Constraints, performance requirements, and tolerances for the APS SPX project

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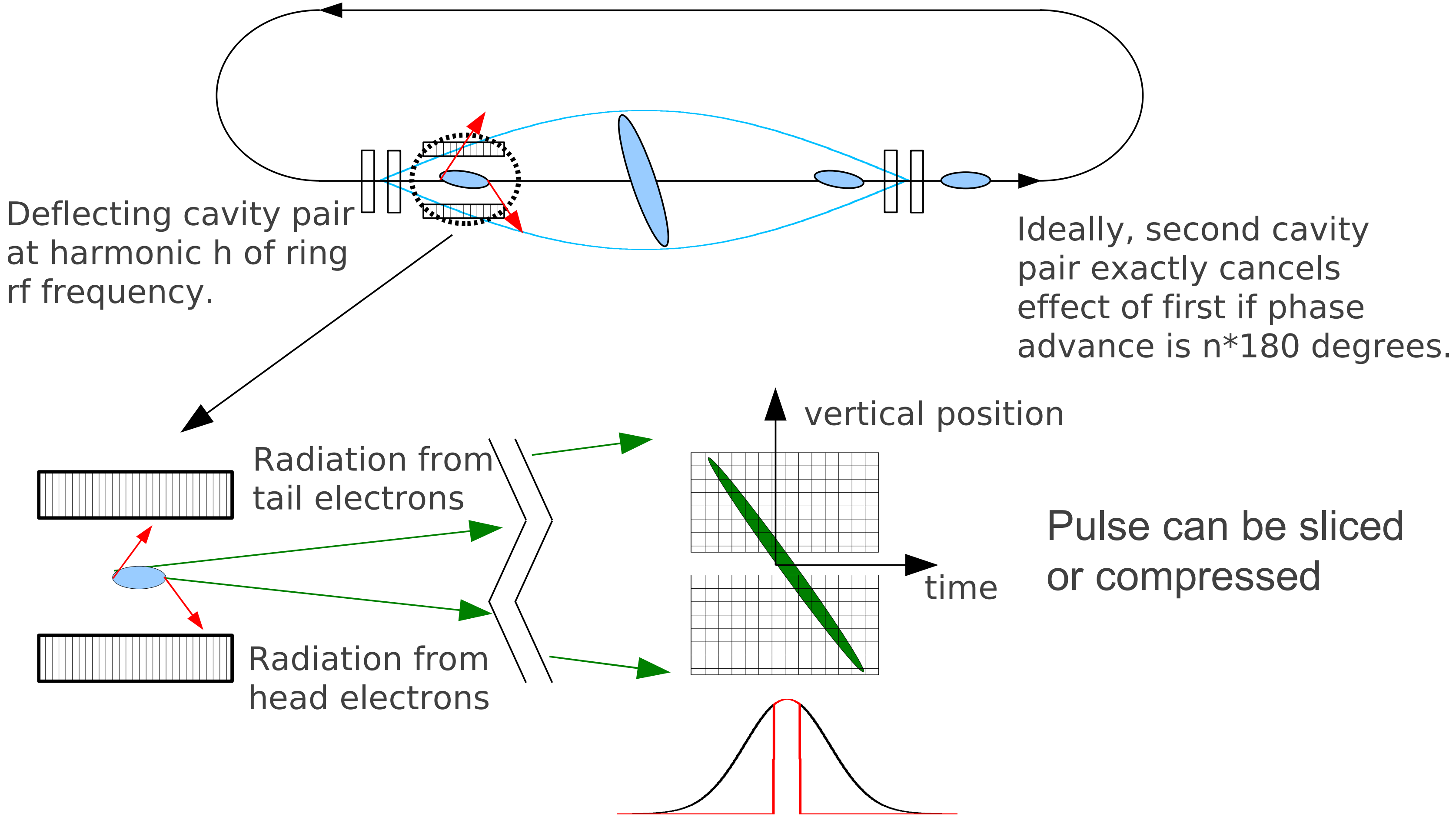
Transverse RF chirp concept[1]



Deflecting cavity pair at harmonic h of ring rf frequency.

Ideally, second cavity pair exactly cancels effect of first if phase advance is n*180 degrees.

Radiation from tail electrons

Radiation from head electrons

Pulse can be sliced or compressed

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

X-ray pulse duration

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

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

→ For 4 MV, 2.8GHz
(h=8),
we get ~ 0.6 ps

- Small vertical emittance is crucial
- Electron bunch length affects intensity, emittance growth

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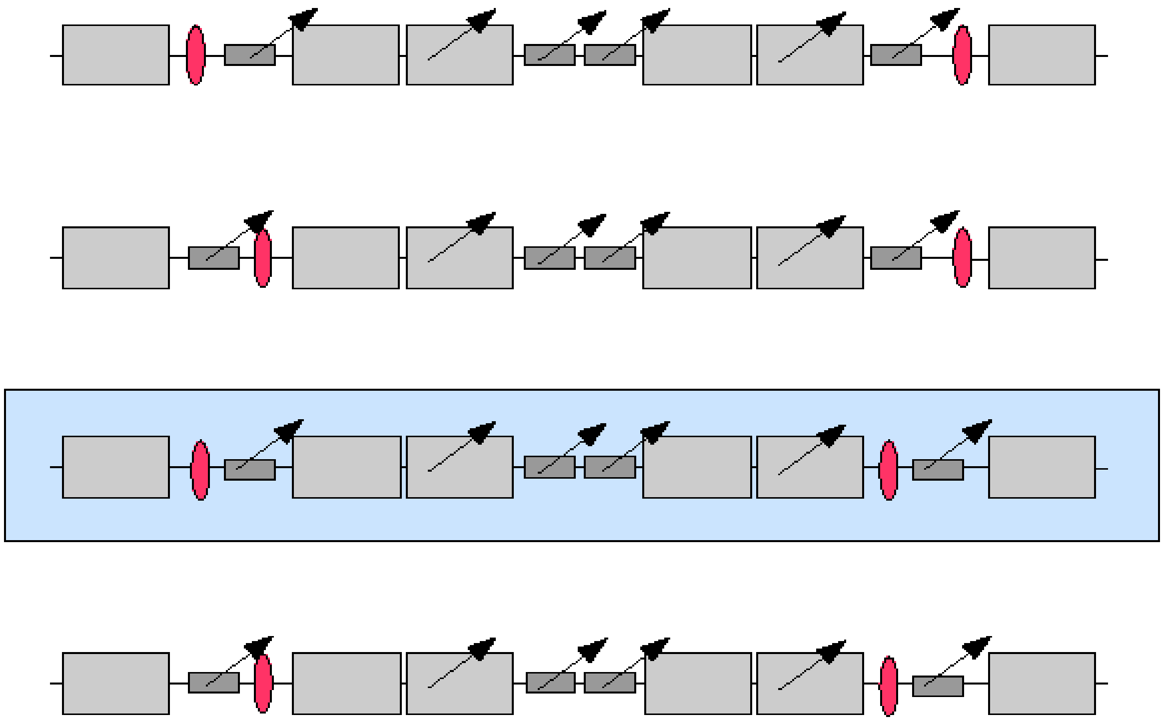
[1] M. Borland, PRSTAB 8, 074001 (2005).

Project goals

	Goals	Acceptable
Pulse duration (70% of the pulse)	1 ps	4 ps
Pulse length fluctuation	10%	10%
Pulse intensity fluctuation	1%	10%
Pulse timing jitter (fraction of pulse length)	10%	10%

Configuration options for APS upgrade



Long
SS
6ID

Short
SS
7ID

Long
SS
8ID

2 sector spacing
4ID + 2BM

2 sector spacing
3ID + 2BM

2 sector spacing
3ID + 2BM

2 sector spacing
2ID + 2BM

Limits on deflecting voltage

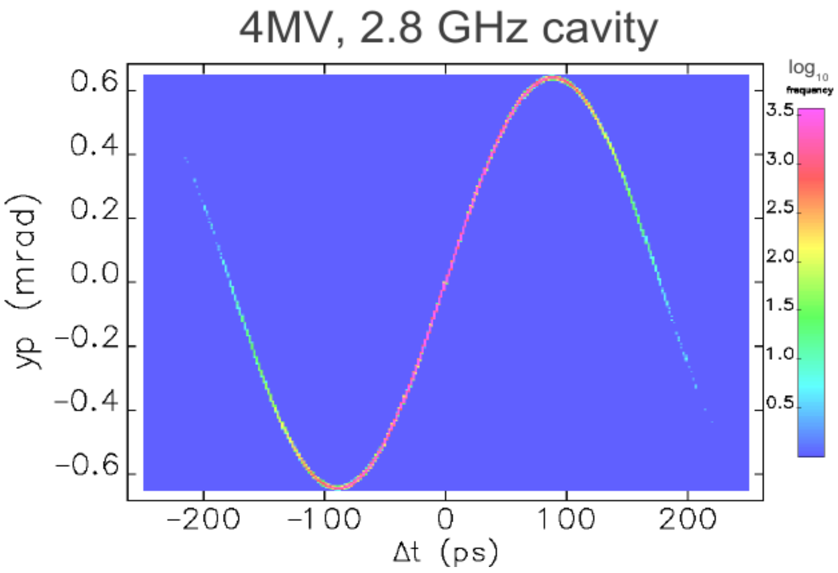
- Need sufficient voltage slope

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

- There are several limits on voltage:
    - Cavity surface field limits
    - Number of cells we can fit in straight section
        - Impedance of cells and difficulty of extracting LOMs and HOMs
    - Quantum lifetime
        - 8-mm ID vacuum chamber limits voltage to 4.1 MV for outside placement and to 7 MV for inside placement

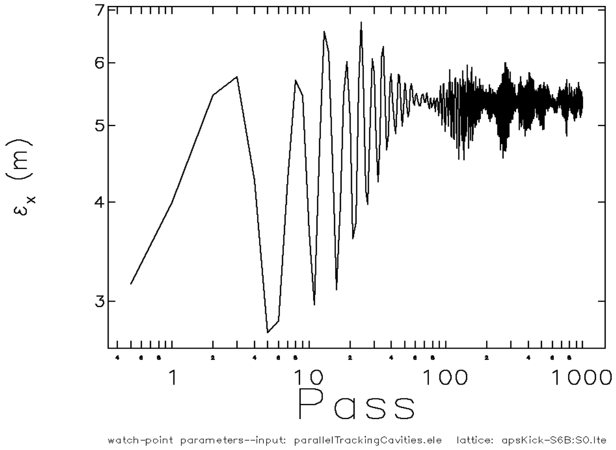
Choice of deflecting frequency

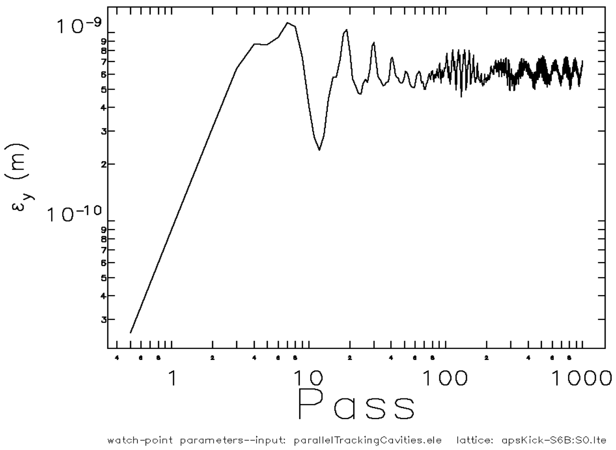
- Electron bunch length could be up to 50 ps
  - Higher frequency
    - Stronger perturbation of the beam
    - More particles at the next zero crossing
  - Lower frequency
    - Reduced voltage slope for the same peak voltage
- Other considerations
  - Availability of RF sources
- Combining these considerations led us to the choice of 2.8 GHz (h=8)



Emittance degradation[1]

- Soon after we started simulating the deflecting cavities, we have found significant emittance blowup in both planes
- This blowup undermines the whole concept – which takes advantage of the small vertical beam size
- It required us to understand the sources of the blowup before we could find ways of minimizing it
- Now we think we can limit the blowup to a reasonable level by optimizing sextupoles between the deflecting cavities





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

Various effects

- In a real machine, many effects could lead to emittance degradation
  - Various errors and imperfections are first things coming to mind
- However, even in a perfect machine the emittance can increase many fold
  - Path length dependence on the particle energy leads to incomplete kick canceling in the second cavity
  - Betatron phase advance dependence on energy (chromaticity) leads to closed bump condition breaking
  - Sextupoles between cavities introduce nonlinearities that generate betatron phase advance dependence on amplitude and linear coupling between horizontal and vertical planes

Momentum compaction

- This effect is present even if there are no errors and nonlinearities but usually small
- It comes from the path length difference between the cavities for particles with different energy
- Additional kick after the second cavity is

$$\Delta y' = \frac{-V \omega \Delta t}{E}$$

Which gives emittance increase of

$$\frac{\Delta \epsilon_y}{\epsilon_y} = \frac{\sqrt{\sigma_{y'}^2 + \sigma_{\Delta y'}^2}}{\sigma_{y'}} - 1$$

- For extreme case of V=6MV and h=8, it gives about 6% increase of emittance in a single turn

Chromaticity and energy spread

- The second cavity is placed at $n\pi$ phase advance to cancel the kick of the first cavity
- If there is chromaticity ξ_y between the cavities, the phase advance of a particle with δ_i is changed by $-2\pi\xi_y\delta_i$ which leads to a particle position change at the second cavity

$$y_2 = \beta y'_1 \sin(2\pi\xi_y\delta_i)$$

- The rms value of the residual amplitude is

$$\sigma_{y_2} = 2\pi\xi_y\beta\frac{V\omega}{E}\sigma_\delta\sigma_t$$

- For APS parameters with uncompensated chromaticity, this works out to a number that is almost 4 times as large as the nominal vertical beam size of 11 μm

Sextupole nonlinearities

- Sextupoles are required to compensate chromaticity

- Sextupoles can affect in two ways:

- By introducing amplitude-dependent focusing
  - For particles going off-axis in sextupoles, the kick cancellation at the second cavity is not perfect
  - For a beam slice, it results in a new closed orbit which amplitude depends on the longitudinal position of the slice
  - Small effect in vertical plane

- By introducing transverse coupling
  - deflecting cavities generate non-zero vertical trajectories in sextupoles
  - Creates coupling between large horizontal and small vertical emittances

Beam dynamics simulation methods

- We use tracking to simulate beam dynamics
- We use parallel elegant[1] typically utilizing 10-50 CPU cores
- Dipoles are modeled as first-order matrix, other magnets as kick elements
- Synchrotron radiation: single lumped elements for average energy loss and quantum excitation
- Accelerating cavities: single zero-length lumped element
- Potential well distortion is important for APS:
  - Bunch lengthening is 50% to 150% for typical fill patterns
  - Mock up by adjusting accelerating cavity harmonic and voltage

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

Deflecting cavity model

- Model cavities as multiple cells
  - 8 cells per cavity
    - Pillbox cavities with $\lambda/2$
    - Center-to-center spacing is $3\lambda/2$
  - Phasing in groups of 4 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 that results from combination of TE- and TM-lie fields[1]
  - Longitudinal electric field included to satisfy Maxwell's equations

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

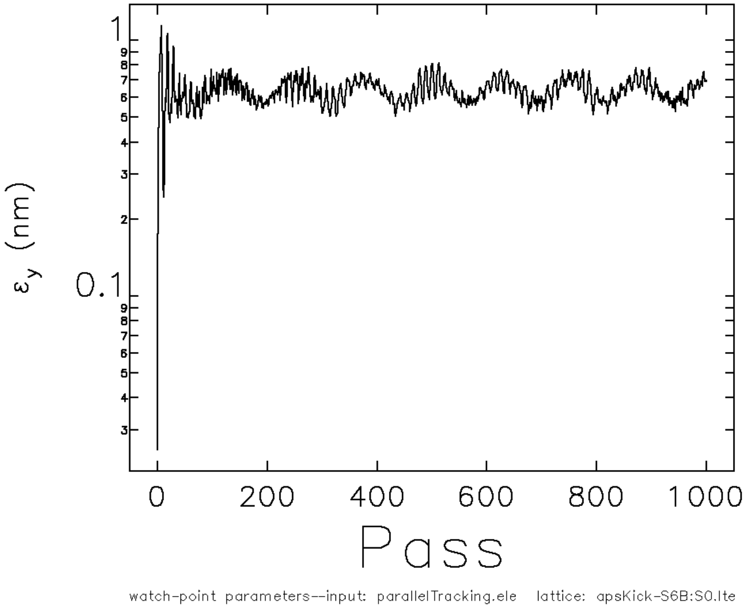
Sextupole optimization

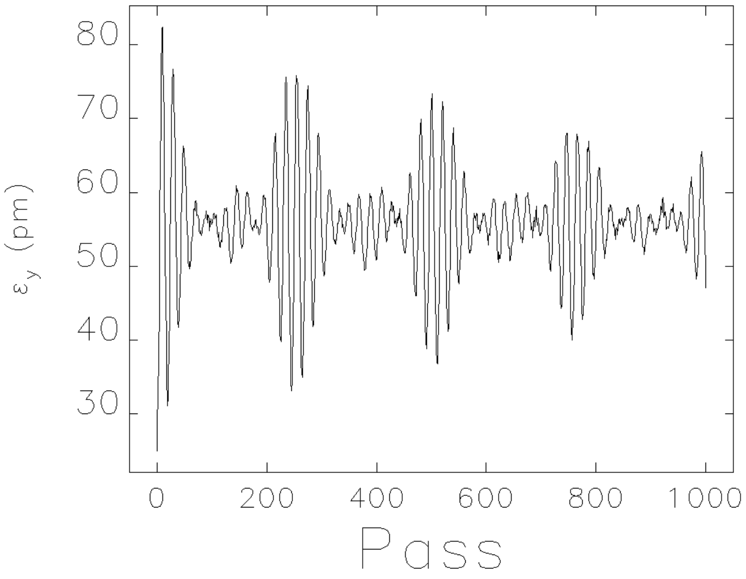
- Sextupole between the cavities are needed to:
  - Compensate natural chromaticity
- At the same time:
  - Minimize coupling on the vertical trajectory
  - Minimize orbit bump leakage to the outside of the bump
  - Maintain satisfactory dynamic aperture (DA) (due to sextupole optimization inside the bump, the sextupole symmetry would be broken)
  - Maintain satisfactory momentum aperture (MA)

- First items are required to keep emittance blowup under control
- Last 2 items are required to maintain good injection efficiency and lifetime of the storage ring
- We have found that if one would not care about the DA/MA, the emittance increase could be almost completely mitigated
- However, the DA/MA requirements limit the freedom of the sextupole changes

Sextupole optimization

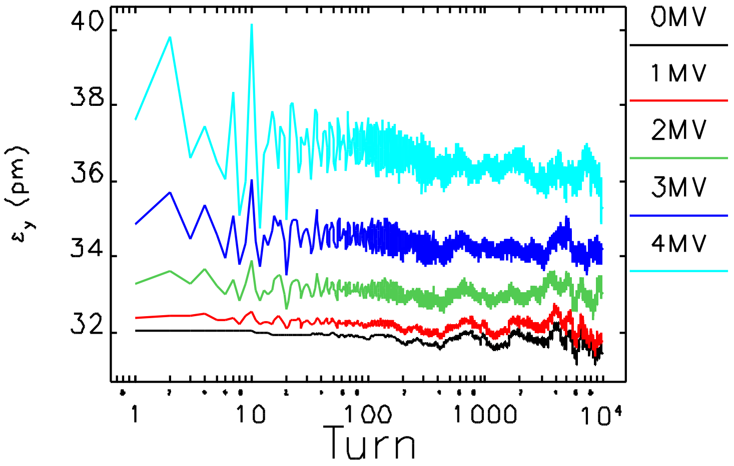
- Sextupole optimization is done using genetic optimizer
- Every optimizer evaluation consists of
  - Linear optics design
  - Interior sextupoles optimization for emittance blowup minimization
  - Exterior sextupole optimization for DA/MA
- It is very CPU-hungry process, but it gives satisfactory results:

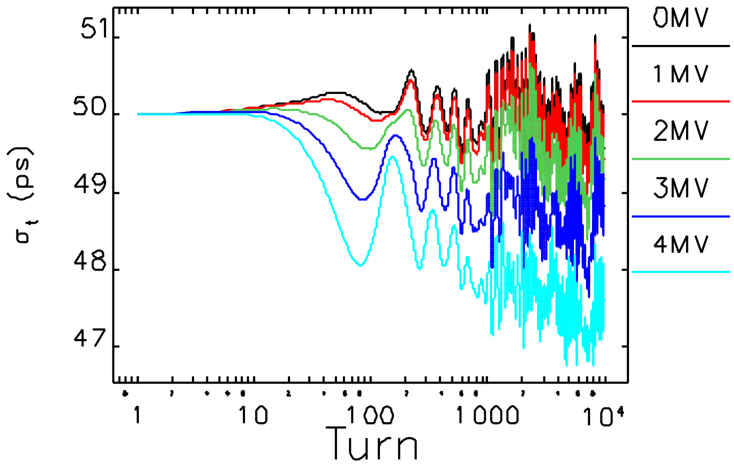


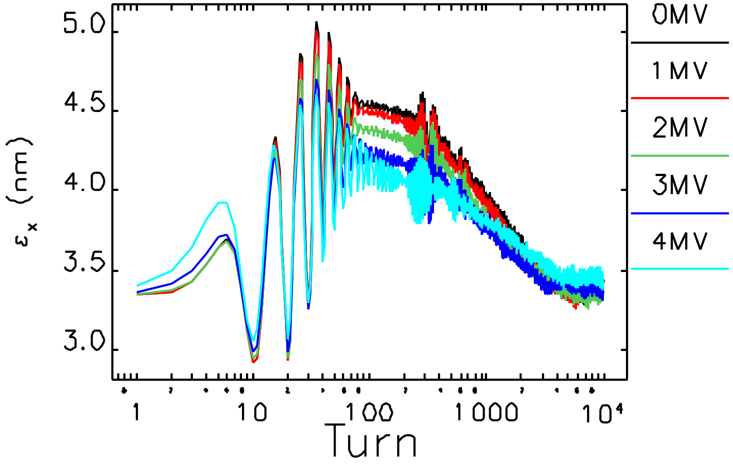


Simulating beam equilibrium

- Track 10k turns with 10k particles
- Average over last 2k turns to get "equilibrium" moments



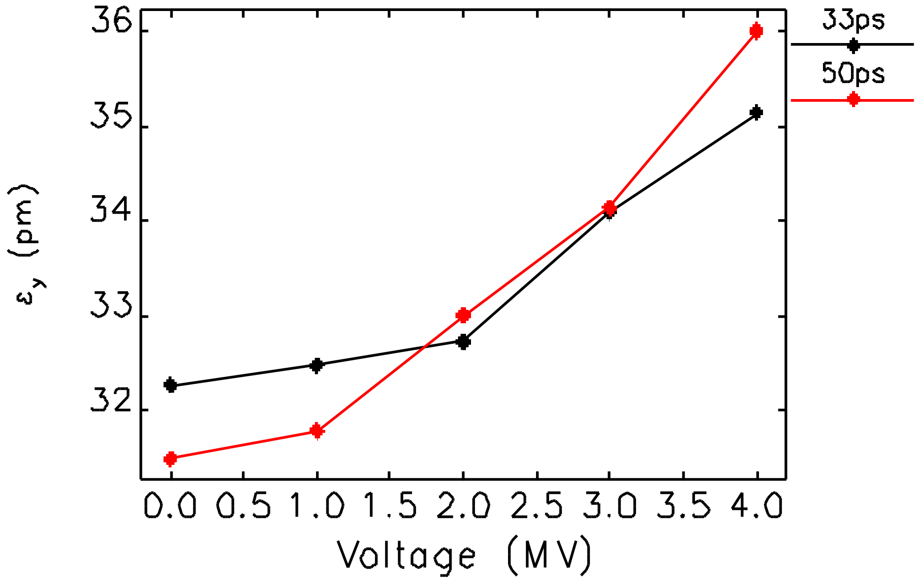




Equilibrium values

- Vertical emittance growth is modest
- Sextupoles were optimized for 50-ps-long bunch and 4MV
- Empirical result:

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



Setting tolerances: Emittance

- Keep vertical emittance **variation** under 10% of nominal 35pm
- Errors affecting the outside emittance
  - Differential crab voltage
  - Vertical betatron phase advance not equal to N*π
  - Beta function mismatch
  - Cavity and magnet roll
- Some of these errors are 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 corrected with additional skew quadrupoles
- Hence, all of our emittance budget is assigned to differential voltage error

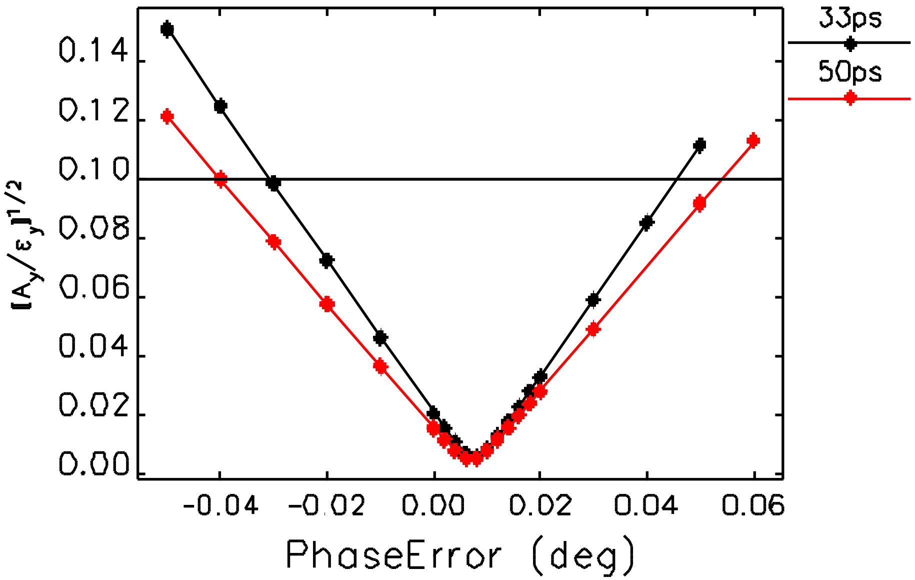
[1] M. Borland, PRSTAB 8, 074001 (2005).

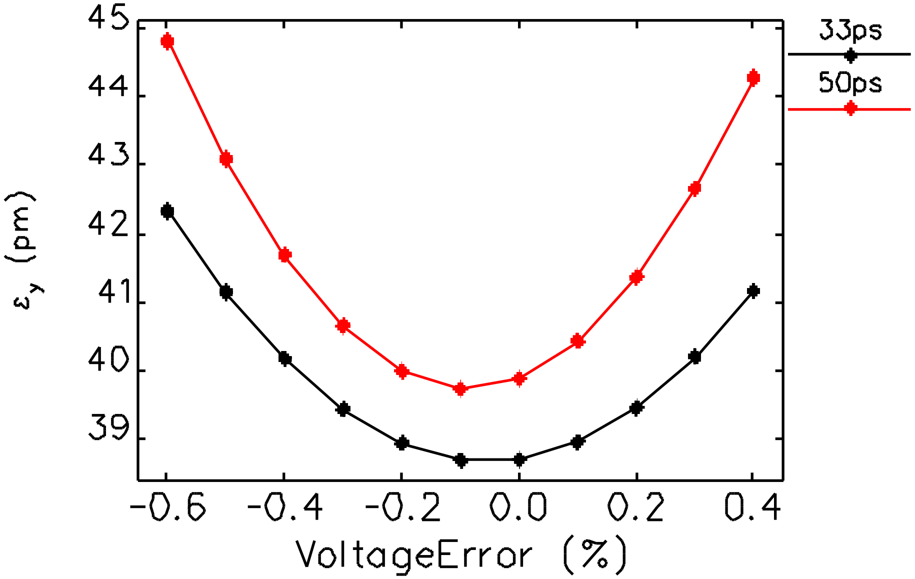
Setting tolerances: Orbit

- 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

Differential phase and voltage error

Outside orbit disturbance sensitive to differential phase error





Emittance is sensitive to differential voltage error

Common-mode voltage errors

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

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

- 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

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

- 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

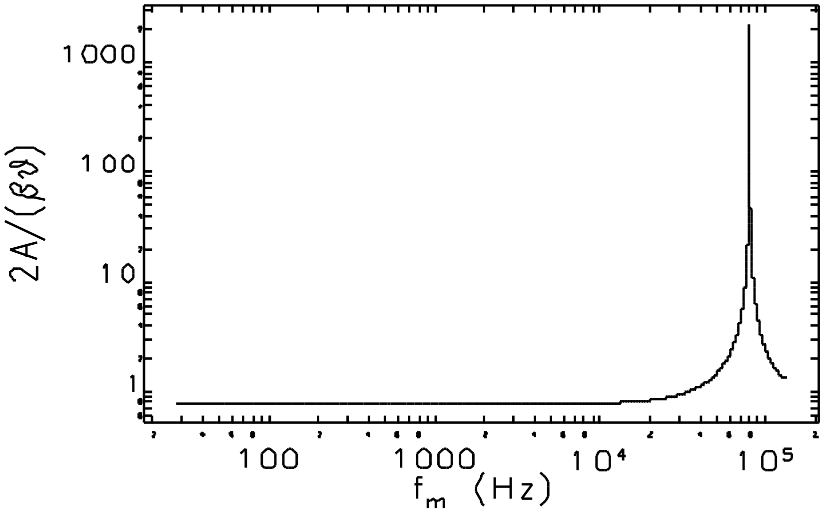
Summary of RF-related tolerances

Quantity	**Driving requirements**	**Tolerances**
Common-mode voltage	Keep intensity and pulse length variation under 1%	±1%
Differential voltage	Keep emittance variation under 10% of nominal 35 pm	±0.5%
Common-mode phase relative to bunch	Constrain intensity variation to 1%	±7 deg
Differential phase	Keep beam motion under 10% of beam size/divergence	±0.03 deg
Rotational alignment	Emittance control	Few mrad

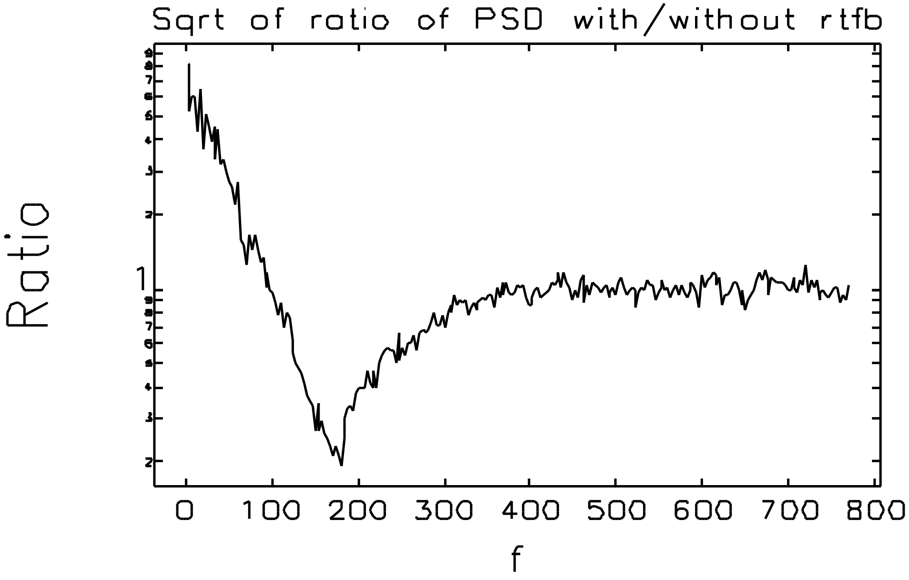
- Errors assumed to be "static", i.e., slowly varying compared to the damping time

Variable errors

- In reality, voltage and phase errors vary in time
- In a simple approximation of a varying centroid kick, the frequency dependence can be obtained analytically

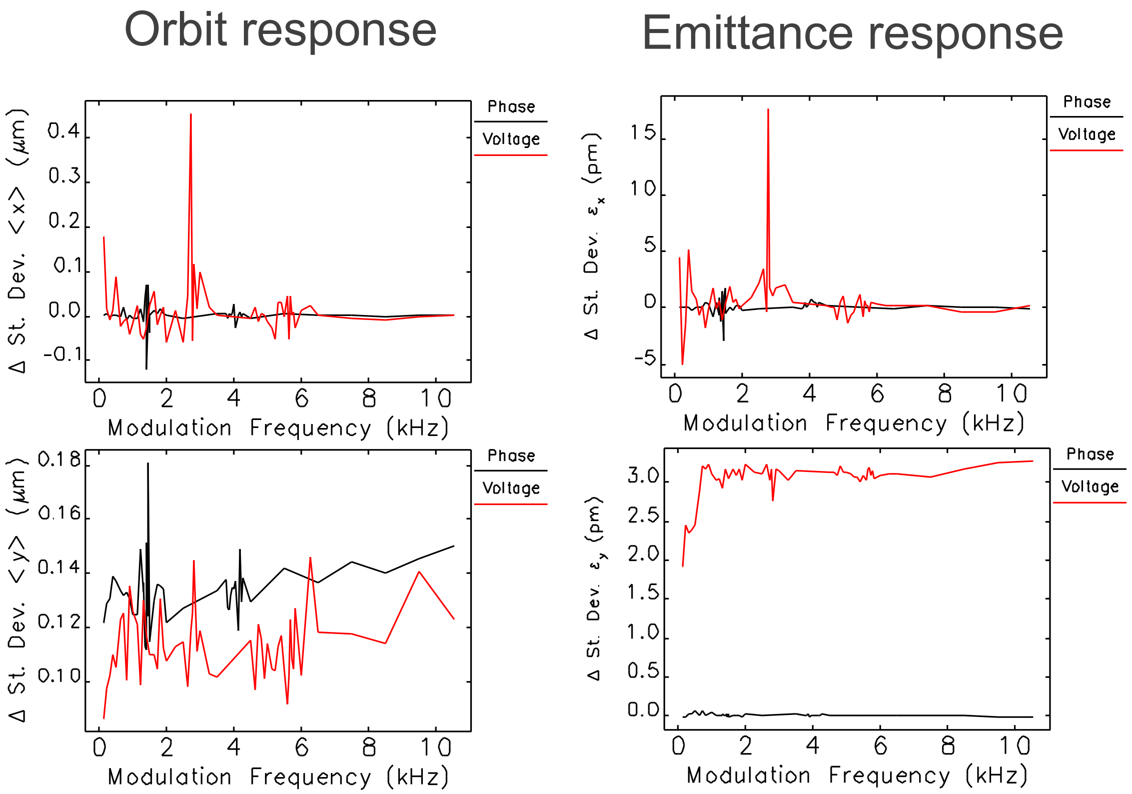


- Orbit correction helps in the low-frequency range



Variable errors - simulations

- Phase and voltage error was imposed on the second set of cavities
- Modulation amplitude was constant (1% in voltage and 0.1 deg in phase)
- Number of turns depends on the frequency

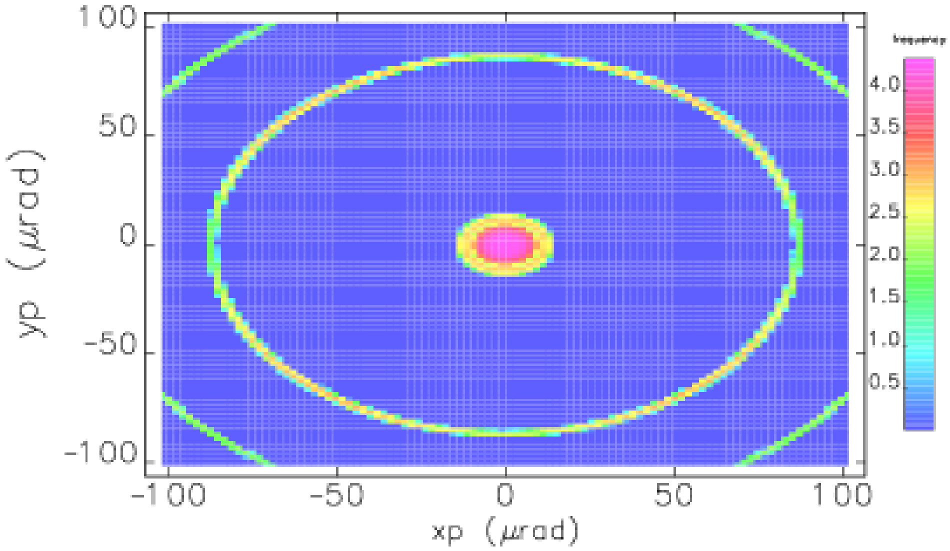


Orbit response

Emittance response

X-ray Slicing Simulation

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



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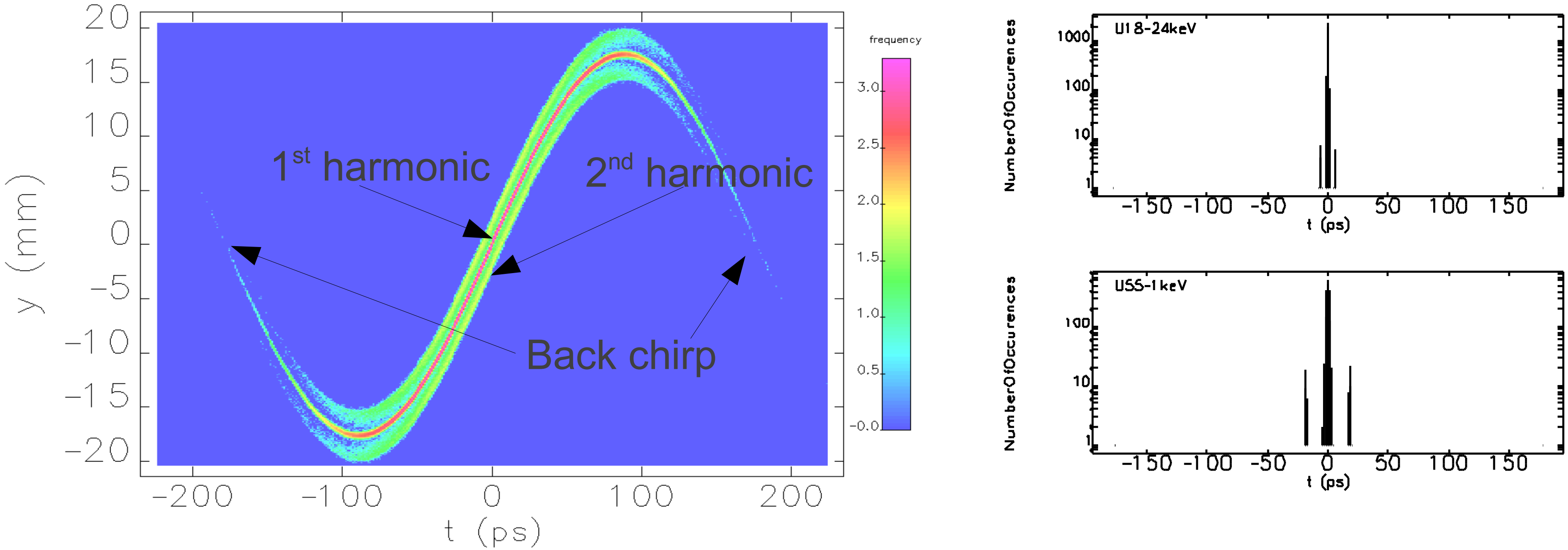
[1] H. Shang, R. Dejus, R. Walker, M. Borland.

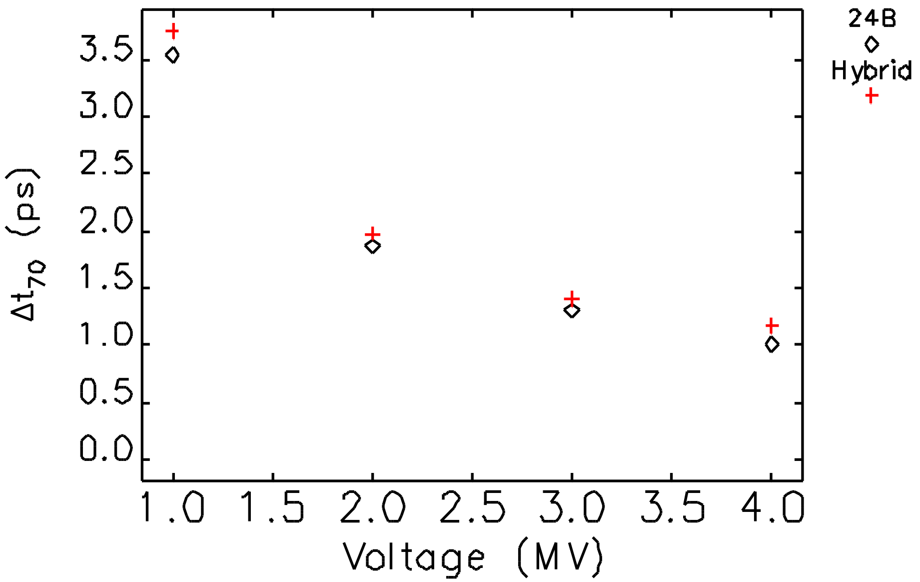
Radiation distribution 26.5 m from source (hybrid)



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.)

Pulse has complicated time structure

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

Conclusions

- 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

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- A lot of people contributed in to this work:
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