Generating Femtosecond to Sub-Femtosecond X-ray pulses in free-electron lasers

Yuantao Ding

8/25/2015

SLAC National Accelerator Laboratory

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Outline

- Introduction/motivation
- **SASE FELs:**
  - ***Few-fs* x-rays with emittance-spoiling foil;**
  - ***Sub-fs* x-rays from nonlinear compression;**
- Self-seeded FELs:
  - Few-fs from a chirped bunch or delay;
  - Sub-fs with a modulated chirped bunch?
- Summary

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Motivation

- X-rays from 4th generation light sources (FELs) are typically about few 10s to 100s of femtosecond, about 3 orders shorter than 3rd generation storage ring pulses;
- This provides a fantastic tool for ultrafast photon science studies, such as measuring the molecular motions in transition states;
- **However**, even shorter pulses, sub-fs or attosecond pulses, are also highly interested, tracing electronic motion?

In Neils Bohr's 1913 model of the Hydrogen atom it takes about **150 as** for an electron to orbit the proton.

– *Atomic transient recorder,* **Nature, 2004**

How to make it shorter

- Reduce charge, → 1 pC
  - Rosenzweig, Reiche et al., NIM A 2008 (1pC). Ding et al., PRL 2009 (20pC);
- Laser-based manipulation
  - Zholents and Fawley, PRL 2004;
  - Saldin, Schneidmiller and Yurkov, Opt. Commun. 2004;
  - Zholents and Penn, PRSTAB 2005 (ESASE)
  - Saldin, Schneidmiller and Yurkov, PRSTAB 2006 (chirp + taper)
  - Zholents and Zolotorev, New J. Phys. 2008 (angular modulation)
  - Ding et al. PRSTAB 2009 (two-color ESASE)
  - Xiang, Huang and Stupakov, PRSTAB 2009 (ECHO based)
  - Qiang and Wu, APL 2011 (modulation compression)
  - **A review paper: Beam by design, Hemsing, Stupakov, Xiang and Zholents, Rev. Mod. Phy. 2014.**
- Slotted-foil
  - Emma et al. PRL 2004
  - Prat and Reiche, PRL 2015 (Foil and Delay)
- Others
  - Schroeder et al., NIM A 2002. (chirp + mono)
  - Tanaka, PRL 2013 (ESASE, Foil, and Delay); Tanaka, PRL 2015 (MCHG)
  - Thompson and McNeil, PRL 2008; Kur et al, New J. Phys. 2011 (mode locked trains)
  - Feng, Chen and Zhao, PRSTAB 2012; Dunning, McNeil and Thompson, PRL 2013 (mode locked trains)
  - Huang, Ding , Huang and Qiang, PRSTAB 2014 (nonlinear compression)
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  - .....

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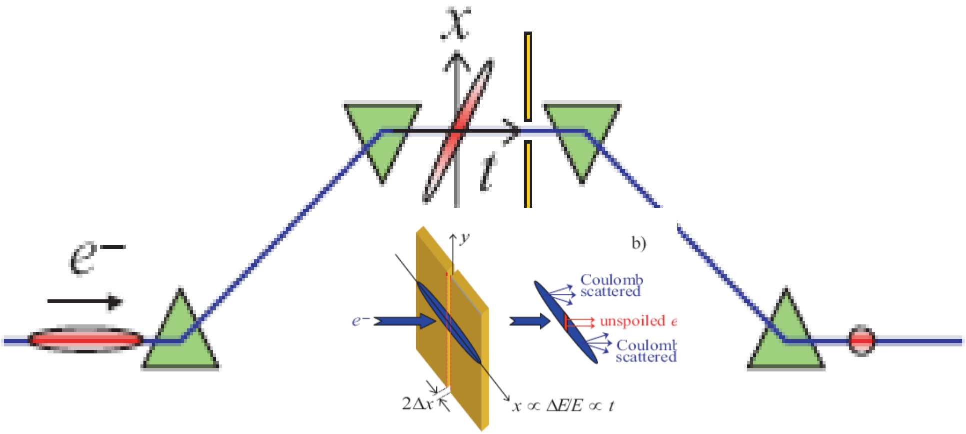
*We will focus on recent **experimental** studies at LCLS, slotted foil, nonlinear compression, etc.*

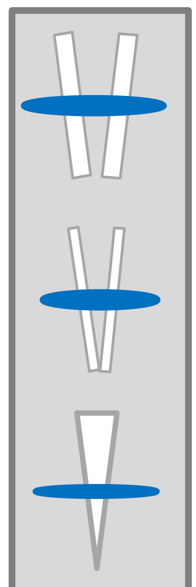
(1) Slotted foil mode

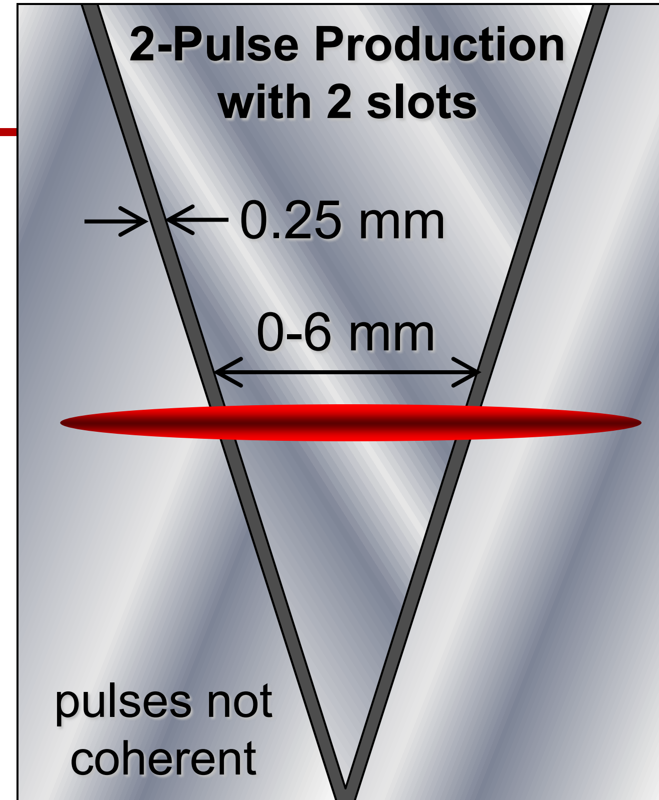
1. Emittance-spoiling foil concept

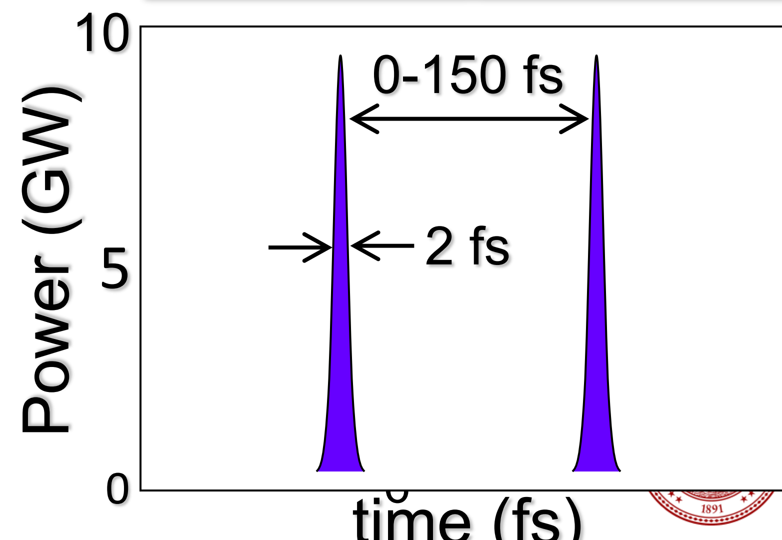


2. E selection correlated with t

3. Generate ultrashort single or double e-bunches for FEL







P. Emma, et al, PRL 92, 074801 (2004)

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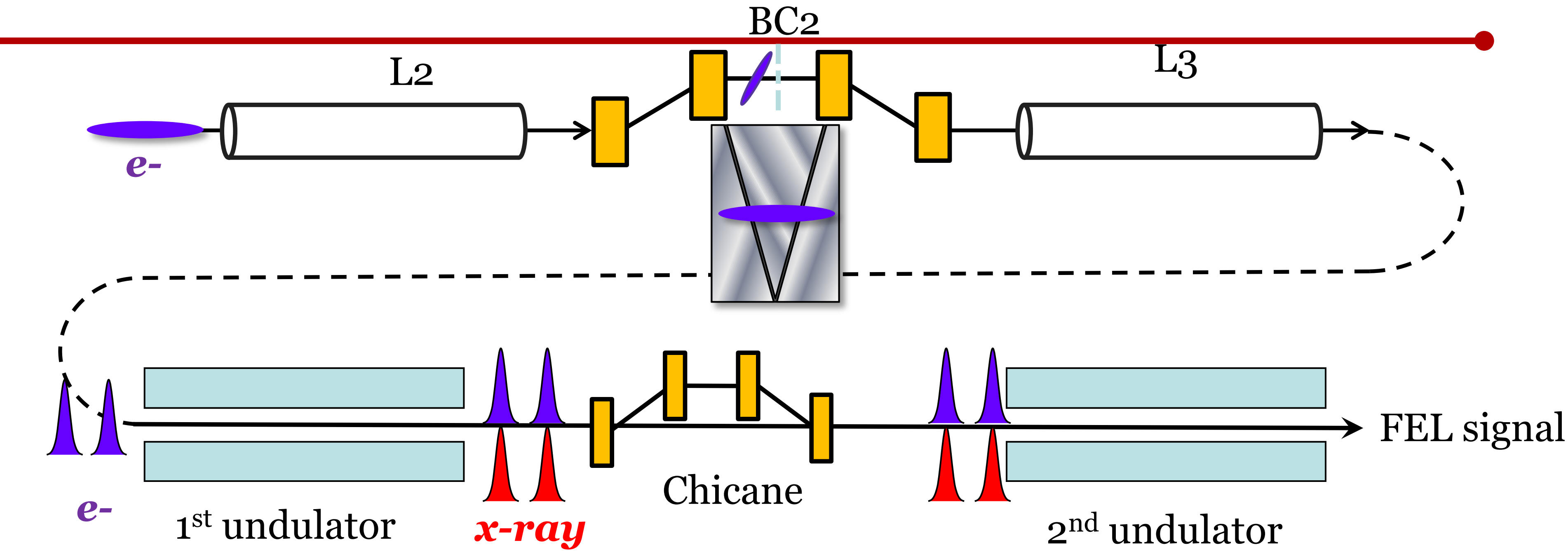
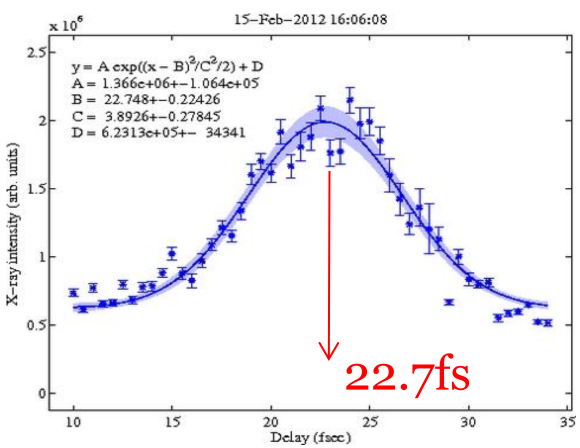
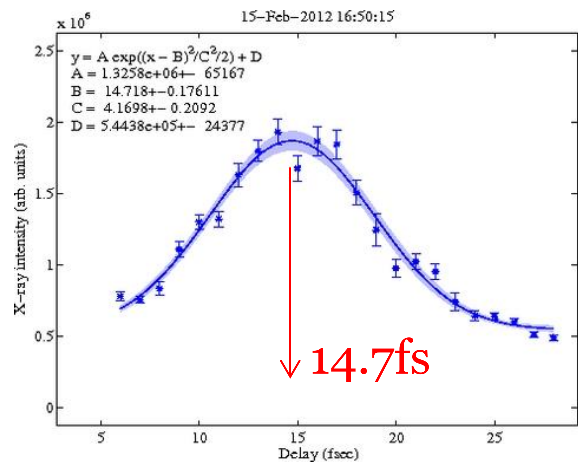
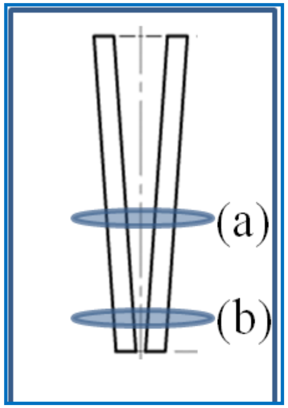
*Cross-correlation** measurements for slotted-foil case









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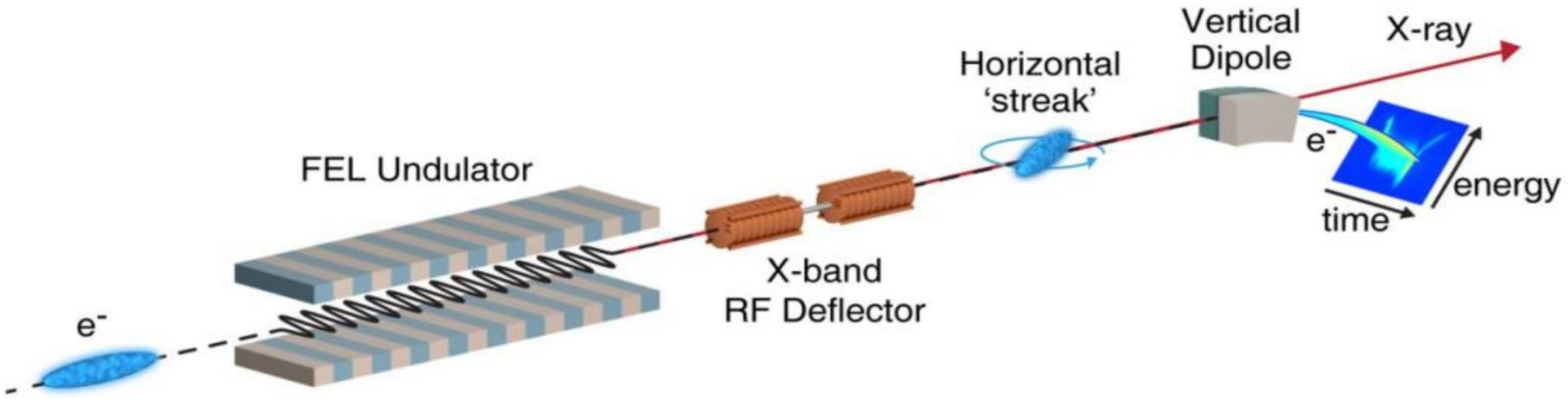
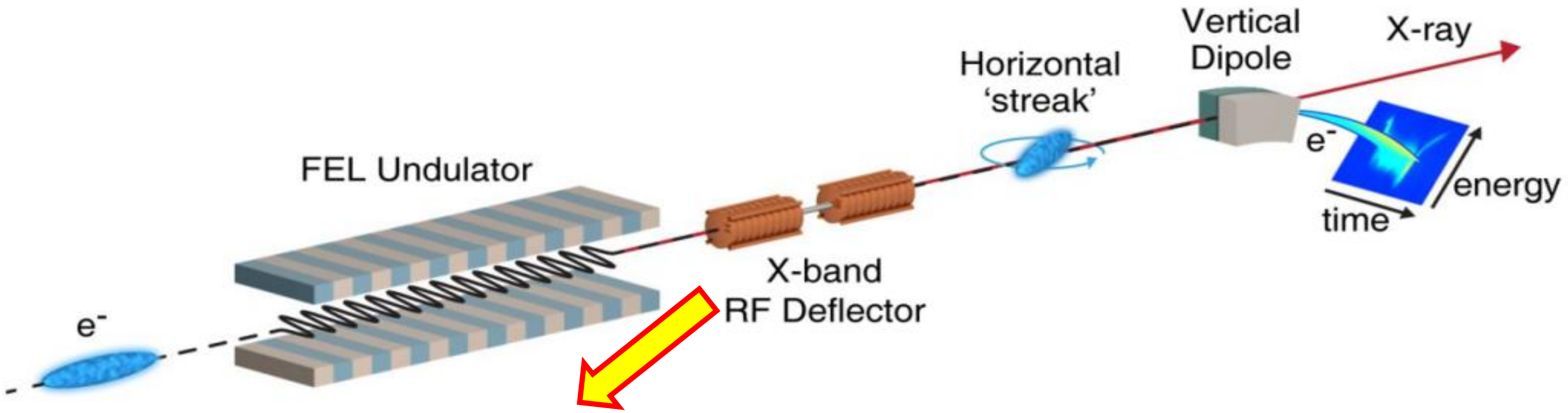
*Geloni et al.,DESY 10-008

Y. Ding, et al, PRL 109, 254802 (2012)
C. Feng, FEL12 Talk, THOC04.

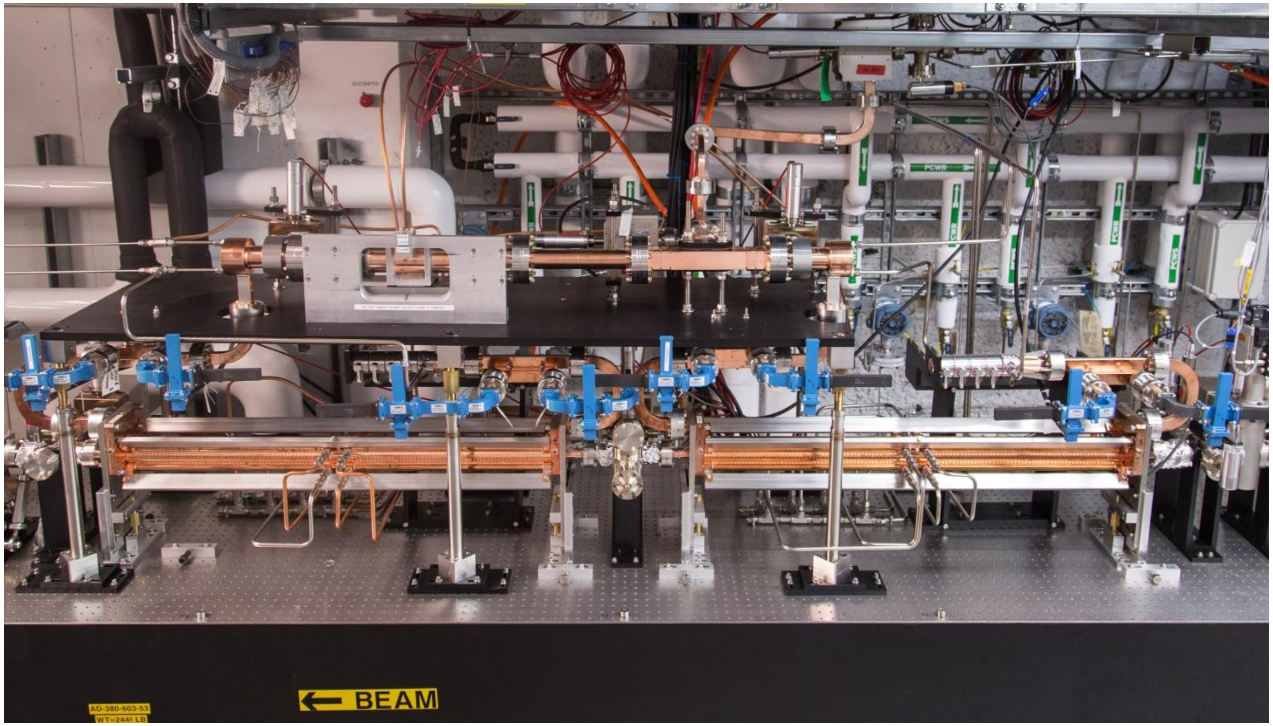
XTCAV: Electron and X-ray temporal diagnostic



XTCAV: Electron and X-ray temporal diagnostic



Installed at the LCLS beamline (May 2013)



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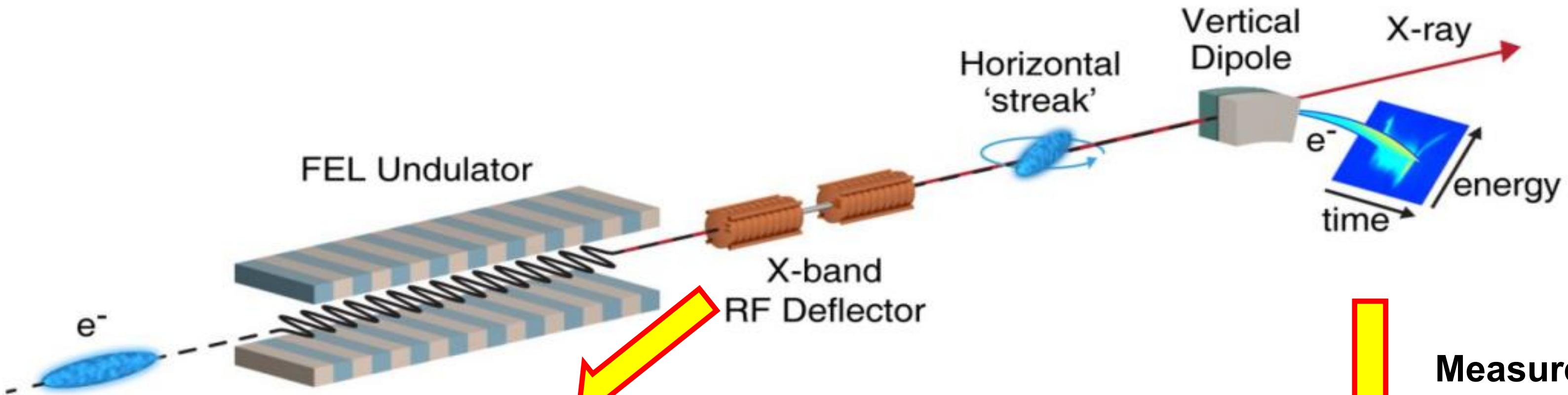

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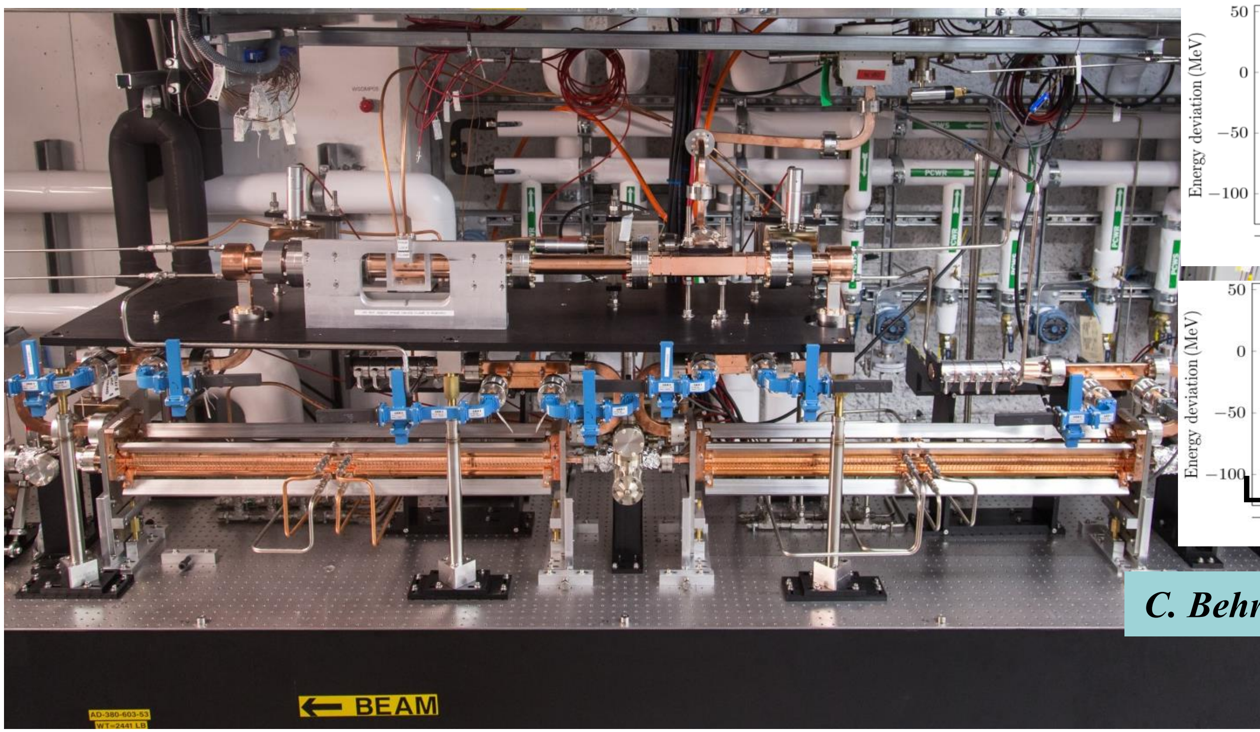
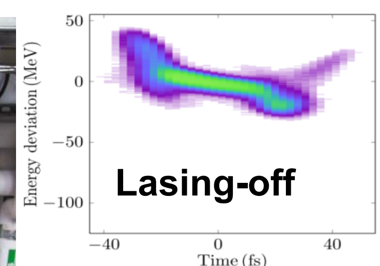
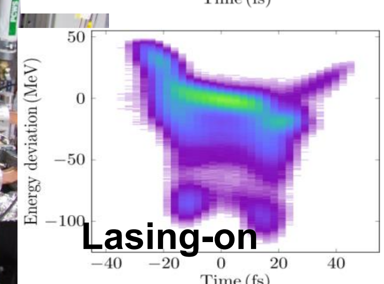
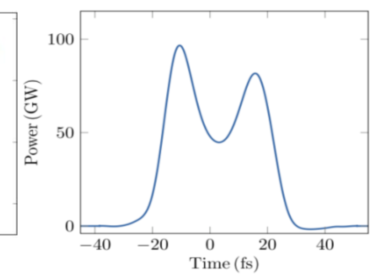


Measurement examples



@10keV



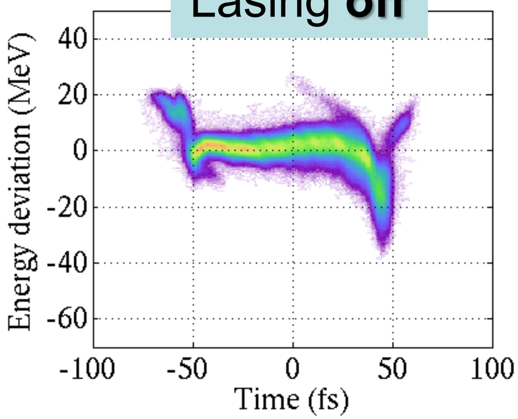


C. Behrens et al., Nat. Commun. 5:3762 (2014).

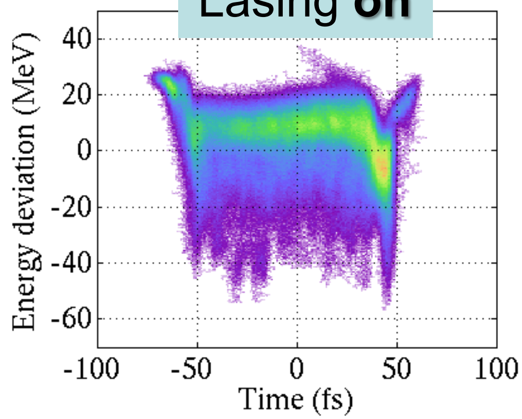
XTCAV measures the lasing, and spoiling

Regular SASE,
Without foil

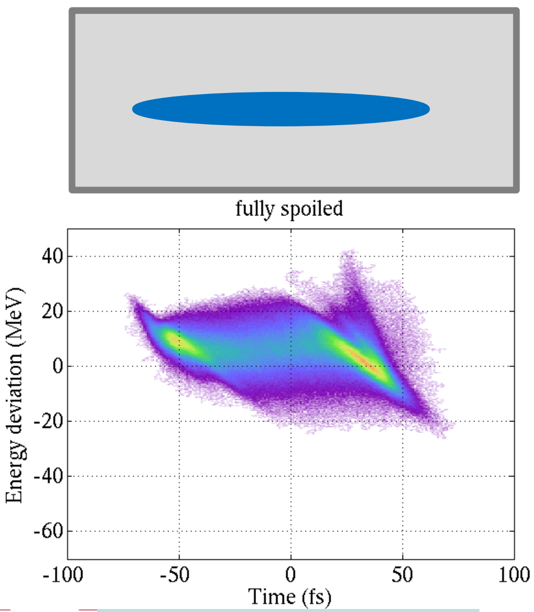
Lasing **off**



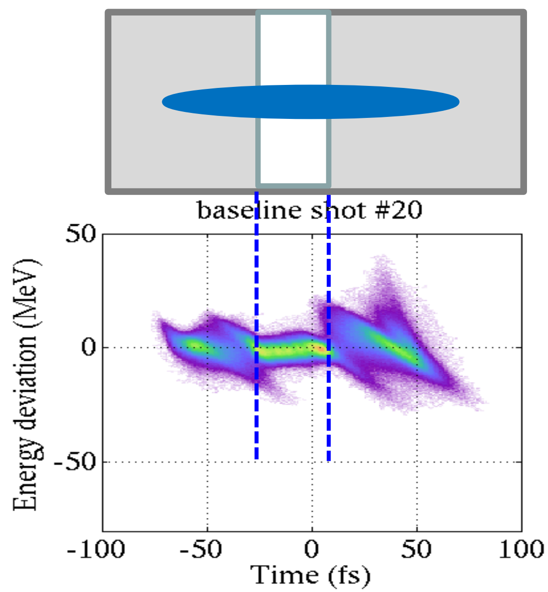
Lasing **on**



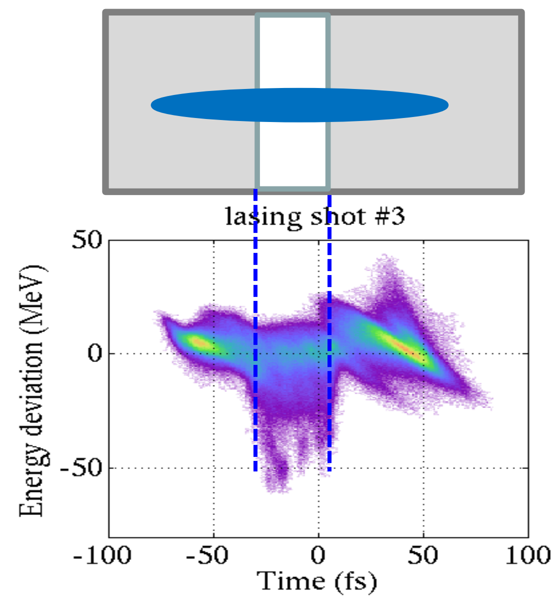
With foil



fully spoiled, no slot

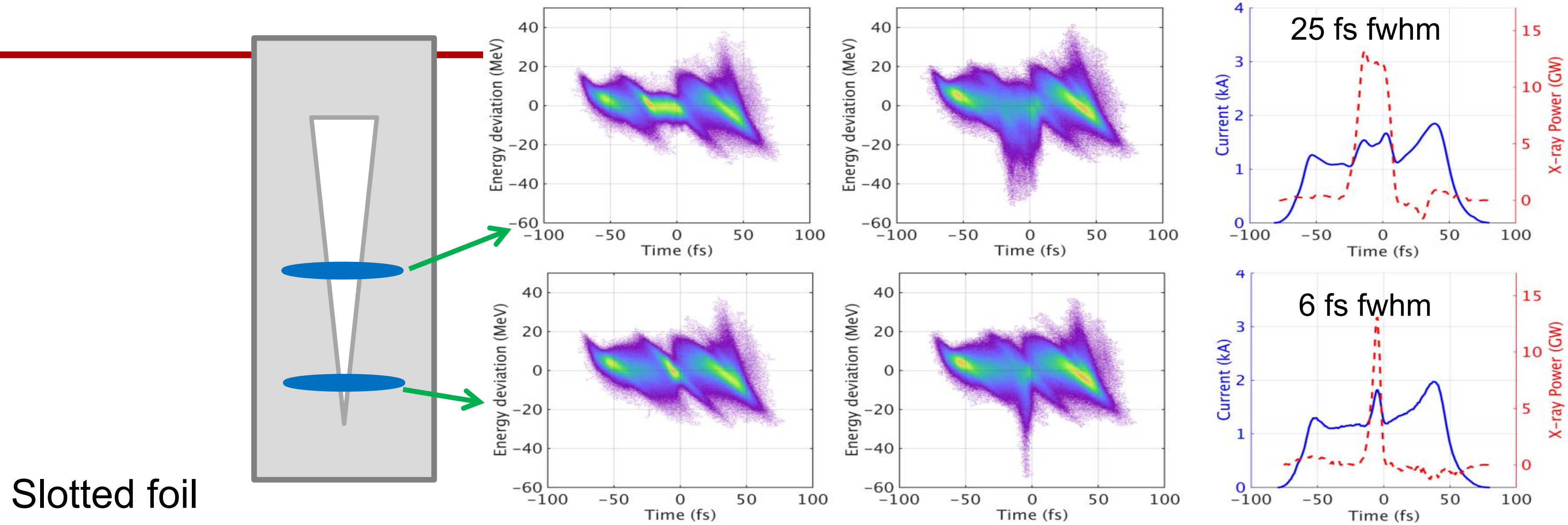


Lasing **off**, single slot



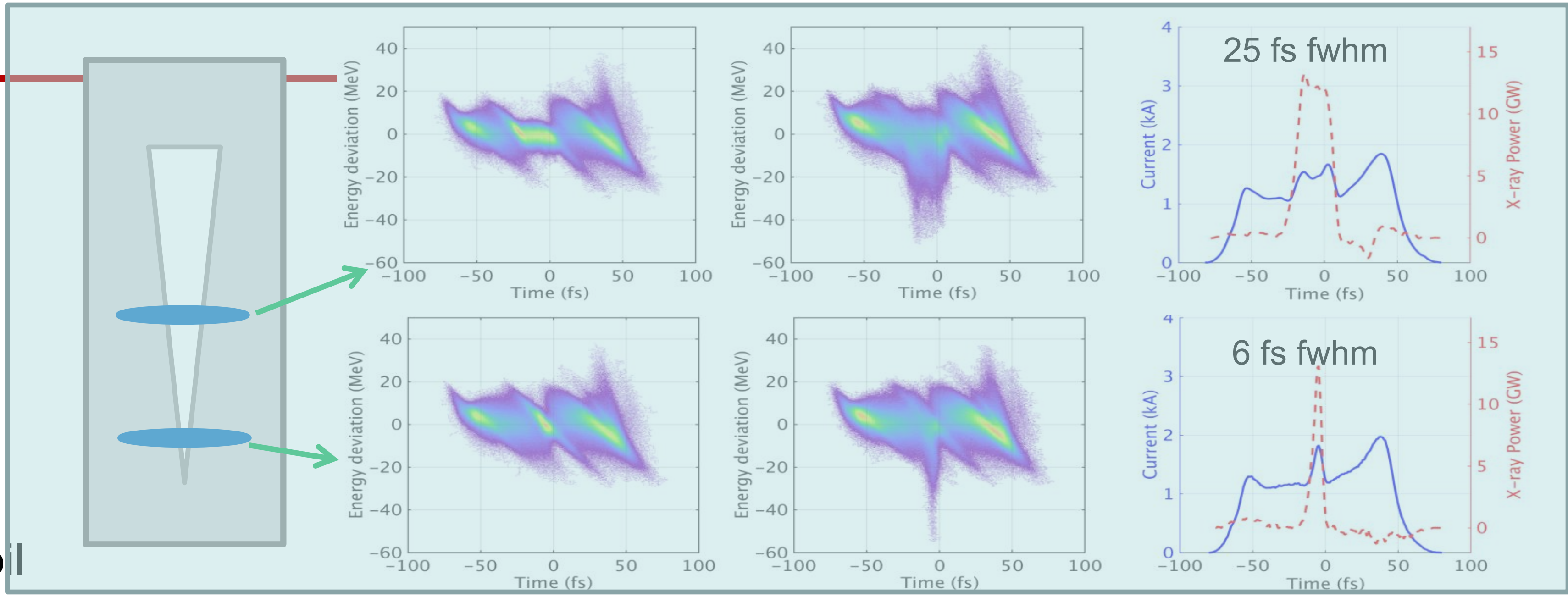
Lasing **on**, single slot

Flexible control of duration or delay



Slotted foil measurements with 180pC, 4.5GeV.

Flexible control of duration or delay



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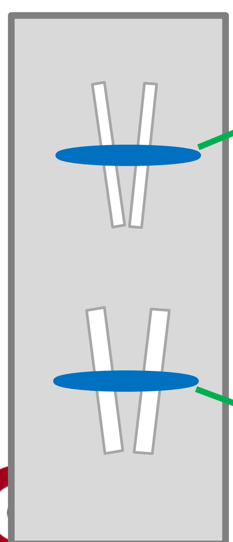

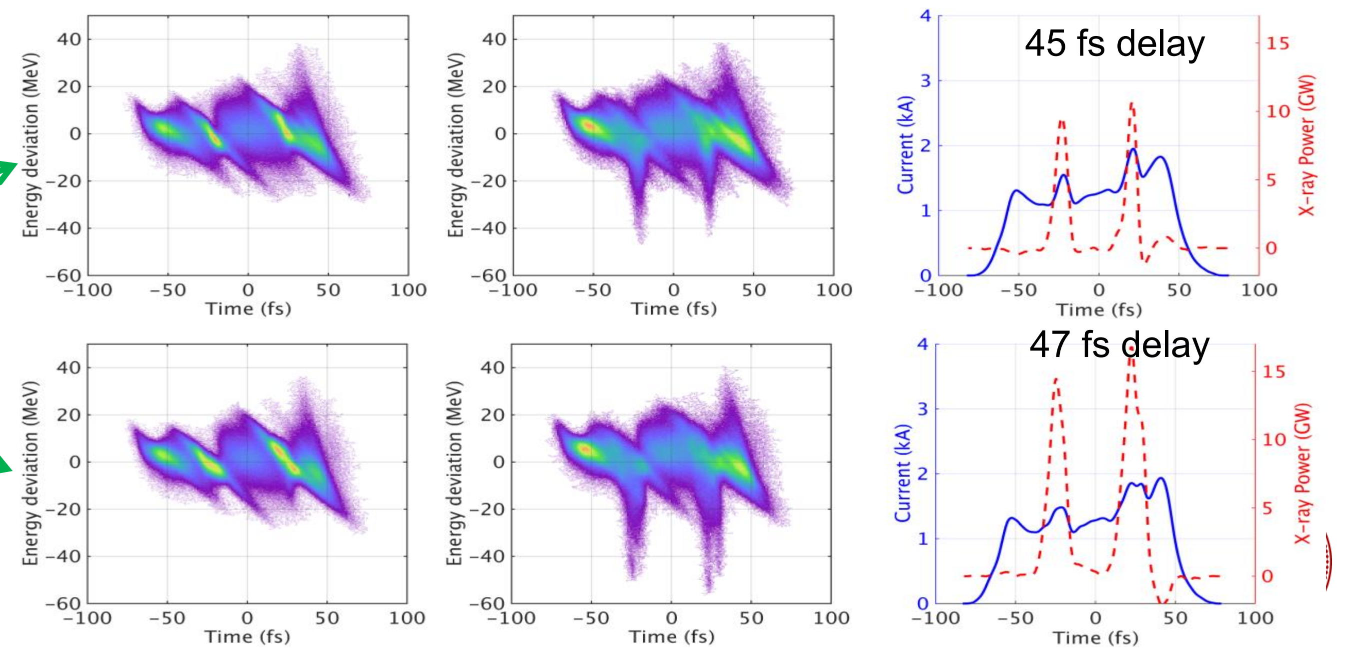

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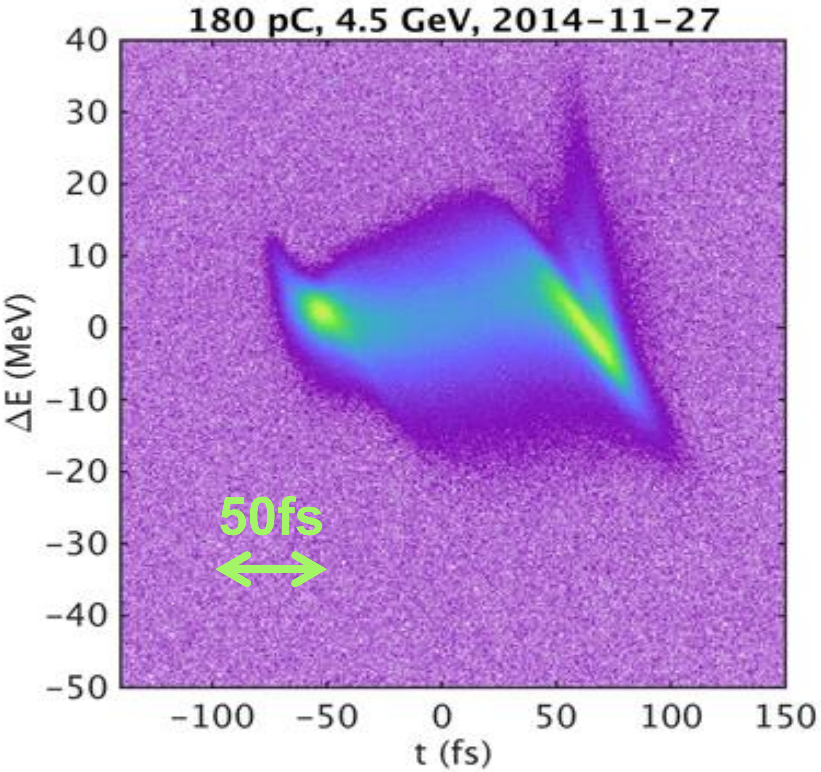
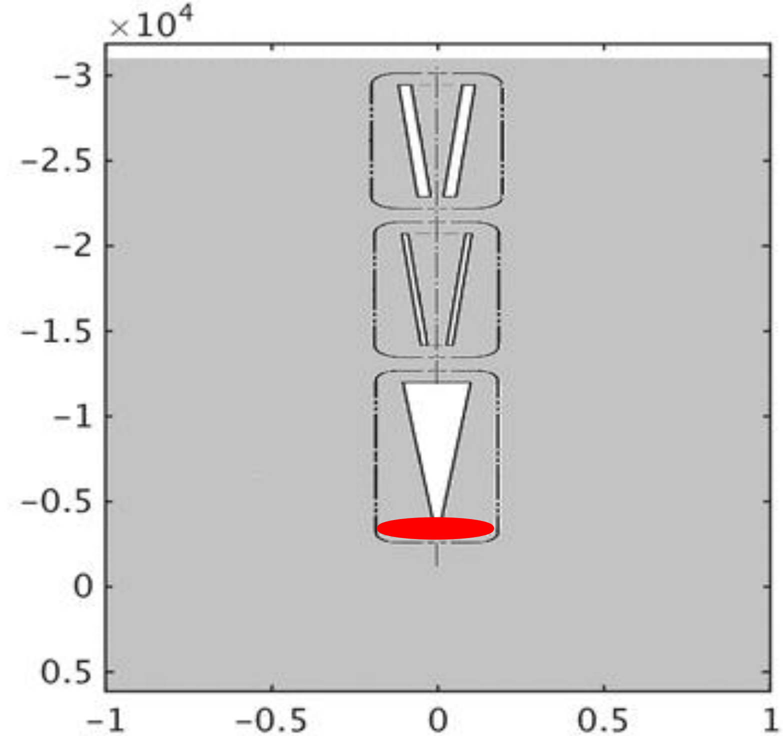
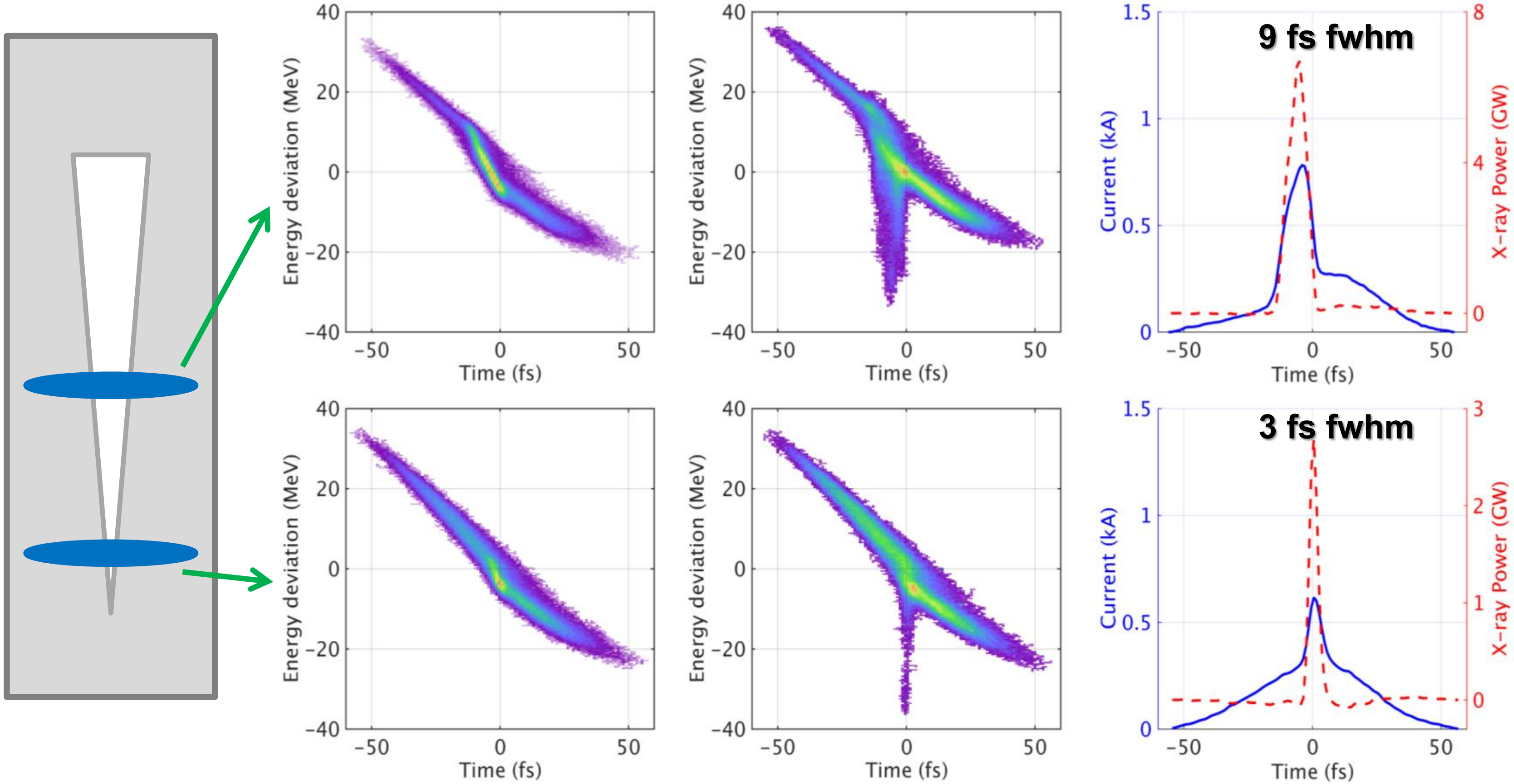
Measurements of pulse control at LCLS





180pC, 4.5GeV, SASE; data on 11/27/2014

Measurements for **low charge** + slotted foil mode

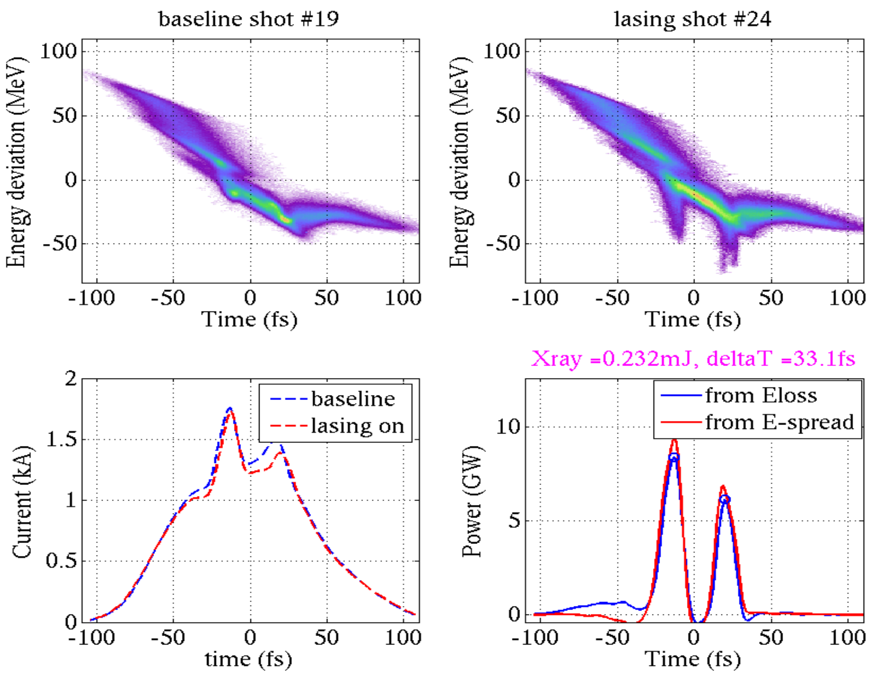


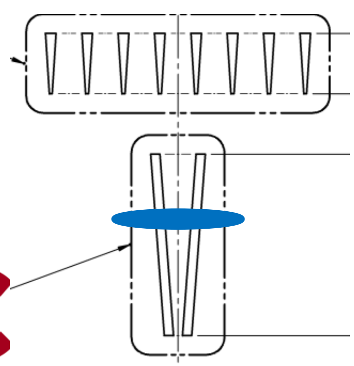
20pC, 4.6GeV, **over-compression** mode, SASE

(Ding et al., SLAC-PUB-16312)

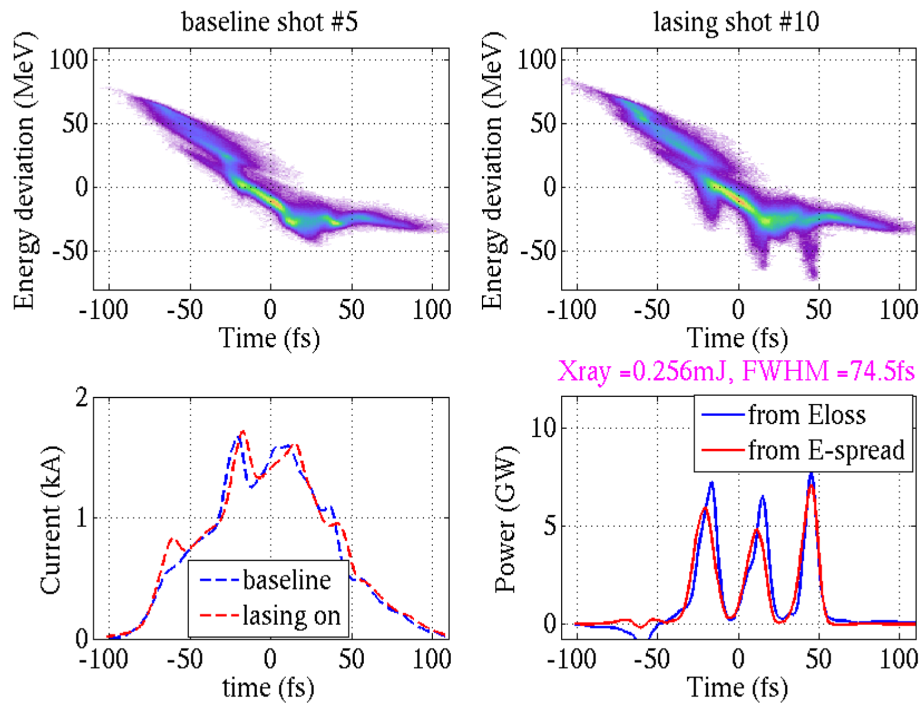
Other features with foil (chirped bunch, multicolors)

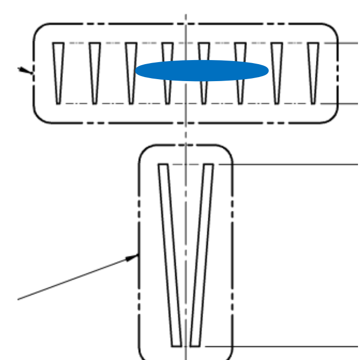
Two-color, twin pulses





Three-color, triple pulses

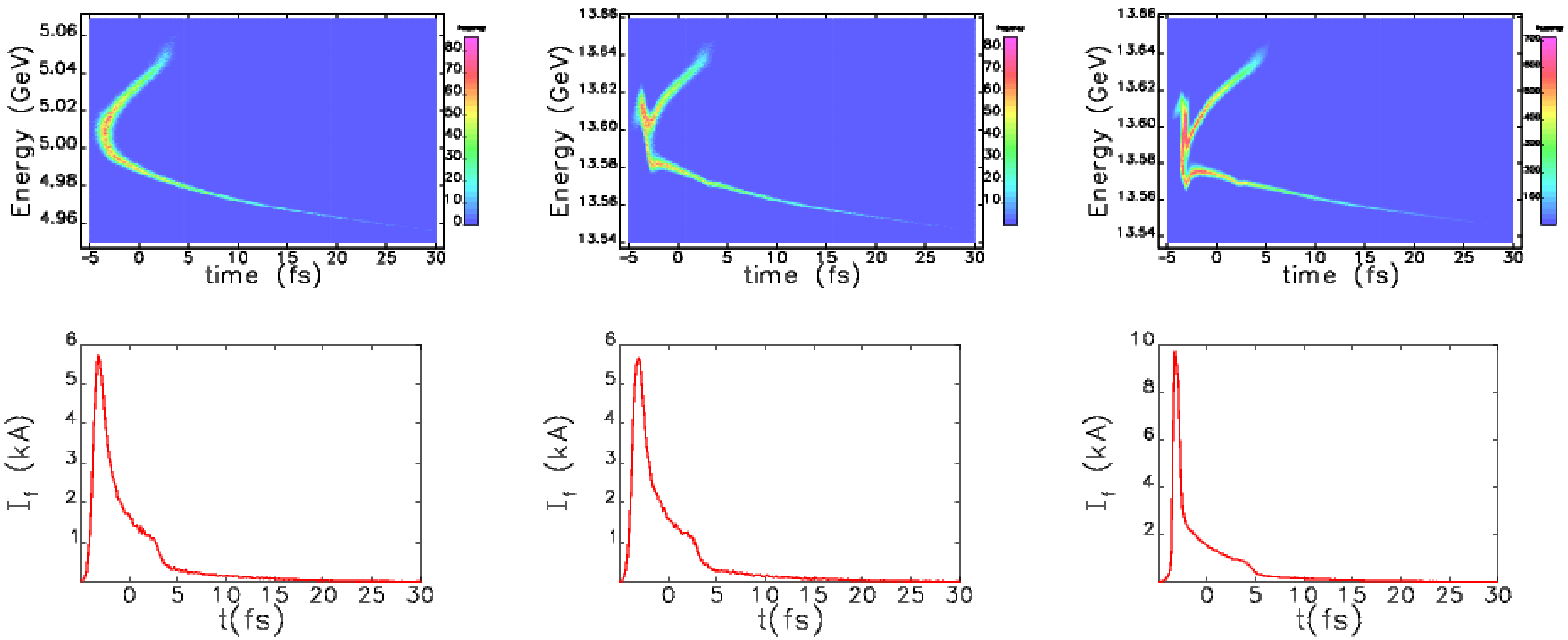




(2) Sub-fs X-rays from nonlinear compression

The idea: lower harmonic cavity (L1X) amplitude and fully compress the core part of the bunch to produce a stable single current horn.

- based on existing hardware;
- generate > 8 kA peak current;
- reverse taper to control lasing.

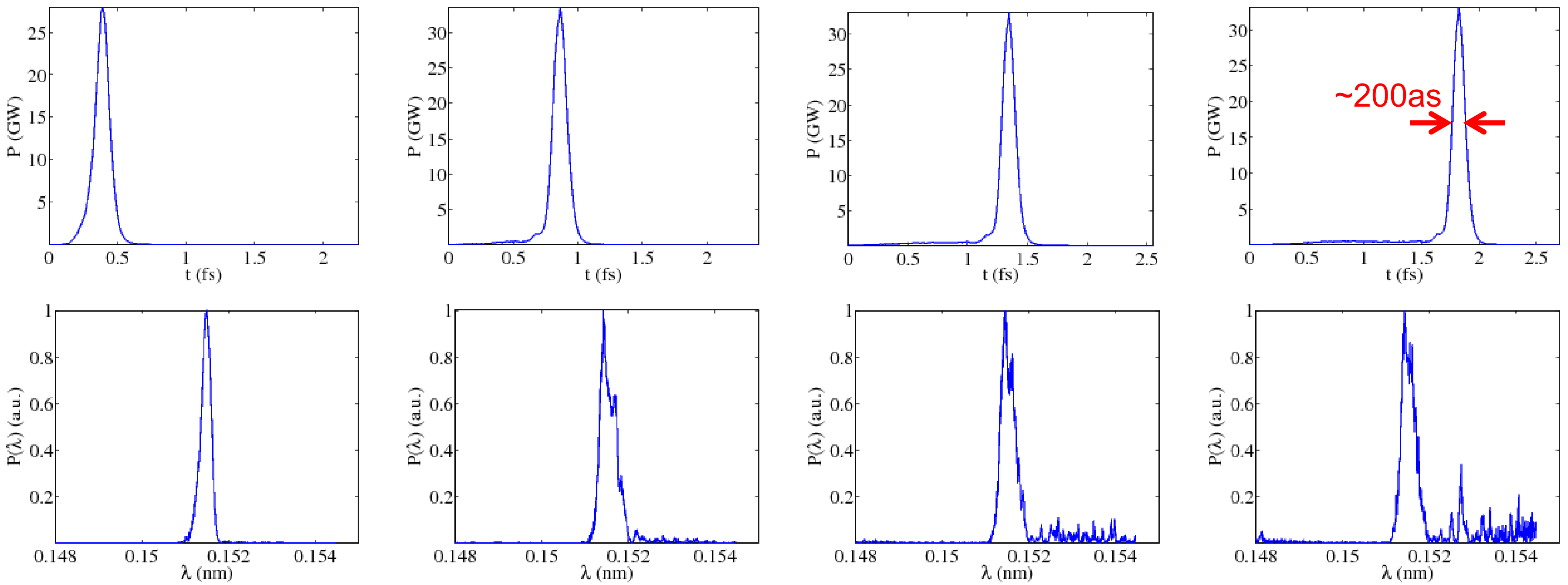


(a) BC2END (b) L3END (c) UNDBEG

(S. Huang, Y. Ding, Z. Huang and J. Qiang, PRSTAB 17, 120703, 2014)

~200as hard X-ray FEL pulses (simulations)

- FEL Simulations used Start-to-end electron beam.
- LSC inside the undulator was included.
- A reverse taper of -1% from 20m to 132m was used.



(a) 60 m (b) 80 m (c) 100 m (d) 120 m

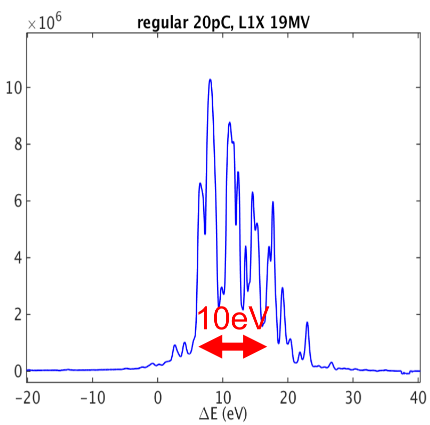
(S. Huang, Y. Ding, Z. Huang and J. Qiang, PRSTAB 17, 120703, 2014)

Experimental measurements at LCLS

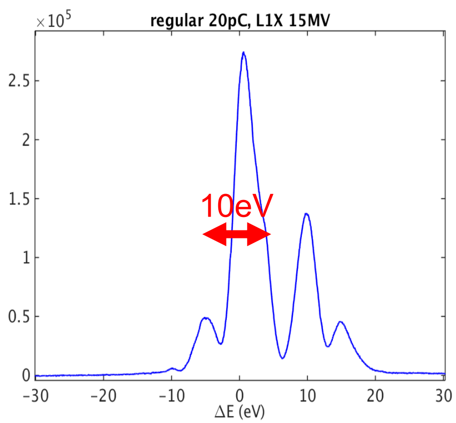
20pC, 9 keV, nonlinear compression;
L1X voltage changed from 19 MV to 15, 12 and 10 MV;
Used the single-shot hard x-ray spectrometer for diagnostic [1].

Measured single-shot x-ray spectrum vs L1X voltage

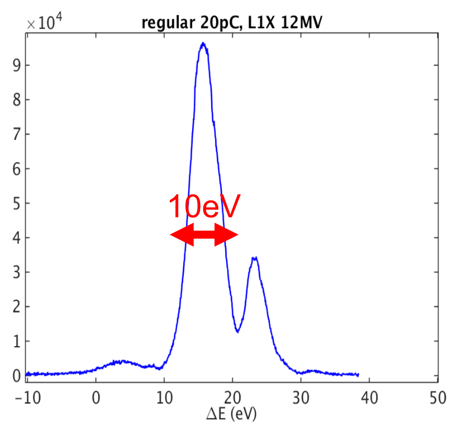
19MV (nominal)



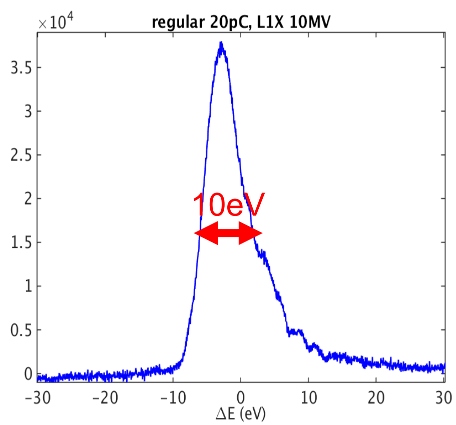
15MV



12MV



10MV



(data on 06/16/2015)

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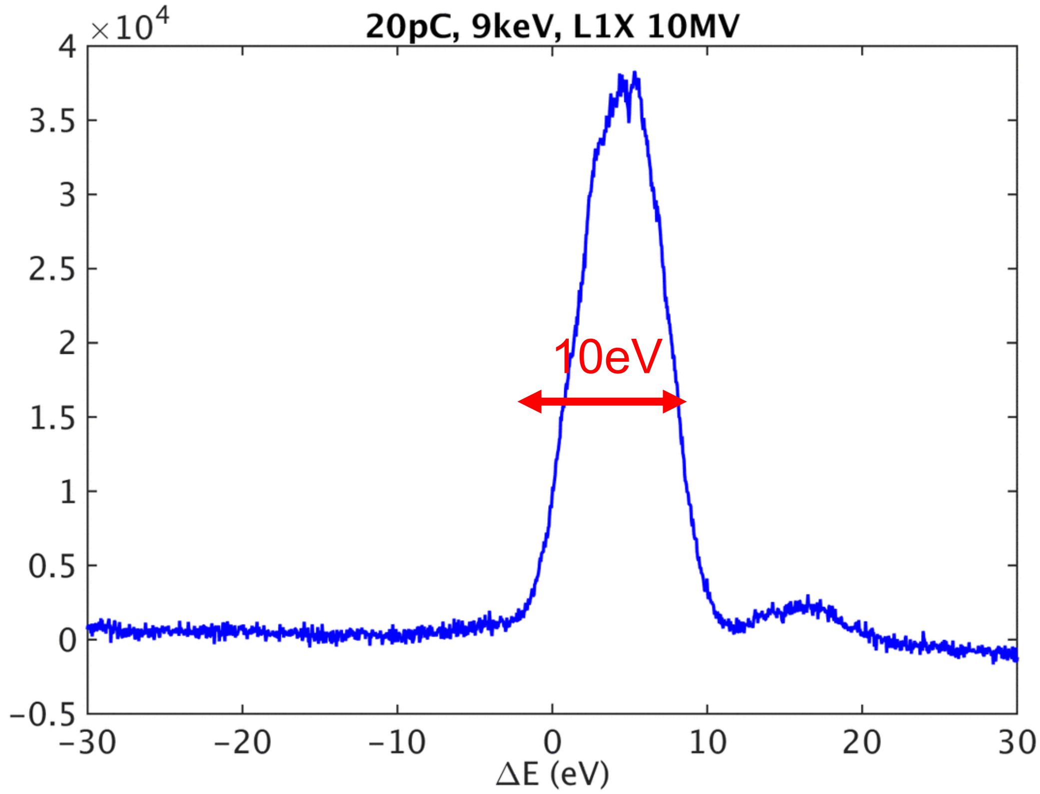
[1]: D. Zhu et al., APL 101, 034103, 2012.

Nonlinear compression with L1X 10 MV

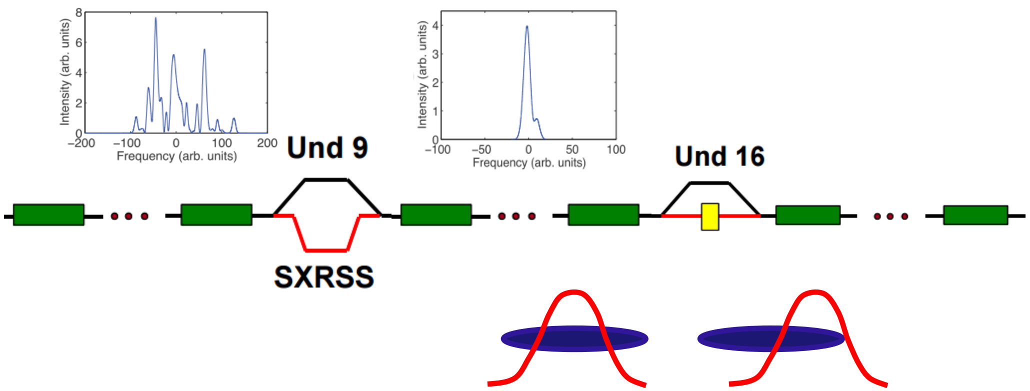
20 pC, 9 keV;
L1X = 10 MV, -170deg;
Reverse taper;
Average about 6 uJ;

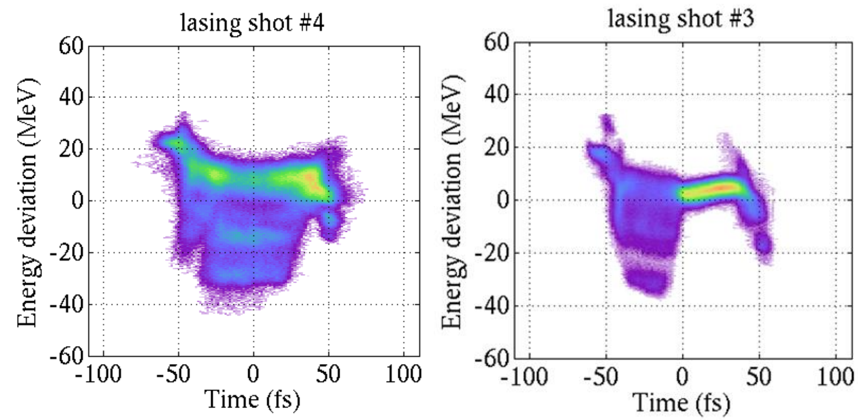


(**Measured** data on 06/16/2015)

(3) Shorter pulse in self-seeding mode

- Use a delay chicane (D. Ratner)

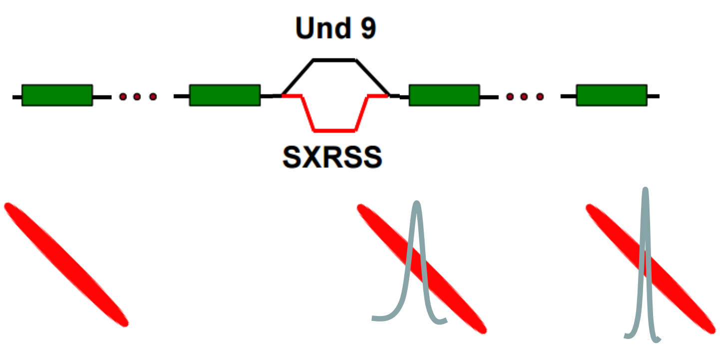




Without delay

Delay 40 fs

- Use a chirped bunch [1]



The final x-ray pulse duration is [2]: $\sigma_t = \frac{\sigma_\omega}{u}$

For a typical chirped bunch at LCLS, 1% over 30fs, the final pulse could be about **6 fs**. Experiments ongoing at LCLS.

[1]: Schroeder et al., NIM A 2002.

[2]: Krinsky and Huang, PRSTAB 2003.

(C. Emma et al., Poster WEP075)

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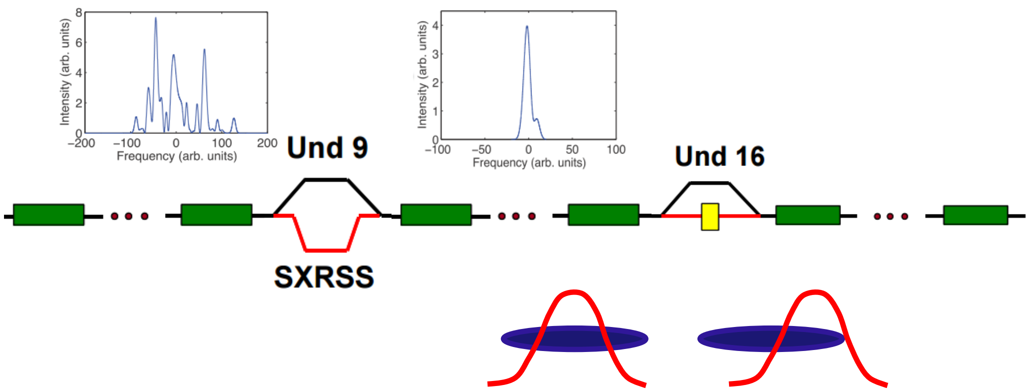
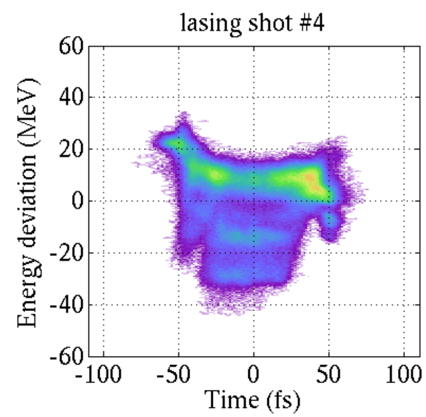
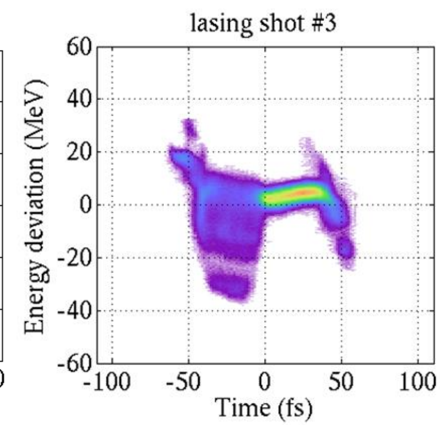




Without delay



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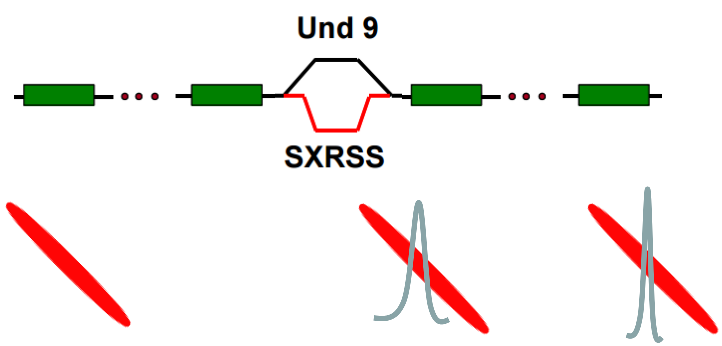
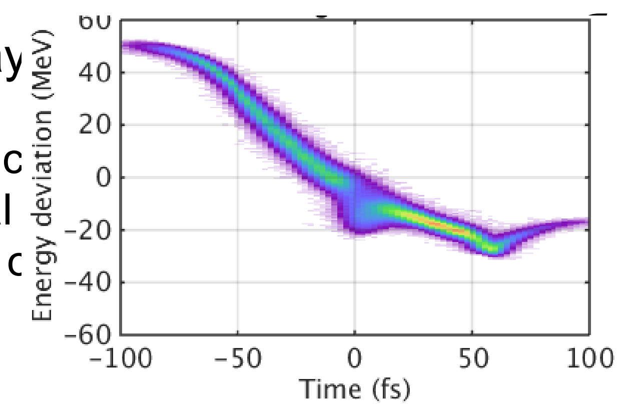


The final x-ray

For a typical c
30fs, the final
Experiments c



[1]: Schroeder et al., NIM A 2002.
[2]: Krinsky and Huang, PRSTAB 2003.

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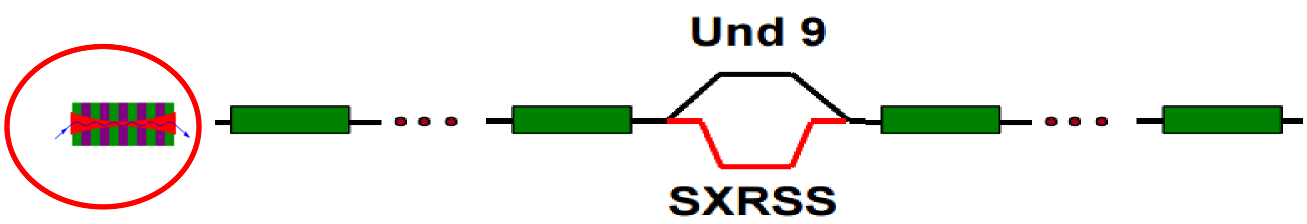
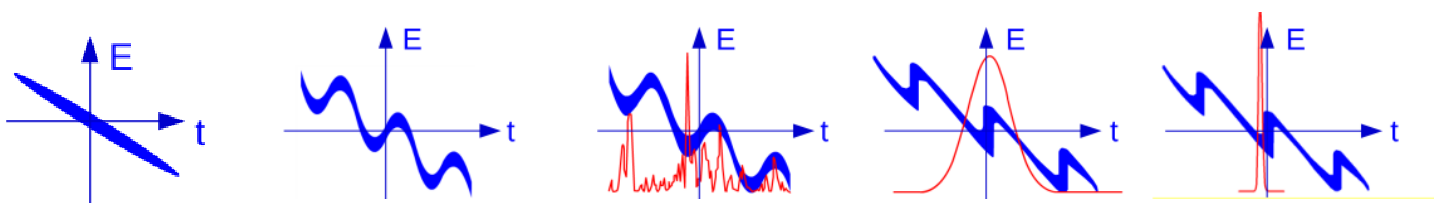
(C. Emma et al., Poster WEP075)

(4) Sub-fs in self-seeding mode?

- Chirped bunch
- \+ self-seeding mode
- \+ laser modulation

Short seed + current spike





(see more from S. Huang, talk TUB03B)

Summary

- Generating pulse durations from ~100 fs to a few fs are routinely deliverable;
- Going to sub-fs regime is an exciting topic both for FEL physicists and photon scientists.

Thanks to all of my colleagues and friends for their contributions to the results discussed here.

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LELAND STANFORD JUNIOR UNIVERSITY DIE LUFT DER FREIHEIT WEHT 1891