Coherent Undulator Radiation and Microbunch Tilt from a Kicked Electron Beam

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SLAC NATIONAL ACCELERATOR LABORATORY

PAUL SCHERRER INSTITUT
PSI

Internal Workshop on Tailored Soft X-Ray Pulses

11.05.2016 – 12.05.2016

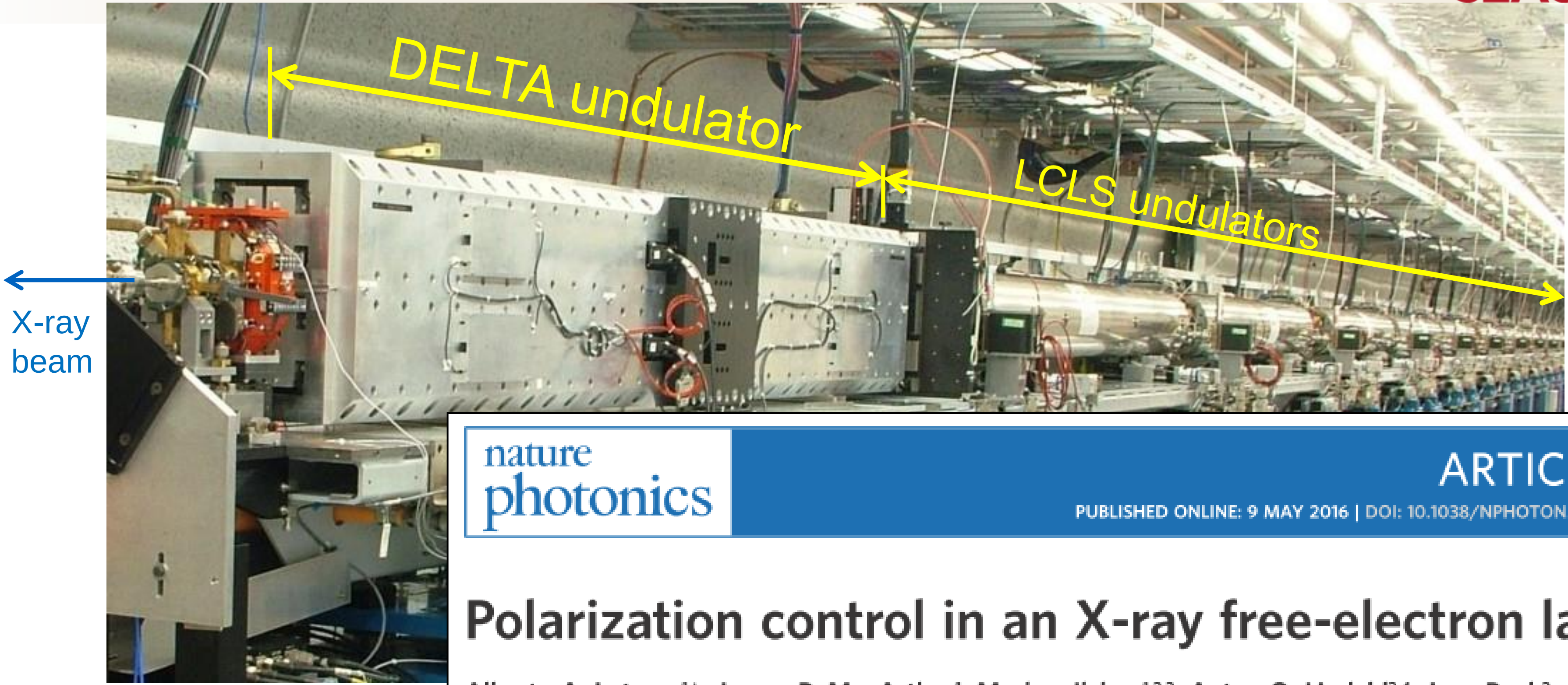
Wednesday, May 11

08h00 – 09h00	Registration & Welcome Coffee
09h00	**Welcome** (Hans-Heinrich Braun, PSI)
	Session 1: Tailoring Scheme *(Chair: tbc)*
09h15	**The ATHOS Machine** (Romain Ganter, PSI)
09h45	**Novel Operating Modes for ATHOS** (Eduard Prat, PSI)
10h15 – 10h45	Coffee Break
10h45	**Operating Modes at FERMI** (Luca Giannessi , FERMI / Elettra)
11h15	**The CLARA Test Facility** (Neil Thompson, ASTeC / STFC)
11h45	**LCLS and LCLS-II operating modes** (Zhirong Huang, SLAC)
12h15 – 13h45	Lunch
	Session 2: Advanced Experiments *(Chair: tbc)*
13h45	**Ultrafast Chemistry** (Alexander Föhlisch, HZB)
14h15	**Soft X-ray Spectroscopy at FLASH, LCLS and FERMI** (Wilfried Wurth, DESY)
14h45	**Non-linear X-ray Optics** (Martin Beye, HZB)
15h15 – 15h45	Coffee Break
15h45	**Coherent Optical Spectroscopy** (Peter Hamm, University of Zurich)
16h15	tbc
17h30 – 20h00	Dinner

Thursday, May 12

08h30 – 09h00	Welcome Coffee
	Session 3: Advanced Experiments and Facility Plans *(Chair: tbc)*
09h00	**Soft X-ray Spectroscopy of correlated electron materials** (Steve Johnson, ETH Zurich
09h30	**ATHOS Beamlines and Experimental Stations** (Luc Patthey, PSI)
10h00 – 10h30	Coffee Break
10h30	**Facility Plans at FERMI** (Filippo Bencivenga, Elettra)
11h00	**Facility Plans at LCLS-II** (William Schlotter, SLAC)
11h00 – 11h15	Short Break
	Session 4: Structured Discussion *(Chair:)*
11h15	**Discussion**
13h15	**Closing Remarks** (Rafael Abela, PSI)
13h30	End of Workshop

LCLS Delta undulator for polarization control



nature photonics

ARTICLES

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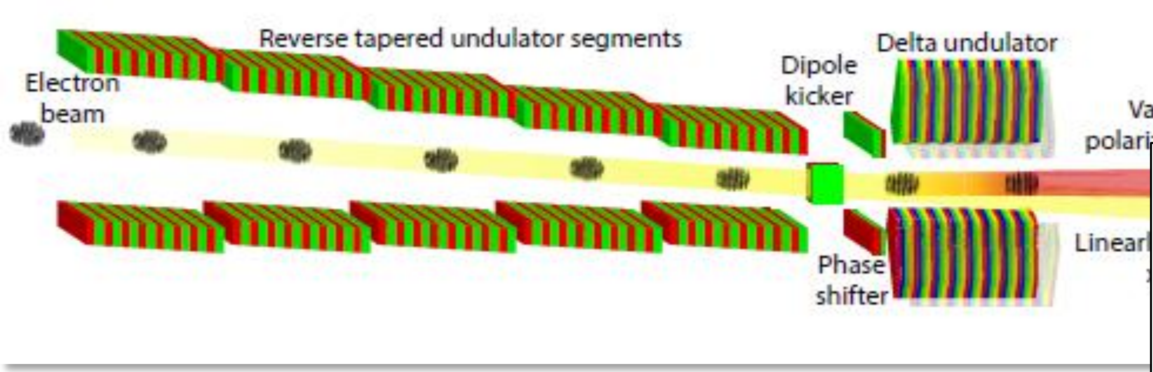
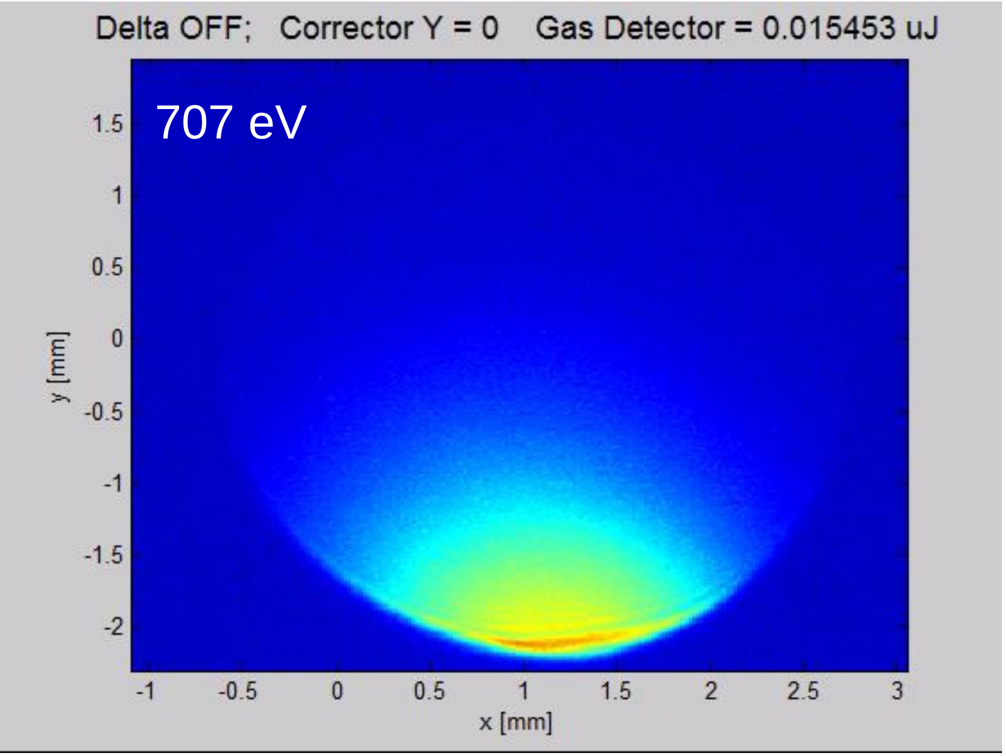
Polarization control in an X-ray free-electron laser

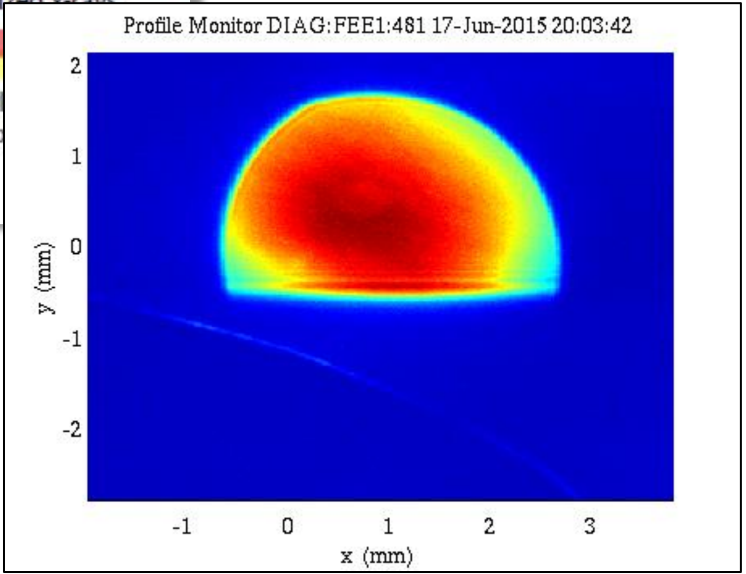
Alberto A. Lutman[1]*, James P. MacArthur[1], Markus Ilchen[1,2,3], Anton O. Lindahl[3,4], Jens Buck[2], Ryan N. Coffee[1,3], Georgi L. Dakovski[1], Lars Dammann[5], Yuantao Ding[1], Hermann A. Dürr[1,3,6], Leif Glaser[5], Jan Grünert[2], Gregor Hartmann[5], Nick Hartmann[1,7], Daniel Higley[1], Konstantin Hirsch[1], Yurii I. Levashov[1], Agostino Marinelli[1], Tim Maxwell[1], Ankush Mitra[1], Stefan Moeller[1], Timur Osipov[1], Franz Peters[1], Marc Planas[2], Ivan Shevchuk[5], William F. Schlotter[1], Frank Scholz[5], Jörn Seltmann[5], Jens Viefhaus[5], Peter Walter[5], Zachary R. Wolf[1], Zhirong Huang[1,3] and Heinz-Dieter Nuhn[1]

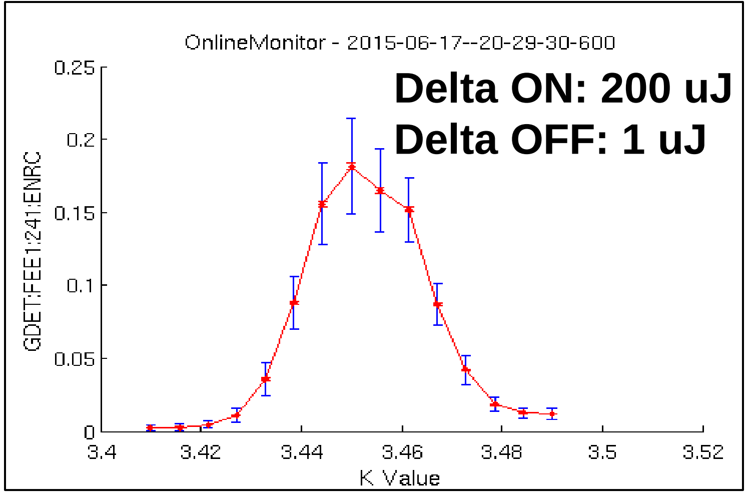
- Four independent rows of permanent magnets move longitudinally at fixed gap.
- Polarization state of the radiation can be controlled over the full range.

Beam diverting to obtain high polarization degree





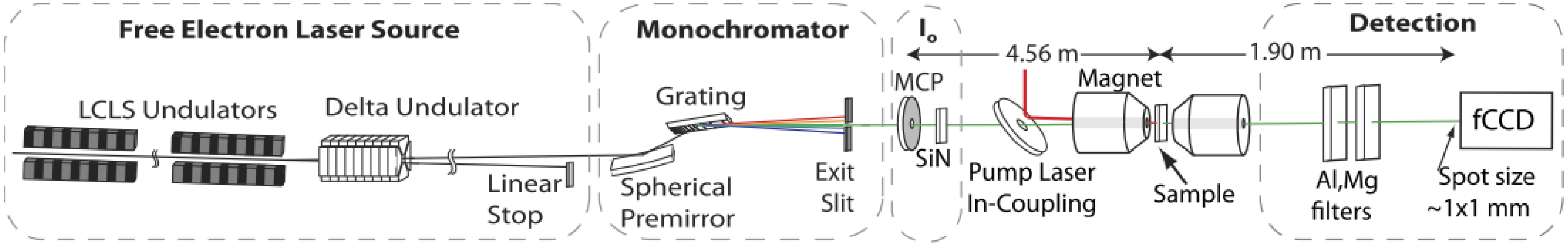


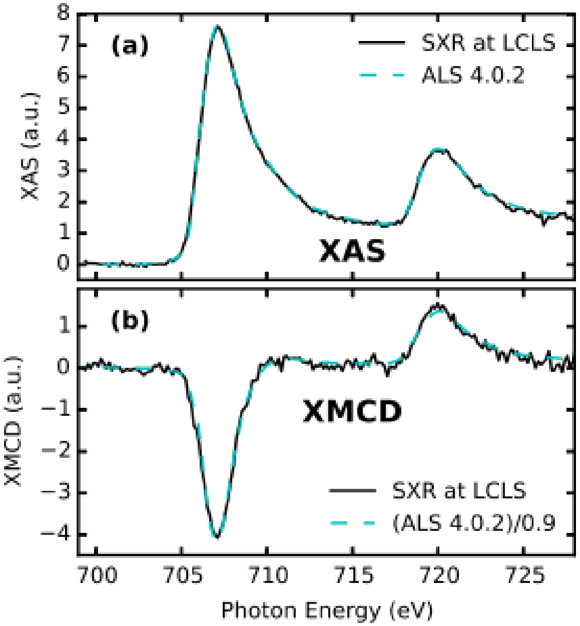


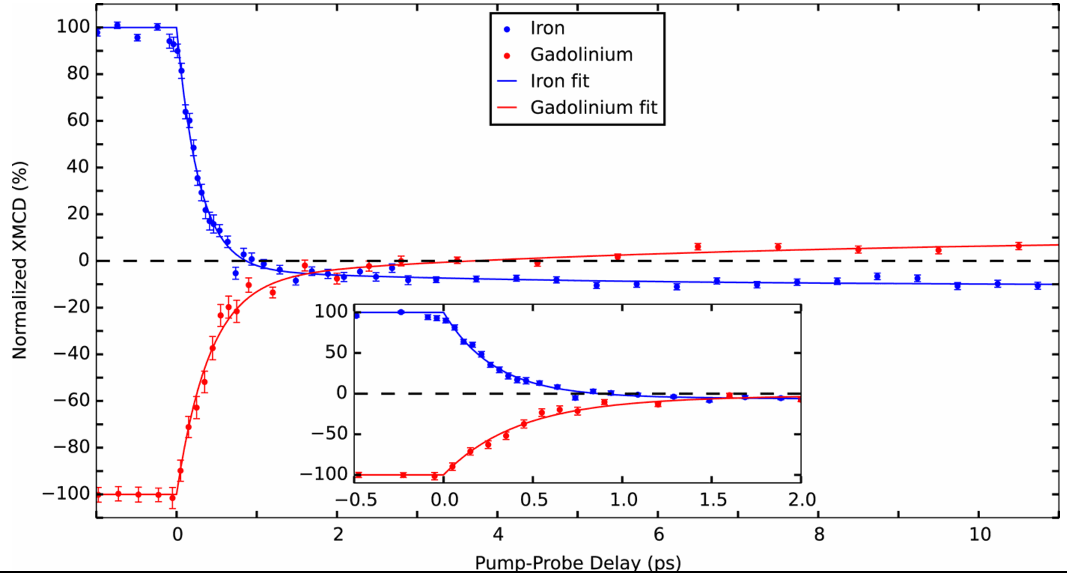
Delta ON: 200 uJ
Delta OFF: 1 uJ

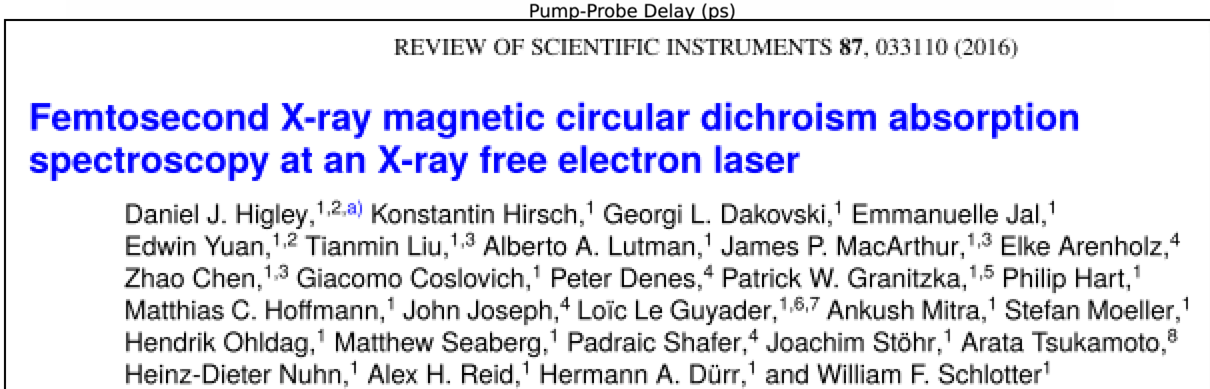
A. Lutman et al., Nature Photonics (May 2016)

First X-ray Magnetic Circular Dichroism taken at LCLS (Nearly 100% degree of polarization measured)









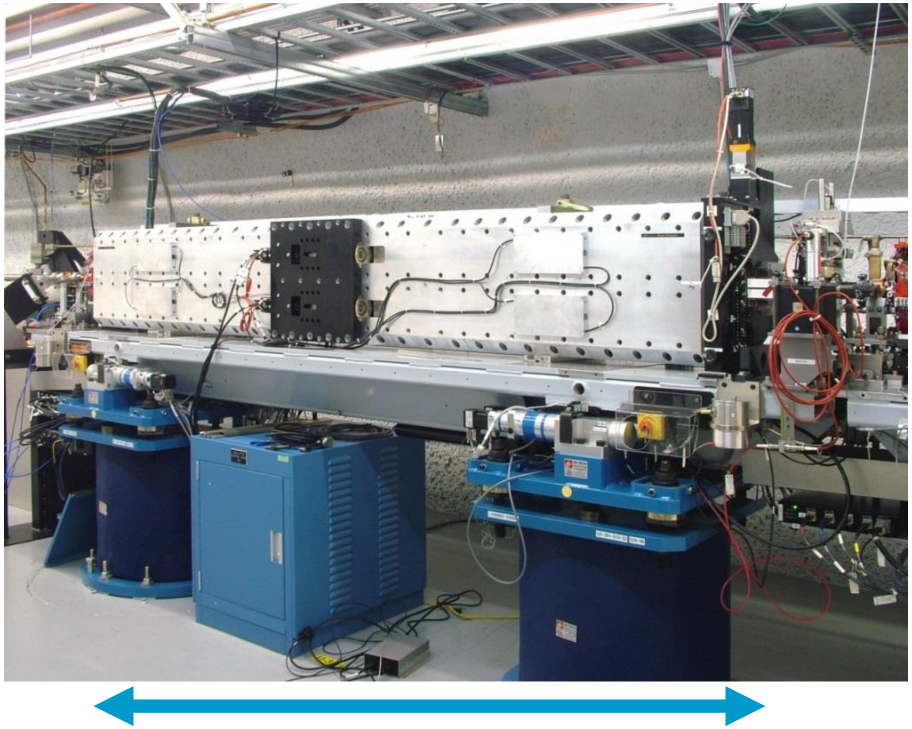
REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 033110 (2016)

Femtosecond X-ray magnetic circular dichroism absorption spectroscopy at an X-ray free electron laser

Daniel J. Higley,[1,2,a)] Konstantin Hirsch,[1] Georgi L. Dakovski,[1] Emmanuelle Jal,[1]
Edwin Yuan,[1,2] Tianmin Liu,[1,3] Alberto A. Lutman,[1] James P. MacArthur,[1,3] Elke Arenholz,[4]
Zhao Chen,[1,3] Giacomo Coslovich,[1] Peter Denes,[4] Patrick W. Granitzka,[1,5] Philip Hart,[1]
Matthias C. Hoffmann,[1] John Joseph,[4] Loïc Le Guyader,[1,6,7] Ankush Mitra,[1] Stefan Moeller,[1]
Hendrik Ohldag,[1] Matthew Seaberg,[1] Padraic Shafer,[4] Joachim Stöhr,[1] Arata Tsukamoto,[8]
Heinz-Dieter Nuhn,[1] Alex H. Reid,[1] Hermann A. Dürr,[1] and William F. Schlotter[1]

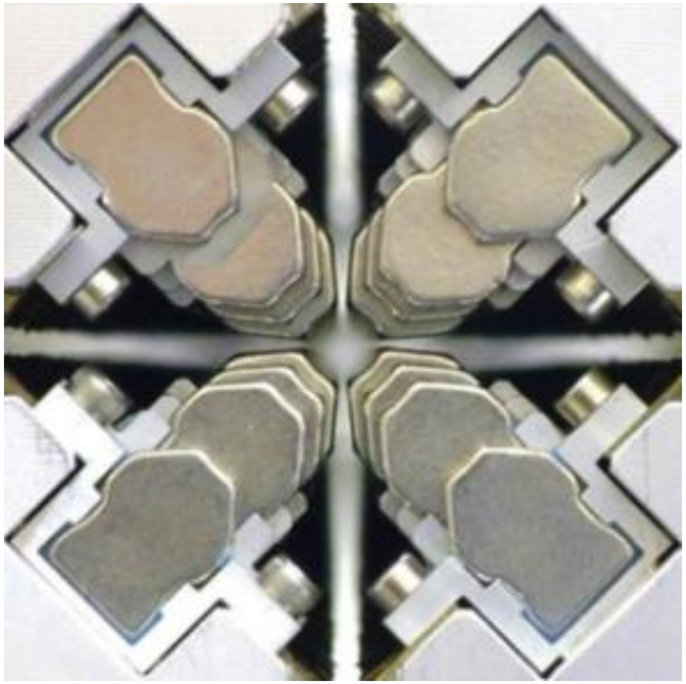
Background: Delta Undulator

Girder 33: Delta Undulator



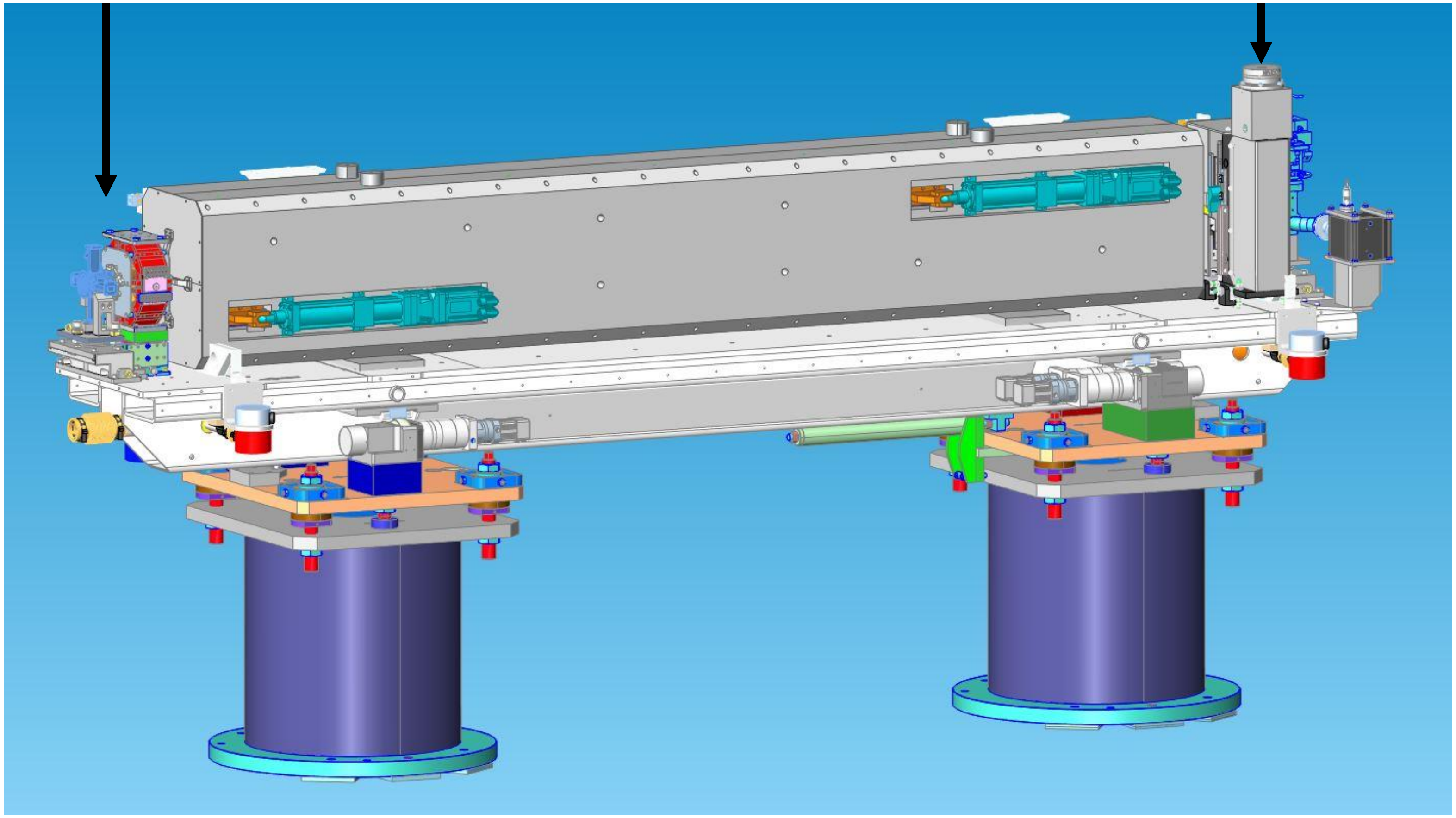
- 3.2 m total, 100 periods
- Installed Sept. 2014
- Includes phase shifter

Delta's Axial View



- 4 independent $Nd_2Fe_{14}B$ magnet row
- 4 magnets per 3.2 cm undulator period

Delta Undulator Detailed View

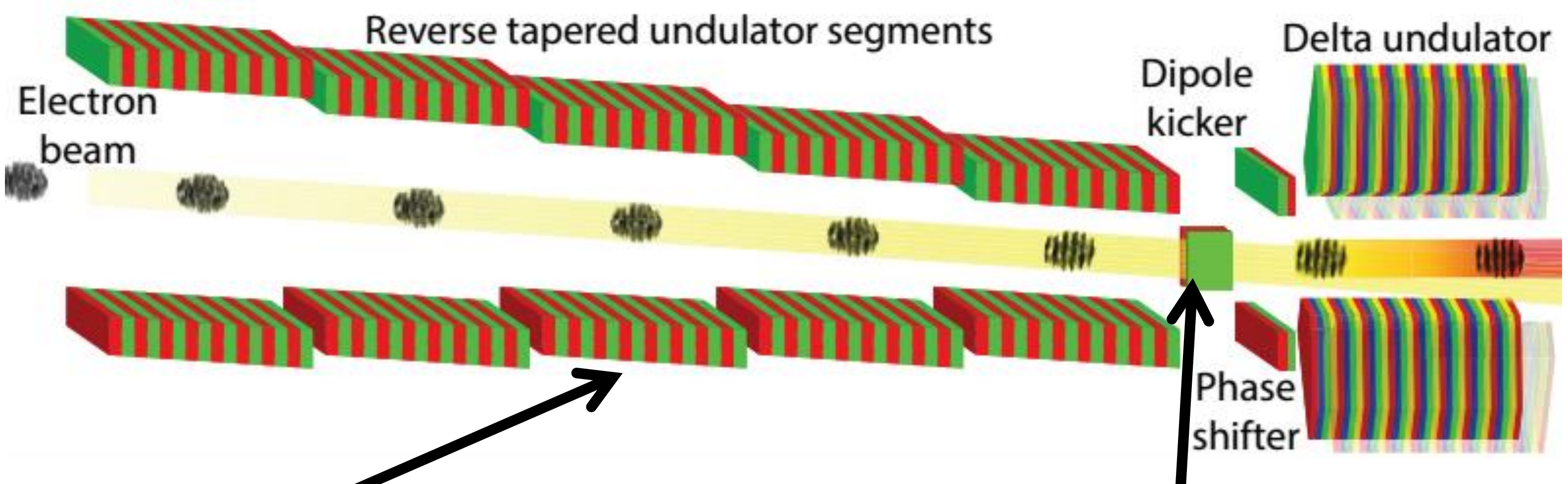


Quadrupole & Cavity BPM

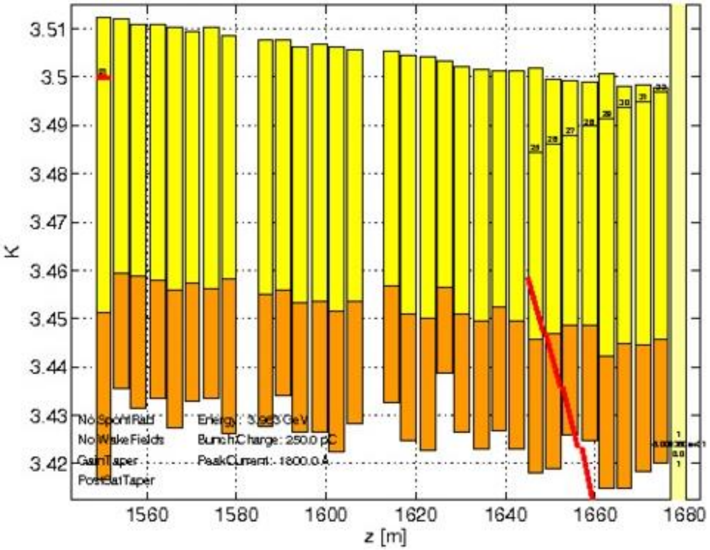
Phase Shifter

Quadrupoles before and after Delta
(Details: H.-D. Nuhn et al., FEL 2013)

Delta in the Afterburner Configuration



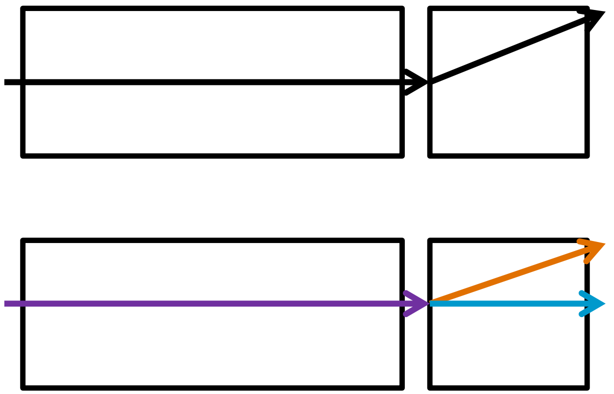
Reverse Tapered



Beam Diverting

Linear Undulator

Delta RCP

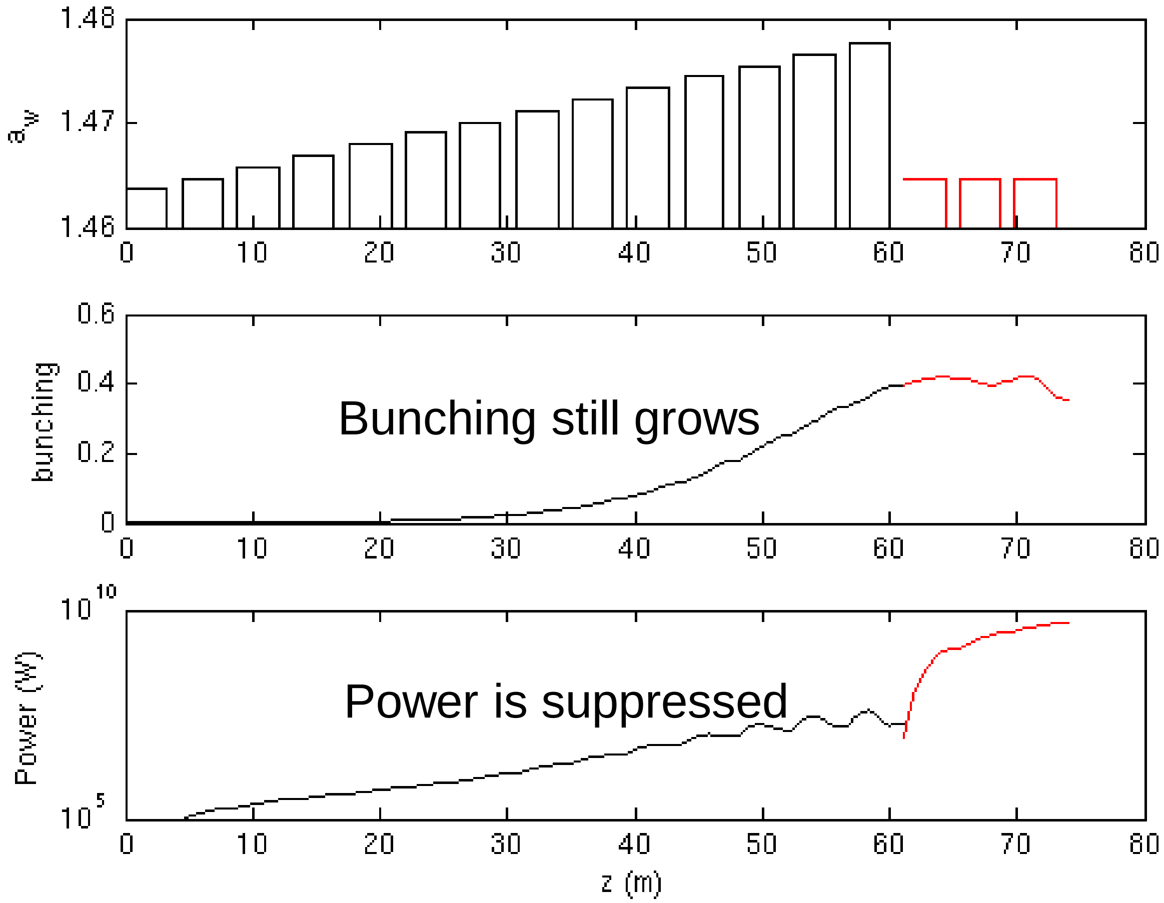


RCP

LCP

Reverse Taper

Reverse Taper + Afterburner Simulation



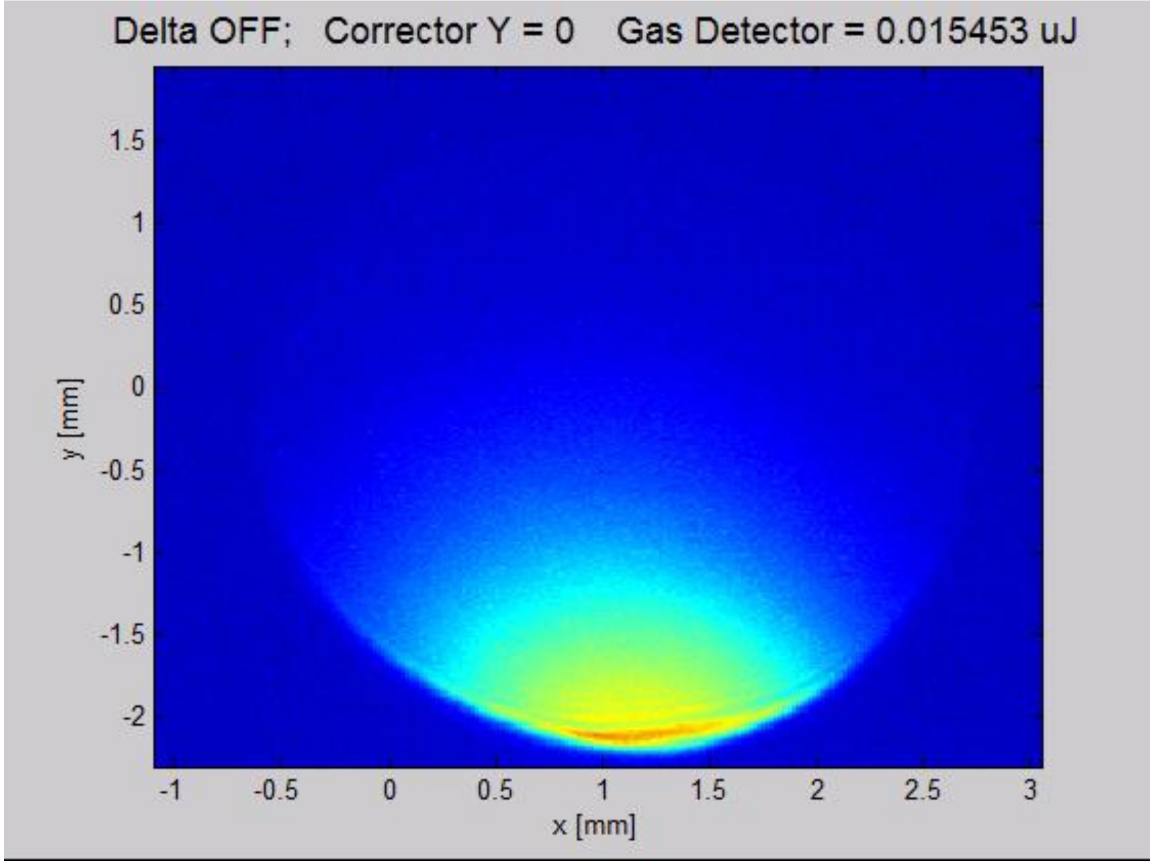
Bunching still grows

Power is suppressed

Rapid increase in power

Reverse taper suggested by Schneidmiller and Yurkov, PRSTAB **16**, 110702 (2013)
Reverse taper power suppression depends on E-energy spread (J. MacArthur, FEL2015)

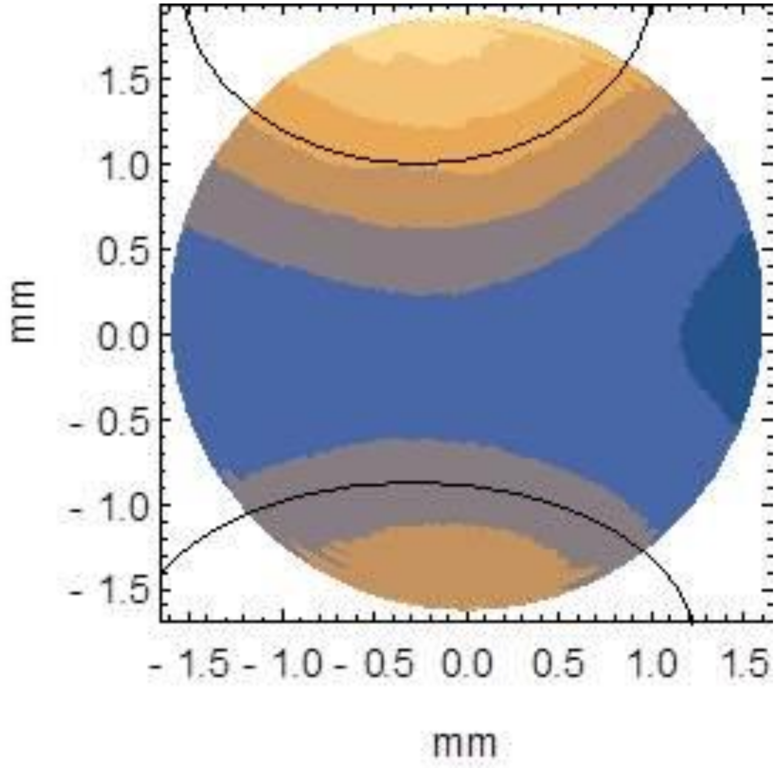
Beam diverting: Substantial Separation Achieved

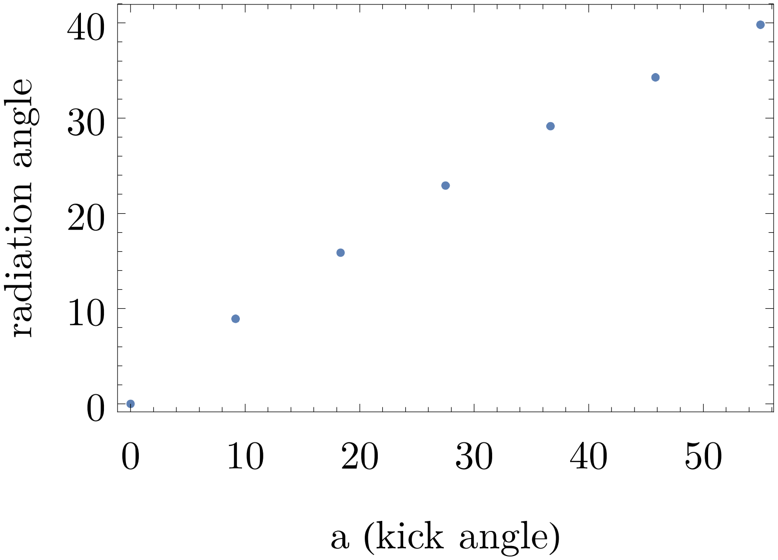


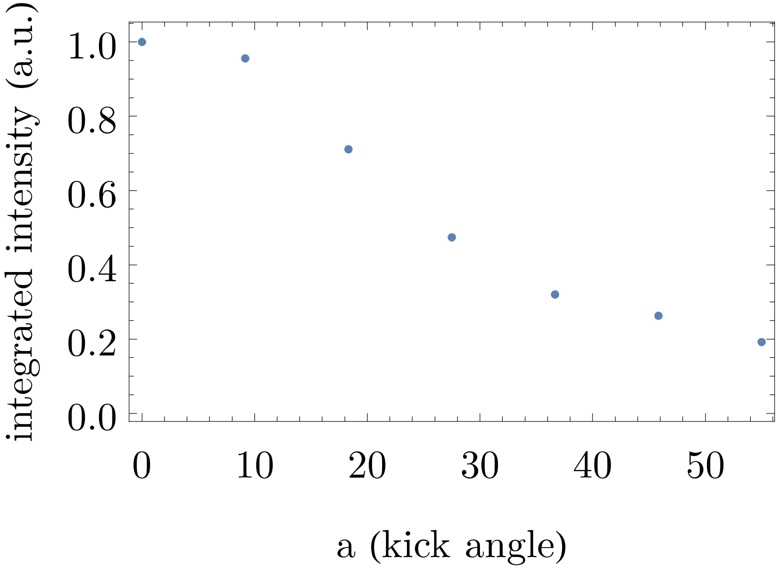
- Direct imager is 87 meters downstream from Delta
- Separations of order 30-40 uRad are observed at lower energies
- Significantly easier to kick in y-axis than x-axis
- Polarization components are separable

Fit to Both Centroid and Integrated Strength

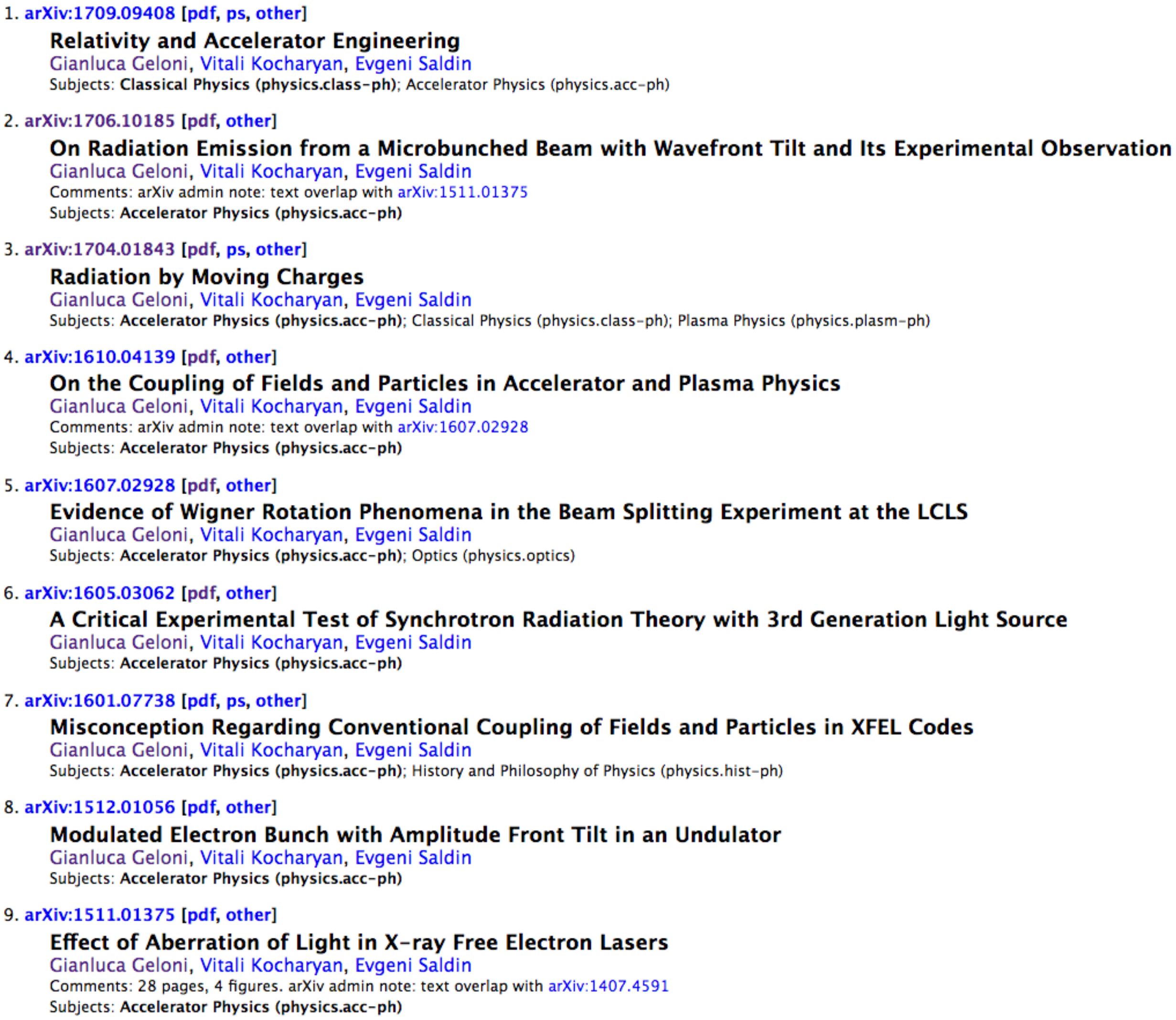
- Two-spot centroid and integrated intensity may be extracted
- Can we simulate and predict such observations?







Saldin, Geloni, & co Showed Interest



1. arXiv:1709.09408 [pdf, ps, other]
   Relativity and Accelerator Engineering
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Subjects: **Classical Physics (physics.class-ph)**; Accelerator Physics (physics.acc-ph)
2. arXiv:1706.10185 [pdf, other]
   On Radiation Emission from a Microbunched Beam with Wavefront Tilt and Its Experimental Observation
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Comments: arXiv admin note: text overlap with arXiv:1511.01375
   Subjects: **Accelerator Physics (physics.acc-ph)**
3. arXiv:1704.01843 [pdf, ps, other]
   Radiation by Moving Charges
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Subjects: **Accelerator Physics (physics.acc-ph)**; Classical Physics (physics.class-ph); Plasma Physics (physics.plasm-ph)
4. arXiv:1610.04139 [pdf, other]
   On the Coupling of Fields and Particles in Accelerator and Plasma Physics
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Comments: arXiv admin note: text overlap with arXiv:1607.02928
   Subjects: **Accelerator Physics (physics.acc-ph)**
5. arXiv:1607.02928 [pdf, other]
   Evidence of Wigner Rotation Phenomena in the Beam Splitting Experiment at the LCLS
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Subjects: **Accelerator Physics (physics.acc-ph)**; Optics (physics.optics)
6. arXiv:1605.03062 [pdf, other]
   A Critical Experimental Test of Synchrotron Radiation Theory with 3rd Generation Light Source
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Subjects: **Accelerator Physics (physics.acc-ph)**
7. arXiv:1601.07738 [pdf, ps, other]
   Misconception Regarding Conventional Coupling of Fields and Particles in XFEL Codes
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Subjects: **Accelerator Physics (physics.acc-ph)**; History and Philosophy of Physics (physics.hist-ph)
8. arXiv:1512.01056 [pdf, other]
   Modulated Electron Bunch with Amplitude Front Tilt in an Undulator
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Subjects: **Accelerator Physics (physics.acc-ph)**
9. arXiv:1511.01375 [pdf, other]
   Effect of Aberration of Light in X-ray Free Electron Lasers
   Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin
   Comments: 28 pages, 4 figures. arXiv admin note: text overlap with arXiv:1407.4591
   Subjects: **Accelerator Physics (physics.acc-ph)**

DESY 16-128

July 2016

Gianluca Geloni,
European XFEL GmbH, Hamburg

Vitali Kocharyan and Evgeni Saldin
Deutsches Elektronen-Synchrotron DESY, Hamburg

Evidence of Wigner Rotation Phenomena in the Beam Splitting Experiment at the LCLS

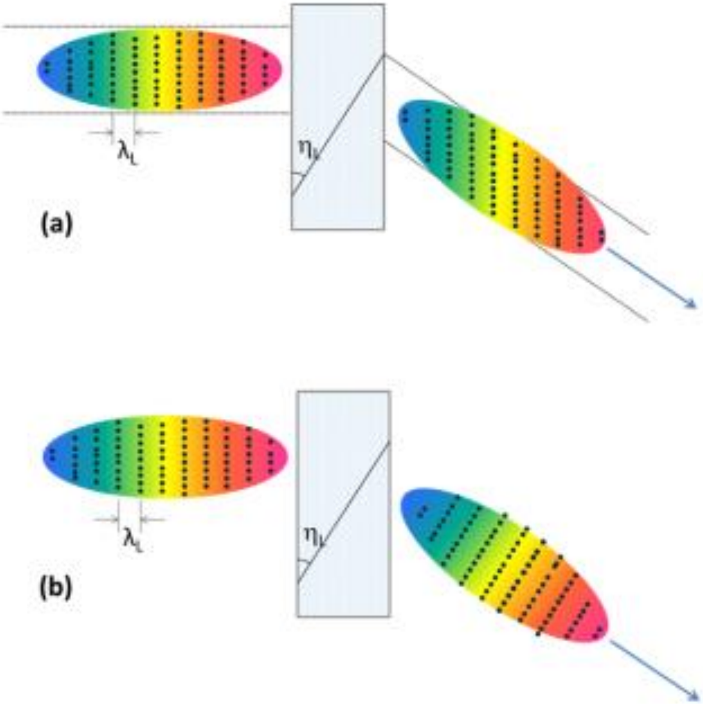
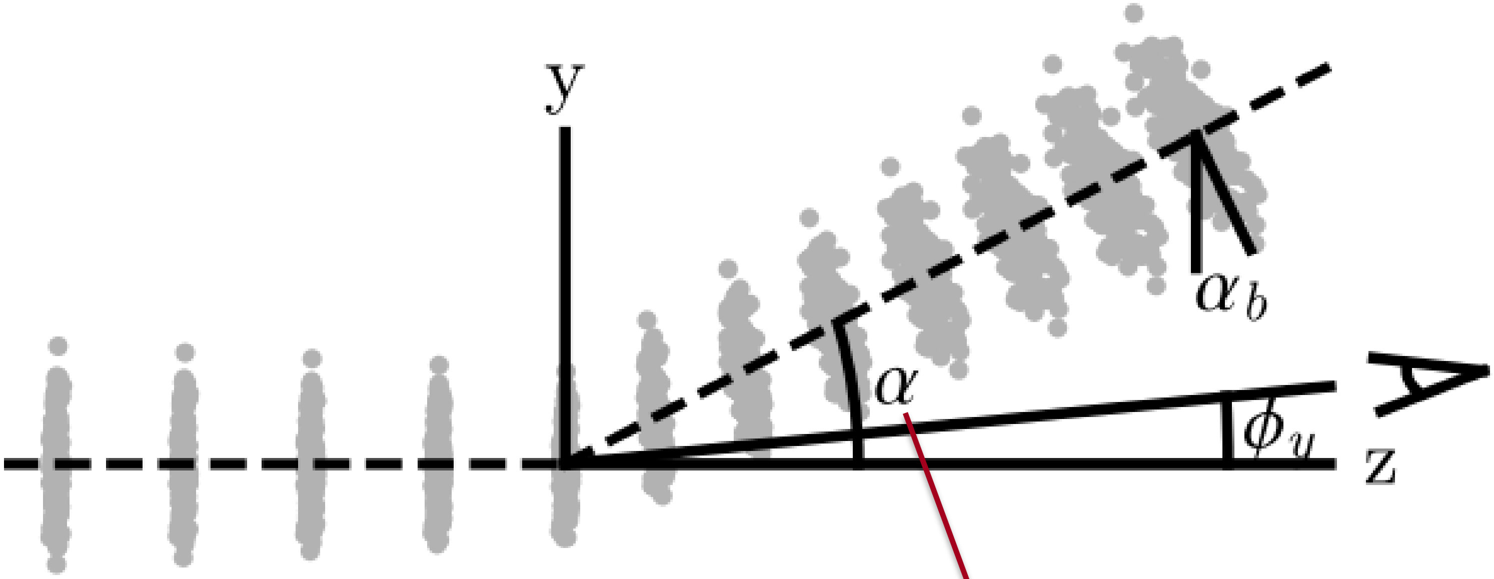


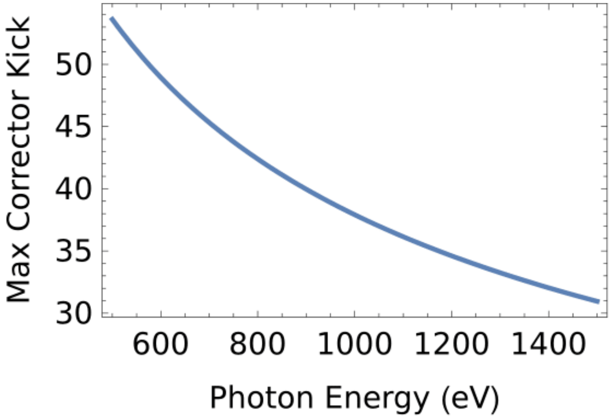
Fig. 1. Illustration of the problem, which arises according to classical particle tracking when a microbunched electron beam is deflected by a dipole magnet by an angle η_L. (a) According to particle tracking results, after passing the dipole the microbunching is preserved, but only along its original direction. (b) Using a different convention the orientation of the microbunching wavefront is always perpendicular to the electron beam velocity.

Our Approach: J. MacArthur et al., in preparation Coherent Undulator Radiation + Beam Dynamics



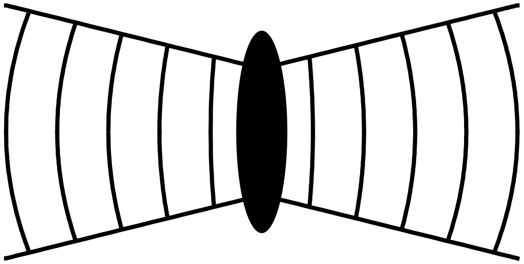
- A pre-bunched beam is deflected at z=0
- **The kick provides no immediate microbunch rotation, but microbunch tilt develops due to beam dynamics**

- An observer sits at an angle ϕ_y.
- The dipole correctors supply 0.006 kGm, limiting the kick to 10s of uRad

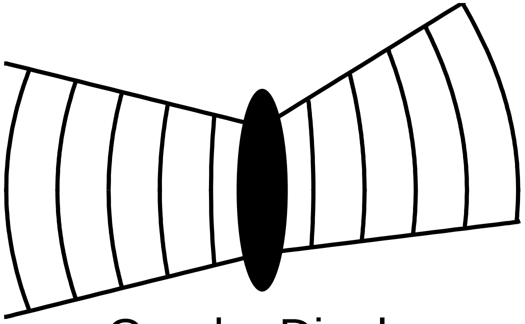


Microbunch tilt develops due to quad + dipole effects

- LCLS Quads can provide up to +/- 4 T integrated field strength, though 3 T is typical operation
- The quadrupole and dipole effects conspire to re-orient the microbunch direction for free



Normal Quad

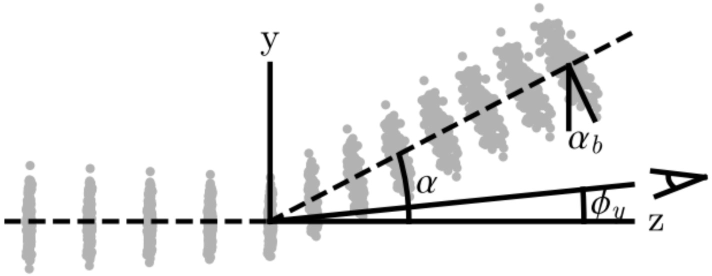


Quad + Dipole

- This effect is relevant when the R_43 of the quadrupole is large (at low energy)

Trajectory In Delta Undulator

The corrector kicks the beam in the +y direction by an angle α and the quad is defocusing in the y dimension:



$$x(z) = x_0 + (x_0' + R_{21} x_0)\, z$$
$$y(z) = y_0 + (y_0' + R_{43} y_0 + \alpha)\, z$$

Assume periodic FODO lattice: in middle of the quad, transverse position and angle are uncorrelated with the distribution function

$$F_0(\mathbf{x}_0, \mathbf{x}_0', \eta; z) = \frac{e^{-x_0^2/2\sigma_x^2}}{\sqrt{2\pi}\sigma_x} \frac{e^{-y_0^2/2\sigma_y^2}}{\sqrt{2\pi}\sigma_y} \frac{e^{-x_0'^2/2\sigma_{x'}^2}}{\sqrt{2\pi}\sigma_{x'}} \frac{e^{-y_0'^2/2\sigma_{x'}^2}}{\sqrt{2\pi}\sigma_{y'}} \frac{e^{-\eta^2/2\sigma_\eta^2}}{\sqrt{2\pi}\sigma_\eta},$$

$R_{43} = 1/(2f)$ (*f* is focal length of the quad, defocusing in y)

3D Maxwell-Vlasov Equations

In principle, the Maxwell-Vlasov equations should be solved self-consistently with the trajectories given before:

detune from resonance

FEL wavenumber

observation angle

E-field

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

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

scaled electron energy

electron distribution

Negligible due to reverse taper and weak interaction in a short Delta undulator

Result #1: Microbunch Tilt Angle

- With no FEL interaction in DELTA and the trajectories given before, the bunching has an expression that generalizes Tanaka's result

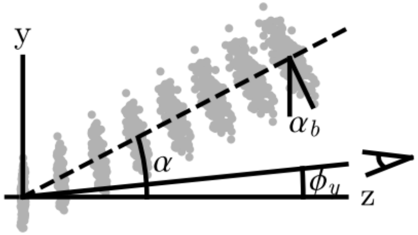
T. Tanaka, H. Kitamura, and T. Shintake, Nucl. Instrum
Methods Phys. Res., Sect. A **528**, 172 (2004).

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

where $\hat{L}=L_u/(2f)$, $\hat{z}=z/(2f)$, $\hat{\epsilon}=\epsilon k$,

- The angle at which |bunching|^2 reaches a maximum yields the amount of microbunching tilt

$$\boxed{\alpha_b(\hat{z}) = \alpha\hat{z}\frac{1}{1+2\hat{z}\frac{\hat{L}-\hat{z}-\hat{z}\hat{\epsilon}^2}{1-\hat{L}+2\hat{z}}}}$$



- In typical FEL regime we have $\boxed{\alpha_b(\hat{z}=\hat{L}) \approx \alpha\hat{L} = \frac{\alpha L_u}{2f}}$.

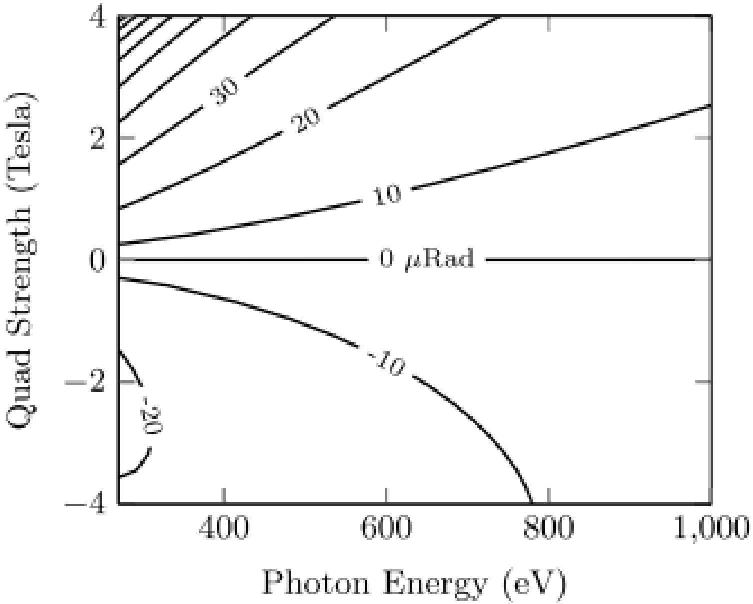
Microbunch tilt comes at a cost

Smearing occurs due to emittance effects. The bunching reduction at the tilt angle α_b is

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

Critical angle $$\phi_c(\hat{z} = \hat{L})^2 \approx \frac{1}{2|f|k\hat{\epsilon}\hat{L}^2}\sqrt{\frac{1+\hat{L}}{1-\hat{L}}} = \frac{1}{k^2\hat{L}^2\sigma_y^2}$$

LCLS tilt angle α_b when kick angle $\alpha=\phi_c$



Result #2: Coherent radiation and optimal detune

- Ignoring energy spread effects, we can find

$$\frac{\partial \tilde{E}_\nu}{\partial z} \propto e^{-\frac{\alpha^2}{2\phi_c^2} - 2\left(k^2 z \epsilon \phi_c \underbrace{(\phi_y - \alpha_b))}_{\text{Microbunching tilt at } \alpha_b}\right)^2 + i\left(k_u \Delta\nu + k \underbrace{\frac{(\alpha - \phi_y)^2}{2}}_{\text{Single } e^- \text{ emits along the kicked angle}}\right) z}$$

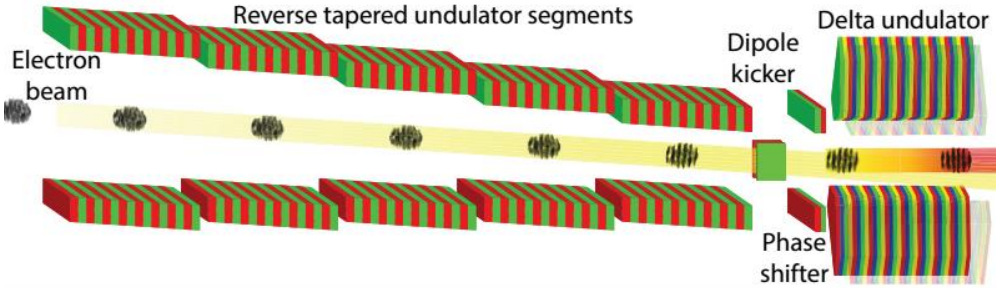
- Detune can be used to offset difference between α and α_b

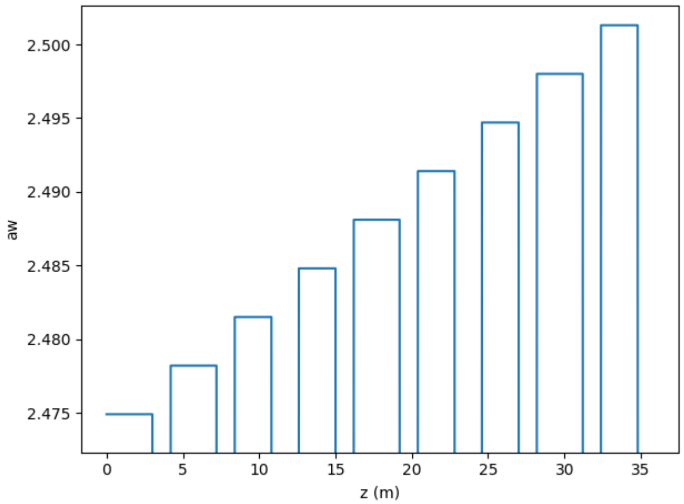
when $\phi_y = \alpha_b$ and $\Delta\nu = -k(\alpha - \alpha_b)^2/(2k_u)$.

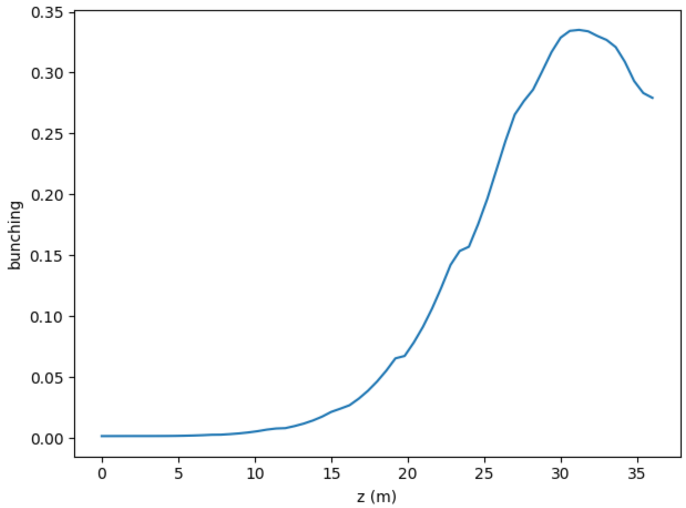
- Detune in DELTA $\boxed{\frac{\Delta K}{K_0} \approx -\frac{k(\alpha - \alpha_b)^2}{4k_u}}$ (a moving target with z!)

Genesis Simulations

- 9 planar undulator reverse taper
- 1 helical undulator afterburner
- K scanned
- 0-60 uRad deflection
- Far field & spectrum analyzed

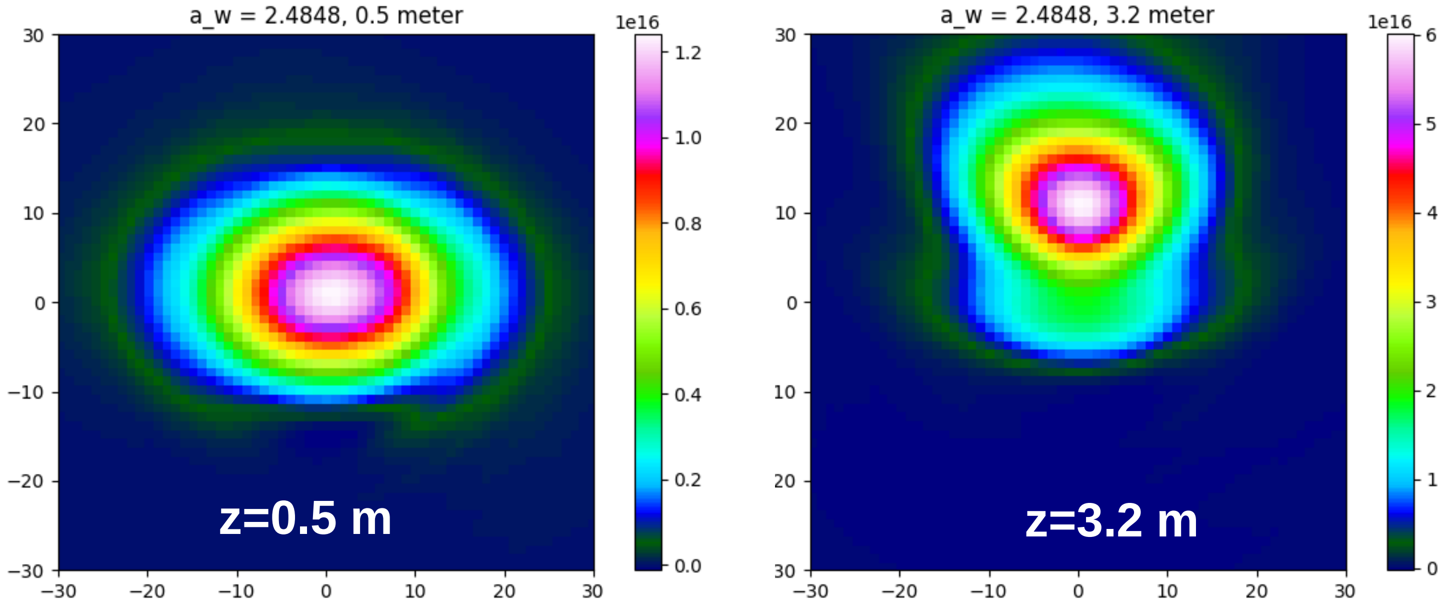



K vs z (850 eV)


Bunching vs z (850 eV)

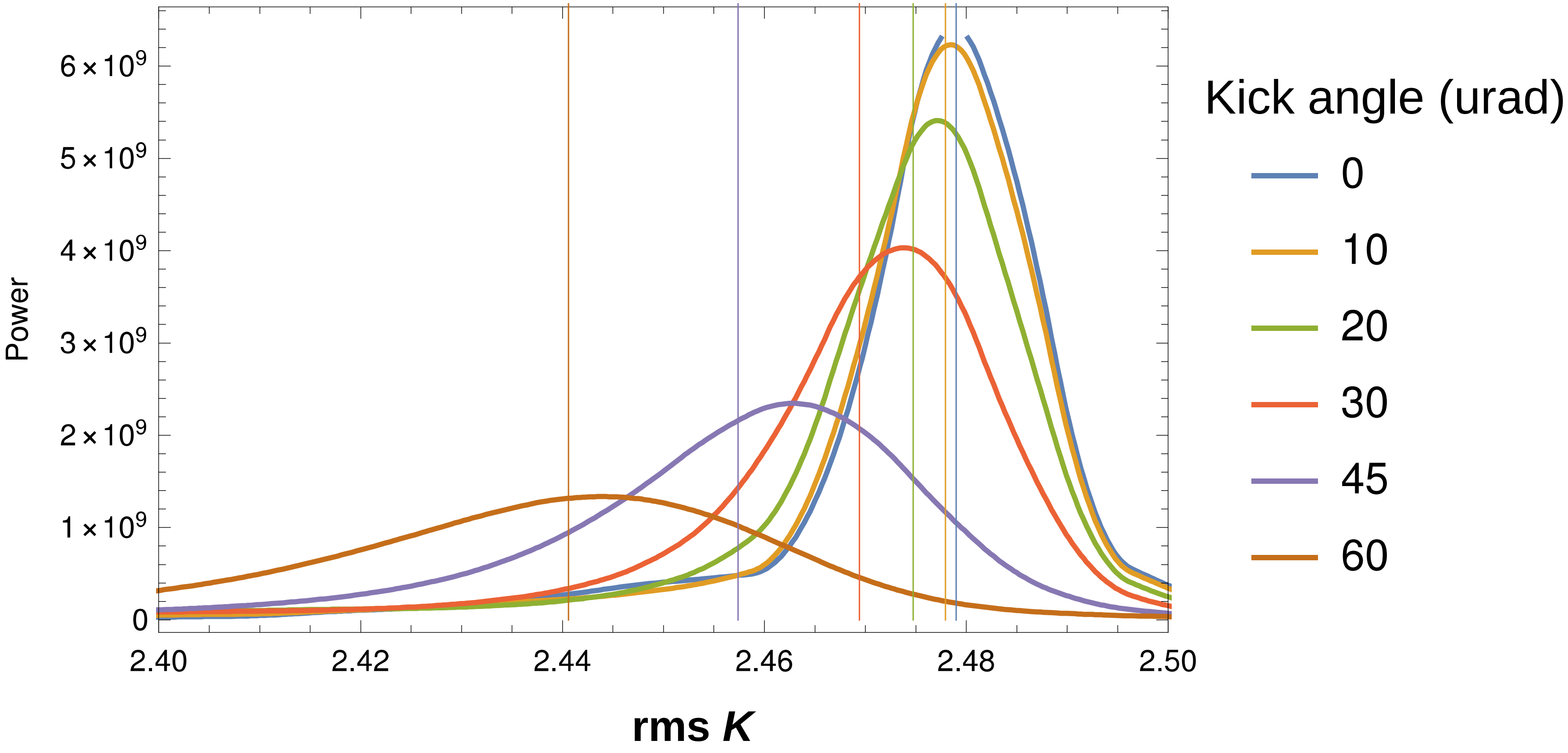
Typical Simulation Output (850 eV)

Far-field radiation evolution of 30 uRad kick afterburner radiation. Only the radiation produced in the afterburner is plotted (seed subtracted from output)



- After z=0.5 m, no microbunch rotation or off-axis radiation have happened
- As z increases to 3.2 , microbunch tilts and more radiation appears off-axis

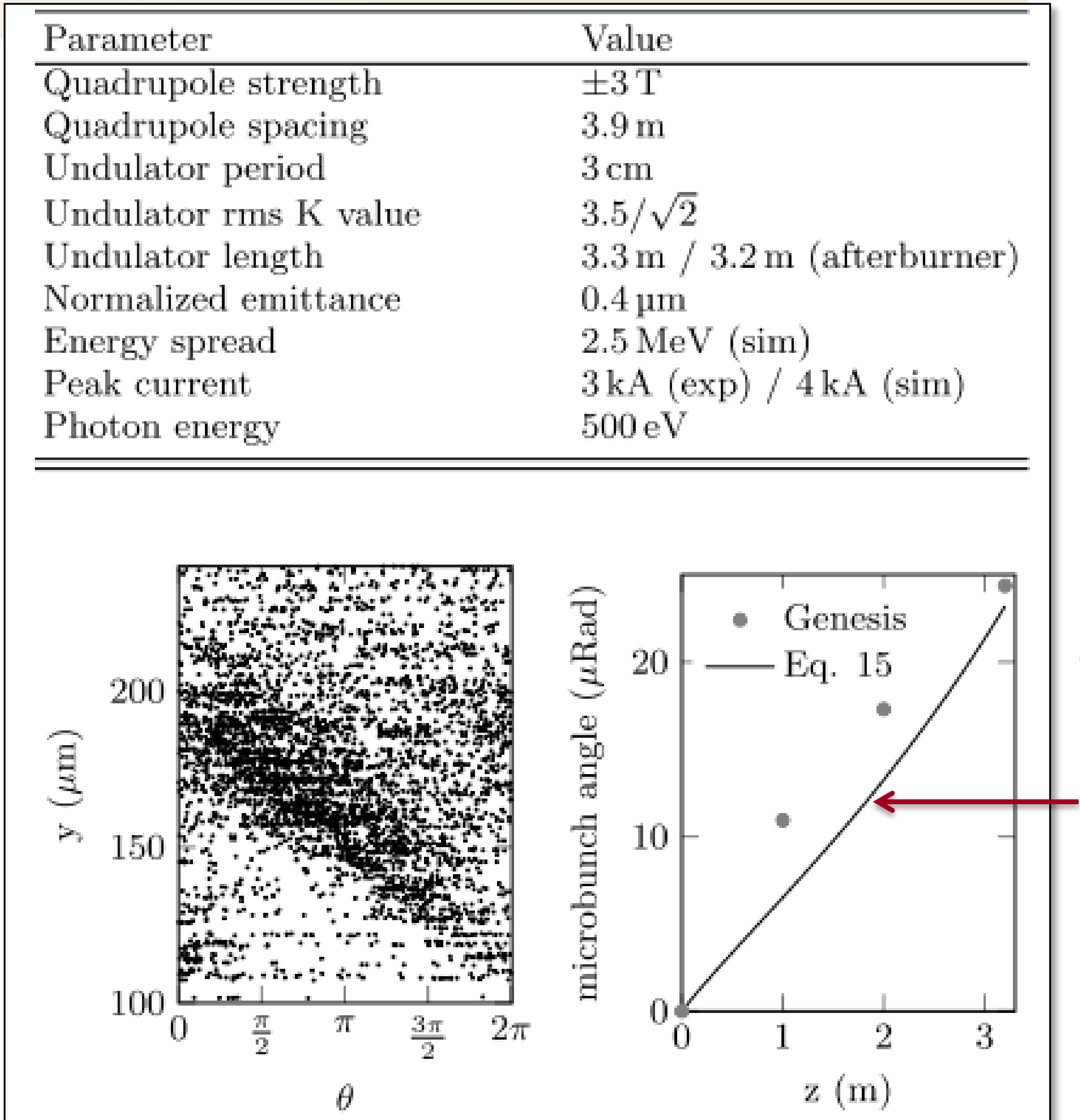
Theory vs. Simulation (850 eV)



- Simulated DELTA power vs. rms *K* at z=3.2 m. Theoretically predicted optimal K is plotted as the vertical line for different kick angles.

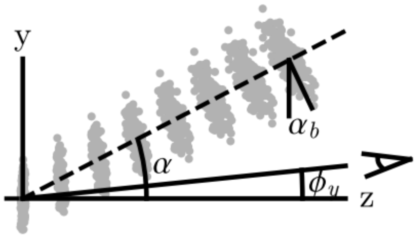
- Theory predicts closely where the optimal *K* should be.

Theory vs. Simulation (500 eV)



Parameter	Value
Quadrupole strength	±3 T
Quadrupole spacing	3.9 m
Undulator period	3 cm
Undulator rms K value	$3.5/\sqrt{2}$
Undulator length	3.3 m / 3.2 m (afterburner)
Normalized emittance	0.4 µm
Energy spread	2.5 MeV (sim)
Peak current	3 kA (exp) / 4 kA (sim)
Photon energy	500 eV

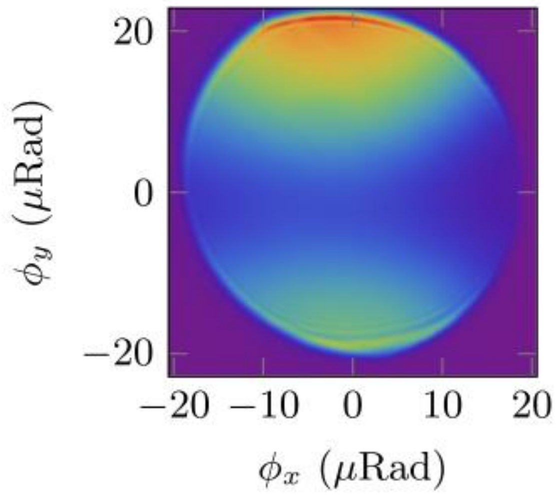
Kick angle
α=54 urad



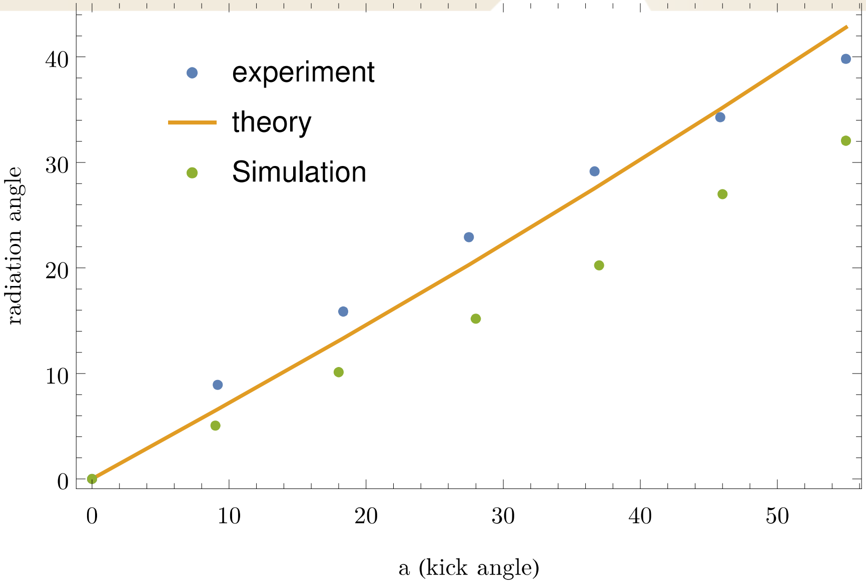
Microbunch tilt angle α_b

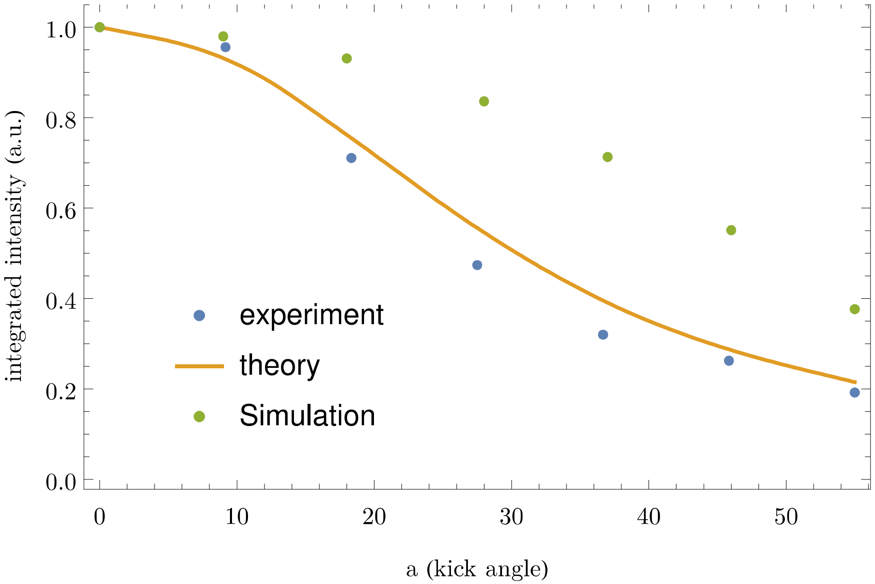
500 eV Data Comparison

- The radiation angle is predicted reasonably well

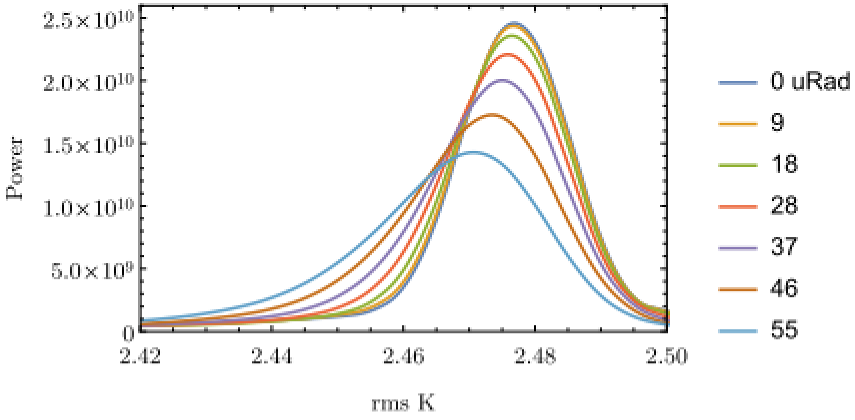


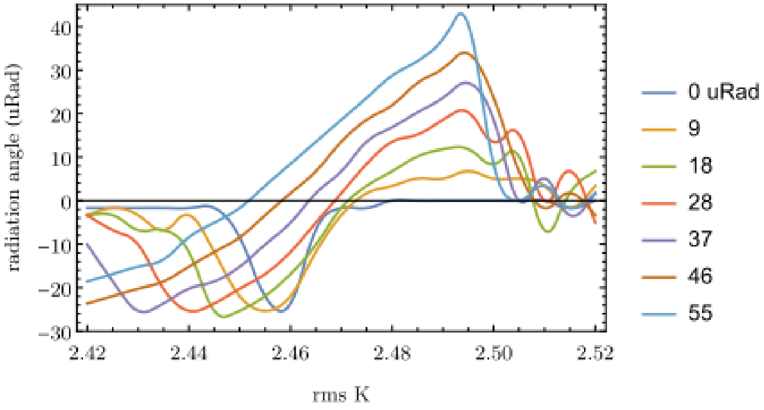
- Power reduction agrees with theory (Data/theory at 3 kA but simulations were done at 4 kA)

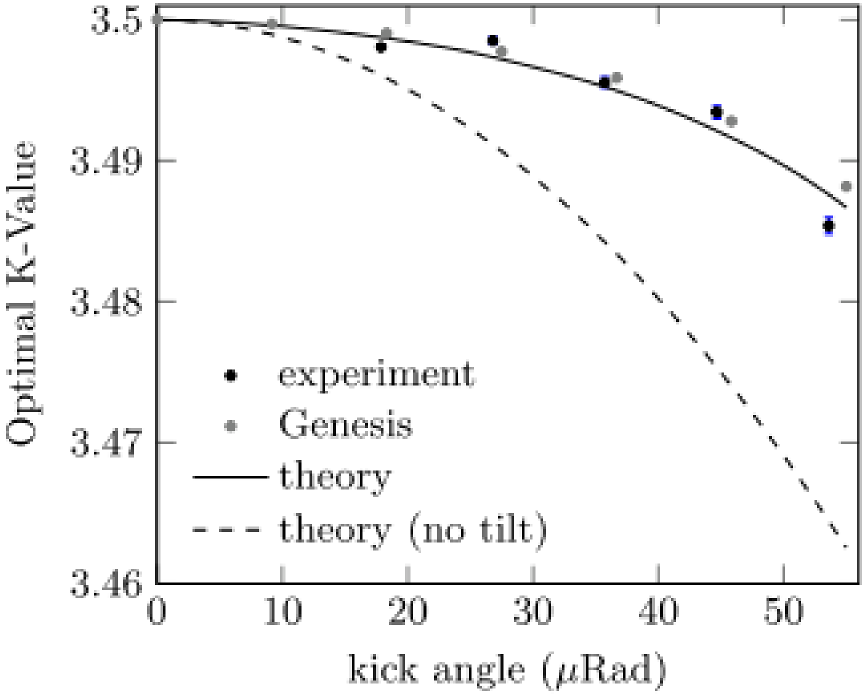




500 eV detune (K) scans

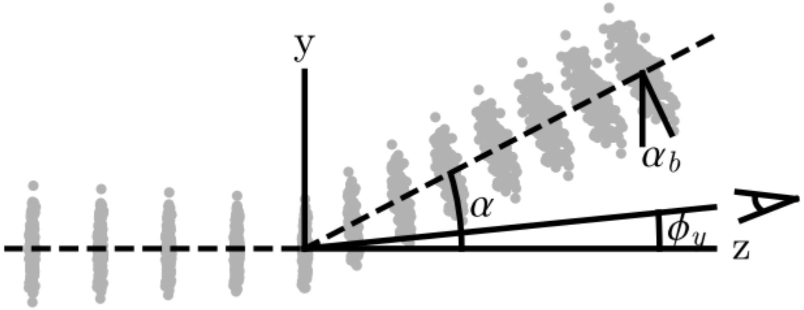


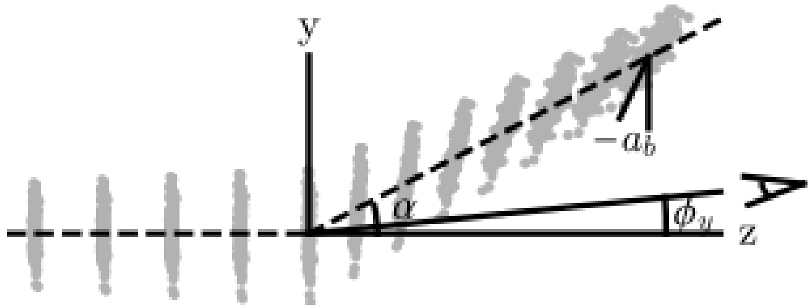




Summary

- Our experimental results appear to be consistent with a classical theory of coherent radiation
- A new way to tilt microbunches was described and verified in simulations





- Such effects may be useful for FEL manipulations in afterburners, multiplexing beamlines, or radiation outcoupling in an oscillator cavity

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