Performance Predictions and Tolerances for SPX

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Outline

- Emittance growth sources and remediation
- Comparison of pulsed and CW cases
  - Emittance growth
  - Brightness impact
  - Predictions of x-ray pulse properties
- Tolerances

Emittance Growth[1]

- In idealized concept, second set of cavities exactly cancels the effect of the first set
  - In reality, doesn't work exactly and we have emittance growth
- Sources of growth in an ideal machine
  - Time-of-flight dispersion between cavities due to beam energy spread
  - Uncorrected chromaticity, if present (normally it is)
  - Coupling of vertical motion into horizontal plane by sextupoles
  - Quantum randomization of particle energy over many turns
- Additional sources of growth in a real machine
  - Errors in magnet strengths between the cavities
  - Roll of magnetic elements about beam axis
  - Roll of cavities about beam axis
  - Orbit error in sextupoles
  - Errors in rf phase and voltage
- Emittance growth is not just a worry for brightness
  - It also limits how short an x-ray pulse can be achieved

[1]M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2005).

Reducing Emittance Growth[1,2,3,4]

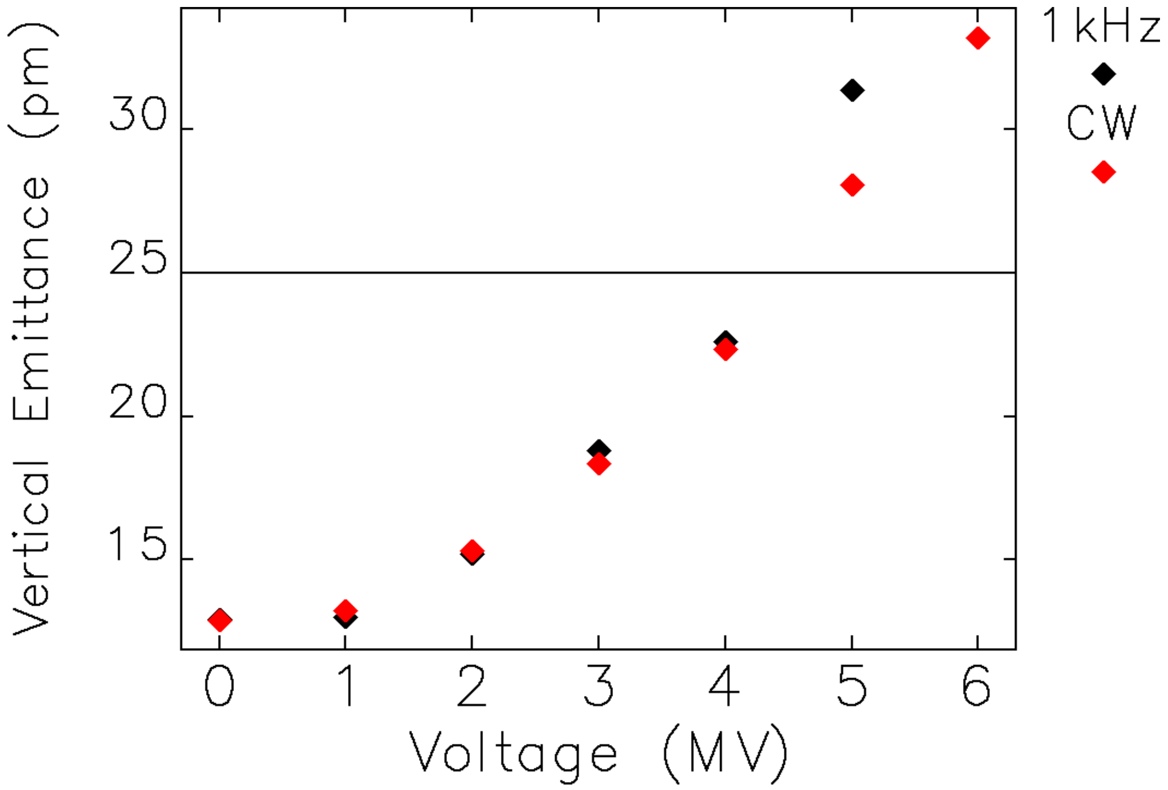
- Methods of reducing emittance growth
  - Don't power cavities past point of diminishing returns
  - Optimize sextupoles to minimize impact
    - *Minimize emittance directly using particle tracking simulation*
    - *Tune sextupoles for zero chromaticity between cavities*
  - Choose vertical oscillation frequency (“tune”) to facilitate multi-turn cancellation of effects
  - Increase separation of horizontal and vertical tunes
- Most of these work for both pulsed and CW cavities.

[1]M. Borland, OAG-TN-2004-026, 9/2004.
[2]M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2005).
[3]V. Sajaev, ASD/APG/2005-06, March 2005.
[4]M. Borland and V. Sajaev, Proc. PAC 2005, 3886-3888.

Operating Modes and Configurations

- Pulsed case
  - Two pairs of three-cell cavities separated by one sector
  - We assume 1kHz pulsing for purposes of this talk
  - Operates in hybrid mode only due to time needed to charge/discharge cavities
  - Cavities nominally impact only the hybrid bunch itself
  - 70 ps rms electron bunch duration
- CW case
  - Two 10-cell cavities separated by one sector
    - *Cell length is $\lambda/2$*
    - *Intercell spacing of λ*
  - Cavities impact all bunches
  - 24 bunch and hybrid modes of interest
    - *Hybrid problematic due to phase variation among bunches*

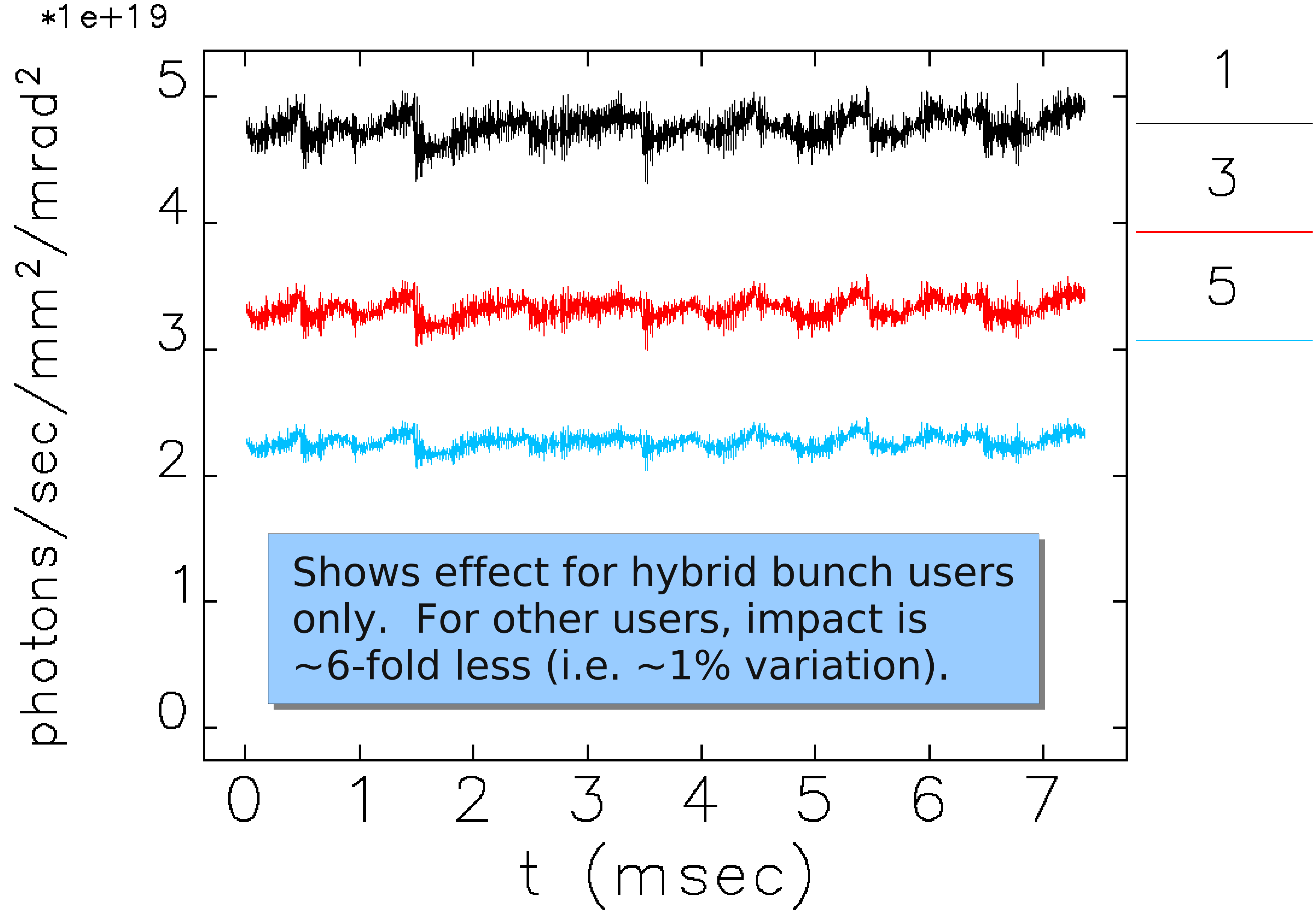
Comparison of Emittance Growth for Pulsed, CW



- Starting vertical emittance is 13 pm (0.5% coupling)
- 10k turn tracking results with parallel elegant[1]
- "1 kHz" shows hybrid bunch emittance only
- "CW" is for 24 bunch mode, all bunches are affected

[1]Y. Wang, M. Borland, Proc. PAC07, www.jacow.org.

Effect of 1 kHz Pulsing on Brightness



Shows effect for hybrid bunch users only. For other users, impact is ~6-fold less (i.e. ~1% variation).

Estimating X-ray Pulse Length

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

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

Electron beam energy

Deflecting rf voltage & frequency

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

Divergence due to undulator (typ. ~5 μrad)

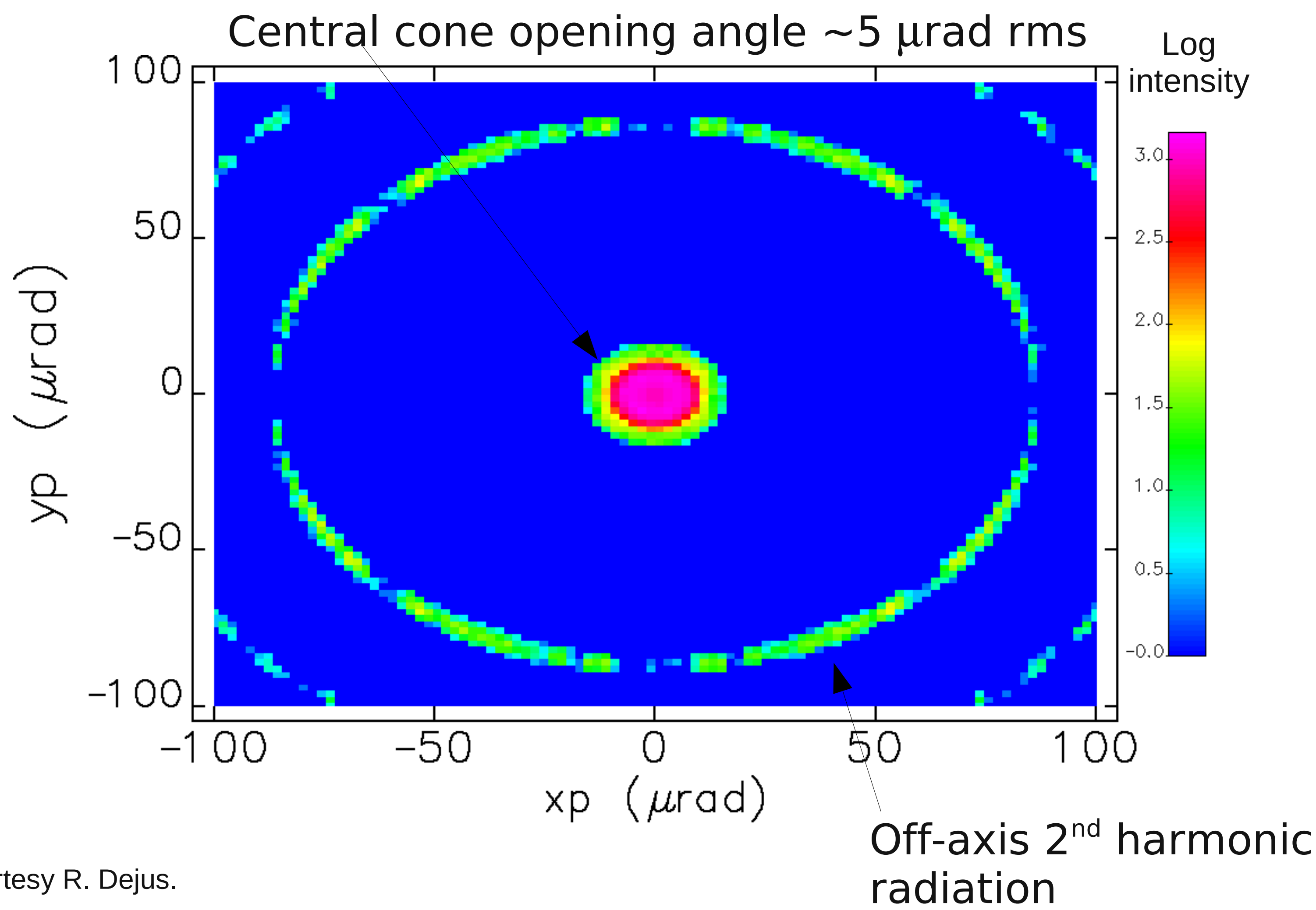
For 4 MV, 2800MHz (h=8) deflecting system, get ~0.6 ps

- Emittance growth matters because it increases the minimum achievable pulse duration
- 30~40% low since single-electron radiation distribution isn't gaussian
- To get accurate results we need to perform modeling.

[1]M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2005).

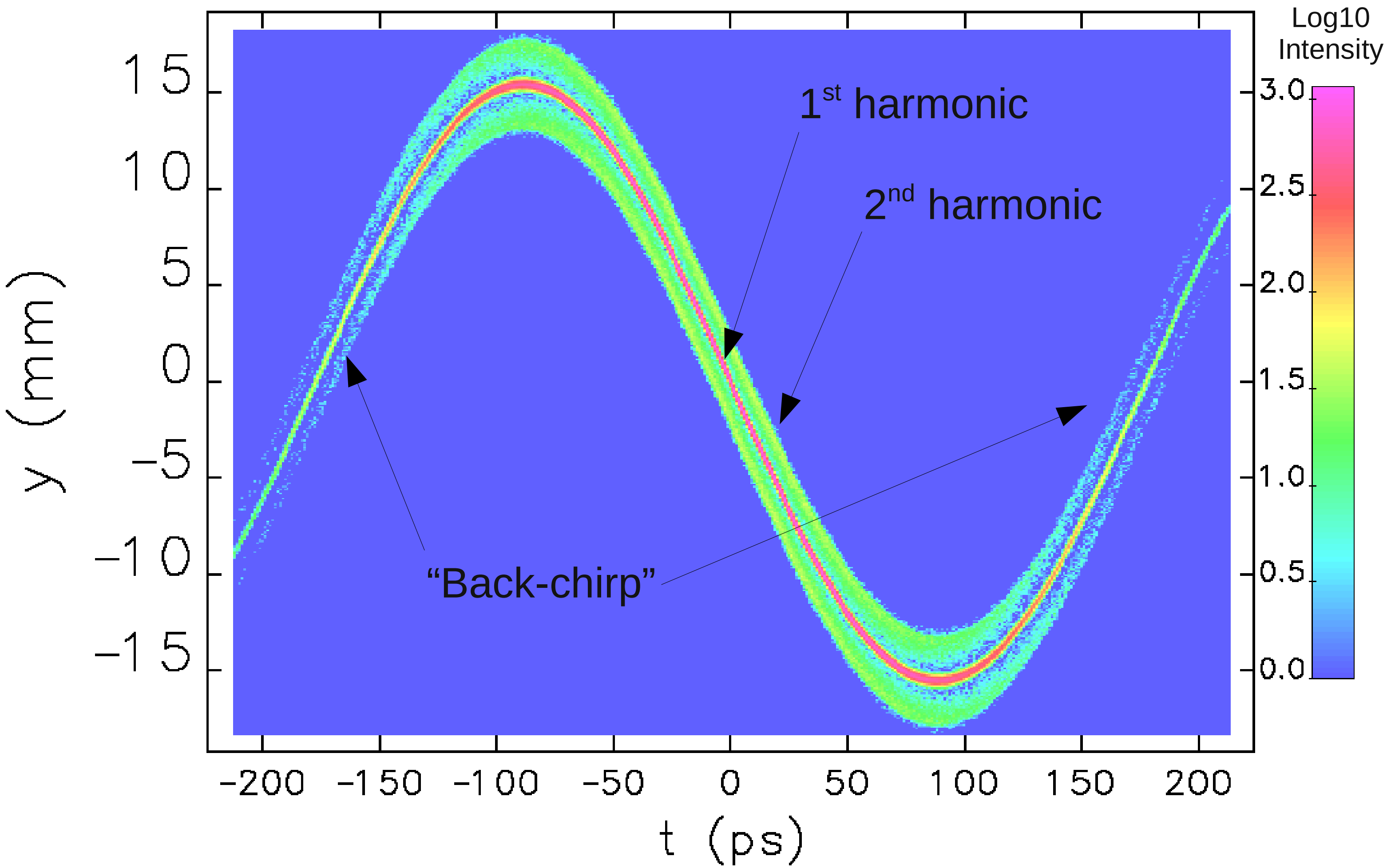
Single-Electron Undulator Radiation Pattern

Results for 10 keV, 2.4m U33



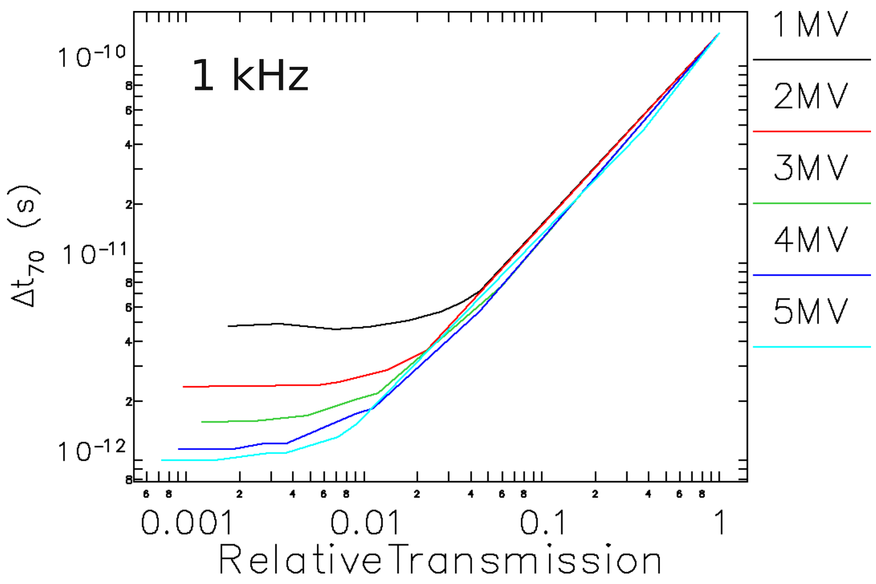
Data courtesy R. Dejus.

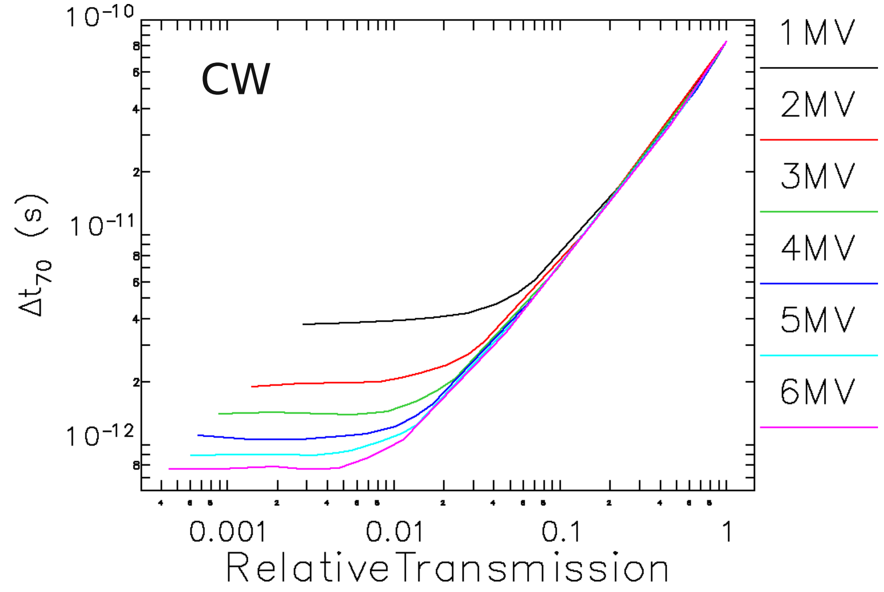
Radiation y-t Distribution at 26.5m, 4 MV Pulsed



26.5m is the distance to a 2mm x 3mm aperture in the ID7 beamline. Aperture is typically set at 0.5 mm in both planes. (E. Dufrense.)

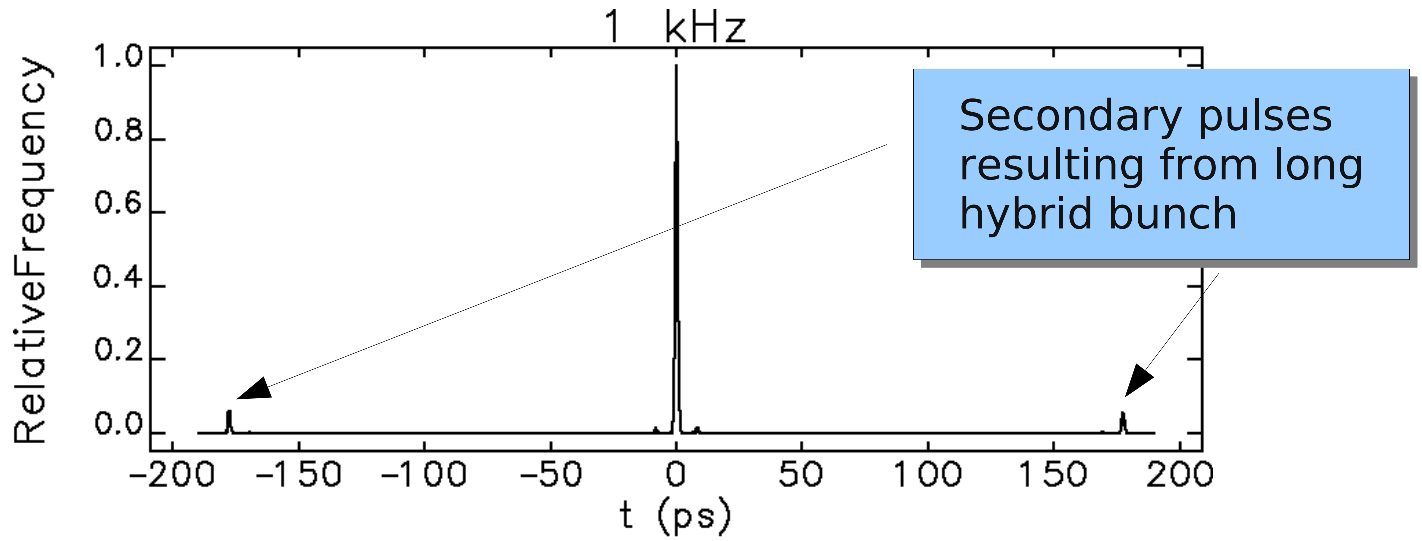
Comparison of X-ray Slicing Results

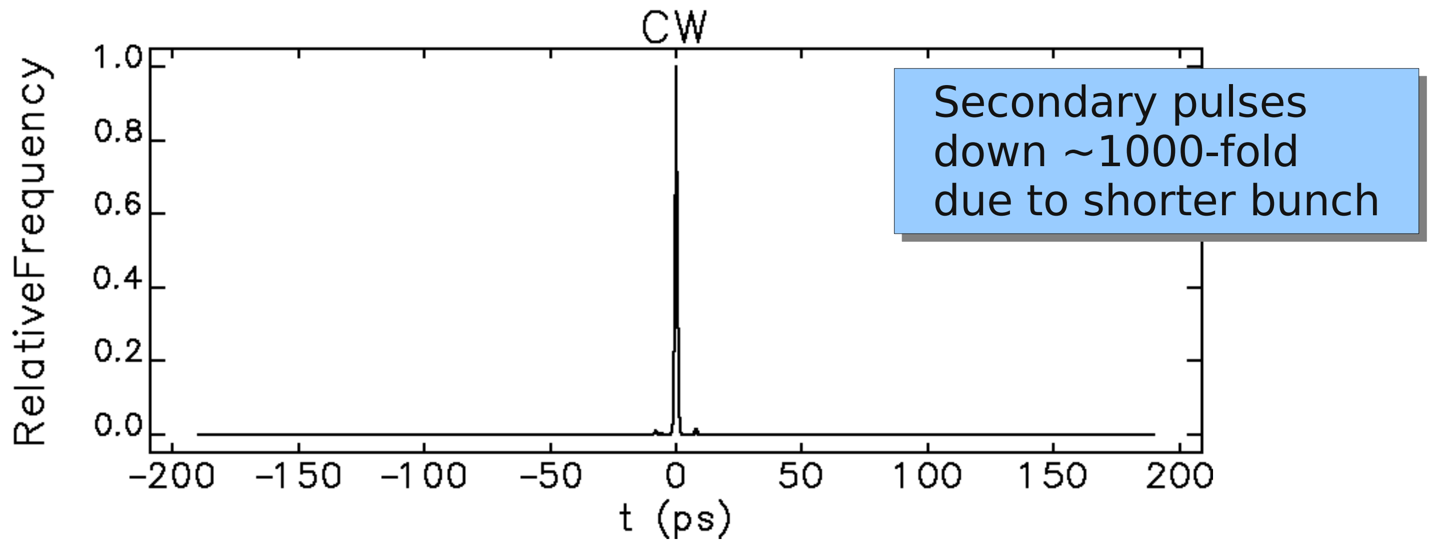




- Two slits at 26.5 m
  - Vertical slit is varied from ±100 mm to ±0.010 mm
  - Fixed horizontal slit of ±0.25 mm (E. Dufrense)
- Results are very similar up to 4 MV
  - Curves flatten out for ~1% transmission
  - Vertical slit is ~ ±0.1 mm at this point
- CW has an edge due to shorter bunch, smaller emittance

Details of X-ray Slicing Results[1]





[1]M. Borland, OAG-TN-2007-016, 3/16/07.

Slits: H=0.5 mm, V=0.2 mm

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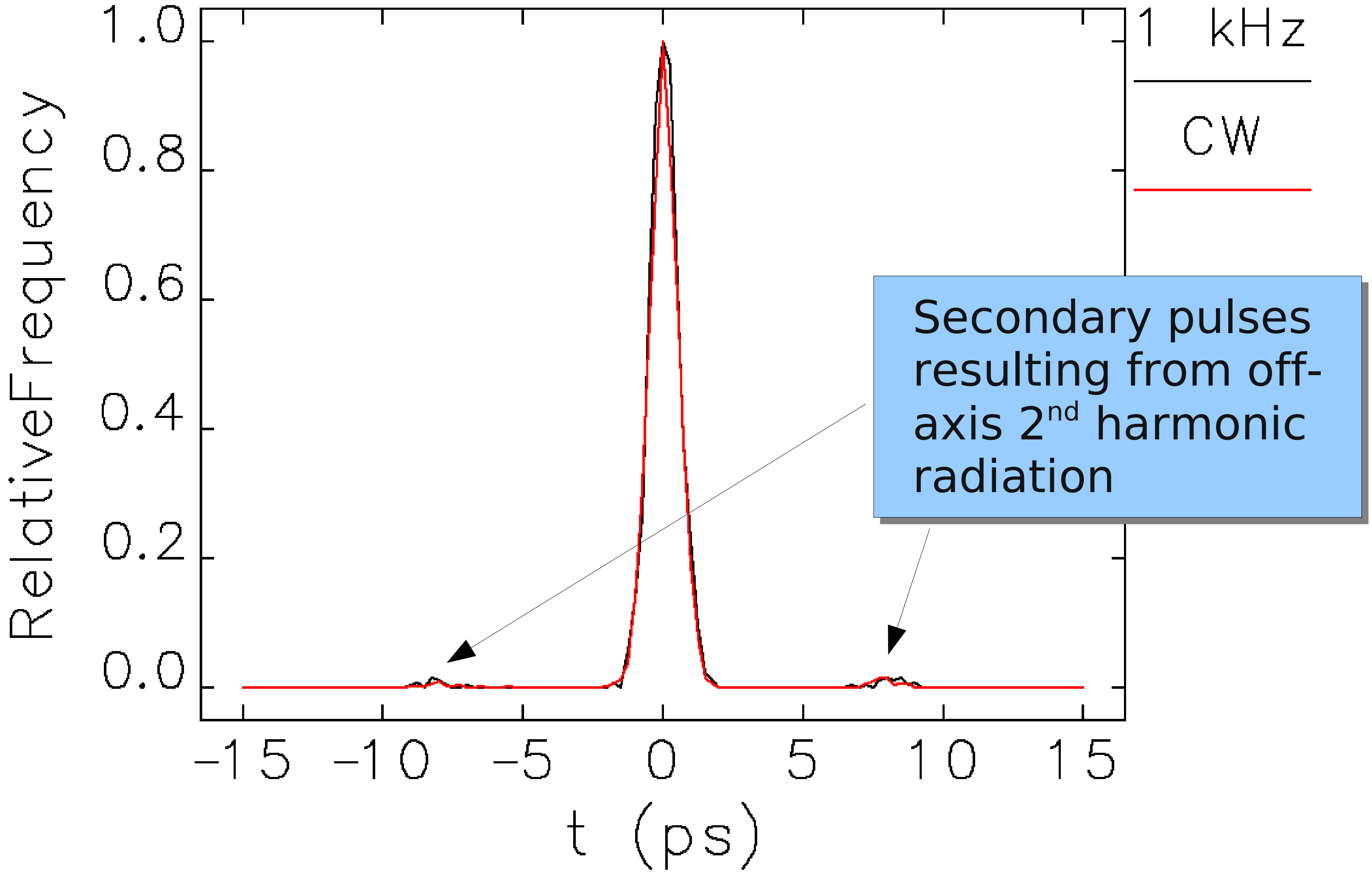
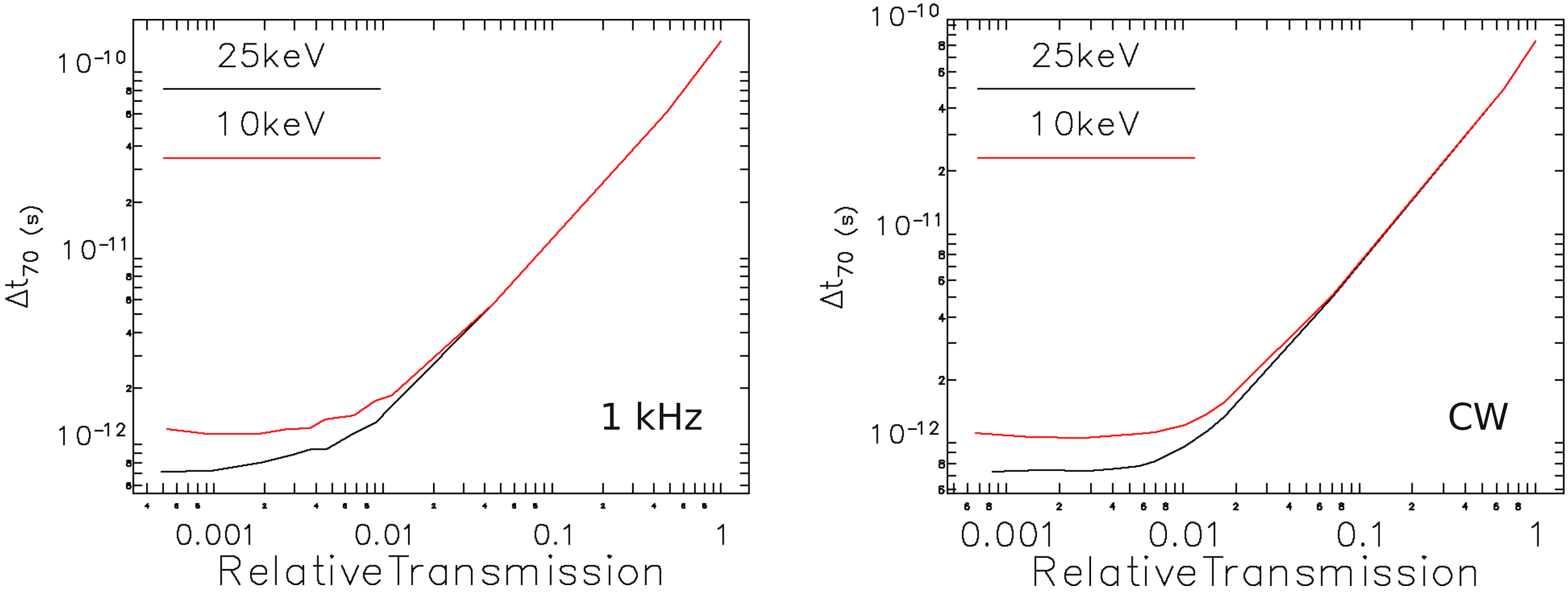


[1]M. Borland, OAG-TN-2007-016, 3/16/07.

Slits: H=0.5 mm, V=0.2 mm

Results for 25 keV, 4.8m U18[1]



- Smaller divergence means we can squeeze below 1 ps FWHM with 1% transmission for CW
- Hard to get more intensity without x-ray compression
  - For CW, we are slicing a ~100 ps FWHM electron bunch
  - A perfect ~1 ps slice will have ~1% intensity

[1]M. Borland, OAG-TN-2007-030.

Tolerances

- Original studies[1] of CW cavities with two-sector separation covered most effects
  - Beta function mismatch at cavities
  - Betatron phase advance error between cavities
  - Lattice coupling between cavities
  - Cavity roll about longitudinal axis
  - Cavity phase errors
  - Cavity voltage errors
- The lattice-related issues appear manageable with standard lattice correction[2]
  - We have not revisited these
- Found cavity-related issues were very challenging
  - These challenges are still present for the pulsed case and the new CW configuration.

[1]M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2005).
[2]V. Sajaev and L. Emery, Proc. EPAC 2002, 742-744.

Time Scales and Types of Cavity-Related Errors

- "Static" errors
  - Vary on times long compared to the pulsing interval, damping time, and cavity filling time
  - Must track ~10k turns to find equilibrium for a specific errors
  - Voltage, phase, and tilt errors can be of this type
- "Dynamic" errors
  - Vary on times comparable to or shorter than pulsing interval, damping time, or cavity filling time
  - No equilibrium: would need to track for long enough to get statistics on the effects
  - Voltage and phase errors can be of this type
- Errors may also be common-mode or differential
  - Differential errors affect all beamlines
  - Common-mode errors mostly affect only SPX users
    - *Tend also to be less serious since cancellation largely still occurs.*

Classification of Errors

	Common-mode	Differential-mode
Static	Pulsed CW	Pulsed CW
Dynamic	Pulsed CW	CW

- Pulsed system has no dynamic differential errors
  - Single klystron with slow external effects (e.g., temperature) and slow feedback loops on cavities
- Microphonics is an acoustic phenomenon, so dynamic differential errors are possible in CW case
- We *assume* that static errors have the worst effect
  - May be untrue if a beam resonance is driven.

Criteria for Setting Error Allowances

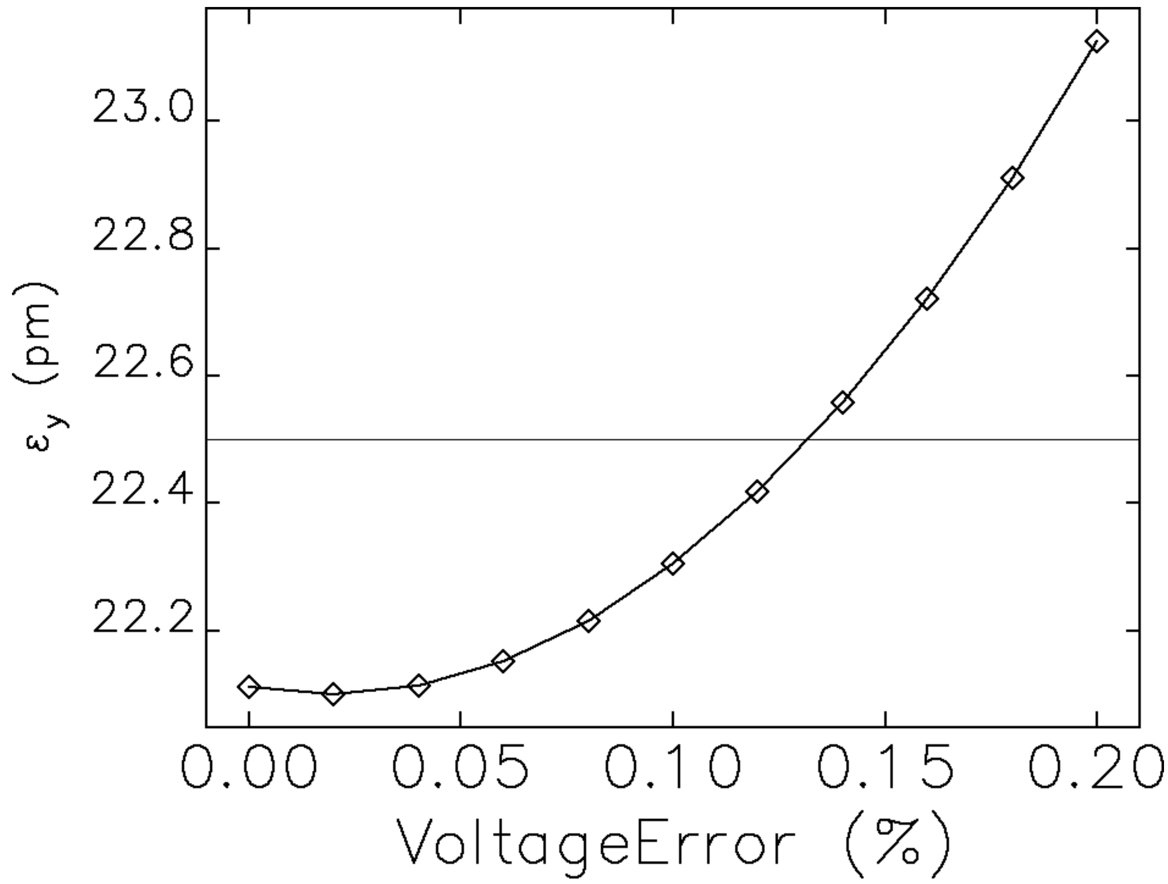
- Vertical emittance should be ~25 pm
  - Choose crab cavity voltage to stay at or under this value
  - Limit variation to <10% of this
- Horizontal emittance should be ~3.1 nm
  - Limit variation to <10% of this
- Beam motion relative to size and divergence should be <10%

Criteria for Setting Error Allowances

- For pulsed case with four cavities
  - Effects of errors from individual cavities assumed (pessimistically) to add linearly
  - Have three differential errors for phase and three for voltage
    - *Each phase or voltage error allowed to produce 1/6th of 10% of 25 pm vertical emittance increase*
- For CW case
  - Individual cells (~10) in cavities have individual coupling and tuner loops but common rf system
  - We made the (mostly) pessimistic assumption that all cells in one cavity have the same error
    - *First cavity can have phase or voltage error that produces 1/2 of 10% of 25 pm vertical emittance increase*
  - Problems with this assumption
    - *Can't assume that it is ok to control only the vector sum from the 10 cells*
    - *Effective cavity center may change even if vector sum is fixed.*

Individual Voltage Errors for 1 kHz[1]

- Get emittance growth because the chirp doesn't cancel fully
- Scanned phase of first 3-cell cavity and determined equilibrium by particle tracking

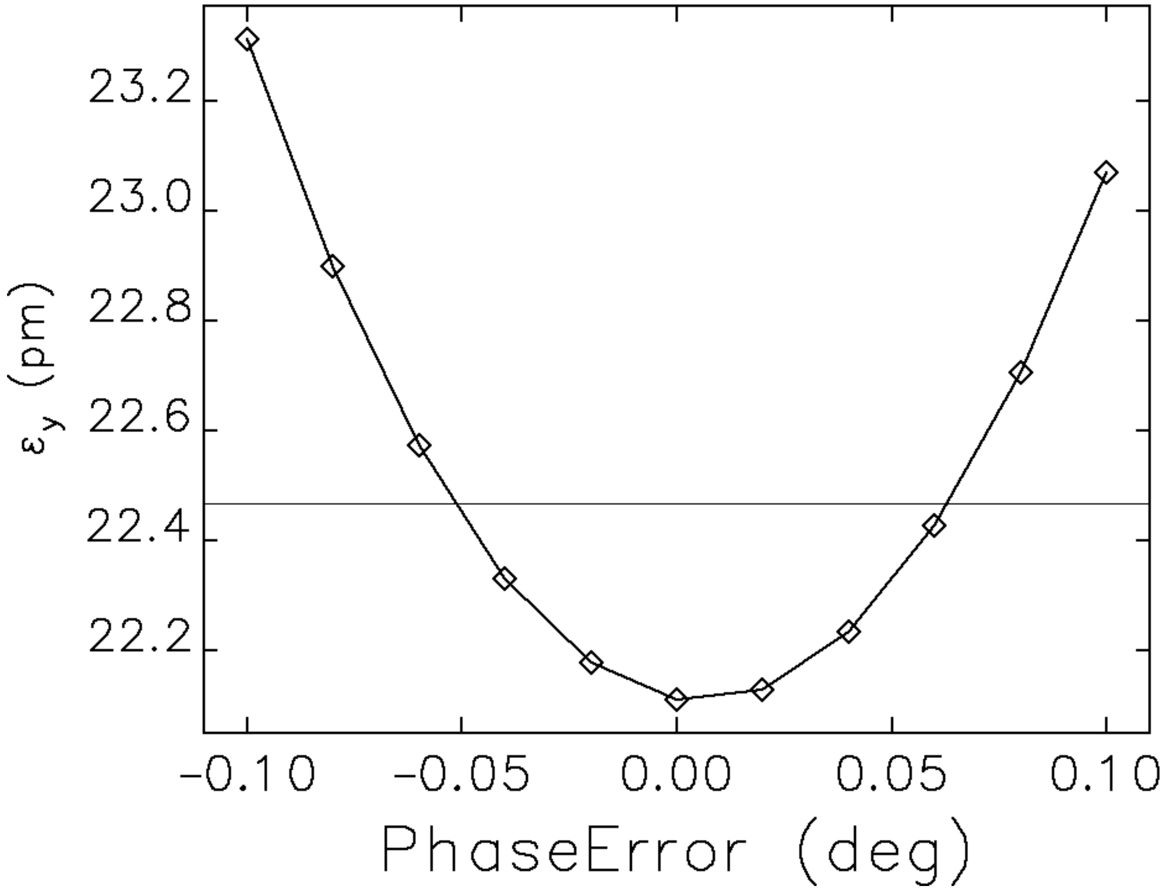


Voltage tolerance is ±0.13%

[1]M. Borland, L. Emery, and V. Sajaev, Proc. PAC 2007, 3429-3431 (2007) jacow.org.

Individual Phase Errors for 1 kHz[1]

- Get emittance growth because the chirp doesn't cancel fully and because beam centroid is kicked
- Scanned the phase error and determined equilibrium by particle tracking

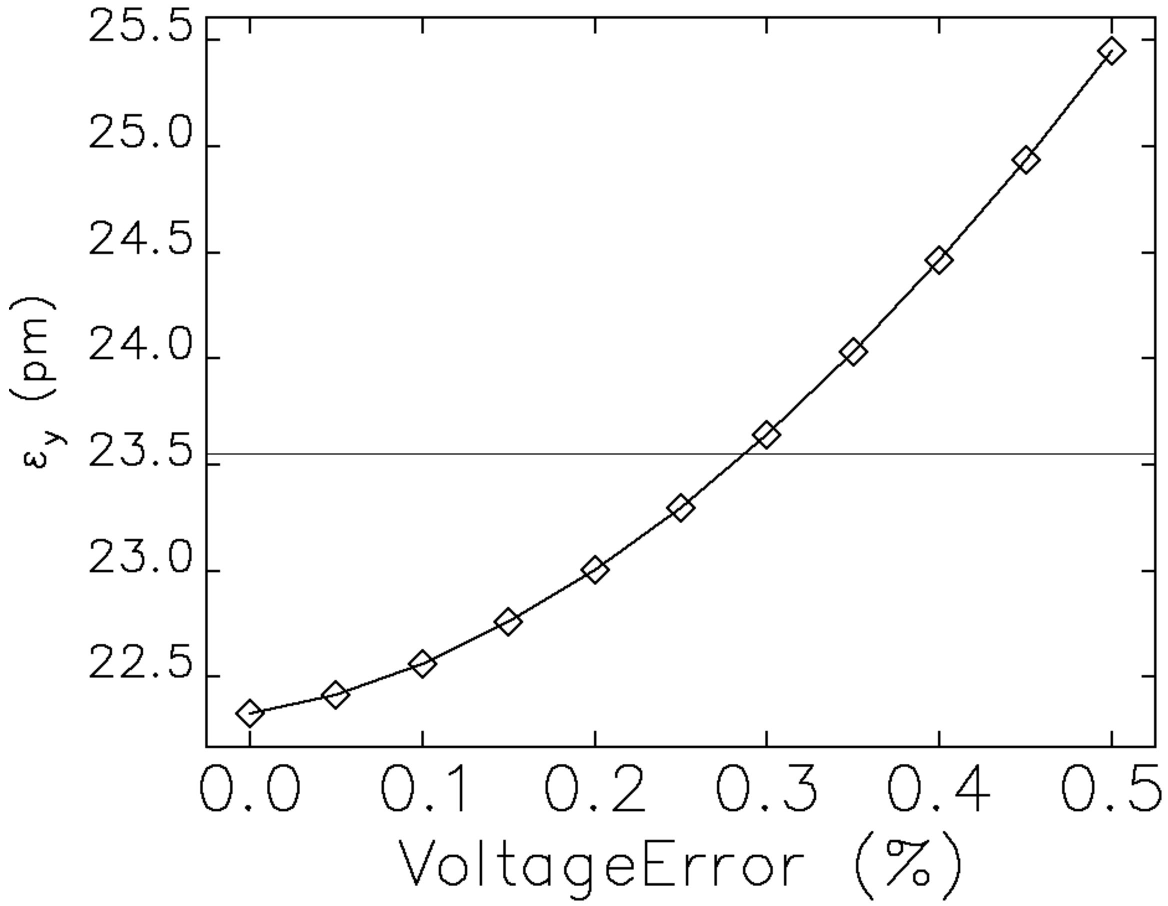


Phase tolerance is ±0.05 degrees

[1]M. Borland, L. Emery, and V. Sajaev, Proc. PAC 2007, 3429-3431 (2007) jacow.org.

Individual Voltage Errors for CW

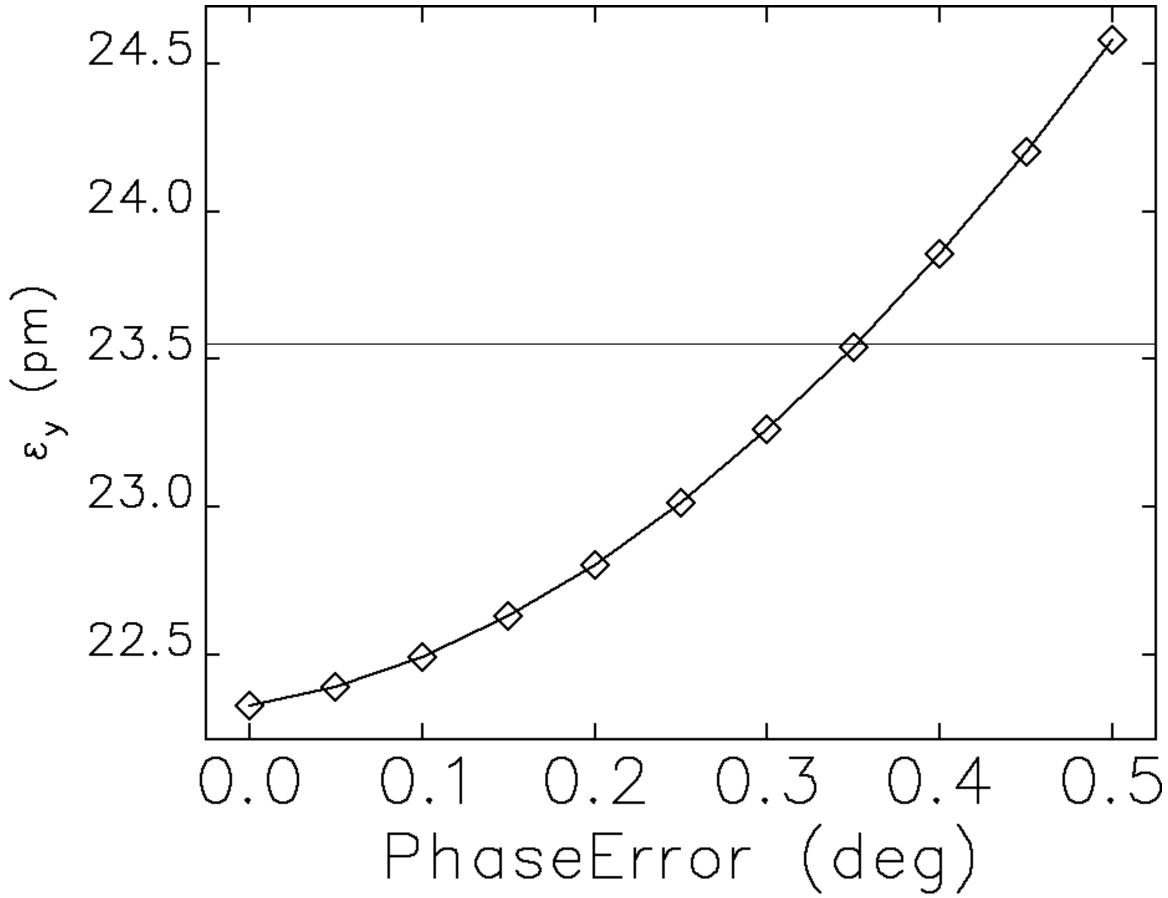
- Get emittance growth because the chirp doesn't cancel fully
- Scanned phase of first 10-cell cavity and determined equilibrium by particle tracking



Voltage tolerance is ±0.29%

Individual Phase Errors for CW

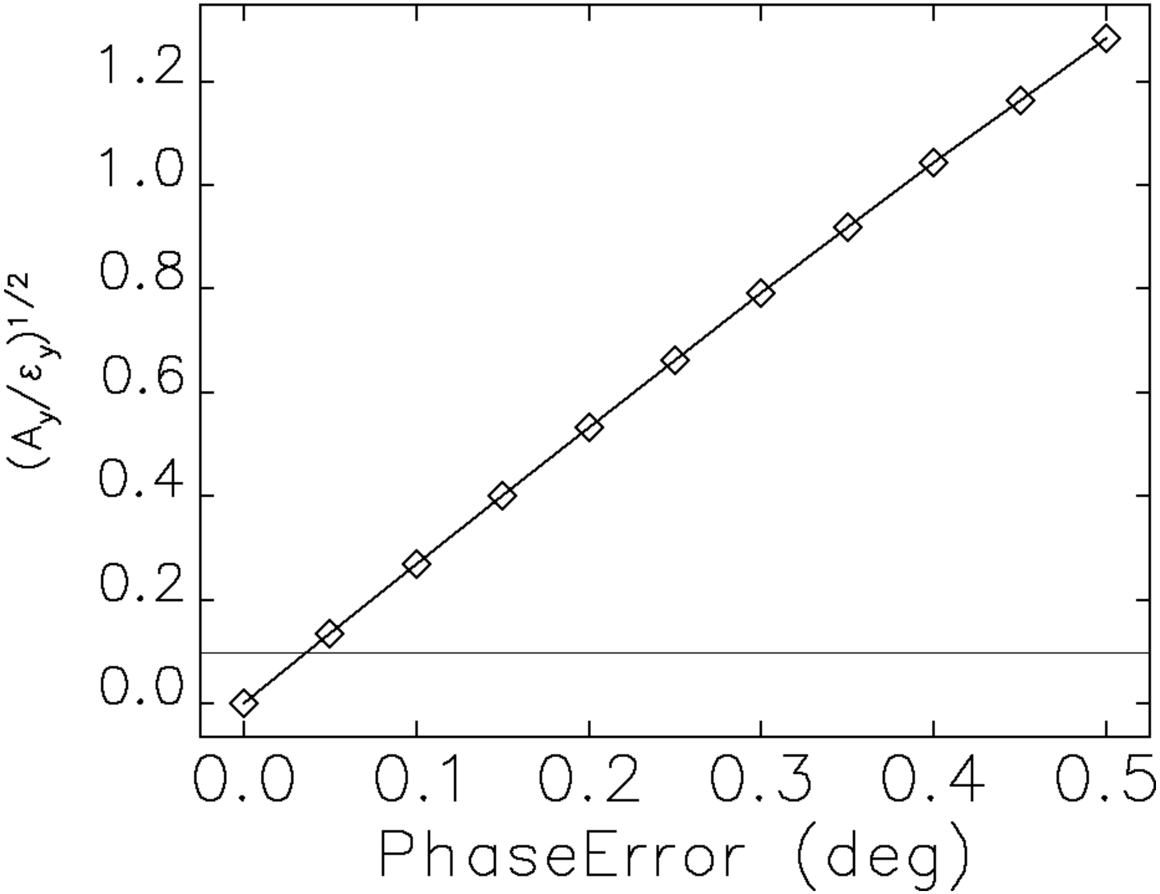
- Get emittance growth because the chirp doesn't cancel fully
- Scanned the phase error and determined equilibrium by particle tracking



Phase tolerance is ±0.35 degrees

Individual Phase Errors for CW (Continued)

- Get centroid offset in addition to emittance growth
- Unlike pulsed case, this doesn't decohere into emittance
- If phase error is slowly-varying, orbit feedback can compensate



Phase tolerance
is ±0.037 degrees

Summary of Tolerances[1]

Quantity	Driving Requirement	120 Hz	1 kHz	CW
Common-mode voltage	Keep intensity and bunch length variation under 1%	±1%	±1%	±1%
Differential voltage	Keep emittance variation under 10% of nominal 25 pm	±0.29%	±0.13%	±0.29%
Common-mode phase relative to bunch arrival	Constrain intensity variation to 1%	±10 deg	±10 deg	±10 deg
Differential phase	Keep emittance variation under 10% of nominal 25 pm	±0.16 deg	±0.05 deg	±0.04 deg
Rotational alignment	Emittance control	~1 mrad	~1 mrad	~1 mrad
Net residual voltage	Emittance control (weak bunches)	26 kV	13 kV	n/a

- Differential errors are assumed to be "static"
- Common-mode errors may be dynamic, but conservatively evaluated as static
- Tolerance on timing signal from crab cavity to users: ±0.9 deg

[1] M. Borland, "Long-Term Tracking, X-ray Predictions, and Tolerances," SPX Cavity Review, 8/23/07.

Conclusions

- Tracking studies have been performed for pulsed and CW systems
  - Presented studies cover only single-particle dynamics
- Emittance growth for 4 MV is acceptable for CW and 1kHz
  - Starting from base of 0.5% coupling, we stay under 1%
  - Little benefit from going to higher voltages
- We can achieve below 2 ps FWHM with ~1% of nominal intensity
- Tolerances have been defined
  - Differential voltage tolerances are tight
  - Differential phase tolerances are very tight, particularly for CW
  - Determined by desire to limit vertical emittance variation and potential beam motion.