Beam Dynamics of Chirp Scheme in Storage Rings

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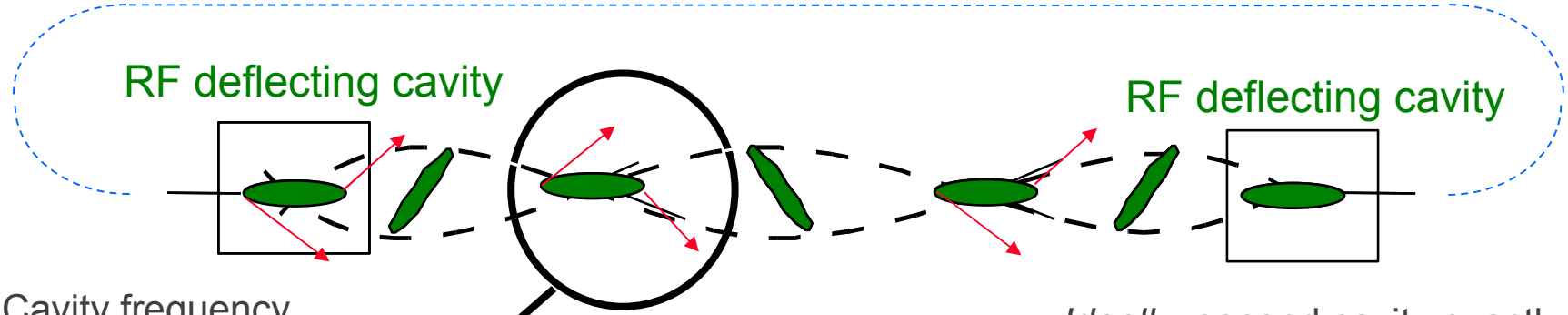
Outline

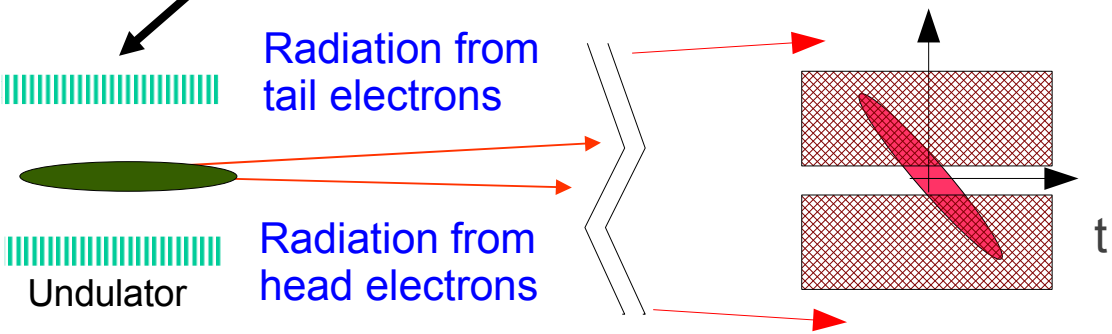
- Review of Zholents' concept
- Basic analysis of x-ray slicing
- Configuration options
- Choice of rf frequency and voltage
- Emittance degradation mechanisms (brief)
- Modeling methods
- Tolerances
- Undulator photon beam modeling and predictions
- Bending magnet modeling and predictions
- Other applications
- Conclusion

Zholents' Transverse Rf Chirp Concept[1]



Cavity frequency is harmonic *h* of ring rf frequency

Ideally, second cavity exactly cancels effect of first if phase advance is n*180 degrees: “outside” users nominally unaffected



Pulse can be sliced or compressed with asymmetric cut crystal

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

[1]A. Zholents *et al.*, NIM A 425, 385 (1999).

Estimating X-ray Pulse Duration

- X-ray pulse duration can be estimated assuming gaussian distributions[1]

Electron beam energy

$$\sigma_t \approx \frac{E}{\frac{\partial V}{\partial t}} \sqrt{\frac{\beta_{id}}{\beta_{rf}}} \sqrt{\frac{\epsilon_y}{\beta_{id}} + \sigma^2_{y',rad}}$$

For 4 MV, 2.8GHz (h=8) deflecting system, get ~0.6 ps

Rate of change of deflecting voltage

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

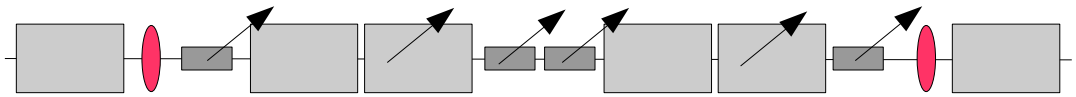
Divergence due to undulator (typ. ~5 μrad)

- Small electron beam vertical emittance is important
- Electron bunch length affects intensity, emittance growth

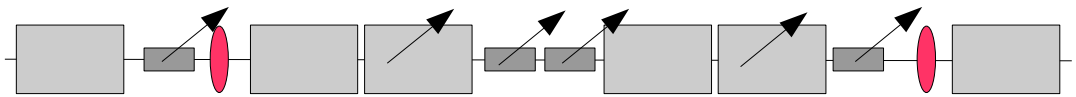
[1]M. Borland, OAG-TN-2005-026, 9/21/05.

Configuration Options for APS Upgrade

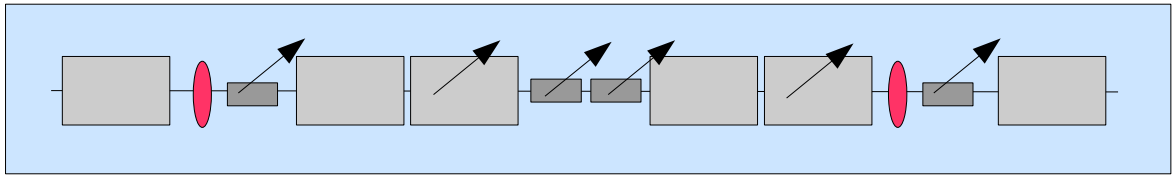
Long SS 6ID | Short SS 7ID | Long SS 8ID



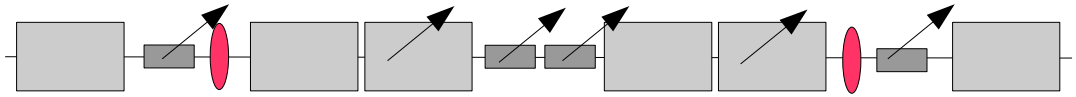
2 sector spacing
4 ID + 2 BM



2 sector spacing
3 ID + 2 BM



2 sector spacing
3 ID + 2 BM



2 sector spacing
2 ID + 2 BM

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

Limits on Deflecting Voltage V_{cc}

- Need sufficient voltage slope

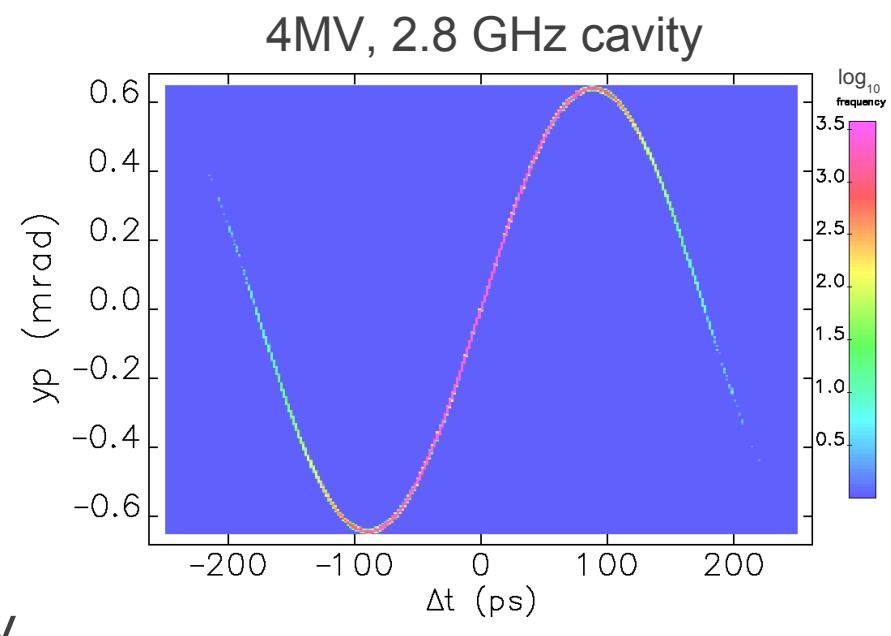
$$\left(\frac{\partial V}{\partial t}\right)_{t=0} = 2\pi h f_a V_{cc}$$

- Several limits on voltage
- Cavity surface field limits
- Number of cells we can fit in (half of) straight section
  - Impedance of cells
  - Difficulty of extracting LOMs and HOMs
- Don't want to scrape beam on ID vacuum chamber
  - Allow ~0.1mm margin for steering and quantum lifetime
  - Limits for our 7mm chamber gap[1]
    - 2.5 MV peak for outside placement
    - ~4.5 MV peak for inside placement

[1]V. Sajaev, private communication.

Choice of Deflecting Frequency hf_a

- Electron bunch length up to 50 ps rms
  - Higher frequency
    → stronger perturbation of beam
  - Higher frequency
    → more particles at next zero crossing
  - Lower frequency
    → reduced chirp for same peak voltage limit
- Other considerations
  - Availability of rf sources
  - Short-range wakefields worse for higher frequency
- Combining these considerations led us to 2.8 GHz (h=8)



Emittance Degradation[1]

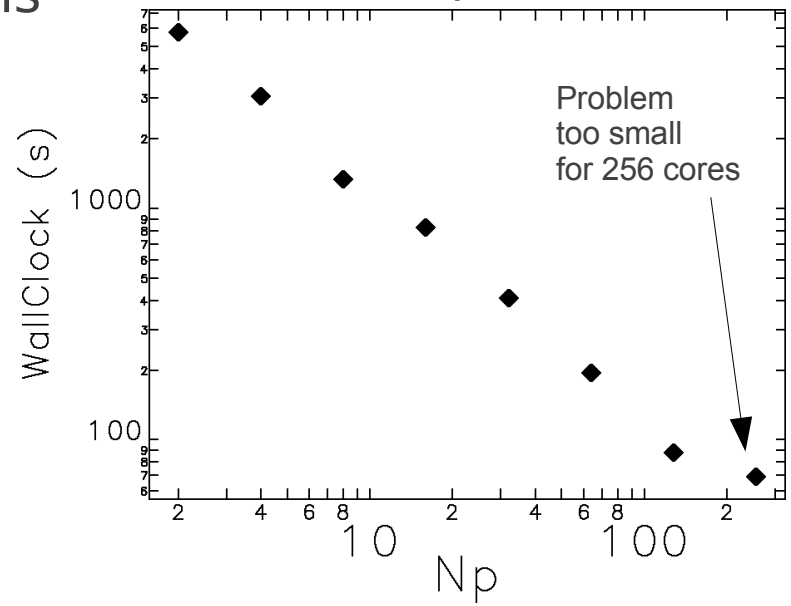
- Second cavity can't *exactly* cancel effect of first
  - Vertical emittance will grow
  - Large vertical motion may be transferred to horizontal plane
- Effects present in a perfect machine
  - Non-zero momentum compaction, chromaticity, and energy spread
  - Strong sextupoles between cavities
  - More detail in V. Sajaev's talk on Friday
- Additional effects in an imperfect machine
  - Lattice errors
  - Rolled elements between cavities
  - Roll of cavities about beam axis
  - Rf phase and voltage errors

[1]M. Borland, PRSTAB 8, 074001 (2005).

Simulation methods

- Use parallel elegant[1] for simulations
  - Typically 10~60 cores
  - Still need to economize CPU time
- Model dipoles with first-order matrix (ρ=38.9m)
- Other magnets: kick elements
- Synchrotron radiation: single lumped element for average loss and quantum excitation
- Accelerating cavities
  - Single zero-length lumped element, exact time dependence
- Potential well distortion important in APS
  - Bunch lengthening of 50% to 150% for typical fill patterns
  - Mock-up by adjusting accel. cavity harmonic and voltage
    - Match measured bunch length for various fill patterns
    - Match expected bucket half-height of at least 2.0%

Parallel elegant scaling test for 1M particle*turns



[1]Y. Wang *et al.*, AIP 877, 241 (2006).

Deflecting cavity model

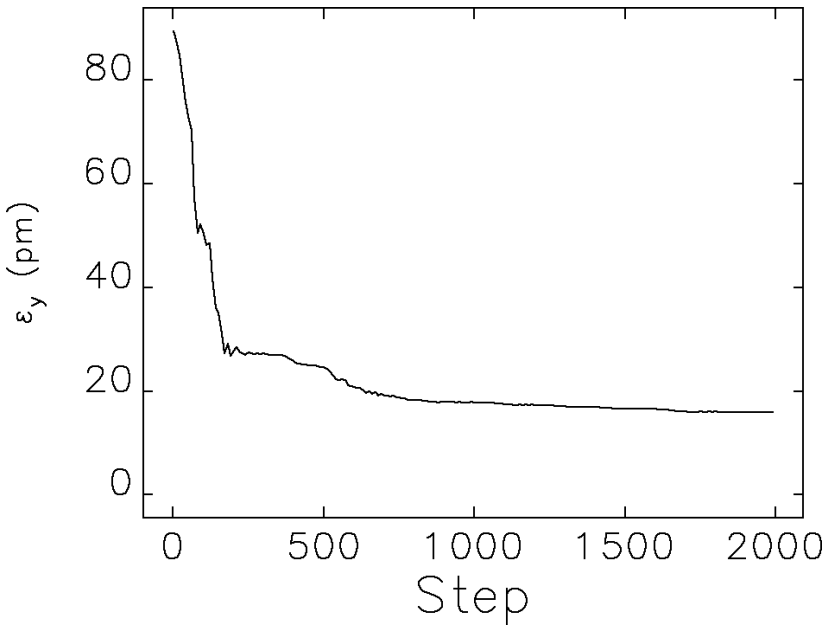
- Model cavities as multiple cells
  - 10 cells per cavity (G. Waldschmidt)
    - Pillbox cavities of length λ/2
    - Center-to-center spacing of 3λ/2
  - Phasing in groups of 5 to suppress position/angle offsets
  - Betatron matching to center of assemblies
- Model deflecting cavities as TM-like mode
  - Kick model with transit time effects
  - Exact time dependence
  - Radius-independent deflection
    - Results from combination of TE- and TM-like fields[1]
  - Longitudinal electric field included to satisfy Maxwell's equations

$$\vec{B} = B\hat{x}\cos\omega t \qquad \vec{E} = B\hat{z}y\omega\sin\omega t$$

[1]M. Nagl, tesla.desy.de/fla/publications/talks/seminar/FLA-seminar_230904.pdf

Optimizing Sextupoles

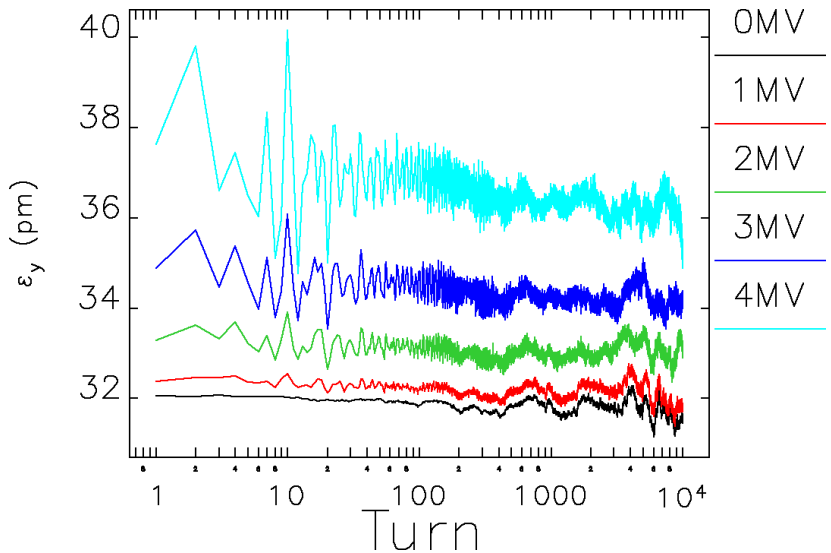
- Sextupoles are the dominant emittance growth source
- We can tune the sextupoles to minimize emittance growth[1]
  - Use optimizer in **Pelegant** to vary interior sextupoles and minimize the single-pass growth
- There are pitfalls to this approach[2,3]
- More detail is presented in V. Sajaev's talk on Friday

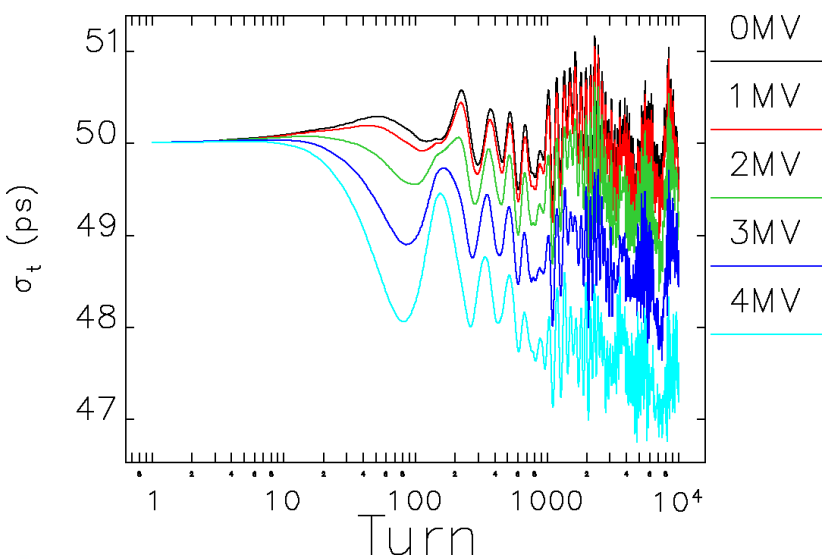


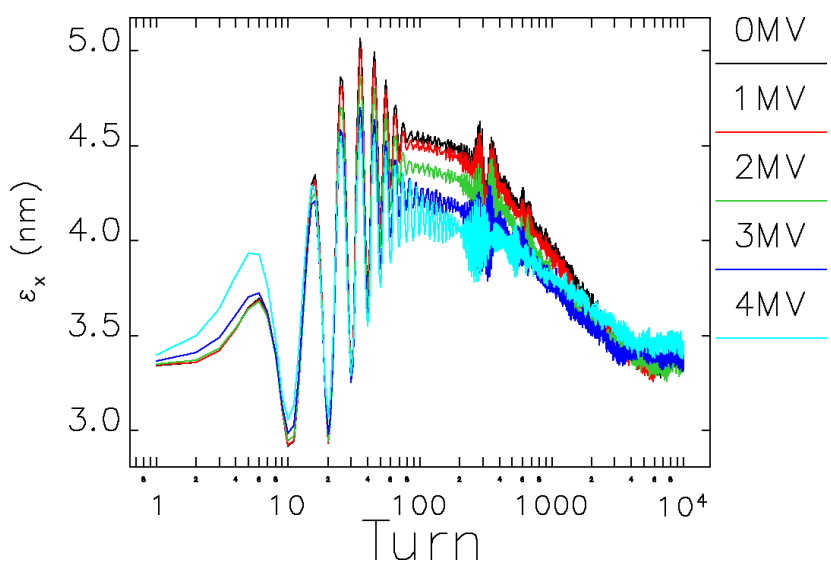
[1]M. Borland, PRSTAB 8, 074001 (2005).
[2]V. Sajaev, ASD/APG/2005-06
[3]M. Borland and V. Sajaev, Proc. PAC2005, 3886-3888.

Simulating Beam Equilibrium

- Setup:
  - Design linear lattice
  - Perform interior sextupole optimization (50ps, 4 MV)
  - Perform outside sextupole optimization for DA/LMA
- Track 10k turns with 10k particles
- Average over last 2k turns to get “equilibrium” moments



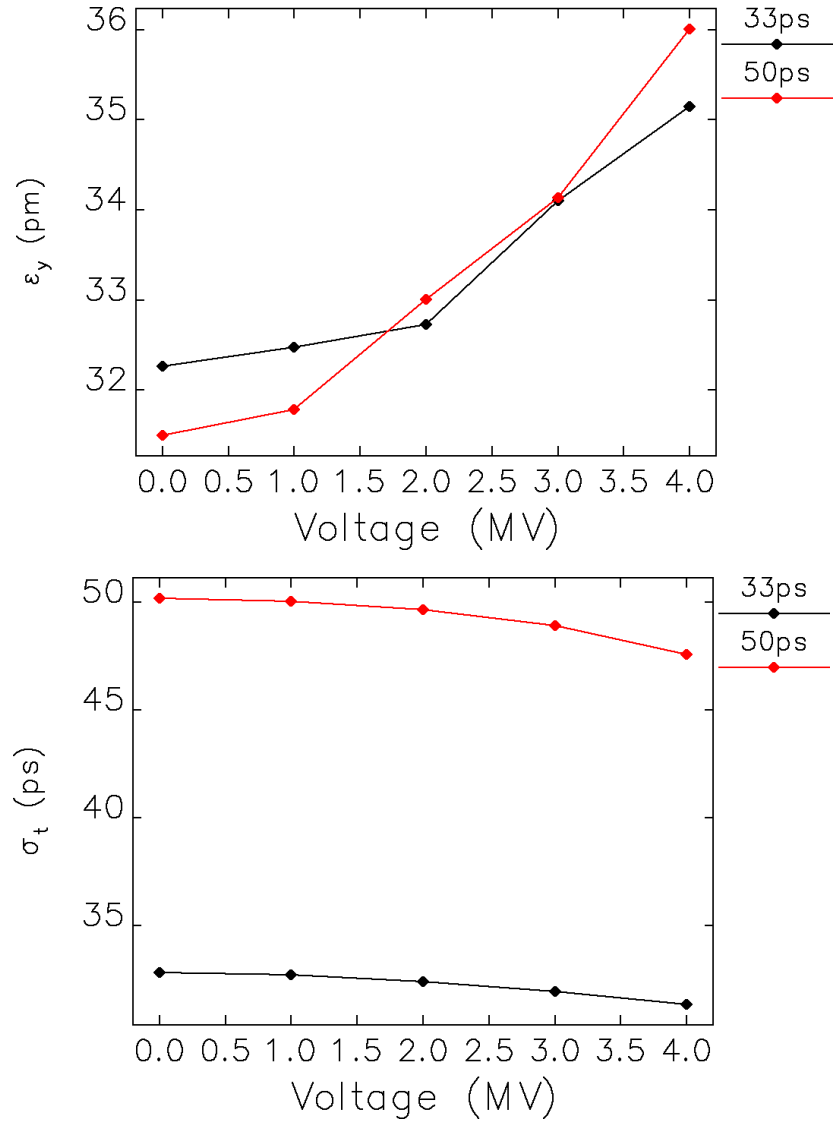




Equilibrium Values

- Vertical emittance growth is modest
- Was optimized for 50ps bunch and 4MV
- Decrease in bunch length wasn't expected
  - Don't have a ready explanation
- For 50 ps case

$$\Delta\epsilon_y[pm] \approx 0.28V^2[MV^2]$$



Setting Tolerances: Emittance

- Want to keep vertical emittance *variation* under ~10% of nominal 35 pm
- Errors affecting the outside emittance
  - Differential crab voltage
  - Vertical betatron phase advance not N*π
  - Beta functions not equal
  - Cavity and magnet roll
- Some of these errors essentially static
  - Beta function error can be compensated by changing relative voltage of second cavity
  - Phase advance error can be compensated by changing relative voltage of first and second set of cells of second cavity
  - Cavity roll is found to be a weak effect[1]
  - Magnet roll can be locally-corrected with additional skew quadrupoles (details TBD)
- Hence, all of our emittance budget is assigned to differential voltage error

[1]M. Borland, PRSTAB 8, 074001 (2005).

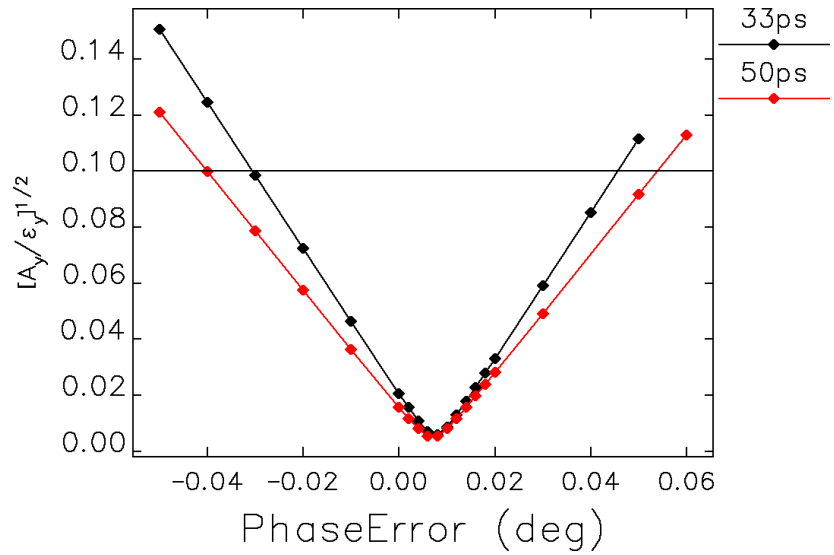
Setting Tolerances: Orbit

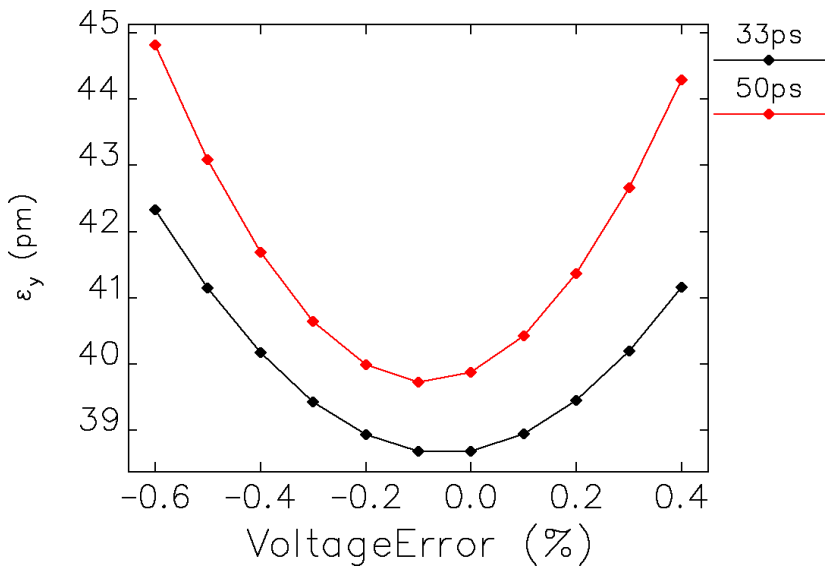
- Phase errors can result in kicks to beam centroid and hence orbit change
- Want to keep orbit variation under ~10% of nominal beam size or divergence
- Differential phase errors affect the orbit everywhere
- Common-mode phase errors affect the interior orbit
  - Beam already large due to the chirp, so this is negligible
  - Primarily affects arrival-time jitter of x-ray pulse
- Hence, all of the orbit budget is assigned to differential phase error
- Note: If phase errors drift slowly, can be corrected by orbit feedback system

Differential Phase and Voltage Errors

Outside orbit disturbance sensitive to differential phase error

Offset due to time-of-flight increase from large vertical oscillations?



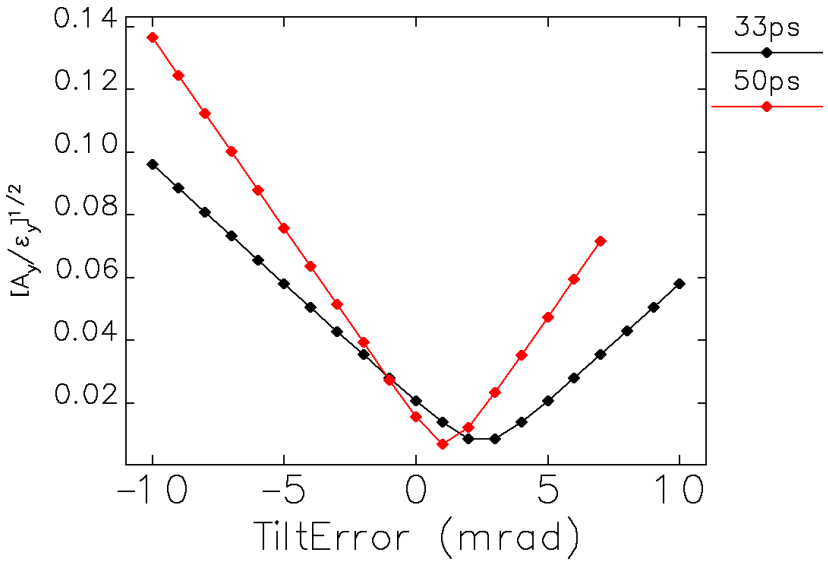


Emittance is sensitive to differential voltage error

Offset due to transfer of motion into x plane?

Cavity Roll Errors

- Sensitivity to roll of second cavity is weak
- Clear offsets from zero
  - Speculate that beam is coupled when arriving at second cavity
  - Effect is weak and static in any case



Common-Mode Voltage Errors

- Common-mode voltage changes the chirp seen by the target beamlines

$$\sigma_t \propto \frac{1}{V} \Longrightarrow \frac{\Delta\sigma_t}{\sigma_t} = -\frac{\Delta V}{V}$$

- Intensity through slits has same variation
- Hence 1% duration/intensity control requires 1% common-mode voltage control

- Emittance effects can be estimated from tracking result

$$\Delta\epsilon_y[pm] \approx 0.28V^2[MV^2]$$

- 4% error at 4 MV translates into 1% emittance growth

Common-Mode Phase Error

- Common-mode phase error changes the portion of the bunch that receives zero kick
  - Interior orbit shift can be ignored (see above)
- For nominal case of narrow vertical slit in beamline, changes only the arrival time of the x-ray pulse and the part of the electron pulse that is “seen”

$$\Delta\phi \approx= 2\sqrt{2}\pi f_{cc}\sigma_t \left|\frac{\Delta I}{I}\right|^{\frac{1}{2}}$$

- For a <1% intensity variation, need < 7° CM phase variation

Summary of Rf-Related Tolerances

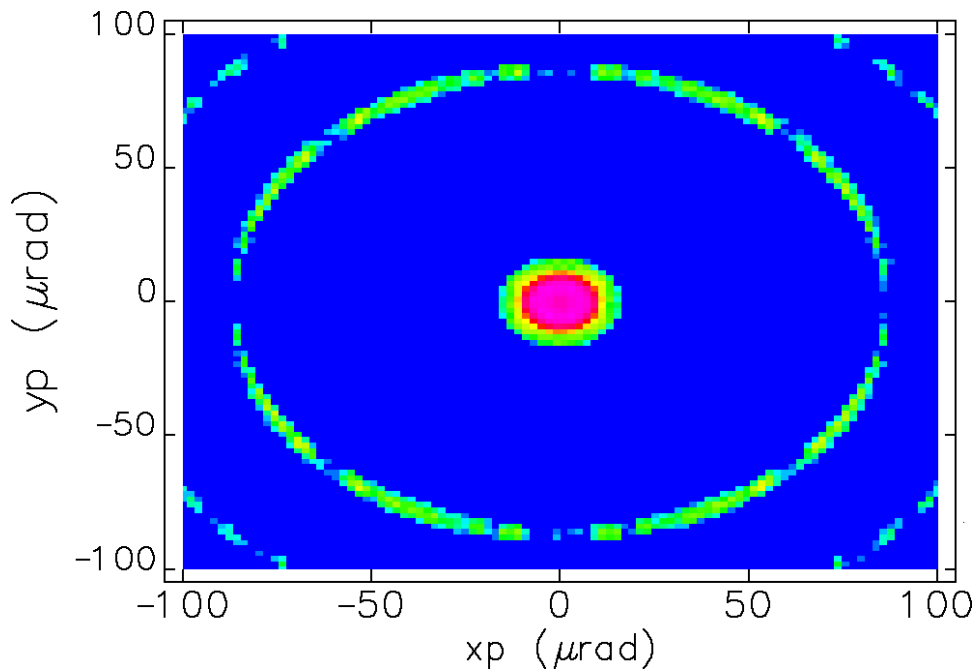
Specification name	Rms Value	Driving requirement
Common-mode voltage variation	$< 1\%$	Keep intensity and pulse length variation under 1% rms
Common-mode phase variation	$< 4.8°$	Keep intensity variation under 1% rms
Voltage mismatch between cavities	$< 0.5\%$	Keep rms emittance variation under 10% of nominal 35 pm
Phase error between cavities	$< 0.07°$	Keep rms beam motion under 10% of beam size/divergence

- Tolerances valid for static changes or modulations far from tunes
- Phase tolerance can be relaxed if phase varies slowly compared to orbit correction bandwidth

X-ray Slicing Simulation

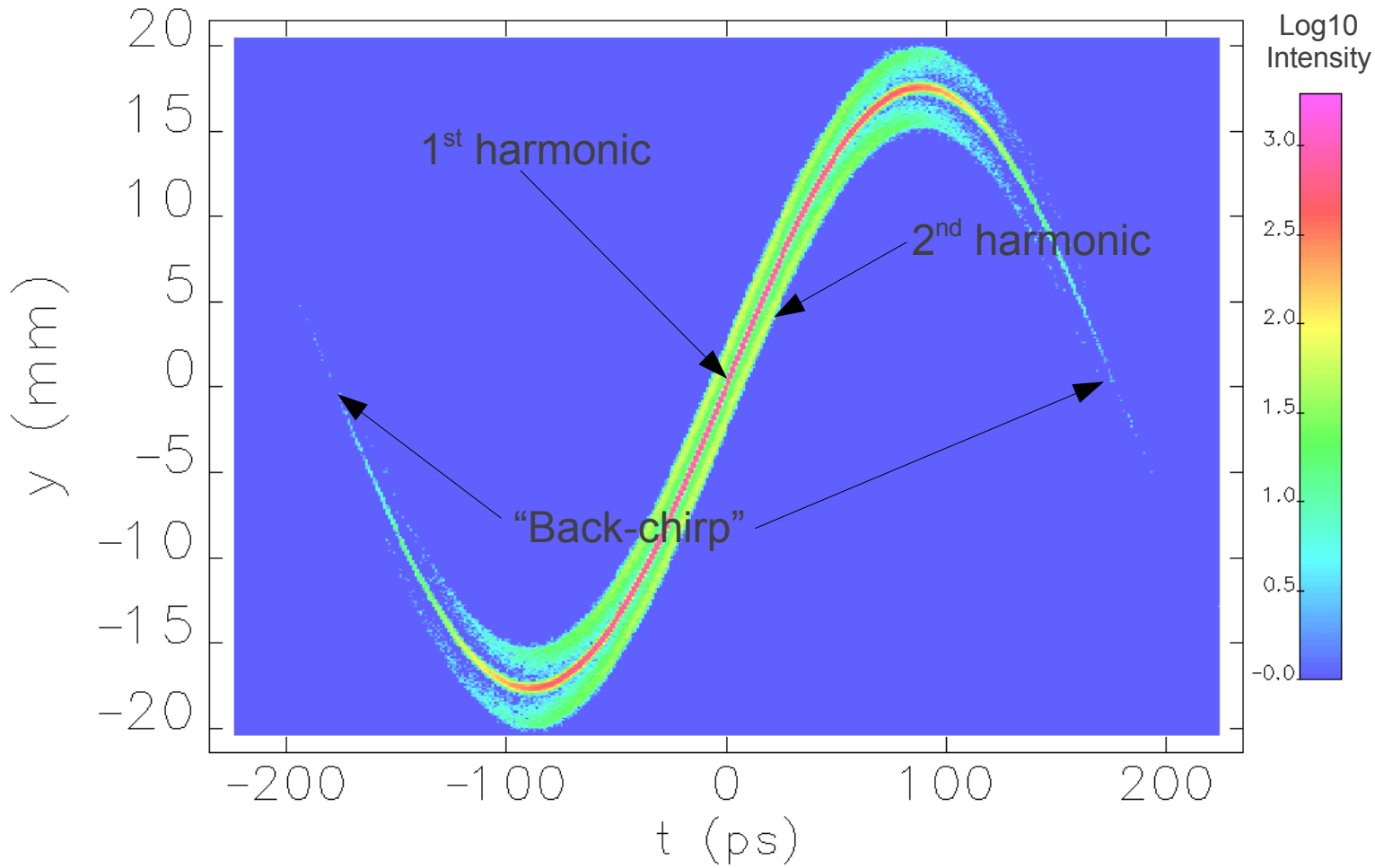
- Program **sddsurgent**[1] computes the radiation pattern for given undulator parameters
- Includes detailed central cone distribution and off-axis higher-harmonics
- Convolve this with electron distribution from **elegant**
- Drift and slit simulation done with **elegant**

10 keV first harmonic radiation from
2.4-m-long U33 undulator



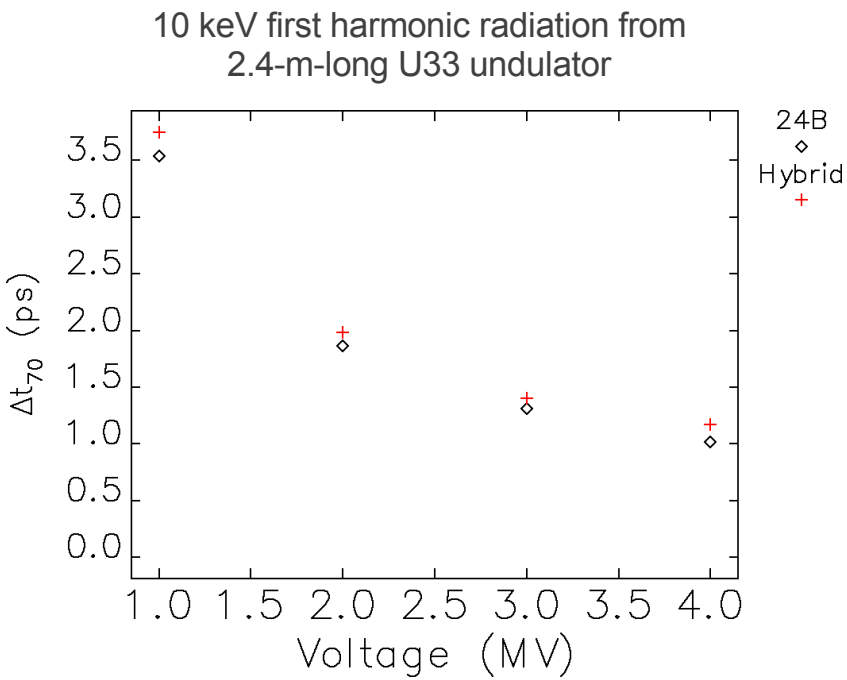
[1]H. Shang, R. Dejus, R. Walker, M. Borland.

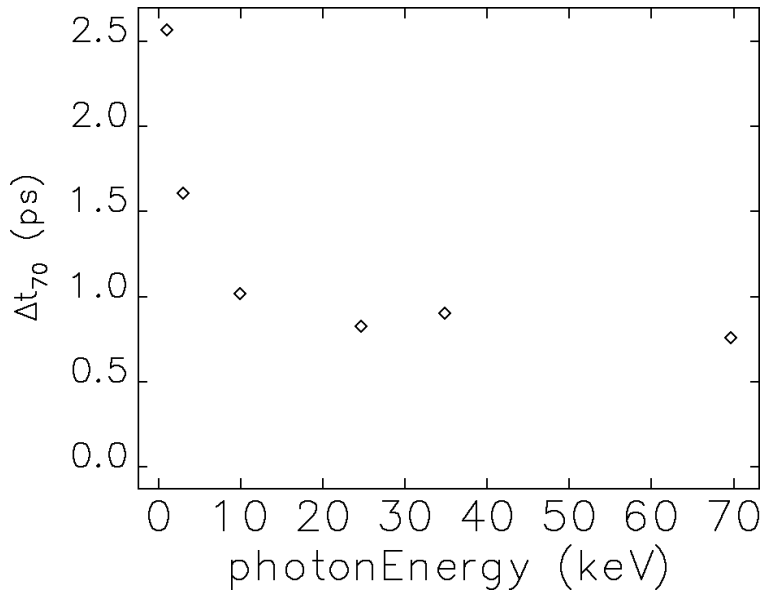
Radiation Distribution 26.5m from Source (Hybrid Mode)



26.5m is the distance to an aperture in the ID7 beamline. Aperture is typically set at 0.5 mm in both planes. (E. Dufrense.)

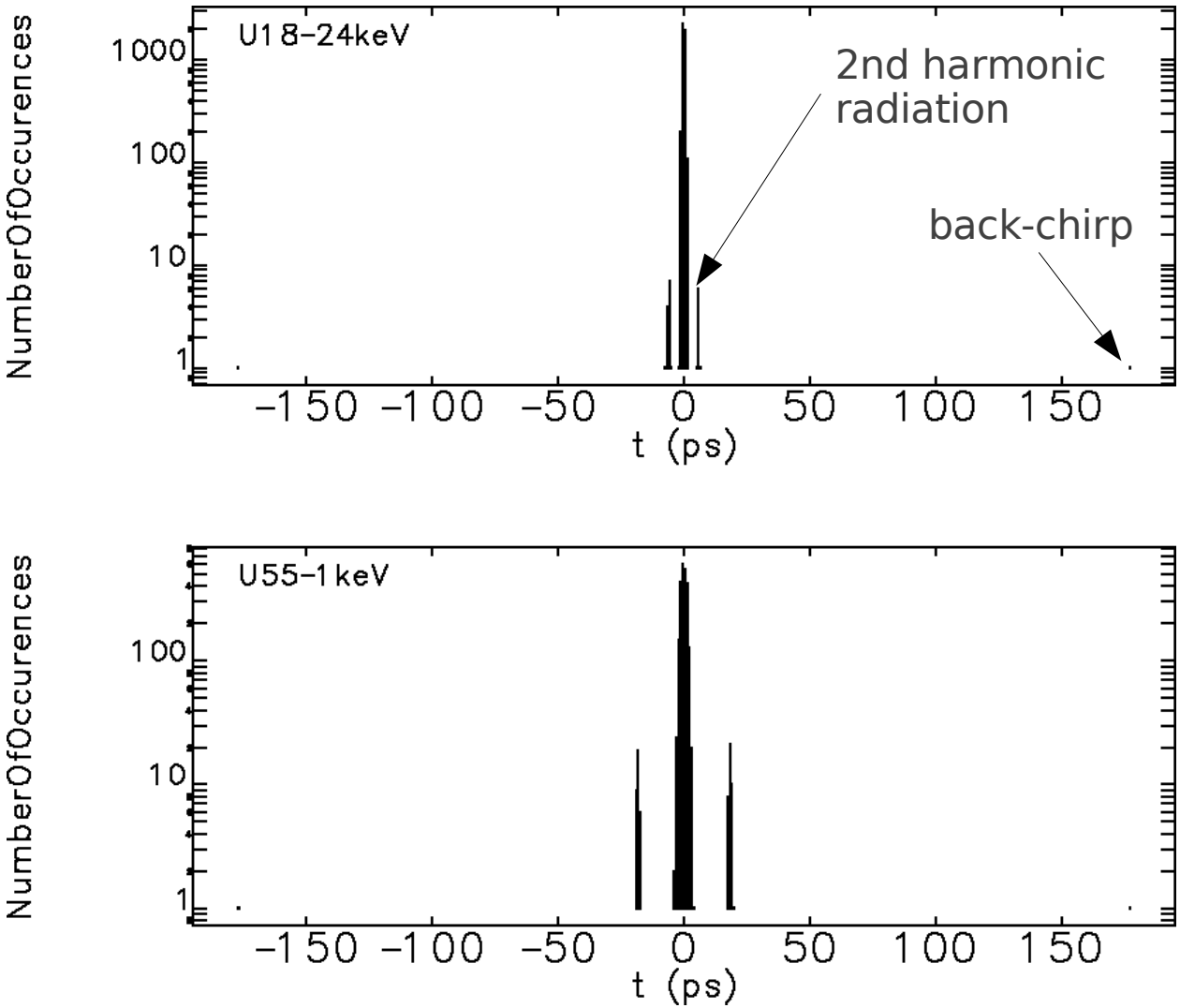
Predicted Pulse Duration





- Diminishing returns seen at 4 MV due to emittance increase
- Results improve for harder x-rays (lower divergence)
- Longer ID can give shorter x-ray pulse (assumed 2.4m)
- Also may benefit from manipulation of beta functions
  - Unfortunately, quads removed for LSS makes this hard

Details of Time Structure (Hybrid Mode)



- Back-chirp pulses have <0.1% of total intensity
- 2nd harmonic pulses have ~1.5% of total intensity

Slits: H=0.5 mm, V=0.2 mm

Simulation Plan

- Understand in detail how orbit feedback and/or bunch-by-bunch feedback can help with tolerances
- Test some assumptions of modeling
  - Presently mock-up PWD using rf frequency and voltage
    - Tests with impedance model looked ok, but needs to be revisited
  - Cavity modeled as pillbox with no radial variation
    - Is this good enough?
  - Presently use lumped synchrotron radiation
    - Check with element-by-element synchrotron radiation
  - Presently use idealized model with 0 to 1 errors
    - Try calibrated model (need to commission mockup lattice first)
    - Look at combined cavity errors for any surprises

Conclusion

- Zholents' scheme for short x-ray pulses has been simulated
  - Tolerances determined, look challenging
  - Detailed performance predictions show promise
- Emittance growth is a primary concern
  - Sextupole optimization makes this manageable
  - Diminishing returns as voltage is raised
- Predicted pulse durations approach 1ps FWHM for hard x-rays
- Pulse structure has complex features due to higher harmonics, long electron bunch
- List of additional simulation work started

Acknowledgements

Thanks to the following people for assistance, information, comments, and suggestions

Y. Chae, T. Berenc, R. Dejus, L. Emery, R. Gerig, E. Gluskin, K. Harkay, A. Nassiri, V. Sajaev, H. Shang, R. Soliday, G. Waldschmidt, Y. Wang, A. Zholents

(Plus others I probably forgot.)