



FEL 2013 | Manhattan, USA

35th International Free-Electron Laser Conference  
August 26-30, 2013

# Methods for Achieving Spectral Purity in SASE FELs

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August 29, 2013

# OUTLINE

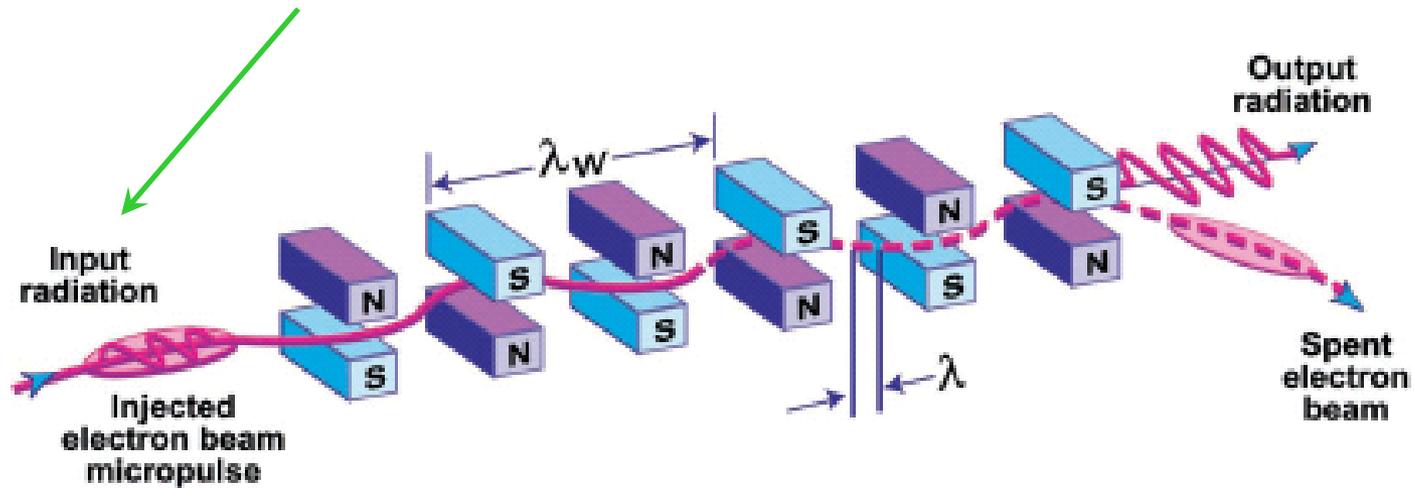
- Brief review of a SASE FEL
- Recent developments for reaching a transform limited FEL at SASE FEL facilities
  - Ultra-short, single spike operation
  - Self-seeding (Hard X-ray and Soft X-ray)
  - Improved SASE (iSASE)
  - Purified SASE (pSASE)
  - High-Brightness SASE (HB-SASE)
  - Mode-lock FEL
- Prospects and Discussion

# FREE ELECTRON LASER

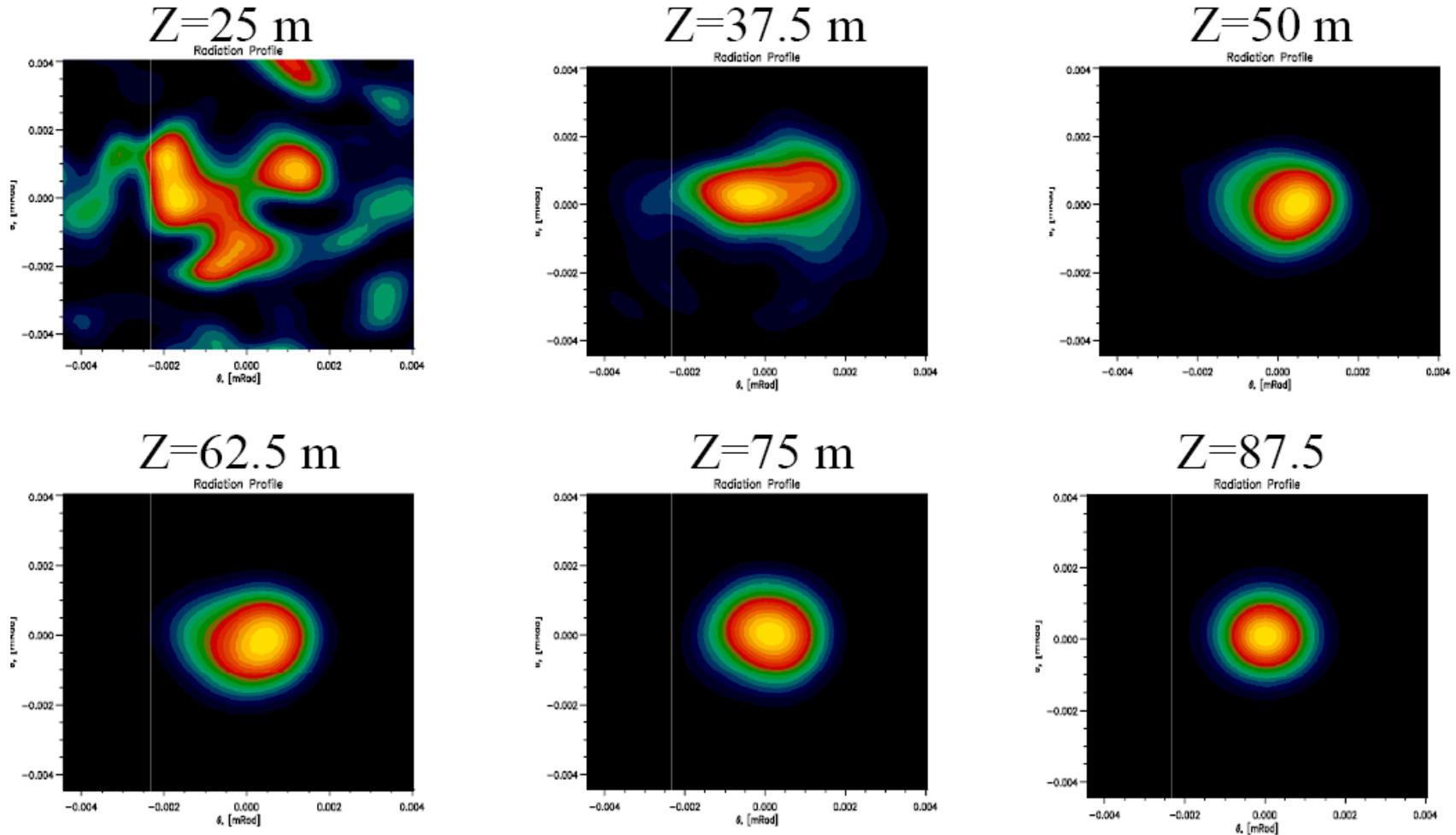
■ Undulator radiation + **feedback** (on the electron distribution) → **instability** → Free electron laser

■ Start from undulator radiation / shot noise → Self-Amplified **Spontaneous** Emission (SASE) → exponential growth → mechanism for LCLS, SACLA, ...

■ Start from a coherent seed → Externally Seeded FEL

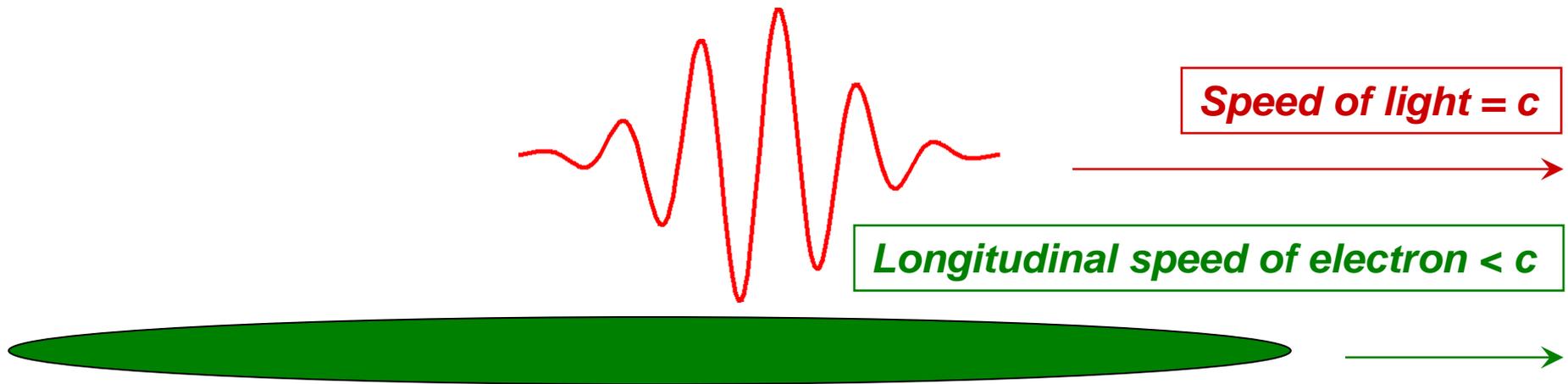


# GOOD TRANSVERSE/SPATIAL COHERENCE: SINGLE MODE



# LIMITED LONGITUDINAL/TEMPORAL COHERENCE

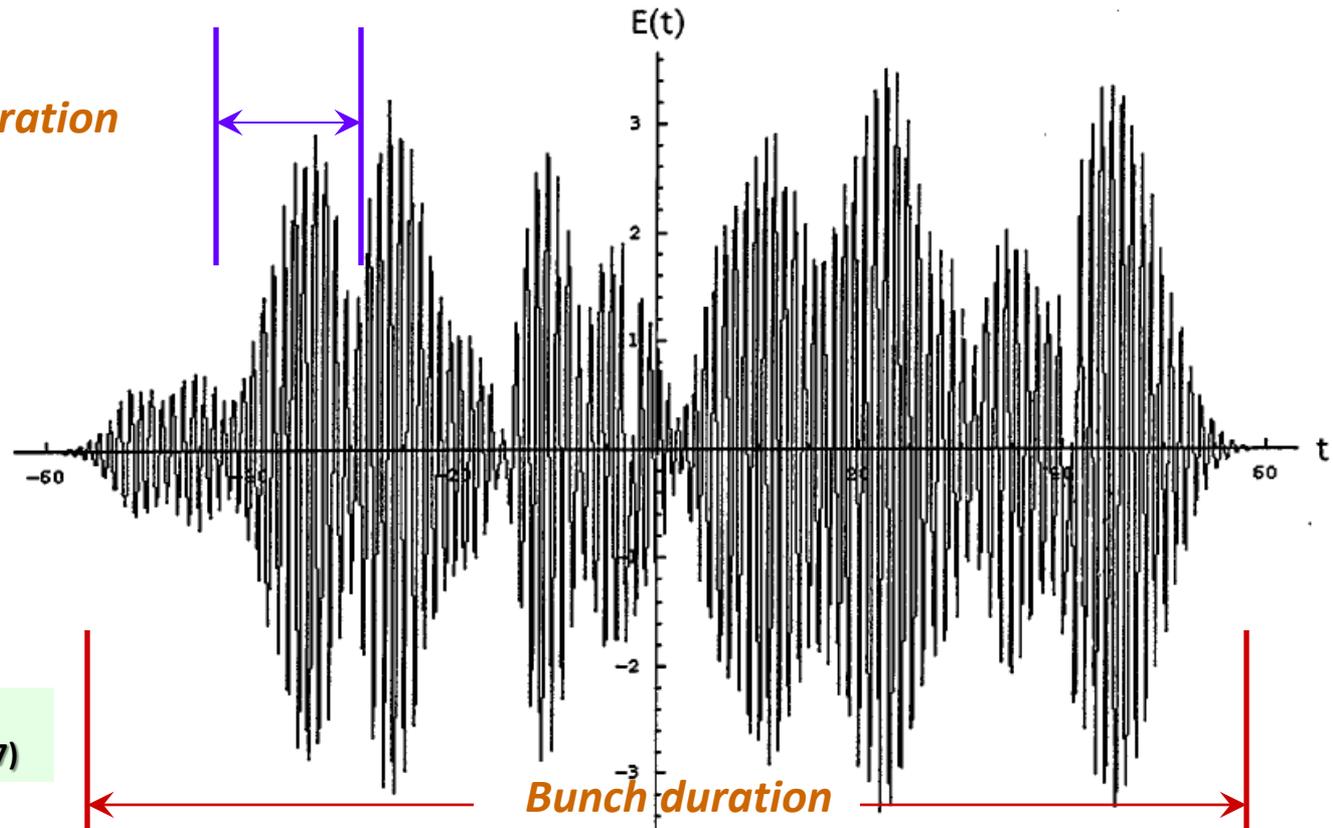
- Longitudinal / temporal enhancement: photon slips (advances) over electron bunch, the electrons being **swept** by the same photon wavepacket (which is also growing due to bunching) will radiate coherently due to the resonant condition  $\Rightarrow$  coherence length  $\Rightarrow$  **coherent** spike



- However, the radiator (electron) is **too fast!** almost the same speed as the signal (photon)  $\rightarrow$  **short** coherent spike  $\rightarrow$  limiting the "stimulation" within short spike

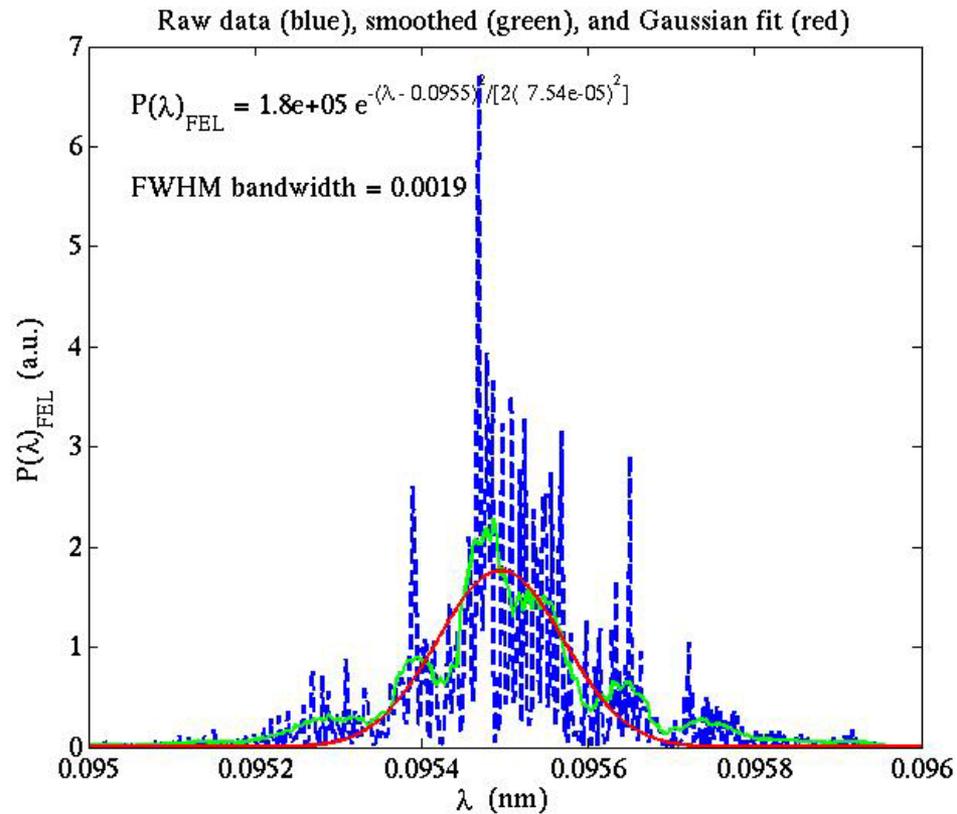
# SASE FEL: POOR LONGITUDINAL COHERENCE

- Each spike was started **randomly** from shot noise. Coherent Spike duration is normally short than the electron bunch duration. This is how a SASE FEL looks like!



**K.J. Kim**  
LBNL Report No. 40672 (1997)  
Office of Science

## Performing a Fourier transform, one gets SASE spectrum



### Example of LCLS-II 13 keV case

# SINGLE SPIKE: ULTRA-SHORT BUNCH

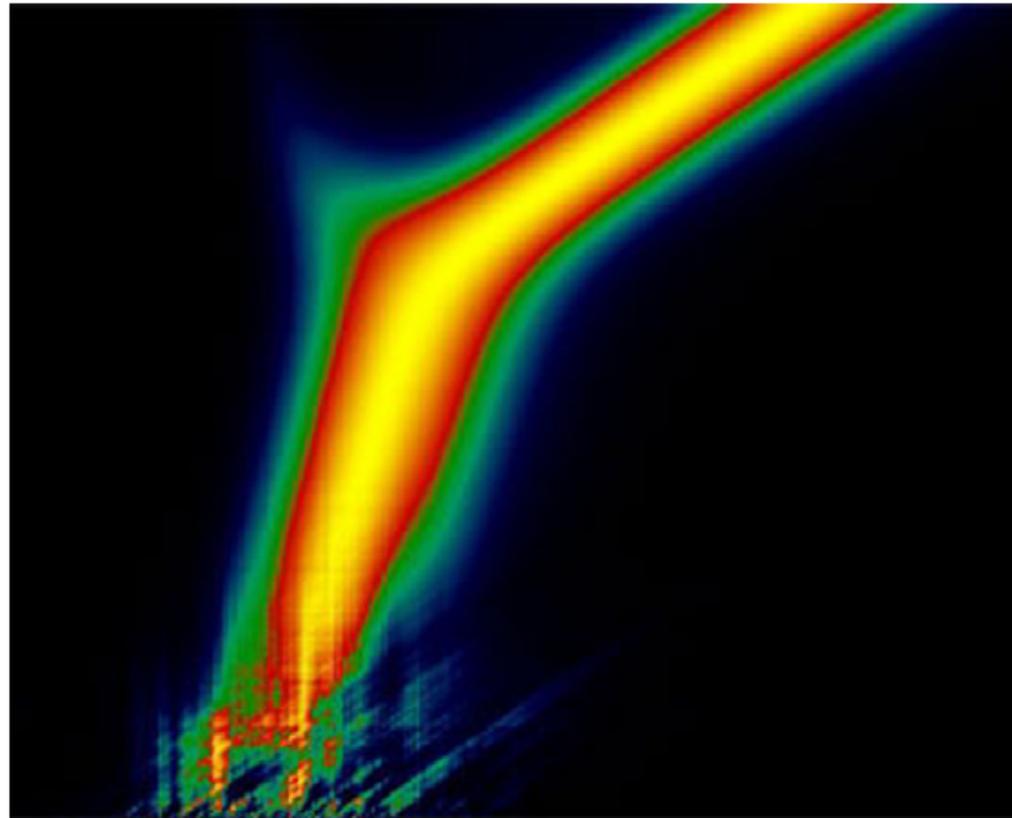
Nuclear Instruments and Methods in Physics Research A 593 (2008) 45–48



## Development of ultra-short pulse, single coherent spike for SASE X-ray FELs

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*UCLA, Department of Physics and Astronomy, 405 Hilgard Ave., Los Angeles, CA 90095, USA*

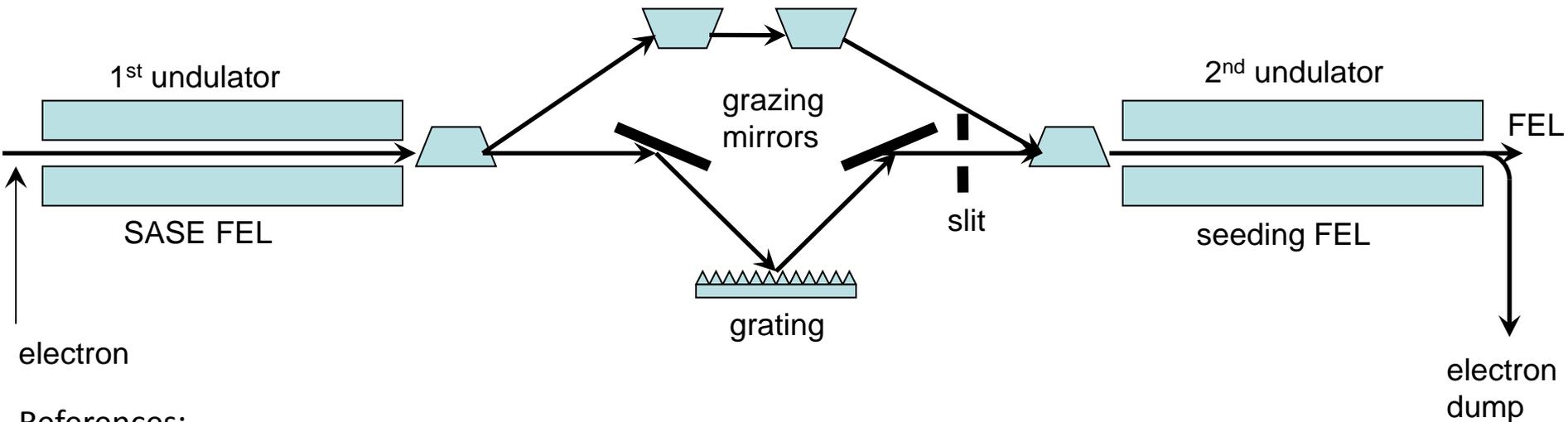


**Fig. 3.** Evolution of the FEL radiation temporal profile (horizontal axis) along the undulator (vertical axis) for the SPARX FEL. At each position the profile has been normalized to exclude the exponential growth of the radiation power, which otherwise would obscure the details in the first half of the undulator.

# SELF-SEEDING SCHEME: SOFT X-RAY

Originally proposed at DESY\*

electron  
chicane



## References:

- \*J. Feldhaus, E.L. Saldin, J.R. Schneider, E.A. Schneidmiller, M.V. Yurkov, *Opt. Comm.*, **140**, 341 (1997)
- Y. Feng, J. Hastings, P. Heimann, M. Rowen, J. Krzywinski, J. Wu, FEL2010, Sweden, TUPB10 (2010)
- Y. Feng *et al.*, FEL2012, Japan, TUOBI01 (2012)
- S. Serkez, G. Geloni, V. Kocharyan and E. Saldin, arXiv: 1303.1392v1 (2013)
- Y. Feng *et al.*, FEL2013, US, WEPSO17, (2013)
- D. Ratner *et al.*, FEL2013, US, WEPSO52, (2013)

# HARD X-RAY SELF-SEEDING

SLAC

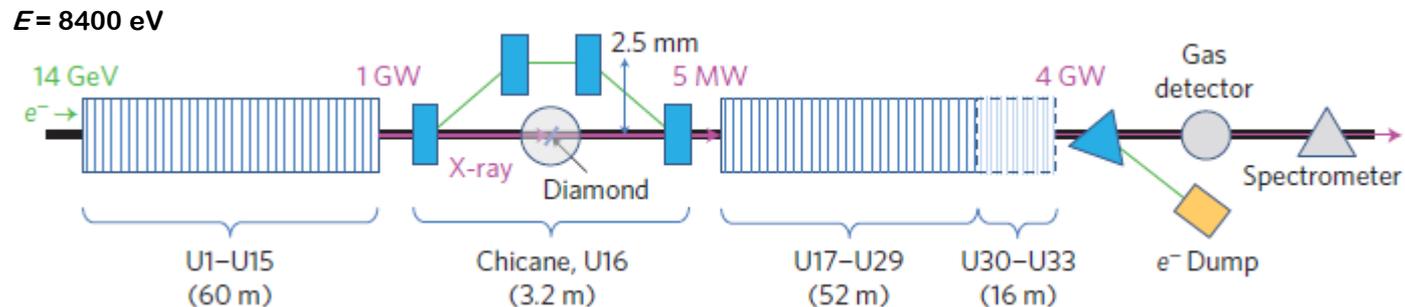
nature  
photonics

ARTICLES

PUBLISHED ONLINE: XX XX 2012 | DOI: 10.1038/NPHOTON.2012.180

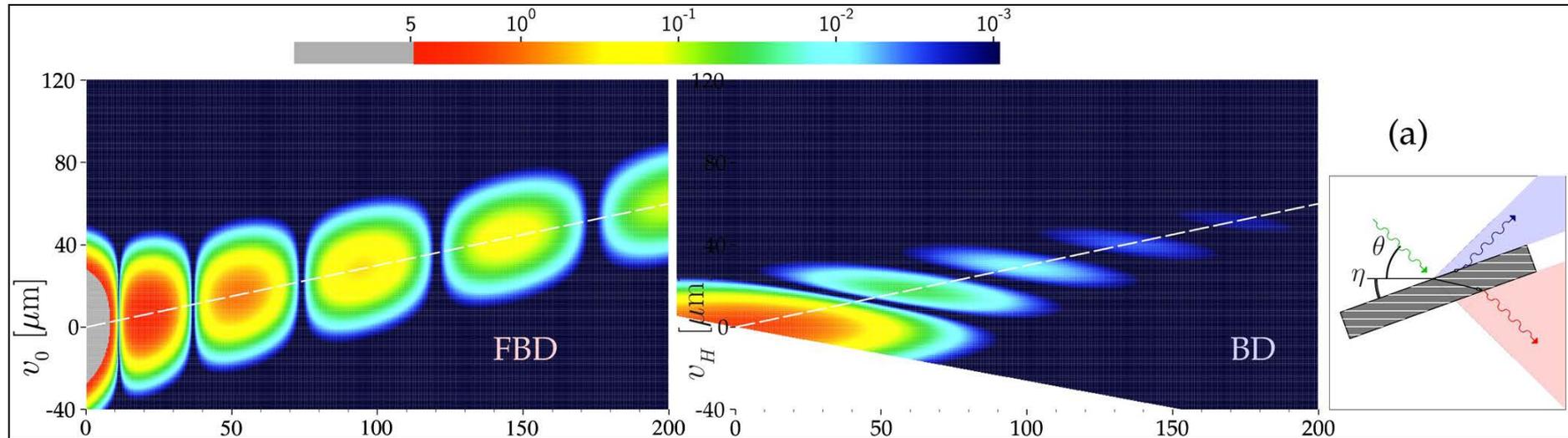
## Demonstration of self-seeding in a hard-X-ray free-electron laser

J. Amann<sup>1</sup>, W. Berg<sup>2</sup>, V. Blank<sup>3</sup>, F.-J. Decker<sup>1</sup>, Y. Ding<sup>1</sup>, P. Emma<sup>4\*</sup>, Y. Feng<sup>1</sup>, J. Frisch<sup>1</sup>, D. Fritz<sup>1</sup>, J. Hastings<sup>1</sup>, Z. Huang<sup>1</sup>, J. Krzywinski<sup>1</sup>, R. Lindberg<sup>2</sup>, H. Loos<sup>1</sup>, A. Lutman<sup>1</sup>, H.-D. Nuhn<sup>1</sup>, D. Ratner<sup>1</sup>, J. Rzepiela<sup>1</sup>, D. Shu<sup>2</sup>, Yu. Shvyd'ko<sup>2</sup>, S. Spampinati<sup>1</sup>, S. Stoupin<sup>2</sup>, S. Terentyev<sup>3</sup>, E. Trakhtenberg<sup>2</sup>, D. Walz<sup>1</sup>, J. Welch<sup>1</sup>, J. Wu<sup>1</sup>, A. Zholents<sup>2</sup> and D. Zhu<sup>1</sup>



# HXRSS EXPERIMENT @ LCLS

Seed is generated via forward Bragg (or Laue) Diffraction



**Shvyd'ko, Lindberg, PRSTAB, 15, 100702 (2012)**

# HXRSS EXPERIMENT @ LCLS

- Seed is the monochromatic wake trailing the SASE pulse
- Electron bunch is time delayed

Electron bunch

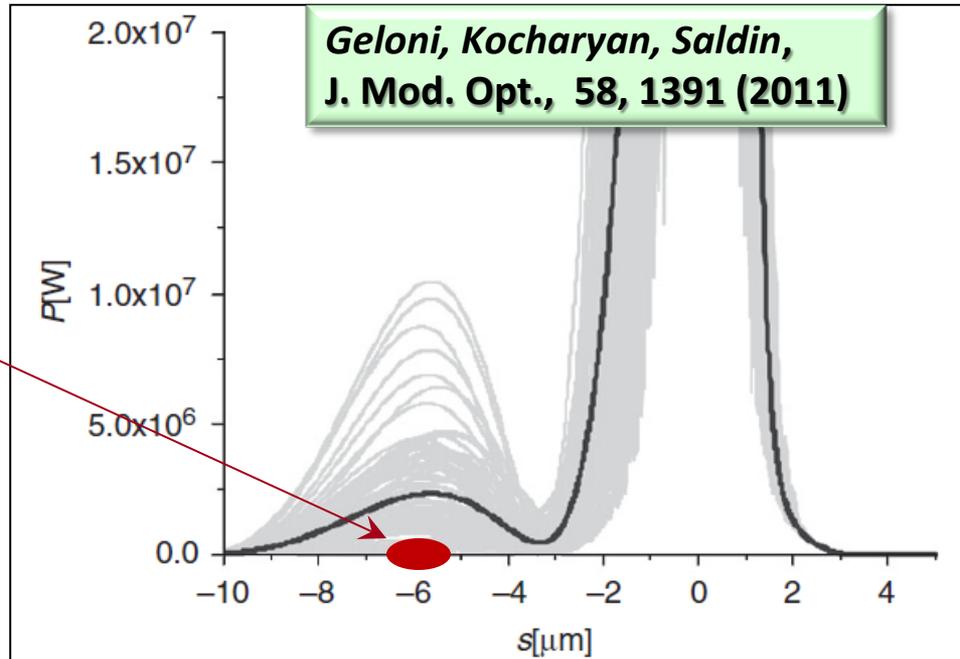
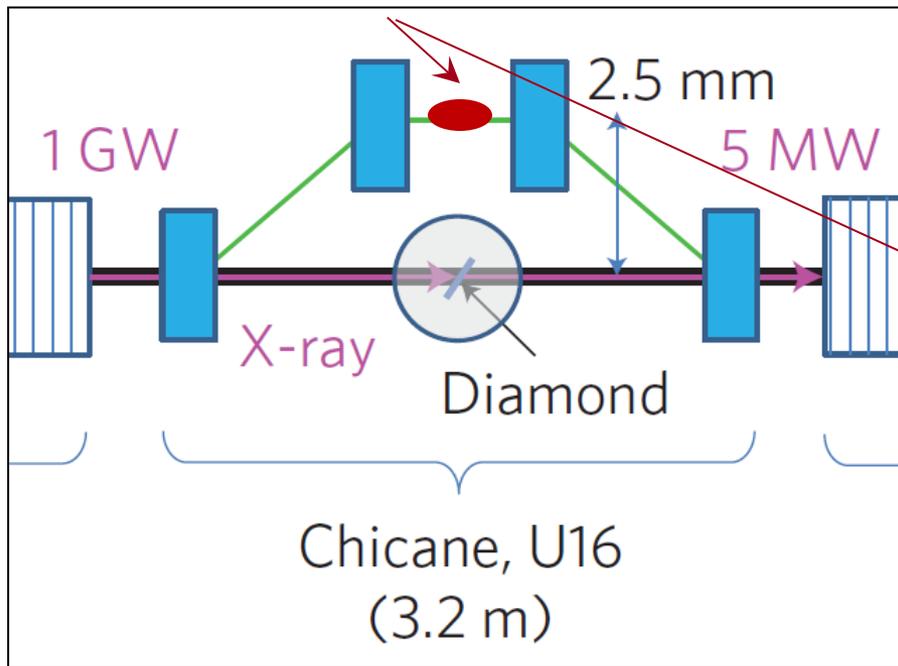
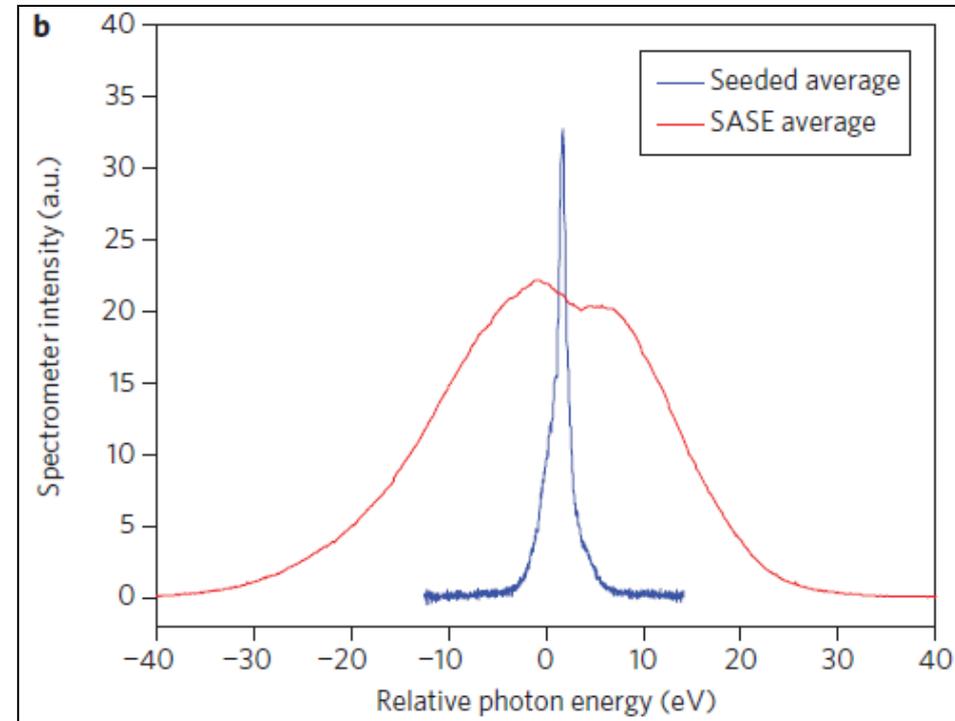
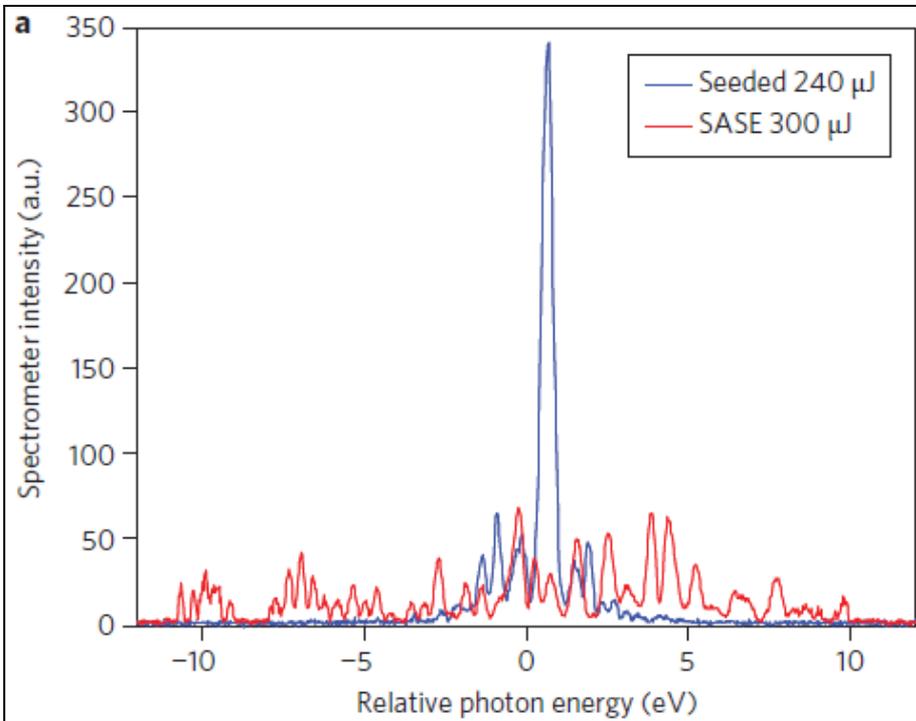


Figure 10. Feasibility study for the LCLS. Power distribution after the diamond crystal. The monochromatic tail due to the transmission through the bandstop filter is now evident on the left of the figure. Gray lines refer to single shot realizations, the black line refers to the average over 100 realizations.

# LCLS: WORLD'S FIRST HARD X-RAY SEEDED FEL

## LCLS – Seeded spectrum vs. SASE spectrum



# SASE FEL: IMPROVE THE LONGITUDINAL COHERENCE

- Approaches: quoting A. Gover, FEL'06, p. 1, FEL prize lecture: “A **third** scheme that should be considered for phase locking and increasing the coherence of the radiation in a SASE FEL consists of imposing **periodic perturbation** on the wiggler (e.g. periodic dispersive sections)”.
- “The filtering effect of the periodic structure may be viewed as the analogue of linewidth narrowing of radiation emitted in a Fabri-Perot resonator.”

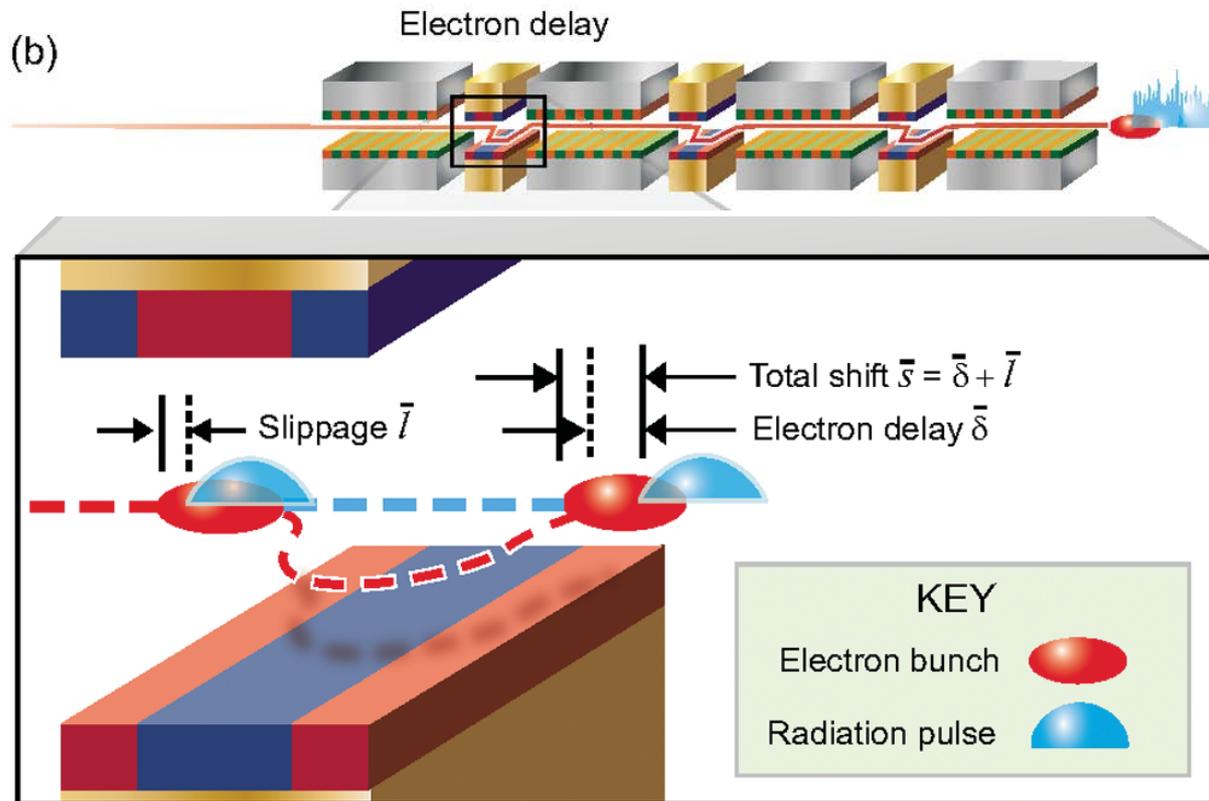
A. Gover and E. Dyunin, FEL'06, p. 1 (2006): FEL prize lecture

Y.-C. Huang, private communications



# PERIODIC EQUAL TEMPORAL DELAYS

■ Electron delay to lengthen the cooperation length



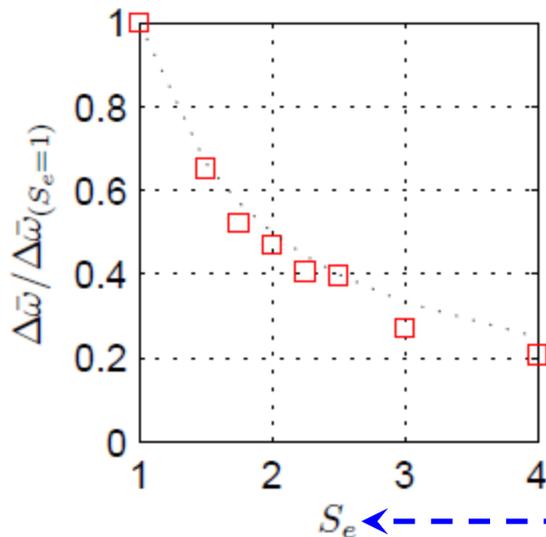
# PERIODIC EQUAL TEMPORAL DELAYS

■ Longer cooperation length  $\rightarrow$  narrower bandwidth

## IMPROVED TEMPORAL COHERENCE IN SASE FELS

N.R. Thompson and D. J. Dunning, ASTeC/CI, STFC Daresbury Laboratory, UK

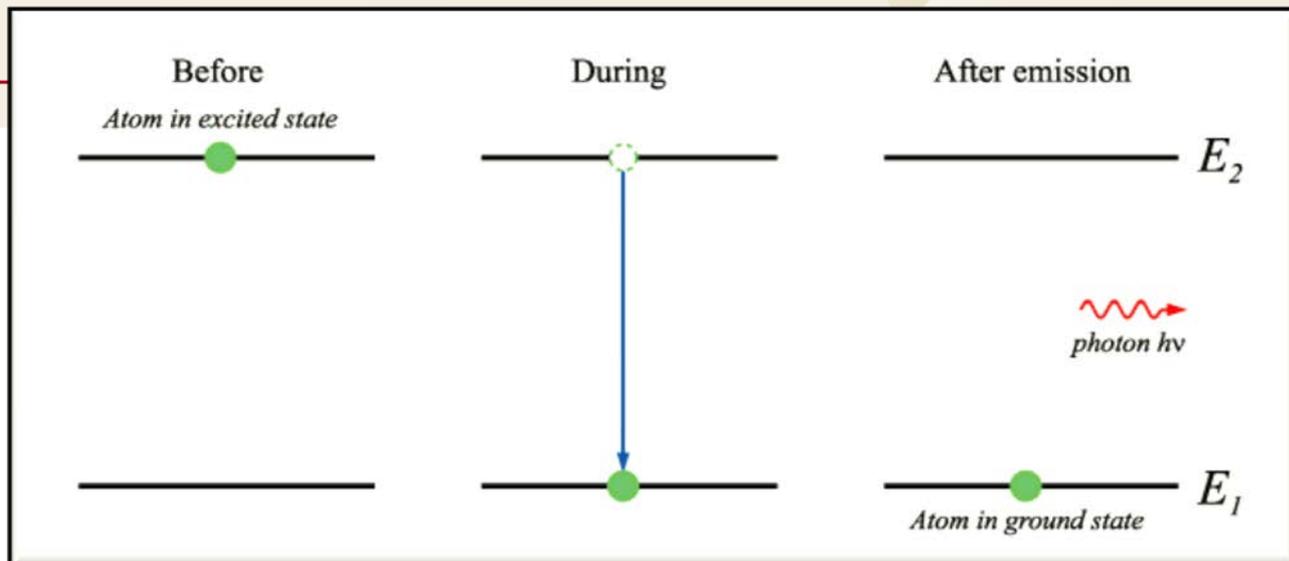
B. W. J. McNeil, University of Strathclyde, Scotland, UK



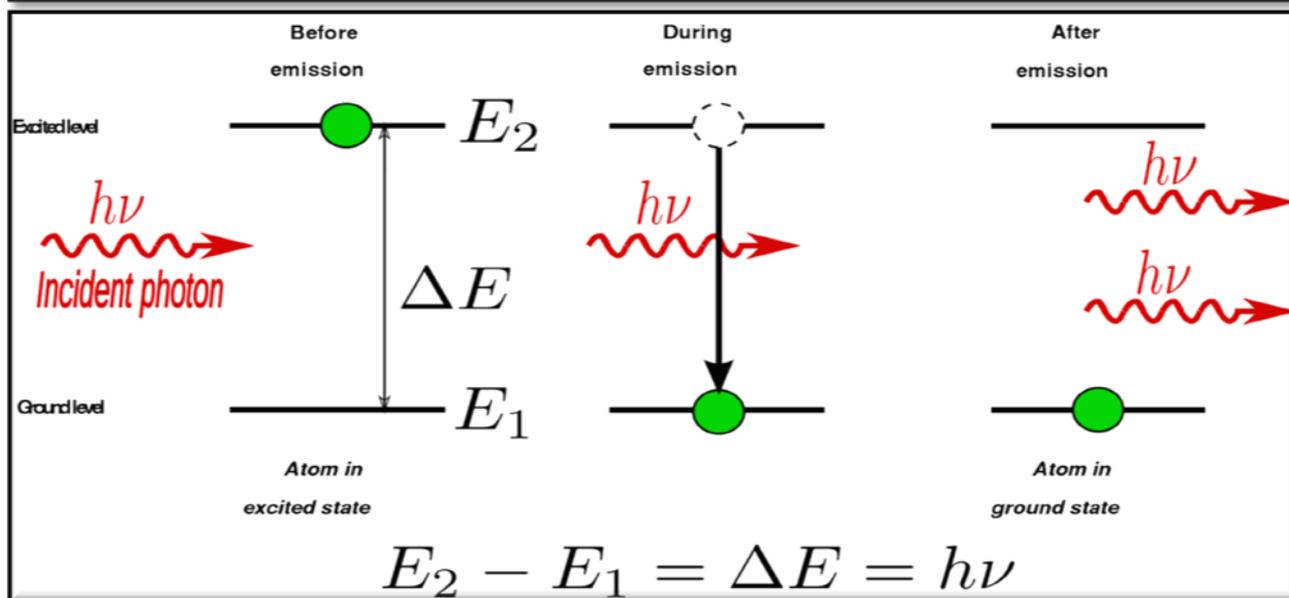
$S_e = \frac{\delta+l}{l}$  with  $\delta$  the additional slippage in the phase shifter

# EMISSION: SPONTANEOUS AND STIMULATED

## Spontaneous:



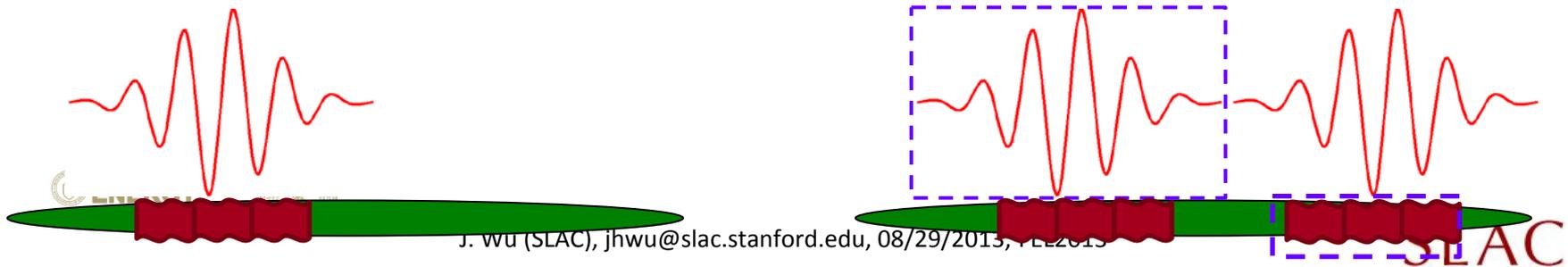
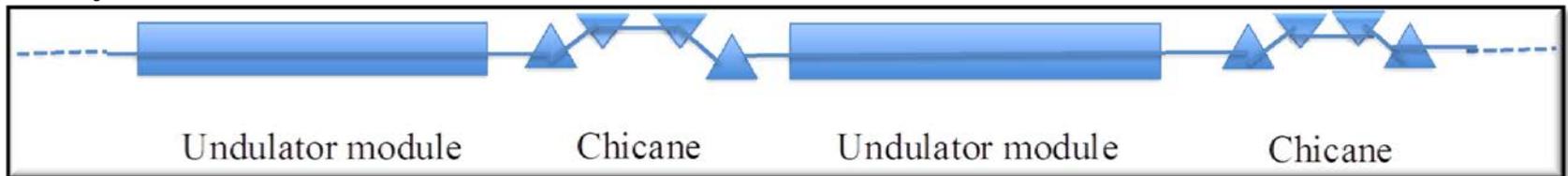
## Stimulated:



What does this imply?

The signal has to meet the radiator

- Do we really need **periodicity**?
- Effectively slow down the emitter (electrons) → signal can **meet** the emitter → extend the coherent length
- Speed up the longitudinal slippage → amplitude and phase **mixing** → improve longitudinal coherence
- Use phase shifter:



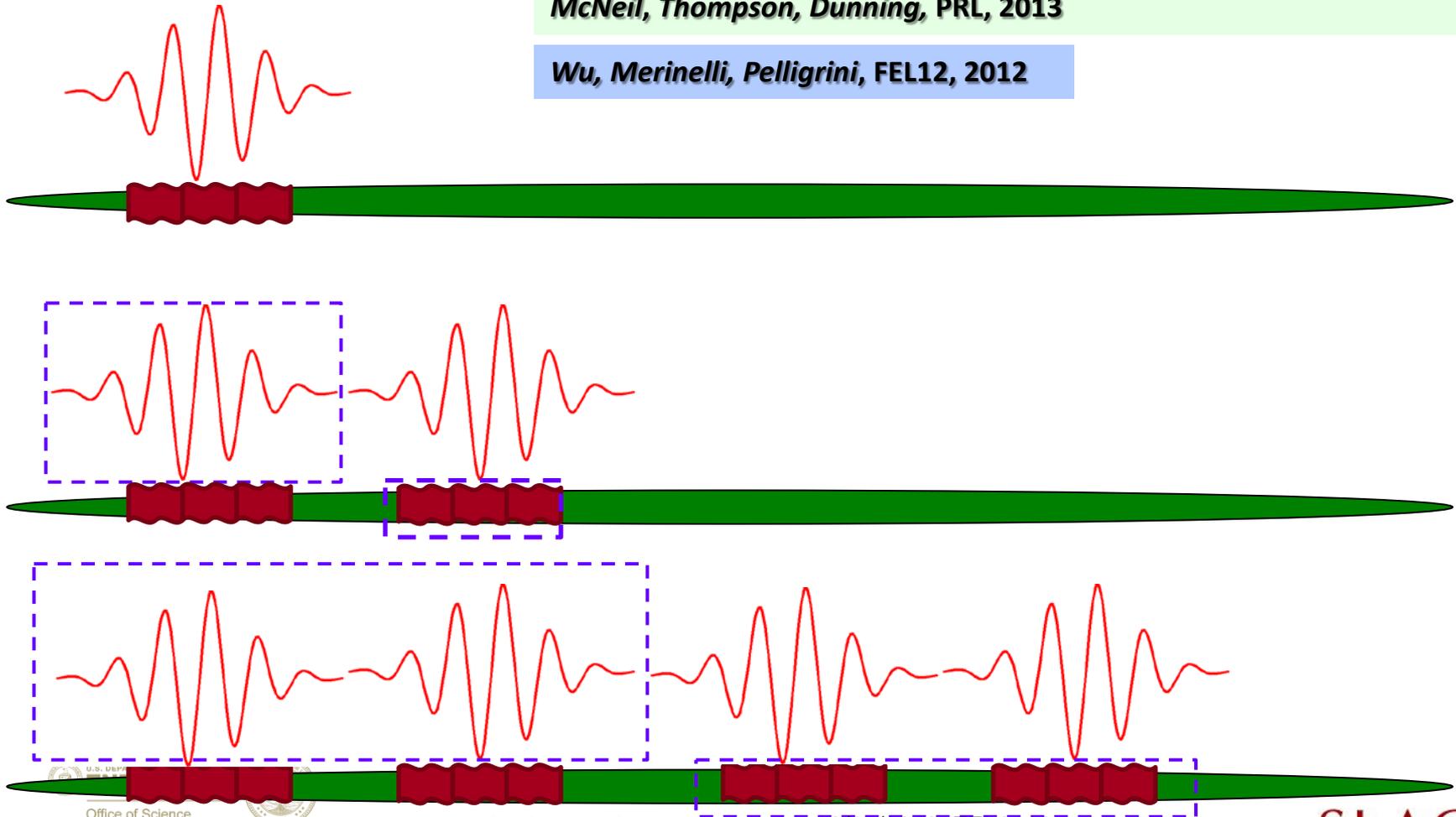
## Geometric

*Thompson, McNeil, PRL, 2008*

*Thompson, Dunning, McNeil, IPAC10, p2257, 2010 with some randomization*

*McNeil, Thompson, Dunning, PRL, 2013*

*Wu, Merinelli, Pellegrini, FEL12, 2012*



## ■ Phase Shifter:

■ Periodic Constant delay:  $L_{\text{coh}} = (N+1) L_{\text{coop}}$

■ Geometric delay:  $L_{\text{coh}} = 2^N L_{\text{coop}}$

■ Considering energy spread: 1,2,4,...,2<sup>N-1</sup>,2<sup>N</sup>, 2<sup>N-1</sup>,...,4,2,1

■ Combination of periodic and geometric: 1,2,1,4,1,8,1,16,1,32,...

Thompson, McNeil, PRL, 2008  
Thompson, Dunning, McNeil, IPAC10,  
p2257, 2010

## ■ **The Bottom Line**: total slippage comparable to the electron bunch duration

■ Periodic delay cleans up the outskirts frequency component

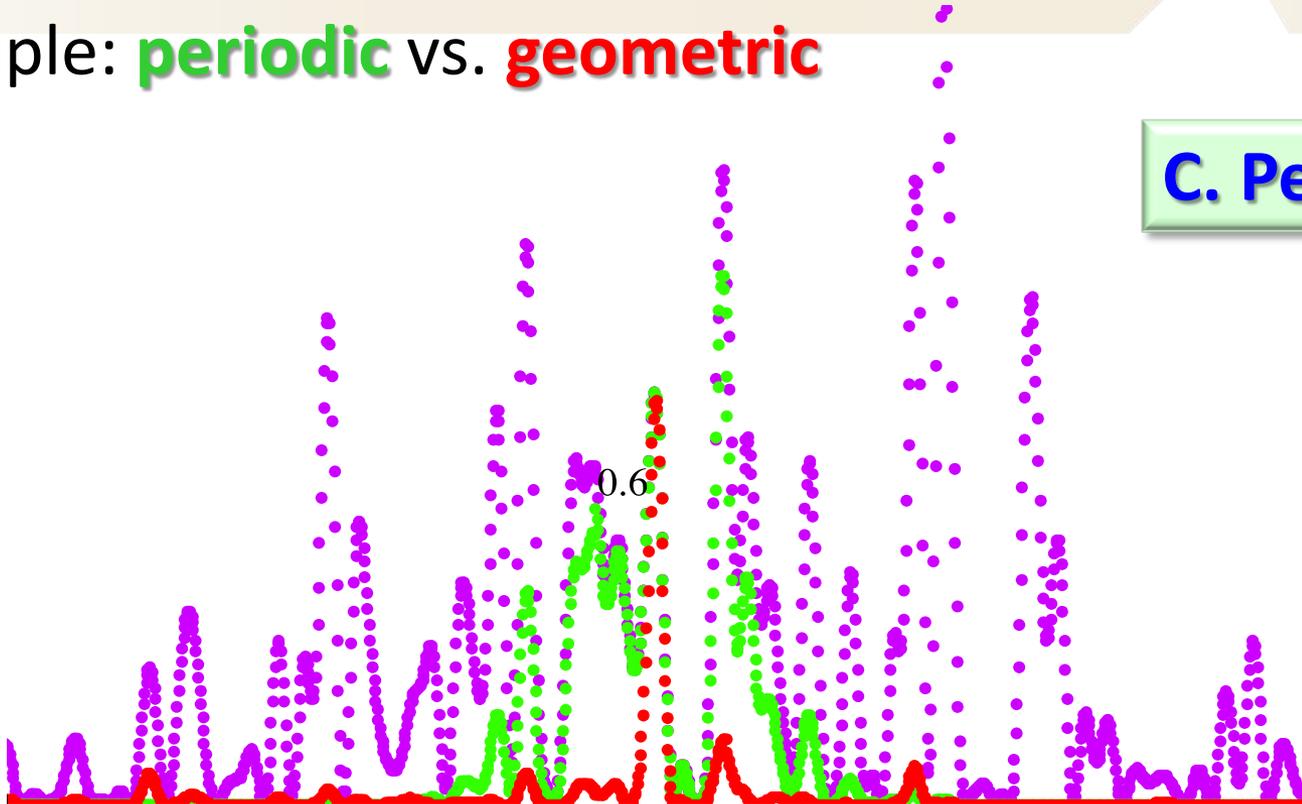
■ Geometric delay shrinks the central part of the frequency

## ■ We call this improved SASE (***i*SASE**)

# 1-D THEORY

■ Example: **periodic** vs. **geometric**

C. Pellegrini

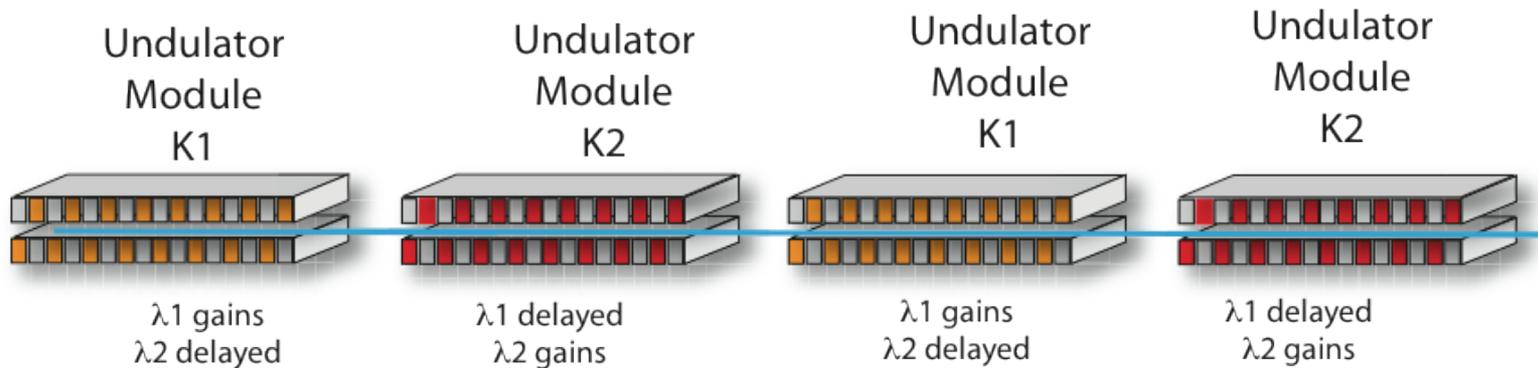


Spectra comparison for three cases:  $\delta = 0$  (in units of coherence length), SASE, purple, line width about 1 (in units of  $\rho$ );  $\delta = 3, 3, 3, 3, 3, 3, 3$ , iSASE, green, line width about 0.2;  $\delta = 1, 2, 4, 8, 16, 32, 64$ , iSASE, red, line width about 0.02.

# LCLS: PROOF-OF-PRINCIPLE EXPERIMENT

## Machine layout:

- First 5 undulator sections on-resonant to establish the FEL wavelength
- From 6<sup>th</sup> on, even number: 6, 8, ..., 30, and 32 largely detuned (can either be **random** or form a separate spectrum line → **two color**)
- From 6<sup>th</sup> on, odd number: 7, 9, ..., 31, and 33 on resonant

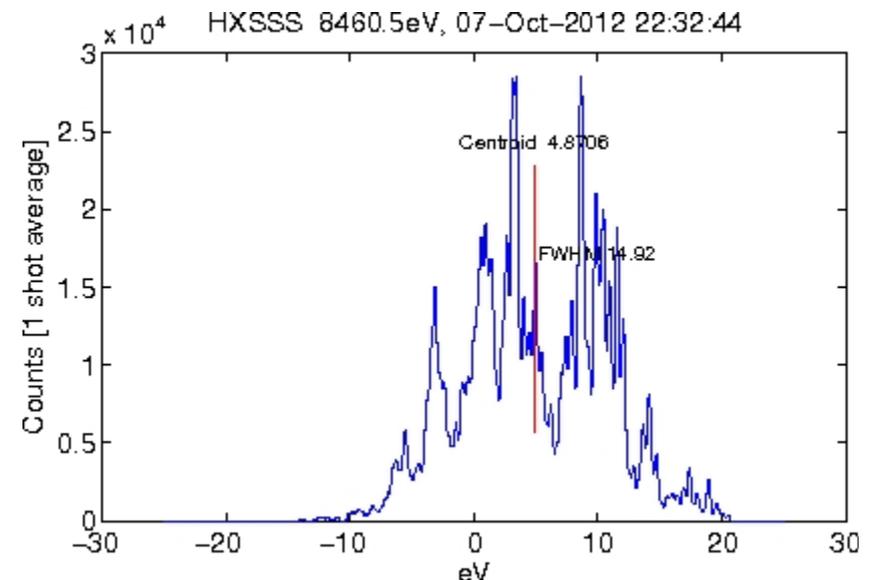
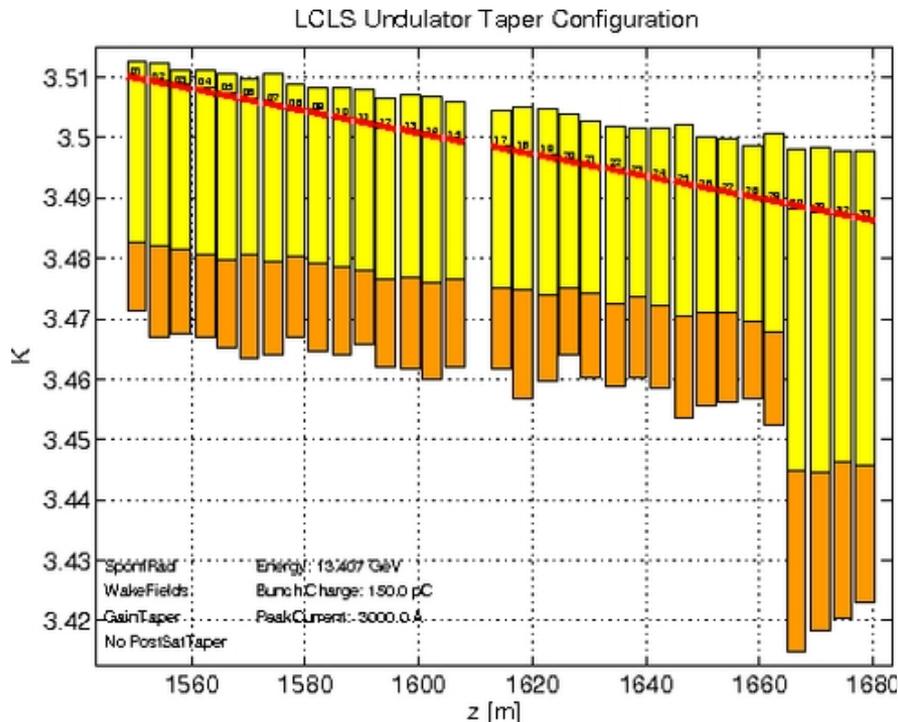


## Perform proof-of-principle experiment on LCLS for an improved SASE (iSASE)

- Electron bunch: 150 pC, compressed to  $\sim 3$  kA
- 8.45 keV FEE HXSSS
- 13.825 GeV electron energy

## ■ No-post saturation taper: 1.21 mJ

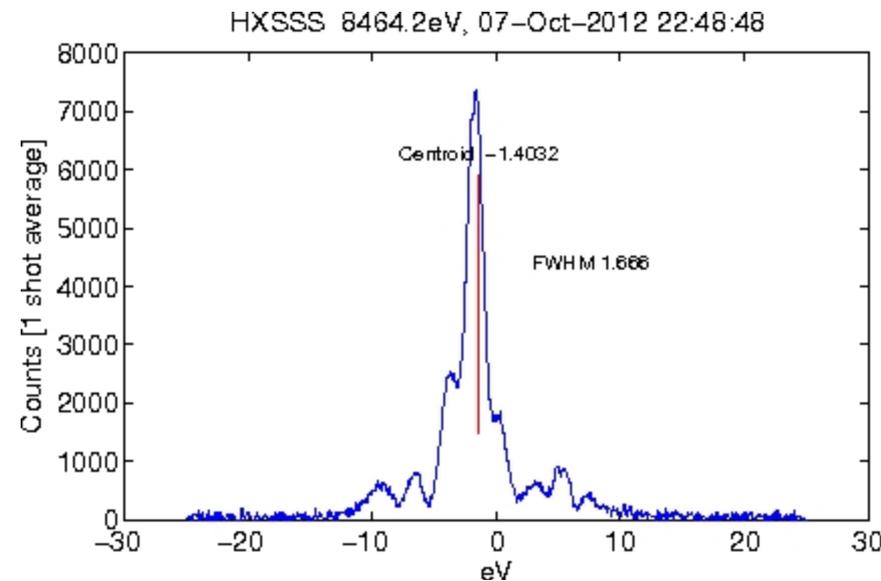
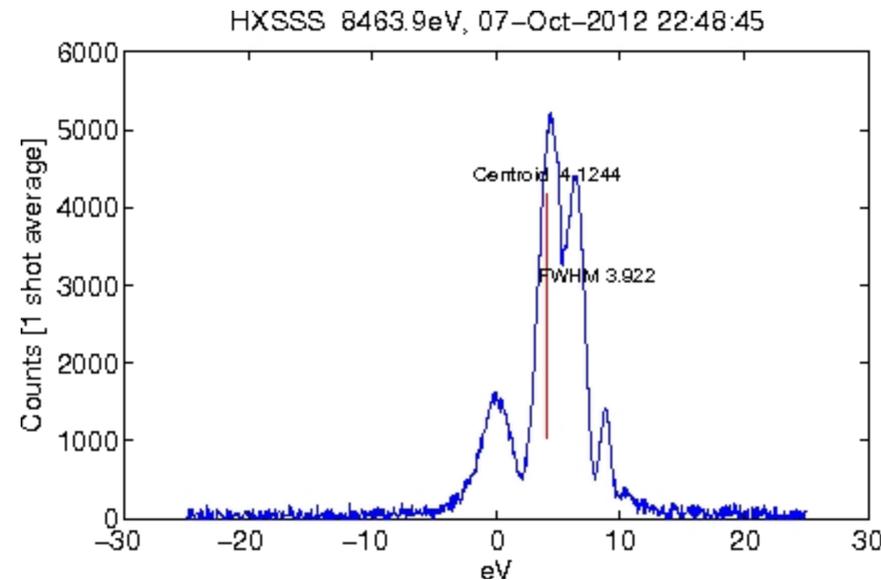
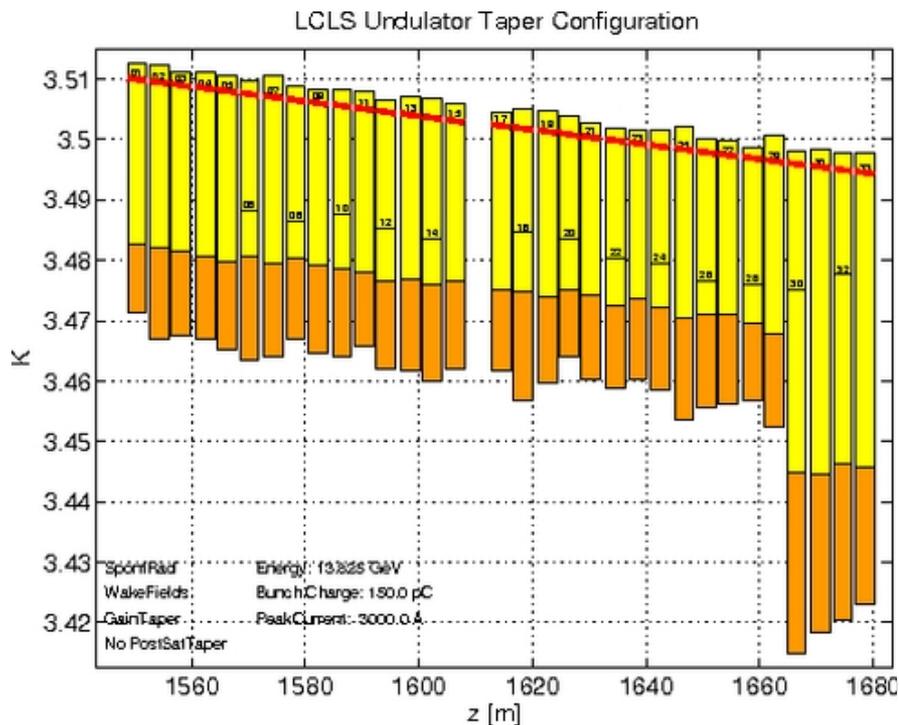
- Taper profile on left: optimized for the gain taper (-31 MeV), and spectrum on right (FWHM **15** eV, **limited** by the FEE HXSSS)



# iSASE: NARROW BANDWIDTH

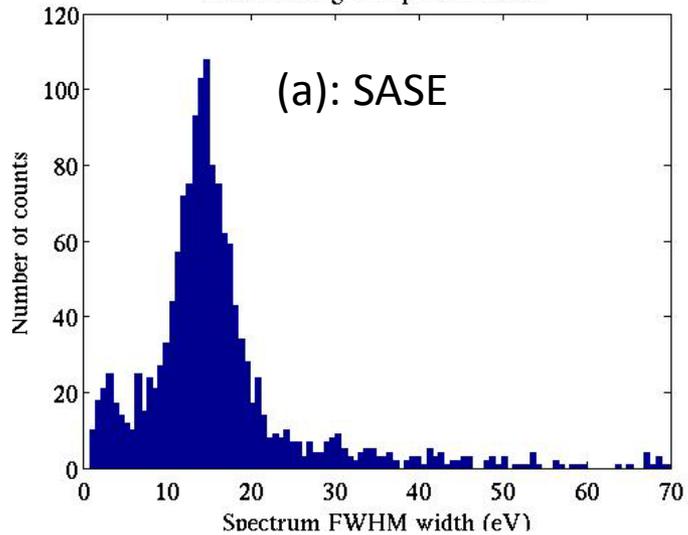
■ iSASE: 0.4 mJ

■ Taper profile on left, and spectrum on right (1.5 – 4 eV)

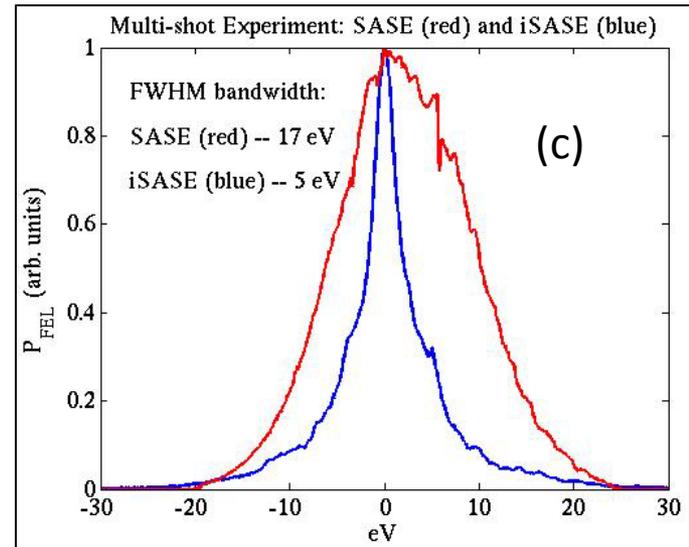
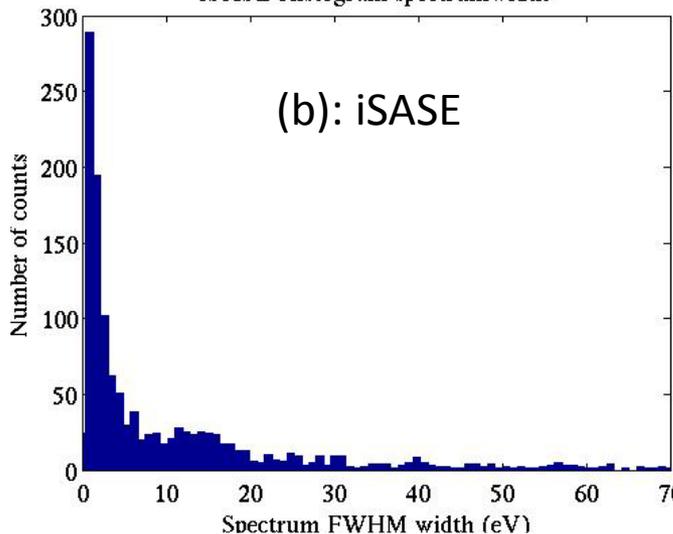


# iSASE FOR NARROW BANDWIDTH AND HIGH-POWER FELS

SASE Histogram spectrumwidth



iSASE Histogram spectrumwidth



- (a) Histogram of SASE FEL spectrum bandwidth;
- (b) Histogram of iSASE FEL spectrum bandwidth;
- (c) Comparison of the SASE FWHM bandwidth (17 eV) to the iSASE FWHM bandwidth (5 eV).

\* The iSASE spectrum bandwidth can be significantly reduced to approach transform-limited bandwidth with dedicated hardware improvement at LCLS/SLAC.

# Purified SASE

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 16, 010703 (2013)



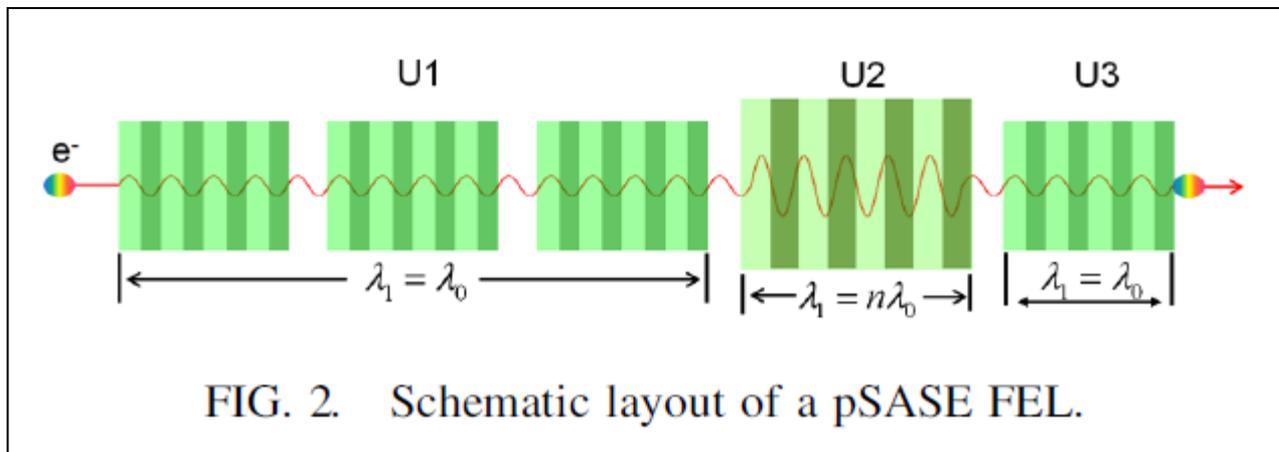
## Purified self-amplified spontaneous emission free-electron lasers with slippage-boosted filtering

Dao Xiang, Yuantao Ding, and Zhirong Huang

*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*

Haixiao Deng

*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, 201800, China*



## pSASE

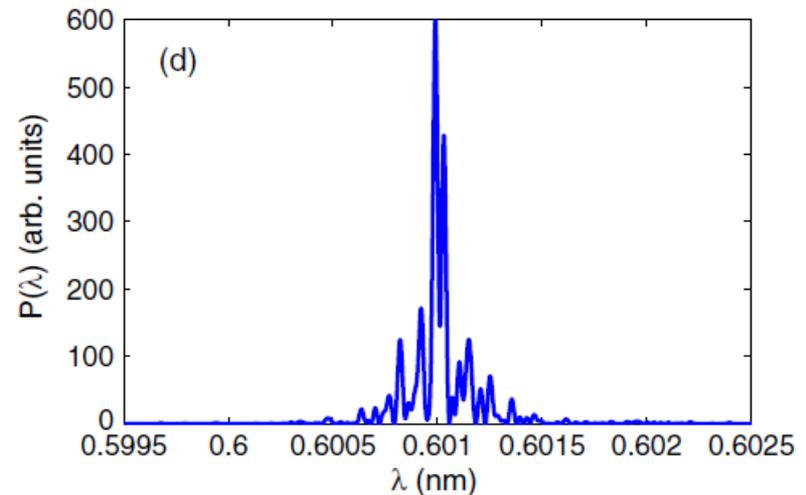
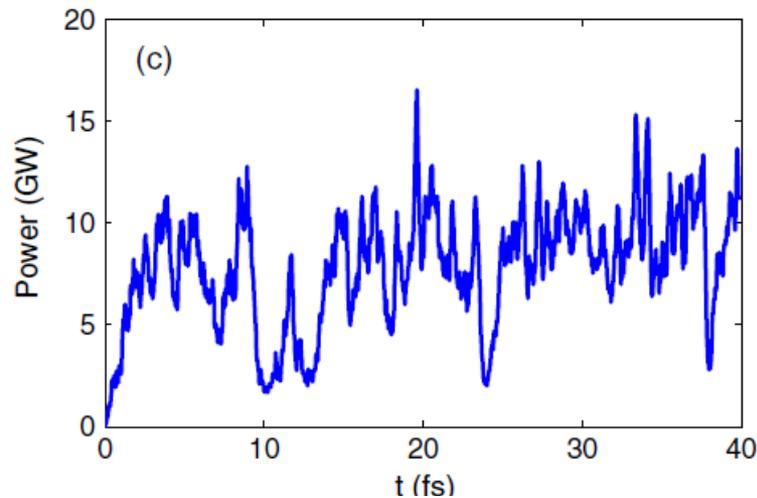
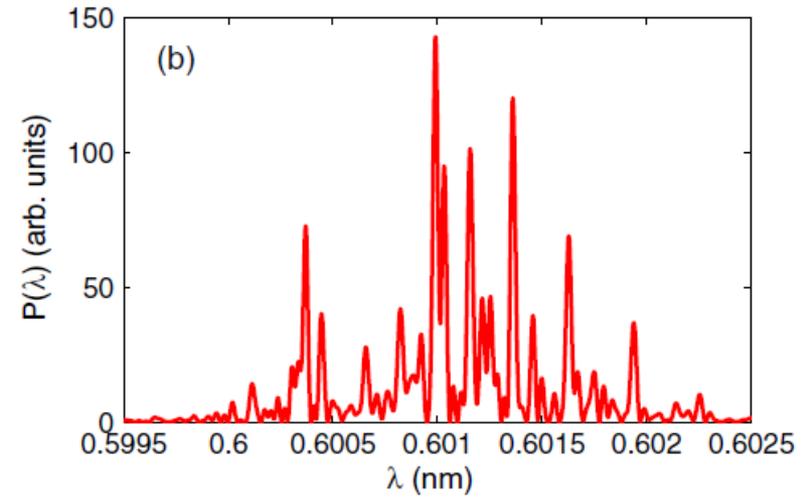
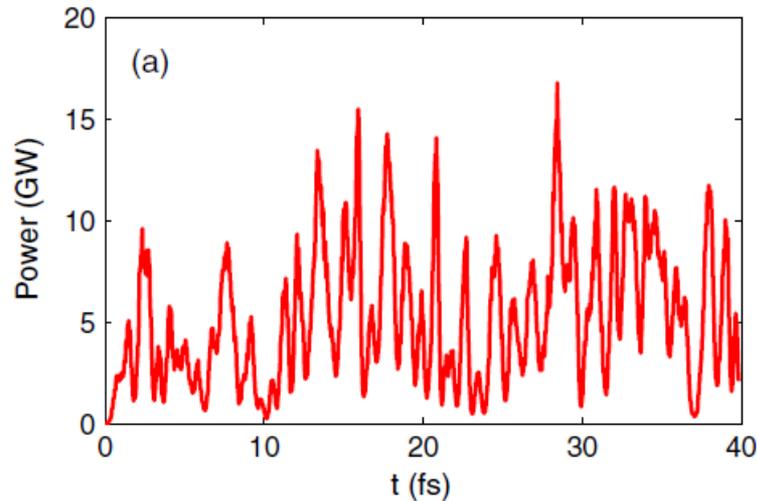


FIG. 6. Representative radiation power profiles and spectra for a standard SASE FEL [(a) and (b)] and a pSASE FEL [(c) and (d)]. The average power for both cases is about 7 GW and in the simulation the beam parameters, lattice functions, and initial shot noise are all the same. The spectral brightness is normalized to the peak spectral brightness at the exit of U1. 27

## Nonequal electron beam delays

PRL **110**, 134802 (2013)

PHYSICAL REVIEW LETTERS

week ending  
29 MARCH 2013

### Transform-Limited X-Ray Pulse Generation from a High-Brightness Self-Amplified Spontaneous-Emission Free-Electron Laser

B. W. J. McNeil,<sup>1,\*</sup> N. R. Thompson,<sup>1,2,†</sup> and D. J. Dunning<sup>1,2,‡</sup>

<sup>1</sup>*University of Strathclyde (SUPA), Glasgow G4 0NG, United Kingdom*

<sup>2</sup>*ASTeC, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom*

(Received 23 December 2012; published 26 March 2013)

$$S_n = \frac{P_n S_1}{2} \text{ with } P_n \text{ a series of primes and } P_1=2.$$

## Non-equal electron beam delays

$$S_n = \frac{P_n S_1}{2} \text{ with } P_n \text{ a series of primes and } P_1=2.$$

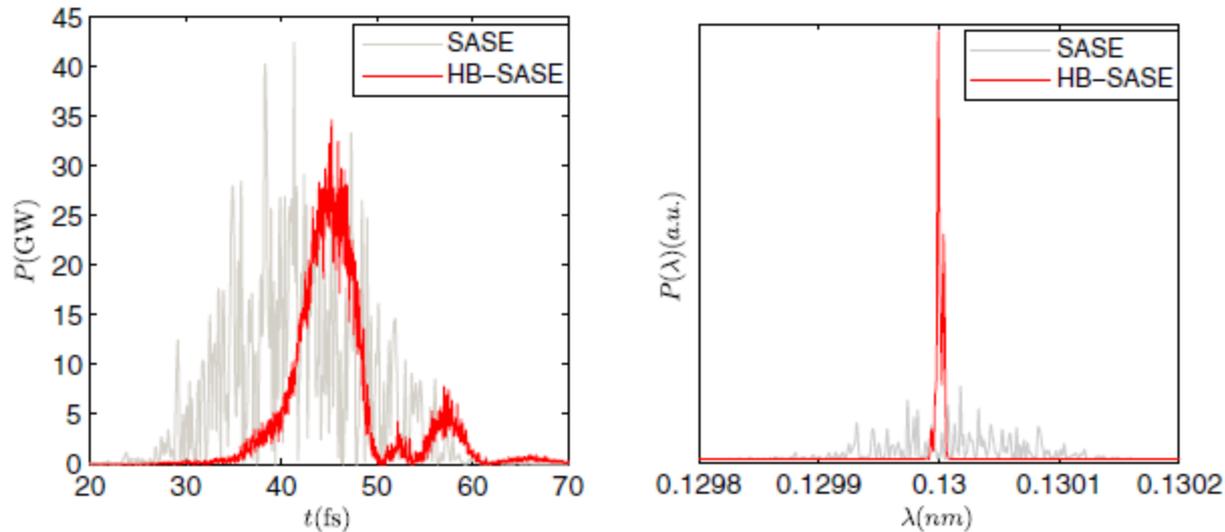


FIG. 3 (color online). Hard x-ray example at  $\lambda_r = 0.13$  nm: the pulse profiles and spectra of SASE and HB-SASE.

# PROSPECTS AND DISCUSSION

- Due to very limited slippage, SASE FEL has limited temporal coherence
- Self-seeding and slippage enhanced approaches (iSASE, pSASE, HB-SASE) are approaches to achieve comparable spectral purity, while taking advantage of the relatively simpler SASE hardware configuration.
  - LCLS Self-seeding and iSASE experimental results are very encouraging

# ACKNOWLEDGEMENT

- Thanks to the committee for inviting me
- Thanks to LCLS team for allowing me to present some recent (unpublished) results
- Thanks for your attention