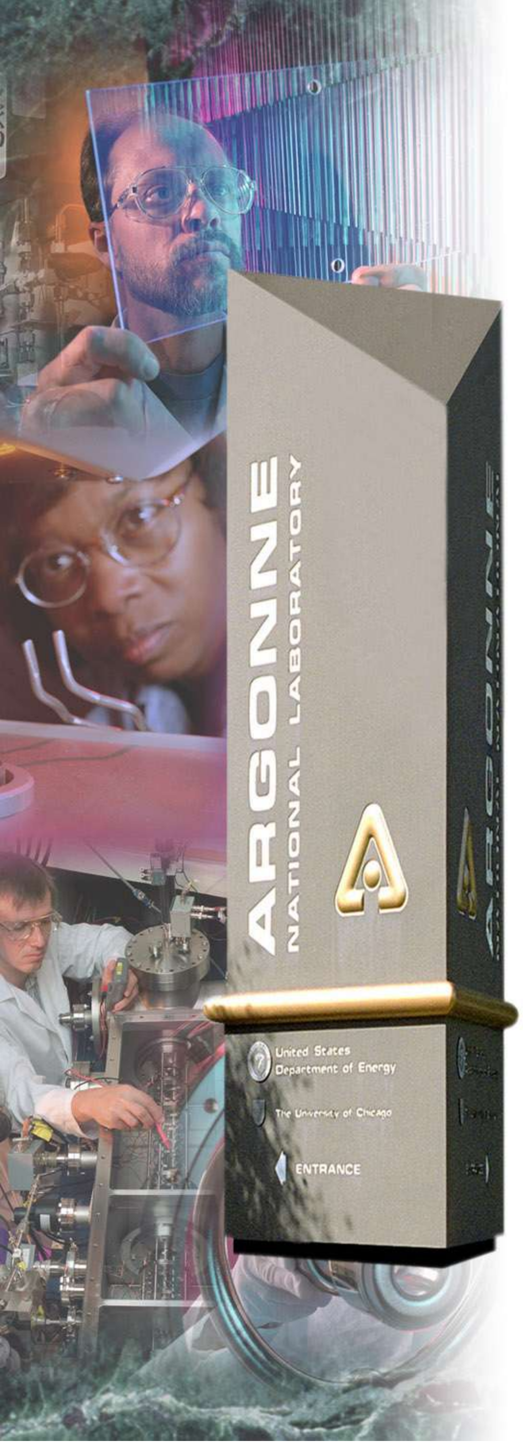

Single-Particle Dynamics for X-ray Compression Using Crab Cavities

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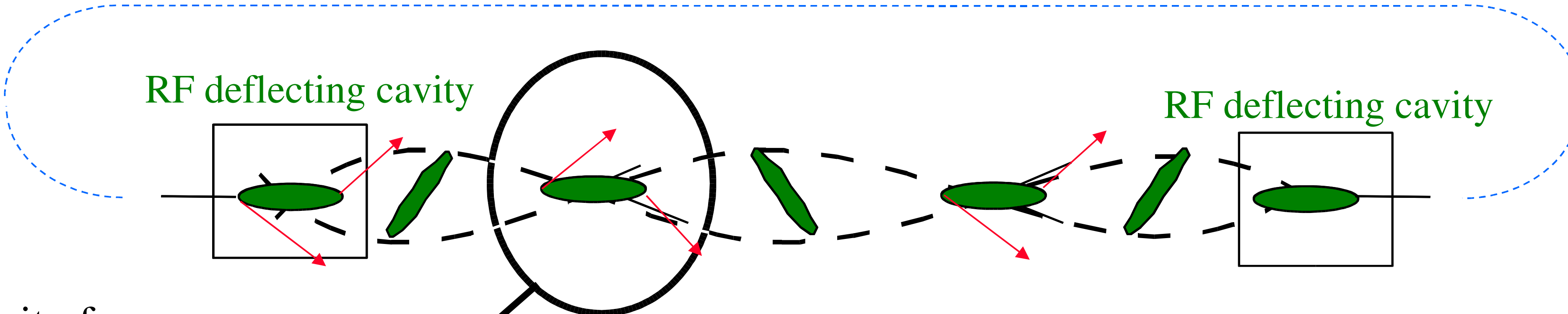
Outline

- Review of Zholents' concept
- Basic analysis of compression
- Simulation code and methods
- Lattice options and constraints
- Choice of voltage and frequency
- Emittance degradation mechanisms
- Error sensitivities
- Photon beam properties
- Optimization of compression
- Pulsed option

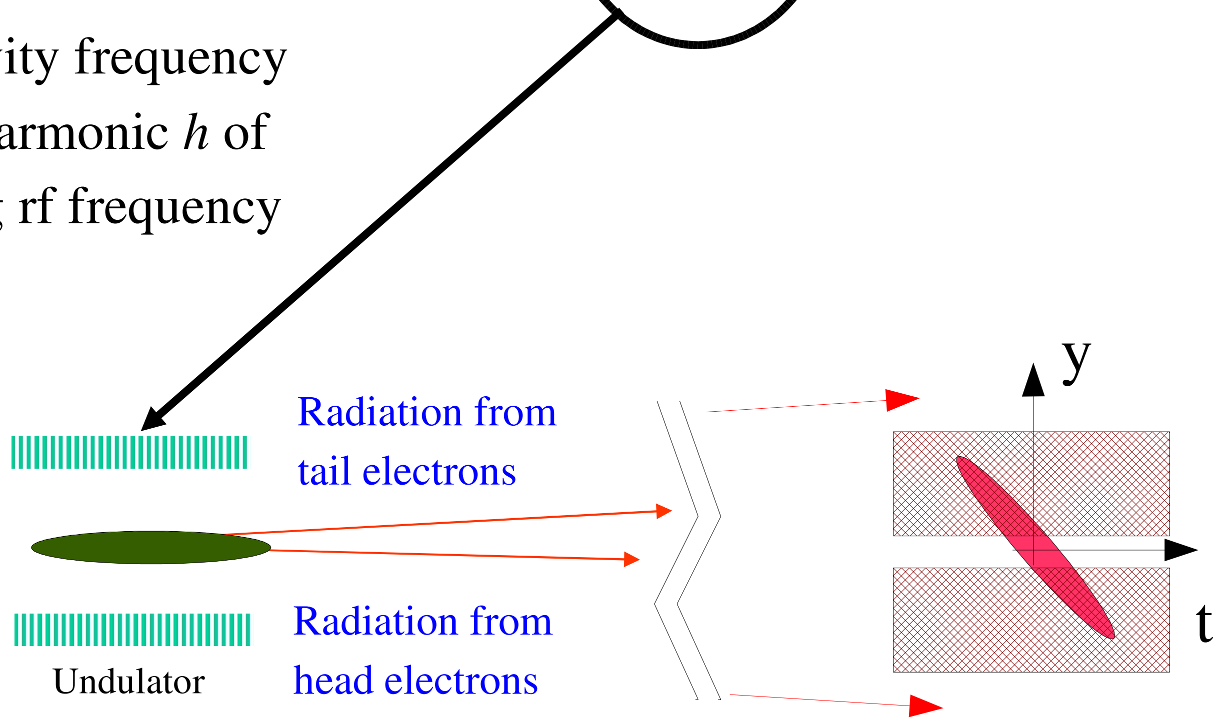
Zholents' Transverse Rf Chirp Concept

(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

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

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

Deflecting rf voltage & frequency

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

Divergence due to undulator (typ. ~5 μrad)

- 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

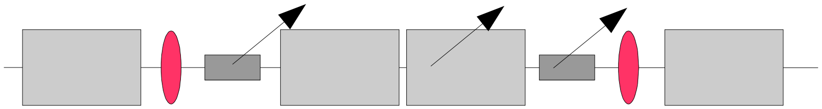
[1]M. Borland, APS LS-287, Sept. 2000.

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
- Single particle longitudinal dynamics is about right

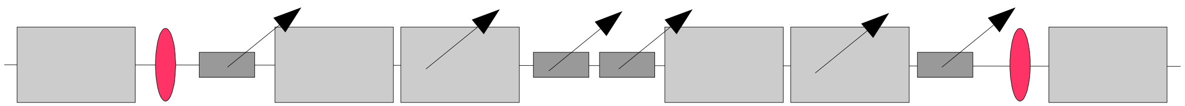
[1]Y.C. Chae, PAC 2001, 1491 (2001)
[2]Y.C. Chae, PAC 2003, 3017 (2003)

Lattice Options



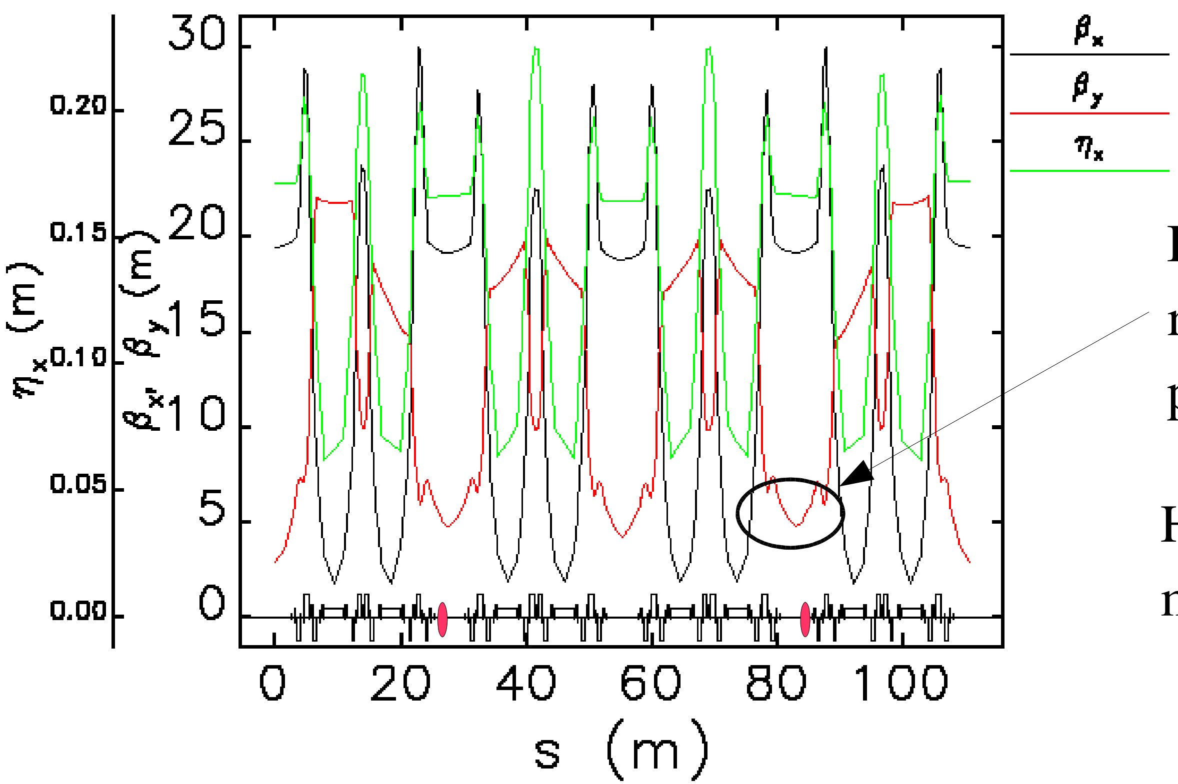
1 sector spacing

2 ID + 1 BM



2 sector spacing

4 ID + 2 BM



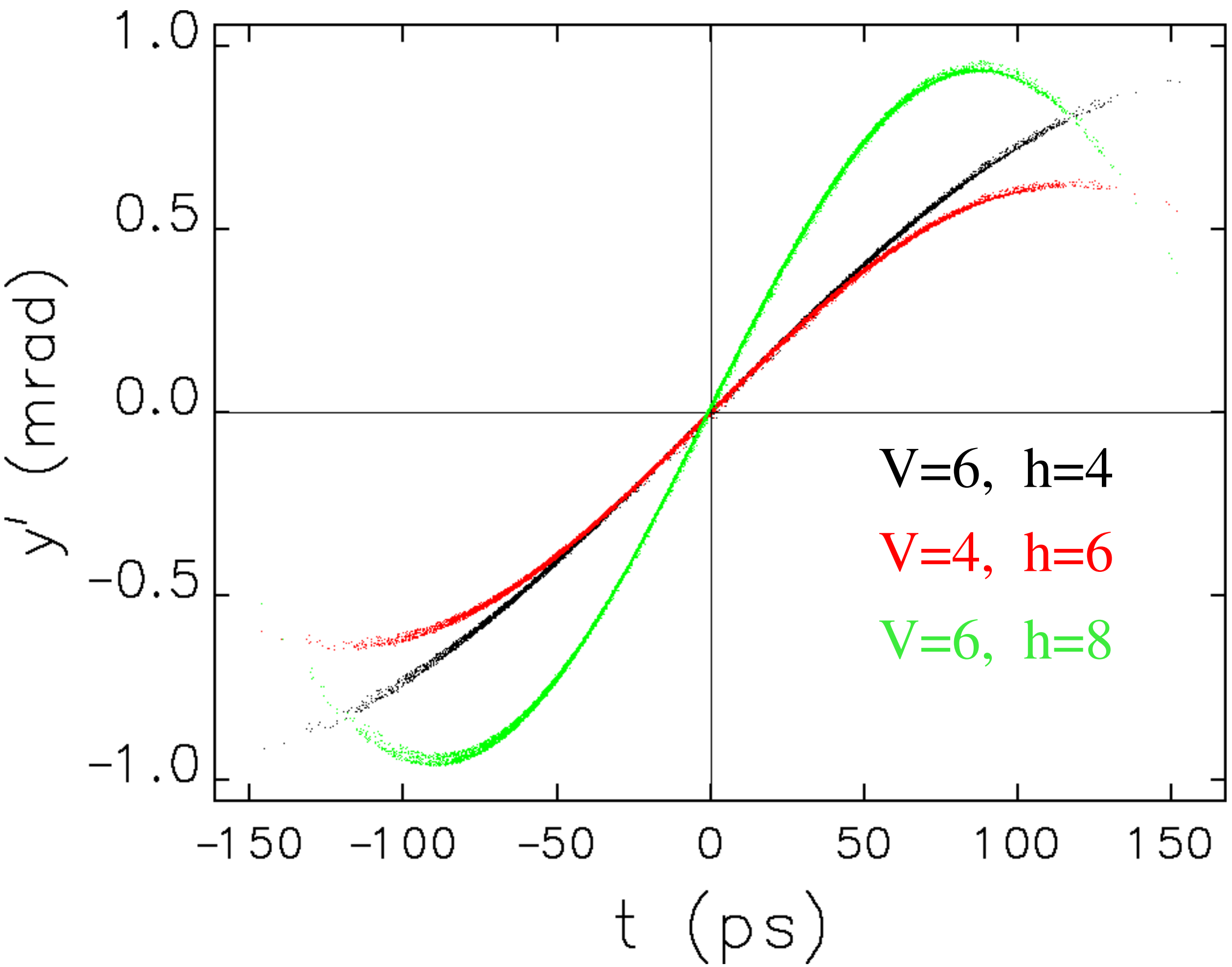
Beta function increase required to get the right phase advance

Helps compression by making divergence smaller

After V. Sajaev

Rf Curvature and Frequency Choice

- Can get the same compression as long as h*V is constant
- Higher V and lower h: more linear, 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
- h=8 (2800 MHz) limit from power source availability[1]
- V=6 MV limit from lifetime



[1]D. Horan

Causes of Emittance Degradation

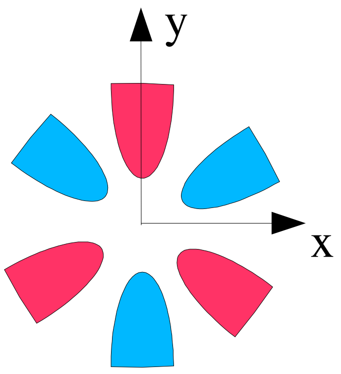
- Less than total kick cancellation will cause emittance increase
- Effects present in a perfect machine
  - Momentum compaction and beam energy spread
  - Sextupole effects
  - Chromaticity and beam energy spread
- Additional effects in an imperfect machine
  - Lattice errors
  - Lattice coupling between 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
- Errors are proportional to momentum offset, “should” cancel over one synchrotron oscillation period

Sextupole Effects

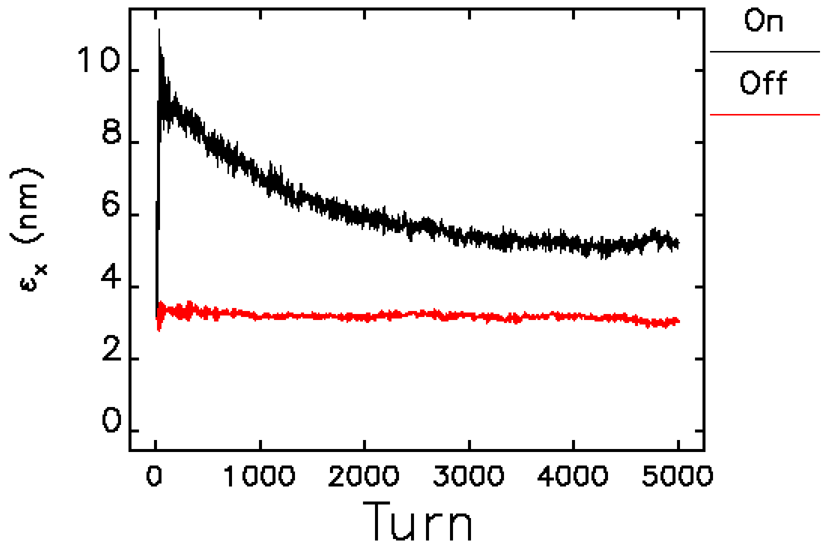
- Sextupoles are necessary
  - Correct chromatic focusing aberrations
  - Defeat beam instabilities
- Sextupoles have undesirable side-effects
  - Phase advance varies with amplitude
    - Kick cancellation varies with amplitude
    - Vertical emittance increases
  - Horizontal and vertical motion gets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



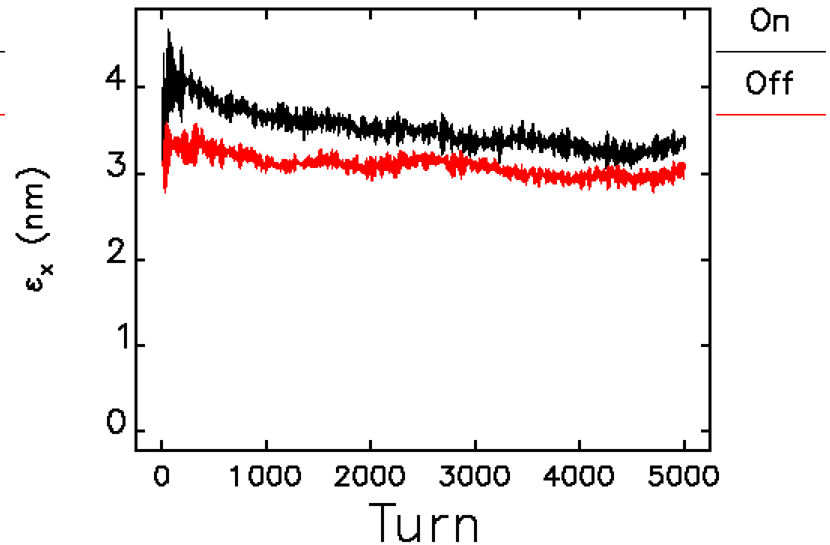
$$B_y = \frac{1}{2} m (x^2 - y^2)$$

$$B_x = m x y$$

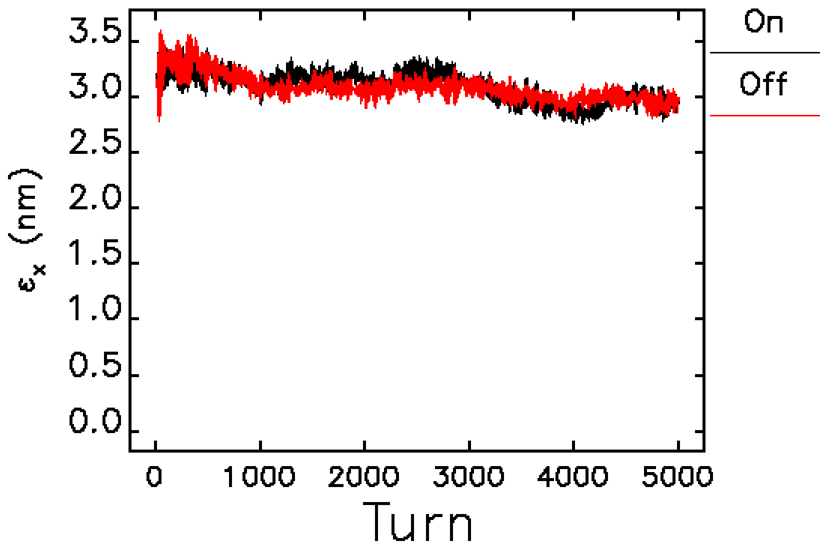
Interior Sextupoles and Horizontal Emittance



6 MV h=8



4 MV h=8

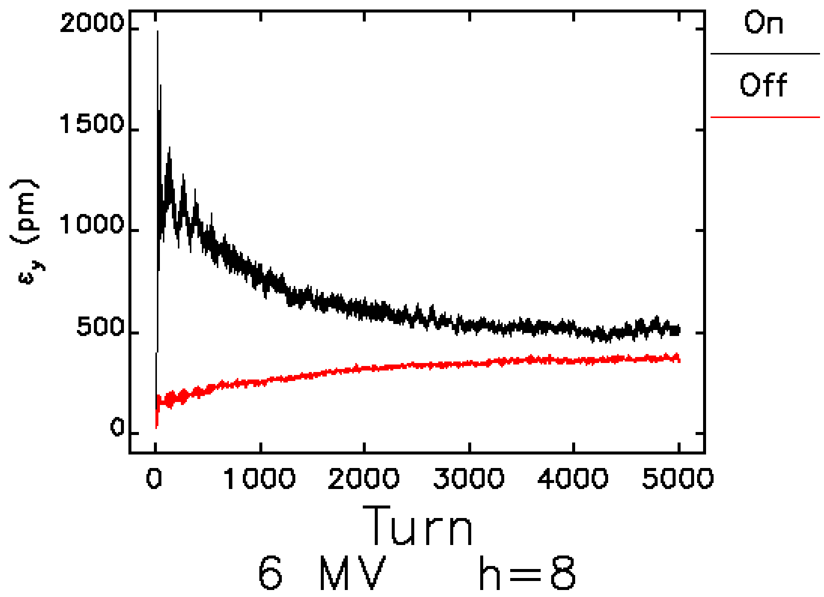


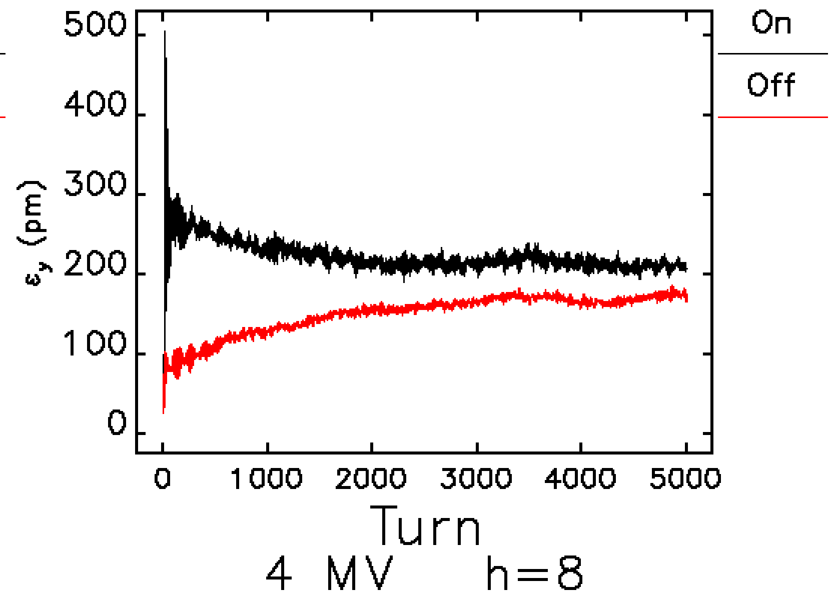
2 MV h=8

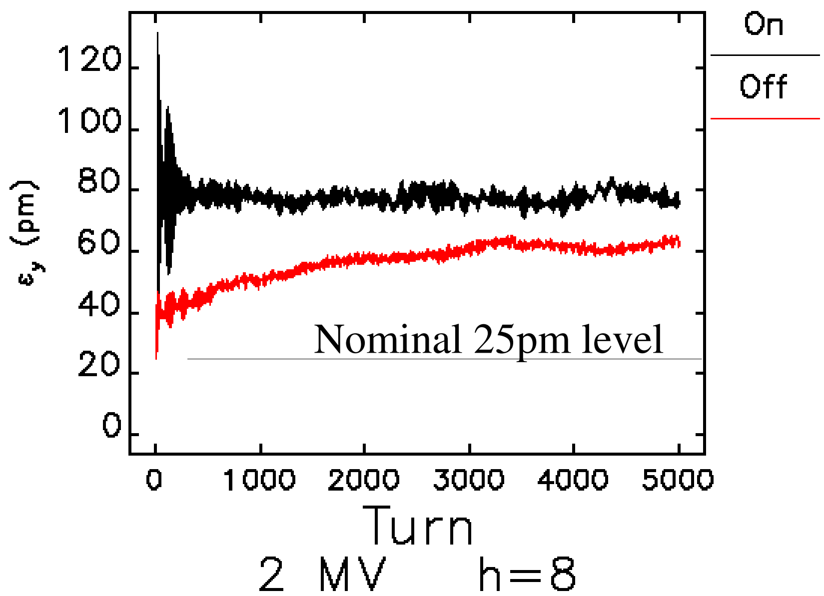
As expected, sextupoles-off is better

Radiation damping helps sextupole-on case

Interior Sextupoles and Vertical Emittance







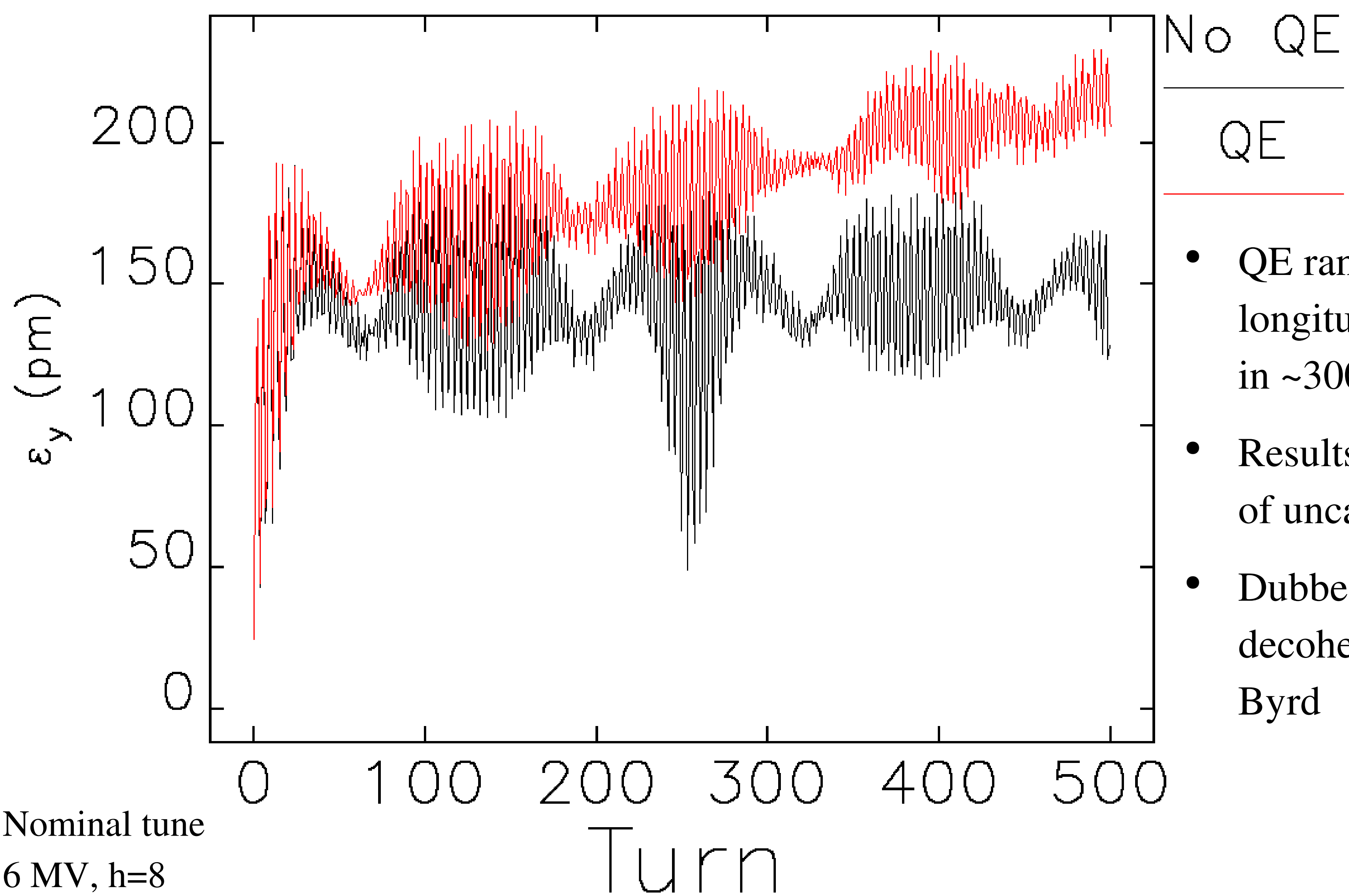
Damping helps sextupoles-on case

QE hurts sextupoles-off case via uncorrected local 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

Effect of Quantum Excitation



- QE randomizes longitudinal motion in ~300 turns
- Results in build-up of uncancelled kicks
- Dubbed “quantum decoherence” by J. Byrd

Nominal tune
6 MV, h=8
Interior sext. off

Optimizing Sextupoles

- Neither standard sextupole settings nor “sextupoles off” case is really acceptable
- Can try to minimize single-pass emittance growth
  - Allow **elegant** to vary the interior sextupoles
  - APS has individual supplies for each sextupole
- Important factors in making this work (V. Sajaev)
  - 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

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

- Maximum number of sectors probably limited by dynamic aperture reduction
- See V. Sajaev's talk later today.

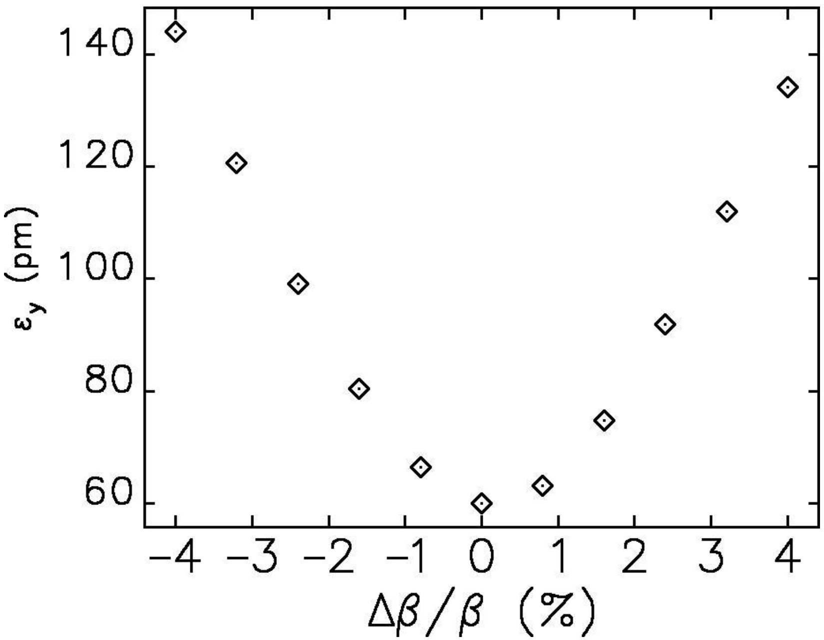
Content courtesy V. Sajaev, APS.

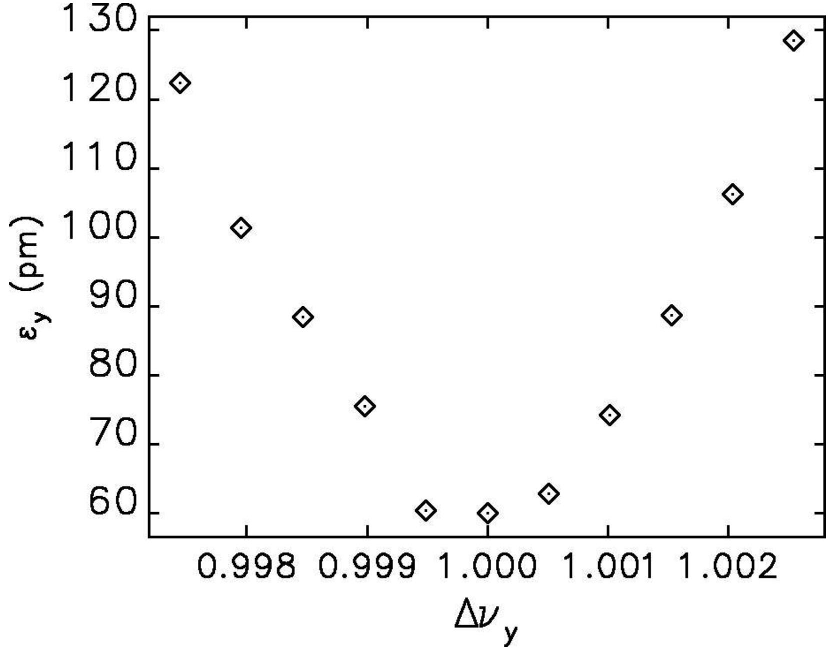
Error Sensitivities

- 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]



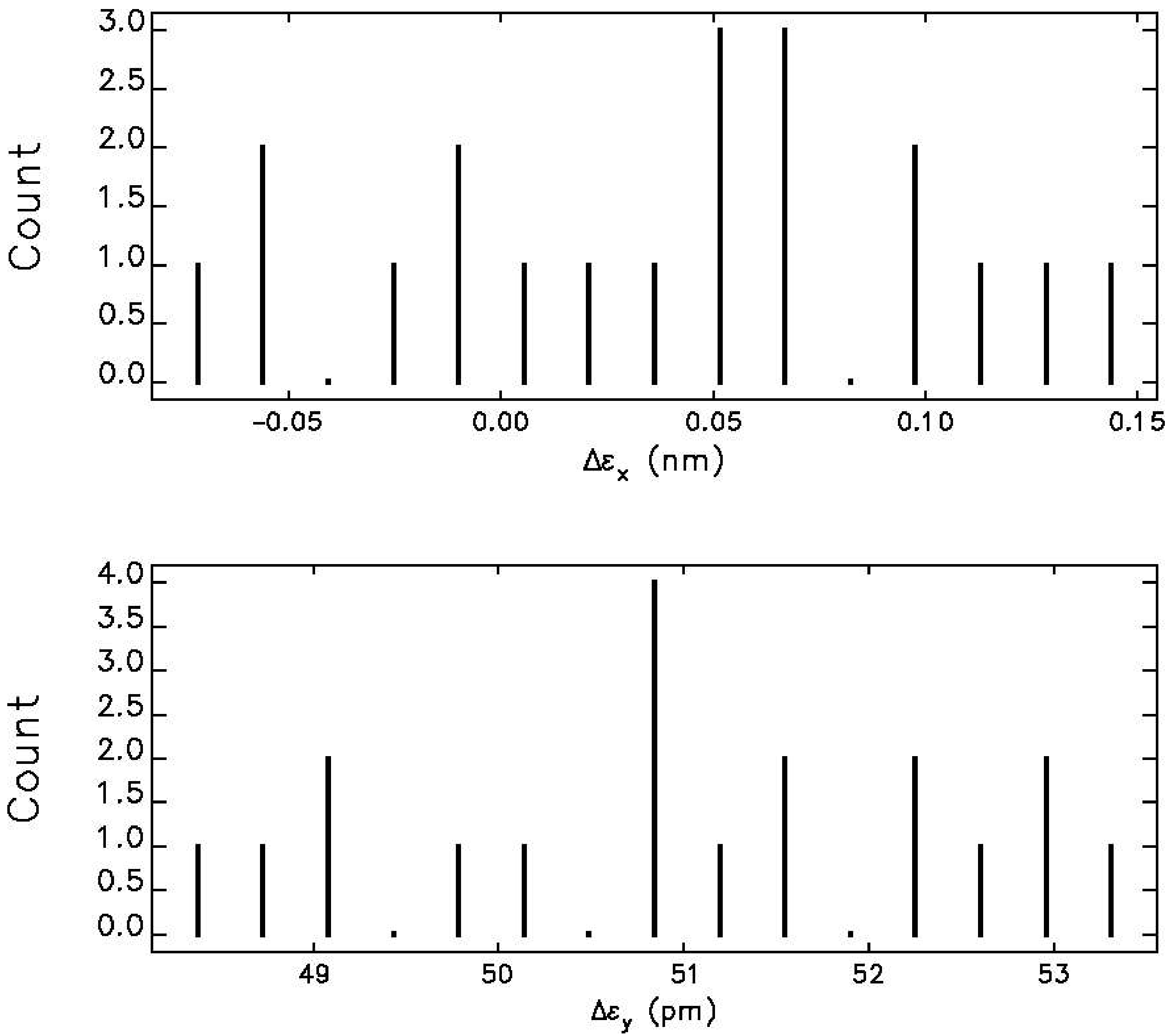


[1]V. Sajaev and L. Emery, EPAC 2002, p. 742

[2]L. Emery

Lattice Coupling Between Cavities

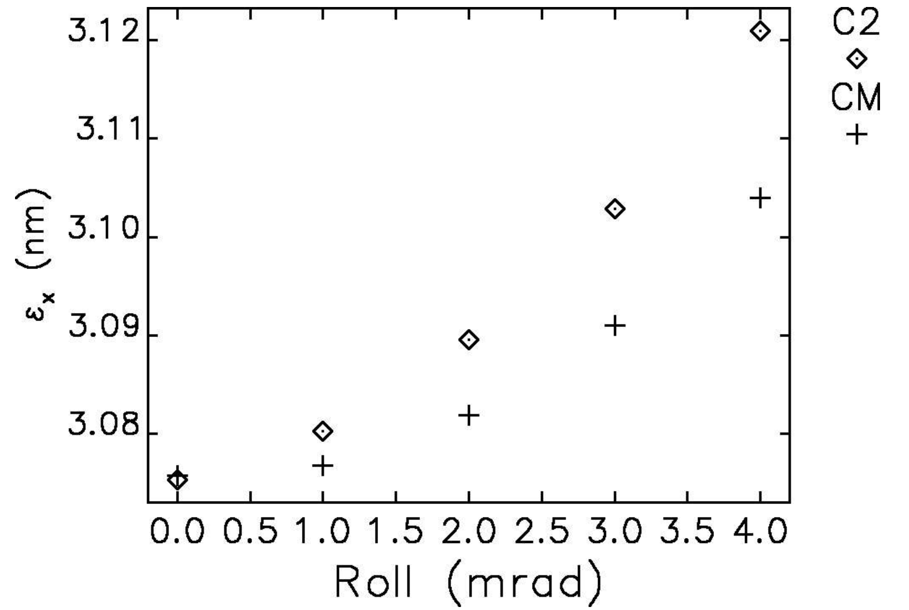
- May have quad and sextupole roll
- Roll is ~0.25 mrad rms[1]
- Performed random roll simulations with 20 seeds
- No coupling correction was employed

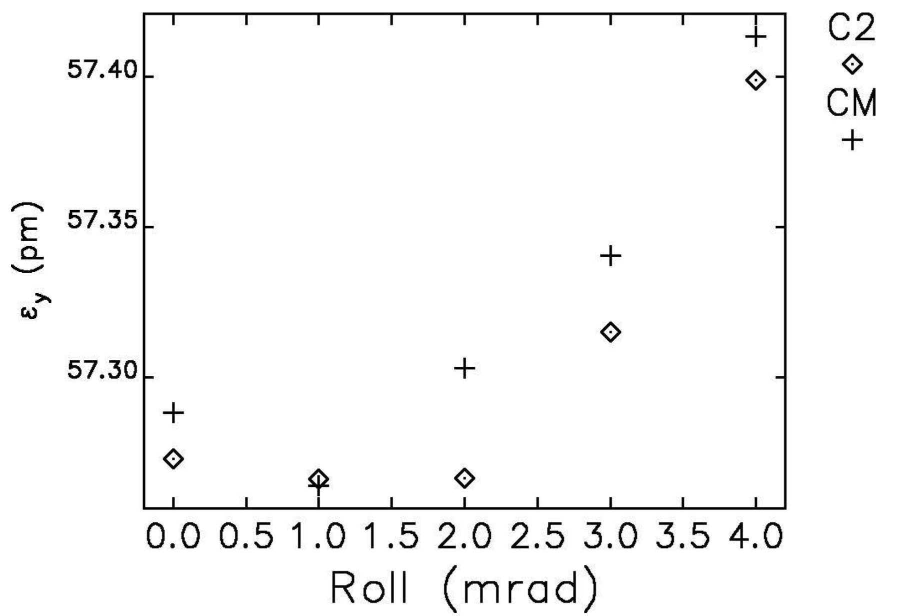


[1]H. Friedsam

Cavity Roll

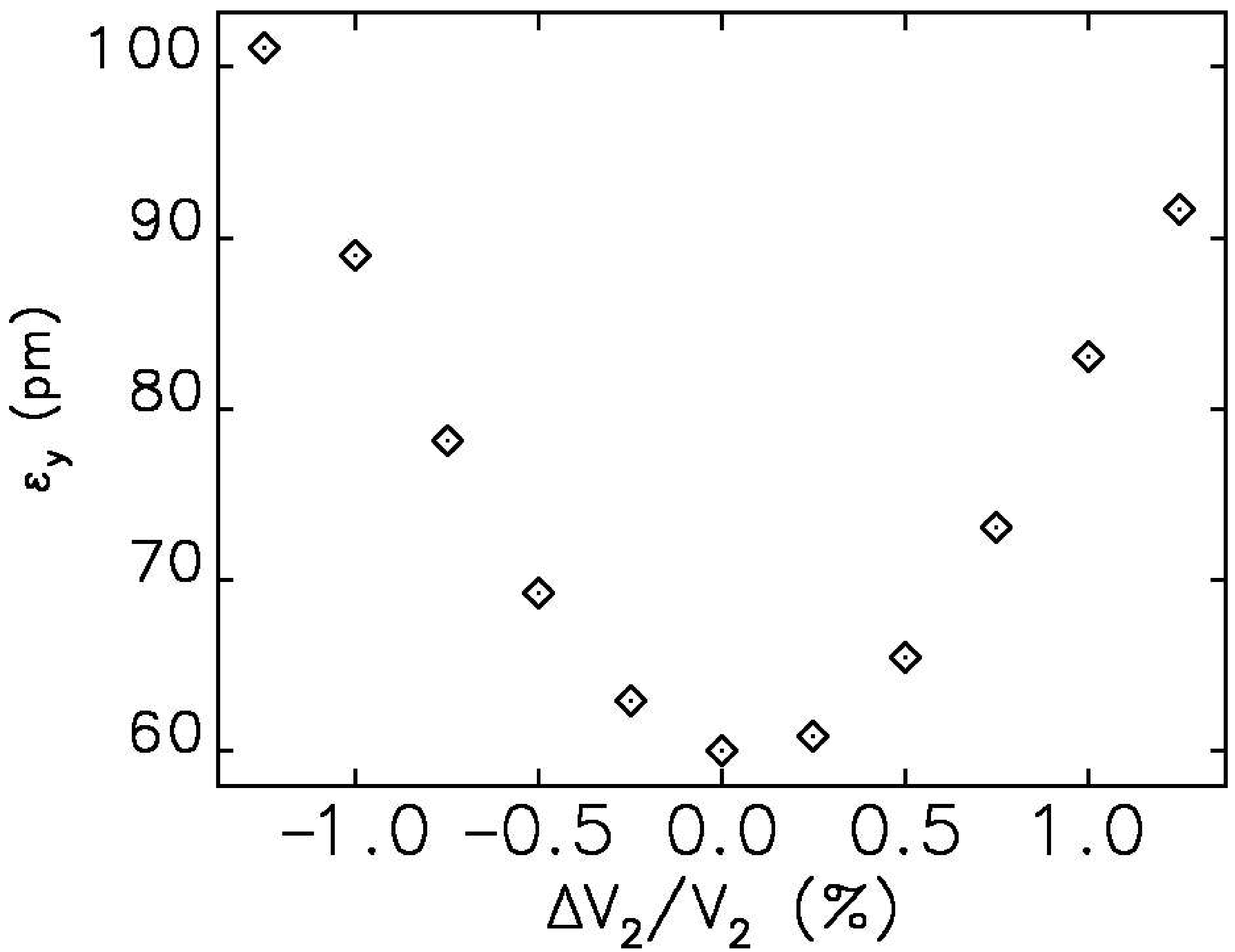
- Cavities may be rolled relative to machine vertical
- Simulated two cases
  - Cavities rolled the same amount (CM)
  - 2nd cavity only rolled (C2)
- Neither is a problem at few mrad level





Intercavity Voltage Error

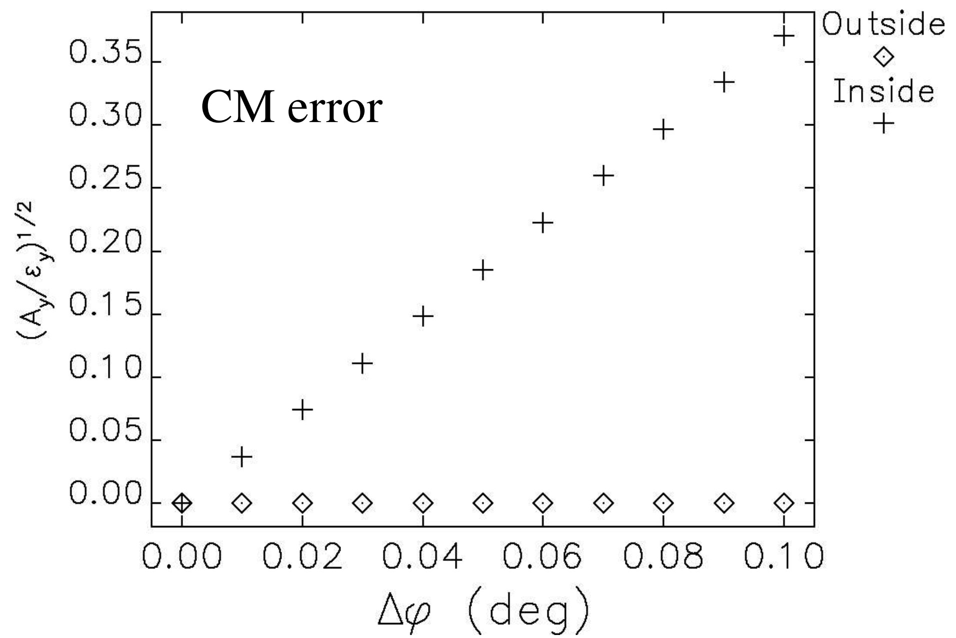
- Imparted errors to one of the cavities
- LCLS *pulsed* S-band system requires <0.1% rms voltage jitter[1]

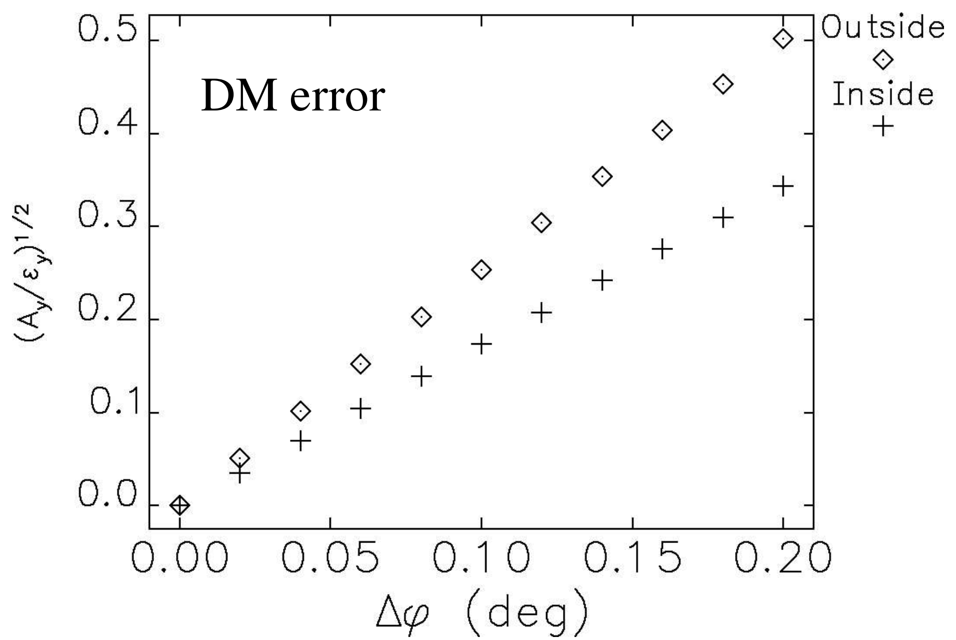


[1]LCLS Design Study Report, SLAC R-521 (1998).

Intercavity Phase Error

- Looked at common- and differential-mode errors
- Emittance growth not an issue, but orbit disturbance is
- SLAC *pulsed* S-band systems have <0.1 deg rms phase jitter[1]

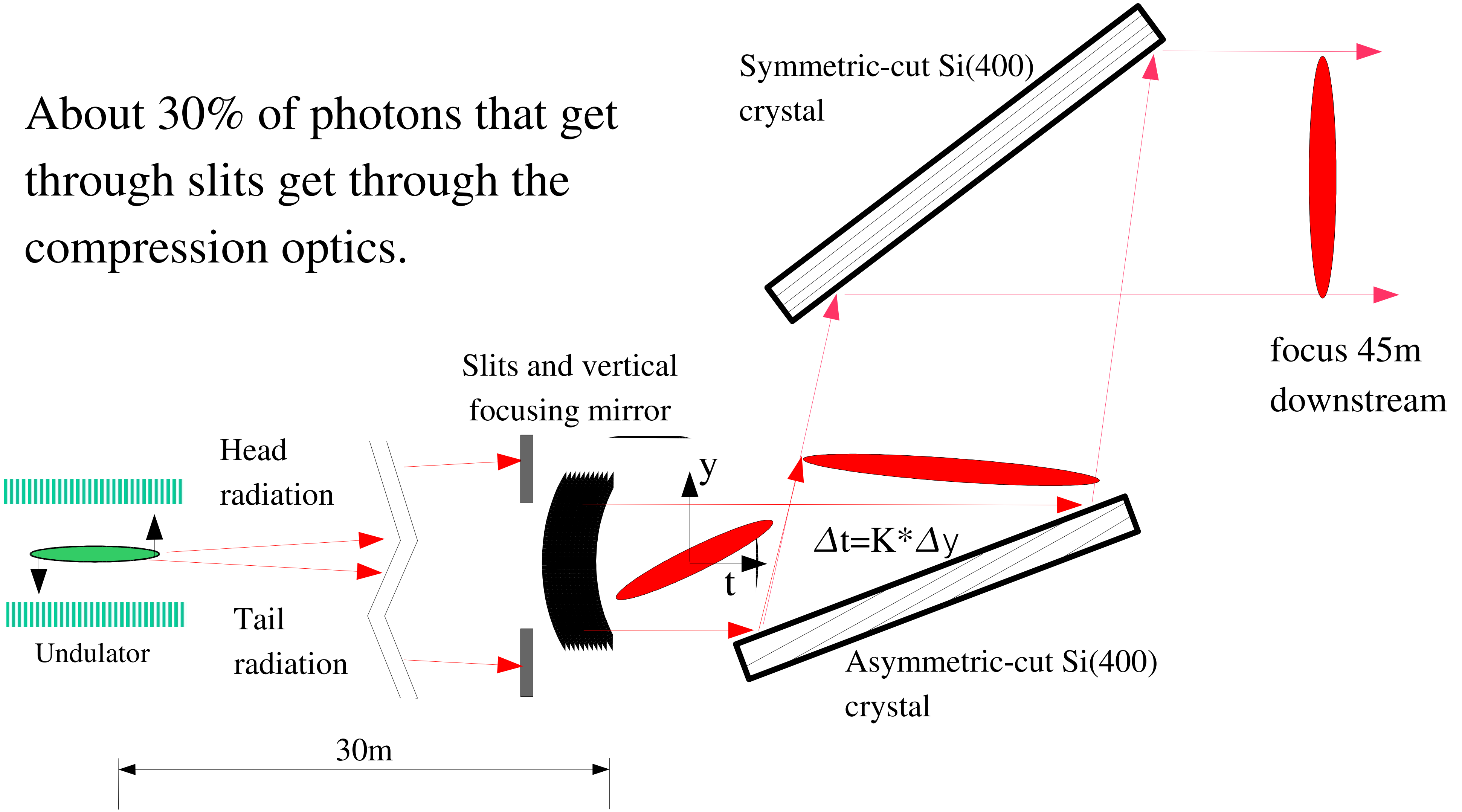




[1]R. Akre et al., SLAC PUB 9421.

Preliminary Optics Concept for 10 keV

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

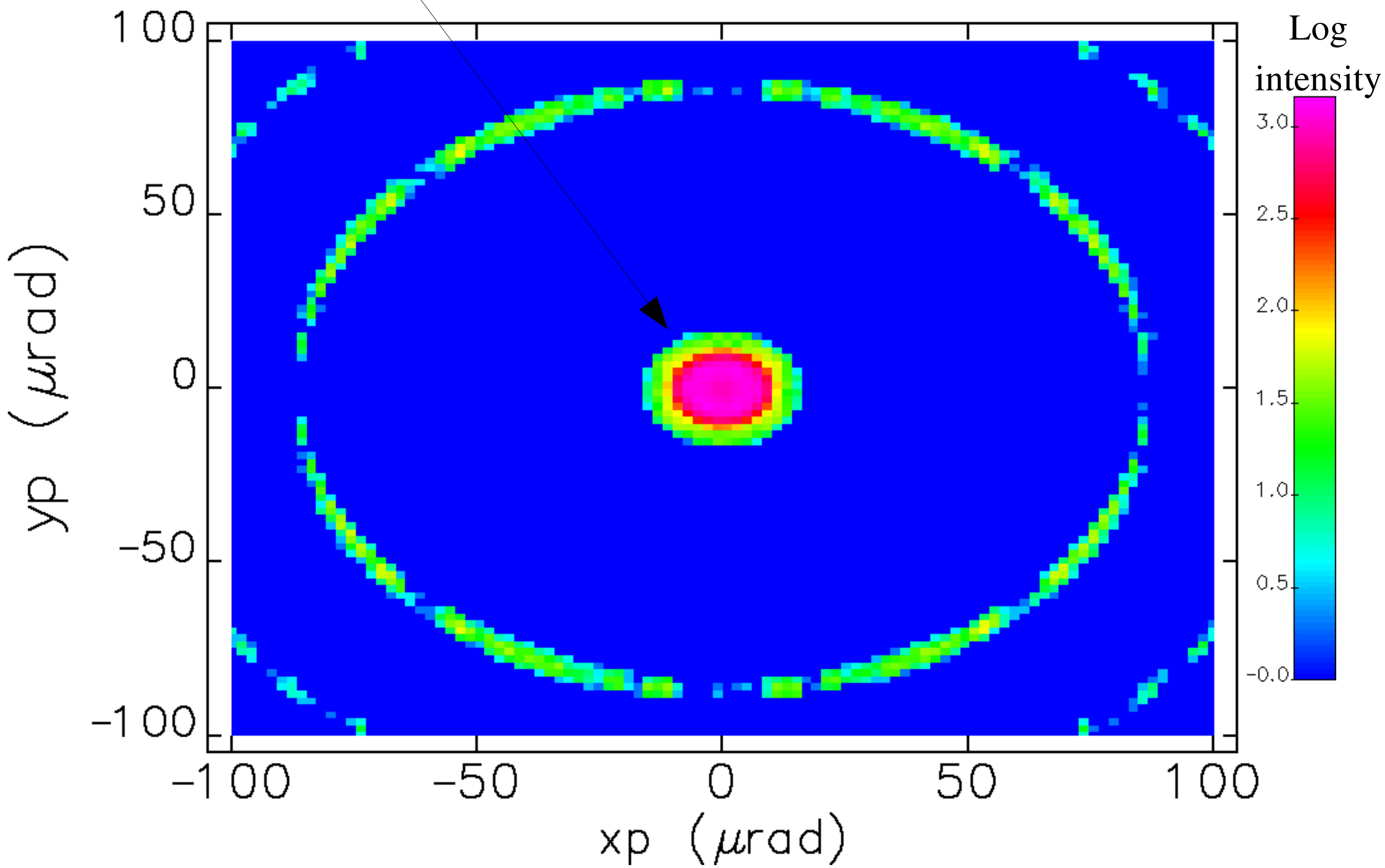


N.B.: Sketch not to scale. Angles are exaggerated.

After S. Shastri, APS

Undulator Radiation Pattern

Central cone opening angle ~5 urad rms



Data courtesy R. Dejus

For estimates, use

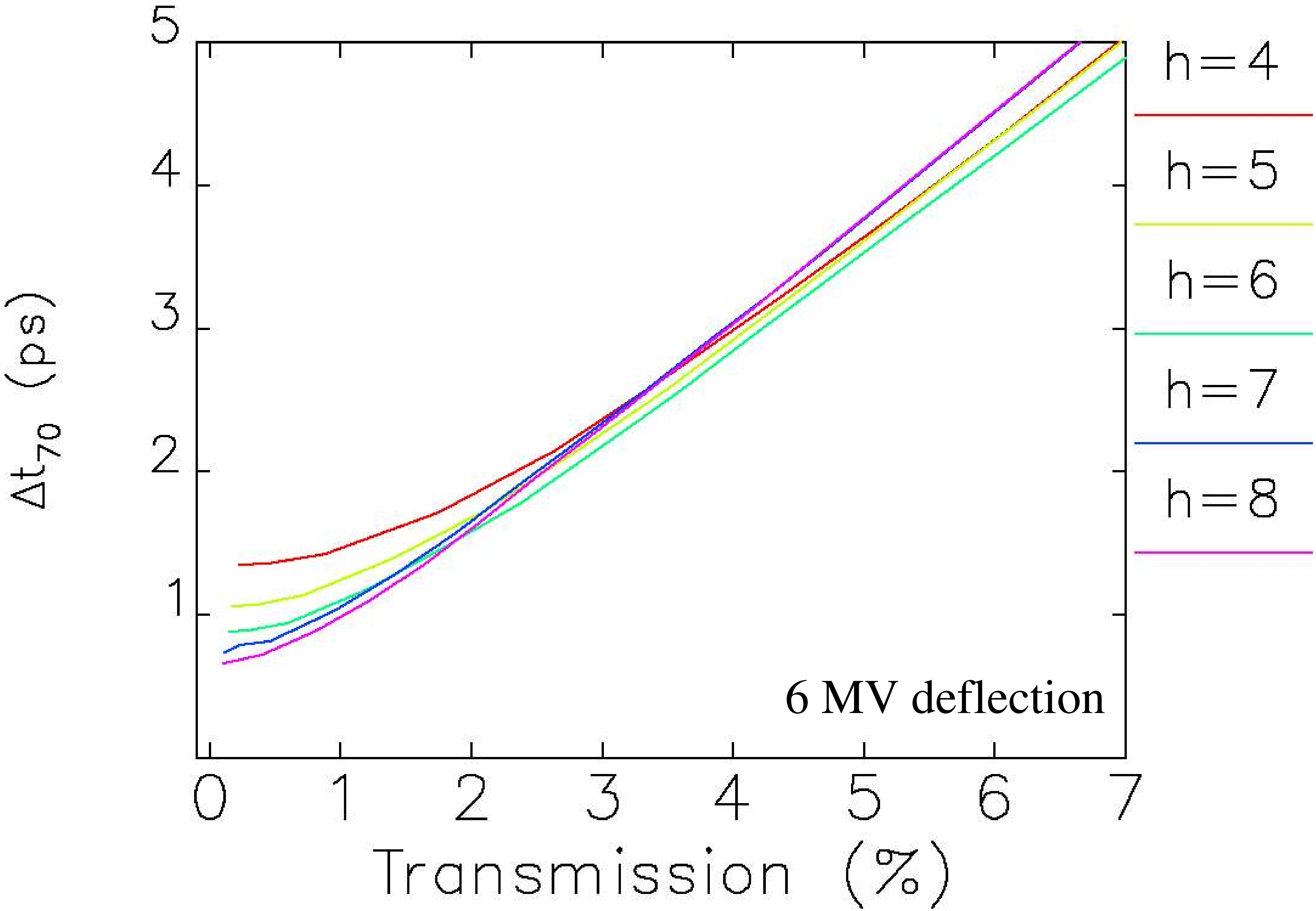
$$\sigma_\theta = \sqrt{\frac{\lambda}{2L}}$$

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)

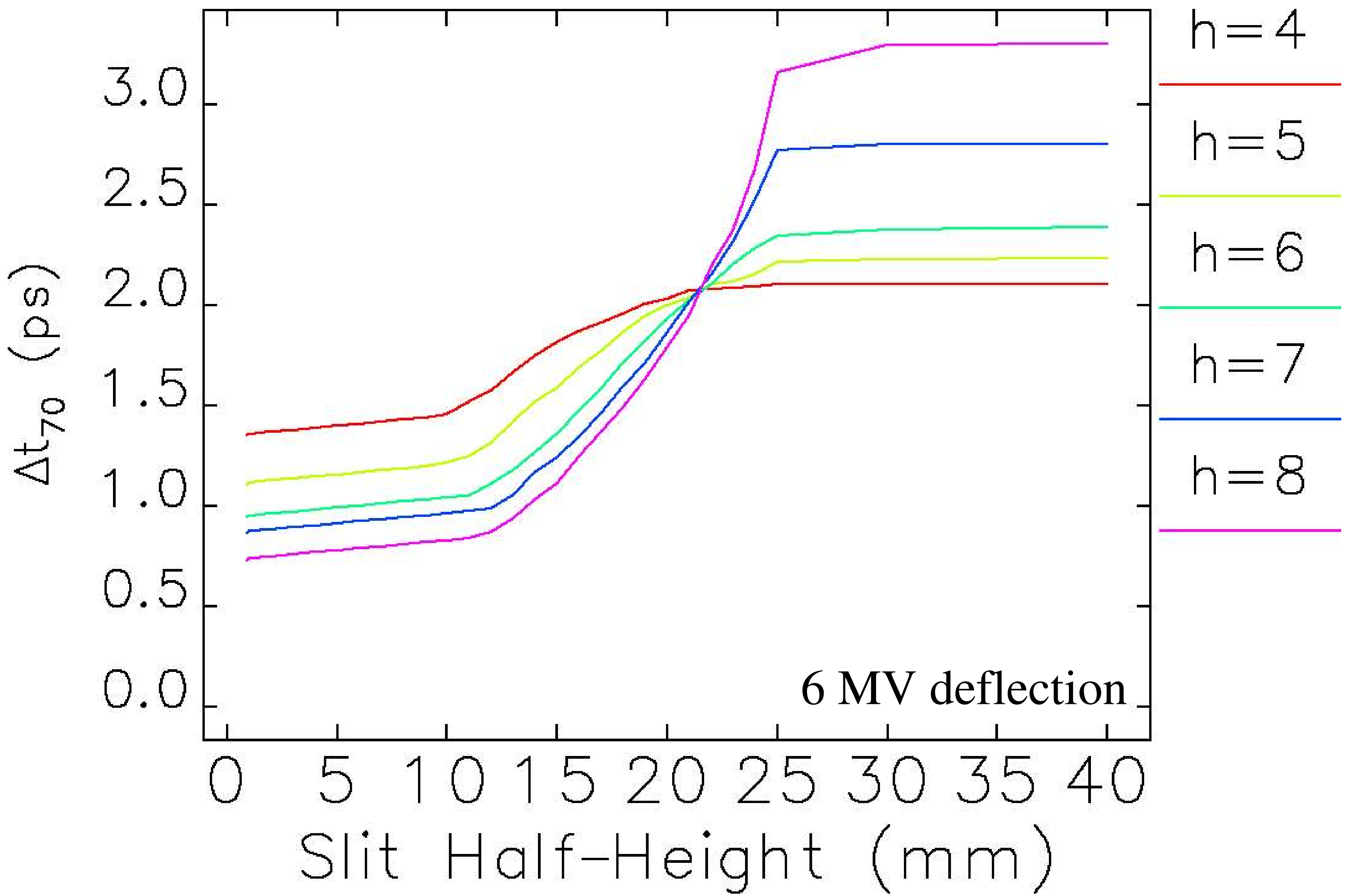
Slicing Results for 10 keV, UA



Compression Simulation

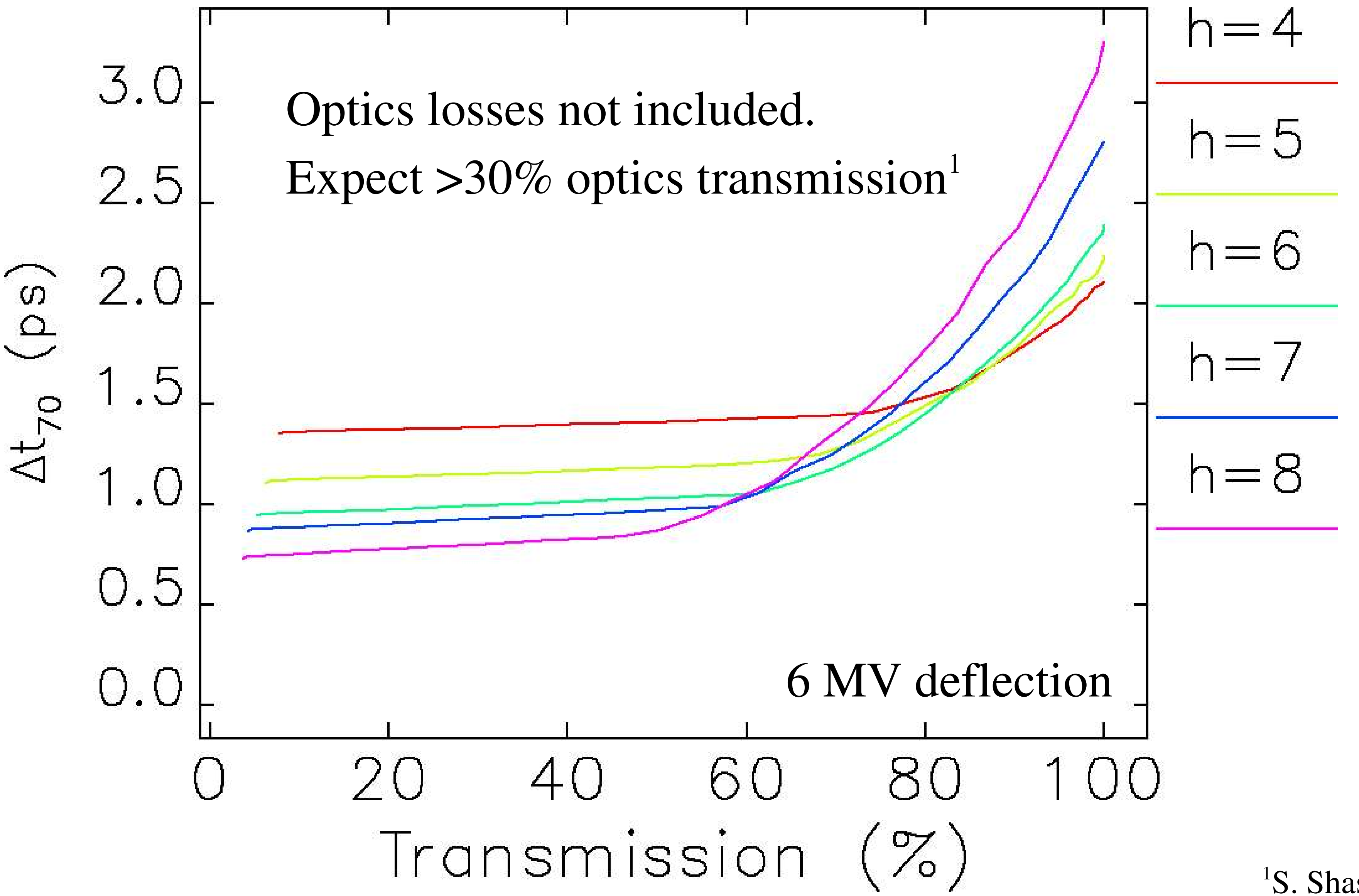
- Generate one photon for each electron by adding samples from the distribution function
- Use **elegant** to optimize compression through system consisting of
  - Drift (30 m)
  - Vertical slits
  - "Compression matrix" (unit matrix except for variable R_{53})
  - Vary R_{53} to minimize time-spread of central 70% of photons
- Repeat optimization for various slit spacings

Compression Results for 10 keV, UA[1]



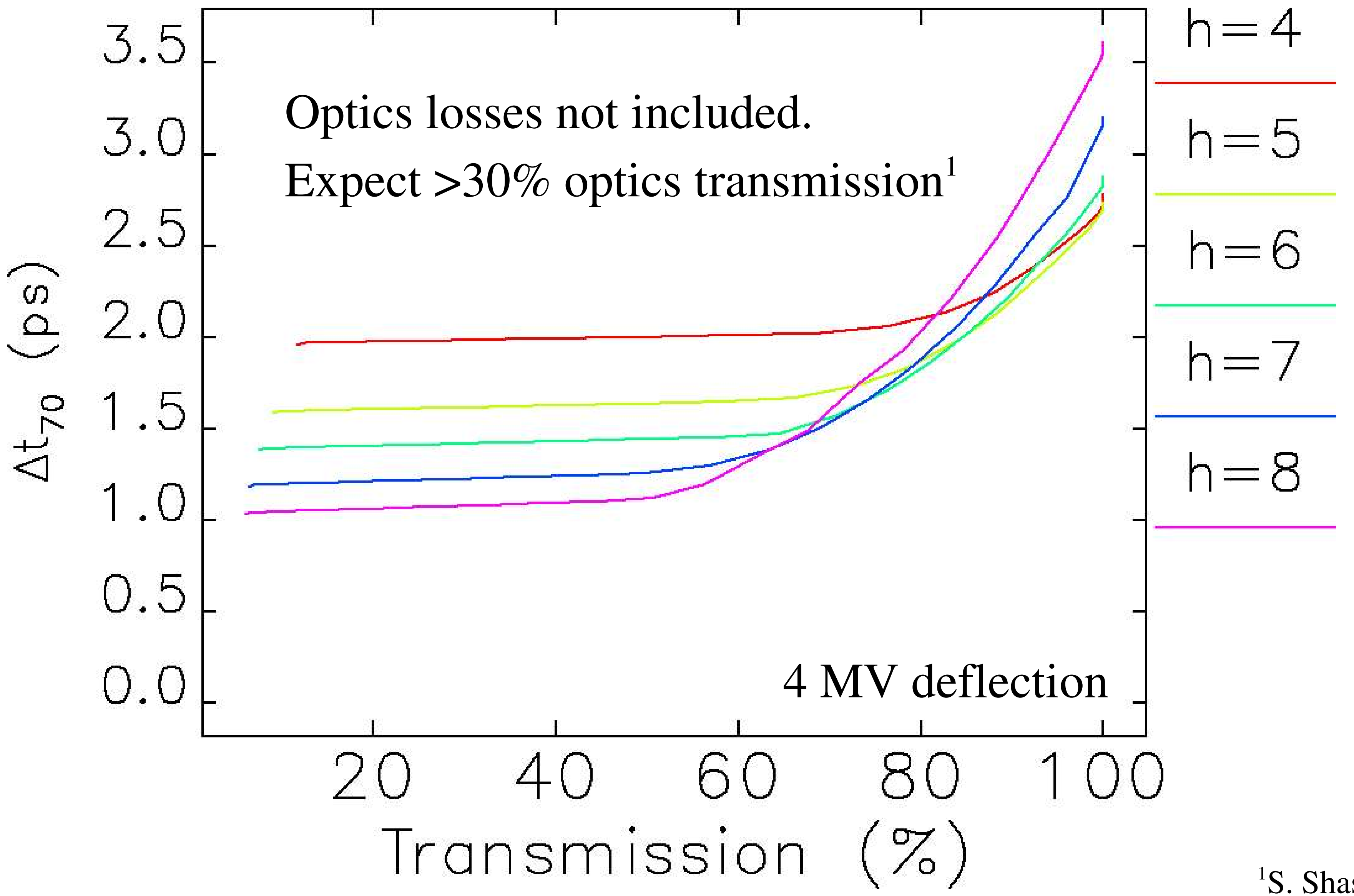
[1] 3.3cm period, 2.4m length

Compression Results for 10 keV, UA



[1]S. Shastri

Compression Results for 10 keV, UA



[1]S. Shastri

Is a Pulsed System Better[1]?

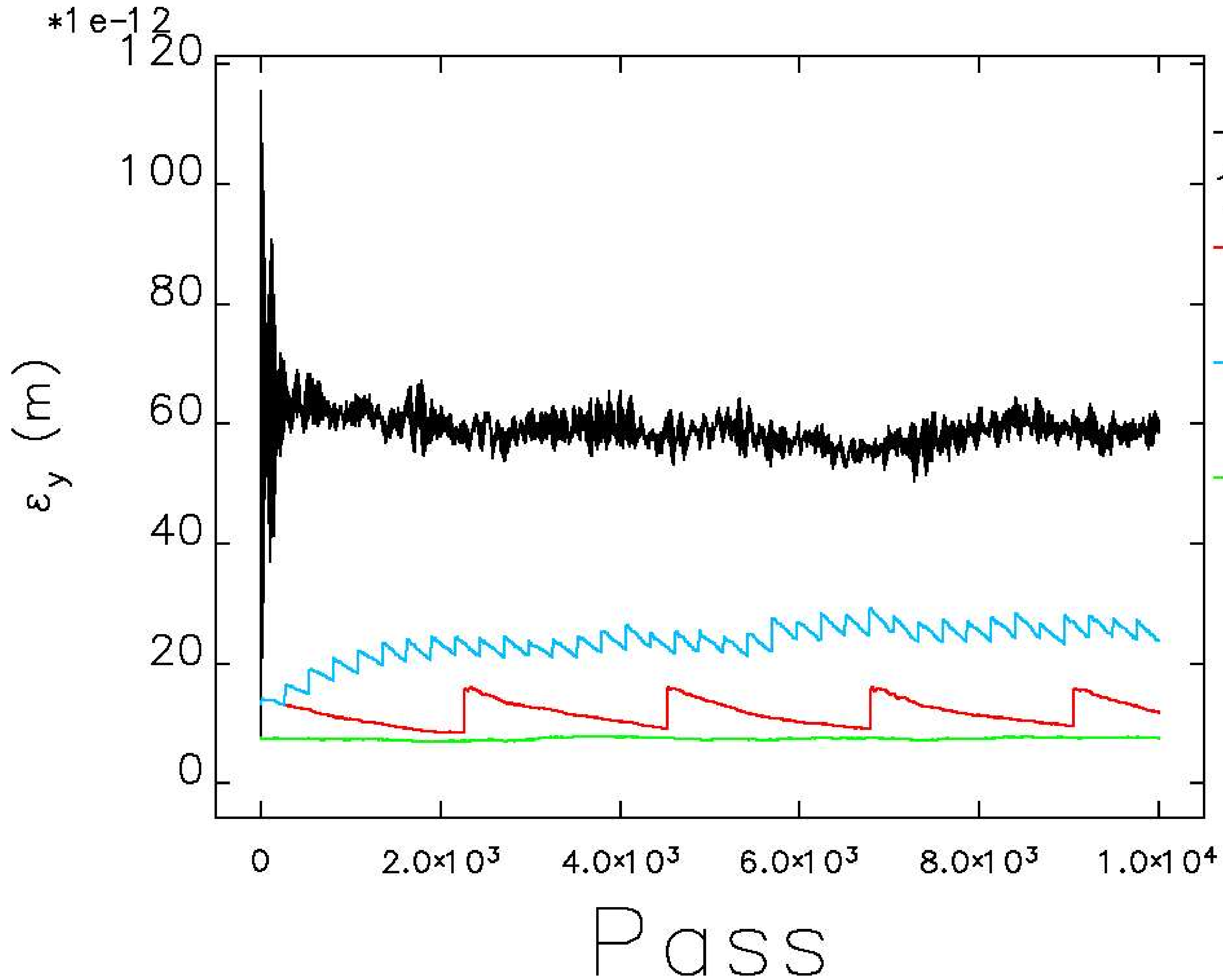
- Most pump-probe experiments use ~1kHz lasers, don't use continuous beam
- Many experiments run from very short to very long time scales
  - Having a chirped pulse just throws away intensity when looking at long time scales
- A pulsed chirping system lets the user choose between chirped and unchirped radiation

[1]P. Anfinrud

Pulsed System Considerations

- Could charge and discharge cavities at 100~1000 Hz
  - Must be a room temperature system
- Advantages over superconducting
  - Shorter development time
  - Significantly cheaper
  - Less emittance growth
- 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

Comparison of Emittance Blowup

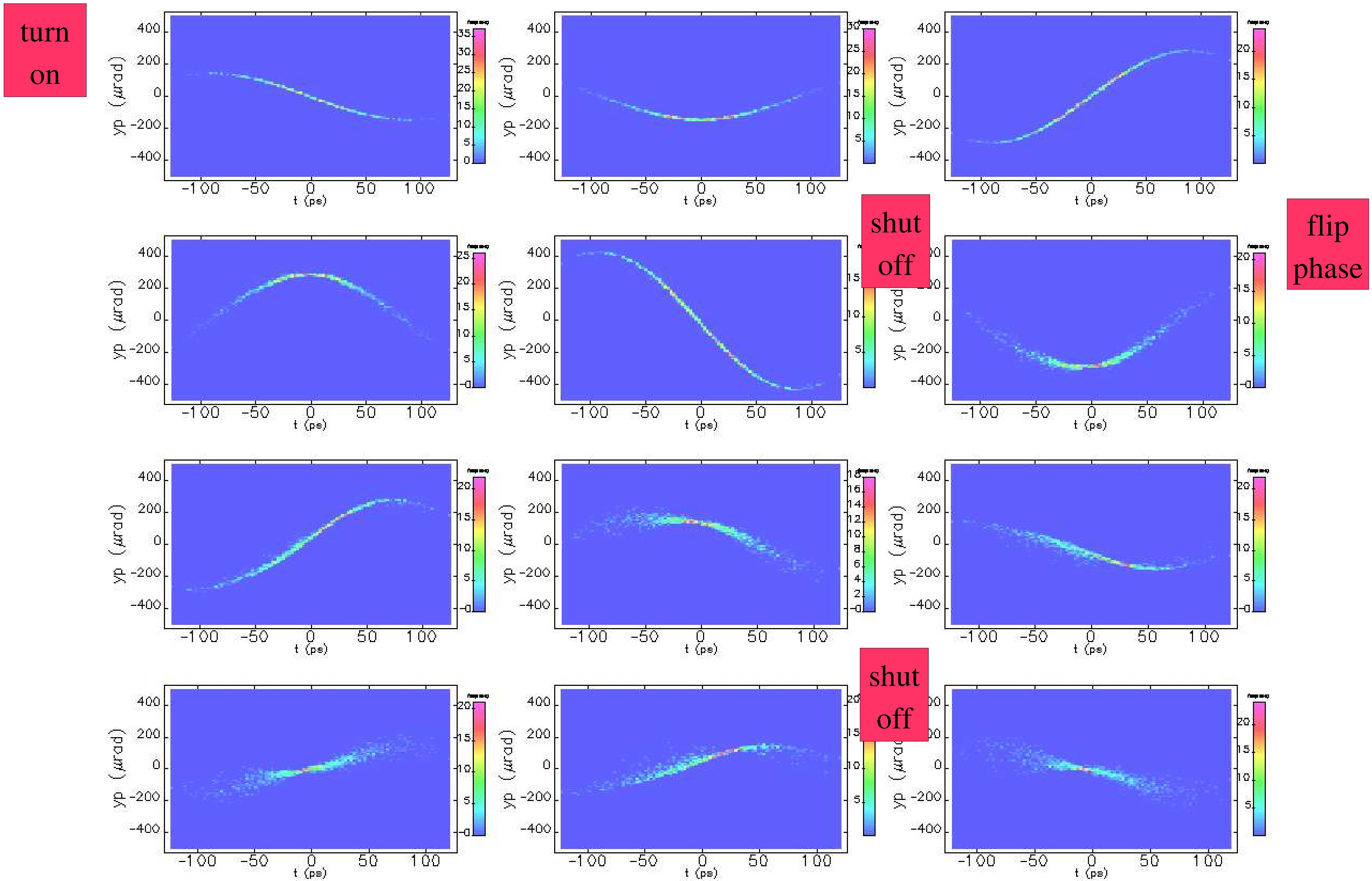


A Low-Cost Proof-of-Concept

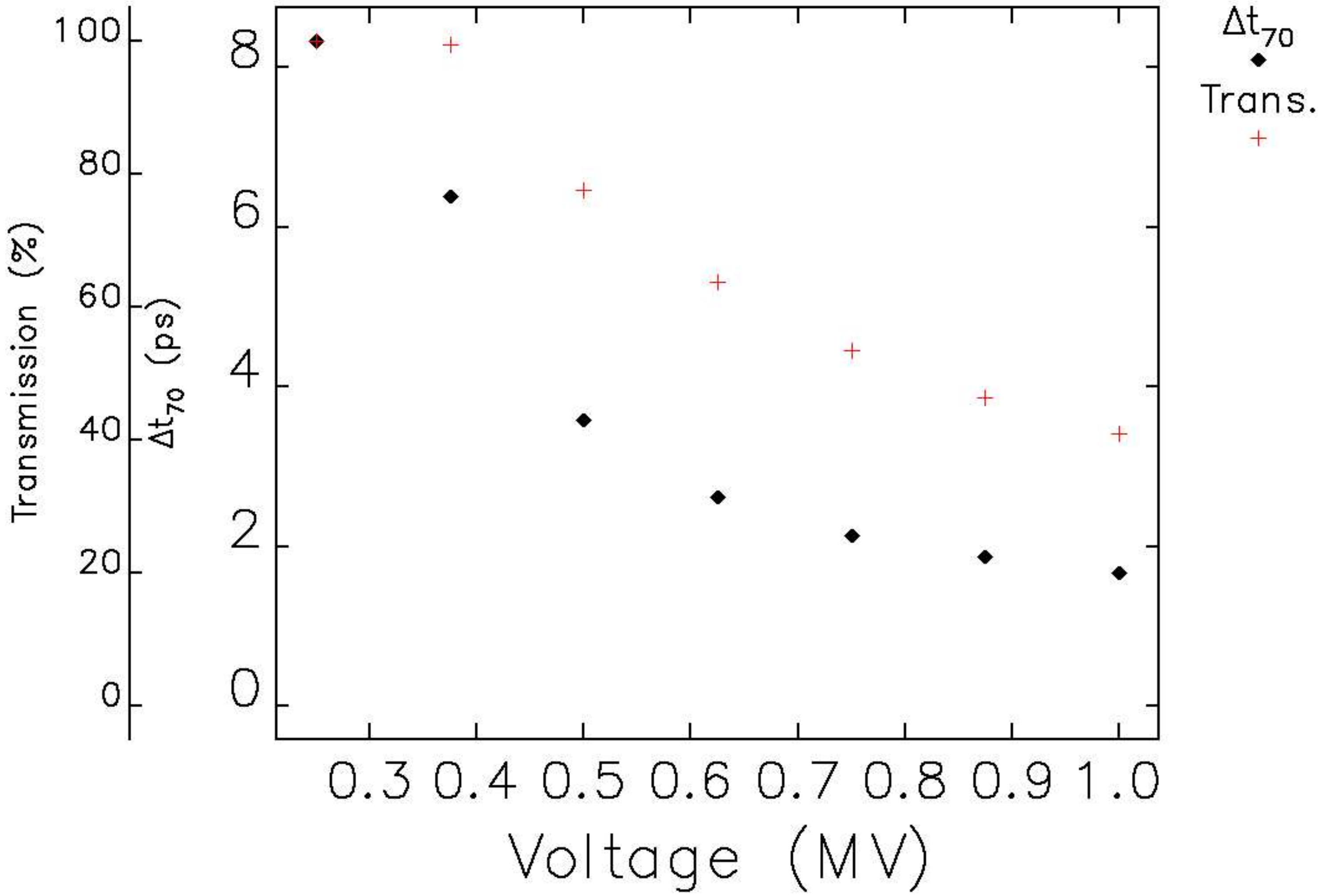
- If we operate near the vertical integer resonance, we can build up a large global chirp using one cavity
- More practically[1], set vertical tune to n+¼ and the chirp cavity frequency to $0.25*f_{rev}$ from the harmonic.
- 25~100 kW of rf power and a 1-m structure give ~2 ps FWHM pulses.
- Limited to about 15 Hz by need to damp blown-up vertical emittance.
- Allows development and testing of optics and experiments

[1] W. Guo

y'-t Phase Space Evolution



Compression Results



Summary

- Zholents' scheme as applied to APS has been studied extensively
- Picosecond x-ray pulses appear feasible with 50~70% transmission through slits
- 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
- Case for a pulsed system is plausible
- A “budget-minded” proof-of-concept is possible