X-ray Slicing and Compression Using Deflecting Cavities at the Advanced Photon Source: a Feasibility Study

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Argonne NATIONAL LABORATORY

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Science drivers for picosecond x-rays

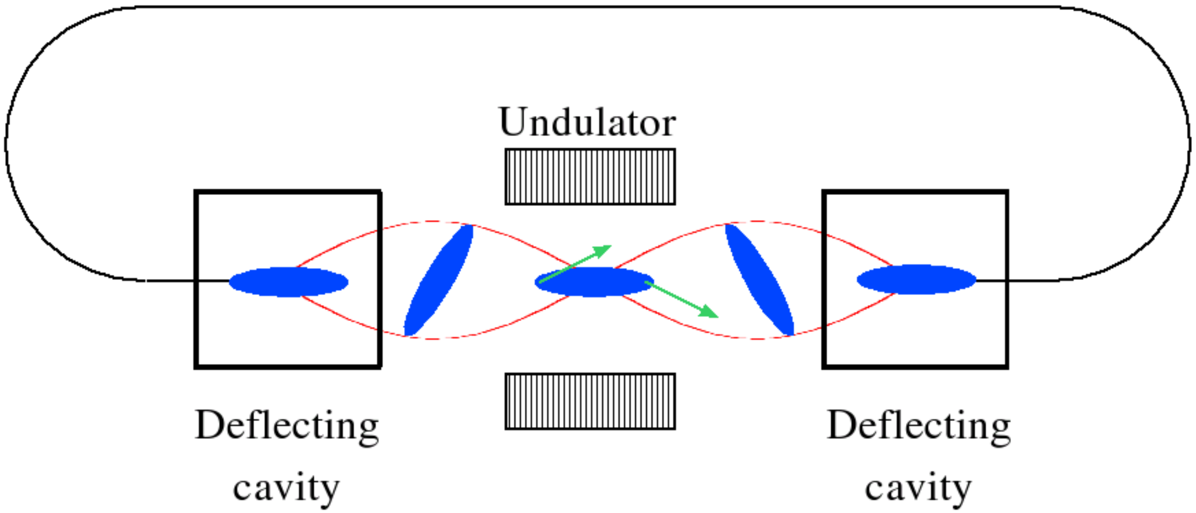
- **APS Strategic Planning Workshop (Aug 2004): Time Domain Science Using X-Ray Techniques:**
  - *"…by far, the most exciting element of the workshop was exploring the possibility of shorter timescales at the APS, i.e., the generation of 1 ps x-ray pulses whilst retaining high-flux. This important time domain from 1 ps to 100 ps will provide a unique bridge for hard x-ray science between capabilities at current storage rings and future x-ray FELs."*
- **New possibilities in:**
  - Atomic and molecular physics
  - Condensed matter physics
  - Biophysics/macromolecular crystallography
  - Chemistry

Producing shorter x-rays in storage rings

- Decreasing equilibrium electron bunch length by reducing momentum compaction factor
  - Allows to achieve a few picosecond FWHM length
  - BESSY has adopted such operation regime and ALS is studying it
  - Main disadvantage – increased emittance and very low beam current
- Using a short femtosecond laser to accelerate a small fraction of electrons in a bunch; radiation from those electrons can later be separated from the radiation of the main bunch
  - X-ray pulse length defined by the laser, can be as low as 100 fs
  - ALS and BESSY have operating beamlines
  - Main disadvantage – very low flux, about 10^{-4} or less of the total radiation
  - Requires too much laser power if applied to high energy light source like APS (7 GeV)
- Using deflecting cavities to chirp electron (and x-ray) bunches[1]
  - Idea by A. Zholents, was not tried yet

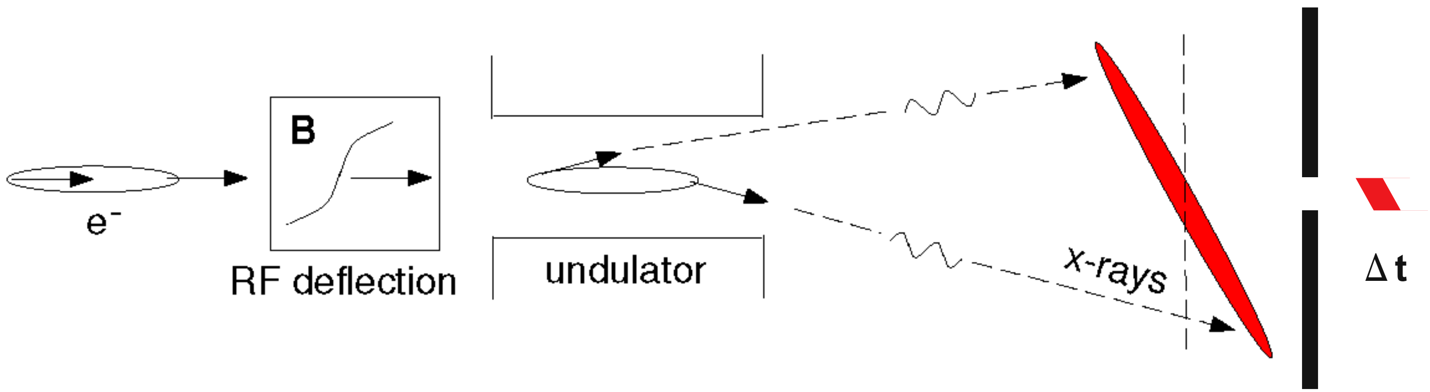
[1] **A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A425 (1999)**

Concept review



- Deflecting ("crab") cavity operates at TM110 mode such that it deflects head and tail of bunch in opposite directions vertically
- Electron vertical momentum is correlated with longitudinal position, photons follow the direction of electrons
- Second deflecting cavity is used to cancel the kick; rest of the storage ring is unaffected

X-ray pulse slicing using slits



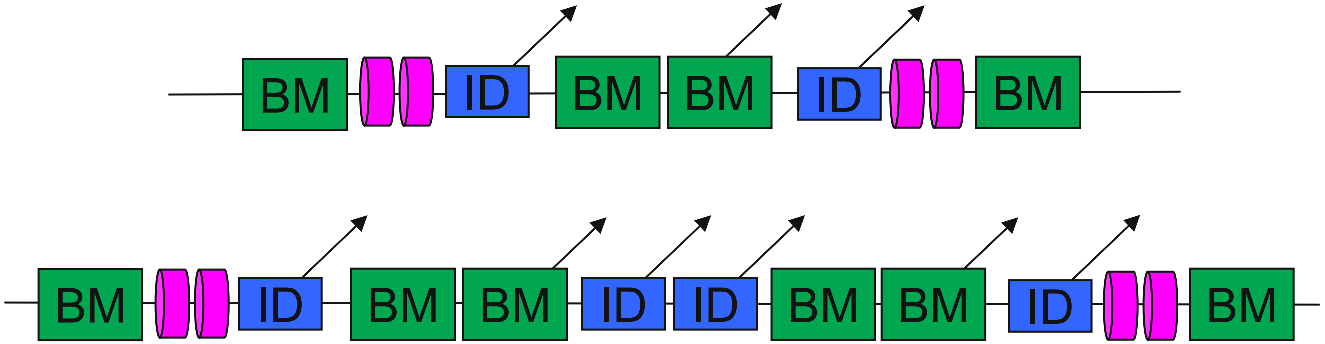
Assuming everything is linear, the minimum achievable pulse for a long beamline is

$$\sigma_{t,xray} = \frac{E}{V\omega}\sqrt{\sigma^2_{y',e} + \sigma^2_{y',rad}}$$

For APS, 6 MV and 2.8GHz deflecting system gives estimated pulse length of 0.4 ps rms.

Lattice options

- Lattice has to be modified to satisfy phase advance between cavities: It is easy to accomplish since phase advance per one lattice cell is 0.49 and all APS quadrupoles have separate power supplies
- ID straight section length is 5-m-long; half is assumed to be occupied by the deflecting cavity



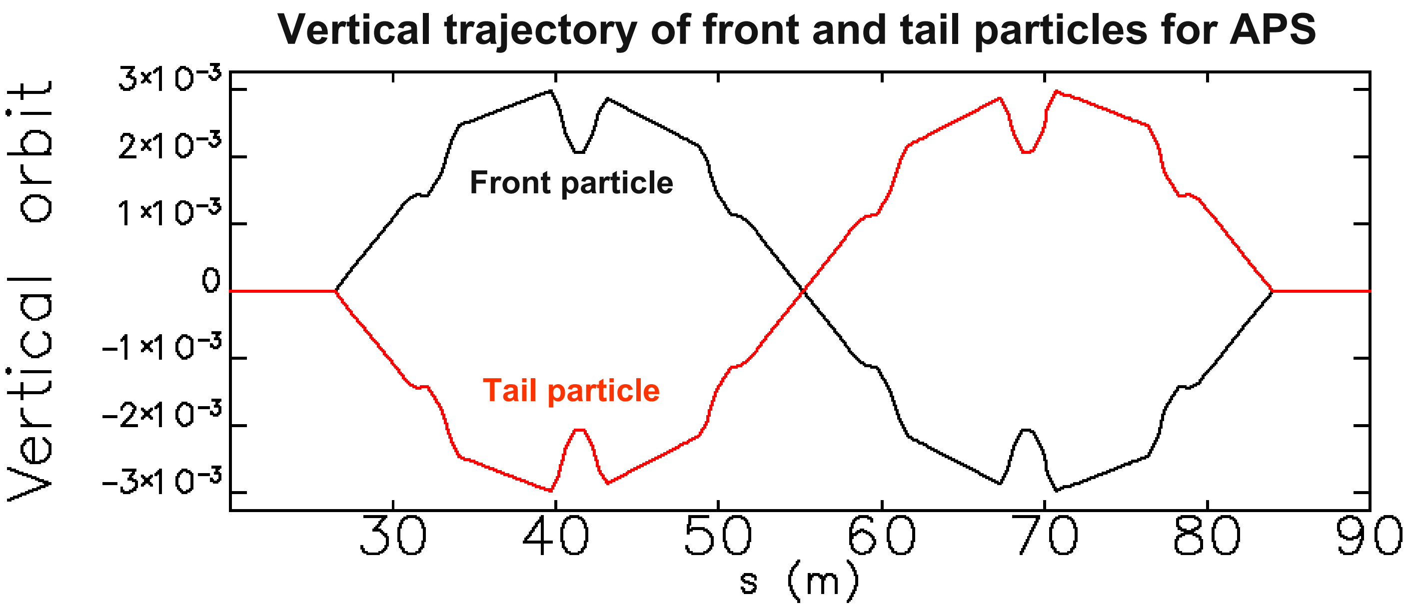
1 sector spacing
2 ID + 1 BM

2 sector spacing
4 ID + 2 BM

- 2 sector spacing will be assumed here

Beam trajectories

- After kick in the first cavity, front particles start moving up and tail particles start moving down with amplitude proportional to their longitudinal position in the bunch
- In an ideal linear system with zero energy spread, the second cavity completely cancels vertical motion of all particles



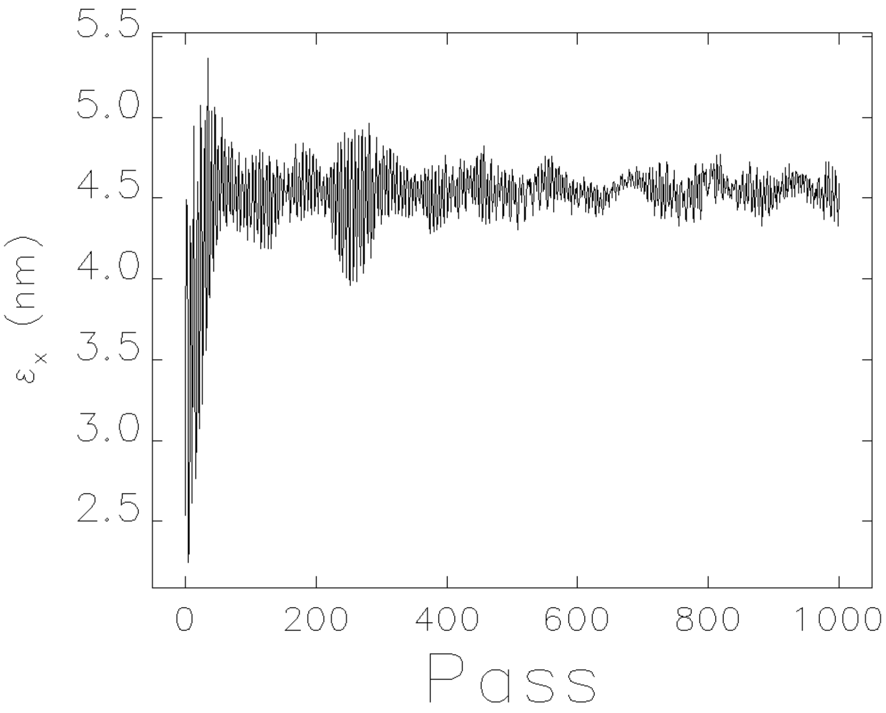
Emittance degradation

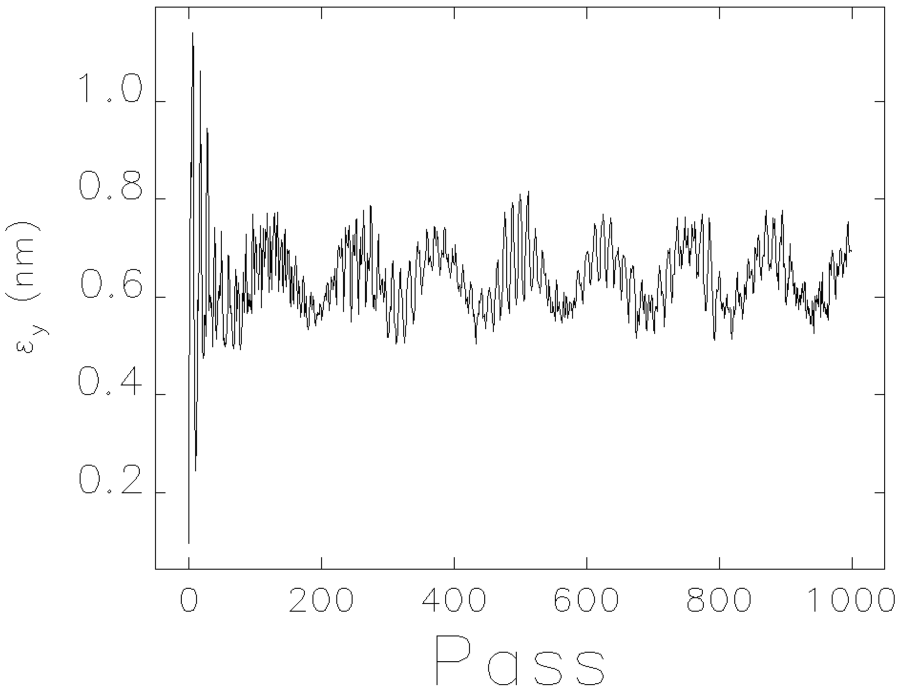
- Effect of deflecting cavities on the beam was studied using tracking[1]. A realistic bunch containing 1000 particles is used.
- Less than total kick cancellation will lead to emittance increase
- Effects that are present in a perfect machine:
  - Momentum compaction and beam energy spread
  - Chromaticity and beam energy spread
  - Sextupole nonlinearities
- Additional effects in an imperfect machine:
  - Lattice errors
  - Lattice coupling between cavities
  - Roll of cavities about axis beam
  - RF phasing and voltage errors

1. M. Borland, elegant: A flexible SDDS compliant code for accelerator simulation, APS LS-287, 2000

Tracking simulations

- Natural emittances are ε_x=2.5 nm and ε_y=0.025 nm
- Emittance as a function of turns in an ideal machine with sextupoles (6MV and 2.8 GHz deflecting cavities)





Momentum compaction[1]

- Momentum compaction is the variation in time-of-flight with energy error
- APS beam has 0.1% rms energy spread
  - For 6 MV, added divergence is 0.8 μm
  - Normal beam divergence is 2.2 μm
  - Vertical emittance growth is 6% in a single pass

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

Chromaticity[1]

- Chromaticity is the variation in phase advance with energy error
- When chromaticity is compensated between the cavities – no emittance growth due to chromaticity. However, if the interior sextupoles turned off, there is very large phase variation between cavities
- APS beam has 0.1% rms energy spread
  - Results in beam spread in the second cavity of 41 μm for 6 MV and 2.8 GHz for uncompensated chromaticity
  - Nominal beam size is 11 μm
  - Vertical emittance increases 3.7-fold in a single pass

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

Sextupole effects

- For a particle traveling with non-zero vertical trajectory, sextupole field is

$$B_y = \frac{1}{2} S\left(x^2 - y^2\right) - S\,y_0\,y - \frac{1}{2} S\,y_0^2,$$

$$B_x = S\,xy + S\,y_0\,x$$

- Additional fields:
  - First order – skew quadrupole
  - Second order - dipole

Sextupole effects - coupling

- Particles with non-zero vertical trajectory in sextupoles see skew quadrupole fields which give rise to emittance ratio:

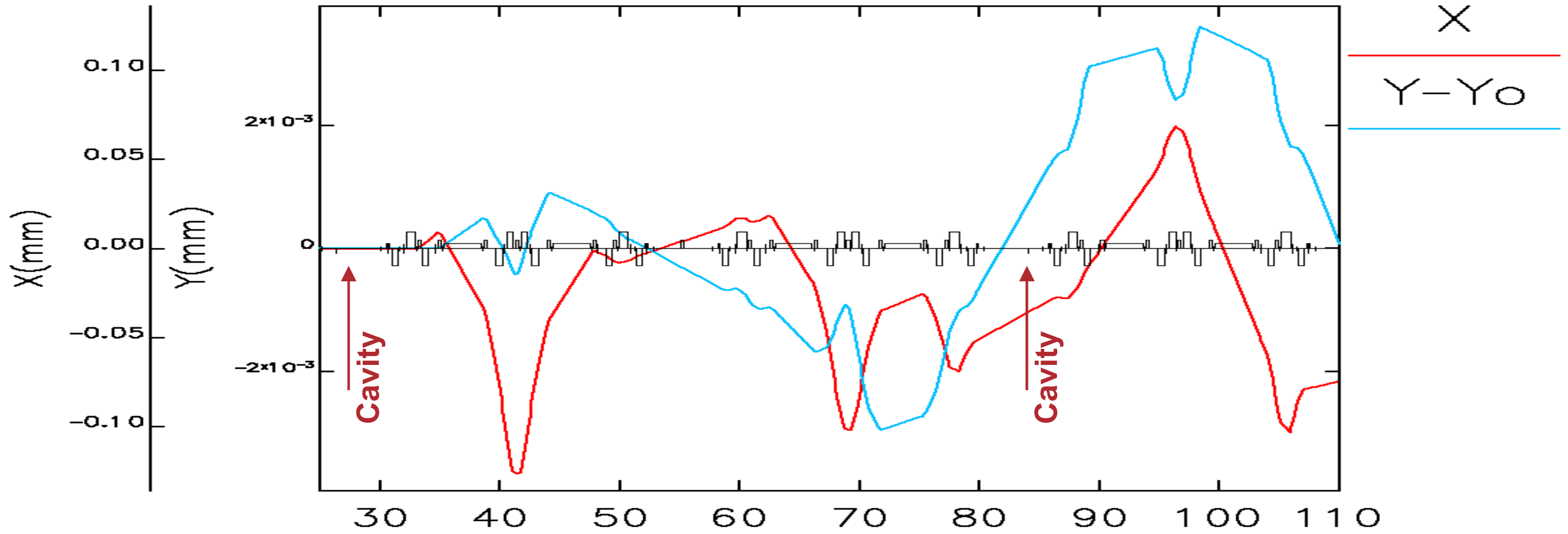
$$\frac{\varepsilon_y}{\varepsilon_x} = \frac{\kappa^2}{\kappa^2 + \Delta^2},$$

$$\kappa_q = \frac{1}{2\pi} \int_0^C \mathrm{K}_s \sqrt{\beta_x \beta_y} e^{i\Psi_q} ds,$$

- Estimation of the coupling harmonic on a trajectory of 1-σ_t-particle gives 30% emittance ratio

Sextupole effects – dipole kicks

- In the first sextupole, a particle experiences only vertical dipole field due to non-zero vertical orbit, which generates horizontal trajectory
- At the second sextupole, the particle has both vertical and horizontal coordinates and experiences both horizontal and vertical dipole kick



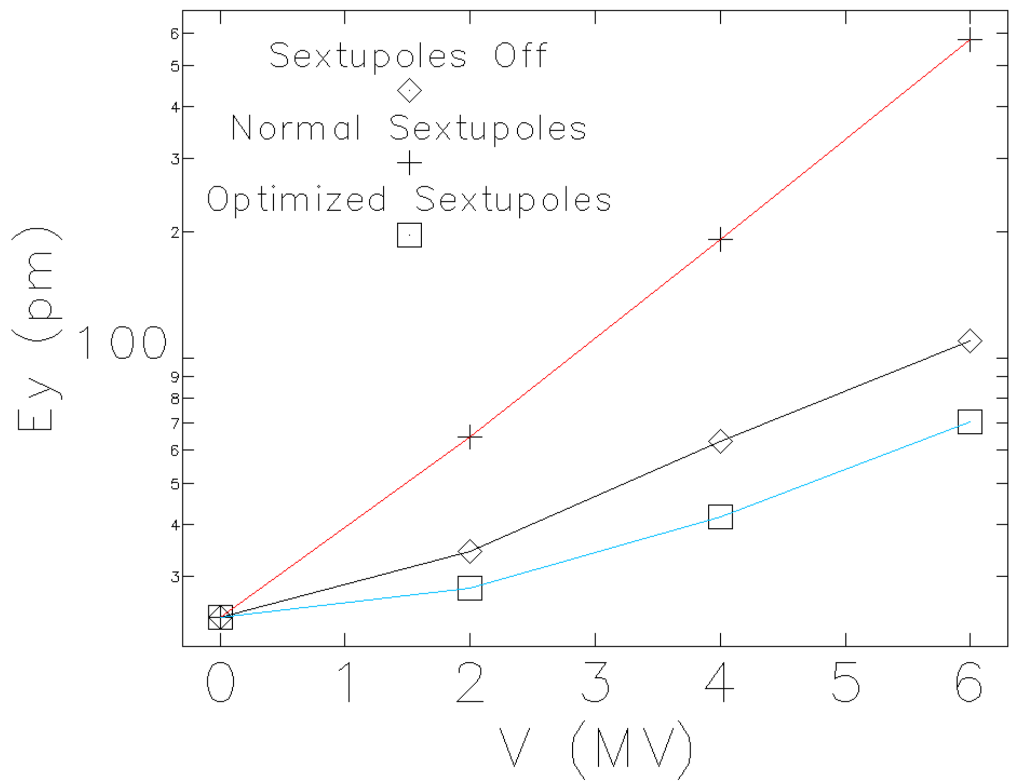
Large linear part of the vertical trajectory is subtracted

Sextupole optimization using `elegant`

- Sextupoles between cavities cannot be turned off due chromaticity effects
- Their strengths can be adjusted to minimize coupling and trajectory non-closure effects and to keep chromaticity compensated
  - Variables:
    - *All sextupoles between cavities grouped into 7 families in a symmetric fashion*
  - Variable limits:
    - *Sextupole signs are kept constant (unipolar power supplies)*
  - Constraints (calculated on vertical trajectory for a particle at $3\sigma_t$):
    - *Minimize 17th coupling harmonic (ν_x=36.20, ν_y=19.26)*
    - *Minimize amplitude of residual orbits in X and Y*
    - *Minimize residual vertical dispersion*
    - *Compensate horizontal and vertical chromaticity*

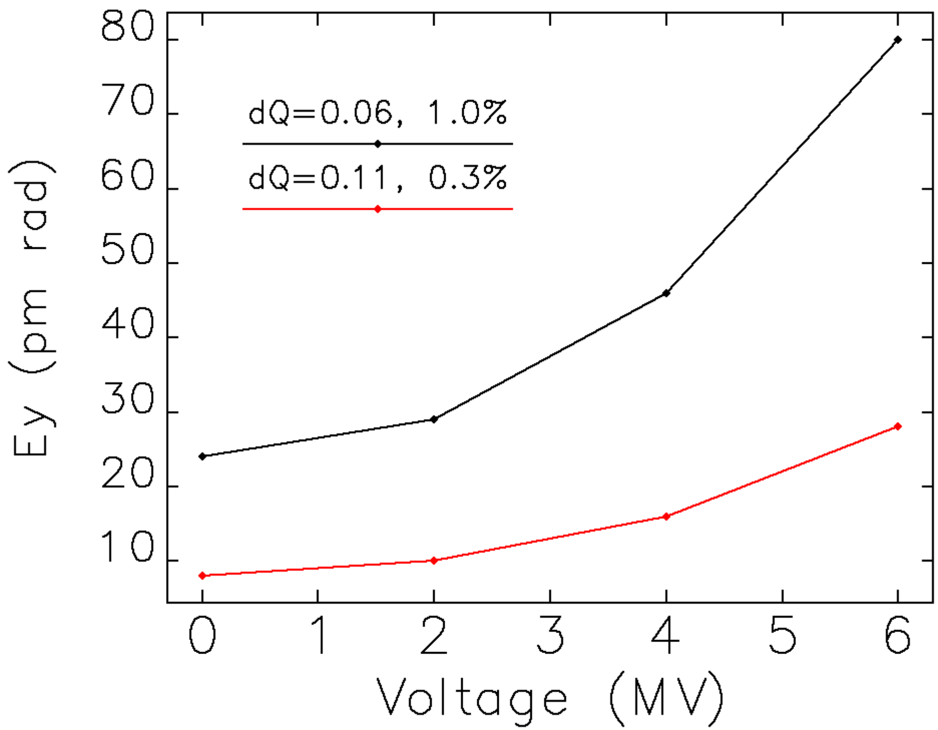
Sextupole optimization results

Comparison of the vertical emittance growth for the three sextupole schemes: Normal sextupoles, Sextupoles off, and Optimized sextupoles (no synchrotron radiation)



Additional options to contain vertical emittance growth

- Increase distance to the coupling resonance (from 0.06 to 0.11 for APS)
- Decrease initial coupling (from 1% to 0.3% for APS)



Machine imperfections, vertical emittance[1]

- Lattice errors can result in beta function errors and phase advance errors
  - For 1% beta function errors, emittance growth is 15%
- Cavity phase and voltage errors
  - 0.1 deg rms phase jitter gives 1% emittance growth
  - 0.1% rms voltage jitter gives 2% emittance growth
- Cavity rolls does not appear to be a problem at all at 2mrad level

1. M. Borland, private communication

Lifetime limit[1]

- If chirp is too large, particles may scrape on chamber – decreasing quantum lifetime
- ID chamber (8 mm total gap) is the aperture limit
- Considering the distance between cavity center to the end of ID chamber to be 3.7 m, the beam chirp at the exit of the ID chamber for 6 MV is $\pm$3.2 mm
- Adding to that possible orbit error of 100 μm and natural beam size, the limit is found to be 7 MV.

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

RF requirements

- Ultimate goal is to achieve 1 ps x-ray pulse length
- No impact on performance outside the insertion section
- RF frequency of 2.8 GHz and deflecting voltage of 6 MV (pulse length is approximately inversely proportional to the RF voltage, therefore 4 MV is acceptable)
- Total length for one cavity is 2.5 m – half of the total length available for insertion devices
- Significant parasitic mode damping is required[1]

1. Y.-C. Chae, private communication

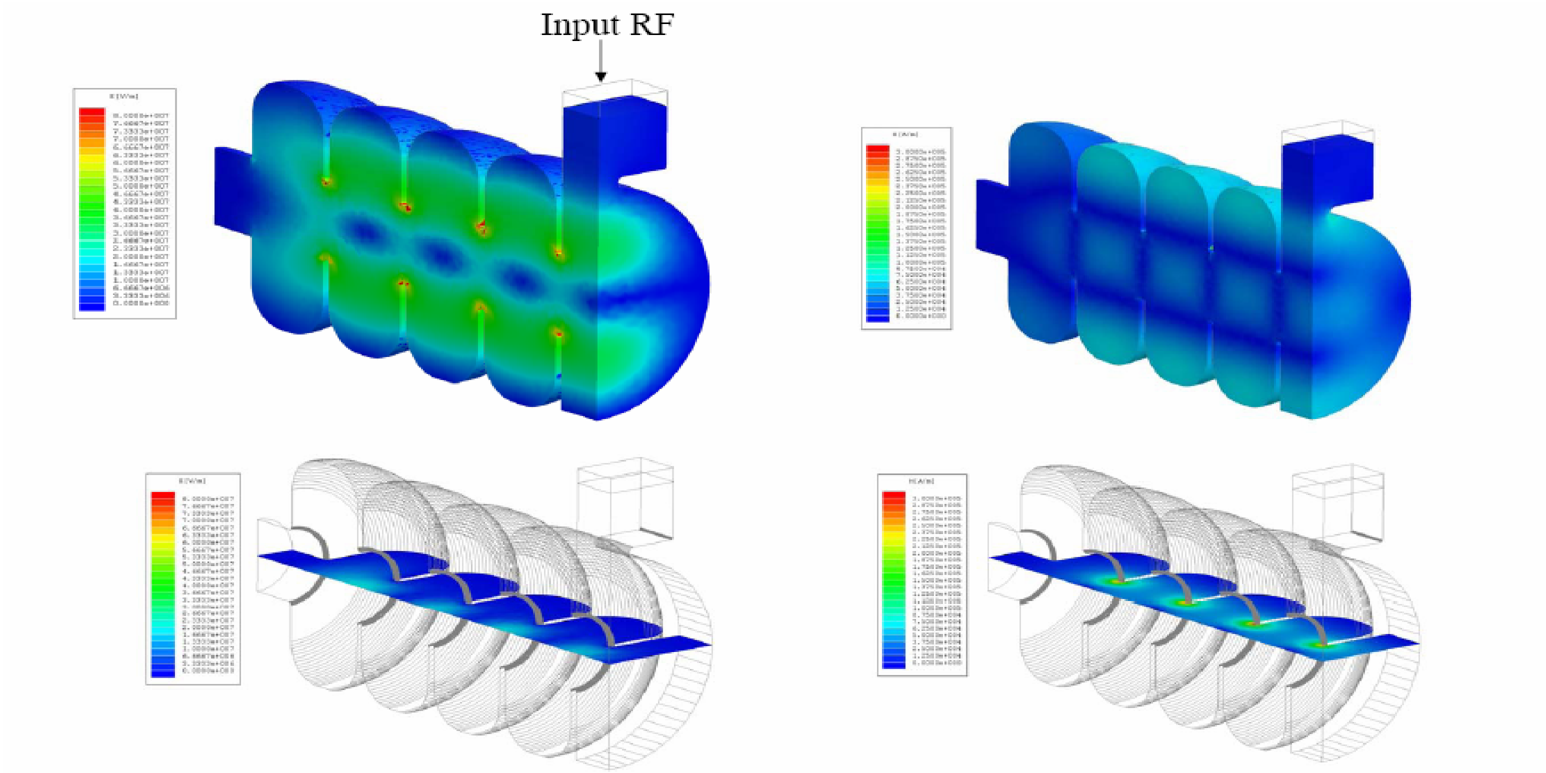
Room Temperature (RT) vs. Super Conducting (SC) RF[1]

- SC system runs CW, repetition rate up to bunch spacing – high throughput for some experiments
- RT pulsed system allows user to “turn off” ps pulse using timing (~1 μs pulse, 0.1 – 1 kHz rep rate)
- Suppression of parasitic modes is challenging for SC cavity, well understood for RT structures
- Need to understand transients during pulsing of RT structure and its effect on beam (including outside of the cavity insertion)
- SC option will likely cost much more than RT option
- Overall, SC option is more attractive
  - May offer a greater degree of compatibility with normal SR operation
  - Compatible with future development of high repetition rate pump probe lasers

1. K. Harkay, A. Nassiri

9 Cell Standing-Wave Deflecting Structure (RT)[1]

- 1 kHz repetition rate
- 1 μs pulse rise and fall times
- 6 MV total per 9-cell structure is possible, total cavity length is 0.52 m



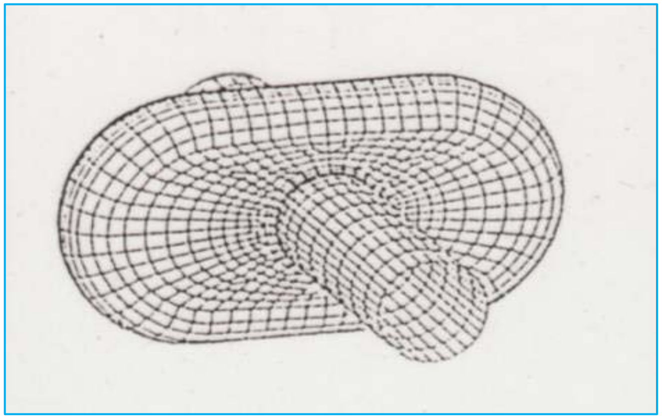
Surface electric field for 5 MW of input power, maximum filed ~70 MV/m

Surface magnetic field for 5 MW of input power, maximum filed ~30 kA/m

1. Design by V. Dolgashev, SLAC

Squashed SC cavity (based on KEK design)

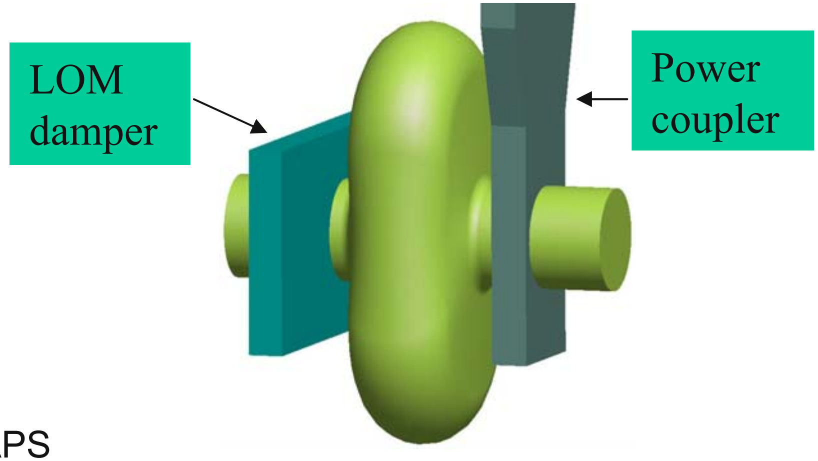
- Due to high voltage, 2 K operation is required
- Multi-cell cavity options were considered but disregarded since heavy damping of parasitic modes was required
- KEK “squashed-cell” design for 500 MHz was adopted and scaled to 2.8 GHz
- Aspect ratio of the squashed-cell cavity is 1.8 to create large separation between degenerate TM_{110} modes



Courtesy G. Waldschmidt, APS

LOM Damping

- Damping load has to be placed outside of cryomodule
- KEK design uses coaxial beampipe transmission line to couple out parasitic modes. However, it was decided that such damper would be difficult to build for 2.8 GHz
- Damper design uses a waveguide to couple the monopole modes in the cavity and to naturally reject the deflecting mode[1]. In such design, degenerate deflecting mode is also strongly damped
- Asymmetric squashed-cell design was reconsidered, but it was found that symmetric (round) cavity has higher surface magnetic fields



Courtesy G. Waldschmidt, APS

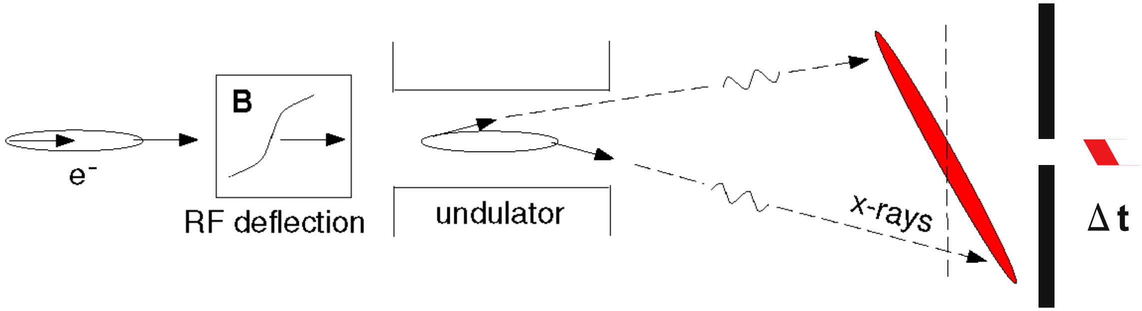
1. D. Li, LBNL, private communication

Cavity parameters

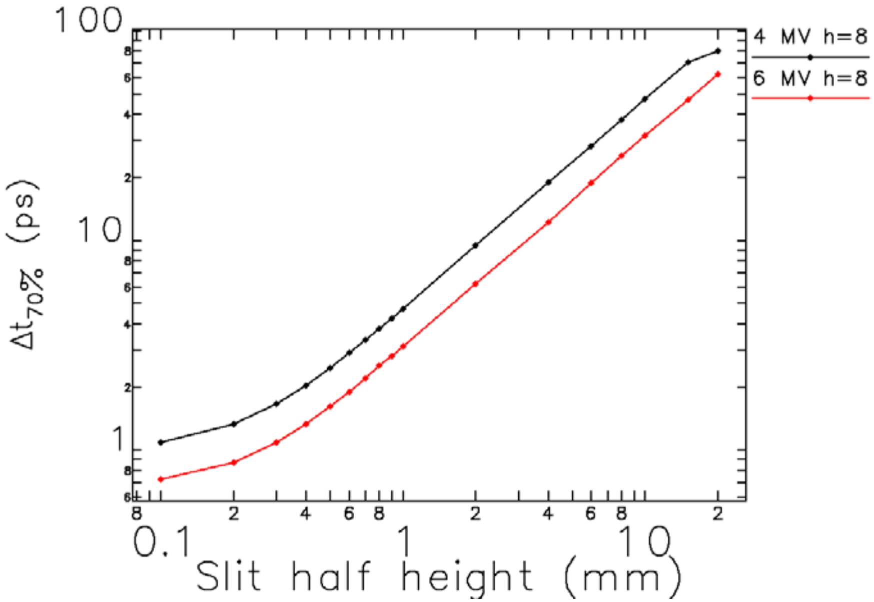
Frequency	2.815 GHz
Number of cavities	10
Beam radius	2.4/1.9 cm
R_T/Q	46.8 Ω/m
Total deflecting voltage	6 MV
Deflecting gradient	11.3 MV/m
B_{sp}	111 mT
RF loss at 2K	7.7 W per cell

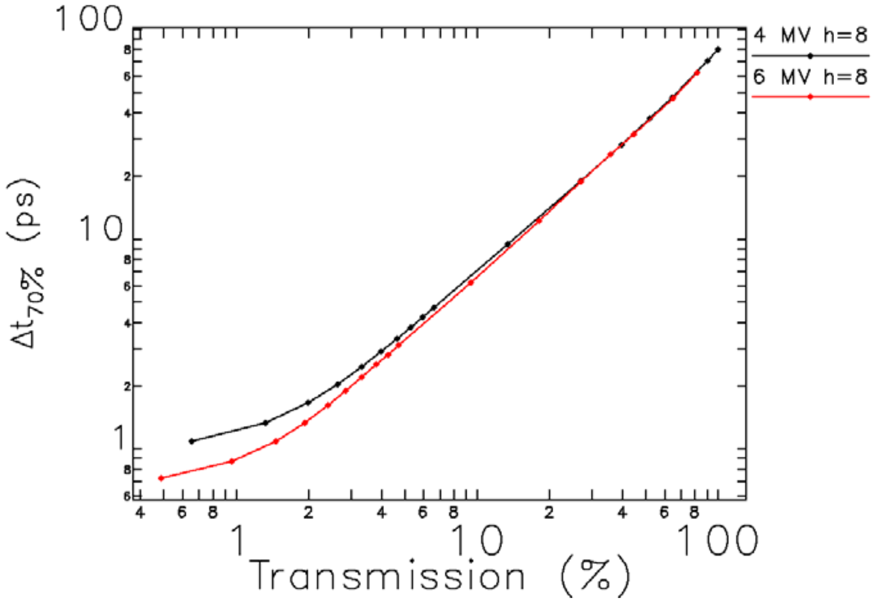
Courtesy G. Waldschmidt, APS

X-ray pulse slicing



- Slit located at some distance from undulator cuts out a part of the beam that is shorter than the entire beam
- At transmission of 1%, a 1 ps FWHM pulse can be achieved

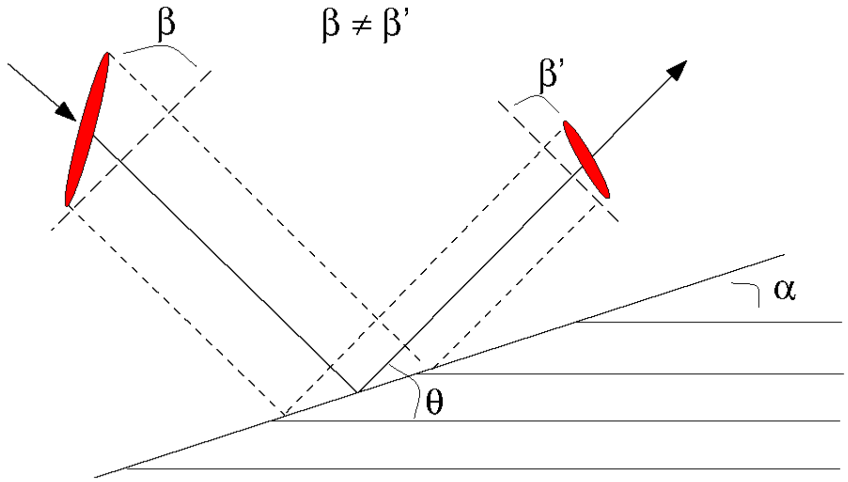




1. M. Borland, Phys. Rev. ST Accel. Beams 8 074001 (2005)

X-ray compression optics

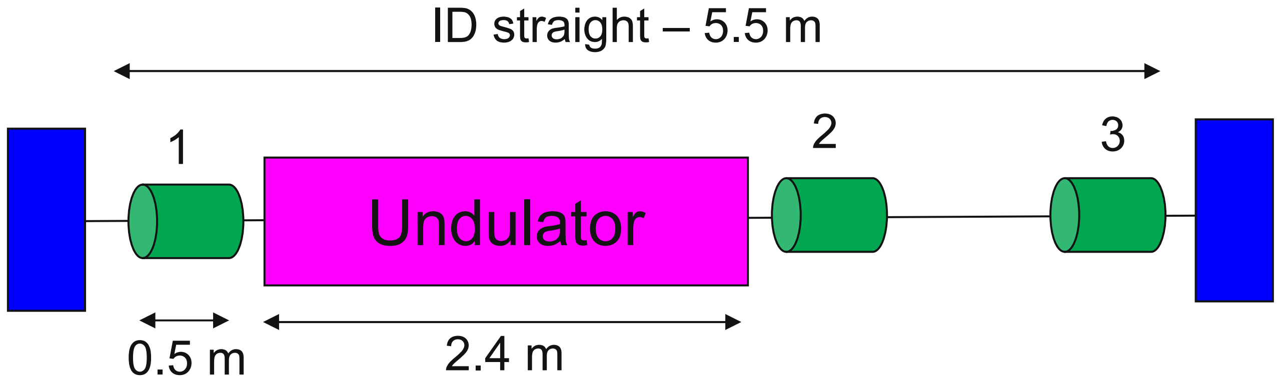
- Asymmetrically cut crystal can be used to increase the intensity of short pulses
- Asymmetrically cut crystal has different incident and diffractive angles which allows to create a path difference across the photon pulse
- Such crystals can increase transmission from 1% to 10-30%. However, the beamline optics seems to be not trivial due to large beam spots



Courtesy S. Shastri, APS

Latest development – all-in-one approach for pulsed option

- Single straight approach – 3 RT pulsed cavities in one ID straight section (like orbit bump)
- In such configuration, cavity 2 has maximum voltage of 6 MV and limits cavity 1 to 1.5 MV
- Minimum achievable pulse length is 1.5 ps rms
- Utilize existing spare klystron – repetition rate 120 Hz (retune from 2856 to 2816 MHz)
- Build in one year without external money
- Second phase – upgrade klystron and modulator to 1 kHz and redesign straight section to increase cavity 1 voltage (second year)



Conclusions

- We have studied a possibility of producing 1-ps x-ray pulse at APS using deflecting cavities and found it feasible
- 6 MV voltage is required; it can be achieved in RT option in pulsed mode or in SC option in continuous mode
- We have studies beam dynamics, found significant emittance degradation effect and resolved it by optimizing sextupole strengths
- We have performed a preliminary design of SC cavity consisting of 10 single cells that is capable of producing 6 MV and fits in 2.5 m length
- We have simulated x-ray pulse production and found that 1-ps pulse can be achieved with 1% transmission using slits
- 1-year plan is adopted to implement the first phase of pulsed option