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Challenges and Opportunities for X-ray Free-electron Lasers

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Outline

- Present status of X-ray FELs
- Future goals:
  - Improving coherence properties
  - Improving efficiency of photon production/electron
  - higher brightness
- X-ray spectrum manipulation:
  - 2 colors
- Improved diagnostics and beam manipulation

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Hard X-rays FELs					
	LCLS	SACLA	European XFEL	Korean X-FEL	Swiss X-FEL
Electron energy range, GeV	2.15-15.9	5.2-8.45	8.5-17.5	4-10	2.1-5.8
Wavelength range, nm	.11-4.4	0.063-0.275	0.04-5.1	0.1-0.6	0.1-7
X-ray pulse energy, mJ,	1-3, $0.1<\lambda<$ 1.5nm	0.2-0.4 for $0.08<\lambda<0.27$ nm	0.67-8.5, $0.04<\lambda<5.1$ nm	0.81-1, $0.1<\lambda<0.6$ nm	0.5-1.3, $0.1<\lambda<7$ nm
Pulse duration, rms, fs	5-250, $0.1<\lambda<$ 1.5nm	4.3, $0.08<\lambda<$ 0.275 nm	1.68-107, $0.04<\lambda<5.1$ nm	8.6-26, $0.1<\lambda<0.6$ nm	2-20, $0.1<\lambda<7$ nm
Line width, rms, %, SASE	0.5-0.1, $0.1<\lambda<$ 1.5nm	0.11-0.37, $0.08<\lambda<0.275$ nm	0.02-0.25, $0.04<\lambda<5.1$ nm	0.15-0.18, $0.1<\lambda<0.6$ nm	0.06-0.4, $0.1<\lambda<7$ nm
Line width, rms, %, seeded	0.01-0.005*, $0.1<\lambda<$ 1.5nm	0.01*-0.003*, $0.08<\lambda<0.275$ nm	0.04-0.005, $0.04<\lambda<5.1$ nm	0.002-0.002, $0.1<\lambda<0.6$ nm	0.01-0.002, $0.1<\lambda<7$ nm

* Values based on simulations

Notes

1. Pulse energy hundreds of μJ to few mJ.
2. Line width in SASE mode about 10^{-3}, order of magnitude of the FEL parameter ρ; expected improvement by factor of ten with self-seeding.
3. Pulse durations from a few to about 100 fs.
4. About 10^{3} photons/electron at about 1 A (10^{-2} for spontaneous radiation).

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Soft X-rays FEL characteristics

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	FLASH	Fermi
Electron beam energy, GeV	0.37-1.25	1.5
Wavelength range, nm	45-4.2	65-10
X-ray pulse energy, mJ	0.2 @ λ_{Max} 0.5 @ λ_{min}	0.03 @ λ_{Max} 0.01 @ λ_{min}
Pulse duration, rms, fs	15-100 @ λ_{Max} 15-100 @ λ_{min}	<40 @ λ_{Max} n.a.
Line width, rms,%, SASE	0.2 @ λ_{Max} 0.5 @ λ_{min}	
Line width, rms, %, seeded		0.06 @ λ_{Max} 0.03 @ λ_{min}

Flash operates as SASE FEL. An upgrade, Flash II, is being built as an HHG laser seeded FEL.

Fermi is presently the only X-ray FEL operated as an HGHG system. The driving laser wavelength is about 260nm. It has two FELs: FEL 1 with $20<\lambda<65$ nm, and FEL 2 with $4<\lambda<10$. FEL 1 is in use for experiments, FEL 2 is in the final commissioning stage.

Pulse energy < 1 mJ,
pulse duration about 15 to 100 fs,
line width about 10^{-3} or larger if SASE.

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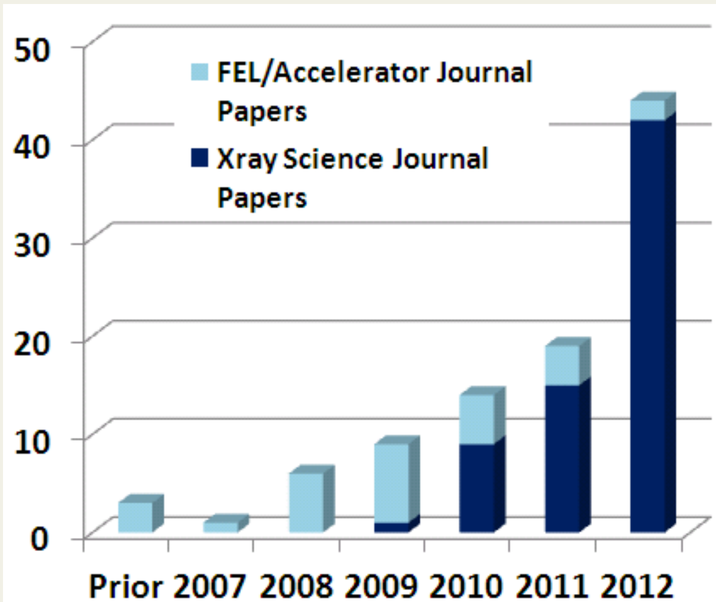
LCLS is expanding our scientific knowledge in biology, chemistry and physics at an increasing rate



Publications using LCLS coherent photons: #/per year
~ 60% of papers in high impact journals, like Nature, Science, Physical Review Letters.

888 proposals: ~15 scientists/proposal, 31 countries

- only 1 in 5 proposals gets beam time in 2013
- one publication per experiment
- very high user satisfaction

Courtesy Uwe Bergmann

X-ray beam delivery is ~95% of scheduled beam time

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Wish list

The existing X-rays FELs are doing quite well and have reached or went above the design parameters. The main areas where their performance can be improved are:

1. Improve the longitudinal coherence of SASE-FELs
2. Increase the energy transfer from the electron to the photon beam, presently about 0.1%, to a few percent
3. Improve the phase space distribution of the electron bunch, the “lasing medium”
4. Manipulate the X-ray spectrum, generate 2 or more lines with variable delay or simultaneous for pump probe or stimulated emission experiments
5. Generate atto-second pulses
6. Improved electron phase-space diagnostics with femtosecond or better resolution

Research, theoretical and experimental, is being actively done in all these area. I will discuss some of the results already obtained.

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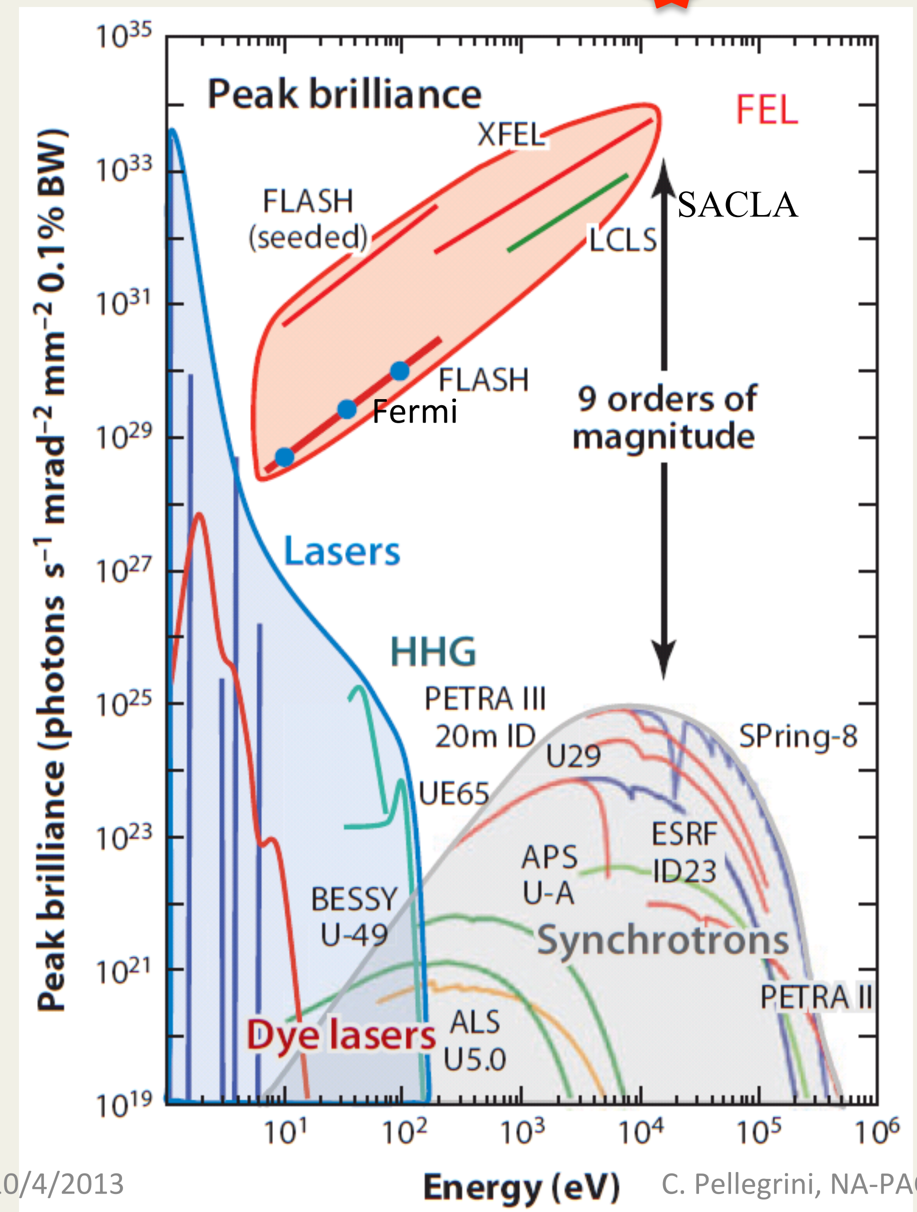
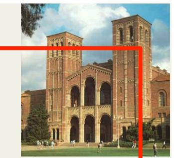
X-FELs and other light sources



Mission: get here !

How to:

1. improve longitudinal coherence
2. Use undulator tapering to increase the intensity/pulse × 10 or more



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The jump by 9 orders of magnitude obtained at LCLS in 2009 is a remarkable event.

Brilliance, also called brightness, is a measure of the coherence of the photon beam. Improved longitudinal coherence will further increase the brilliance.

Plot from J. Ullrich, A. Rudenko, R. Moshammer, Ann. Rev. Phys. Chem. **63**, 635 (2012)

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Challenges and opportunities

- Presently all hard X-ray FELs operate in SASE mode. In this mode the line width is the FEL parameter *ρ,* between 5×10^{-4} and 10^{-3} for all systems . The X-ray pulse is spiky while the transform limited line width is ρ/N_S , the number of spikes.
- For FEL parameters between 5×10^{-4} and 10^{-3} the exponential gain length is about 100×undulator period, the cooperation length is about 100×wavelength and the full spike length is about 600×wavelength .
- Low charge single spike FELs, $L_{bunch} < L_{cooperation}$ are transform limited. This condition can be realized at a charge of a few pC. (Elba, Wacker)

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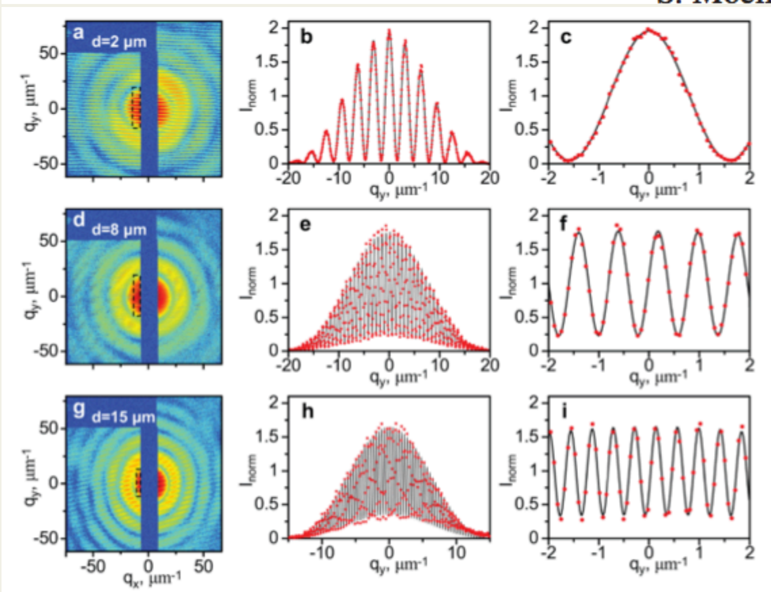
Single-shot Young's double slit measurements on LCLS x-ray beam

PRL 107, 144801 (2011) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2011

Coherence Properties of Individual Femtosecond Pulses of an X-Ray Free-Electron Laser

I. A. Vartanyants,[1,2,*] A. Singer,[1] A. P. Mancuso,[1,†] O. M. Yefanov,[1] A. Sakdinawat,[3] Y. Liu,[3] E. Bang,[3] G. J. Williams,[4] G. Cadenazzi,[5] B. Abbey,[5] H. Sinn,[6] D. Attwood,[3] K. A. Nugent,[5] E. Weckert,[1] T. Wang,[4] D. Zhu,[4] B. Wu,[4] C. Graves,[4] A. Scherz,[4] J. J. Turner,[4] W. F. Schlotter,[4] M. Messerschmidt,[4] J. Lüning,[7] Y. Acremann,[8] P. Heimann,[9] D. C. Mancini,[10] V. Joshi,[10] J. Krzywinski,[4] R. Soufli,[11] M. Fernandez-Perea,[11] S. Hau-Riege,[11] A. G. Peele,[12] Y. Feng,[4] O. Krupin,[4,6] S. Moeller,[4] and W. Wurth[13]



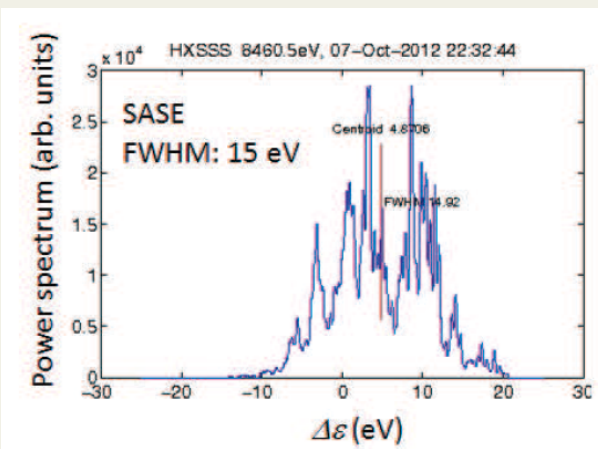
Transverse coherence quite good, the X-ray beam is diffraction limited, in agreement with XFEL theory. Spatial coherence is essential for applications like coherent x-ray diffractive imaging, x-ray holography and x-ray photon correlation spectroscopy. The recovery of structural information from coherent imaging experiments relies on a high degree of spatial coherence in the incident field to enable the phasing of the diffraction pattern produced by its scattering from the sample.

VOLUME 73, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1994

Spectrum, Temporal Structure, and Fluctuations in a High-Gain Free-Electron Laser Starting from Noise

R. Bonifacio,[1,2] L. De Salvo,[1] P. Pierini,[2] N. Piovella,[1] and C. Pellegrini[3]

Longitudinal coherence for long, many spikes, bunches: Not good.
The temporal profile, and the spectrum, of the X-ray pulse is spiky.



LCLS spectrum in SASE mode.
8keV photon energy, 1.5 A.

A SASE FEL starts from noise. Electron interact through the radiation they emit. Photons move faster than electrons and "slip" ahead one λ per undulator period. In one gain length the radiation emitted by one electron can interact wit electrons as far ahead as the cooperation length, the slippage in one gain length.
The bandwidth is determined by the spike length and not by the bunch length. The X-ray pulse is not transform limited.

Longitudinal coherence for short, single spike, bunches. Transform limited.

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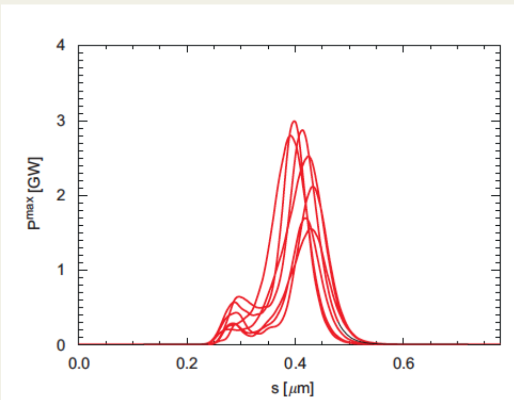
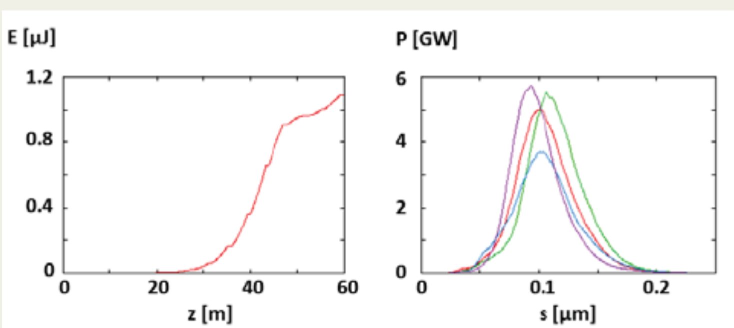
Development of ultra-short pulse, single coherent spike for SASE X-ray FELs
S. Reiche , P. Musumeci, C. Pellegrini, J.B. Rosenzweig, NIM A 593, 45 (2008).



1 pC bunch, 1.5 A, LCLS simulation, FWHM ≈0.1 μm, 300 as.

Short means bunch length < spike length

Sub-femtosecond Hard X-ray pulse from very low charge beam at LCLS.
V. Wacker, Y. Ding, Z. Huang, C. Pellegrini, F. Zhou, Proc. FEL 2012, p. 606, (2012), Nara, Japan.



LCLS, optimized, 1.5 A, 1 pC, 200 as FWHM, 5 GW peak

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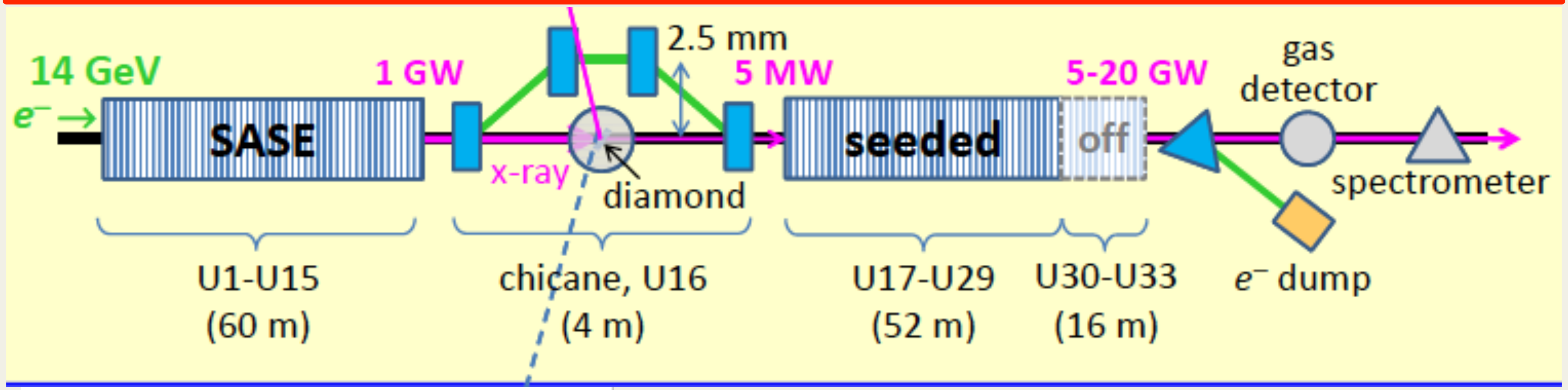
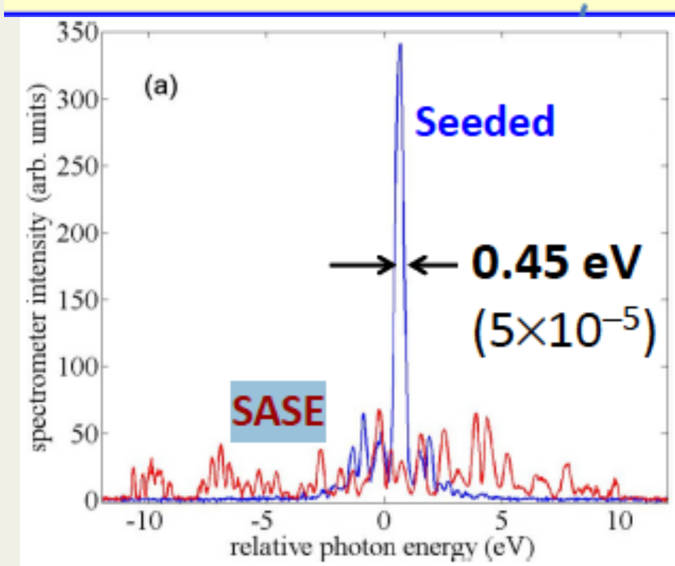
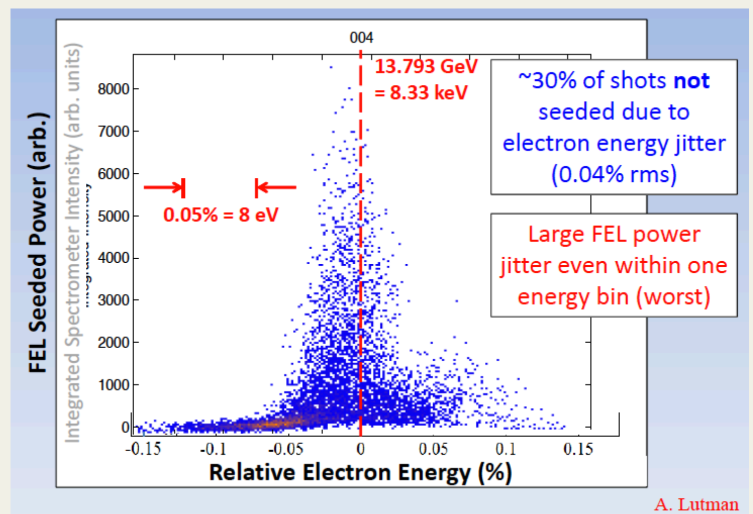
Long bunch case

Demonstration of self-seeding in a hard-X-ray free-electron laser, J. Amann, et al. Nature Photonics, DOI: 10.1038/NPHOTON 2012.180







A. Lutman

Experimental demonstration of X-ray free-electron laser frequency spectrum line-width control with phase and amplitude mixing, J.Wu, A. Marinelli, and C. Pellegrini, submitted to Phys. Rev Lett. (2013);
X-Ray Spectra and Peak Power Control with iSASE, J. Wu, C. Pellegrini, A. Marinelli, H.-D. Nuhn, F.-J. Decker, H. Loos, A. Lutman, D. Ratner, Y. Feng, J. Krzywinski, D.

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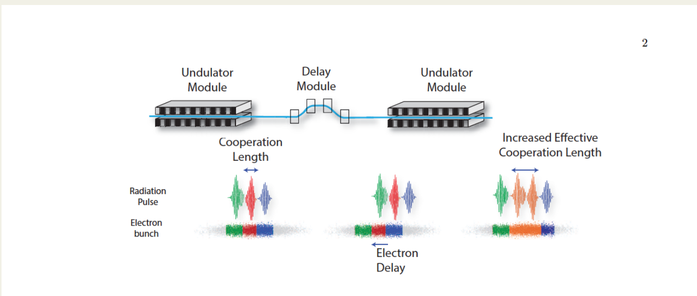
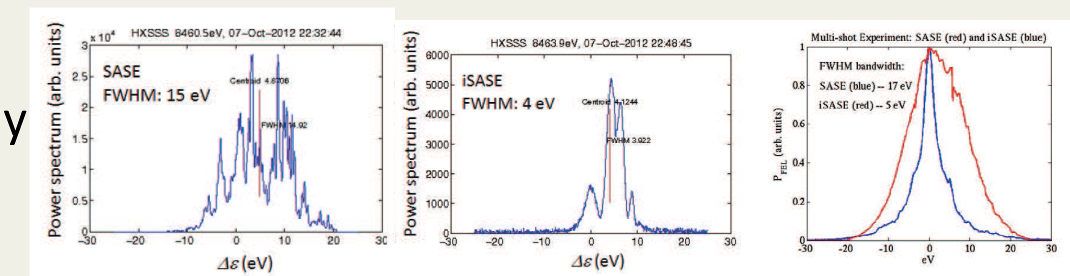


Mixing phase and amplitude of spikes by delaying the electrons by one or more cooperation length leading to an effective increase of cooperation length.



Experiment done by repeated delay of one cooperation length. Line width reduction by factor of 3 in agreement with theory.

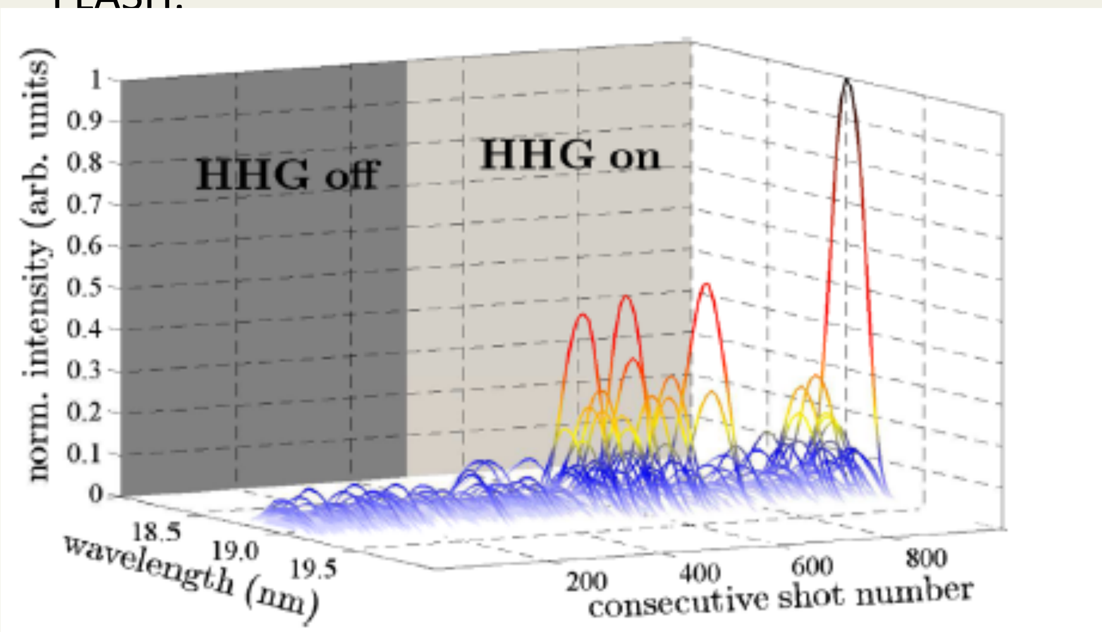
Optimizing the delays can lead to transform limited pulse
J.Wu, A. Marinelli, C Pellegrini, Proc. FEL Conf. p. 237, Nara Japan (2012),
B.W.J. McNeil, N.R. Thompson, and D.J. Dunning, Phys. Rev. Lett. 110, 134802 (2013).

PRL **111**, 114801 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Generation of Coherent 19- and 38-nm Radiation at a Free-Electron Laser Directly Seeded at 38 nm

S. Ackermann et al. sFLASH

First successful seeding at a wavelength as short as 38.2 nm, resulting in GW-level, coherent FEL radiation pulses at this wavelength as well as significant second harmonic emission at 19.1 nm. The seeding pulse is the 21st harmonic of an 800-nm, 15-fs (rms) laser pulse generated in an argon medium. The experiment was done at FLASH.



1000 consecutive spectra of the second harmonic of the seeded FEL with (HHG on) and without (HHG off) seeding.

Increasing the FEL efficiency by undulator tapering

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Single shot imaging of matter in disordered states (not in crystal form) and nonlinear X-ray science require to increase the number of photons/fs or equivalently the number of photons/electron.

At a wavelength of about 1A: number of coherent photons/electron about 10^{-2} for spontaneous radiation, 10^{3} for an FEL at saturation.

We want $\geq 10^{4}$.

To reach this goal we follow N.M. Kroll, P.L. Morton, M.N. Rosenbluth*,* [IEEE J. Quantum Electronics, QE-17*, 1436 (1981)*] proposal to increase the energy transfer from the electron to the photon beam beyond saturation by adjusting the undulator magnetic field to compensate for the electron energy losses, a "tapered" undulator.

The increase is much larger for a seeded FEL compared to a SASE FEL.

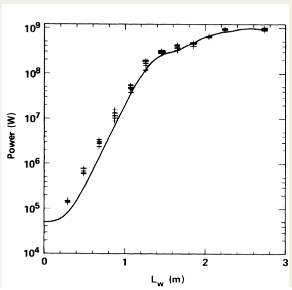
Tapering improves the spectrum and generates strong coherent harmonics.

A multidimensional model to optimize tapering is discussed in: "Modeling and multidimensional optimization of a tapered free electron laser", Y. Jiao, J. Wu, Y. Cai, A.W. Chao, W.M. Fawley, J. Frisch, Z. Huang, H.-D. Nuhn, C. Pellegrini, S. Reiche, PRSTAB, 15*, 050704 (2012)*

VOLUME 57, NUMBER 17 PHYSICAL REVIEW LETTERS 27 OCTOBER 1986

High-Efficiency Extraction of Microwave Radiation from a Tapered-Wiggler Free-Electron Laser

T. J. Orzechowski, B. R. Anderson, J. C. Clark, W. M. Fawley, A. C. Paul, D. Prosnitz, E. T. Scharlemann, and S. M. Yarema

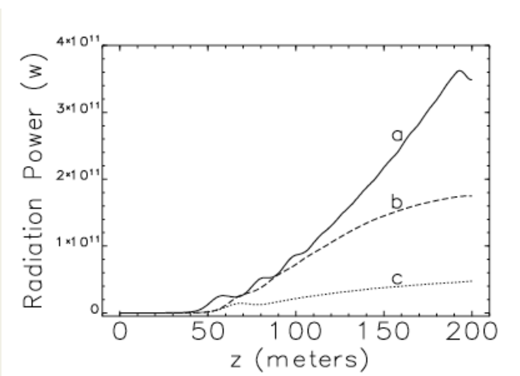


Experiment was done at LLNL with a seeded, 1 cm wavelength FEL and a tapered Undulator.

Tapered undulators for SASE FELs ☆

NIM A483, 537 (2002)

William M. Fawley[a], Zhirong Huang[b,*], Kwang-Je Kim[b], Nikolai A. Vinokurov[c]



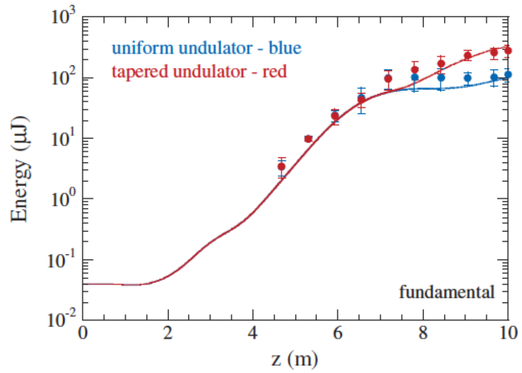
Comparison of the predicted radiation power for the LCLS: (a) tapered monochromatic amplifier, (b) tapered SASE, and (c) untapered SASE.

Some form of seeding is important to increase the efficiency.

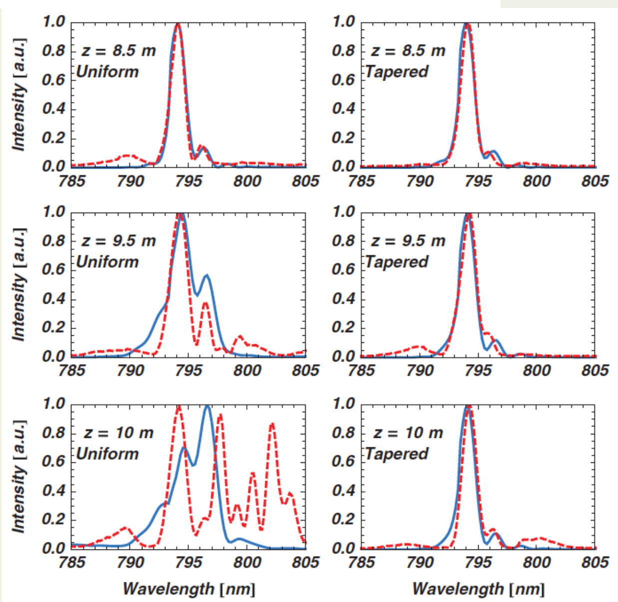
PRL 103, 154801 (2009) PHYSICAL REVIEW LETTERS week ending 9 OCTOBER 2009

Efficiency and Spectrum Enhancement in a Tapered Free-Electron Laser Amplifier

X. J. Wang,[1] H. P. Freund,[2] D. Harder,[1] W. H. Miner, Jr.,[2] J. B. Murphy,[1] H. Qian,[1] Y. Shen,[1] and X. Yang[1]



Experiment at BNL SDL, at 793 nm, seeded FEL using a 10 m long undulator gives a factor of 3 increase in the fundamental intensity and 50% on the 3rd harmonic.



Spectra for the experiment (red) and simulation (blue) for uniform and tapered undulators.

Tapering cleans the spectrum from sidebands and improve the spectrum and brightness.

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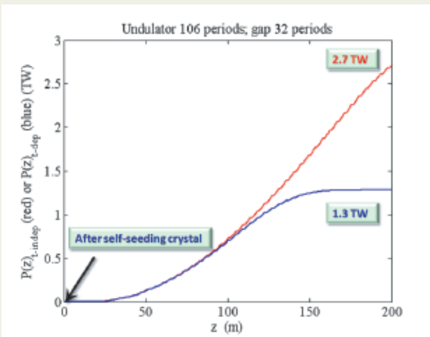
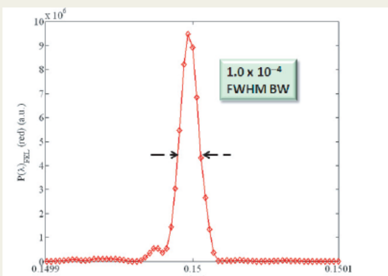
TOWARD TW-LEVEL, HARD X-RAY PULSES AT LCLS, Proceedings of FEL2011, Shanghai, China

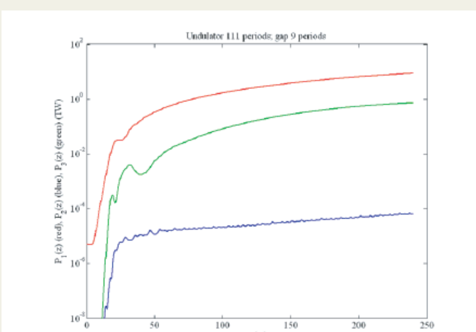
W. M. Fawley et al., p. 160 (2011)



GENESIS predictions for amplification of a 5-MW seed in a tapered, 200-m long undulator for time-steady (red), full time-dependent “fresh” bunch (blue), and start-to-end (green) conditions.



Spectrum is clean.



Harmonics also benefit from tapering.
Fundamental, red, 2nd harmonic, green, 3rd harmonic, blue.

GENERATION OF LONGITUDINALLY COHERENT ULTRA HIGHPOWER X-RAY FEL PULSES BY PHASE AND AMPLITUDE MIXING, J. Wu, A. Marinelli and C. Pellegrini, Proc. Conf. FEL 2012, p. 237 (2012)

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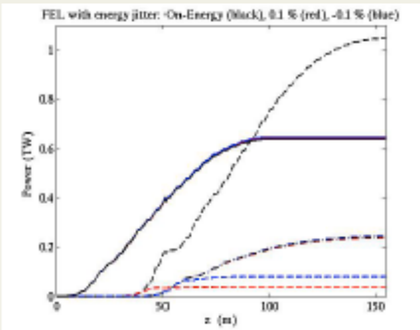
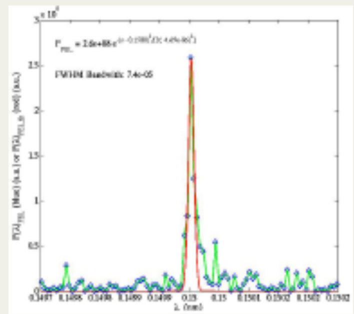


Using iSASE and a LCLS-II type variable gap undulator it is possible to reach 0.6 TW.



iSASE spectrum, tapered undulator end, bandwidth close to transform limit. Red curve is a fitting to the raw data (blue diamond connected by green line).

Proposal for a scheme to generate 10 TW-level femtosecond x-ray pulses for imaging single protein molecules at the European XFEL, S. Serkeza, V. Kocharyana, E. Saldina, I. Zagorodnova, G. Geloni, and O. Yefanovc, DESY 13-101 (2013), arXiv:1306.0804v1.

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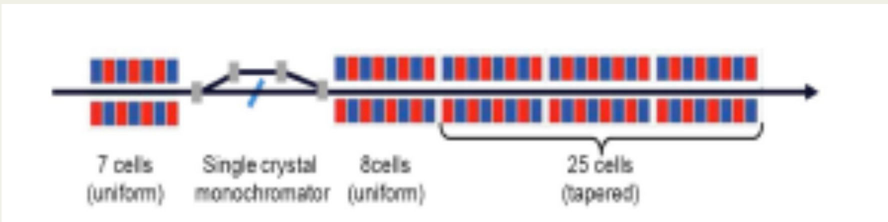
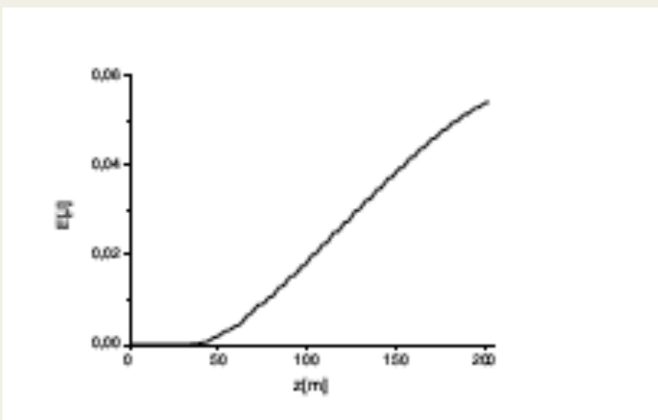
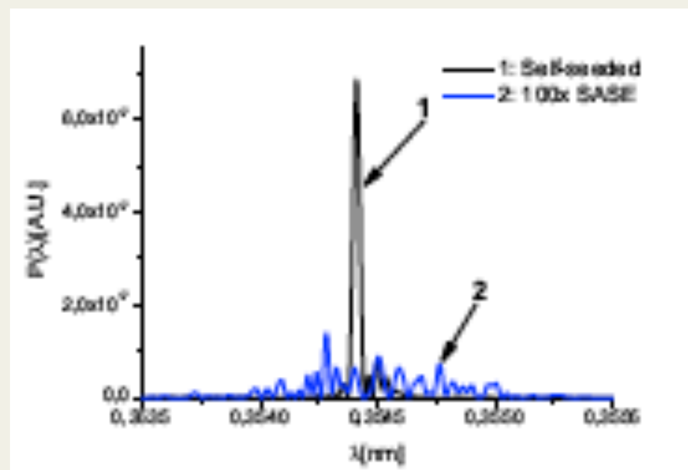


Configuration combining self-seeding and undulator tapering techniques with the emittance-spoiler method to increase the XFEL output peak power and shorten the pulse duration. Goal: performing bio-imaging of single protein molecules at the optimal photon energy range, i.e. around 4 keV.



Output ≈50 mJ, 10 fs, 10^{14} photons



SASE background ×100

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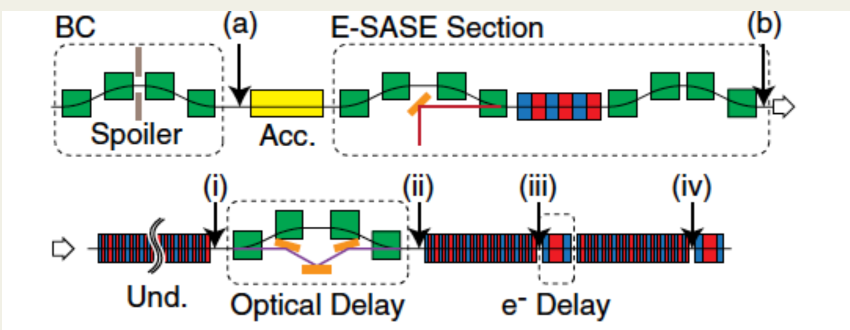
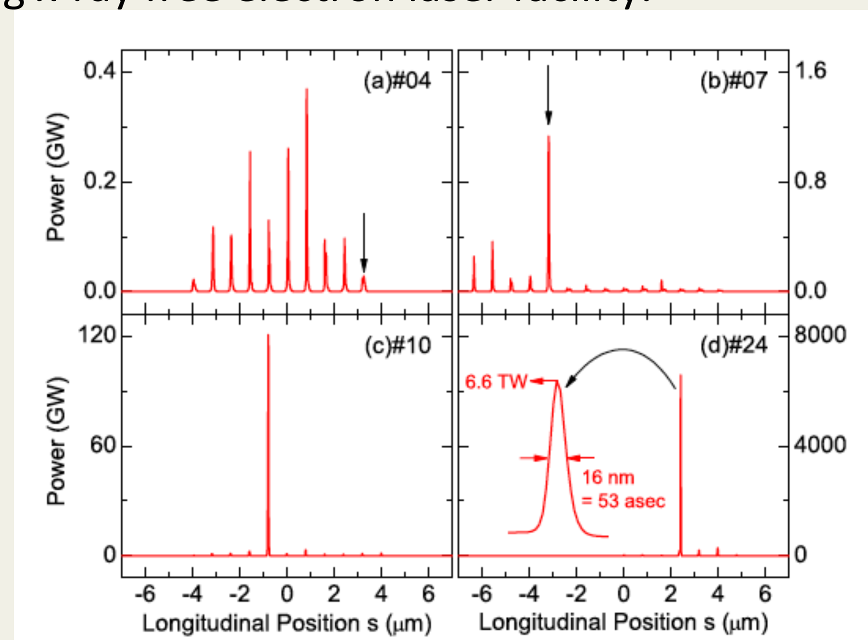
PRL 110, 084801 (2013) PHYSICAL REVIEW LETTERS week ending 22 FEBRUARY 2013

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

Takashi Tanaka*

A novel scheme to compress the radiation pulse in x-ray free electron lasers is proposed not only to shorten the pulse length but also to enhance the peak power of the radiation, by inducing a periodic current enhancement with an optical laser and applying a temporal shift between the optical and electron beams. Calculations show that a 10-keV x-ray pulse with a peak power of 5 TW and a pulse length of 50 as can be generated by applying this scheme to an existing x-ray free electron laser facility.





X-ray pulse temporal structures calculated at the ends of different undulator segments. Power 6.6 TW in 53 as. Intensity ≈0.3 mJ.

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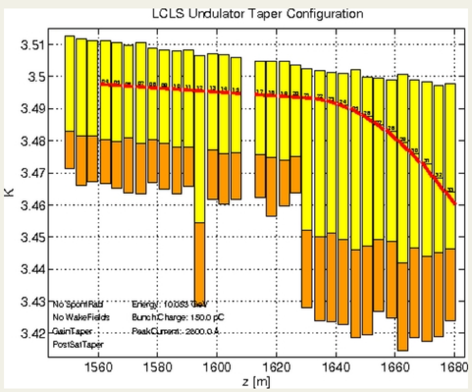
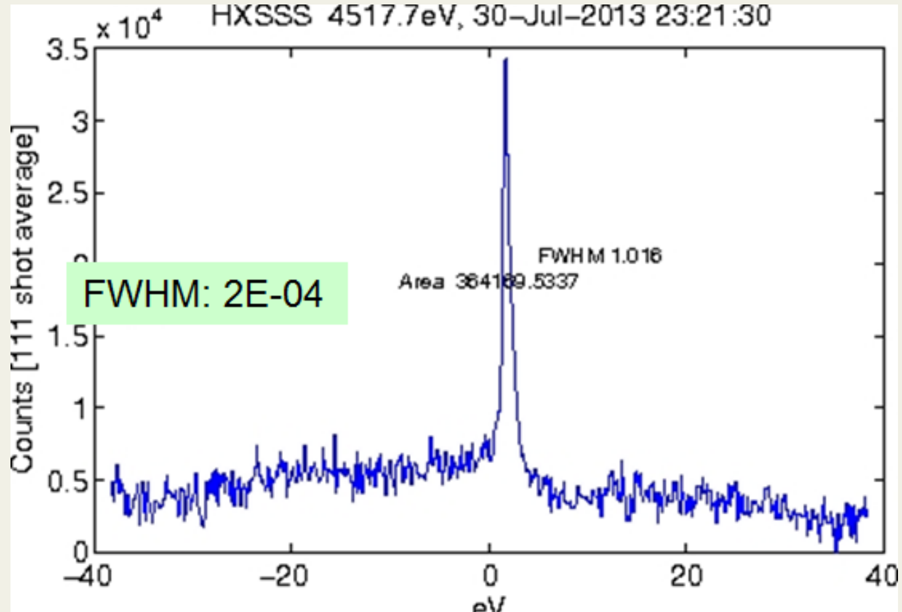
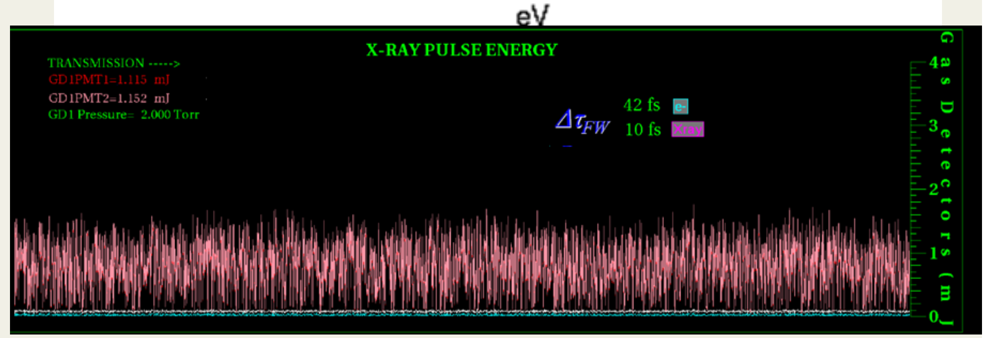
PATH TO HIGH-POWER FEL VIA SELF-SEEDING @ 4.5 KEV

- Experiment: > 1 mJ in 10 fs → peak power: 100 GW
- ~ 1 eV FWHM for 4.5 keV → FWHM Bandwidth: 2E-04







J. Wu, private communication

Peak power limited by length and tapering of LCLS undulator. Demonstrates tapering capability

Two Colors Spectra for X-ray FELs

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Two-color operation of x-ray FELs is important for: physical chemistry to extend traditional optical techniques of stimulated Raman spectroscopy to the x-ray regime; in the condensed phase, stimulated resonant inelastic x-ray scattering in solids could bring key time resolution; extending x-ray scattering techniques such as multi-wavelength anomalous diffraction (MAD) to time-resolved interactions allows phase retrieval for diffraction studies of femtosecond scale dynamically evolving molecular structures.

Five different schemes developed and tested. They can be used separately or in combination.

1. SASE two undulators K_1 and then K_2
   Tunable, large color separation, controlled delay and pulse duration, not simultaneous
2. Gain modulation, periodic change of undulator magnetic fields
   Tunable, line width smaller than SASE, simultaneous.
3. Two color self seeding
   Self seeding line-width, color separation limited to FEL gain bandwidth
4. Two peaks energy distribution within one bunch, or with double pulse within one RF cycle.
5. Seeding a long electron bunch with two different wavelengths and variable delay. Color separation limited to gain bandwidth.

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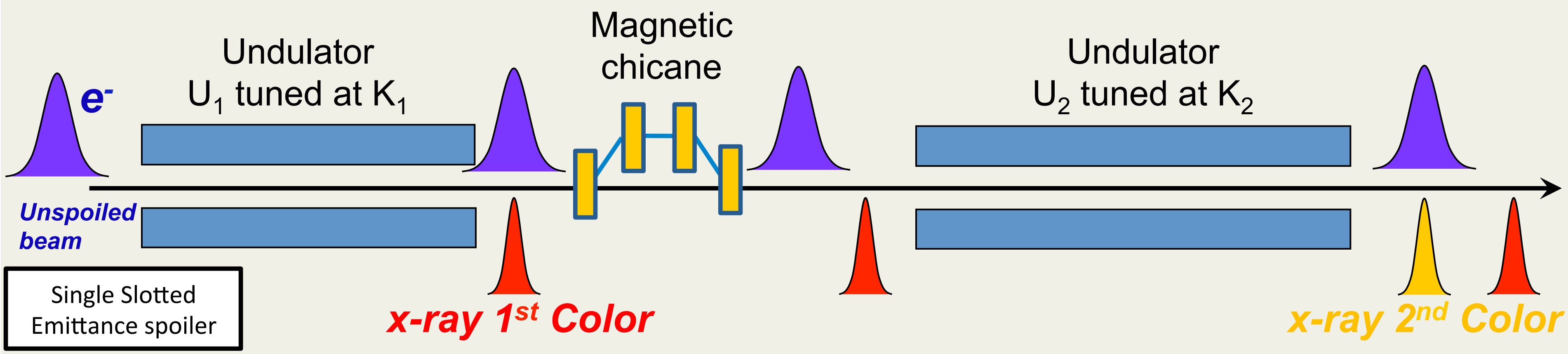
PRL **110,** 134801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron Lasers

A. A. Lutman, R. Coffee, Y. Ding,* Z. Huang, J. Krzywinski, T. Maxwell, M. Messerschmidt, and H.-D. Nuhn



- Single slotted foil controls the pulse duration
- K_1 and K_2 control the output wavelength
- Magnetic chicane controls the delay between the pulses

Color 1 cannot achieve saturation

Pulse duration, output wavelength and delay between pulses are independently controlled

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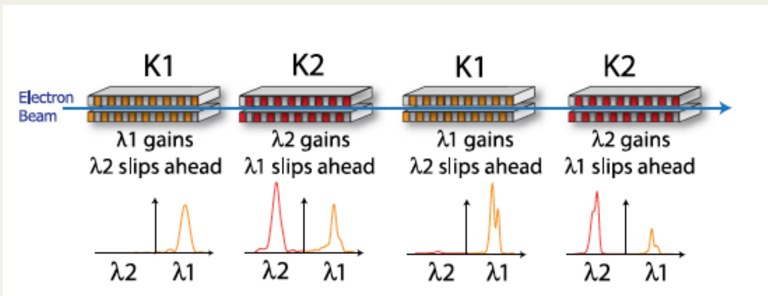
Demonstration Of Two-color X-FEL Operation and Autocorrelation Measurement at SACLA, T.Hara, Y. Inubushi, T. Ishikawa, H. Tanaka, T. Tanaka, K. Togawa, M. Yabashi, T. Katayama, T. Togashi, K. Tono, T. Sato, Proc. of the 2013 FEL Conf. New York

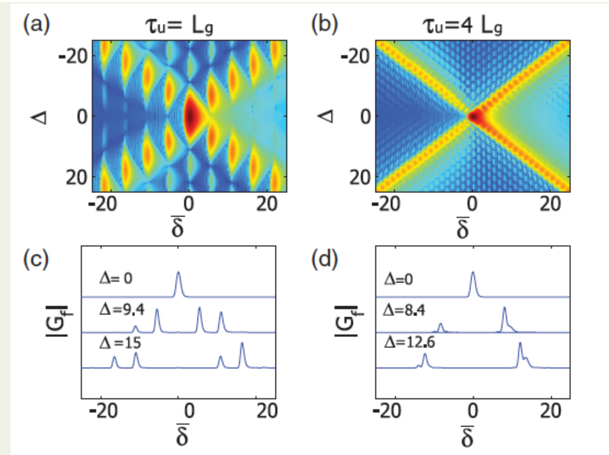
Recently two-color XFEL operation with a relative wavelength separation of 30 % has been achieved at SACLA in hard x-rays. In the two-color operation at SACLA the first and second halves of the undulators are set at different K values. Time delay between the two-color photon pulses is given by a magnetic chicane installed between the two undulators. The delay can be adjusted up to 40 fs. Photon pulse length of single-color operation < than 10 fs (FWHM). Femtoseconds pulses and GW peak power give an ideal light source for x-ray pump-probe experiments.

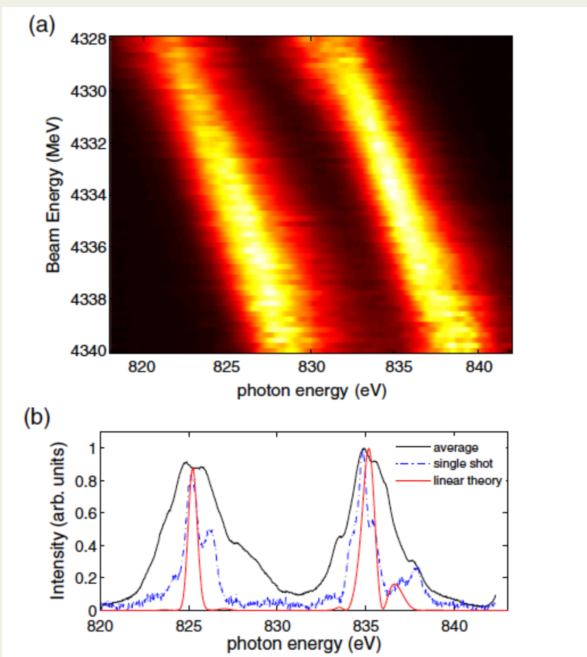
PRL **111,** 134801 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

A. Marinelli,[1,*] A. A. Lutman,[1] J. Wu,[1] Y. Ding,[1] J. Krzywinski,[1] H.-D. Nuhn,[1] Y. Feng,[1] R. N. Coffee,[1] and C. Pellegrini[2,1]







2 colors are simultaneous, important for stimulated emission. Line separation larger than bandwidth. Delay effect reduces bandwidth.

The two undulator methods and the gain modulated method have been used together at LCLS to study correlated electron motion in femtosecond timescale. Allows the exploration of C, N, O, *K*-shell resonances in 250 – 540 eV range. Electronic excitations separated by ≈ 5 – 10 eV.

Two-color pump-probe experiments with a twin pulse seed extreme ultraviolet free-electron laser, E. Allaria et al. Nature Comm., DOI: 10.1038/ncomms3476 (2013)

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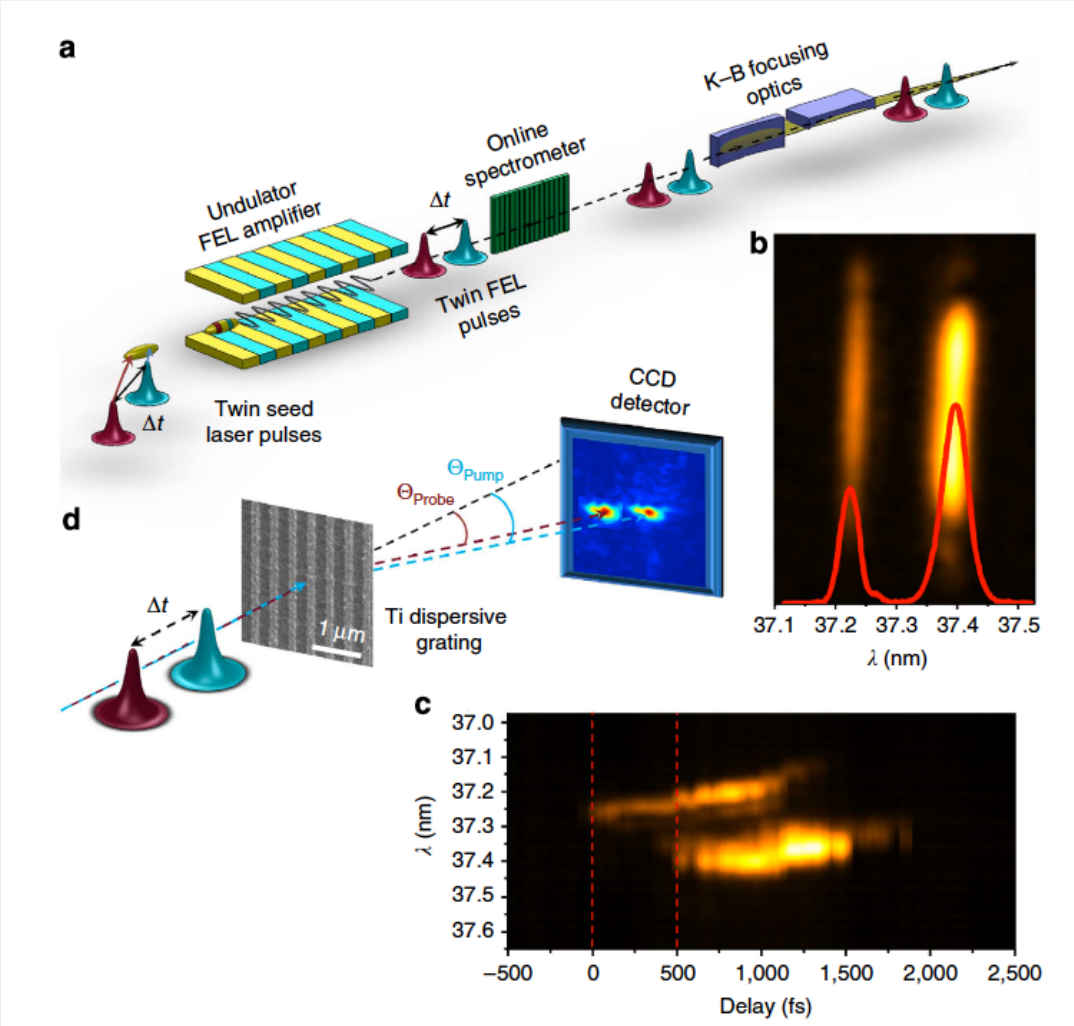
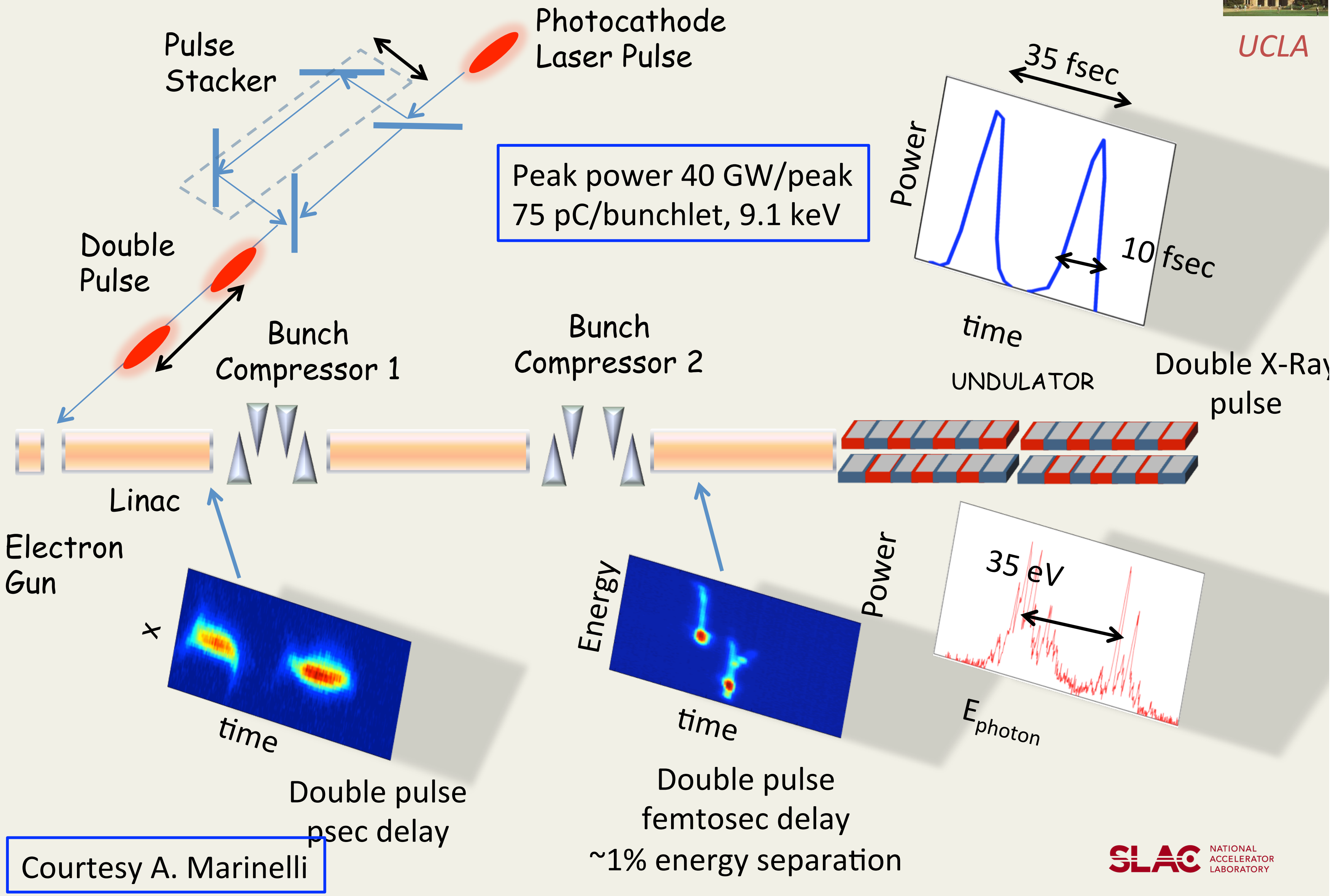


Fermi uses two different wavelength seed laser pulses, 180 fs long, seed at 260-262 lambda, fundamental at 784 nm, color separation inside gain bandwidth. The two pulses are separated in time and in wavelength.

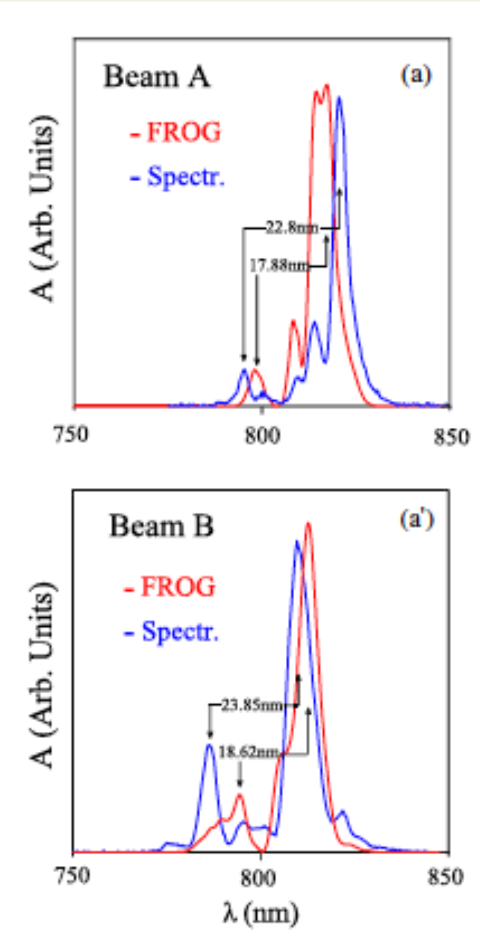
Two color schemes at LCLS, A. Marinelli et al., Private Communication.



PRL 111, 114802 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Observation of Time-Domain Modulation of Free-Electron-Laser Pulses by Multipeaked Electron-Energy Spectrum

V. Petrillo et al.



New scheme for the generation of ultrashort pulse trains based on free-electron-laser (FEL) emission from a multi-peaked electron energy distribution. Two electron beamlets with energy difference larger than the FEL parameter are generated by illuminating the cathode with two ps-spaced laser pulses, followed by a rotation of the longitudinal phase space by velocity bunching in the linac. The resulting SASE FEL radiation shows a double-peaked spectrum and a temporally modulated pulse structure.

FROG spectral signal (red, light curve) and spectrometer signal (blue curve, presenting an offset of 10 nm with respect to the FROG trace).

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Progress in diagnostics and instrumentation

Key to improve the electron bunch phase-space distribution, improve the "lasing medium".

Two examples: X-band transverse cavity and energy chirp control.

Femtosecond Electron and X-ray Beam Temporal Diagnostics Using an X-band Transverse Deflector at LCLS, Y. Ding et al. Presented at the FEL'13 Conf.

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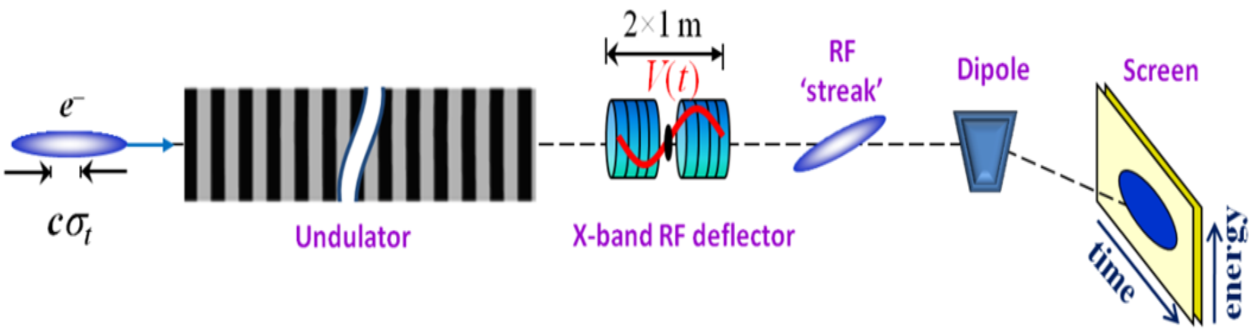
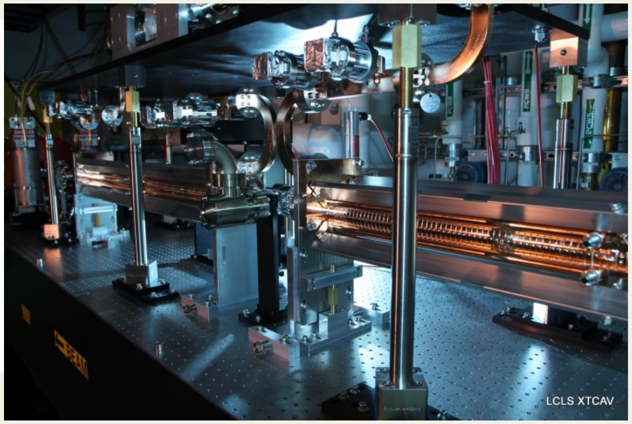
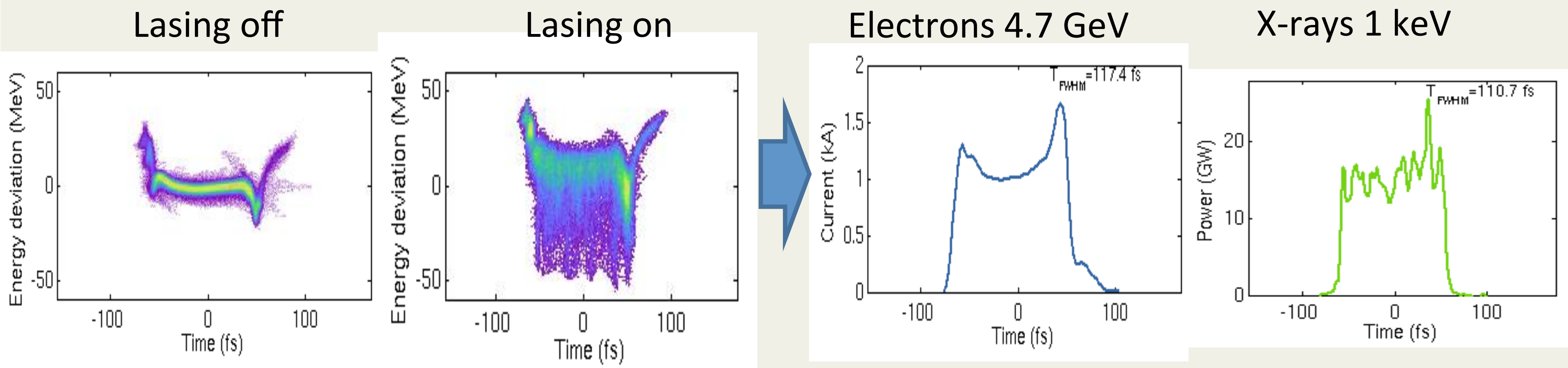


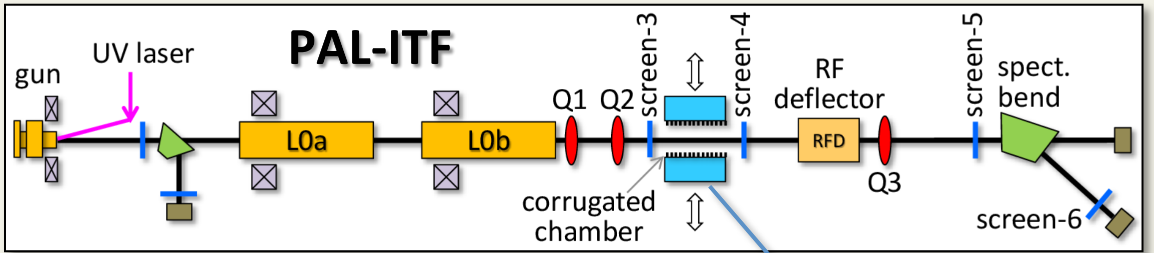


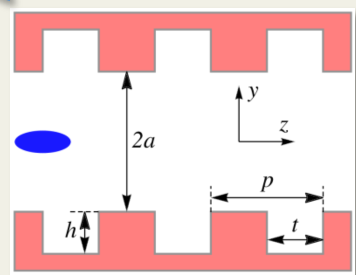
Courtesy Y. Ding



So far, best resolution achieved about 1.2 fs rms at 4GeV; and about 3 fs rms at 13GeV.

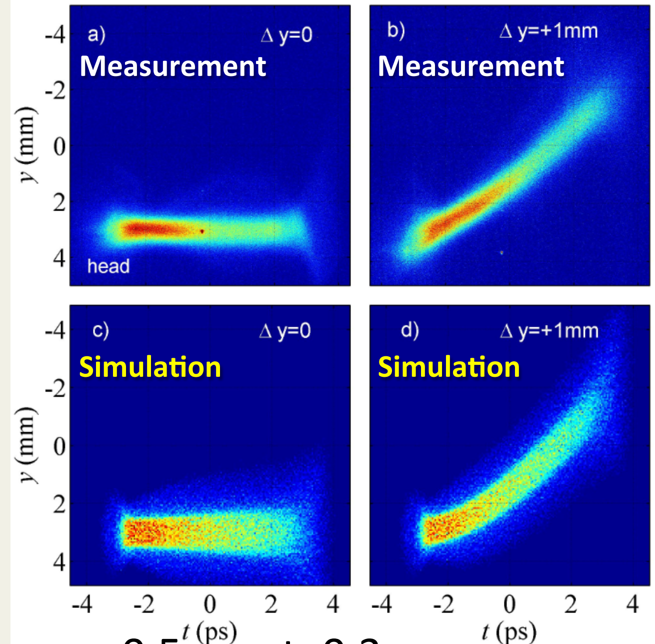
Wakefield Dechirper Chamber – Simulation & Measurement



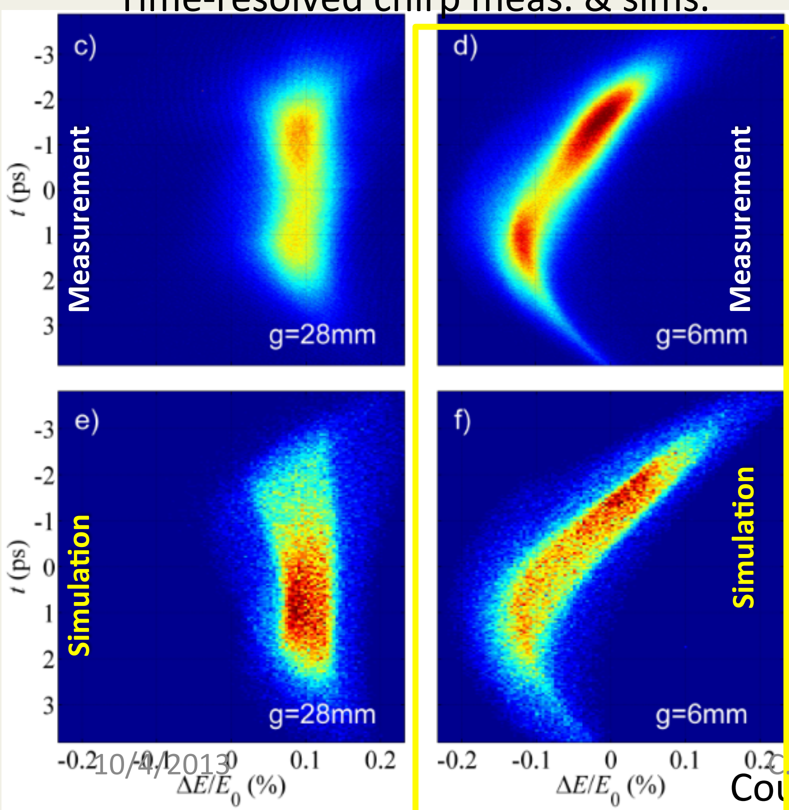


corrugated chamber

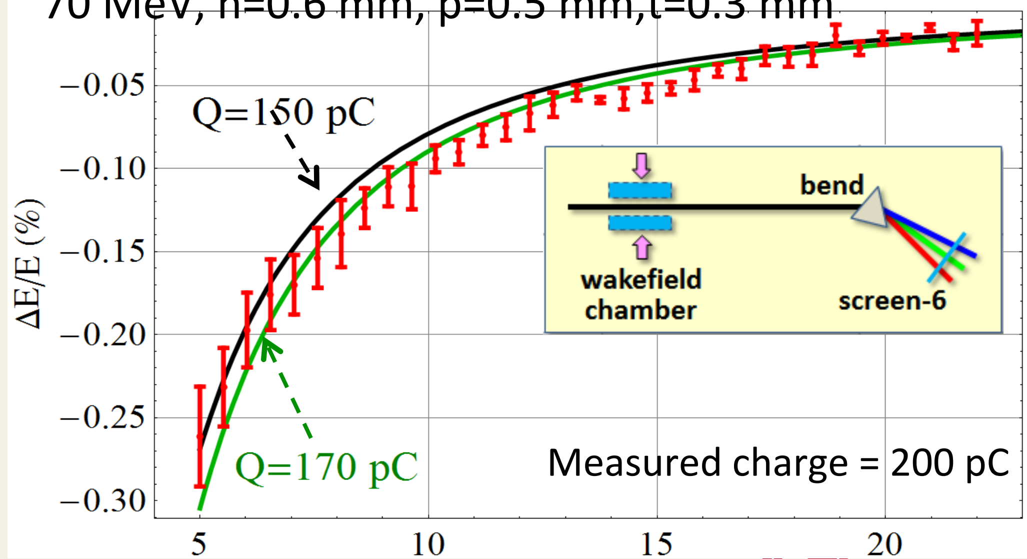
Time-resolved T-wake meas. & sims.



Time-resolved chirp meas. & sims.



70 MeV, h=0.6 mm, p=0.5 mm,t=0.3 mm



Courtesy K. Bane, P. Emma, H.-S. Kang, G. Stupakov, M. Venturini, e

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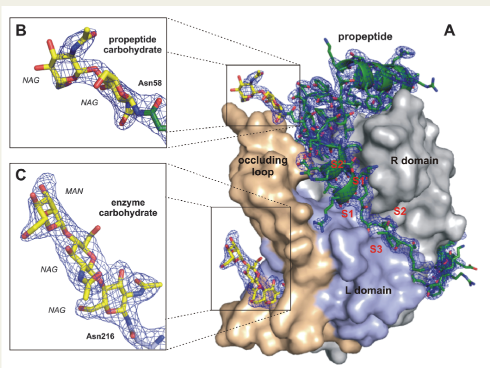
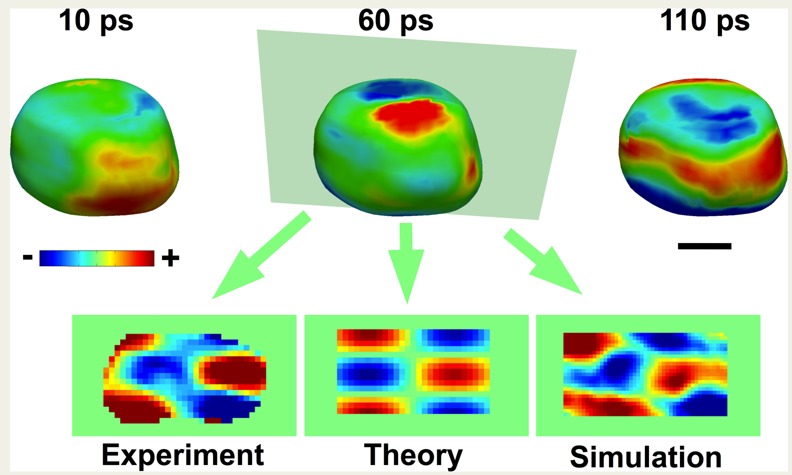
Conclusions

X-ray FELs give us an unprecedented view of the structure and dynamics of matter at the angstrom, fs time scale. The flexibility of the system allows to optimize the X-ray pulse intensity, time duration and spectral properties to the experiment being done.



Natively Inhibited Trypanosoma brucei Cathepsin B Structure Determined by Using an X-ray Laser, L. Redecke et al. Science 339, 227 (2013)



Ultrafast Three-Dimensional Imaging of Lattice Dynamics in Individual Gold Nanocrystals, J. N. Clark et al., Science, 341, 6141 (2013)

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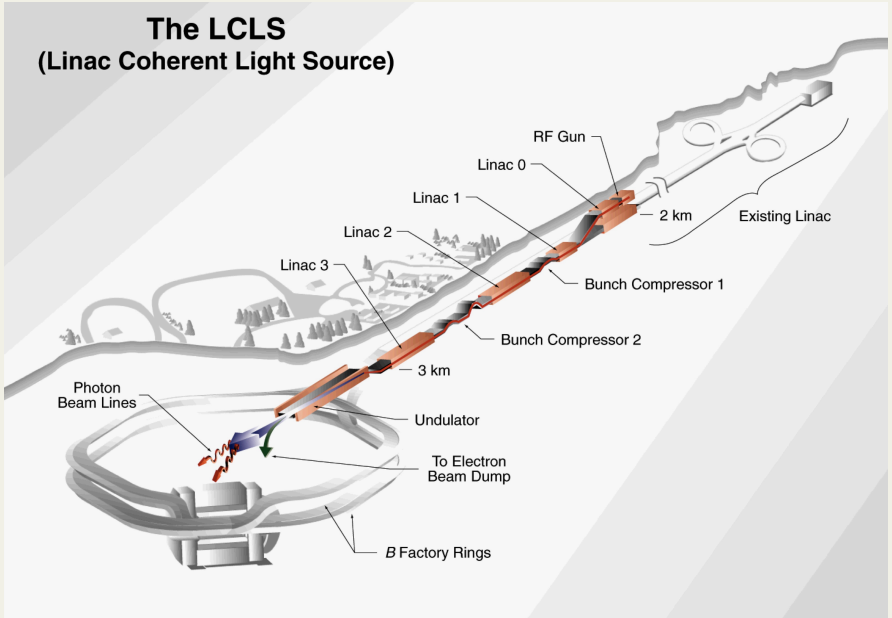
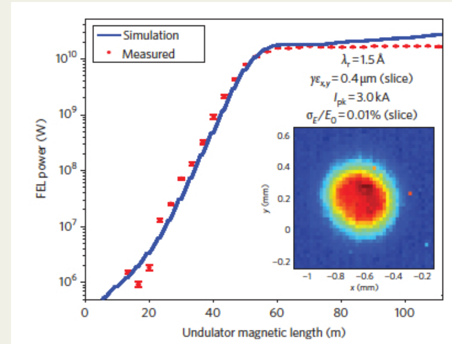
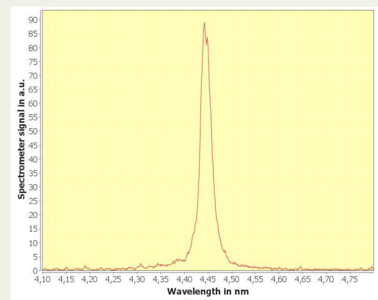
X-ray FELs: 1992-2013

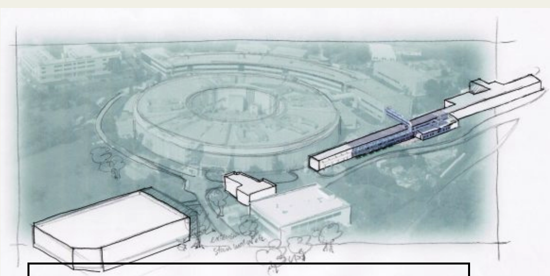




LCLS, 1.5 Å, 4/2009, 1-3 mJ



Flash: 4.45 nm, 0.3 mJ, 6/2010



Fermi@Elettra, 4nm, 2013

SACLA, 0.8 Å, 6/2011

> 2013- New projects in construction: European XFEL, LCLS-II, Swiss X-FEL, Korean X-FEL