Beam Dynamics for Crab Cavities in the APS Upgrade

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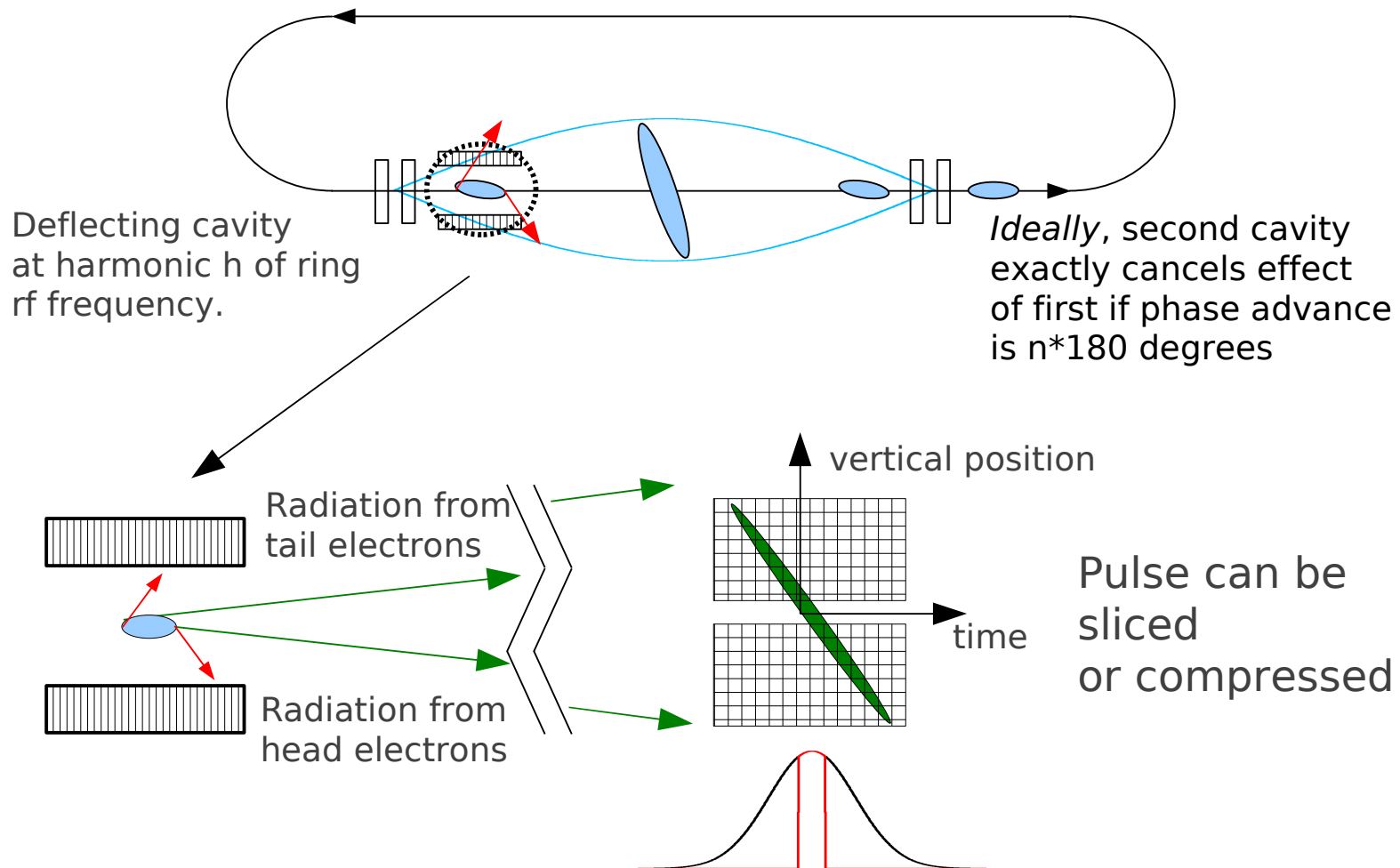5th TLEP Workshop July 25th-26th, 2013

Outline

- Why mention APS Upgrade at this workshop?
- Deflecting cavity scheme description
- Challenges in beam dynamics of crab cavities

Applications of deflecting cavities in storage rings

- Two major applications for deflecting cavities:
  - Restoring head-on collisions in crab crossing in colliders
    - Suppresses synchro-betatron resonances excited by crab crossing
  - Generating short X-ray pulses in light sources
    - Allows to take advantage of small vertical beam size to generate temporally short pulses
- Some beam dynamics issues are similar:
  - Additional impedance
  - Cavity generated beam noise
- Some are different
  - Beam-beam related effects in colliders
  - Coupling increase and related nonlinear dynamics complications in light sources
- Major difference is deflection plane: vertical for light sources and horizontal for colliders
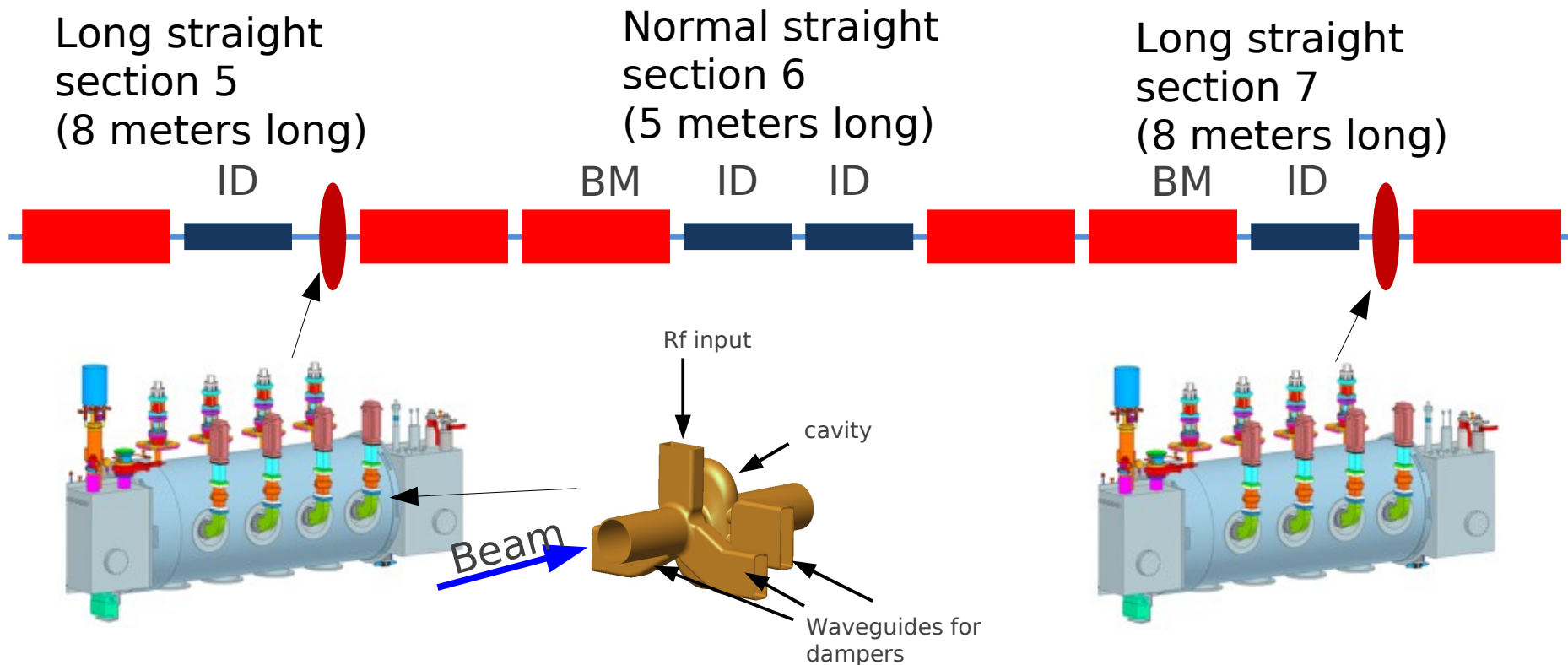
Deflecting cavities concept[1]

Deflecting cavity at harmonic h of ring rf frequency.

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

Radiation from tail electrons

Radiation from head electrons

vertical position

time

Pulse can be sliced or compressed

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

Short-Pulse X-ray source

- Few picosecond x-ray pulses by applying a local (y,y')-z correlation ("chirp") bump to stored beam
- Superconducting radio-frequency deflecting cavities operated in continuous-wave mode
- Up to 4 ID and 2 BM beam lines, operation in 24 singlets mode

Long straight
section 5
(8 meters long)

Normal straight
section 6
(5 meters long)

Long straight
section 7
(8 meters long)

ID

BM   ID   ID

BM   ID

Rf input
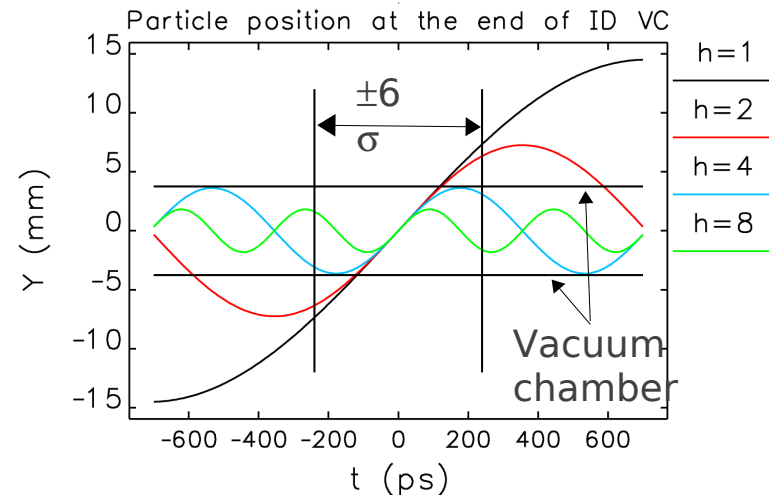
cavity

Beam

Waveguides for
dampers

Choice of parameters

- To obtain rms pulse length of 1 ps (2 ps FWHM), the deflecting voltage amplitude times harmonic has to be (assuming no changes to SR optics):

$$h\,V \approx \frac{E}{\sigma_s\,f_{rf}}\sqrt{\frac{\beta_{id}}{\beta_{rf}}}\sqrt{\frac{\epsilon_y}{\beta_{id}} + \frac{\lambda_{rad}}{2\,L_u}} \approx 15\,MV$$

- Cavities will share straight sections with insertion devices which means there will be narrow-gap vacuum chamber

- Large vertical beam size inside narrow-gap VC puts lower limit on frequency due to lifetime, *h > 4*

- Chosen deflecting voltage parameters: next to them

  V = 2 MV
  h = 8

Particle position at the end of ID VC

Effect of cavities on the beam

- Less than total kick cancellation at the second cavity could lead to beam emittance increase and to orbit distortion
- Nonlinear beam dynamics is affected
- Cavities introduce additional impedance, and therefore can affect single-bunch and multi-bunch instabilities

Effect on emittance

- 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 ways
    - 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 comes from the path length difference between the cavities for particles with different energy
- This effect is present even if there are no errors and nonlinearities
- For a particle with energy deviation δ_i, the time of flight differential $\Delta t_i = \alpha_c \delta_i T_0$
- Additional kick after the second cavity is $\Delta y_i' = \dfrac{-V \omega \Delta t_i}{E}$

  which gives emittance increase of

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

- For APS case, it gives about 0.3% increase of emittance in a single turn which gives negligible effect on overall emittance increase

Chromaticity

- The second cavity is placed at $n\pi$ phase advance to cancel the kick of the first cavity
- If there is non-zero 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

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

- 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 (no sextupoles in these two sectors), this works out to be over 50% of the nominal vertical beam size of 11 μm
- **To avoid this emittance increase, sextupoles are required between the cavities**

Sextupole nonlinearities

- Introduces amplitude-dependent focusing
  - for particles going off-axis the kick cancellation at the second cavity is not perfect
- Introduces transverse coupling
  - deflecting cavities generate large vertical trajectories in sextupoles
  - Vertical trajectory in sextupoles creates coupling between large horizontal and small vertical emittances
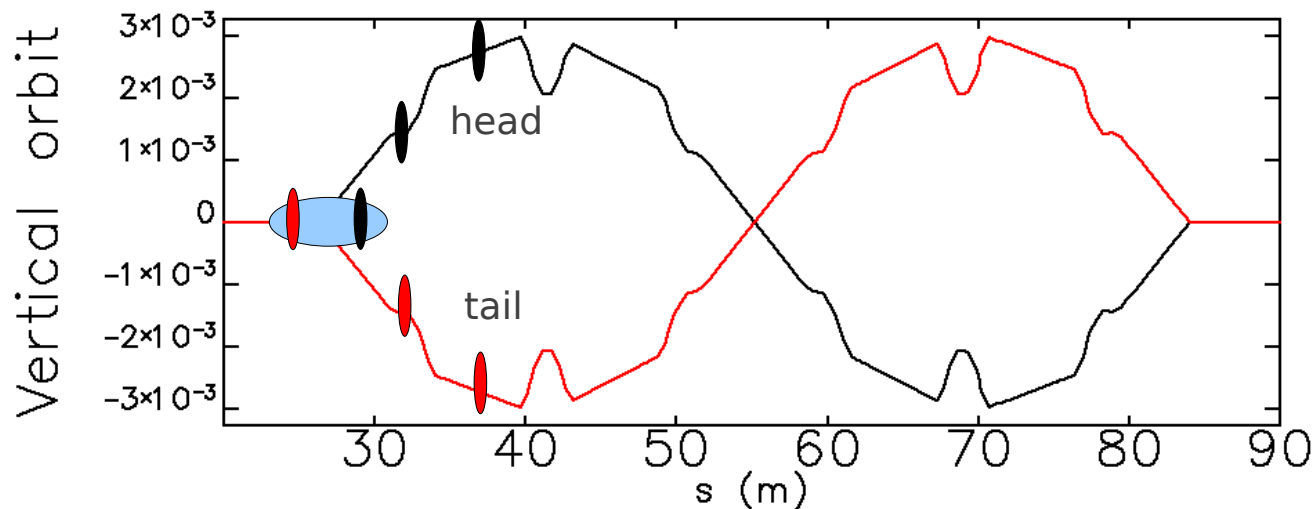
Beam dynamics simulation methods

- We use tracking to simulate beam dynamics
- We use parallel elegant[1] typically utilizing 10-50 CPU cores
- Accelerating cavities are required to simulate synchrotron motion
- Synchrotron radiation is essential: to damp initial cavity effects
    - Tracking is done for 10k turns – about 4 damping times
- Deflecting cavity is simulated as TM-like mode, deflection is radius independent resulting from combination of TM- and TE-like field[2]
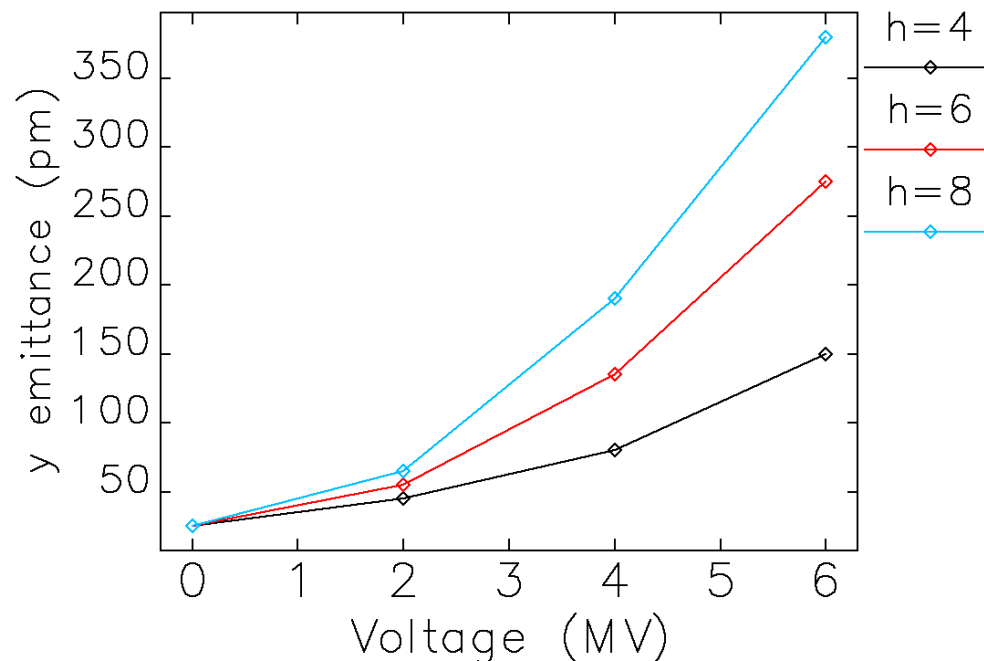
[1]Y. Wang et al., AIP 877, 241 (2006).

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

Initial results of the deflecting cavity application

- Right away, we have found significant blow-up of vertical emittance due to increased coupling. This can be fixed by adjusting sextupole gradients in the two sectors, but creates a major problem

# Nonlinear dynamics challenge in general

- Light sources tend to minimize their beam emittance to the level where Dynamic Aperture (DA) and lifetime are barely enough for operation

- Many sextupole families are utilized to achieve workable DA and lifetime, i.e. for symmetric optics without deflecting cavities.

- A local sextupole adjustment that minimizes vertical emittance growth will violates the earlier sextupole optimization of the whole ring

- Even small reduction of DA and lifetime can be crucial

- Further investigations requires including the deflecting cavity effects on nonlinear dynamics

- The cavity effects are defined by large vertical trajectories between deflecting cavities:

  - Physical acceptance is decreased

  - Additional linear and nonlinear coupling is introduced

Injection and lifetime with deflecting cavities

Lifetime reduction with original sextupoles
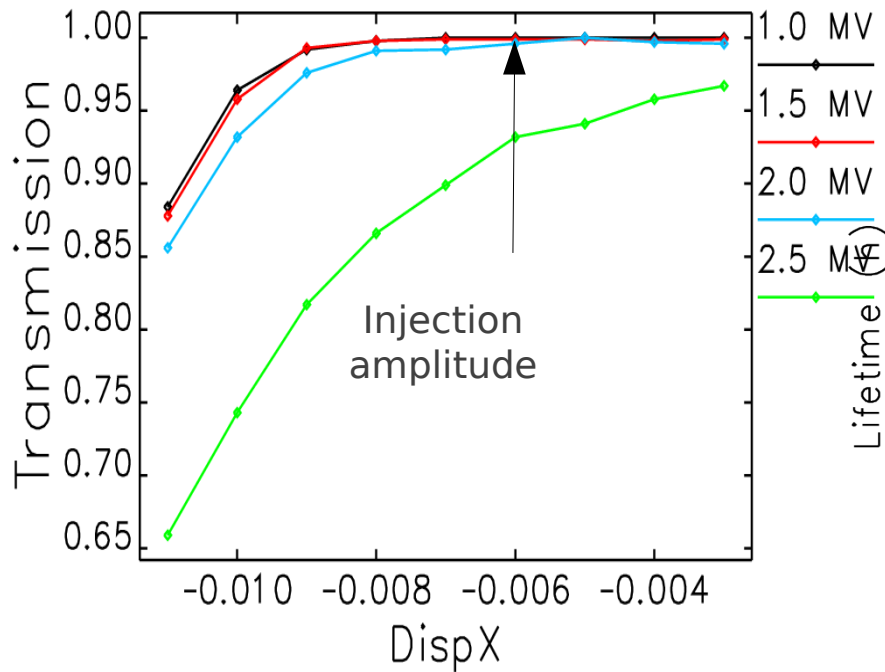
Reduction due to vertical physical aperture
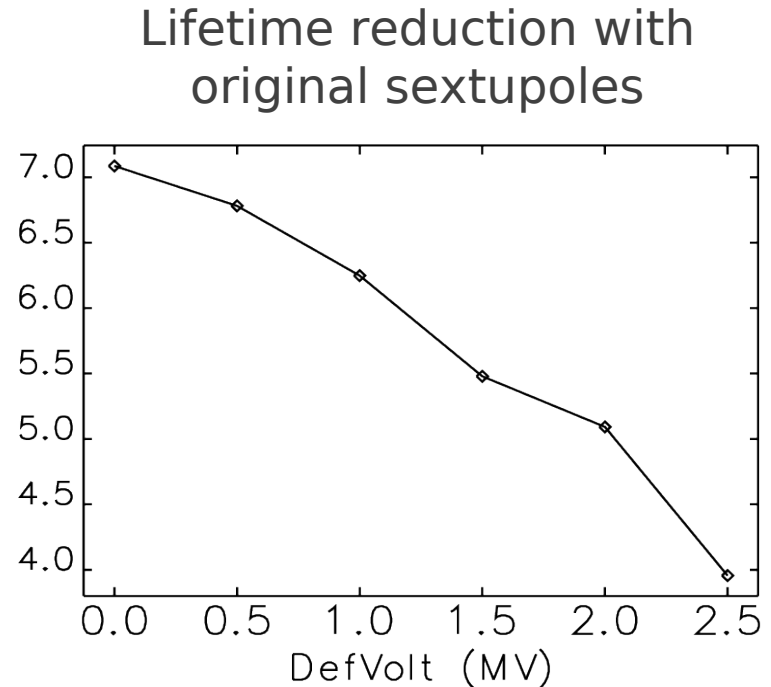
Reduction due to a skew sextupole resonance with original sextupole distribution

Sextupole optimization with deflecting cavities

- Sextupoles between the cavities are needed to compensate for natural chromaticity
- At the same time large vertical trajectories in sextupoles lead to vertical emittance increase and nonlinear dynamics deterioration
- Optimization of sextupoles between cavities allows to solve each problem separately
- Now we need to satisfy everything at the same time
- The best way to do it is to use multi-objective optimization, and do it as a part of overall lattice design

Sextupole optimization (2)

- The optimization is done using a genetic optimizer
- Every optimizer evaluation consists of
  - Linear optics design (if required)
  - Interior sextupoles optimization for vertical emittance blowup minimization
  - Exterior sextupole optimization for DA/LMA
- The penalty functions are vertical emittance increase, DA area, and lifetime
- It is very CPU-hungry process, it requires parallel computations, but it gives satisfactory results
  - We are able to achieve satisfactory dynamic aperture and lifetime without any increase of vertical emittance
- DA/LMA evaluation with cavities on is not included in optimization yet

Vertical emittance after global sextupole optimization

- Particles are tracked for 10k turns (several damping times)
- Sextupoles were optimized for extreme case of 50-ps-long bunch and 4MV
- Vertical emittance growth below 10% is achieved
- Two bunch lengths corresponding to two different operating conditions are shown
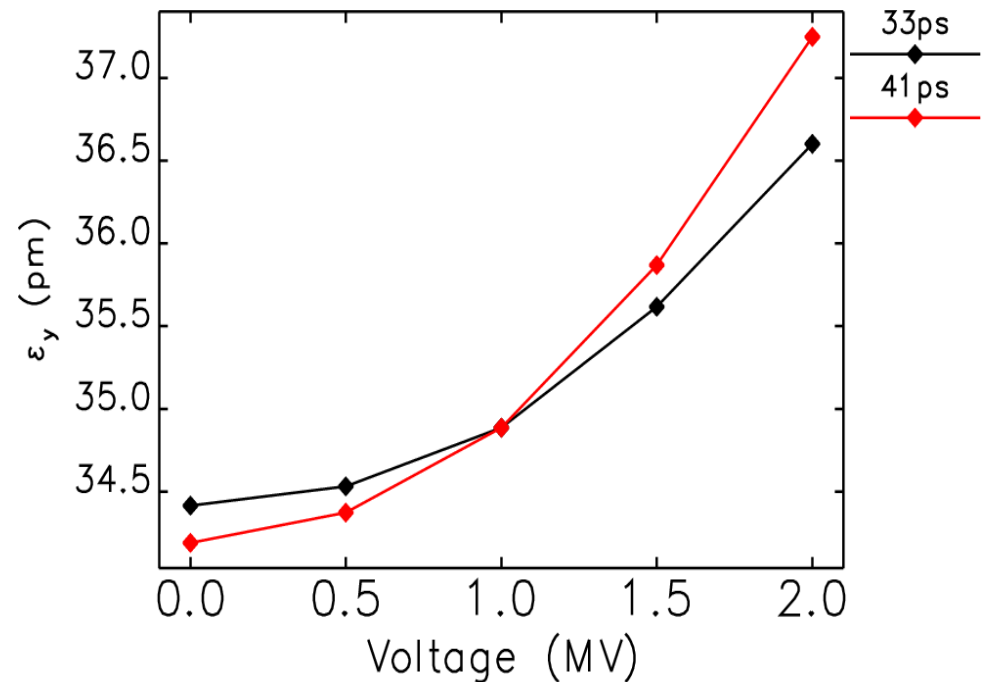
Deflecting voltage tolerances

- The voltage could vary in amplitude and phase, and variations at both cavities could follow each other (common-mode) or not (differential-mode)
- Common-mode variations affect the beam only between the cavities
  - Important for colliders
  - Not as important for light sources because the beam size between cavities is greatly increased
- Differential-mode variations affect the beam everywhere
  - Give very tight tolerances for light sources due to small vertical beam sizes
- Will not talk about common-mode tolerances

Differential mode tolerances

- When the voltage waveform in the second cavity does not exactly follow the first cavity, the resulting effect of two cavities on the beam is non-zero:

$$V \sin(\omega t) - (V + \Delta V) \sin(\omega t + \Delta \phi) \approx V \cos(\omega t) \sin(\Delta \phi) - \Delta V \sin(\omega \phi)$$

- The first term provides a net orbit kick because its value is non-zero at the center of the bunch ($t=0$)

- The second term generates beam tilt outside of the deflecting cavities and affects projected beam sizes

- The effect can be treated as a single source orbit distortion and a single deflecting cavity with voltage ΔV.
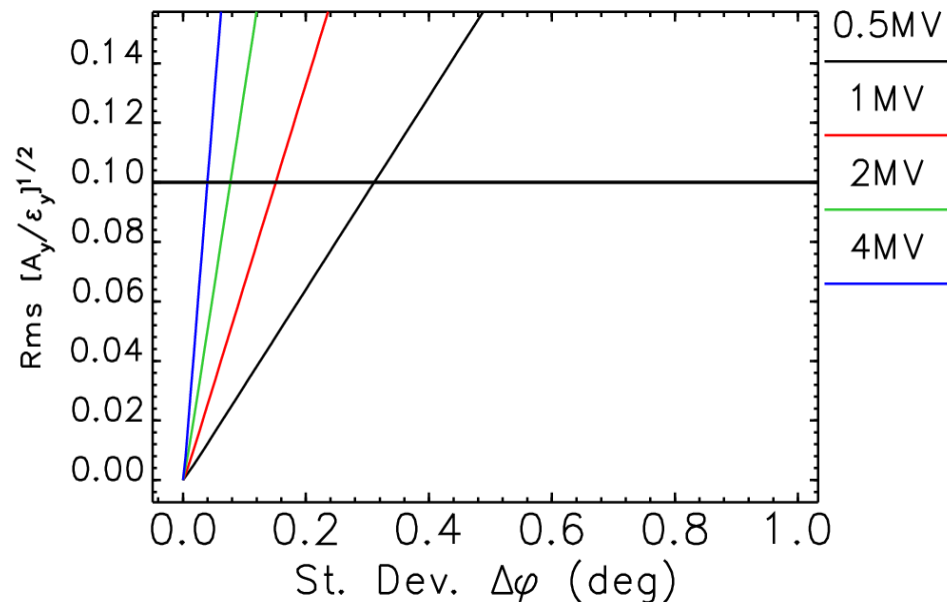
Tolerances: Orbit

- Want to keep orbit variation under some fraction of nominal beam emittance (total APS beam motion budget in terms of beam motion invariant is 1% of beam emittance)

- Using APS parameters, we get:

$$\Delta\phi < 0.08 \text{ deg or } 80 \text{ fs}$$

- This is quite a tight tolerance for rf phase

Tolerances: Emittance

- Various errors affect the outside beam sizes
  - Differential deflecting voltage
  - Vertical betatron phase advance not equal to N*π
  - Beta function mismatch
  - Cavity and magnet roll
- All these errors except differential deflecting voltage 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 sets of cells in second cavity
  - Cavity roll is found to be a weak effect[1]
  - Magnet roll can be corrected with additional skew quadrupoles
- We will only look at effect of differential voltage errors

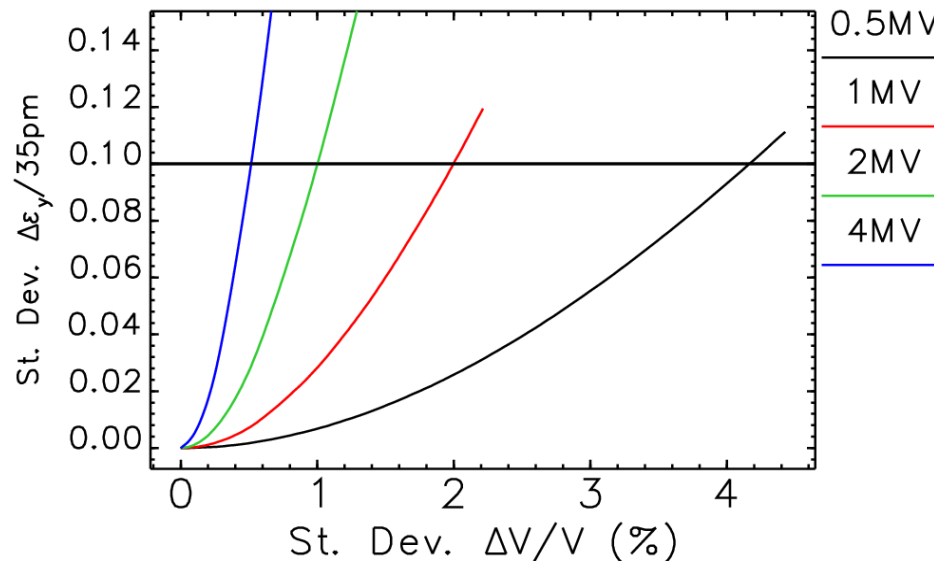[1]M. Borland, PRSTAB 8, 074001 (2005).

Tolerances: Emittance (3)

- If we require that the beam size increase does not exceed 10% of the total beam size, for APS parameters we get:

$$\frac{\Delta V}{V} < 0.01$$

- Realistic tracking simulations of the emittance sensitivity to the voltage errors show good agreement:

Collective effects

- Can be separated into short- and long-range effects
- Long-range effects generate multi-bunch instabilities
- Short-range wake fields limit single bunch current

Cavity impedance requirements

- Initial estimates of largest allowable resonator impedances (assuming high Qs) for bunch train stability were given to rf designers

Shunt impedance	Limit
Longitudinal	
$(R_s f_{HOM})$ for one monopole HOM/LOM	0.44 MΩ-GHz
R_s for one monopole HOM/LOM at 2 GHz	0.22 MΩ
Transverse	
R_t for one x-plane HOM/LOM	1.3 MΩ/m
R_t for one y-plane HOM/LOM	3.9 MΩ/m

- Dampers were designed that produced very low Qs and shunt impedances
- Monte Carlo simulations of the damped-Q HOM resonators (with randomized frequency) verifies stable beam conditions

Collective effects (2)

- Short-range wake fields could limit single bunch current
- Additional impedance comes from cavities and vacuum chamber transitions
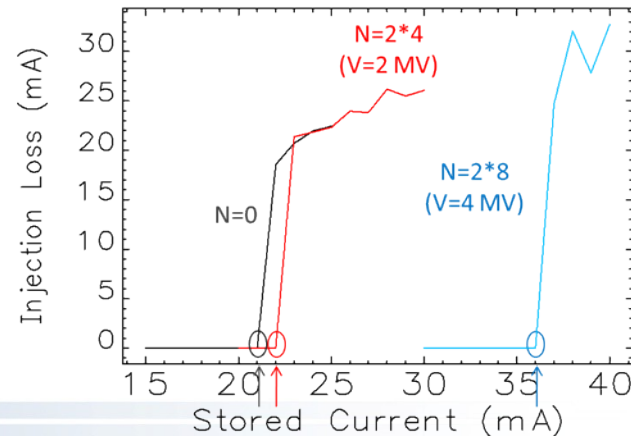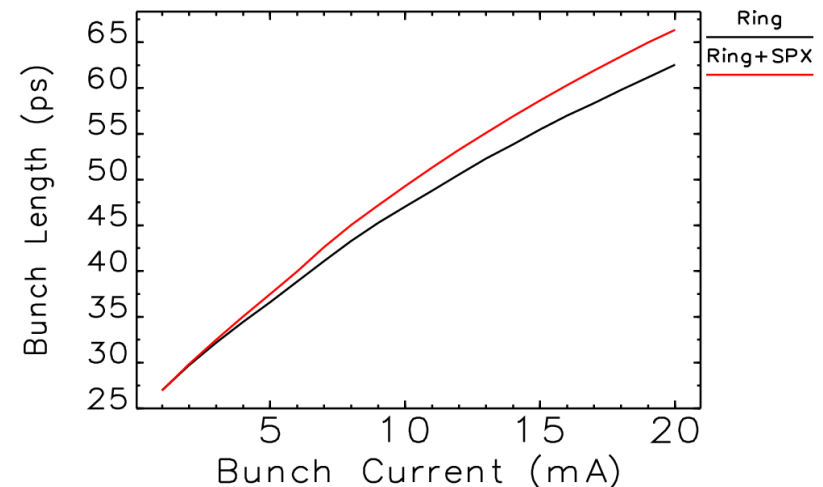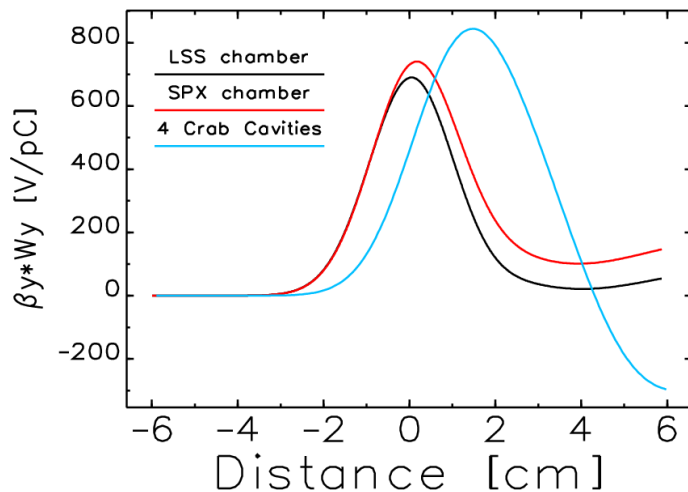
Cavity alignment requirements

- Cavity misalignment has several effects:
    - Beam-induced power generation due to transverse misalignment could damage the rf components
    - Beam arrival jitter combined with transverse offset leads to rf phase noise
    - Cavity roll can affect beam emittance
- Beam orbit can only be steered through "average" cavity center but cavity-to-cavity misalignment cannot be compensated
- Realistically achievable alignment is taken into account

	Cryomodule alignment	Cavity inside cryomodule
ΔX	$\pm 500 \ \mu m$	$\pm 500 \ \mu m$
ΔY	$\pm 200 \ \mu m$	$\pm 200 \ \mu m$
ΔZ	$\pm 1000 \ \mu m$	$\pm 1000 \ \mu m$
Yaw	± 10 mrad	± 10 mrad
Pitch	± 10 mrad	± 10 mrad
Roll	± 10 mrad	± 10 mrad

Here X is horizontal, Y is vertical, and Z is longitudinal directions.

Conclusions

- Deflecting cavities could affect single particle beam dynamics through nonlinearities on large trajectories between the cavities
  - Sextupoles and nonlinearities of the deflecting fields could limit momentum and dynamics aperture
  - Sextupoles could greatly increase transverse coupling
  - Sextupole distribution solved by genetic algorithm and massive tracking on computer cluster
- Cavities could increase beam emittance and generate beam motion through rf noise in cavities
  - Leads to engineering tolerances
- Cavities introduce additional impedance, and therefore can affect single-bunch and multi-bunch instabilities
  - Approach the same way as other rf cavities, i.e. dampers, careful design of tapers, feedback systems.