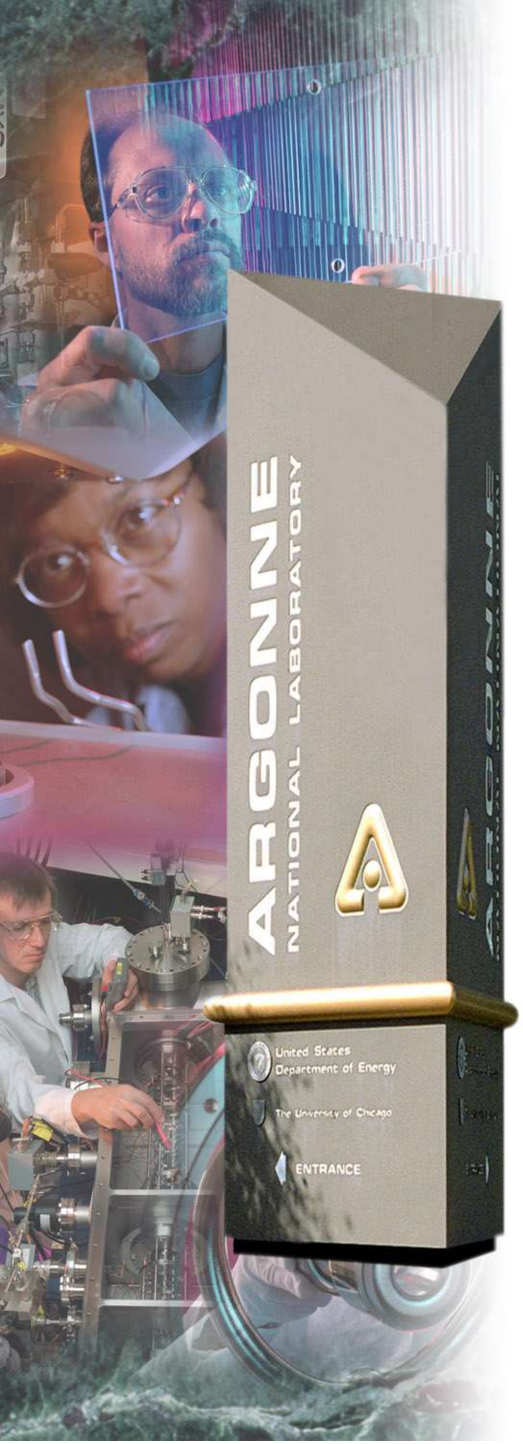

Producing Chirped Electron Beams in the APS

Michael Borland
Operations Analysis Group
APS Operations Division
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Office of Science
U.S. Department of Energy

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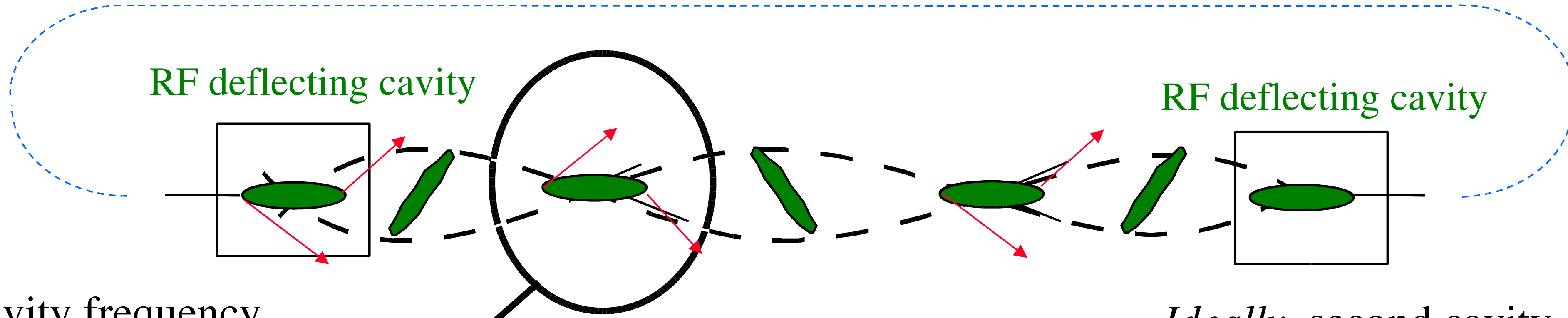
Outline

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

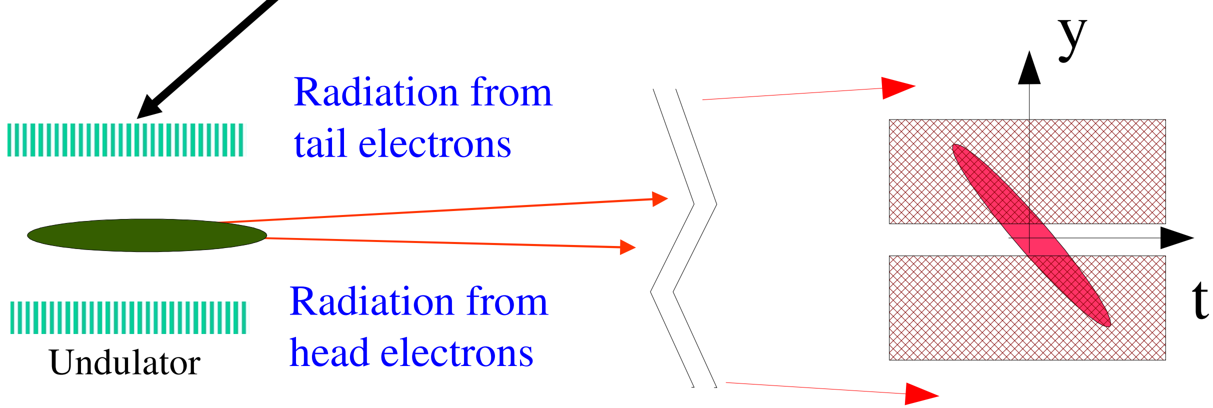
Zholents' Transverse Rf Chirp Concept

(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

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

Electron beam energy (E)

Deflecting rf voltage & frequency (V, ω_a)

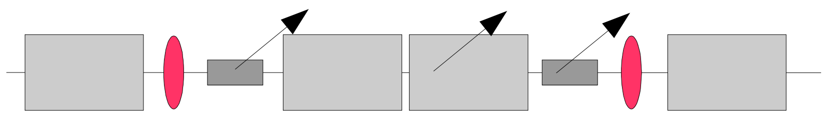
Unchirped e-beam divergence (typ. 2~3 µrad) ($\sigma_{y',e}$)

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

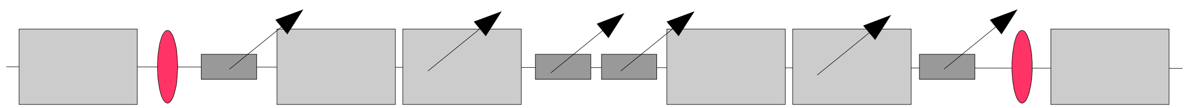
→ For 6 MV, 2800MHz (h=8) deflecting system, get ~0.4 ps!

- Normal APS bunch is 40 ps rms

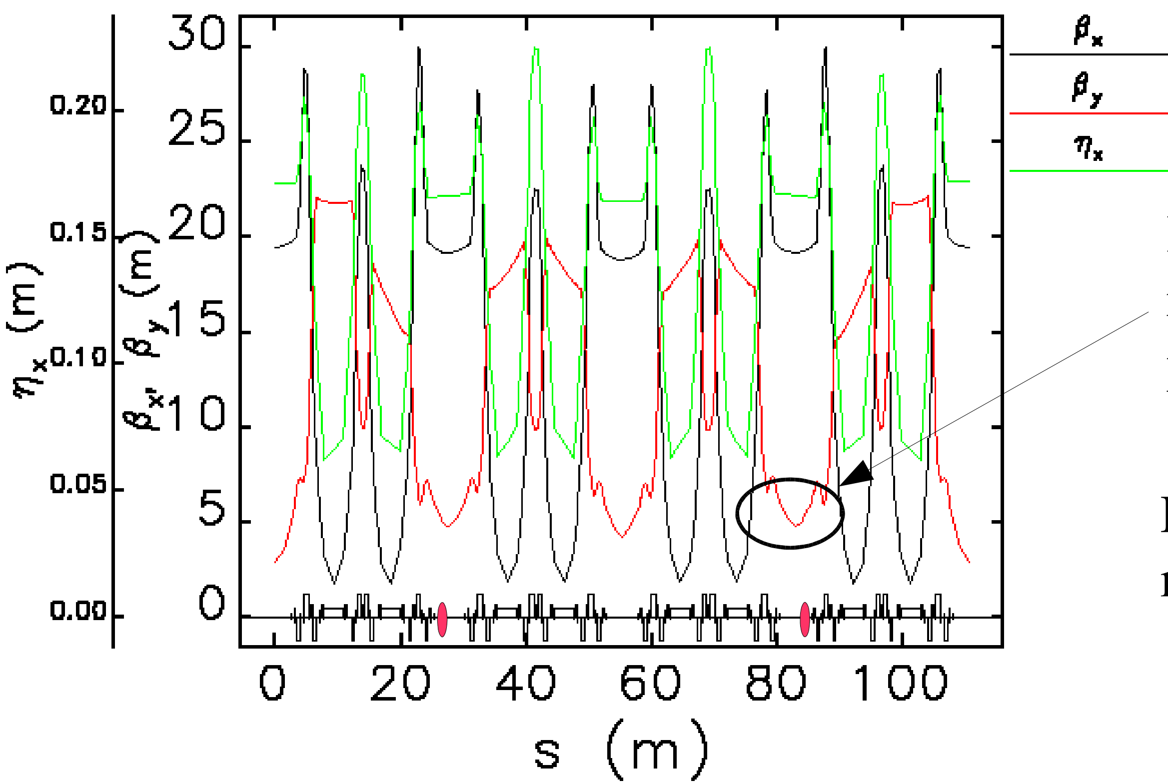
Lattice Options



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

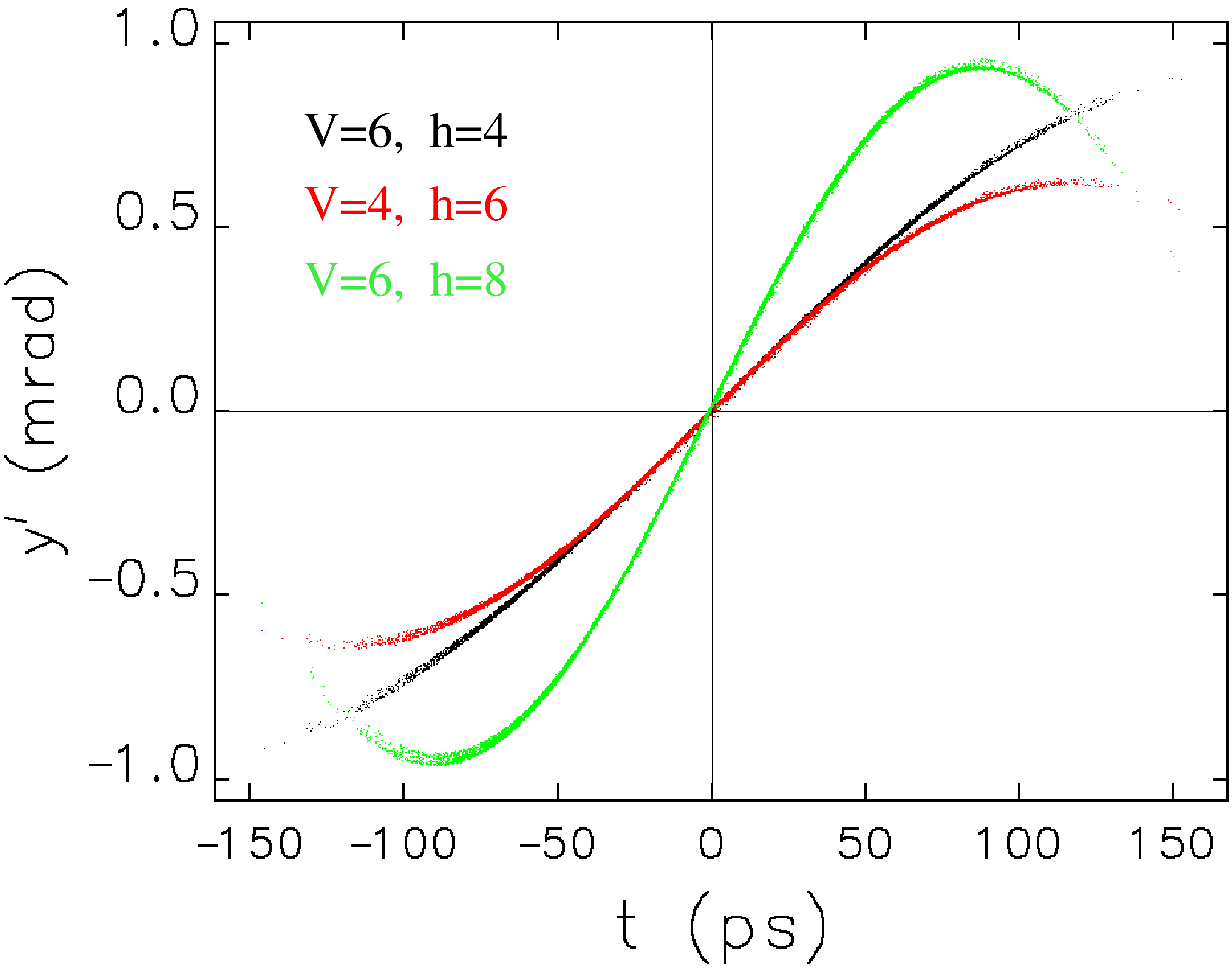
- The maximum angular deflection seen by any particle is V/E
- We can preserve lifetime by requiring

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

- 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

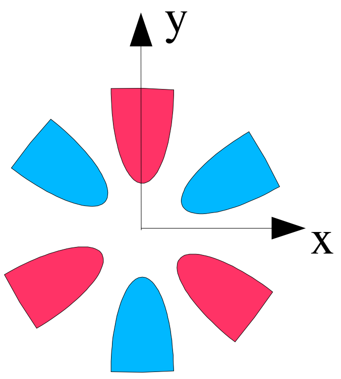
Higher h and maximum V: shortest pulse, acceptable lifetime

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

Sextupole Effects

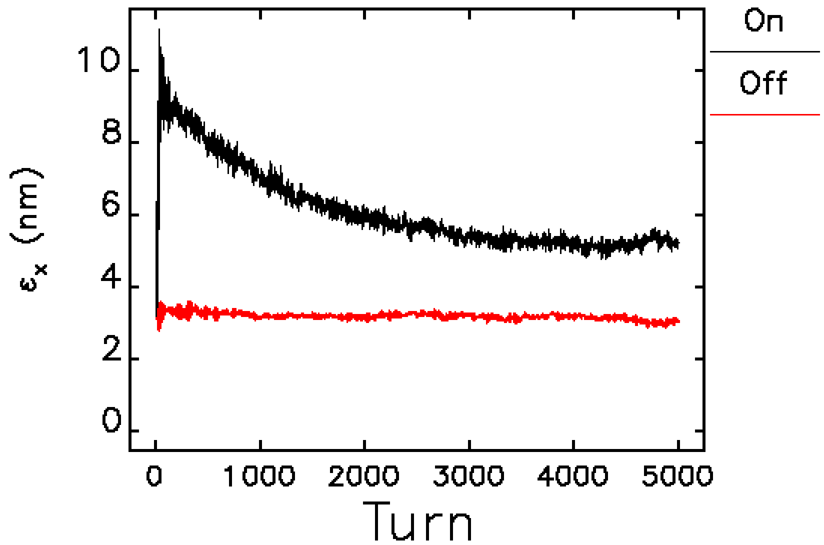
- Sextupoles are necessary
  - Correct chromatic focusing aberrations
  - Defeat beam instabilities
- Sextupoles have undesirable side-effects
  - Phase advance varies with amplitude
    - Kick cancellation varies with amplitude
    - Vertical emittance increases
  - Horizontal and vertical motion gets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



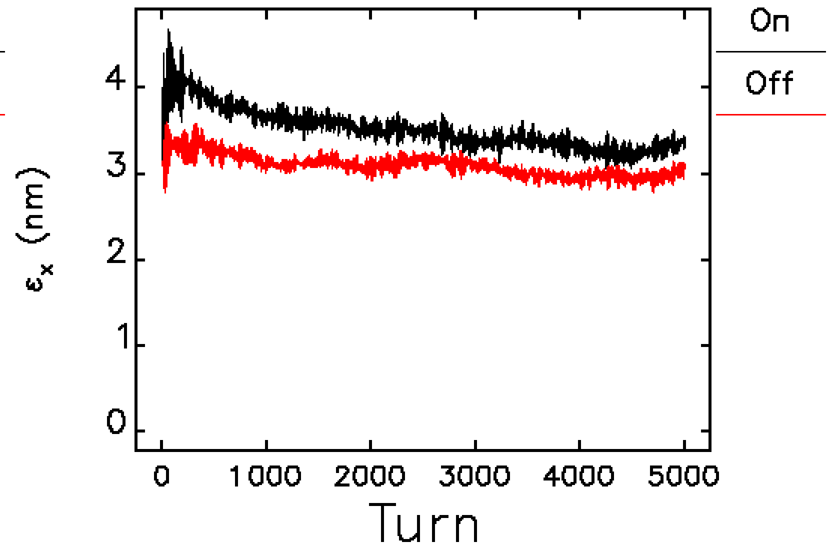
$$B_y = \frac{1}{2} m (x^2 - y^2)$$

$$B_x = m x y$$

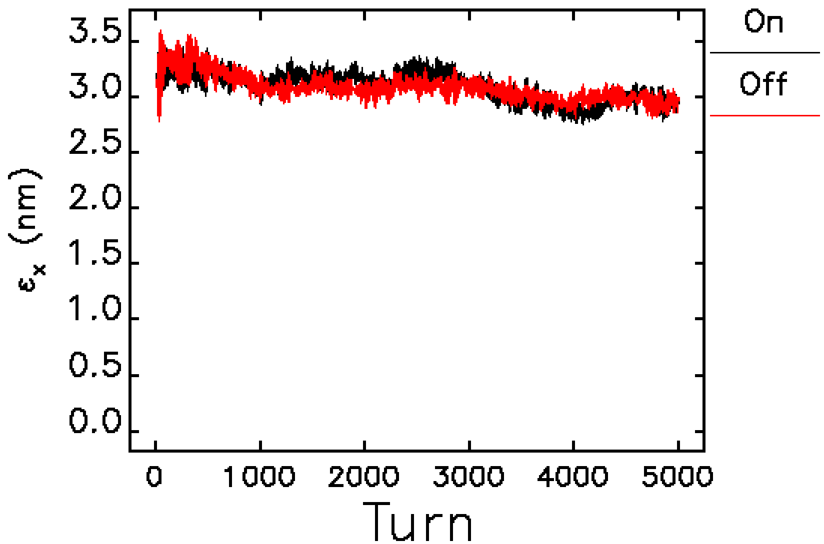
Interior Sextupoles and Horizontal Emittance



6 MV h=8



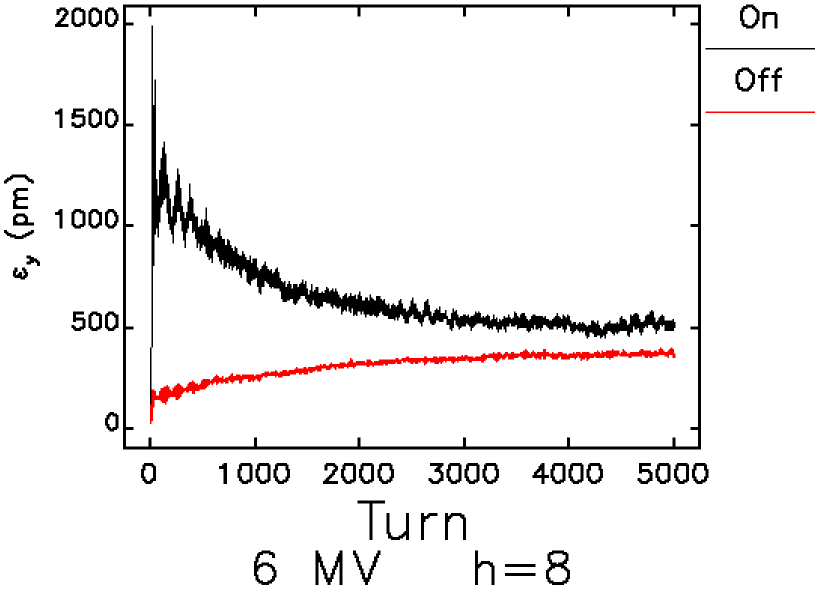
4 MV h=8

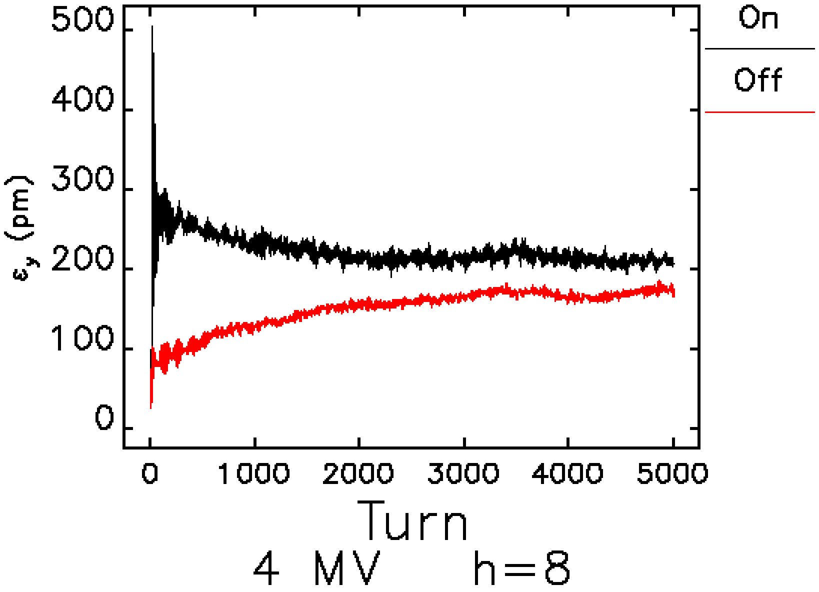


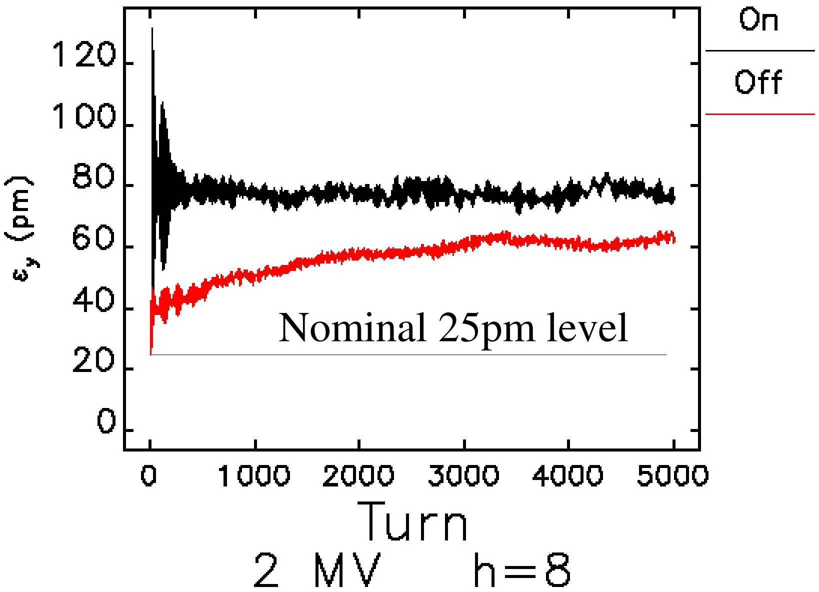
2 MV h=8

Radiation damping helps sextupole-on case

Interior Sextupoles and Vertical Emittance







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

Are we limited to 2 MV?

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

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
- Can also make the starting vertical emittance smaller (as small as 8 pm) instead of starting with nominal 25 pm

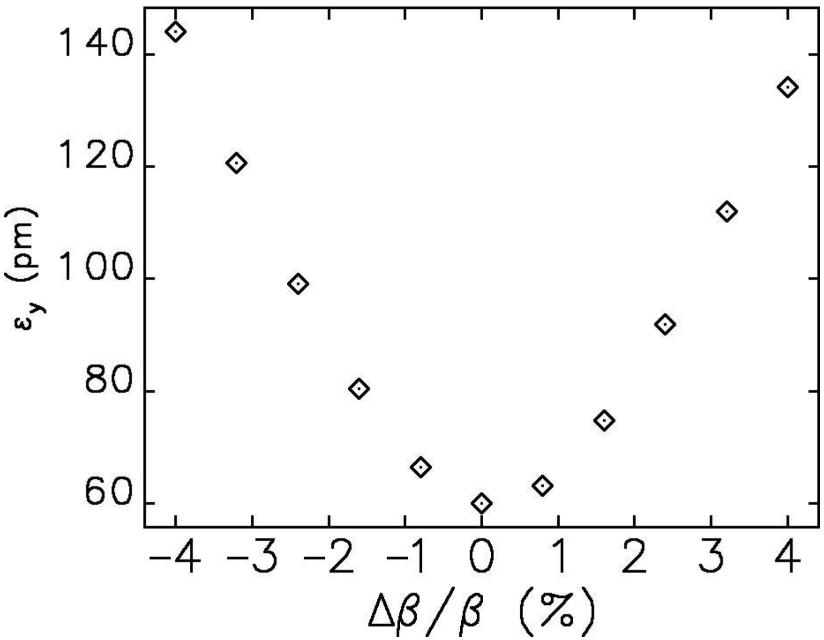
Content courtesy V. Sajaev, APS.

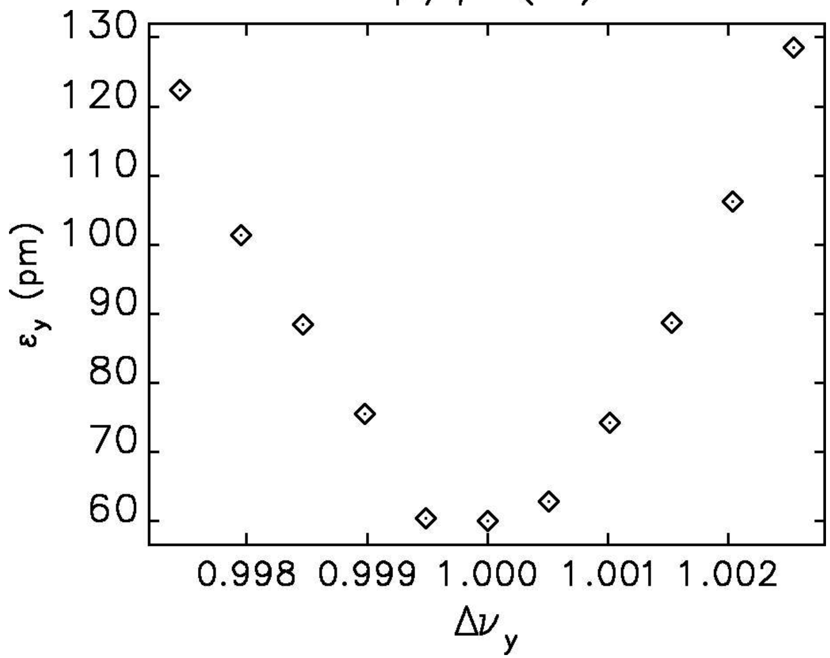
Error Sensitivities

- 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

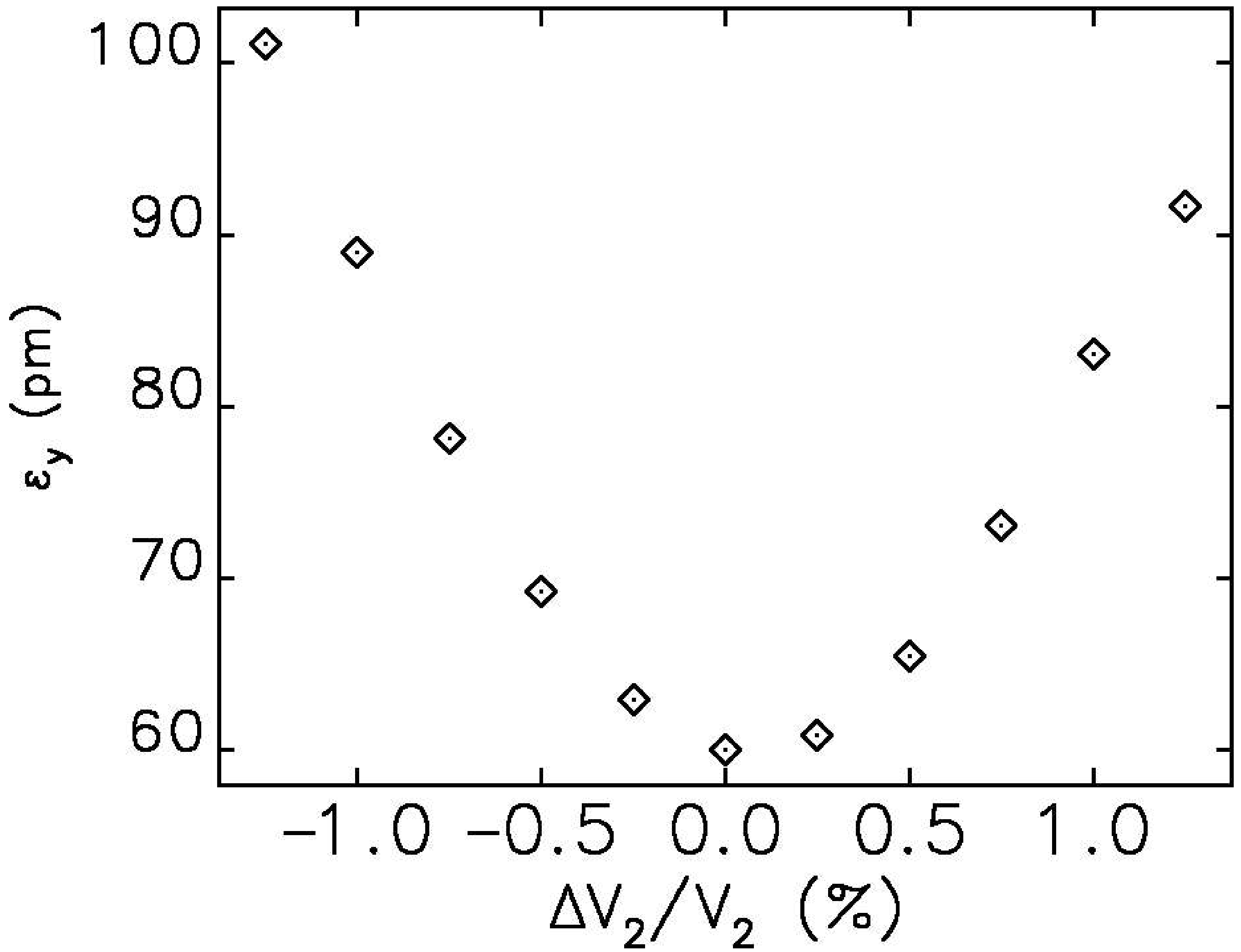
x-y Coupling

- Coupling y motion into x plane can cause problems
- May result from
  - Rolled cavities
  - Rolled quadrupole or sextupole magnets
- Simulations show that this isn't an issue for
  - Few mrad alignment of cavities
  - Typical 0.25 mrad[1] alignment of magnets

[1]H. Friedsam

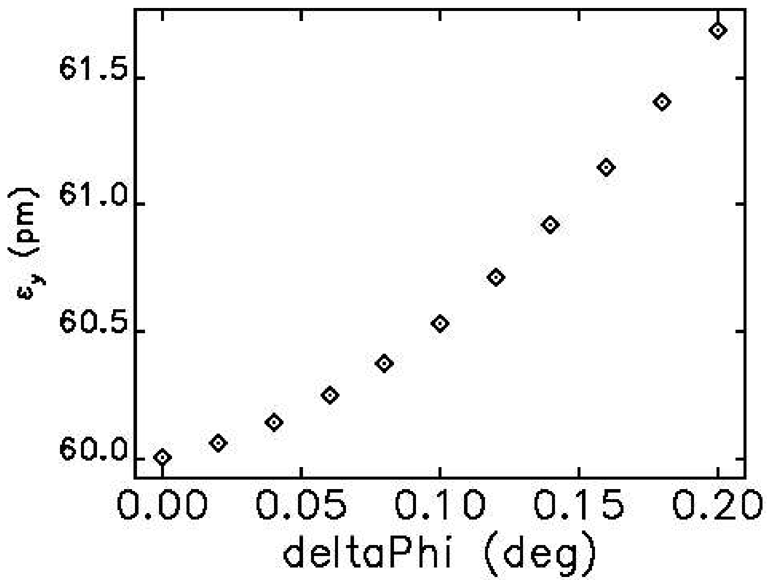
Intercavity Voltage Error

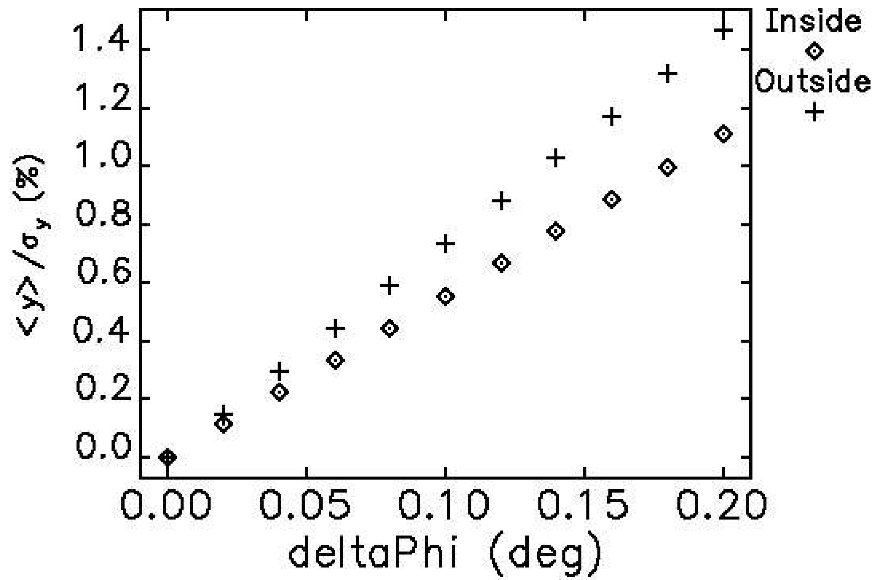
- Imparted errors to one of the cavities
- LCLS *pulsed* S-band system requires <0.1% rms voltage jitter[1]

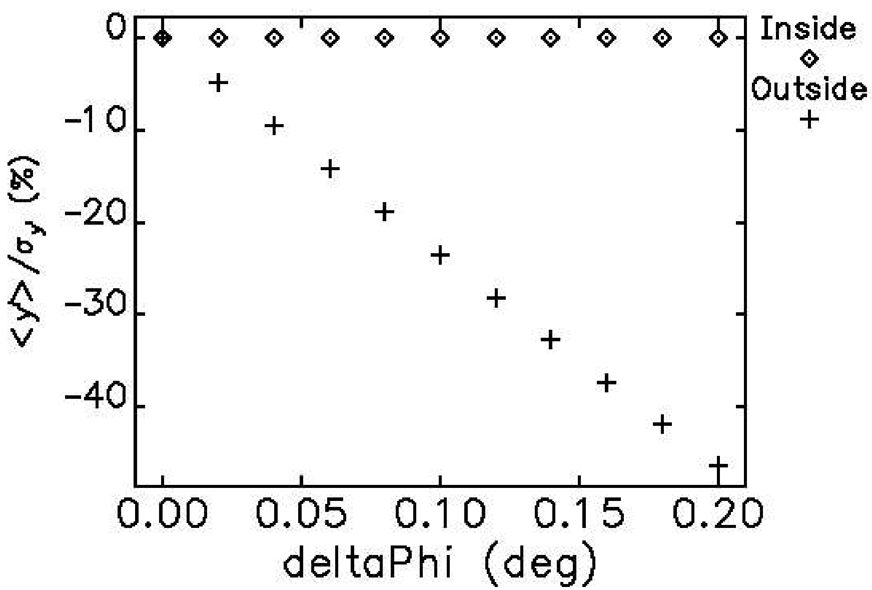


[1]LCLS Design Study Report, SLAC R-521 (1998).

Intercavity Phase Error







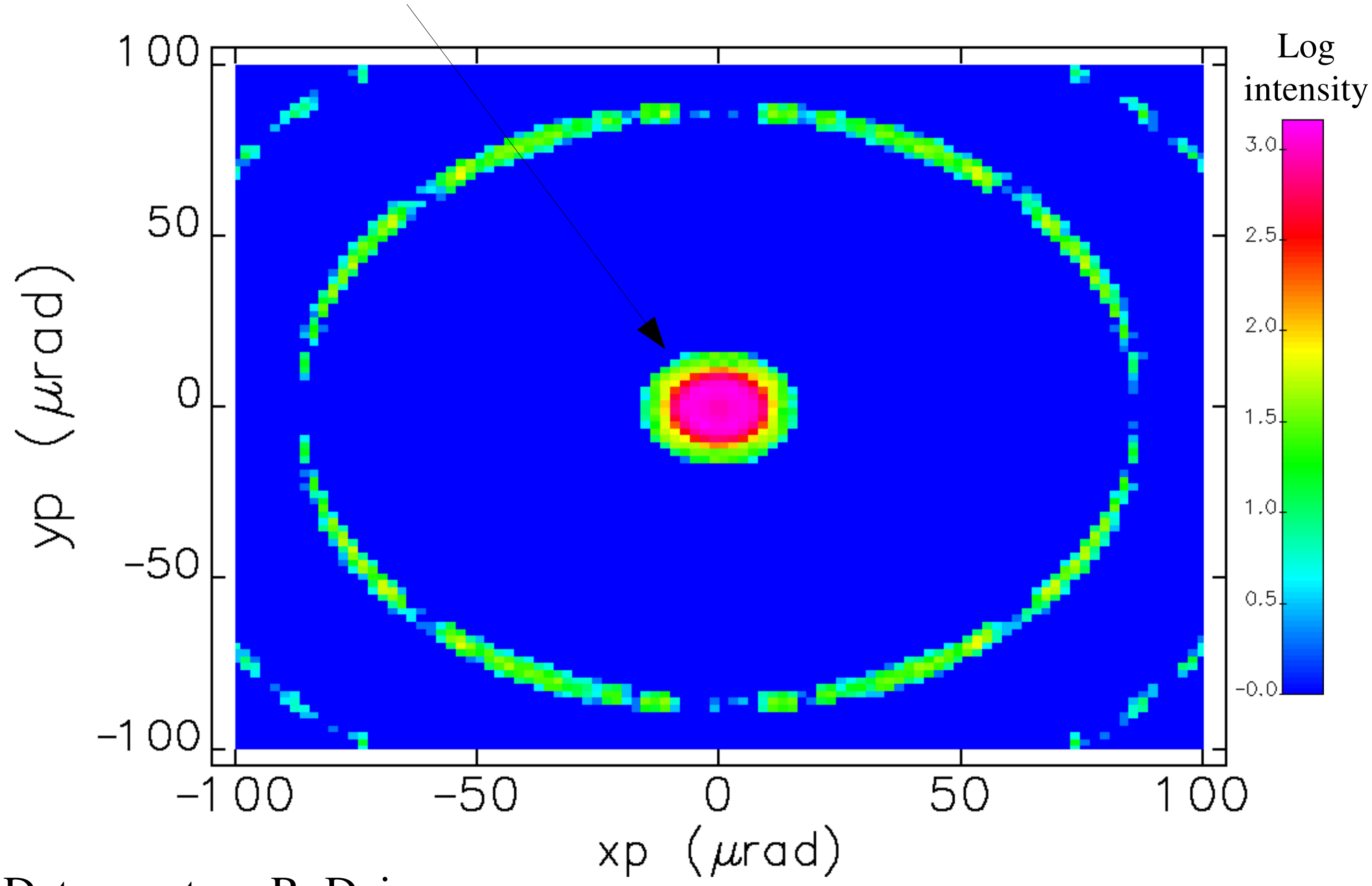
SLAC *pulsed* S-band systems have <0.1 deg rms phase jitter[1]

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

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

Undulator Radiation Pattern

Central cone opening angle ~5 urad rms



Data courtesy R. Dejus

For estimates, use

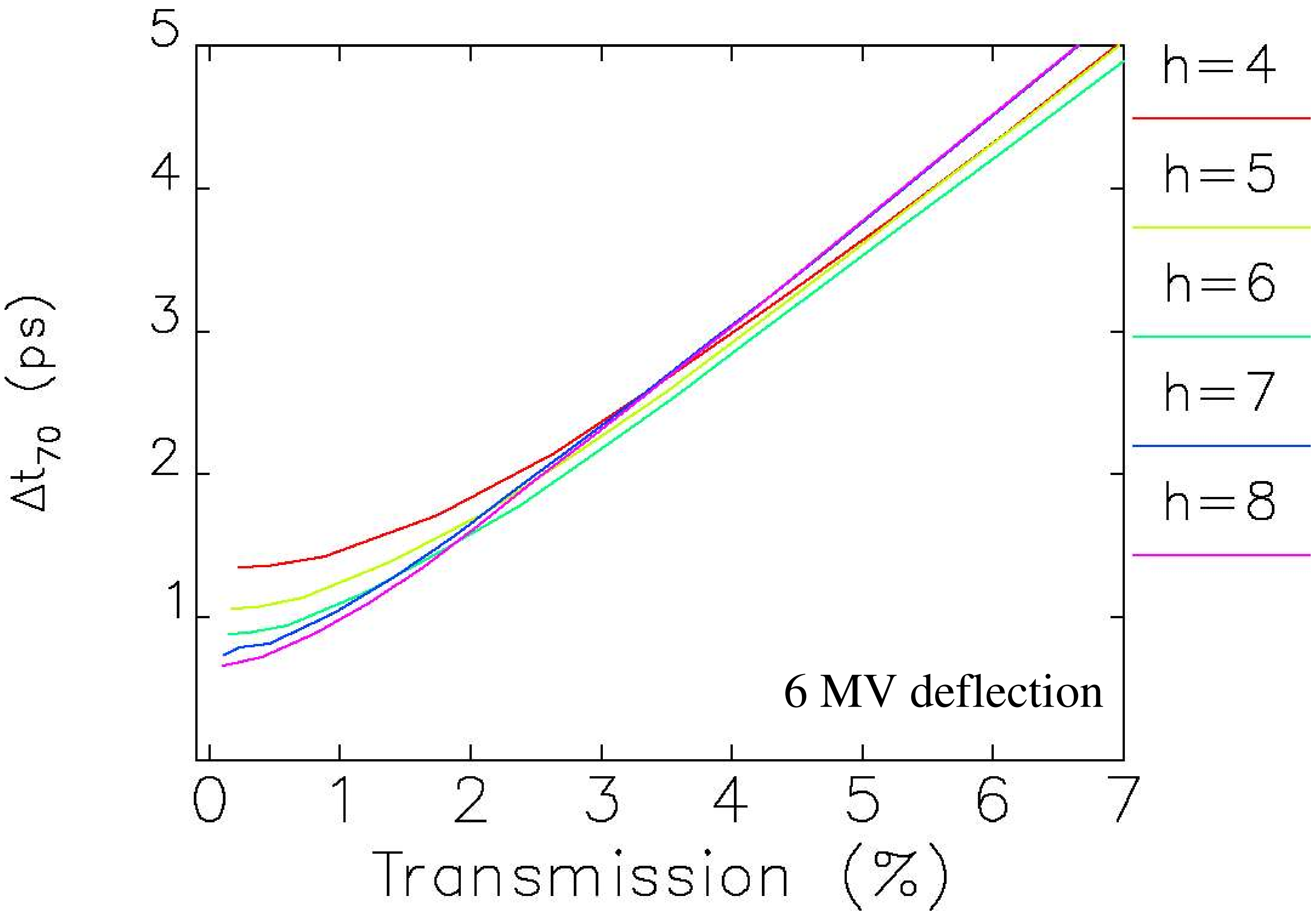
$$\sigma_\theta = \sqrt{\frac{\lambda}{2L}}$$

Simulations use distribution function[1]

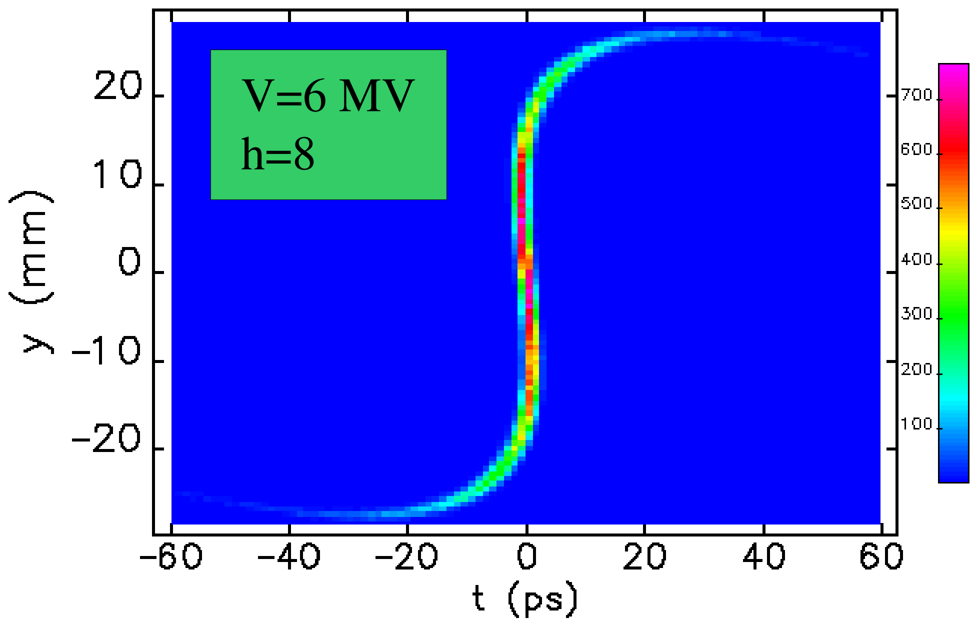
$$S(\theta) \approx sinc^2\left(\frac{n N \pi \gamma^2 \theta^2}{1+K^2}\right)$$

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

Slicing Results for 10 keV, UA

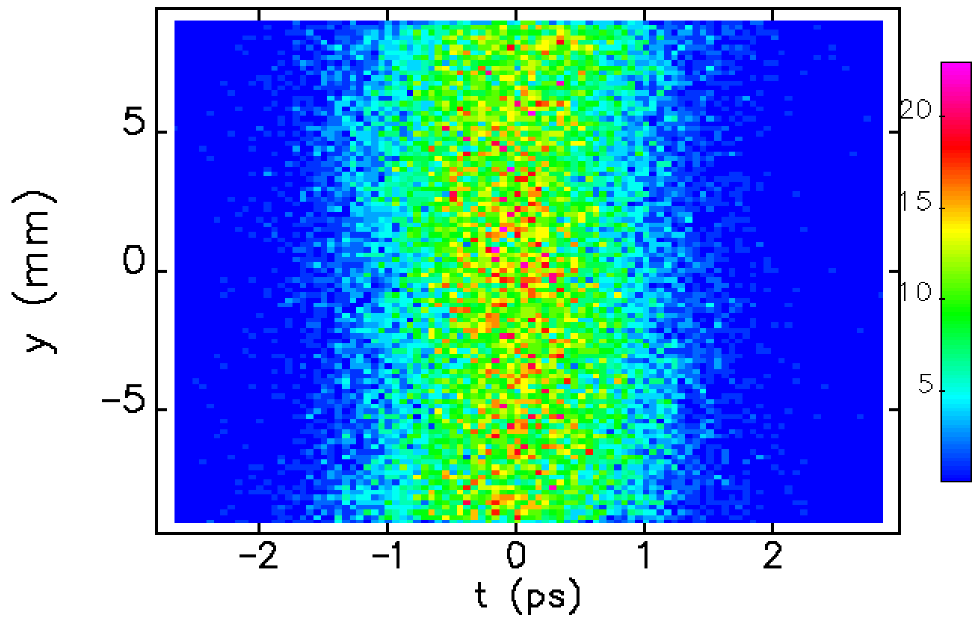


Need for Slits with Compression

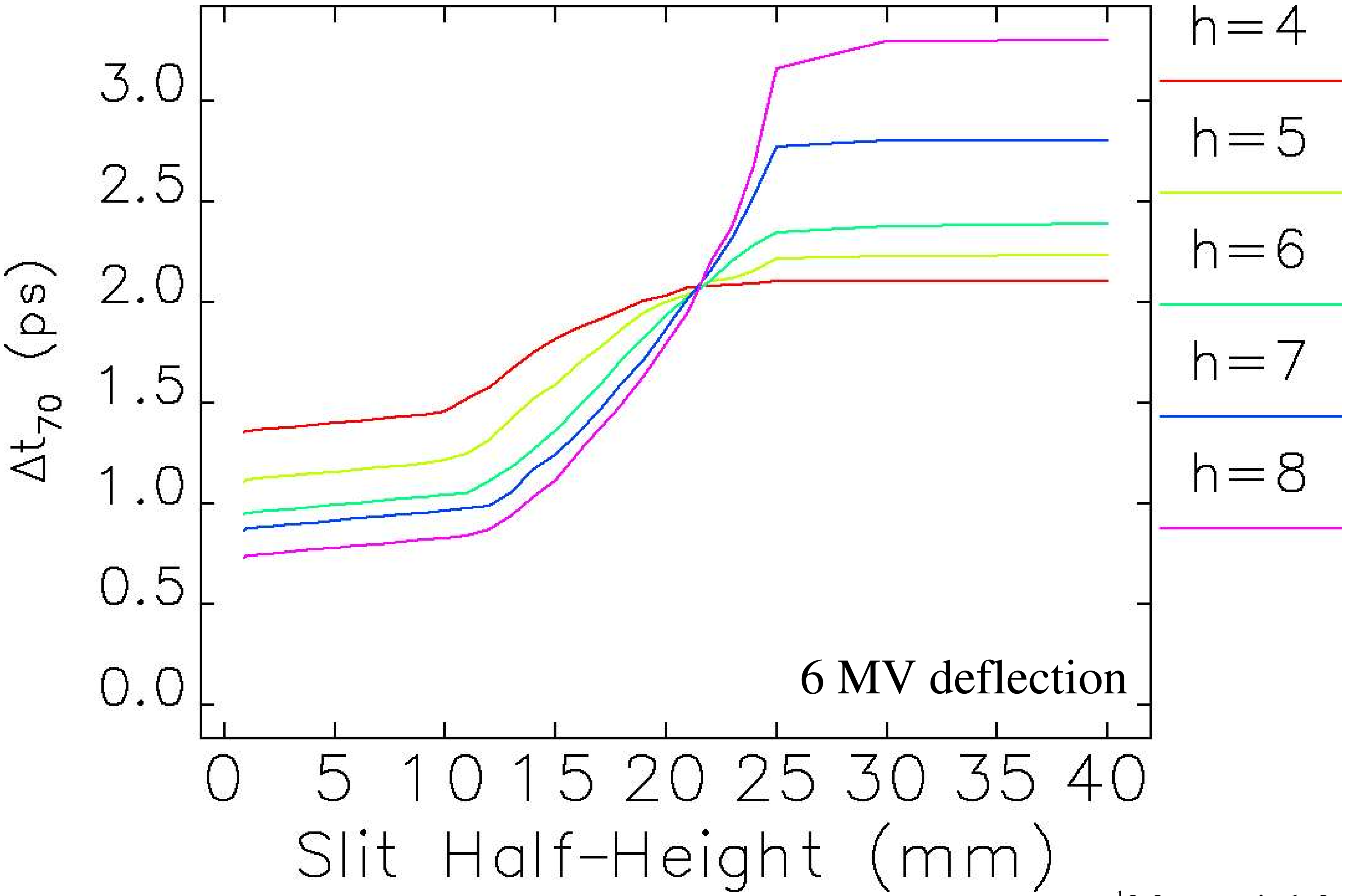


Without slits, rf curvature prevents complete compression

With slits, we lose intensity but get complete compression

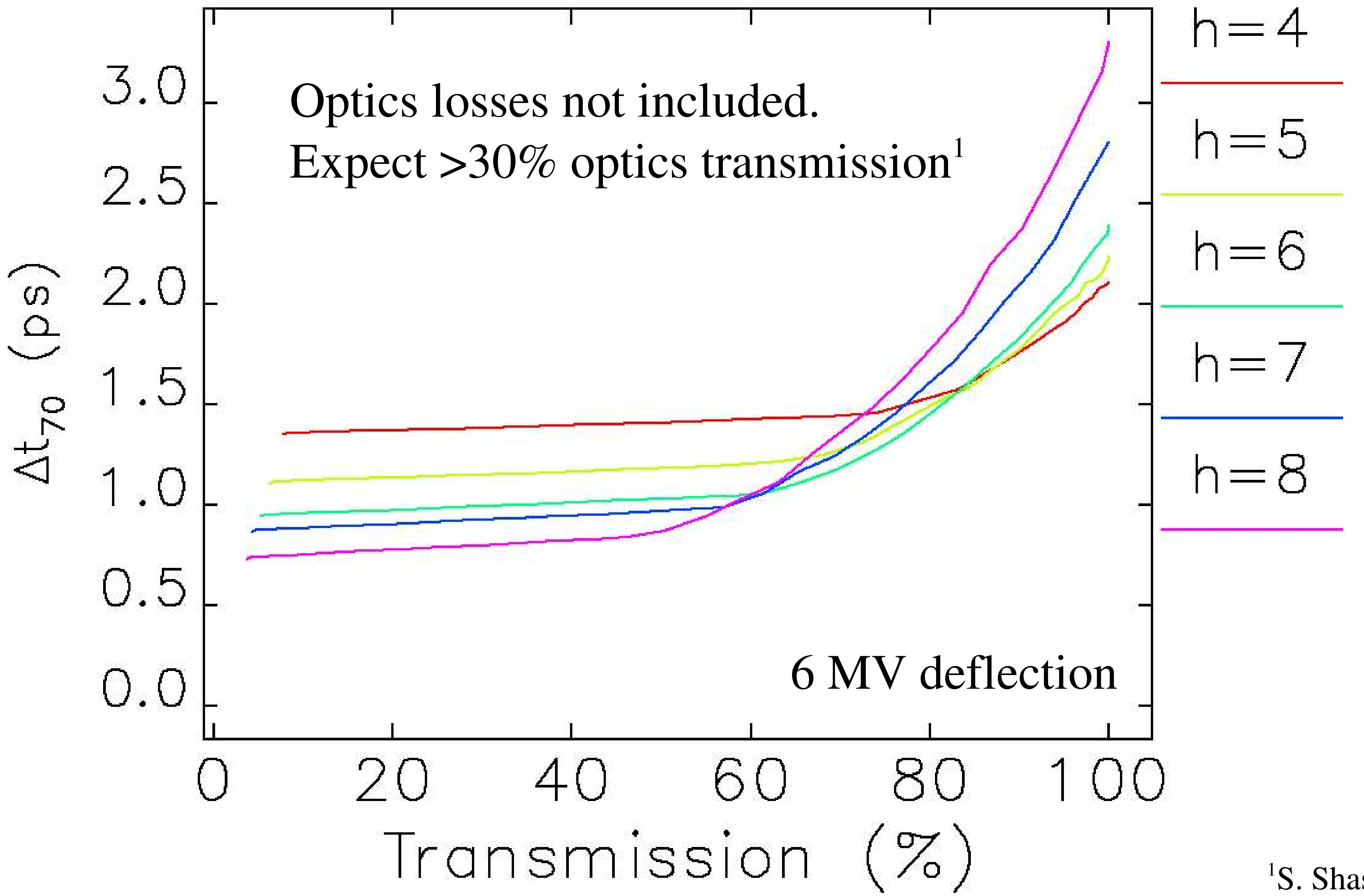


Compression Results for 10 keV, UA[1]



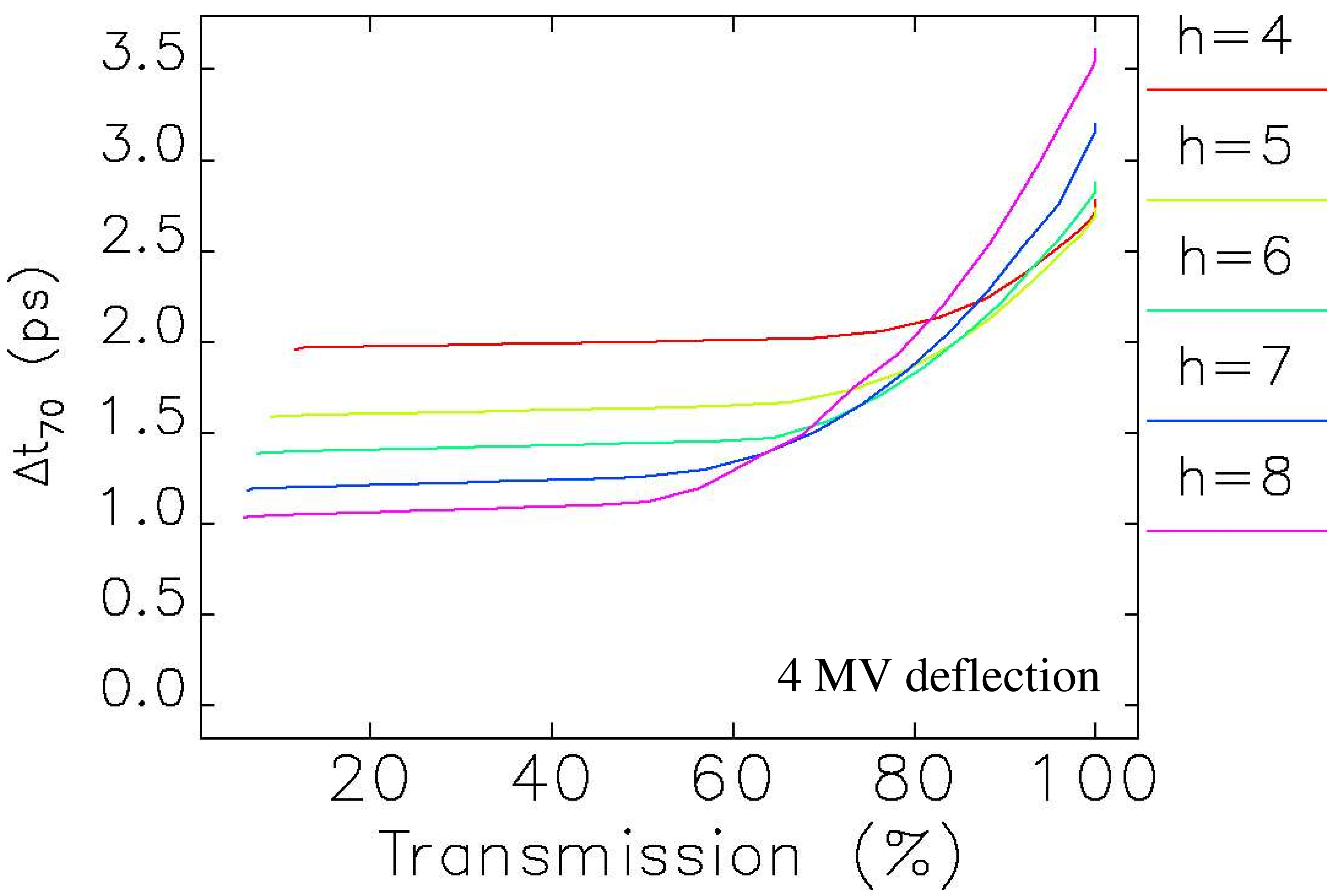
[1]3.3cm period, 2.4m length

Compression Results for 10 keV, UA



[1]S. Shastri

Compression Results for 10 keV, UA



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

[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 look at stability of the delivered pulses
- Picosecond x-ray pulses appear feasible with 50~70% transmission through slits
- Case for a pulsed system is plausible