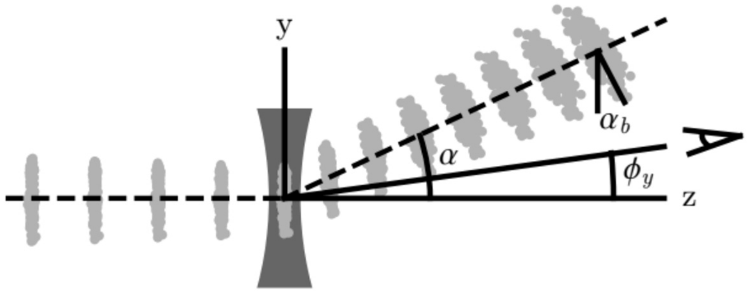
Microbunch Rotation and Coherent Undulator Radiation from a Kicked Electron Beam



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Jacek Krzywinski, Zhirong Huang

May 21, 2019

Preview

Motivation

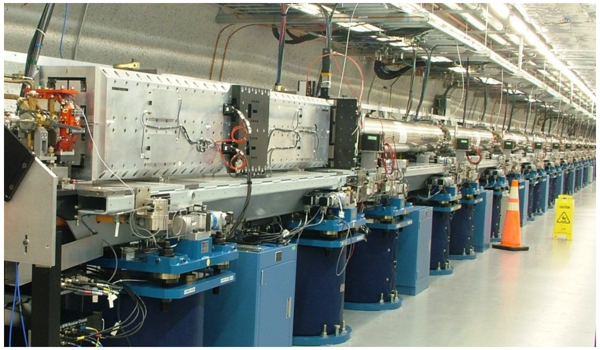
- Isolated circular x-ray production at LCLS
- Beam diversion: unexpectedly successful

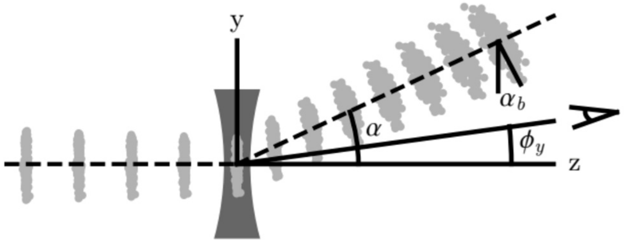
Rotation

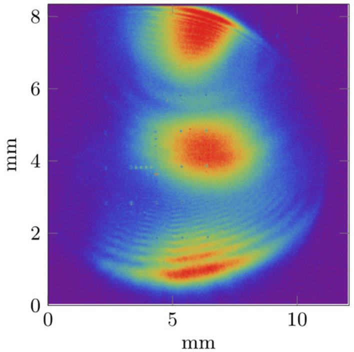
- Microbunch dynamics in a FODO lattice
- The theory that matches experiment

Extensions

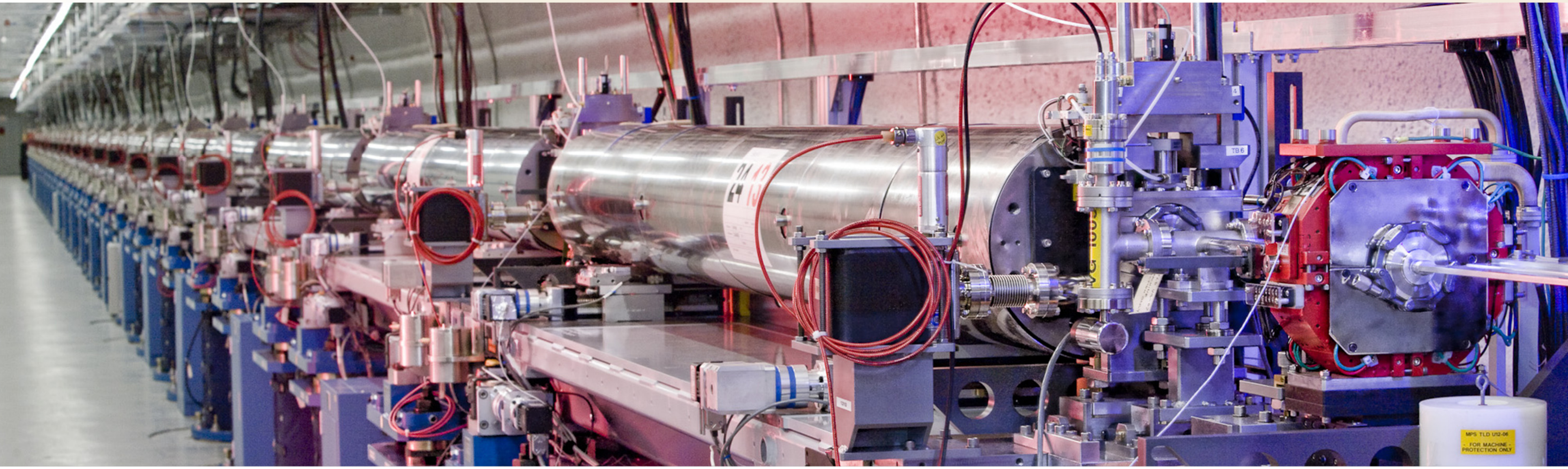
- Multiplexing at soft x-rays: 3 beams
- Multiplexing at hard x-rays: 2 beams





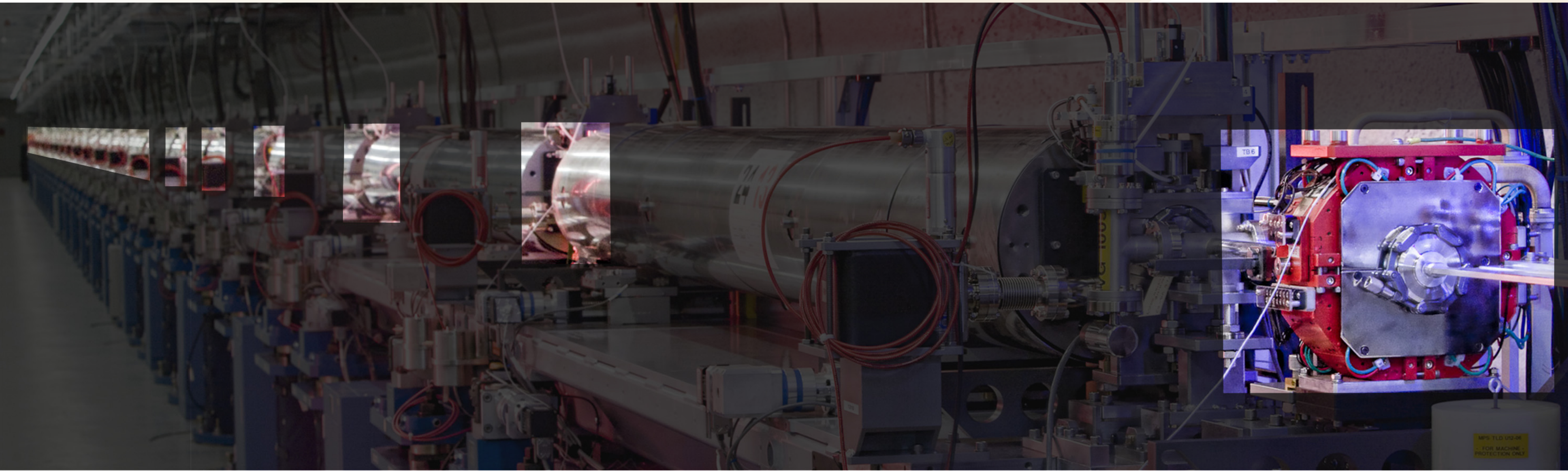


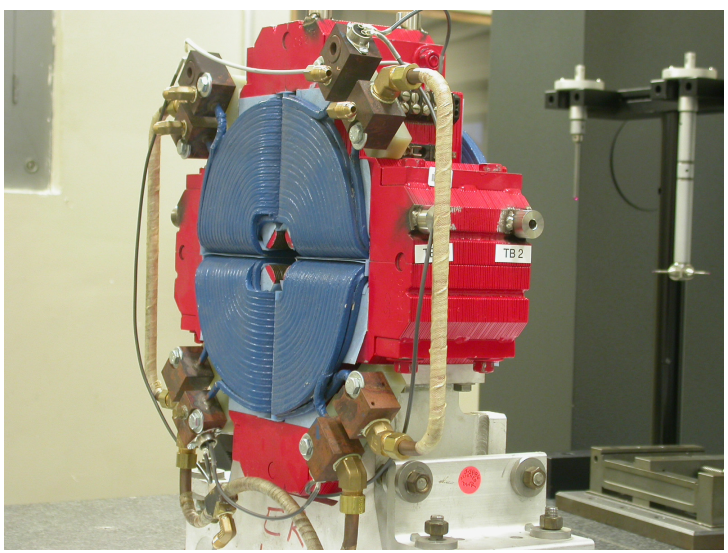
LCLS Undulator Magnetic Lattice



LCLS Undulator Magnetic Lattice

SLAC

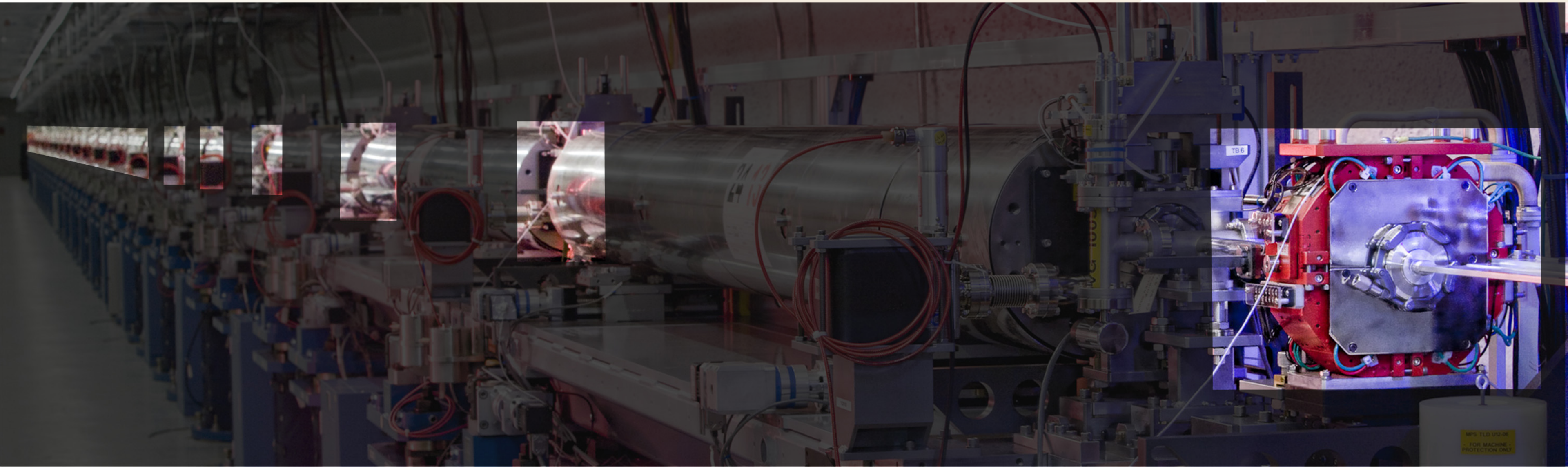


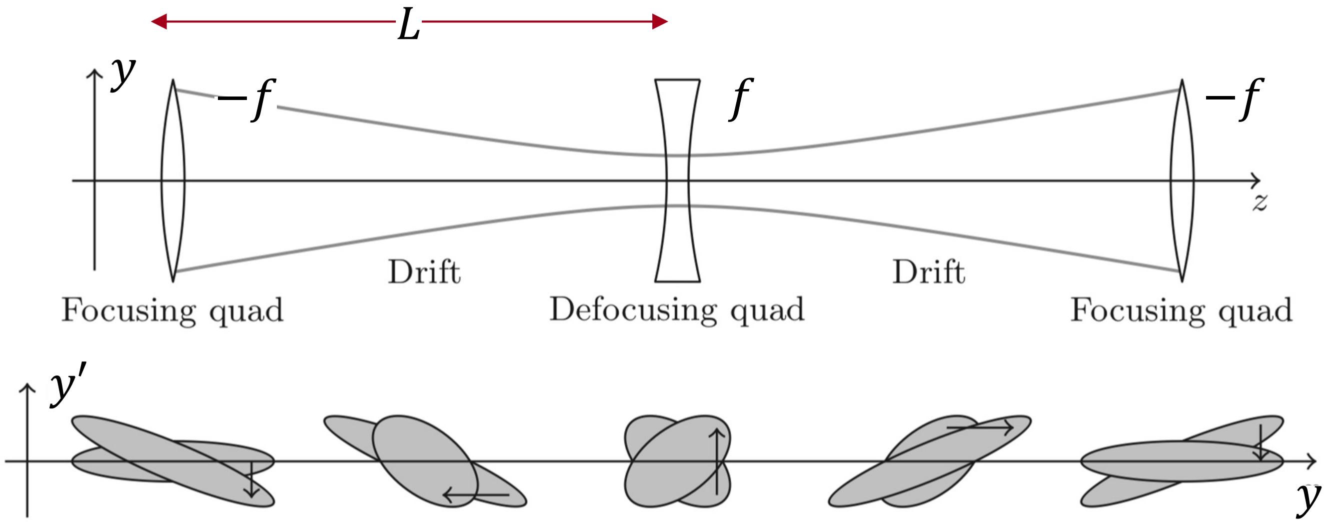


Magnetic Quadrupole & Corrector

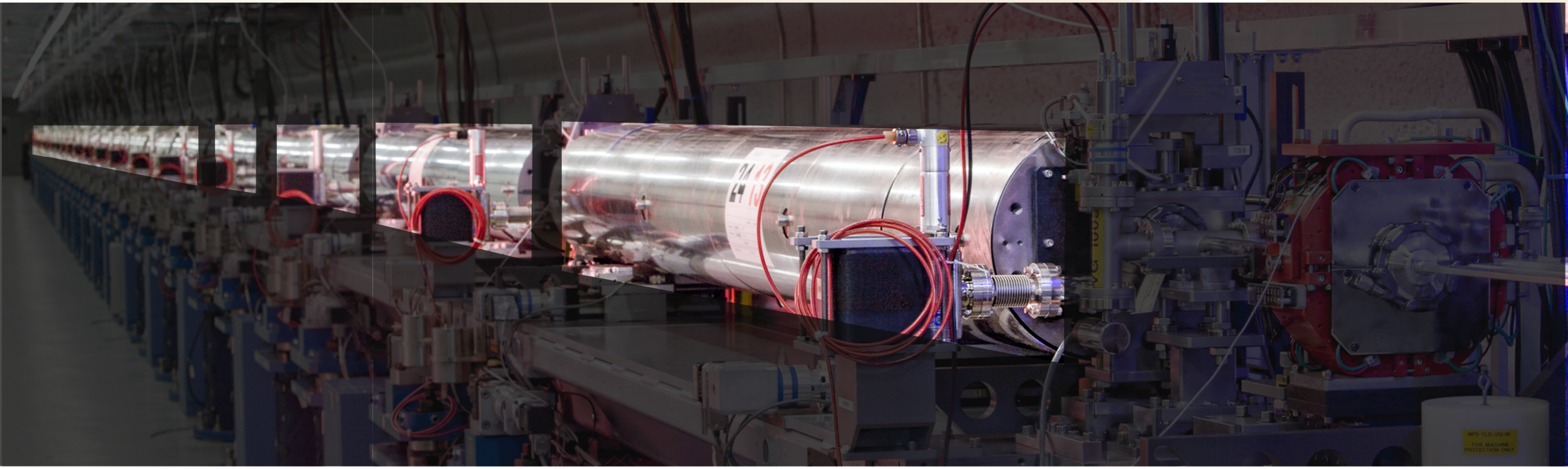
- Tunable -40 kG to 40 kG quadrupole
  - Focal length ~ 4 meters for 500 eV operation
- Tunable -6 G·m to +6 G·m dipole
  - Max kick ~ ±55 uRad for 500 eV operation
- Quadrupole may also be offset to provide additional dipole kick

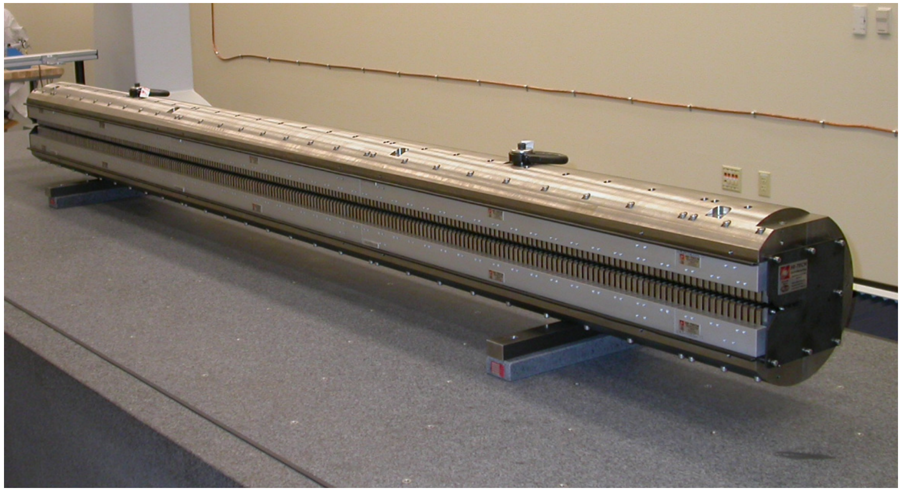
LCLS Undulator Magnetic Lattice





LCLS Undulator Line

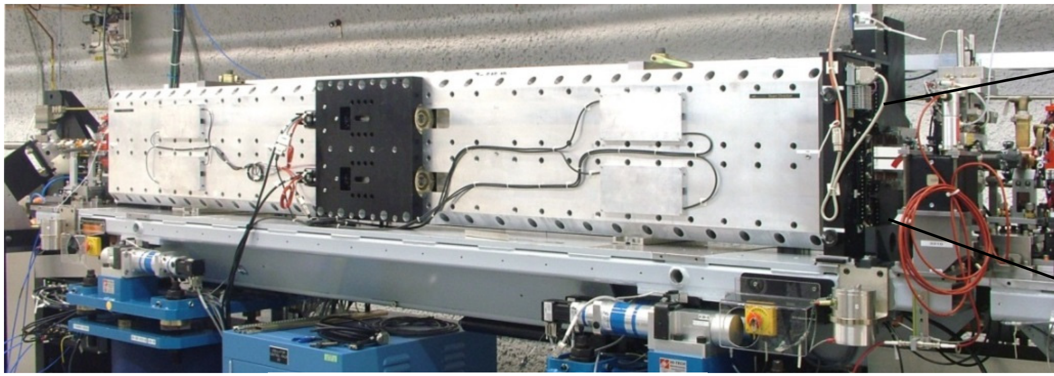


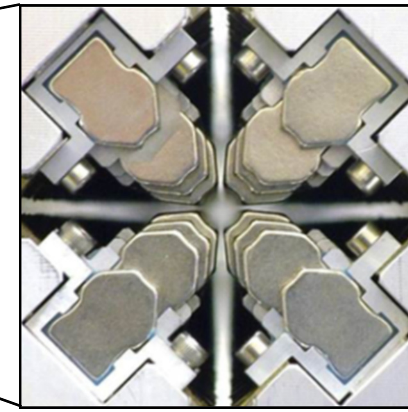


LCLS-I Undulators

- Linear polarization only
- 110 periods, 3 cm period
- Canted poles, K = 3.44 – 3.5
  - Note: LCLS-II will have a larger K range via variable gap
- Saturation length = 10’s – 100 m

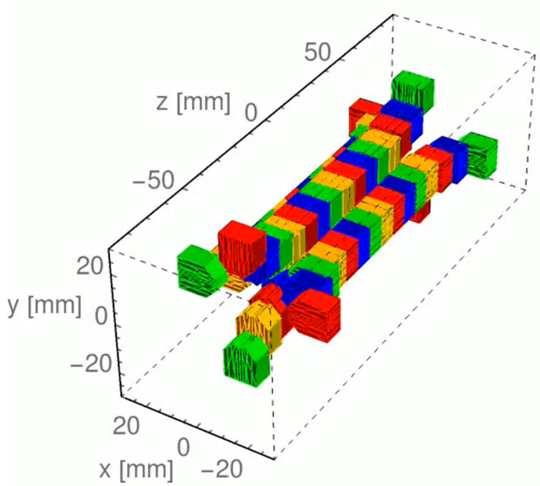
Delta Undulator

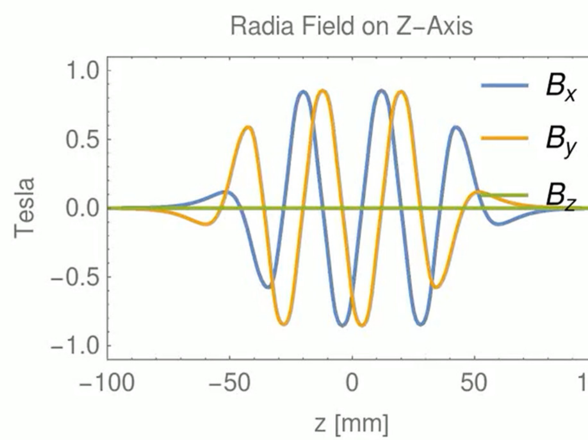




Axial View

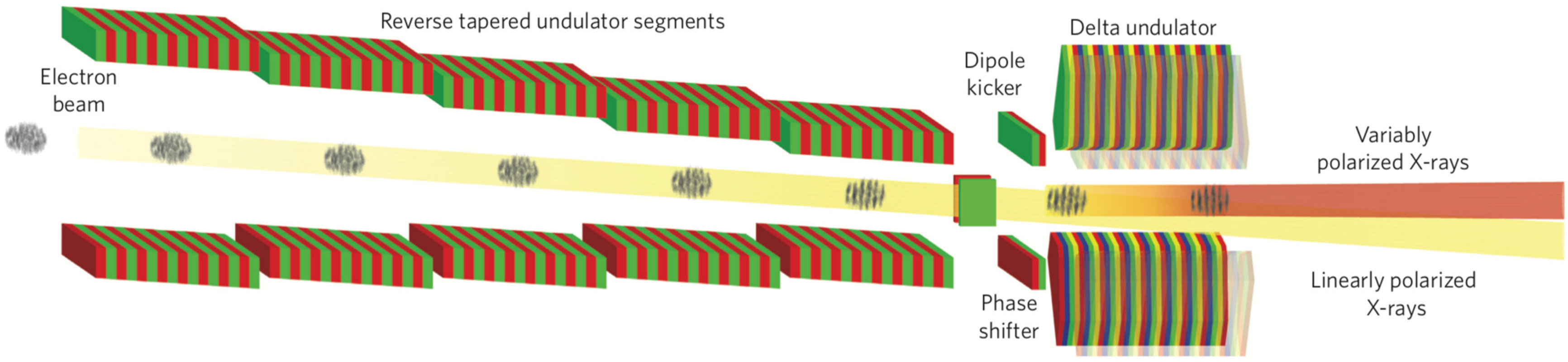
← 3.2 m, 100 periods →



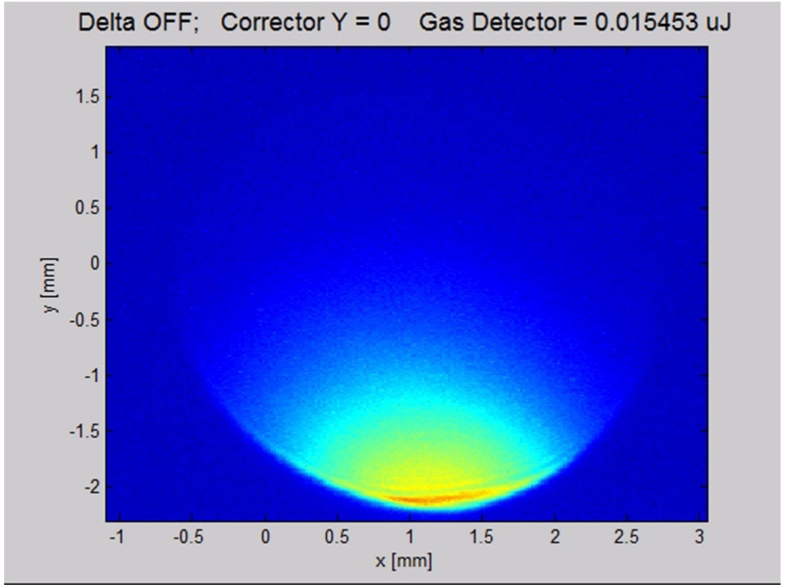


[Radia Simulation]

Isolated Circular Beam



- Reverse taper
  - Bunching with minimal field
  - *Schneidmiller & Yurkov, PRSTAB **16**, 110702 (2013)*
- Beam diversion
  - Transverse kick before Delta
  - Circular light isolated with jaw
  - Results in *Lutman, MacArthur et al., Nat. Photonics **10** 468 (2016)*

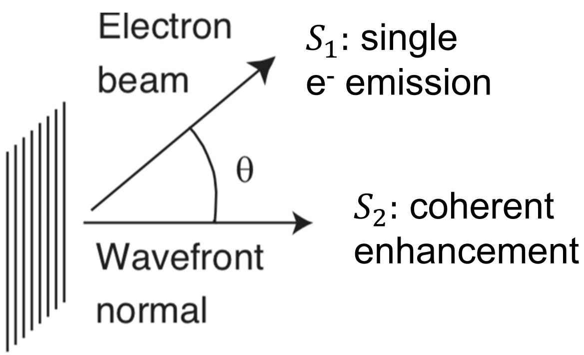


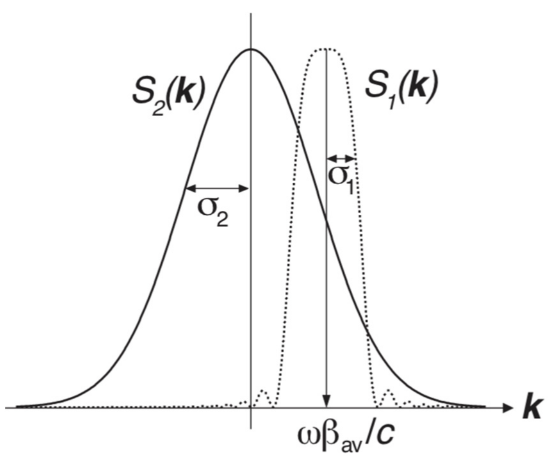
[Lutman 2016]

An Unexpected Success

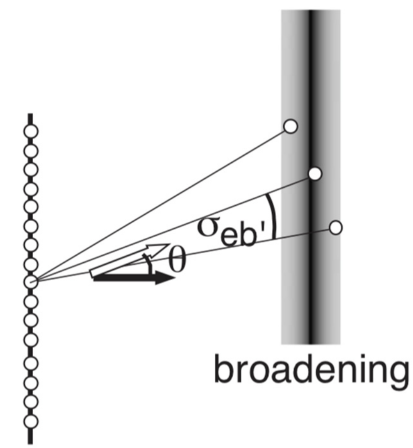
In 2004 T. Tanaka identified effects to prevent off-axis lasing (see T. Tanaka et al., NIMA **528** 172 (2004)):

Radiation Suppression



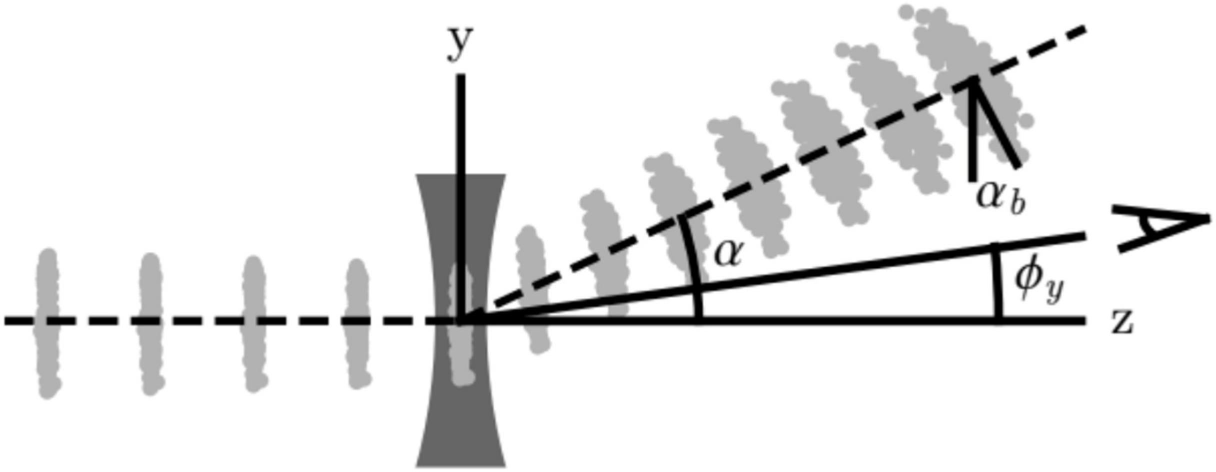


Microbunch Smearing



Kick + angular spread = smearing

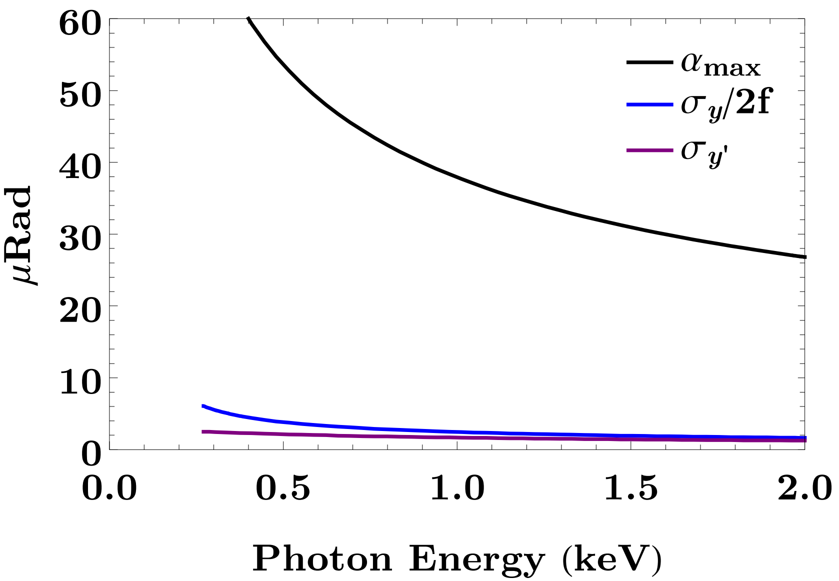
New Approach: The Quadrupole Matters



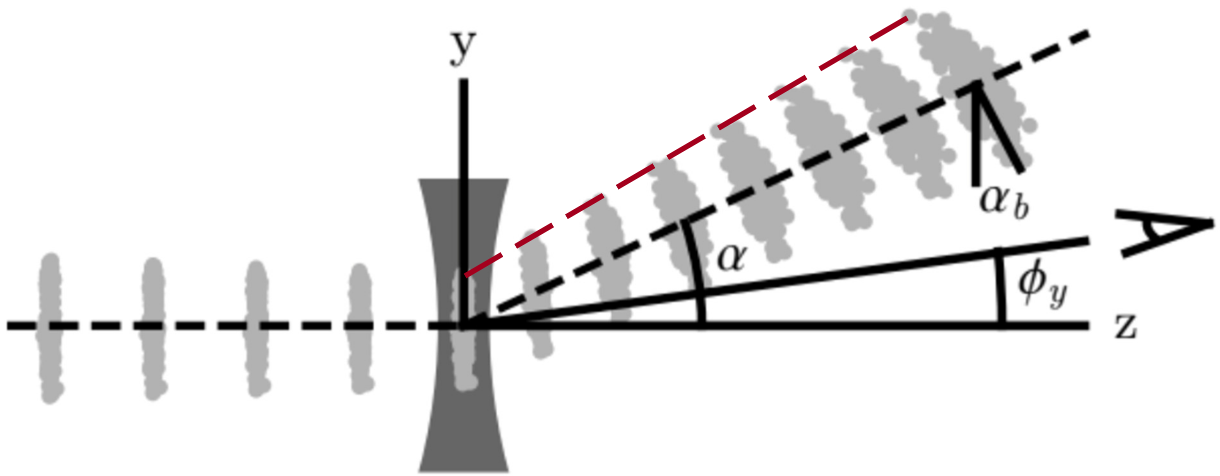
- Trajectory (z=0 mid-quad):

$$y(z) = y_0 + \left(y_0' + y_0/(2f) + \alpha\right) z$$

- The maximum kick at LCLS depends on the photon energy



Intuitive Picture



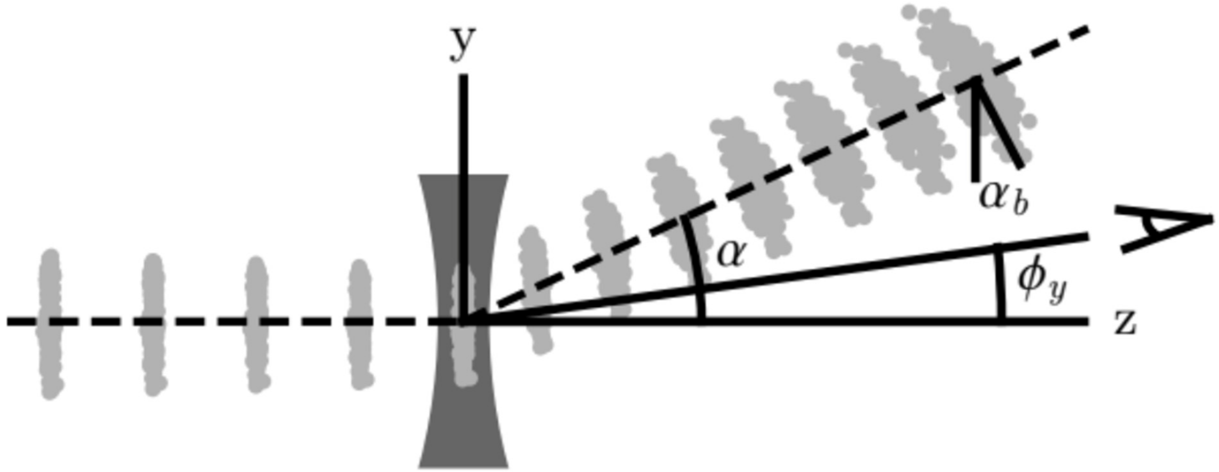
$$\Delta s \approx z\cos\left(y_0' + y_0/(2f) + \alpha\right) - z\cos\alpha$$

$$\approx \frac{\alpha z}{2f} y_0 + \alpha z y_0' + \frac{z}{2}\left(\frac{1}{2f} y_0 + y_0'\right)^2$$

tilt (α_b) — smearing — curvature, other

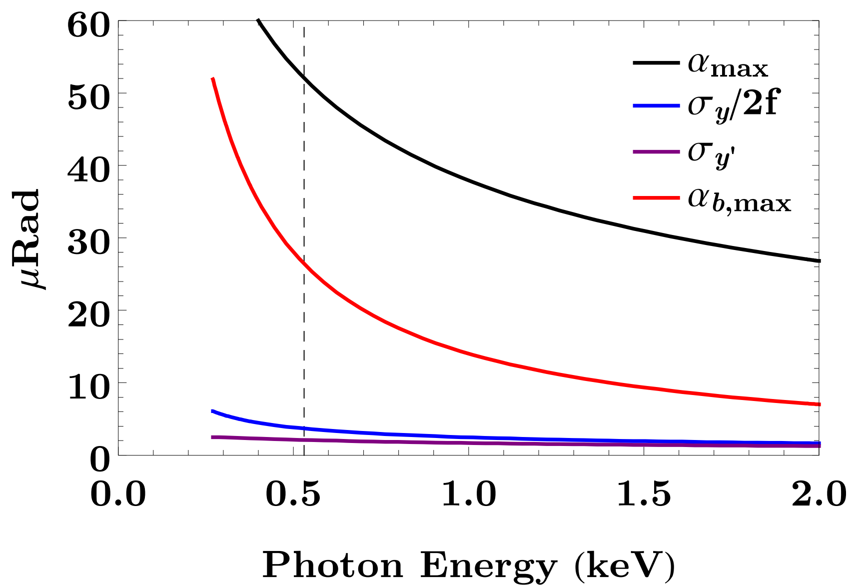
(2nd order beam transport in a drift: $T_{544} = -z/2$)

Angle Comparison

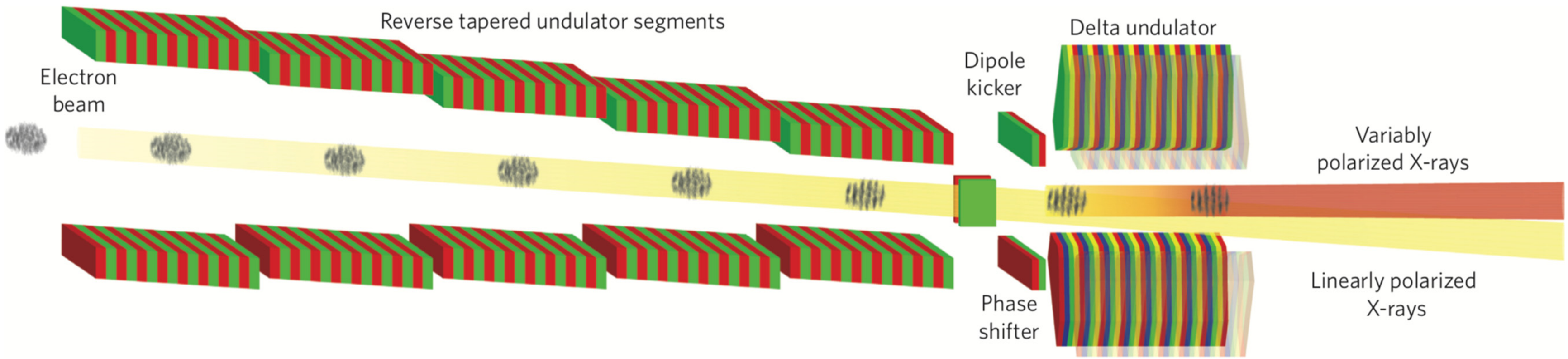


$$y(z) = y_0 + \left(y_0' + y_0/(2f) + \alpha\right) z$$

$$\Delta s \approx \frac{\alpha z}{2f} y_0 + \;\ldots$$



A More Careful Approach



Large bunching, small field

Radiation with **minimal gain**

Field growth: $$\left[\frac{\partial}{\partial z} + i\Delta\nu k_u + \frac{ik}{2}\phi^2\right]\tilde{E}_\nu = -\kappa_1 n_e \int d\mathbf{x}' d\eta \tilde{F}_\nu$$

Microbunch evolution: $$\left[\frac{d}{dz} + i\left(2\nu\eta k_u - \frac{k}{2}\mathbf{x}'^2\right)\right]F_\nu = -\chi_1 E_\nu \frac{\partial \bar{F}}{\partial \eta},$$

~0

MacArthur et al., PRX **8**, 041036 (2018)

Result #1: The Bunching Rotation Angle

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With no field interaction and the trajectories given before, the bunching has an analytic expression. It's ugly…

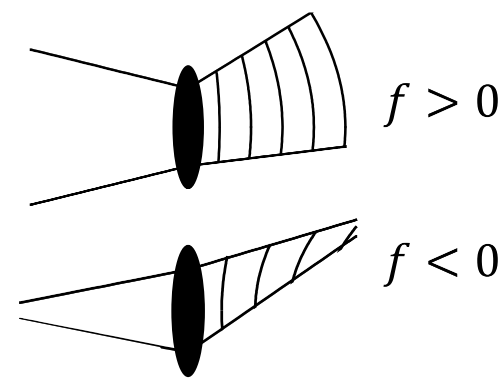
$$\left[\frac{d}{dz} + i\left(2\nu\eta k_u - \frac{k}{2}\mathbf{x}'^2\right)\right] F_\nu = -\chi_1 E_\nu \frac{\partial \bar{F}}{\partial \eta},$$

~0

$$\frac{b_\nu(\phi_x = 0, \phi_y; z)}{b_\nu(\phi_x = 0, \phi_y; 0)} = \frac{e^{-2(k_u \sigma_\eta \nu z)^2 + \frac{|f| k (i\psi + \zeta)}{\sqrt{1-\hat{L}^2} - 2i\hat{\epsilon}|\hat{z}|}}}{i + \frac{2\hat{\epsilon}|\hat{z}|}{\sqrt{1-\hat{L}^2}}}$$

$|b(\phi)|$ is maximized at an angle α_b that matches the geometric prediction $\left(\hat{z} = z/2f, \hat{L} = L_u/2f, \hat{\epsilon} = k\epsilon\right)$

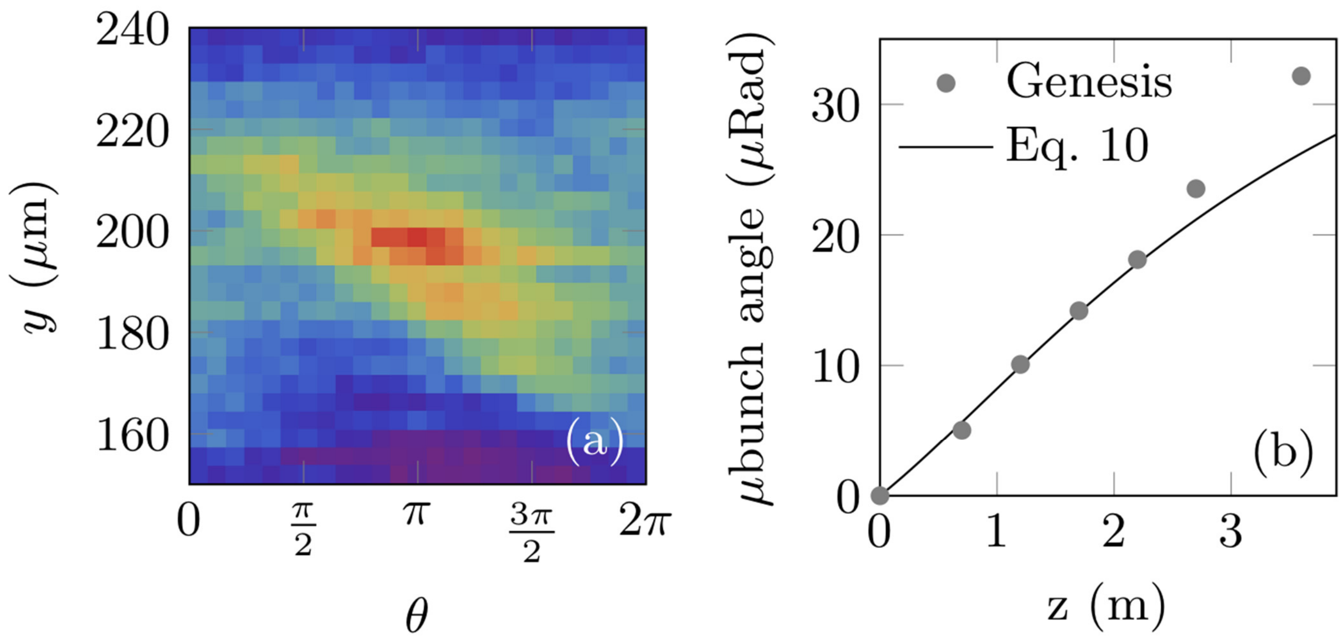
$$\hat{\epsilon}^2 \hat{L}^2 \ll 1 - \hat{L}^2 \quad \Rightarrow \quad \boxed{\alpha_b(\hat{z} = \hat{L}) \approx \alpha \hat{L} = \frac{\alpha L_u}{2f}}$$



Genesis Comparison

The previous result can be compared with Genesis simulations

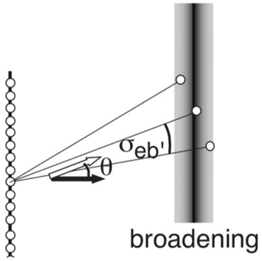
$$\alpha_b(\hat{z} = \hat{L}) \approx \alpha\hat{L} = \frac{\alpha L_u}{2f}$$



Result #2: A New Critical Angle

Tanaka showed that the bunching is suppressed when kicked,

$$|b_\nu(\phi_x = 0, \phi_y = \alpha_b; z)|^2 \propto e^{-\alpha^2/\phi_c^2}$$



A larger critical angle when bunches rotate:

$$\phi_c^2 = \sigma_{y'}^2 + \frac{\sigma_y^2}{\epsilon_y^2 k^2 z^2} \quad \Rightarrow \quad \phi_c^2 = s_{y'}^2 + \frac{s_y^2}{\epsilon_y^2 k^2 z^2}$$

Tanaka critical angle — New critical angle

The RMS beam size and divergence after a drift z replace the beam size and divergence in the quad:

$$s_y^2 = (1 + z/2f)^2 \, \sigma_y^2 + \sigma_{y'}^2 z^2$$

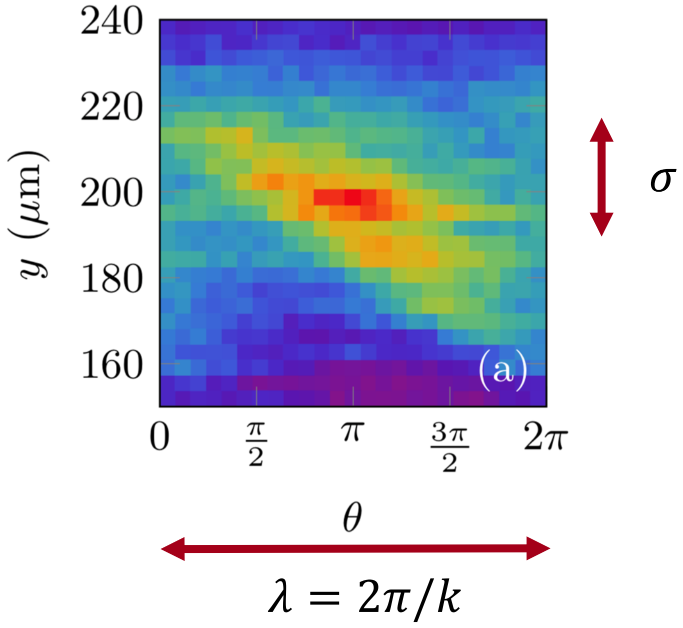
$$s_{y'}^2 = \sigma_{y'}^2 + \sigma_y^2/(2f)^2$$

Tilt At The Critical Angle

Suppose we kick at the critical angle, how much do the bunches rotate?

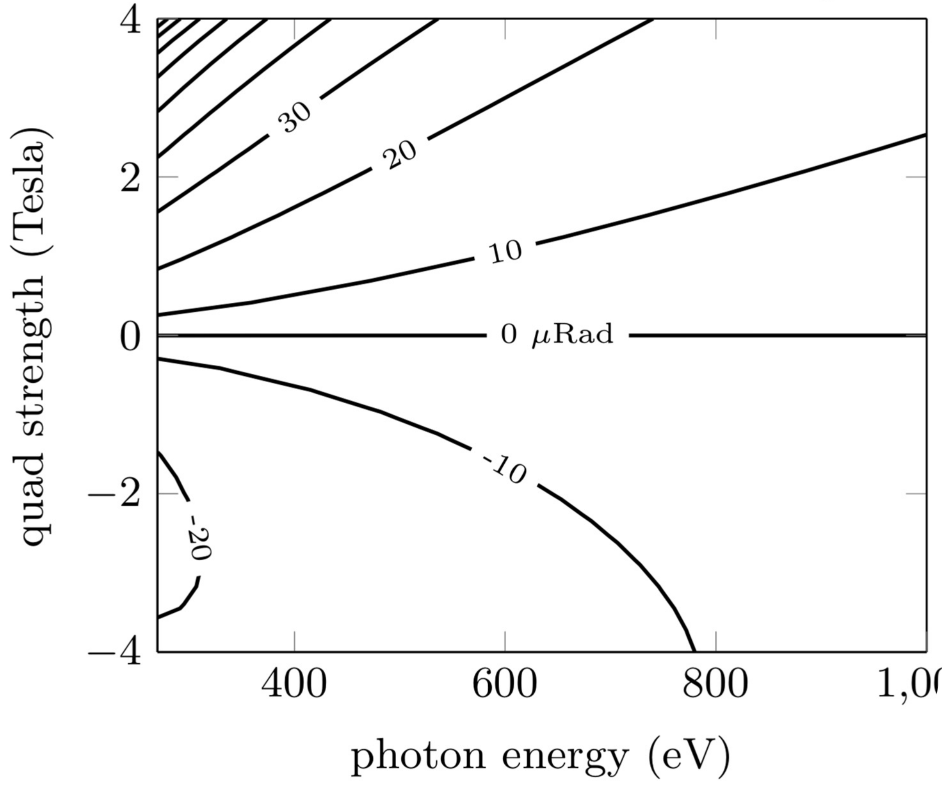
$$\alpha_b(\hat{z} = \hat{L}, \alpha = \phi_c) \approx \frac{1}{k\sigma_y} \frac{f}{|f|}.$$

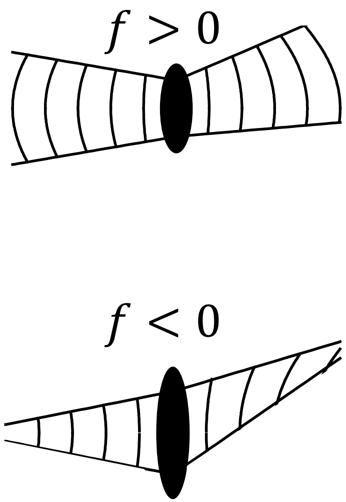
So when the tilt approaches a wavelength over a beam radius, the bunching suffers:



When Does Rotation Matter at LCLS?

$$\alpha_b(\hat{z} = \hat{L}, \alpha = \phi_c) \approx \frac{1}{k\sigma_y} \frac{f}{|f|}$$





Result #3: The Field Produced By A Rotating Bunch

Plug in expression for microbunch dynamics to field equation

$$\left[\frac{\partial}{\partial z} + i\Delta\nu k_u + \frac{ik}{2}\phi^2\right]\tilde{E}_\nu = -\kappa_1 n_e \int d\mathbf{x}' d\eta \tilde{F}_\nu$$

$$\left[\frac{d}{dz} + i\left(2\nu\eta k_u - \frac{k}{2}\mathbf{x}'^2\right)\right] F_\nu = -\chi_1 E_\nu \frac{\partial \bar{F}}{\partial \eta},$$

Result: equation showing the field grows with z:

$$\frac{\partial \tilde{E}_\nu}{\partial z} \propto e^{-\frac{\alpha^2}{2\phi_c^2} - \frac{1}{2}\left(k^2 z \epsilon \phi_c (\phi_y - \alpha_b)\right)^2 + i\left(k_u \Delta\nu + k\frac{(\alpha - \phi_y)^2}{2}\right) z}$$

Result #3: More Radiation Off-Axis, Less Detune

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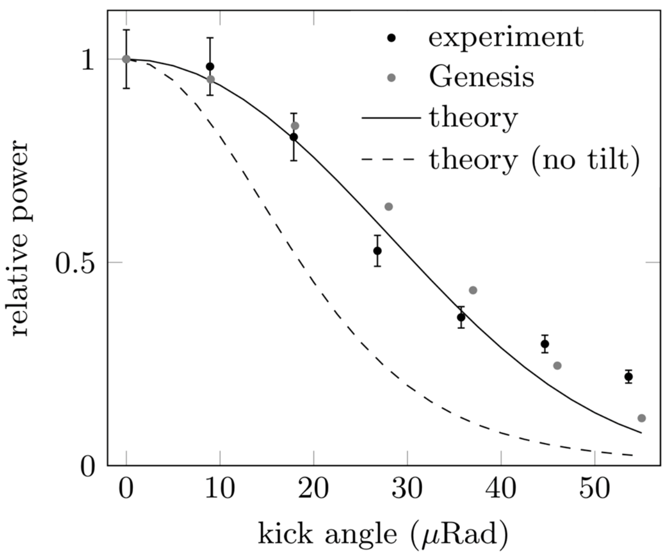
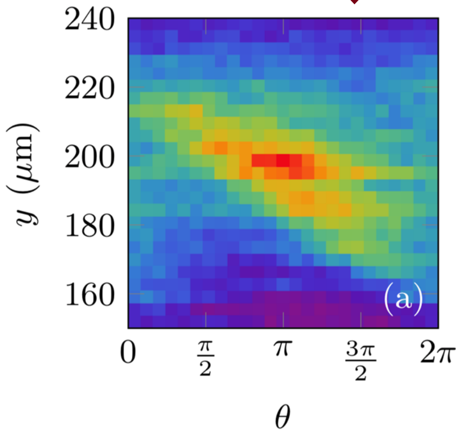
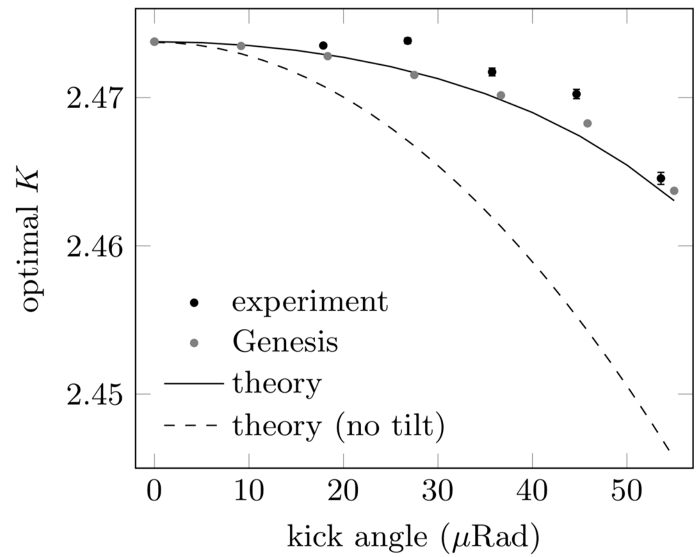
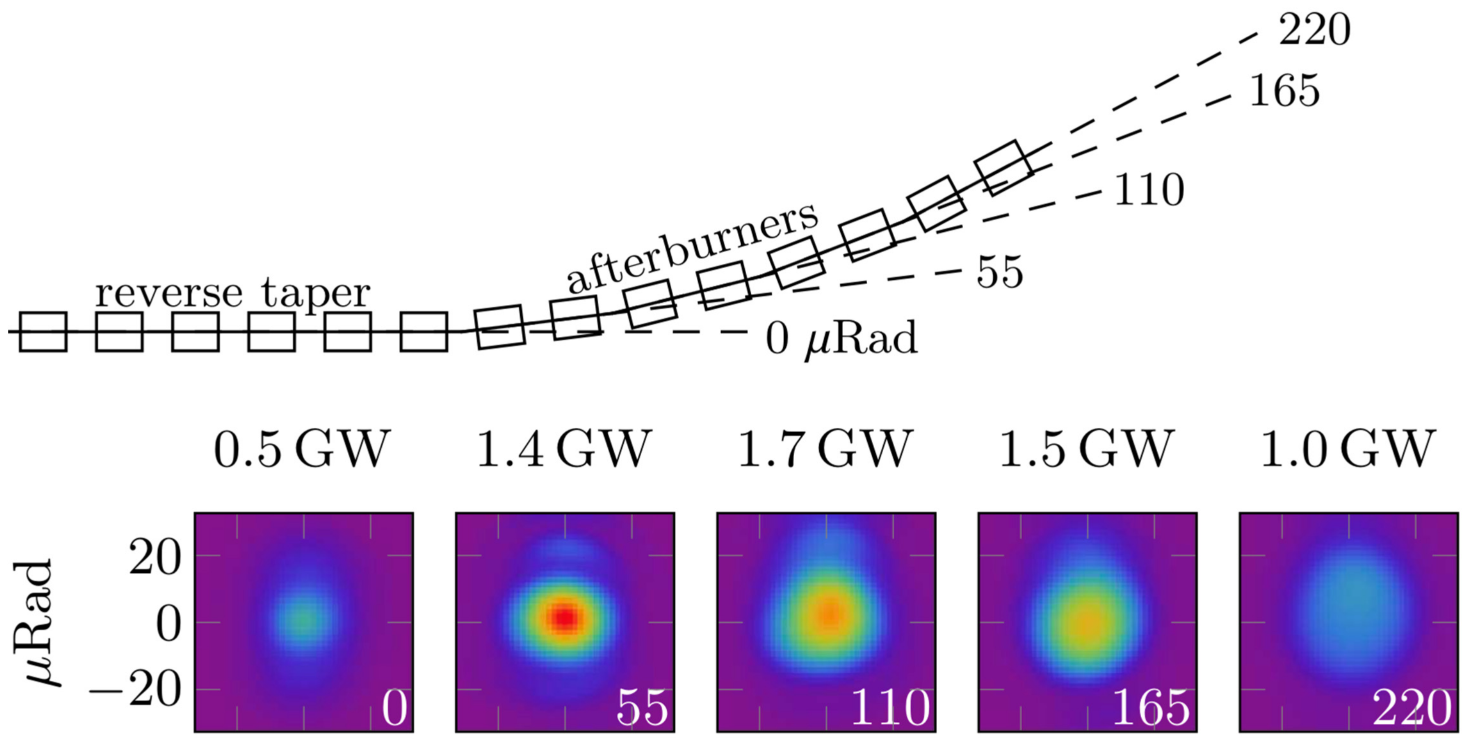
$$\frac{\partial \tilde{E}_\nu}{\partial z} \propto e^{-\frac{\alpha^2}{2\phi_c^2} - \frac{1}{2}\left(k^2 z \epsilon \phi_c (\phi_y - \alpha_b)\right)^2 + i\left(k_u \Delta\nu + k\frac{(\alpha-\phi_y)^2}{2}\right)z}$$





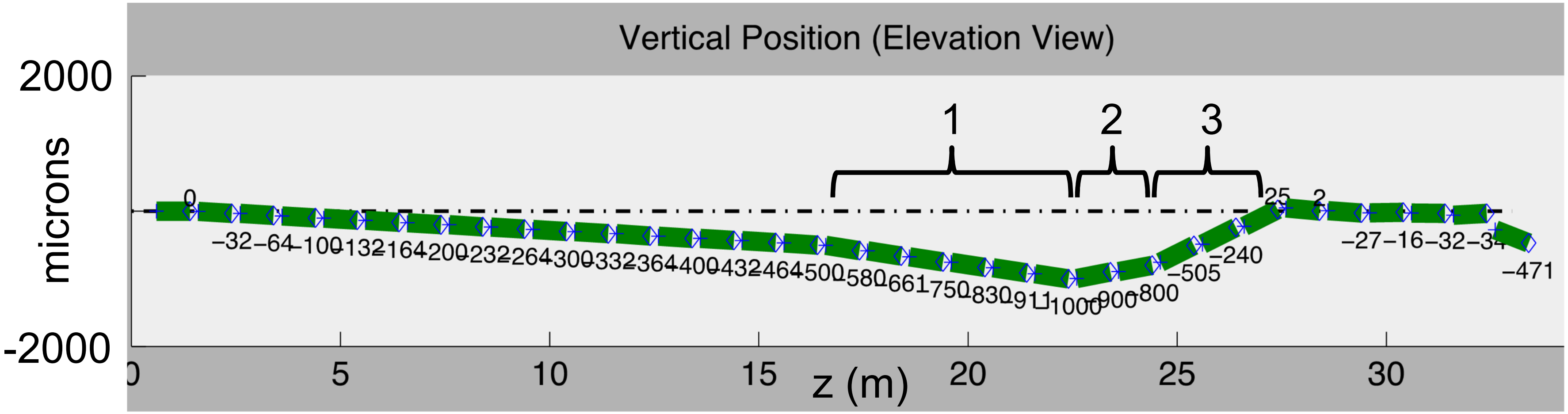


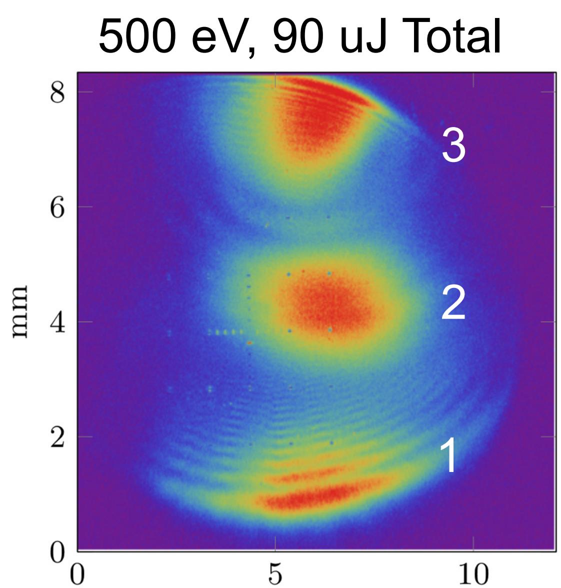
Multiplexing Possibilities (530 eV Simulation)



Note: critical angle for a single kick is only 25 uRad!

530 eV Multiplexing Experiment

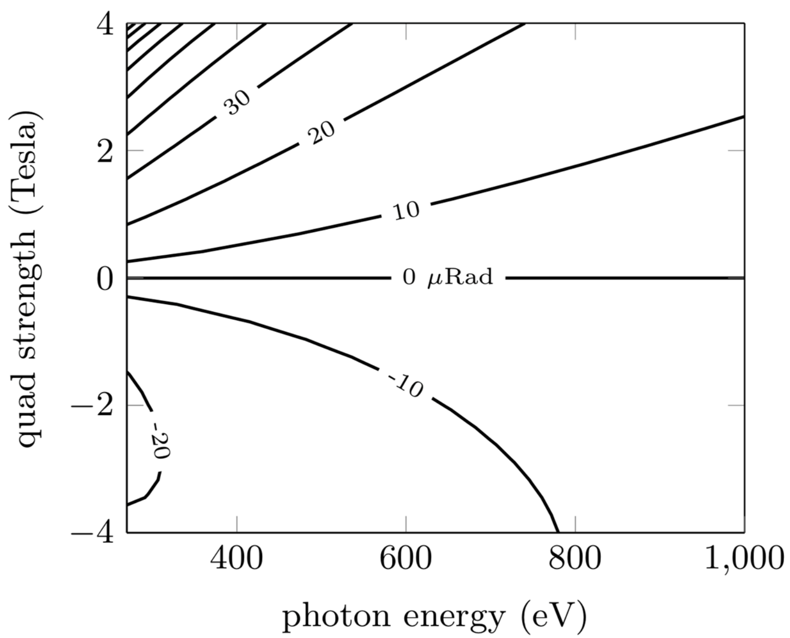


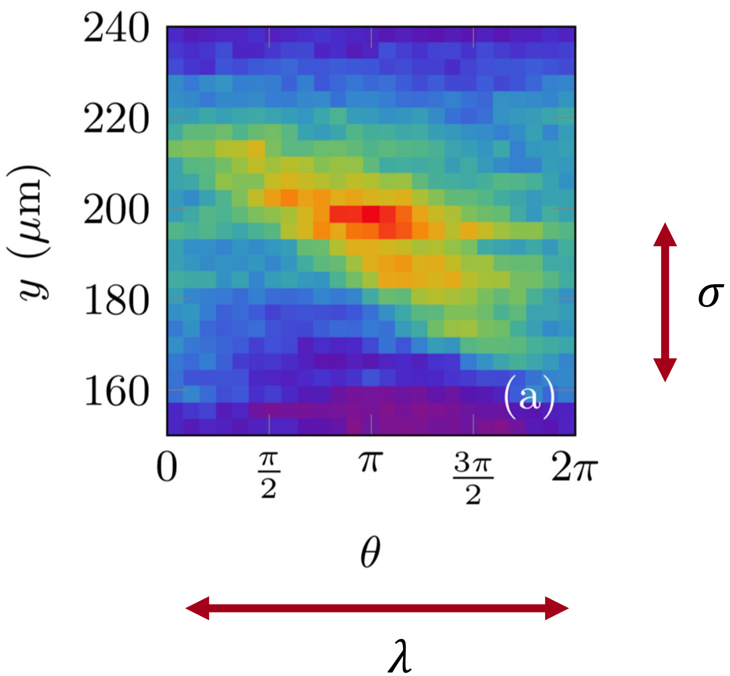


Hard X-Rays: Delicate Microbunches

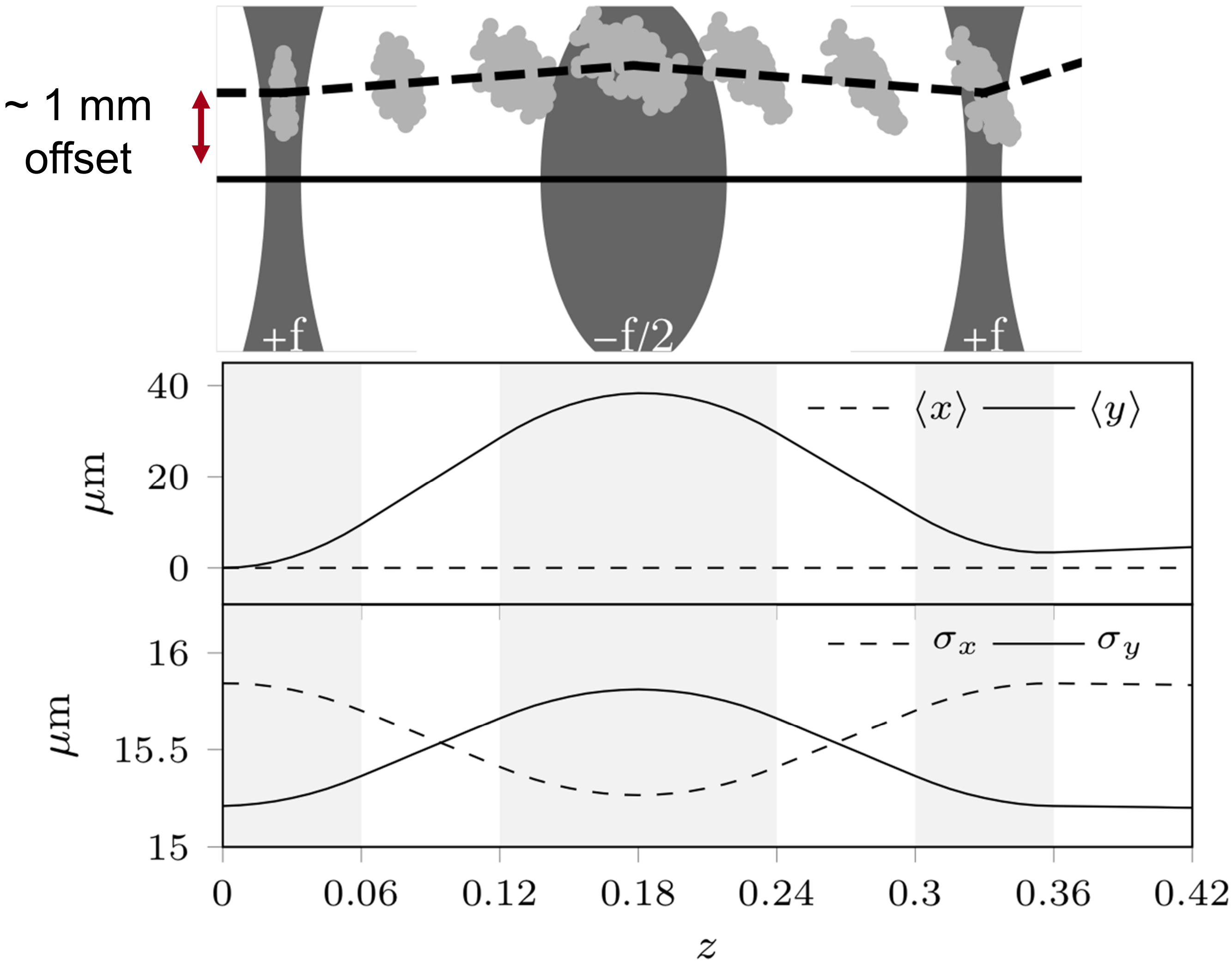
$$\Delta s \approx z\cos\left(y_0' + y_0/(2f) + \alpha\right) - z\cos\alpha$$
$$\approx \frac{\alpha z}{2f} y_0 + \alpha z y_0' + \frac{z}{2}\left(\frac{1}{2f} y_0 + y_0'\right)^2$$

$$\alpha_b(\hat{z} = \hat{L}, \alpha = \phi_c) \approx \frac{1}{k\sigma_y}\frac{f}{|f|}$$

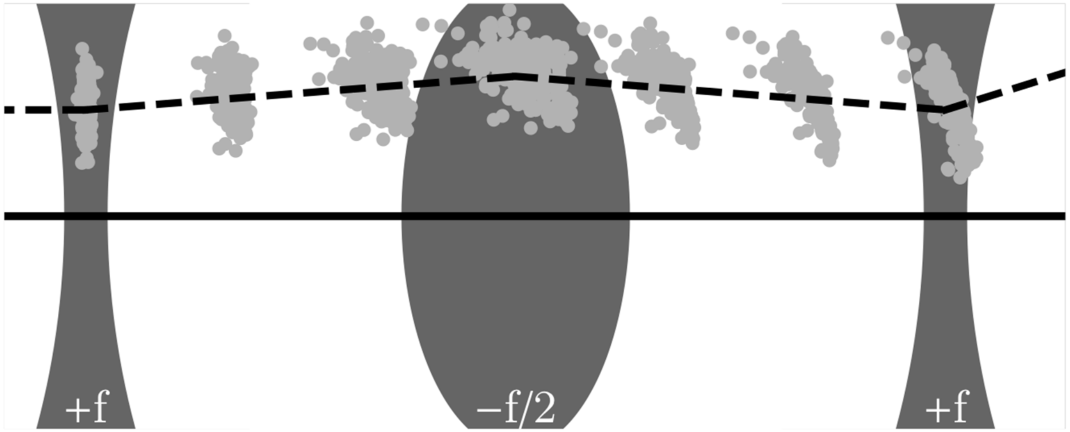




The Offset Triplet

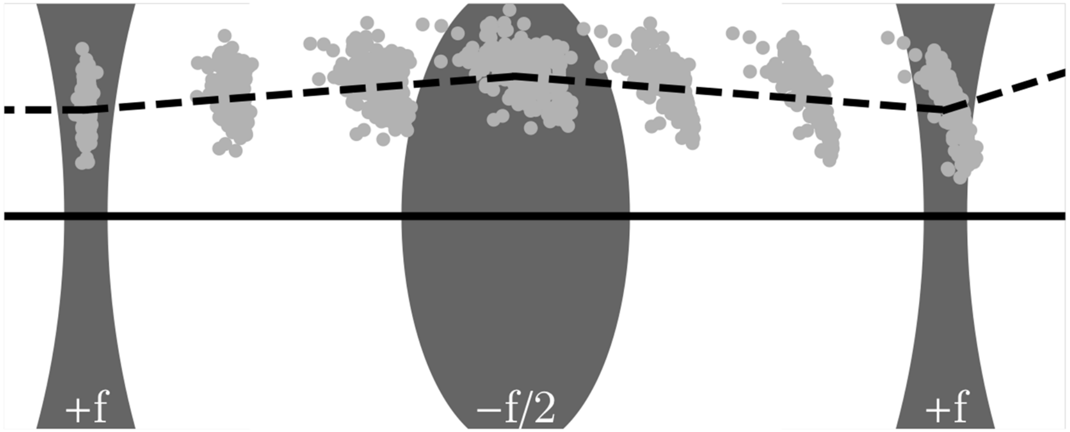


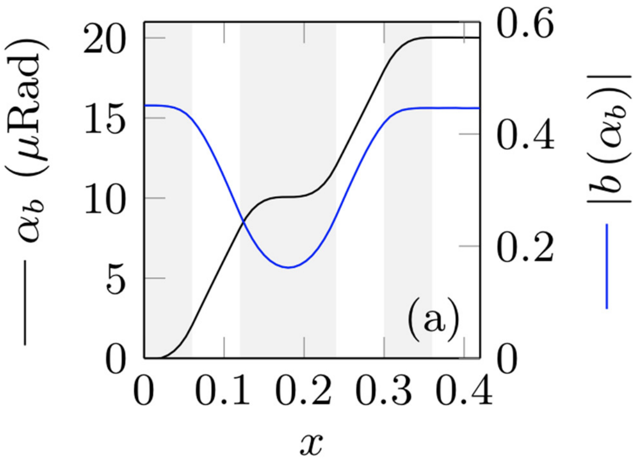
Microbunch Recovery

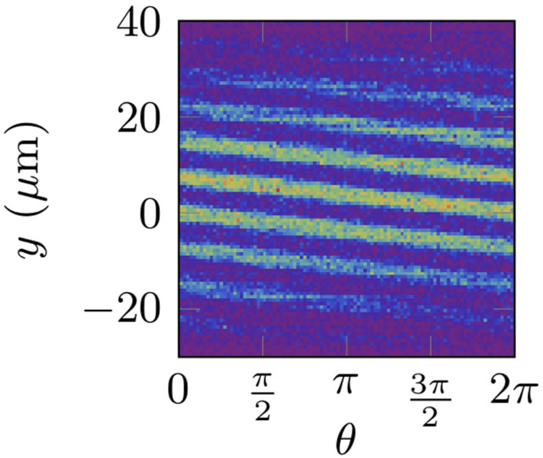


$$\Delta s \approx \frac{\alpha z}{2f} y_0 + \alpha z y_0' + \frac{z}{2}\left(\frac{1}{2f} y_0 + y_0'\right)^2$$

10x Rotation, Minimal Degradation







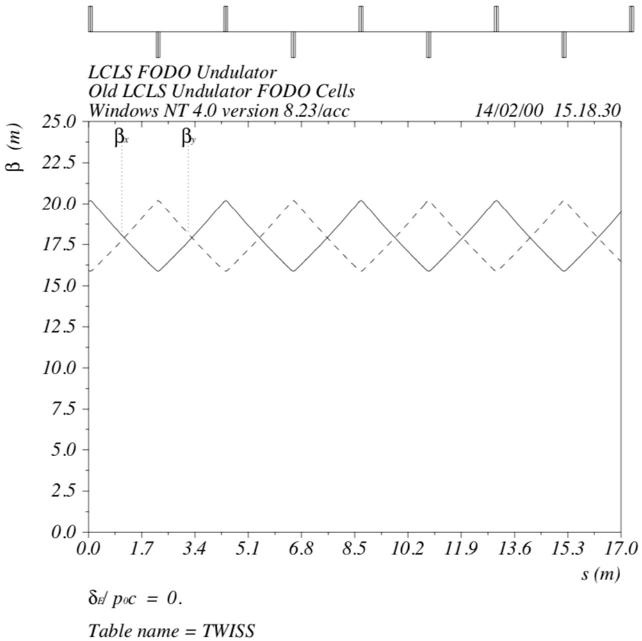
~20 uRad rotation, 10x critical angle

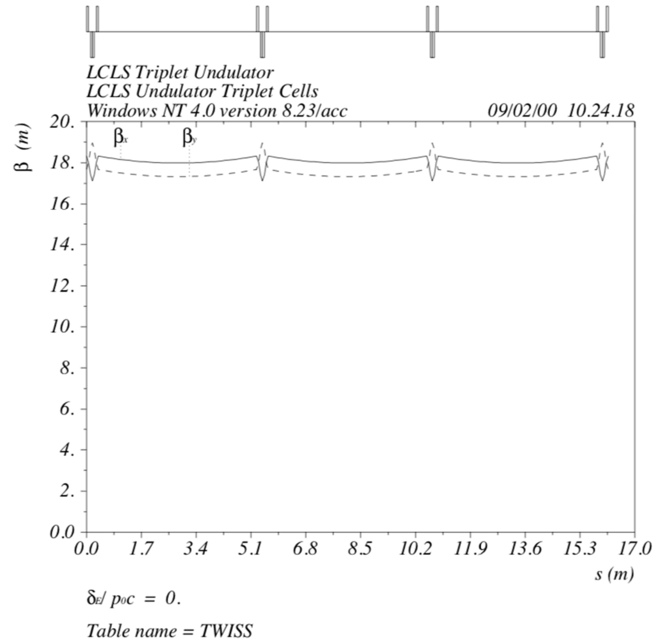
The Magnetic Triplet at LCLS

Quadrupole Magnet Error Sensitivities for FODO-Cell and Triplet Lattices in the LCLS Undulator

Paul Emma
Heinz-Dieter Nuhn
SLAC

February 24, 2000





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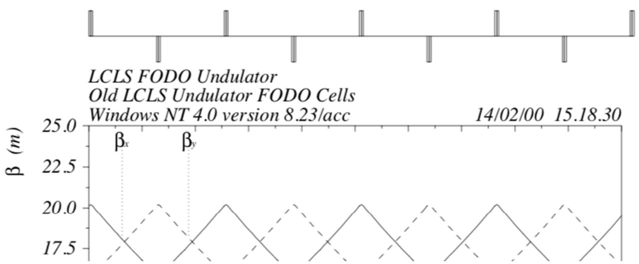
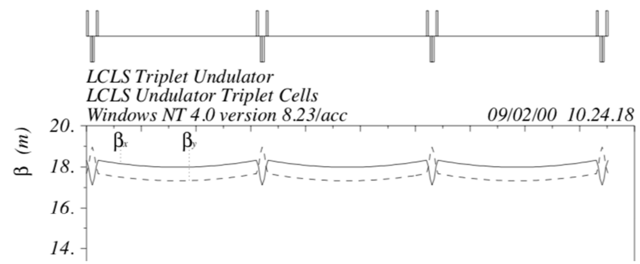
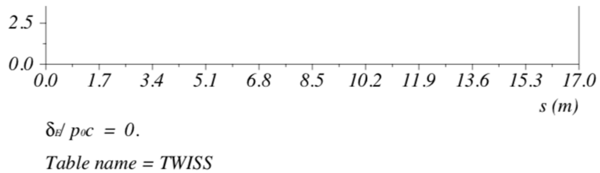
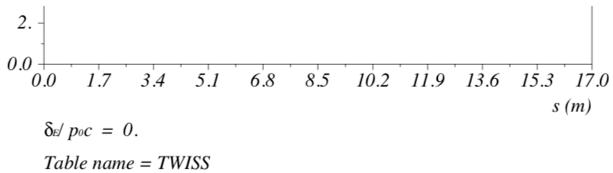




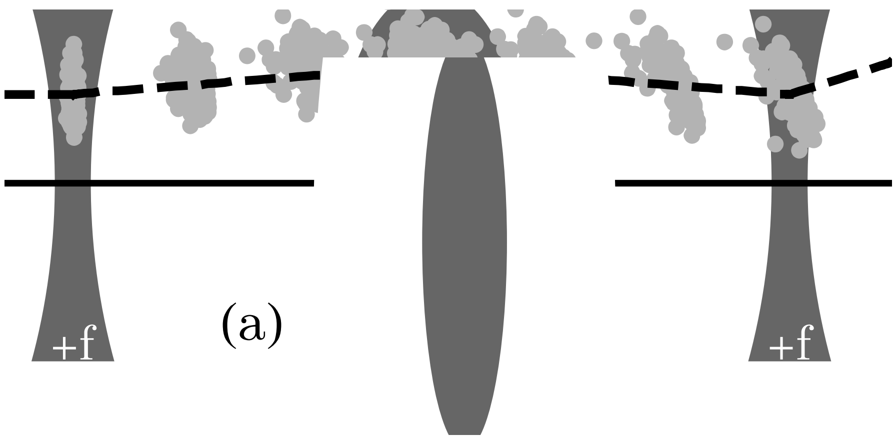
5 Summary

The triplet lattice for the LCLS undulator is a clear prescription for failure.

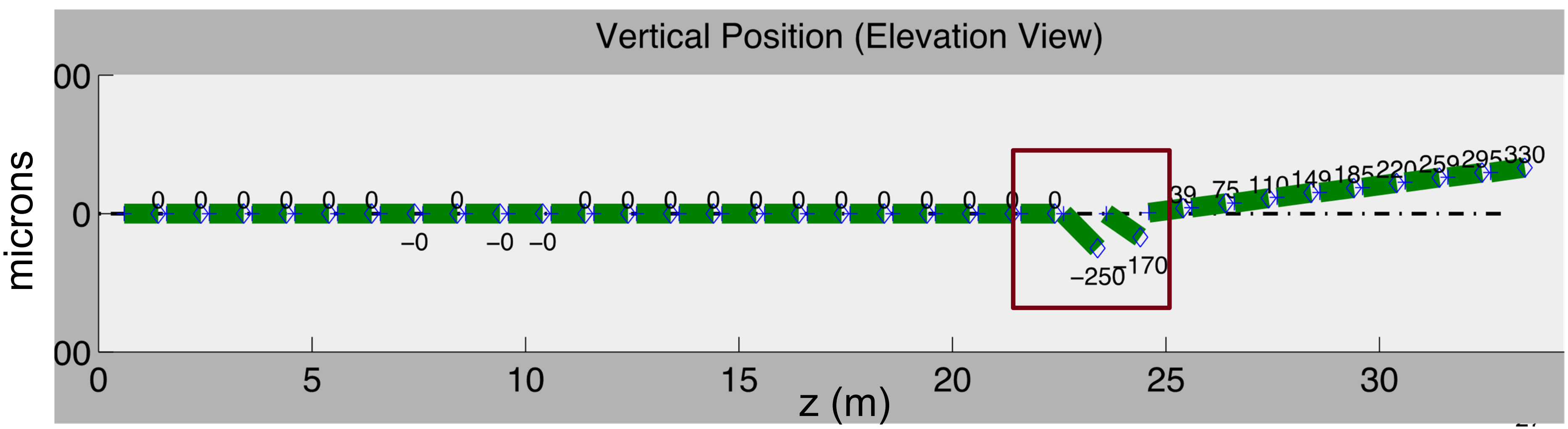




Girder Gymnastics

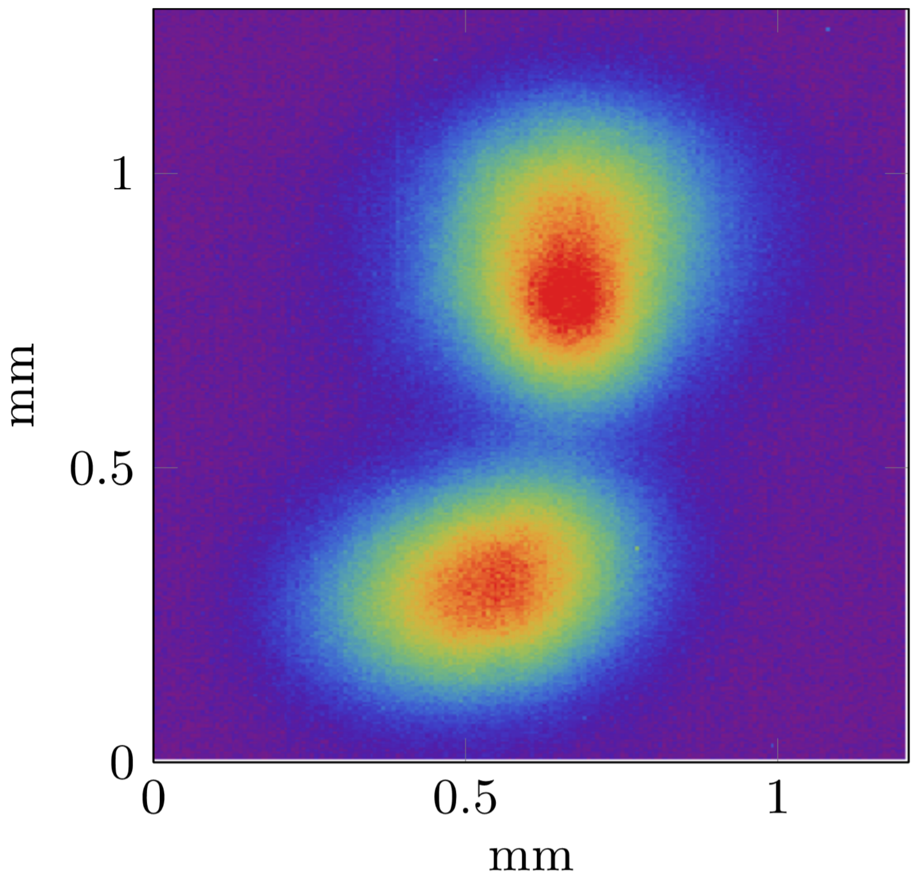


U22 end: Beam kicked up with dipole corrector. Beam defocused.
U23 end: Beam kicked down with mis-aligned quad. Beam focused.
U24 end: Beam kicked along new u-bunch direction with quad. Beam defocused

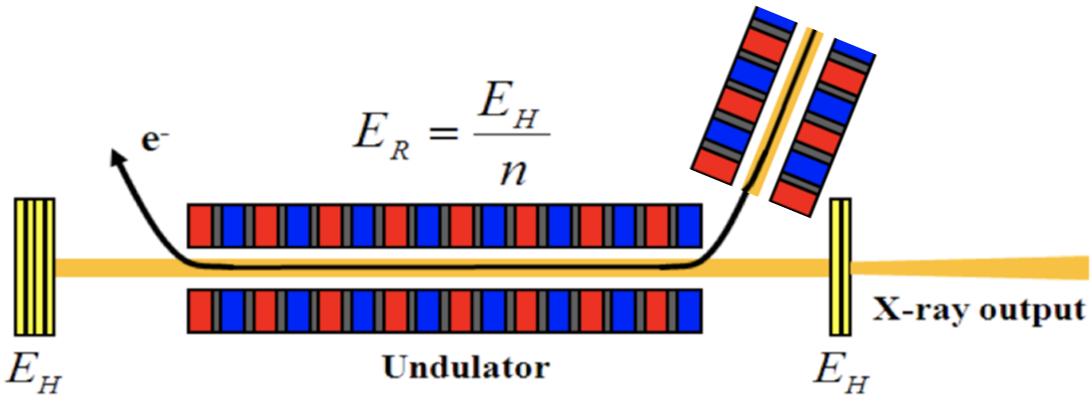


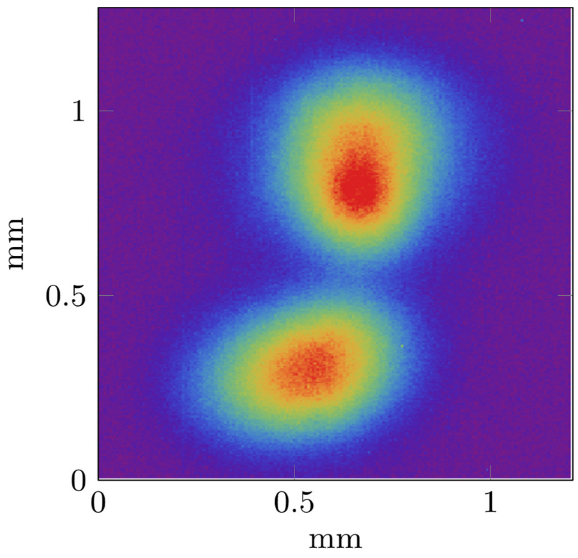
Hard X-Ray Microbunch Rotation Experiment

- Dec 19, 2018
  (last day of LCLS-I)
- Two hard x-ray spots produced
- 850 uJ, split equally between spots
- ~5 uRad separation
- First validation of microbunch rotation at hard x-ray (9.5 keV)
- Analysis & simulation ongoing (R. Margraf)



Oscillator Application



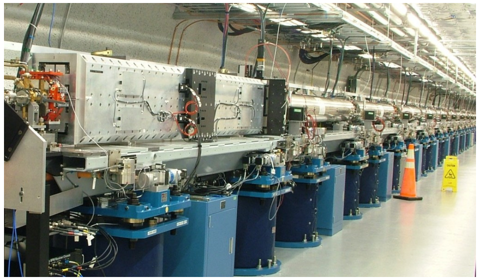


Summary

SLAC

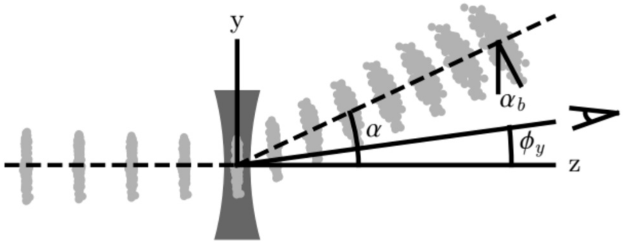
Motivation

- LCLS produces circular beams by beam diversion



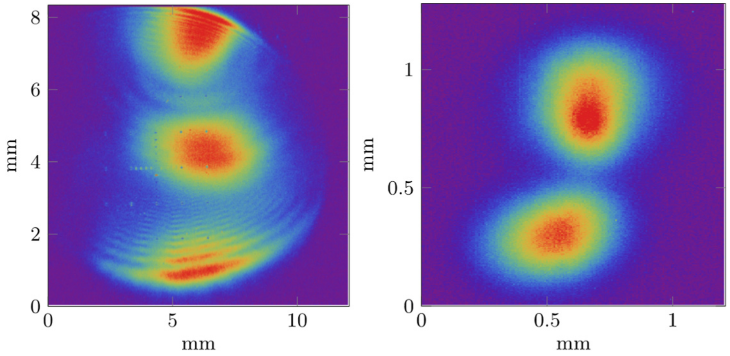
Rotation

- Microbunches rotate in response to a kick
- Consistent with simulation and experiment



Extensions

- Multiplexing at soft x-rays: 3 beams
- Multiplexing at hard x-rays: 2 beams



Questions?

Microbunch rotation and coherent undulator radiation from a kicked electron beam

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