Generation of high power short X-ray FEL pulses

Physics & Applications of High Efficiency Free-Electron Lasers Workshop

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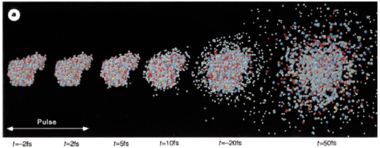
April 13, 2018

U.S. DEPARTMENT OF ENERGY
Office of Science

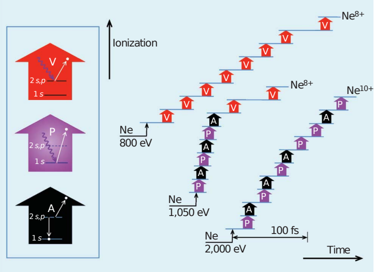
SLAC NATIONAL ACCELERATOR LABORATORY

Science Case For Short High Intensity Pulses

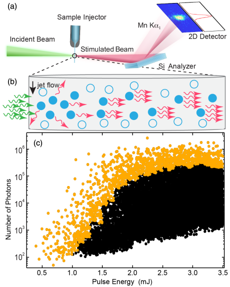
Structural determination before destruction requires photon pulse length < 10 fs



Multi-photon processes require high 3D photon density



$K\alpha$ emission by 1s core-hole population inversion



Potential for biomolecular imaging with femtosecond X-ray pulses, R Neutze et al, Nature 406, 752 (2000), doi:10.1038/35021099

Femtosecond electronic response of atoms to ultra-intense X-rays, L Young et al, Nature 466, 56 (2010), doi:10.1038/nature09177

Stimulated X-Ray Emission Spectroscopy in Transition Metal Complexes, T Kroll et al, PRL 120, 133203 (2018), doi:10.1103/PhysRevLett.120.133203

Motivation for Higher Peak Current

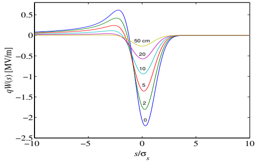
- Increase peak current to increase the FEL power (1D)

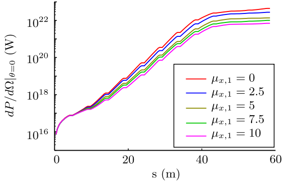
$$\rho_{\text{FEL}} = \frac{1}{2\gamma_{\text{rel}}} \sqrt[3]{\frac{I}{I_A}\left(\frac{\lambda_{\text{u}} A_u}{2\pi\sqrt{\beta\varepsilon_x}}\right)^2}$$

$$\text{Power} \propto I^{\frac{4}{3}}$$

- CSR limits peak current power due to beam yaws

$$L_g'' = \frac{L_g}{1-\pi(\theta/\theta_c)^2} \qquad \theta_c = \sqrt{\frac{\lambda}{L_g}}$$





Design optimization for an x-ray free electron laser driven by slac linac, M Xie, PAC (1995) doi:10.1109/PAC.1995.504603

Consideration on the BPM alignment tolerance in X-ray FELs, T Tanaka et al, NIMA (2004) doi:10.1016/j.nima.2004.04.040

CSR wake for a short magnet in ultravistic limit, G Stupakov et al, SLAC-PUB 9242 (2002)

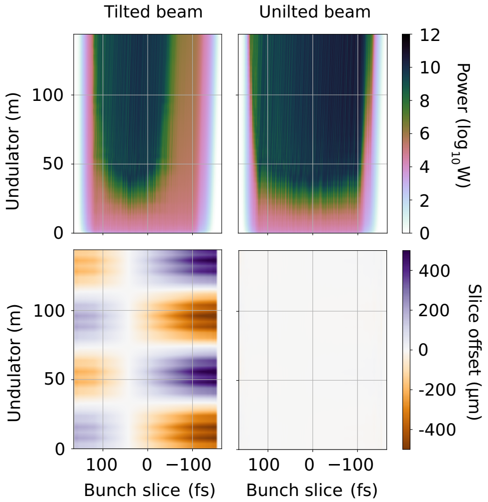
Optimization of free electron laser performance by dispersion-based beam-tilt correction, M Guetg et al, PRSTAB (2015) doi: 10.1103/PhysRevSTAB.18.030701

Impact of Tilted Electron Beams

- Off center particles undergo betatron-oscillations
- Reduce overlap between electrons and radiation
- Reduces micro-bunching
- Difference in projected and slice parameters which increases operation difficulties

Primary Sources

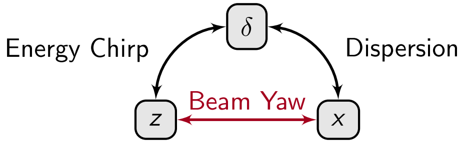
- Coherent Synchrotron Radiation
- Transverse wakefields
- Offaxis RF fields



Beam Yaw Correction Concept

Indirect Beam yaw correction requires

- Strong linear energy chirp
- Dispersion control



Requires measurement of

- Lattice dispersion
- Beam yaw

Requires for 4 correctors which differ

- Phase advance ($\neq \pi$)
- Energy chirp

Dispersion in LCLS is controlled by

- Quadrupole magnets in dispersive areas
- Orbit bumps

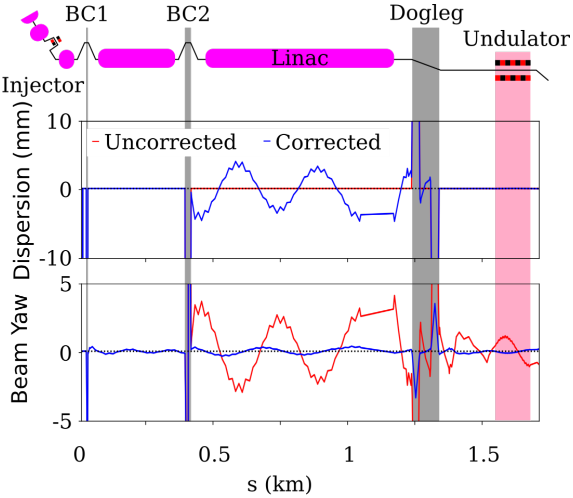
Correction of Dispersion and Beam Yaw

Used correctors

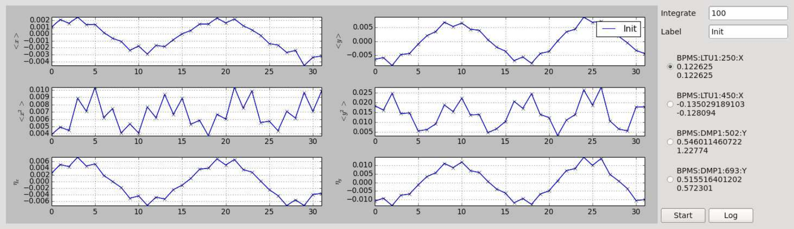
- ▷ BC2 quadrupole magnets (2x)
- ▷ LTU orbit bumps (x & y)
- ▷ LTU quadrupole magnets (2x)

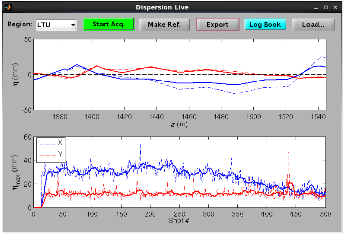
Correction algorithm

- ▷ Measure response of corrector
- ▷ Use pseudo-inverse to calculate needed correction
- ▷ Iterate



Measurement of the Lattice Dispersion



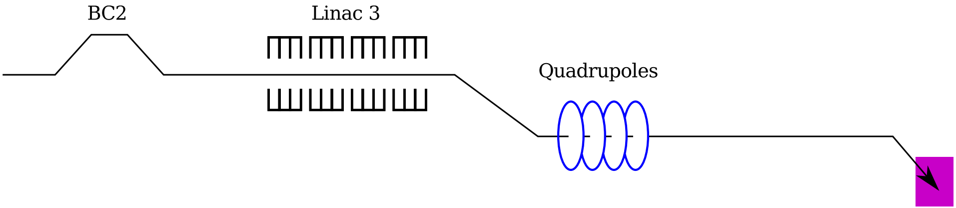


Requires beam synchronous recording of BPMs

Correlate BPM in high dispersive are with BPM in target location

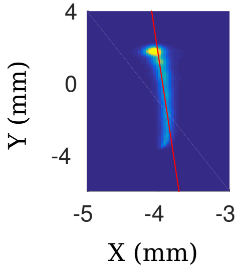
Model independent

Measurement of the Beam yaw

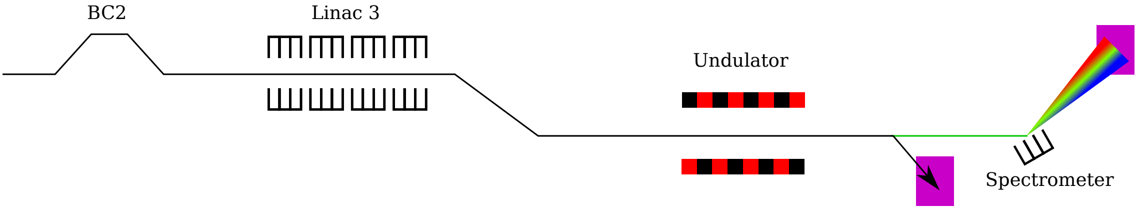


Streak with dispersion

- ✓ No additional hardware required
- ✓ Measures amplitude and phase
- ✗ Requires over-compression
- ▷ Used for over-compression

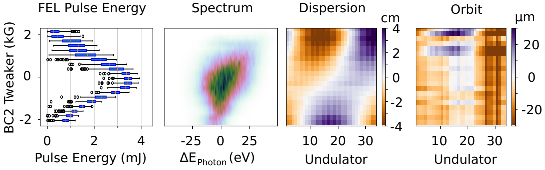


Measurement of the Beam yaw



Measure spectrum response

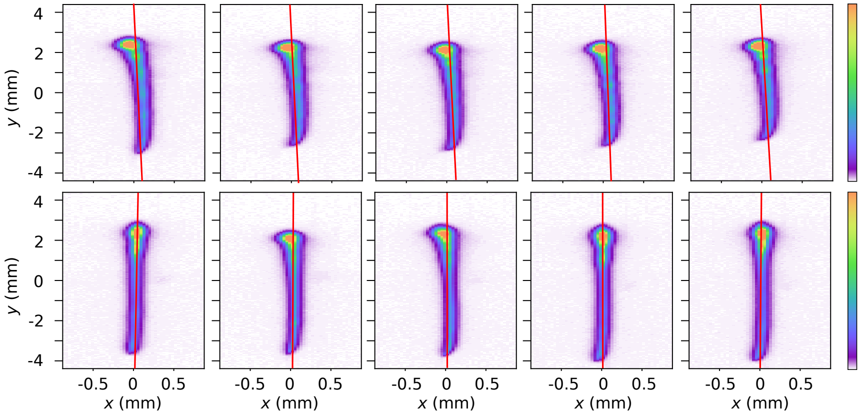
- ✓ Only requires small energy chirp
- ✗ Does not measure yaw phase
- ▷ Used for under-compression



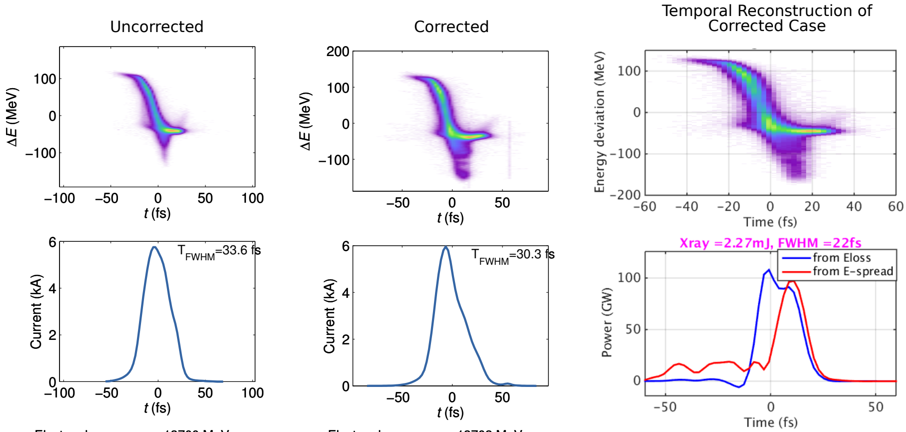
Beam Yaw Measurements for Various Phase Advances

Uncorrected

After one correction iteration



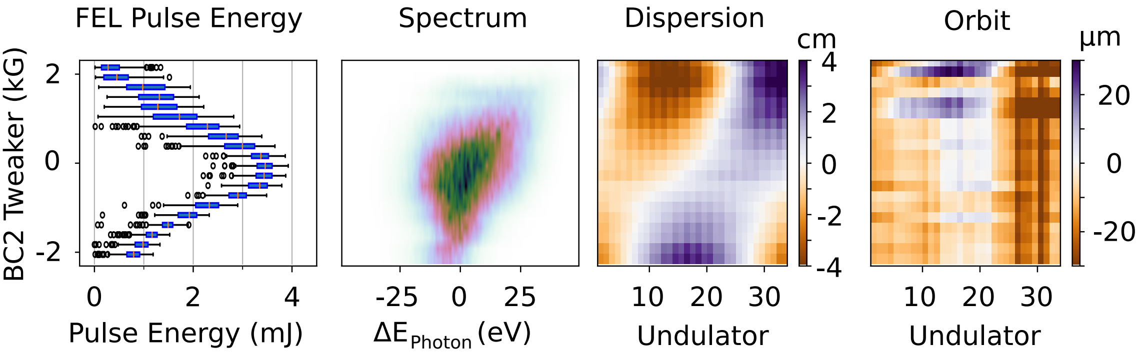
Temporal Reconstruction for over-compression



Electron beam energy:13700 MeV
Bunch charge: 200 pC
Bunch current (BC1, BC2): 200 A, 3232 A
X–ray pulse energy: 1.41 mJ

Electron beam energy:13703 MeV
Bunch charge: 200 pC
Bunch current (BC1, BC2): 200 A, 3587 A
X–ray pulse energy: 2.43 mJ

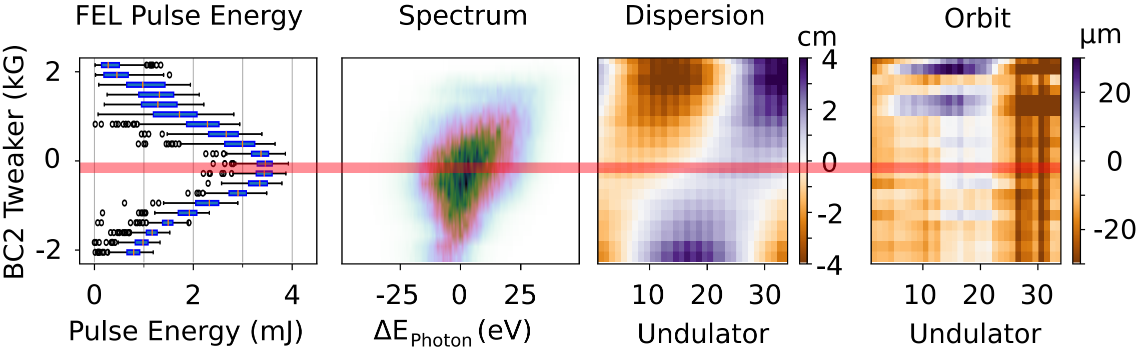
Optimization for Normal Compression



Optimum lasing position is different than minimal dispersion

Center of mass orbit does not influence power

Optimization for Normal Compression

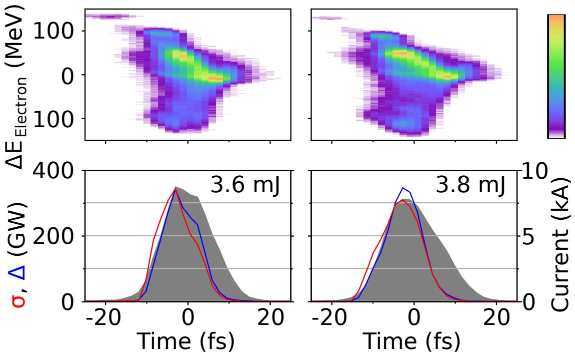


Optimum lasing position is different than minimal dispersion

Center of mass orbit does not influence power

Temporal Reconstruction

Parameter	Mean	RMS
Charge at the gun (pC)	250	2
Charge at undulator (pC)	128	1
BC1 peak current (A)	160	3
BC2 peak current (A)	6000	330
Electron Energy (MeV)	12000	6
Photon peak power (GW)	276	26
Photon pulse energy (mJ)	3.4	0.34
Photon pulse FWHM (fs)	10.3	1.6



Normal power for a good day is between 50 – 100 GW (peak!)

Tapered for FEL power stability

Going to even shorter pulses (<3fs)

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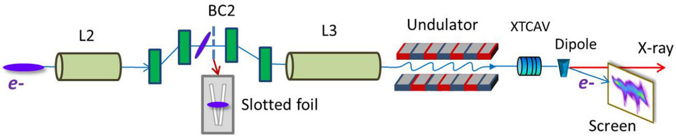
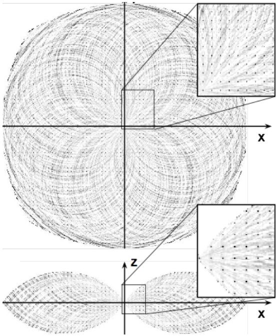


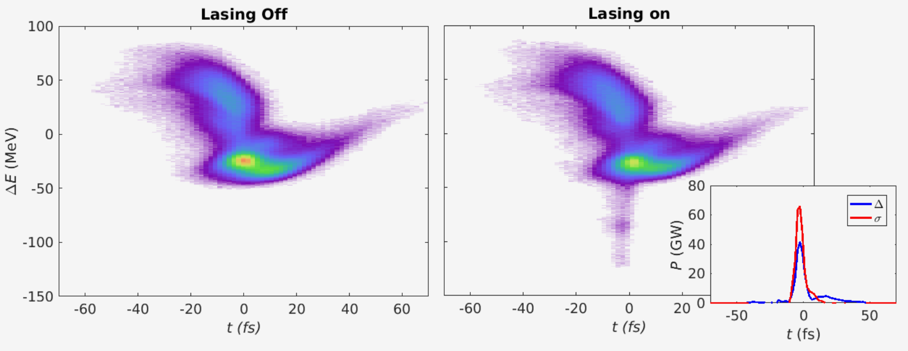


A slotted foil spoils part of the electron beam
Unspoiled area loses minimally in power

- Can be combined with emittance spoiling foil for even shorter pulses
- Create even shorter high power pulses

Generating femtosecond X-ray pulses using an emittance-spoiling foil in free-electron lasers, Y Ding et al, doi: 10.1063/1.4935429
curtersy of H Chapman

Going to even shorter pulses (<3fs)

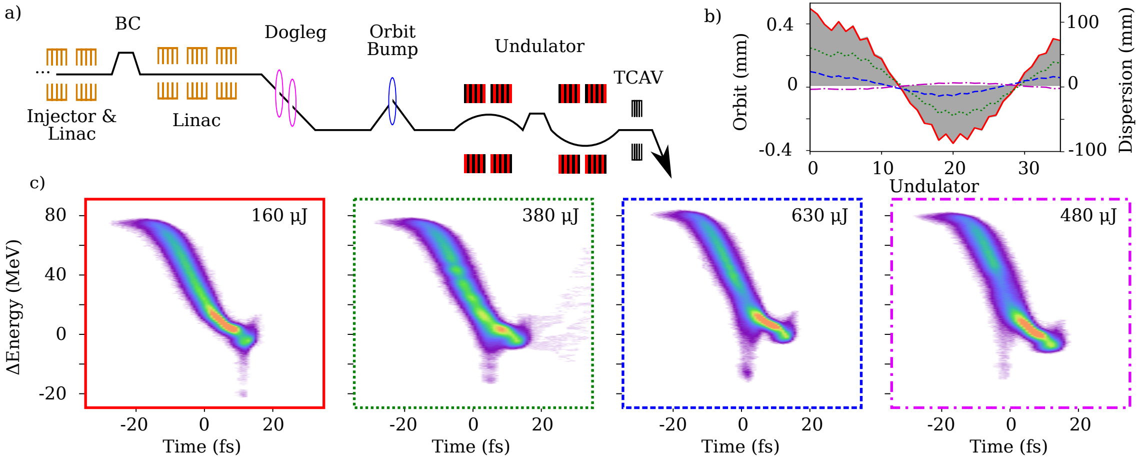


Temporal reconstruction is resolution limited, Peak power is believed to be 150 GW (Pulse energy > 400 μJ)

Tapered for power

Even shorter pulses are possible

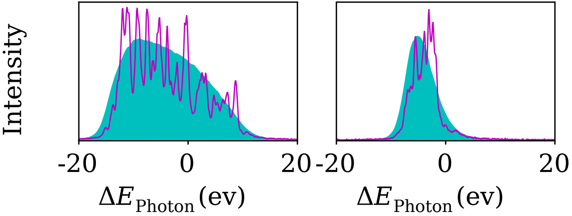
Dispersion Based Fresh Slice

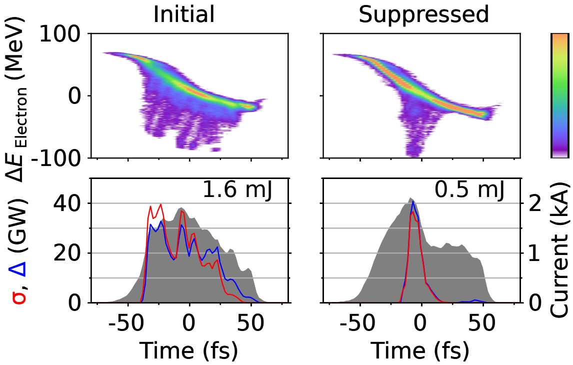


Proof-of-Principle

Successful bunch shortening

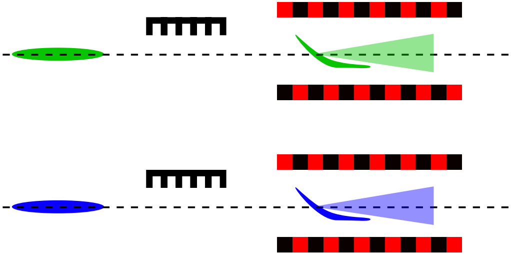
Narrowing of spectrum





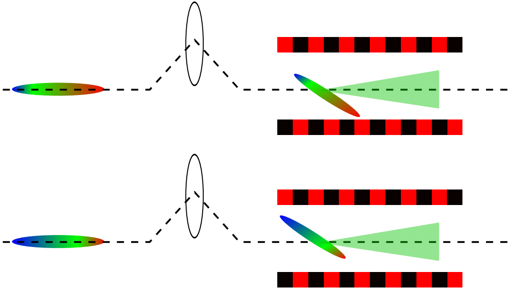
Spectral Stability

Dechirper based fresh slice



Lasing position depends on longitudinal position

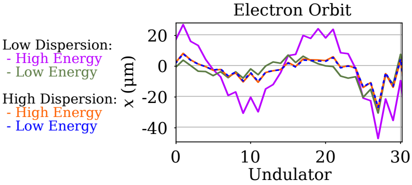
Dispersion based fresh slice

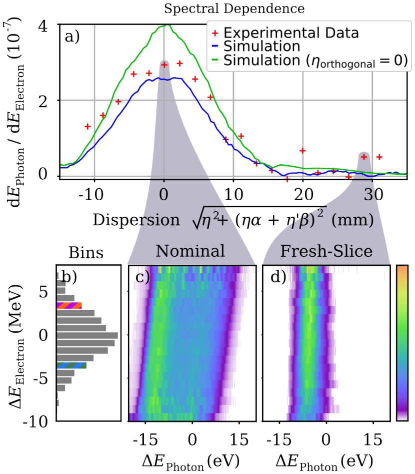


Lasing position depends on energy

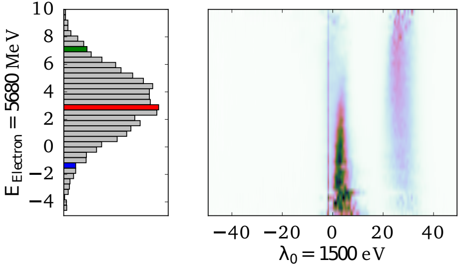
Spectral Stability

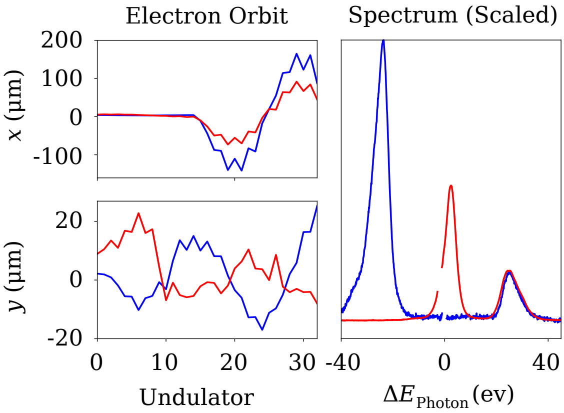
Energy fluctuations translates into orbit (dispersion)
Lasing slice has constant energy
Lower spectral energy dependence believed to be due residual vertical dispersion





- Two color operation
- Adjust color in each undulator section
- Variable delay (range = ± 700 fs)
- Spectral stability in two colors
- Color fine tuning with taper





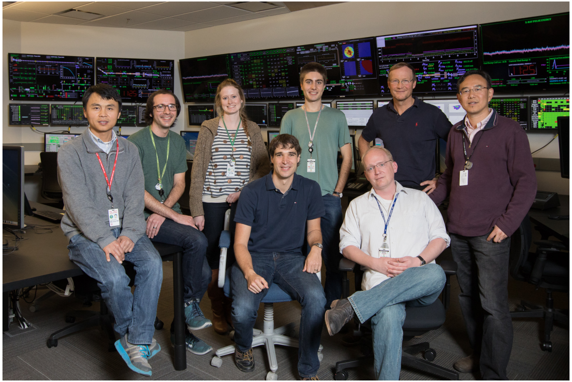
Summary

- Works for both under and over-compression
- FEL pulses with high power down to 3 fs were produced
- Average FEL power above 270 GW (typically < 100 GW)
- Indirect proof that beam tilt is limiting FEL
- Enables running with higher peak current
- Was already used for user delivery

- Dispersion based fresh-slice allows creation of short-pulses
- Two color operation
- Suitable for high repetition rate machines
- Does not require additional hard-ware

Acknowledgment

- Alberto Lutman
- Yuantao Ding
- Tim Maxwell
- Zhirong Huang
- Uwe Bergmann
- Paul Emma
- Operators of LCLS
- DOE Contract #DE-AC02-76SF00515



Work Aiming to Achieve This Goals

SLAC

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 030701 (2015)

Optimization of free electron laser performance by dispersion-based beam-tilt correction

Marc Walter Guetg,* Bolko Beutner, Eduard Prat, and Sven Reiche
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
(Received 29 August 2014; published 2 March 2015)

PHYSICAL REVIEW LETTERS **120,** 014801 (2018)

Editors' Suggestion

Generation of High-Power High-Intensity Short X-Ray Free-Electron-Laser Pulses

Marc W. Guetg,* Alberto A. Lutman, Yuantao Ding, Timothy J. Maxwell, Franz-Josef Decker, Uwe Bergmann, and Zhirong Huang
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 100703 (2016)

Beam shaping to improve the free-electron laser performance at the Linac Coherent Light Source

Y. Ding,* K. L. F. Bane, W. Colocho, F.-J. Decker, P. Emma, J. Frisch, M. W. Guetg, Z. Huang, R. Iverson, J. Krzywinski, H. Loos, A. Lutman, T. J. Maxwell, H.-D. Nuhn, D. Ratner, J. Turner, J. Welch, and F. Zhou
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 24 June 2016; published 27 October 2016)

PRL **110,** 084801 (2013) PHYSICAL REVIEW LETTERS week ending 22 FEBRUARY 2013

Proposal for a Pulse-Compression Scheme in X-Ray Free-Electron Lasers to Generate a Multiterawatt, Attosecond X-Ray Pulse

Takashi Tanaka*
RIKEN SPring-8 Center, Koto 1-1-1, Sayo, Hyogo 679-5148, Japan
(Received 6 November 2012; published 20 February 2013)

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 100701 (2015)

Efficient generation of short and high-power x-ray free-electron-laser pulses based on superradiance with a transversely tilted beam

Eduard Prat,* Florian Löhl, and Sven Reiche
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
(Received 22 July 2015; published 12 October 2015)

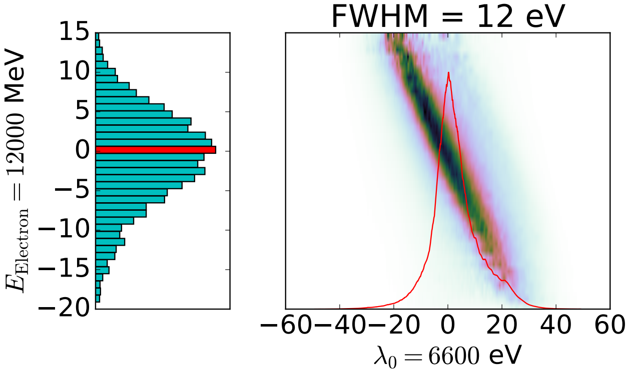
nature photonics | ARTICLES
PUBLISHED ONLINE: 24 OCTOBER 2016 | DOI: 10.1038/NPHOTON.2016.201

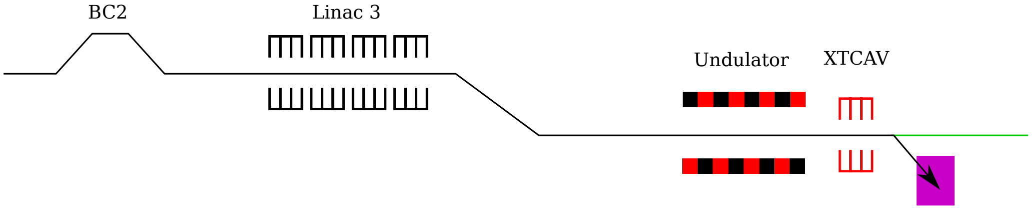
Fresh-slice multicolour X-ray free-electron lasers

Alberto A. Lutman[1]*, Timothy J. Maxwell[1], James P. MacArthur[1], Marc W. Guetg[1], Nora Berrah[2], Ryan N. Coffee[1,3], Yuantao Ding[1], Zhirong Huang[1,3], Agostino Marinelli[1], Stefan Moeller[1] and Johann C. U. Zemella[1,4]

Reduced Bandwidth

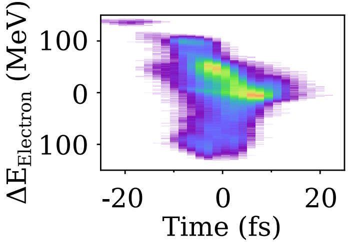
Reduction of bandwidth reducing BC1 peak current to 130 A



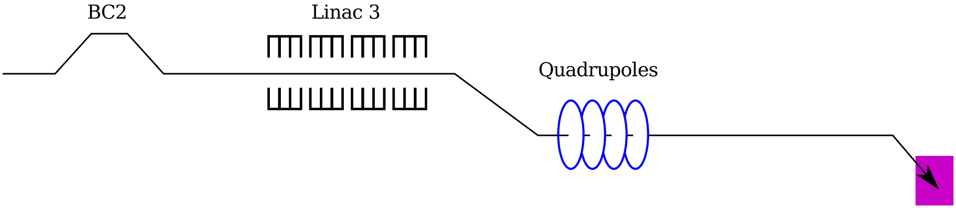


Temporal Reconstruction

- ✓ Standard setup
- ✓ Measure lasing uniformity
- ✗ Does not measure yaw phase
- ✗ Low resolution

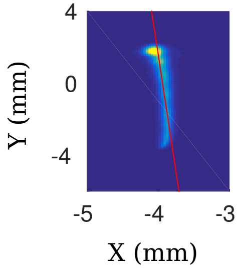


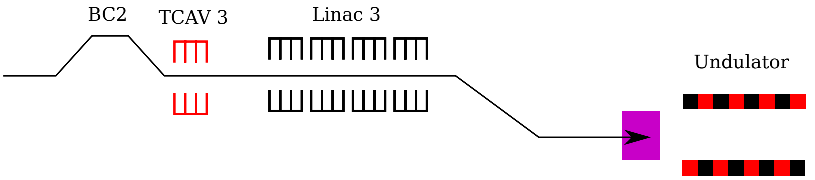
Measurement of the Beam yaw



Streak with dispersion

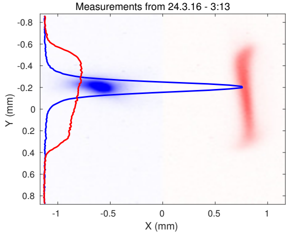
- ✓ No additional hardware required
- ✓ Was used for over-compression case
- ✓ Measures yaw phase
- ✗ Requires over-compression

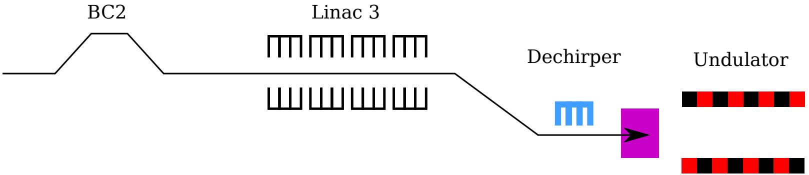




Streak with TCAV

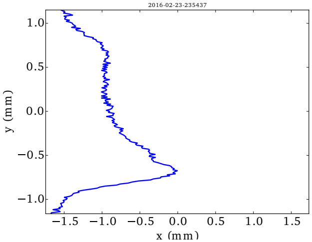
- ✓ Direct meausurement of yaw
- ✓ Measures yaw phase
- ✗ Insufficient resolution
- ✗ Does not measure yaw sources after TCAV



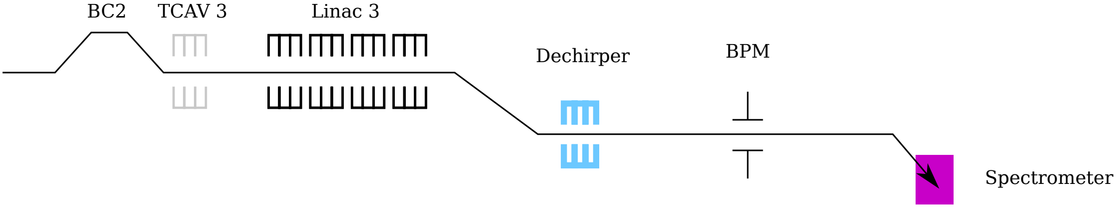


Dipole wake with dechirper

- ✓ Allows creation of strong streak
- ✓ Measures yaw phase
- ✗ Non-linear streak
- ✗ Does not resolve head

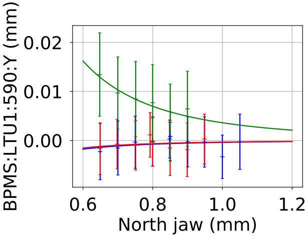


Measurement of the Beam yaw

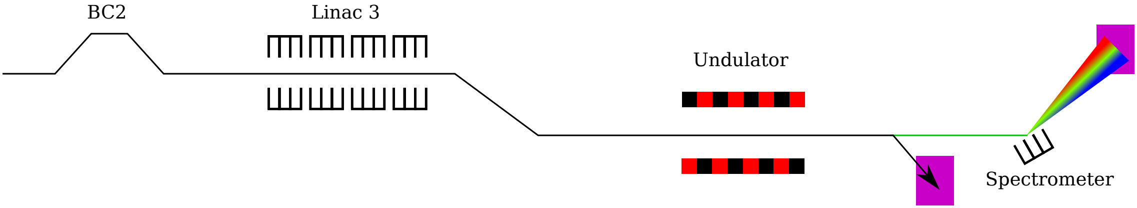


Quad wakes of dechirper

- ✓ Is independent on chirp
- ✓ Does not require screen
- ✗ Very low resolution



Measurement of the Beam yaw



Measure spectrum response

- ✓ Offers high resolution
- ✓ Only requires small energy chirp
- ✓ Was used for normal compression
- ✗ Does not measure yaw phase