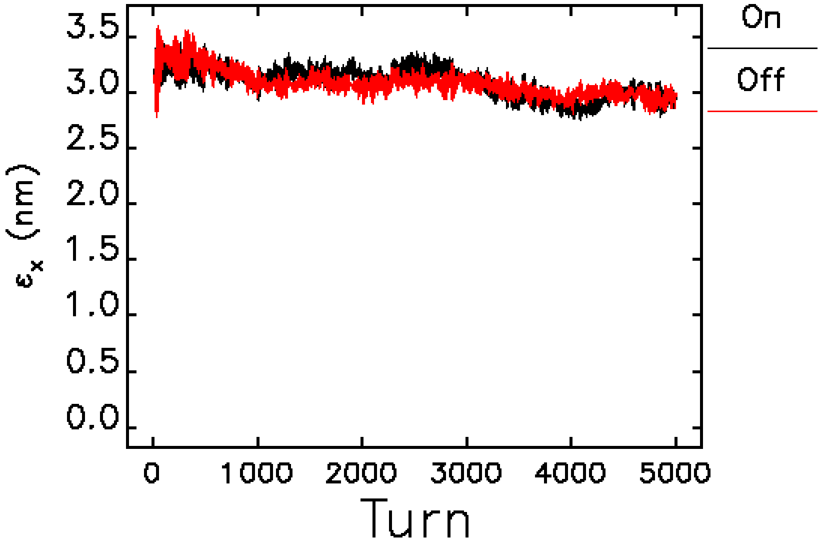
Interior Sextupoles and Horizontal Emittance



6 MV h=8



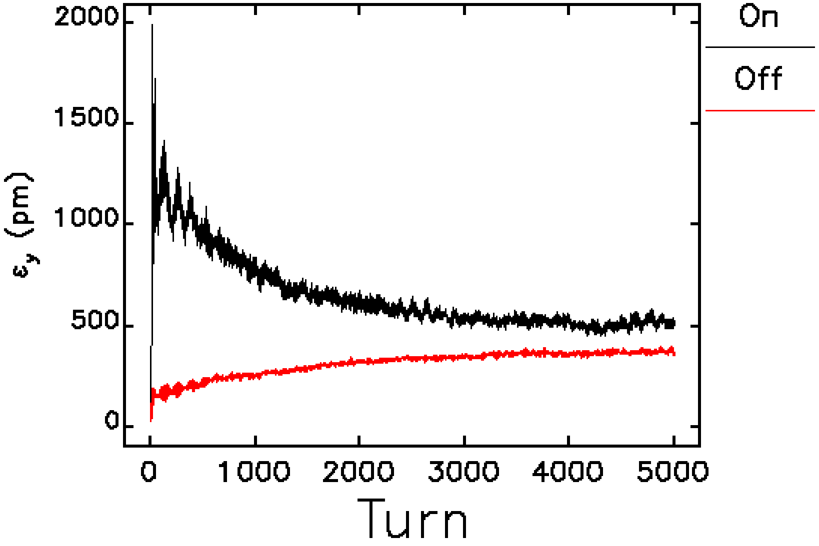
4 MV h=8



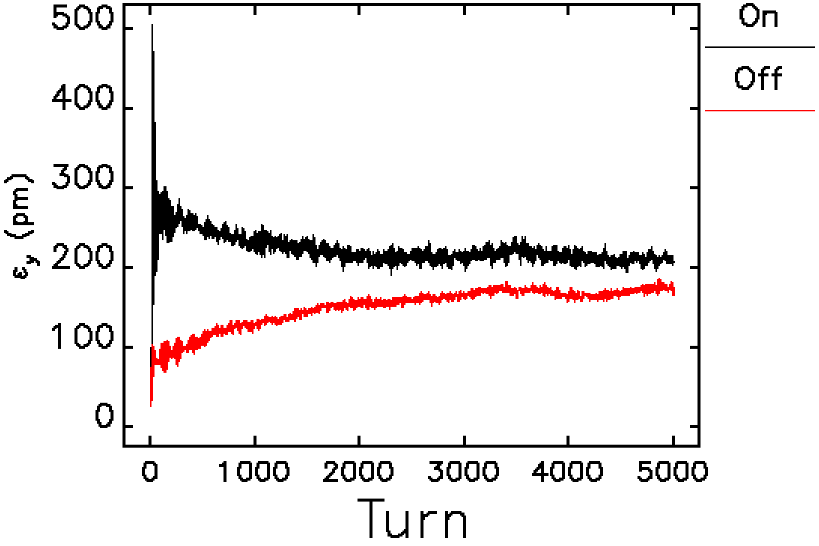
2 MV h=8

Radiation damping helps sextupole-on case

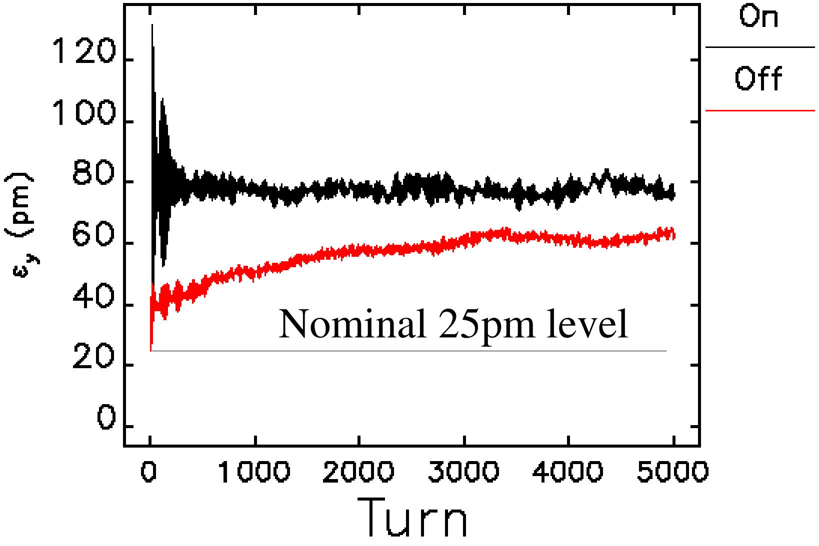
Interior Sextupoles and Vertical Emittance



6 MV h=8



4 MV h=8



2 MV h=8

Damping helps sextupoles-on case

QE hurts sextupoles-off case via uncorrected chromaticity

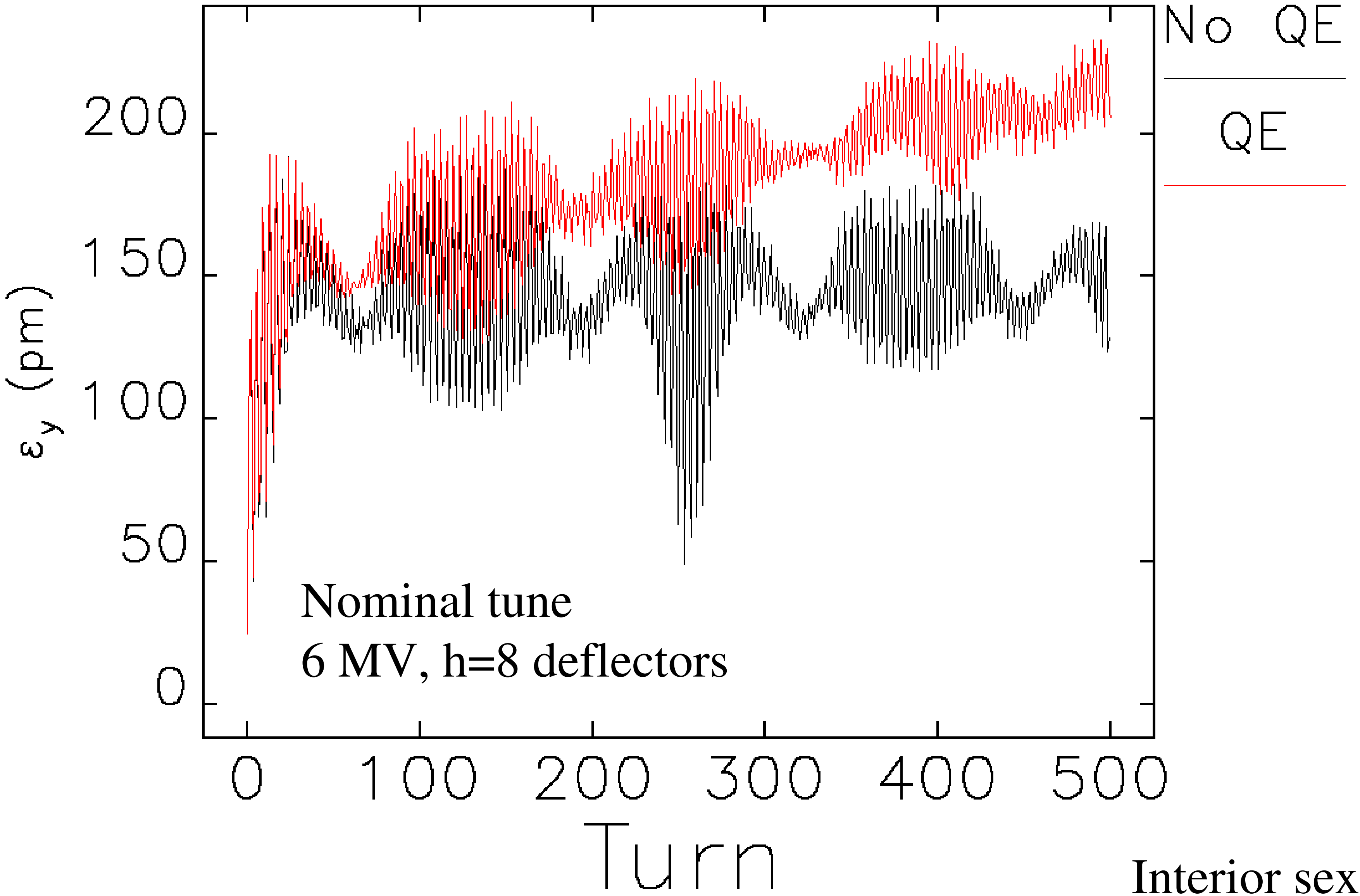
Chromaticity

- 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
- Errors are proportional to momentum offset, “should” cancel over one synchrotron oscillation period

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

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

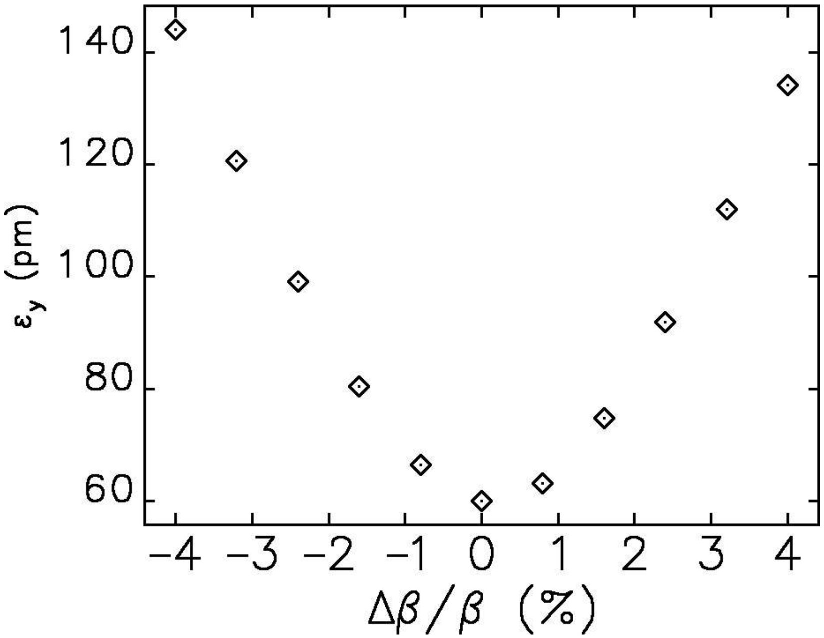
[2] V. Sajaev

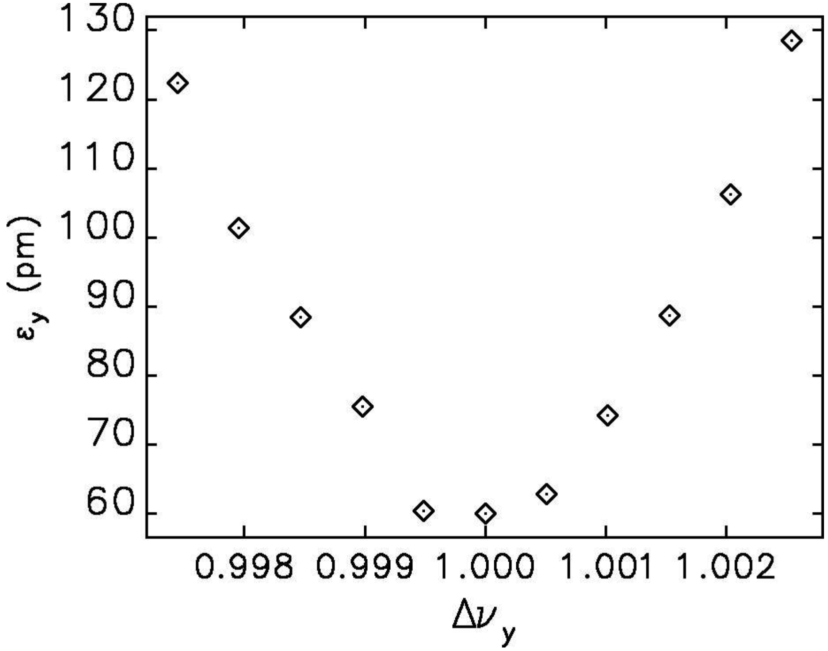
Error Sensitivities

- 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]



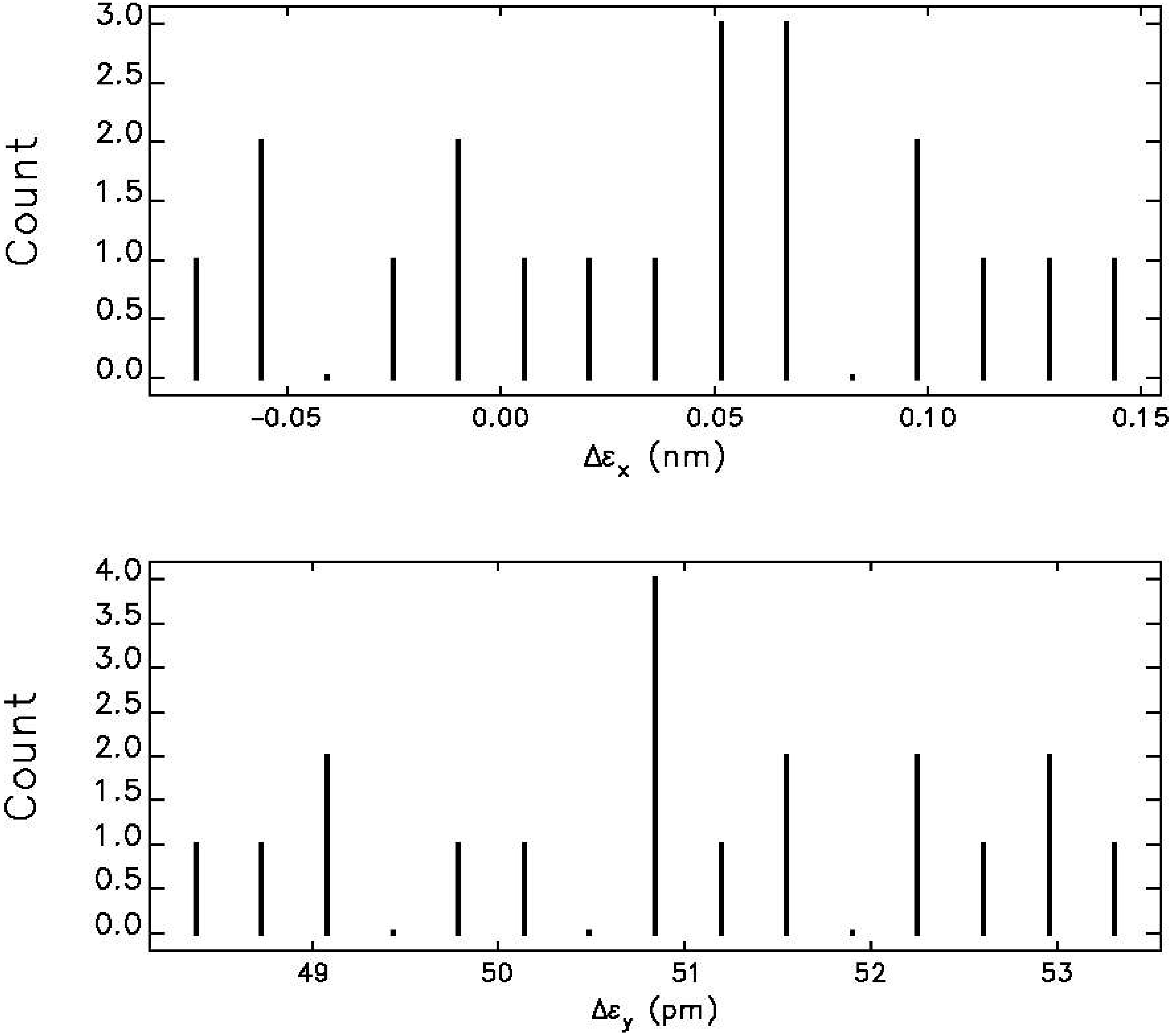


[1] V. Sajaev and L. Emery, EPAC 2002, p. 742

[2] L. Emery

Lattice Coupling Between Cavities

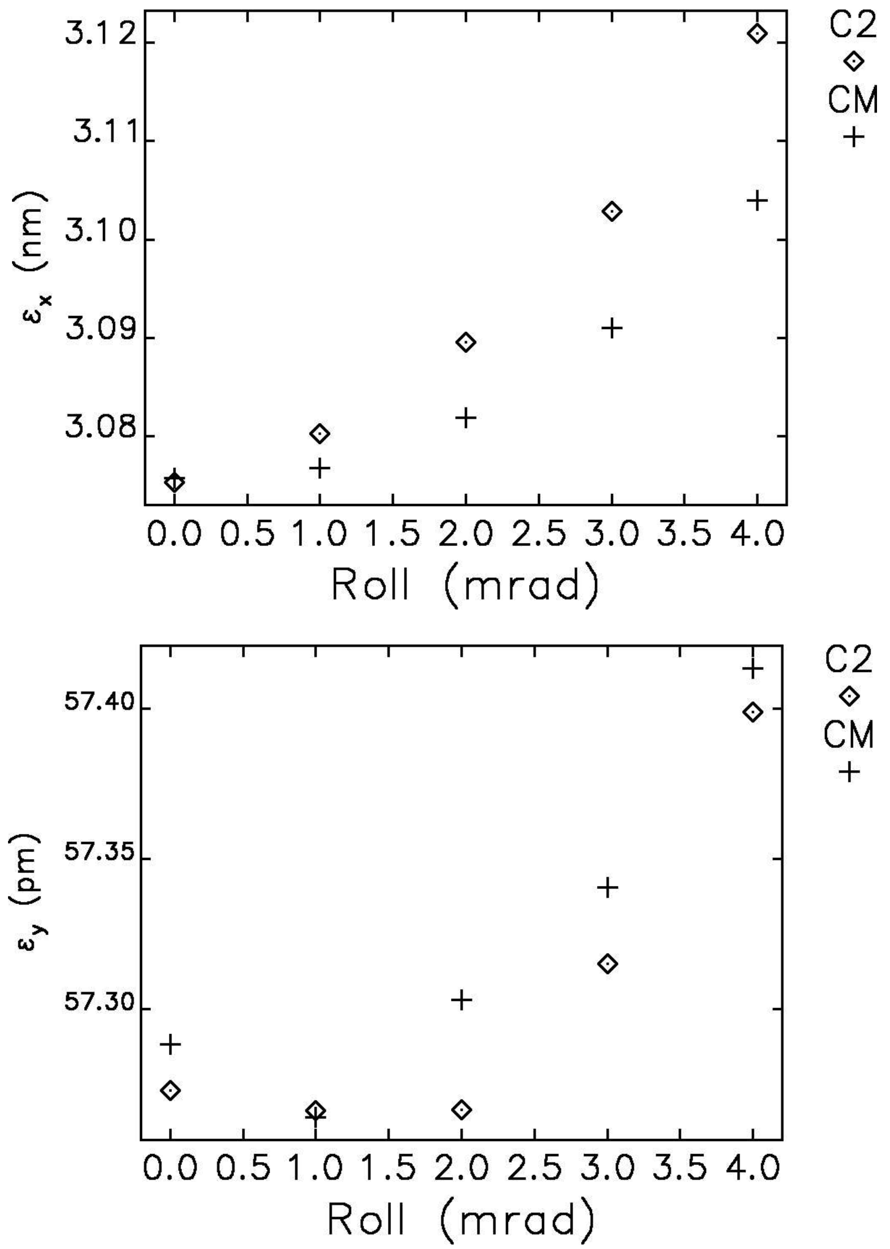
- May have quad and sextupole roll
- Roll is ~0.25 mrad rms[1]
- Performed random roll simulations with 20 seeds
- No coupling correction was employed



[1] H. Friedsam

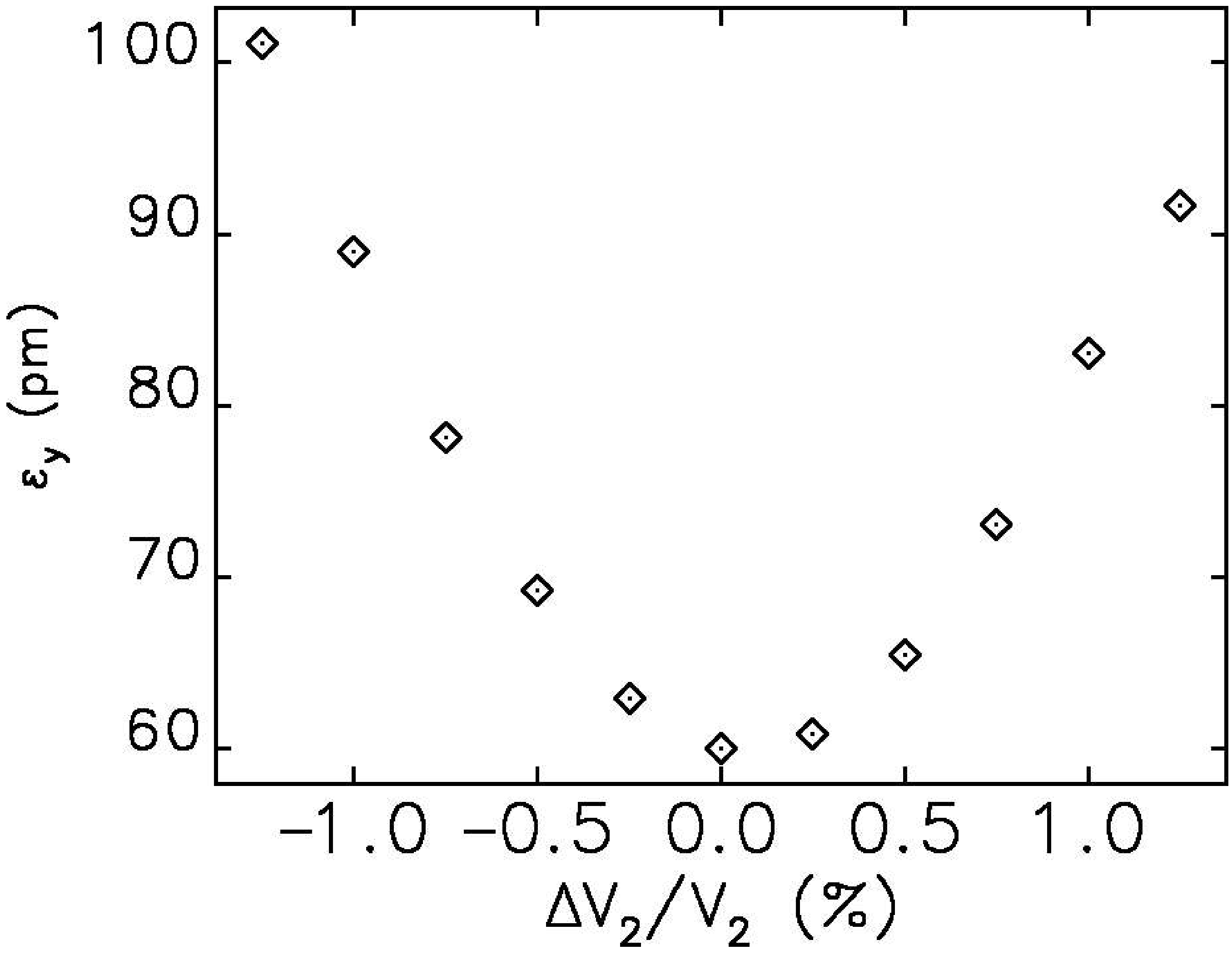
Cavity Roll

- 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]



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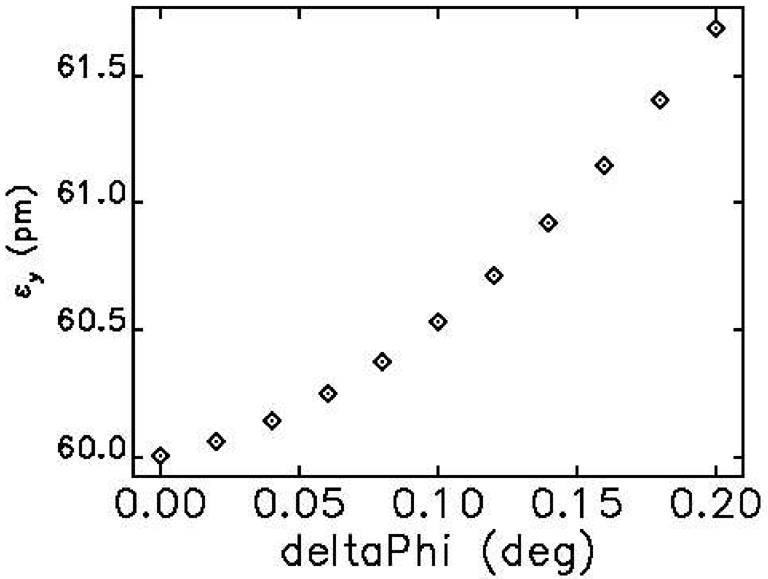
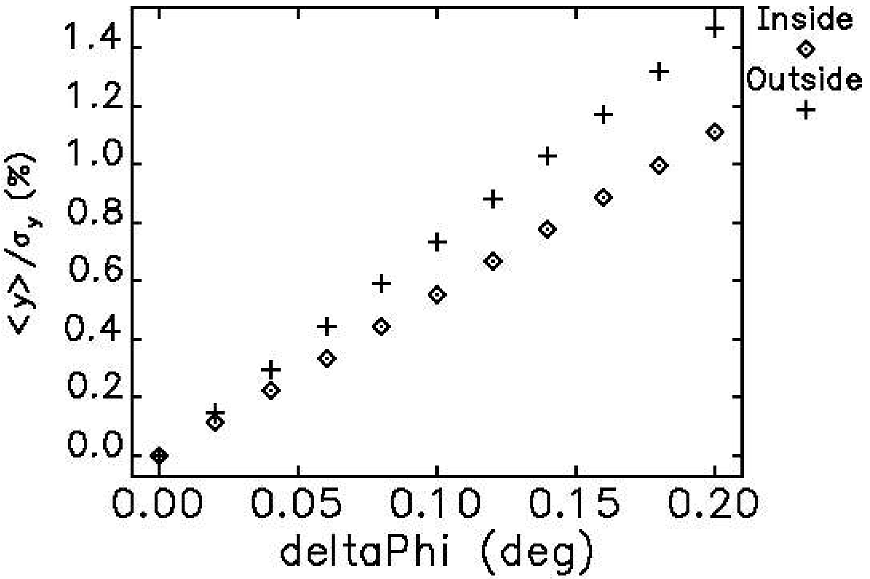
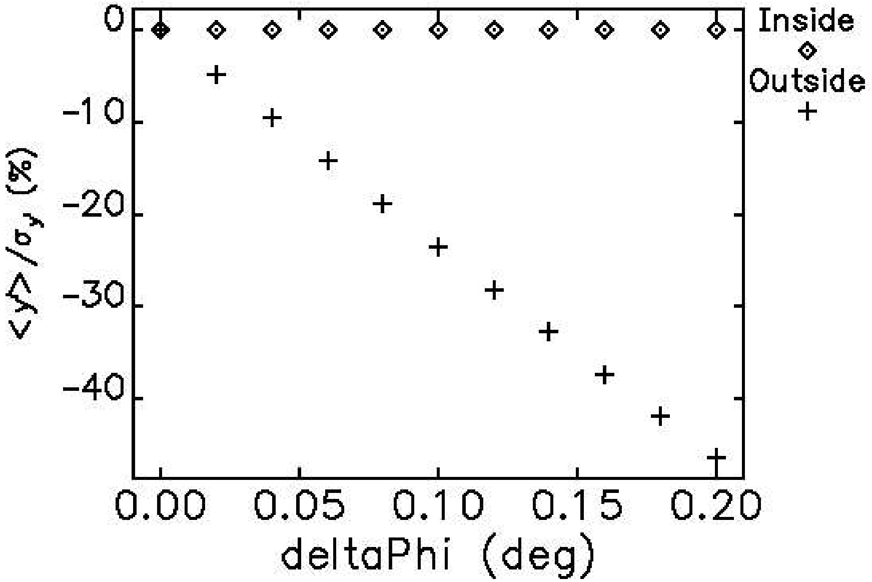
[1] LCLS Design Study Report, SLAC R-521 (1998).

Intercavity Phase Error







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

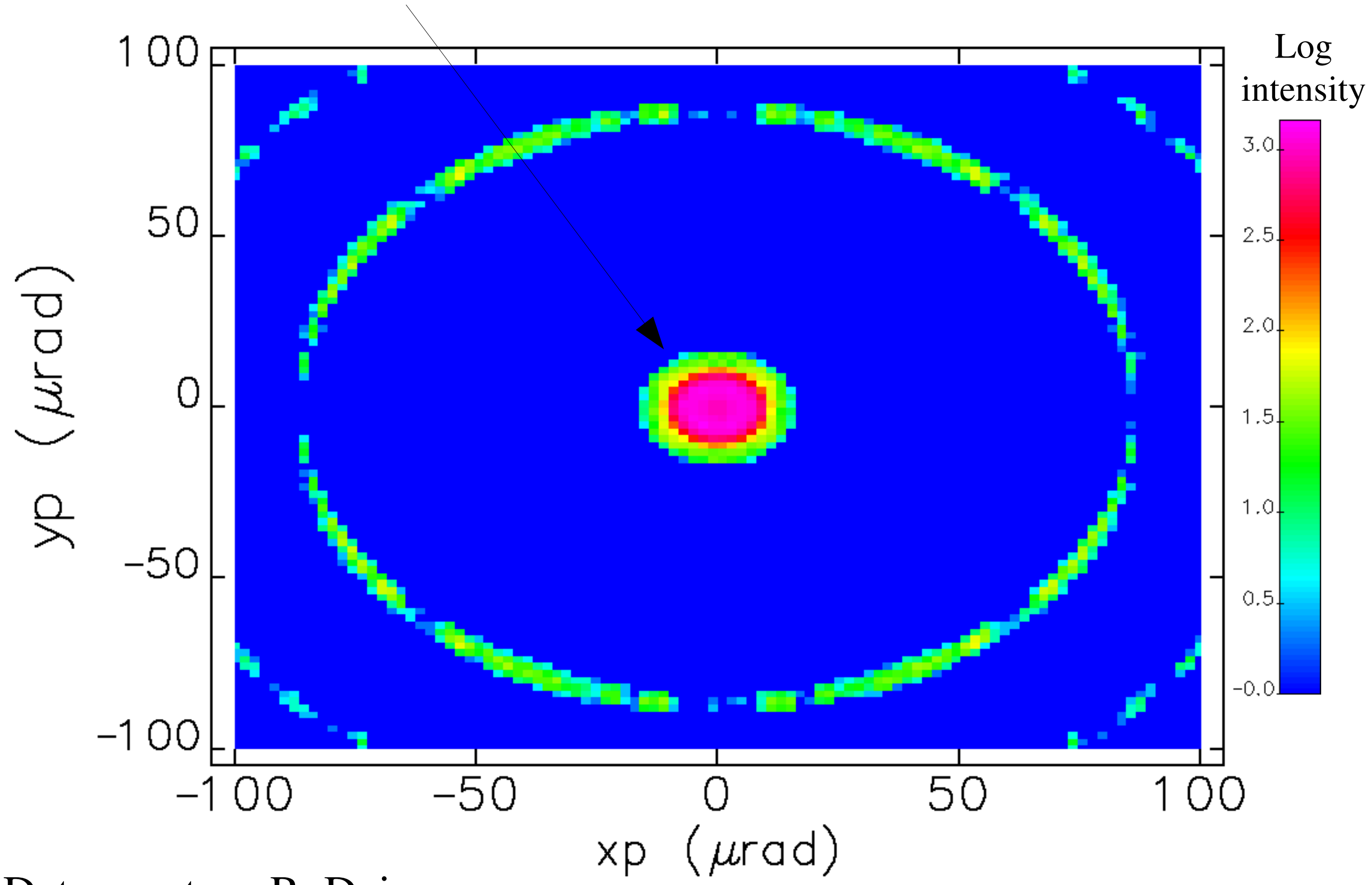
Most difficult issue is orbit disturbance outside the inter-cavity region.

[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


Central cone opening angle ~5 urad rms

Data courtesy R. Dejus

For estimates, use

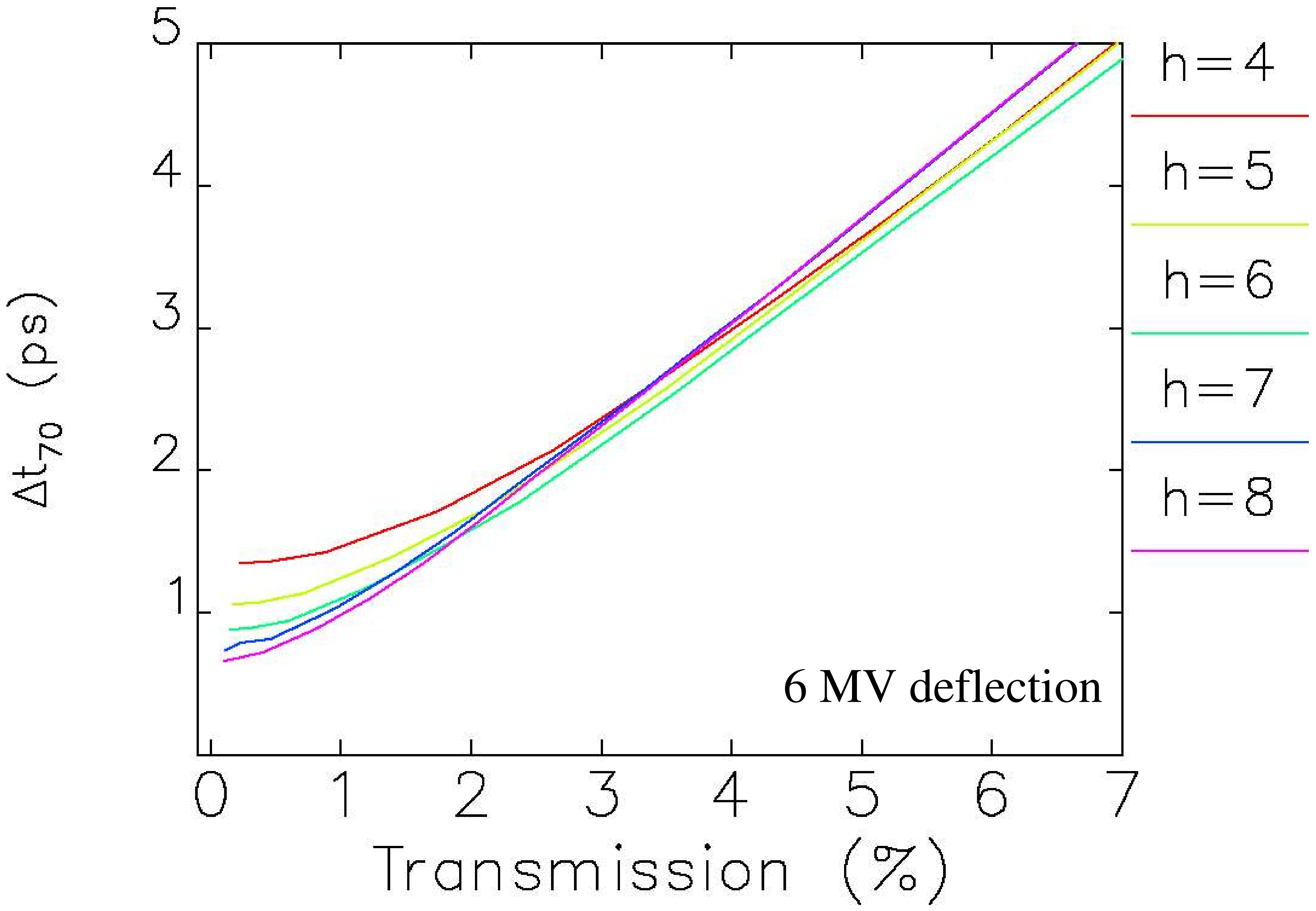
$$\sigma_\theta = \sqrt{\frac{\lambda}{2L}}$$

Simulations use distribution function[1]

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

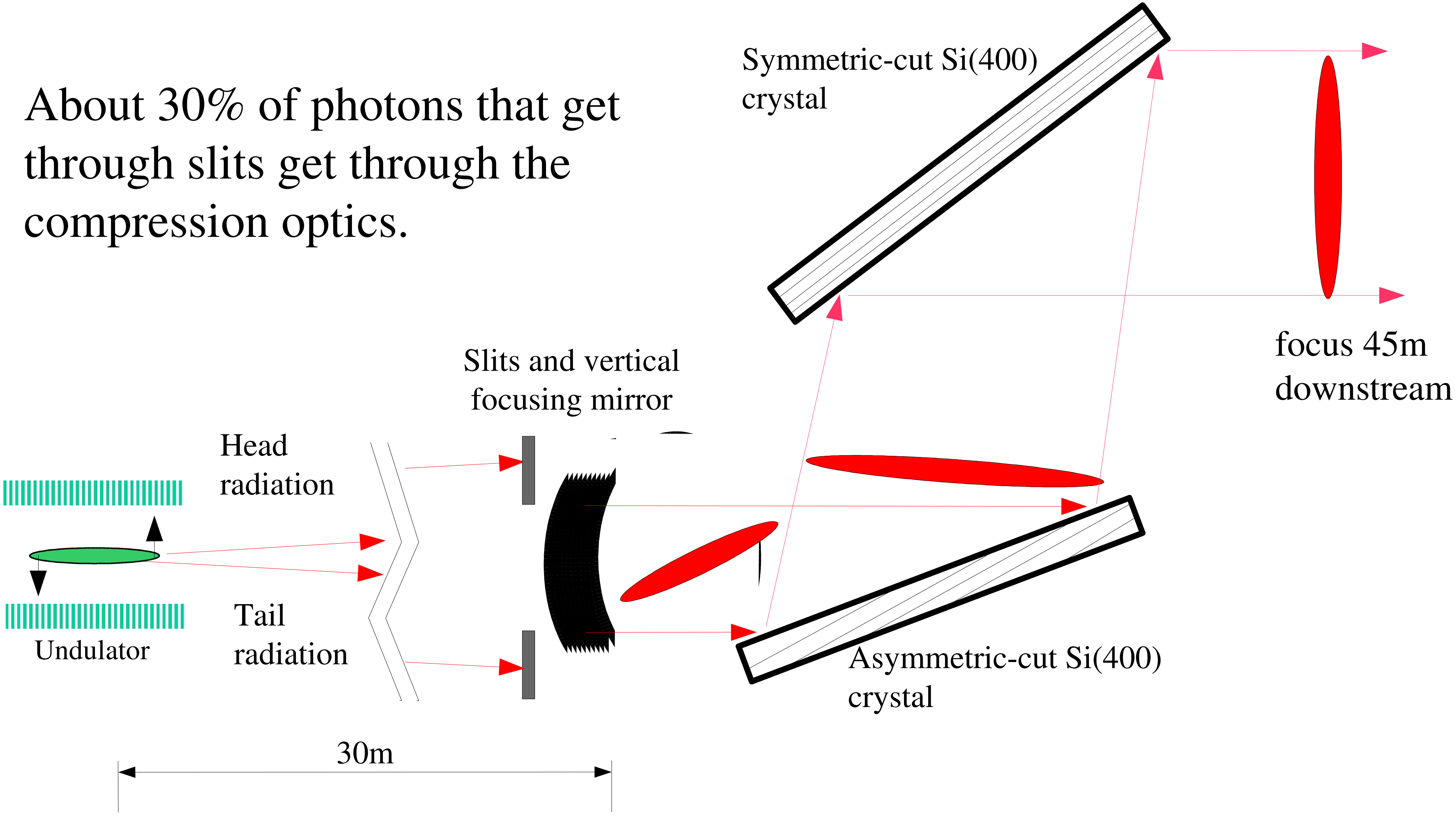
[1] K.J. Kim, AIP 565 (1989)

Slicing Results for 10 keV, UA



Preliminary Optics Concept for 10 keV

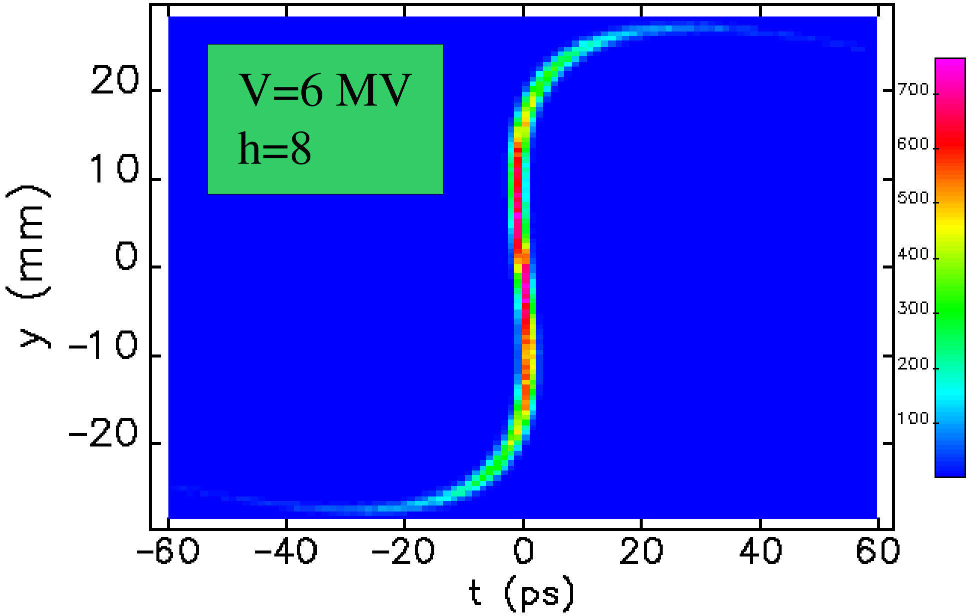
About 30% of photons that get through slits get through the compression optics.



N.B.: Sketch not to scale.
Angles are exaggerated.

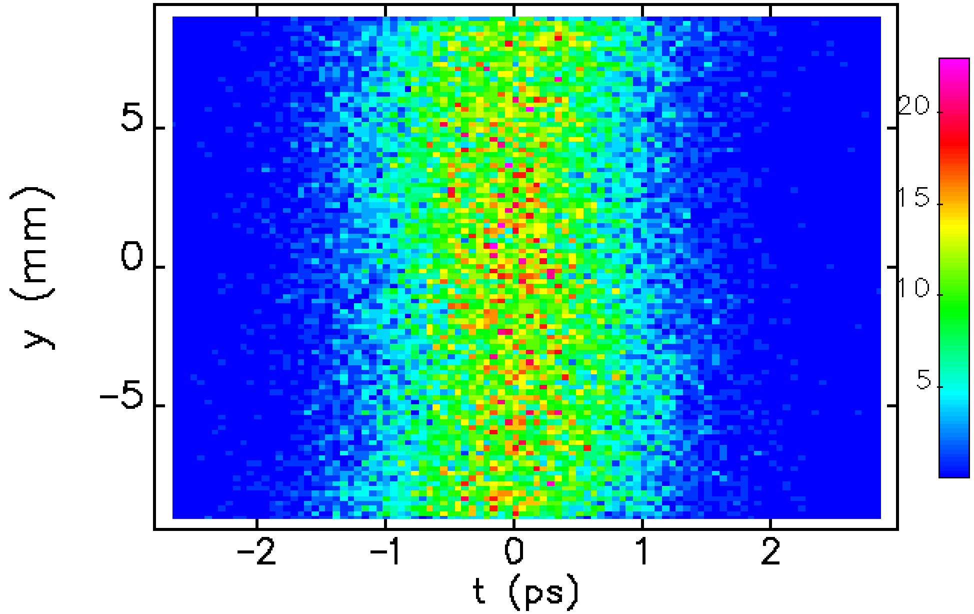
After S. Shastri, APS

Need for Slits with Compression

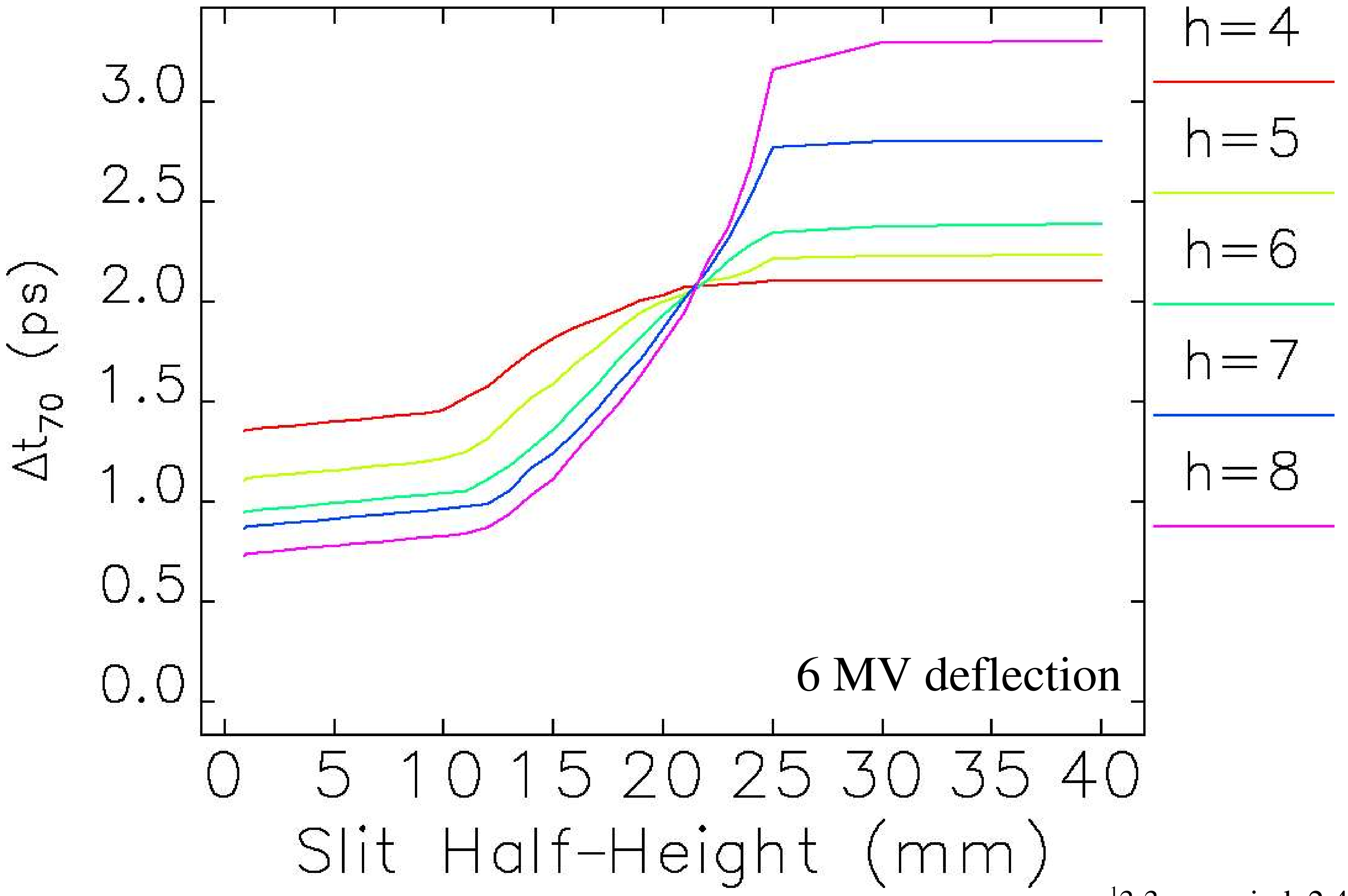


Without slits, rf curvature prevents complete compression

With slits, we lose intensity but get complete compression

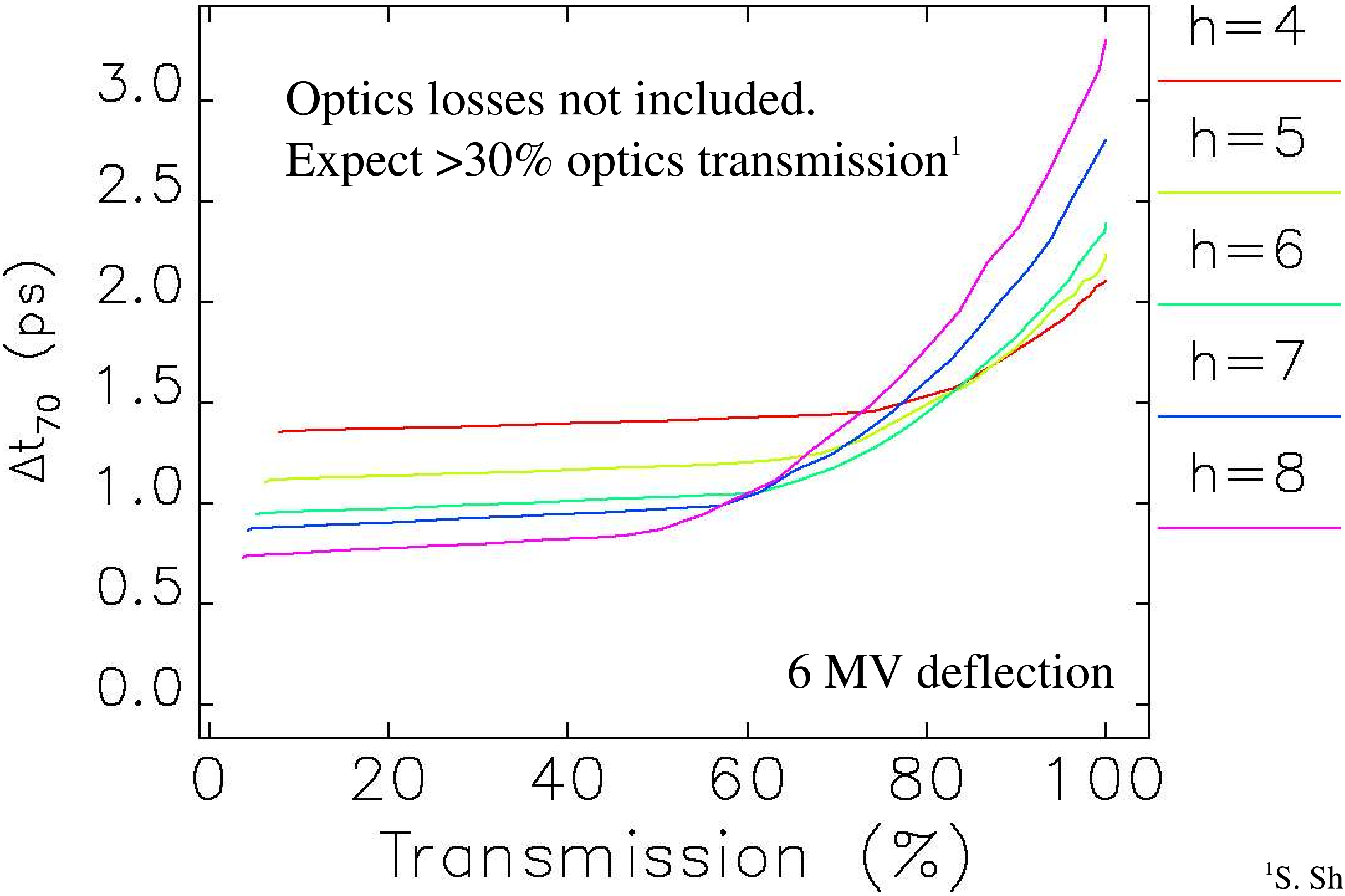


Compression Results for 10 keV, UA[1]



[1] 3.3cm period, 2.4m length

Compression Results for 10 keV, UA



Optics losses not included.
Expect >30% optics transmission[1]

6 MV deflection

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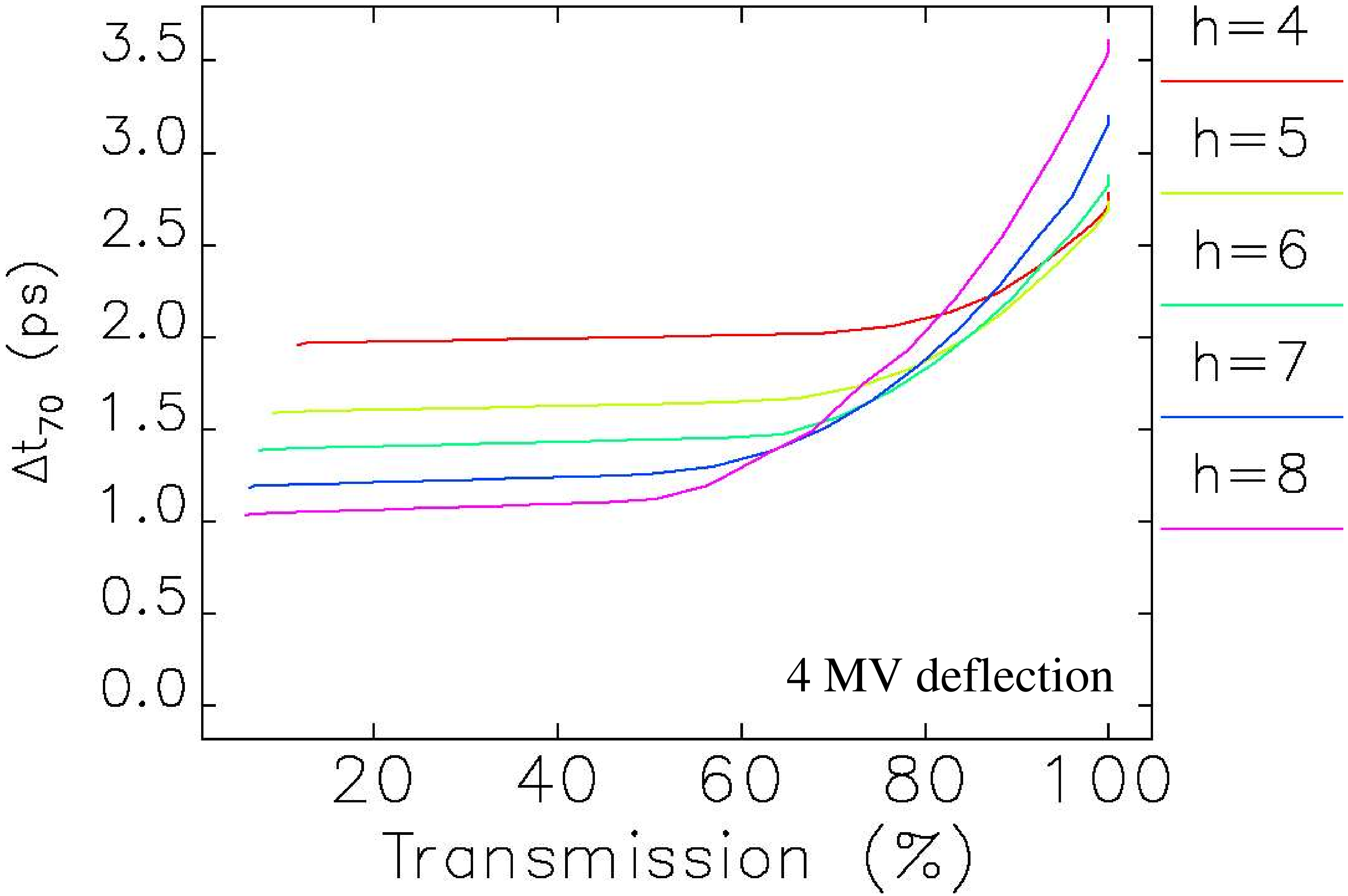
[1] S. Shastri

Compression Results for 10 keV, UA



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

Is a Warm Pulsed System Better?

- It has been argued[1] that a pulsed system would be better
- Most pump-probe experiments use ~1kHz lasers, so continuous beam isn't useful
- Many experiments run from very short to very long time scales
  - Many experiments employ choppers with small apertures and hence cannot vary pulse length by varying slits
  - Having a chirped pulse just throws away intensity when looking at long time scales
  - Such experiments can be done more efficiently if the chirp can be turned off at will
- A pulsed chirping system lets the user do this via timing

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[1] P. Anfinrud

Pulsed System Considerations

- Could charge and discharge cavities at 100~1000 Hz
  - Could start low and upgrade later
- Pulse could be of order the revolution time (3.68 μs)
  - Power load should be manageable
  - 6 MV should be no problem
  - Emittance effects greatly reduced
- Ideally make the rf pulse last several revolution times
  - Chirp would be time-modulated, not just on/off
  - This could be an upgrade

Pulsed System Considerations

- Advantages over superconducting
  - Short development time
  - Much cheaper
- Can we maintain the required phase tolerance?
  - Need single klystron feeding both cavities
  - Need careful temperature control of
    - Cavities
    - Long waveguide runs
- Will the pulse-to-pulse chirp variation be acceptable?

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
- Picosecond x-ray pulses appear feasible with 50~70% transmission through slits
- Cause for a pulsed system is plausible