Innovative ideas for single-pass FELs

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Single-pass Short-wavelength FELs

SASE FELs

- SASE (Self-Amplified Spontaneous Emission) was proposed in 1980's [1,2] and experimentally demonstrated at DESY TTF in 2000 at 109 nm [3].

- SASE eliminates an optical cavity, resulting in the lack of longitudinal coherence.

- SASE requires highly bright electron beams, but the linac based source limits the number of beamlines.

[1] A.M. Kondratenko et al., Part. Accel. 10, 207 (1980).
[2] R. Bonifacio et al., Opt. Commun. 50, 373 (1984).
[3] J. Andruszkow et al., PRL 85, 3825 (2000).

SASE FELs

Fully coherent source

✧ Seeded FEL
✧ Frequency upshift
✧ Increase of correlation length

Better performance and usability

✧ Short pulse
✧ Higher photon energy
✧ Multi-color multi-pulse operation
✧ Multi-energy beam operation

To improve longitudinal coherence

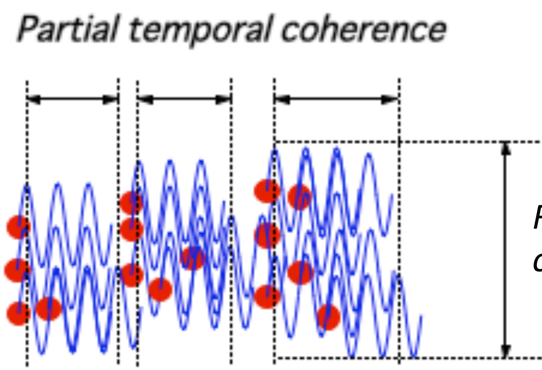
- To improve spiky spectra and temporal distribution.
  - Amplification of coherent seed
    - Direct seed using HHG (High-order Harmonic Generation) [1]
    - Self-seeded FEL [2, 3]
  - Frequency up-conversion of external coherent source
    - HGHG (High-Gain Harmonic Generation) [4], Cooled HGHG [5]
    - EEHG (Echo Enabled Harmonic Generation) [6]
  - Increase correlation length
    - Mode locked SASE [7]
    - pSASE (Purified SASE) [8]
    - iSASE (Improved SASE) [9]
    - HB-SASE [10] (High-Brightness SASE)
  - X-ray cavity [11]

[1] G. Lambert et al., Nat. Phys. 4, 296 (2008).
[2] G. Geloni et al., J. Mod. Opt. 58, 1391 (2011).
[3] J. Amann et al., Nat. Photon. 6, 693 (2012).
[4] L.H. Yu et al., Science 289, 932 (2000).
[5] H. Deng et al., PRL 111, 084801 (2013).
[6] G. Stupakov, PRL 102, 074801 (2009).
[7] N.R. Thomson et al., PRL 100, 203901 (2008).
[8] D. Xiang et al., PRST-AB 16, 010703 (2013).
[9] J. Wu et al., Proc. IPAC2013, 2068 (2013).
[10] B.W.J. McNeil et al., PRL 110, 134802 (2013).
[11] K-J. Kim et al., PRL 100, 244802 (2008).

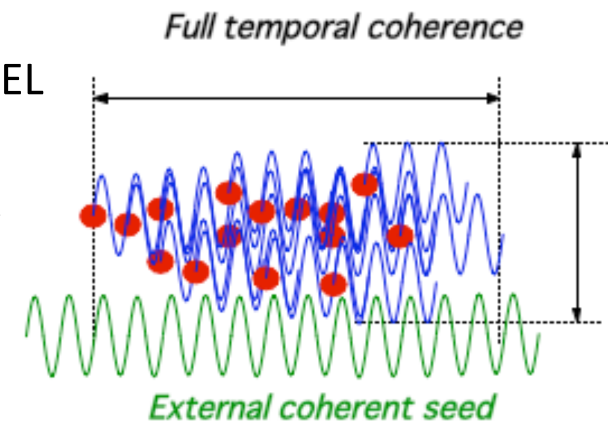
Seeded FEL

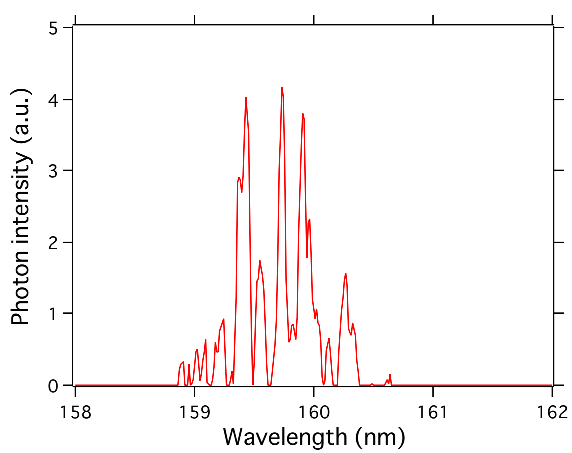
As a short-wavelength coherent source, high-harmonic generation in gas has been used down to several tens of nm.

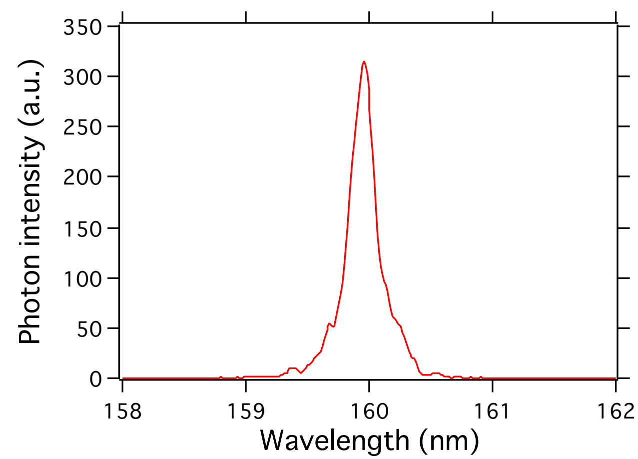
SASE FEL



Seeded FEL







Spectra measured at the SCSS test facility.

Self-seeding in hard X-rays

- No coherent source is practically available in hard X-rays, monochromatized SASE is used as a seed.
- Geloni et al. proposed a clever idea to use only one crystal in a simple configuration by using a trailing coherent wakes.

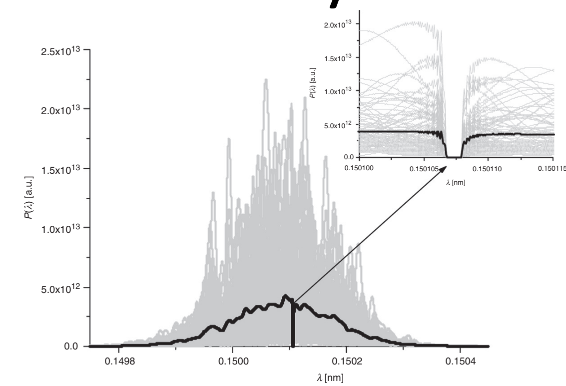
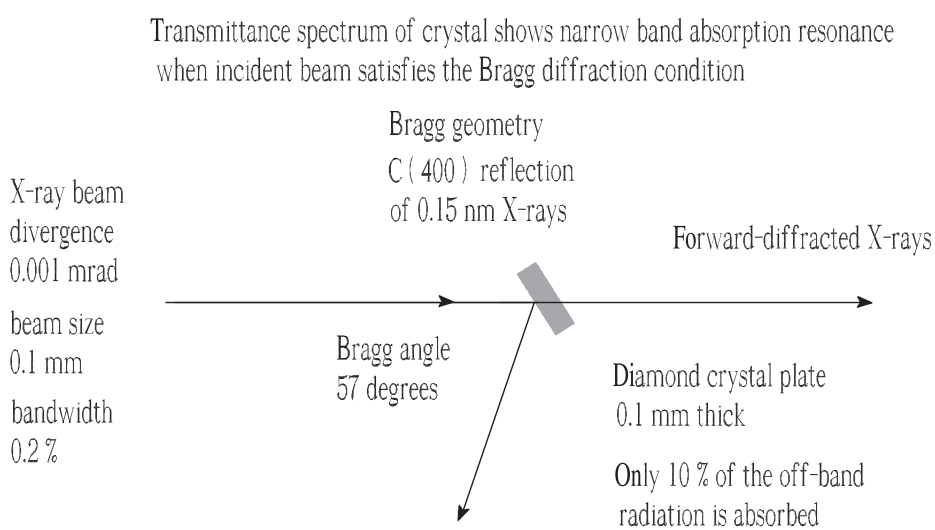
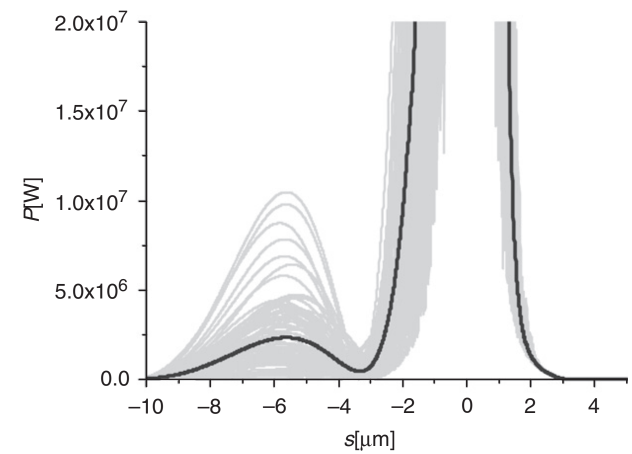


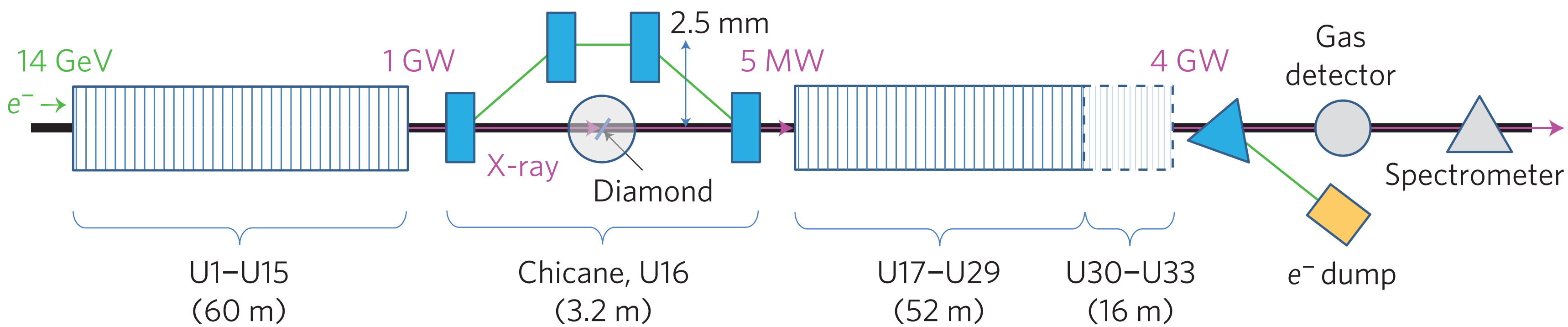
Figure 9. Feasibility study for the LCLS. Spectrum after the diamond crystal, C(400) reflection. The bandstop effect is clearly visible, and highlighted in the inset. Gray lines refer to single shot realizations, the black line refers to the average over 100 realizations.

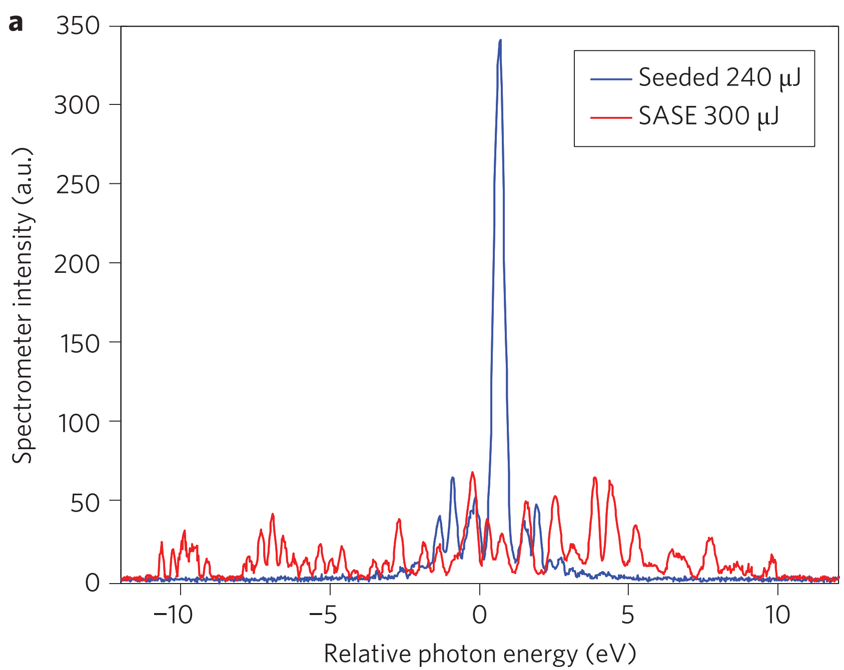




G. Geloni et al., J. Mod. Opt. 58, 1391 (2011).

First experimental demonstration of self-seeded FEL at LCLS

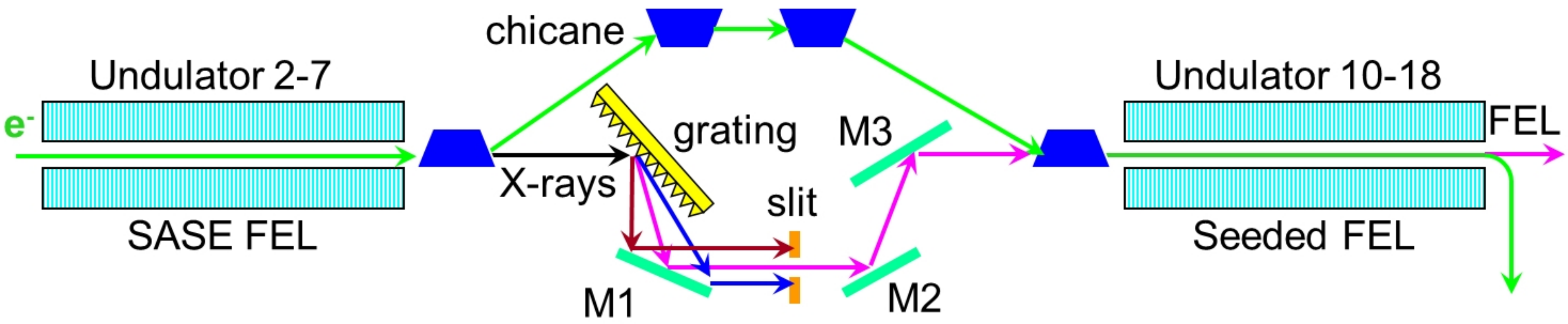


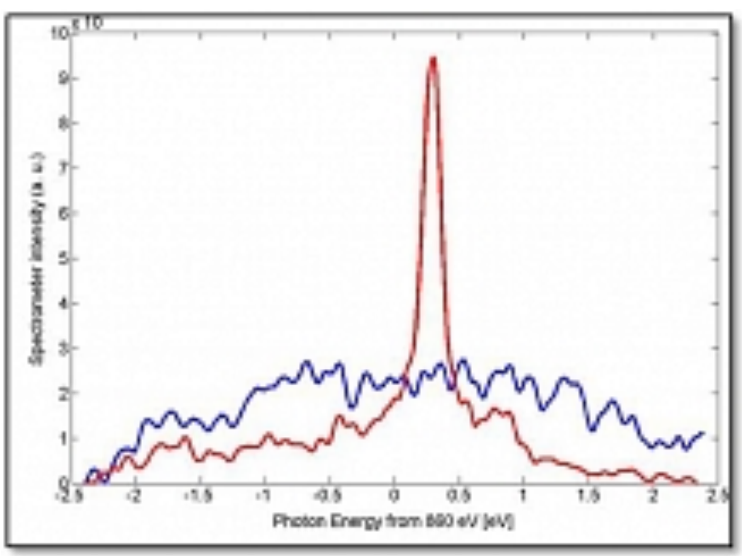


Recent efforts on the beam energy jitter reduction significantly improves the seeding efficiency.

J. Amann et al., Nat. Photon. 6, 693 (2012).

Self-seeded FEL in soft X-rays at LCLS



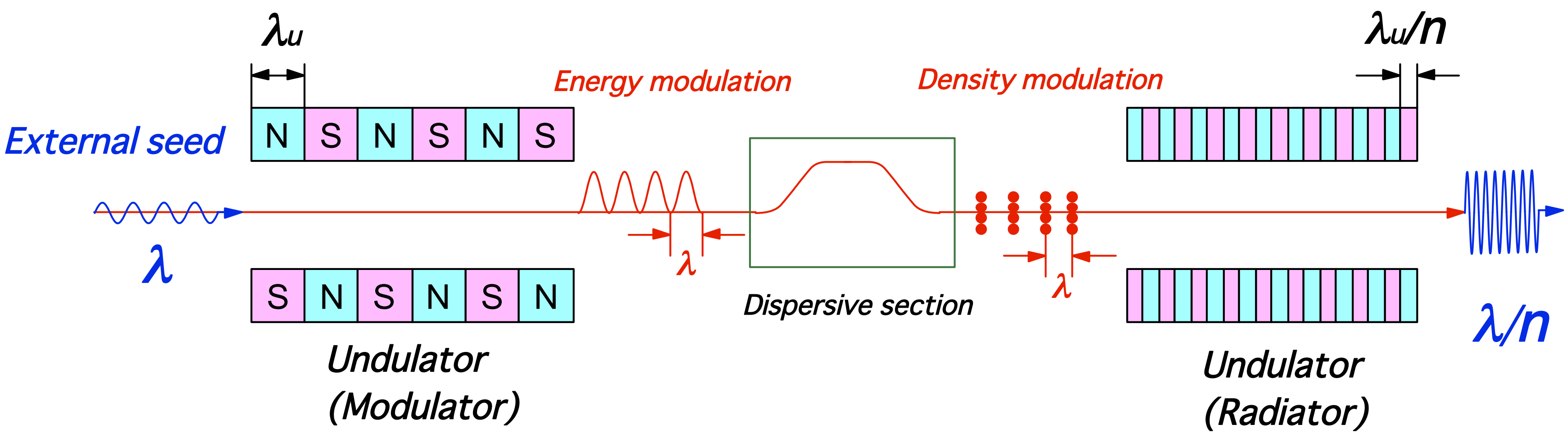


LCLS-LBN-PSI collaboration achieves the self-seeded FEL in soft X-rays.

https://www6.slac.stanford.edu/news/2014-03-10-new-way-tune-x-ray-laser-pulses.aspx

HGHG FELs

- Modulate the electron density at a long wavelength and upshift the frequency using a harmonic relation.

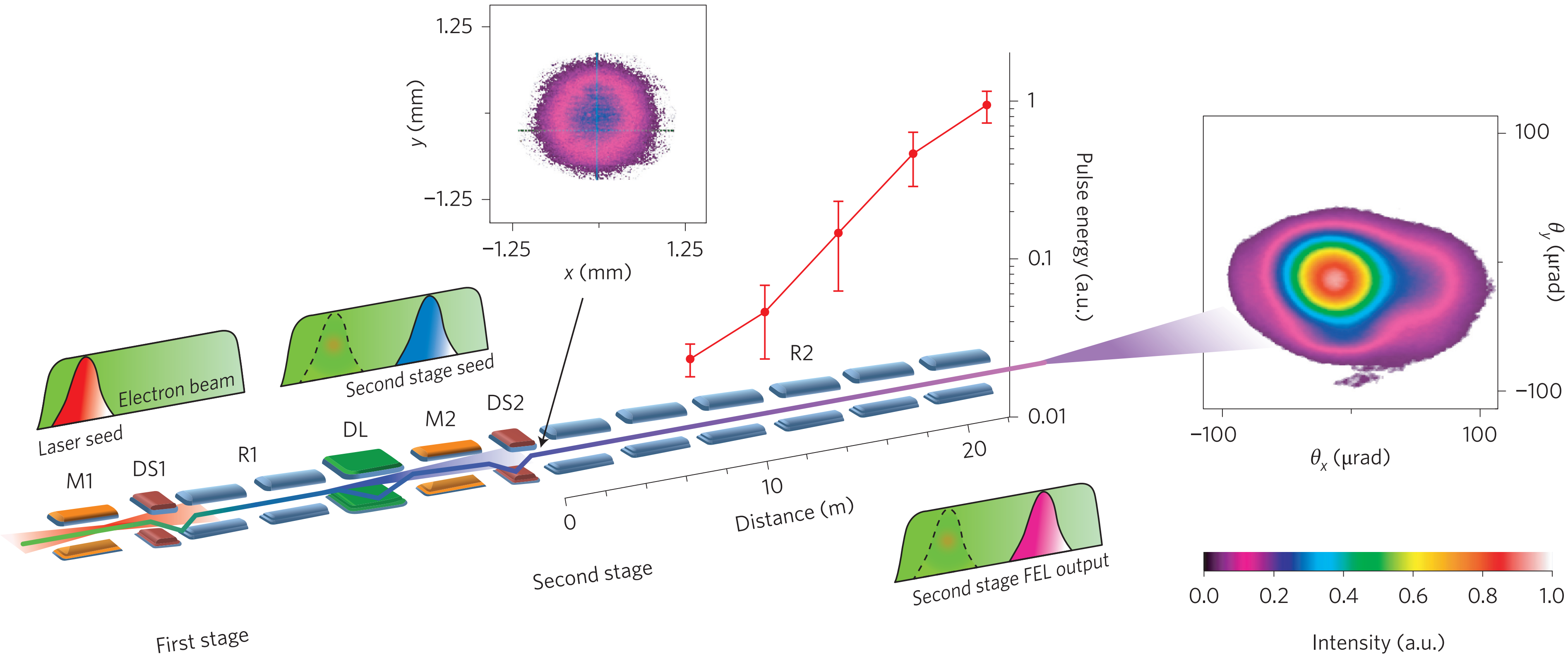


- Originally proposed and experimentally demonstrated at BNL by Yu et al at infrared and visible wavelengths.
- Multi-stage and the so-called "fresh bunch technique" required to reach short wavelengths.
- "Cooled HGHG" recently proposed to increase the efficiency and harmonic order.

L.H. Yu et al., Science 289, 932 (2000),
I. Ben-Zvi et al., NIMA 318, 726 (1992).

HGHG FELs

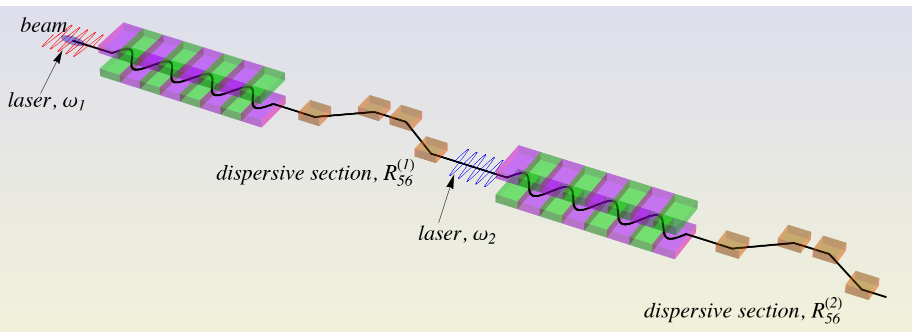
- FERMI in Italy is the first user facility based on HGHG FEL.
- Successful operation down to the water window (4.3 nm) with 2-stage HGHG.

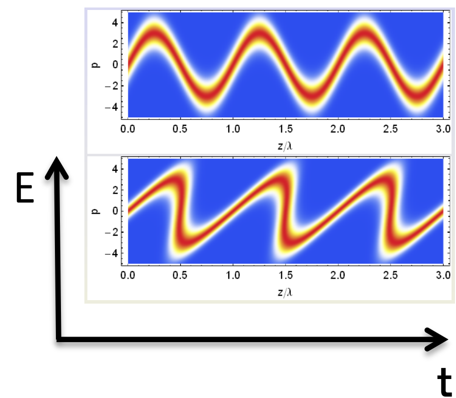


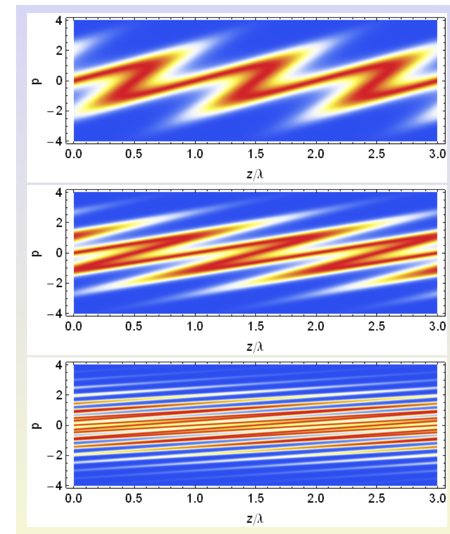
E. Allaria et al., Nat. Photon. 7, 913 (2013).

EEHG FELs

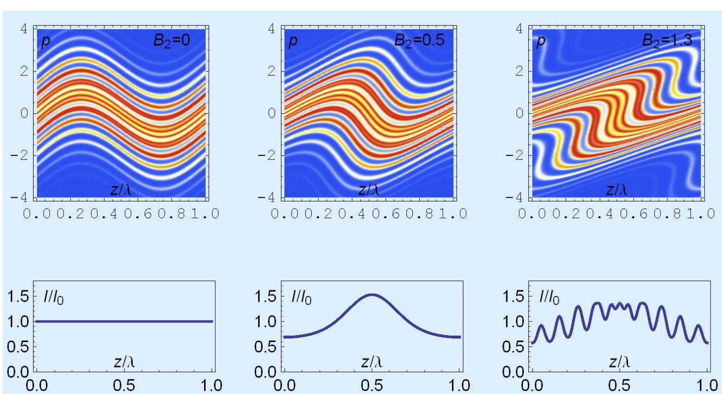
- Modulate the electron density at a long wavelength and upshift the frequency through manipulation of the electron beam.
- First chicane to fold and pile up the electron beam by over-bunching .







- Density modulation emerged after the second chicane.

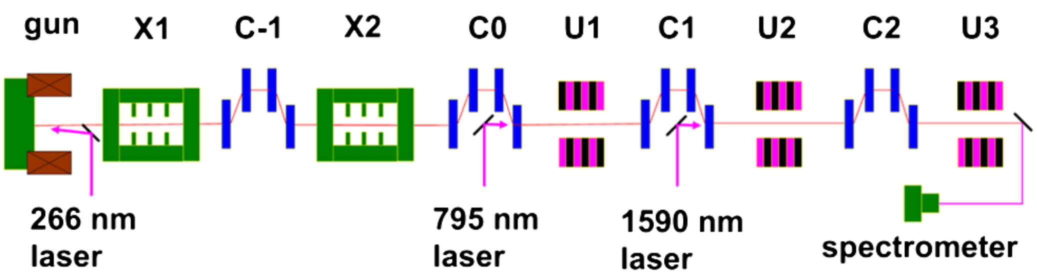


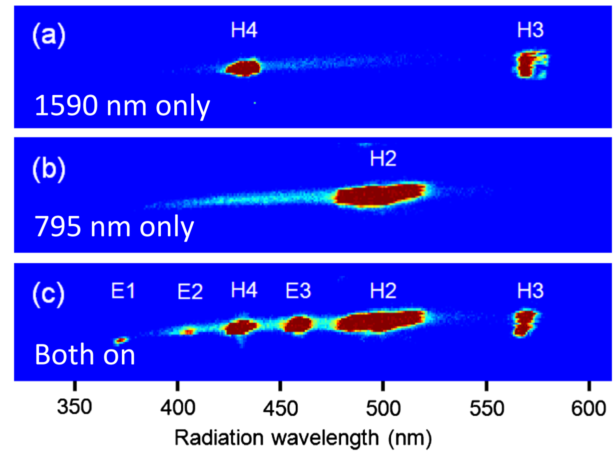
The period of density modulation is upshifted from the initial laser wavelength.

G. Stupakov, IPAC'10 (2010).
G. Stupakov, PRL 102, 074801 (2009).

EEHG FELs

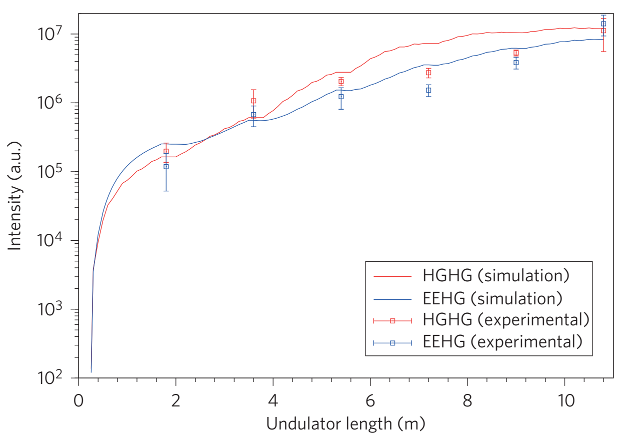
- First proof-of-principle experiment at SLAC NLCTA in visible wavelengths, later in UV with 7th harmonic.

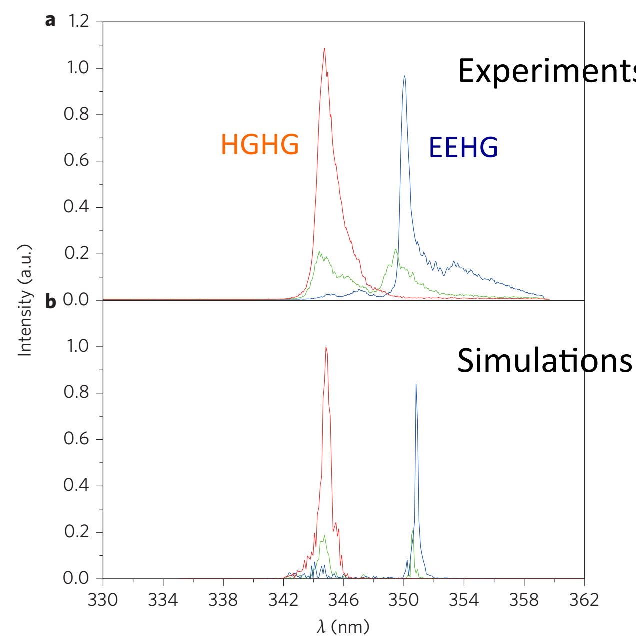




D. Xiang et al., PRL 105, 114801 (2010).
D. Xiang et al., PRL 108, 024802 (2012).

- Lasing of EEHG confirmed at SDUV-FEL at Shanghai.

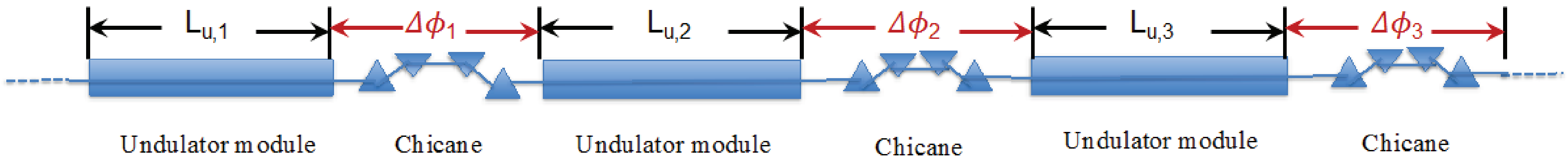


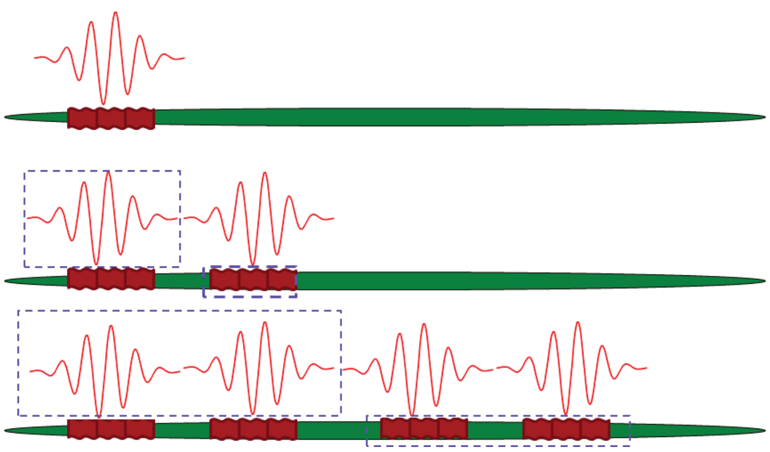


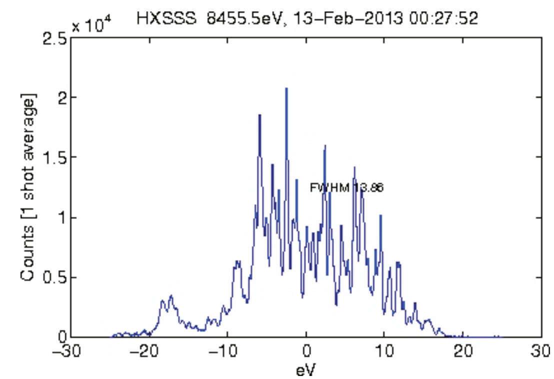
Z.T. Zhao et al., Nat. Photon. 6, 360 (2012).

Improved SASE (iSASE)

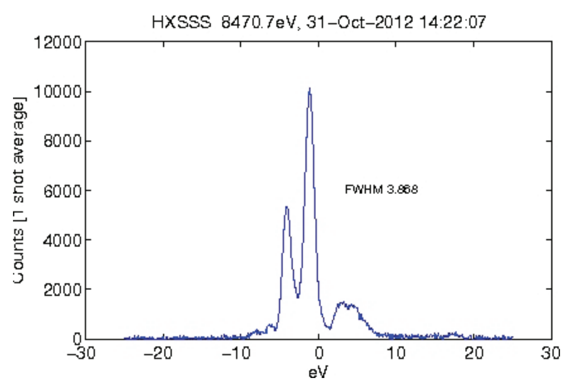
- Delay the electron bunch to increase phase correlation over the electron bunch. Demonstration performed at LCLS.







SASE spectrum



iSASE spectrum

J. Wu et al., Proc. IPAC2013, 2068 (2013).

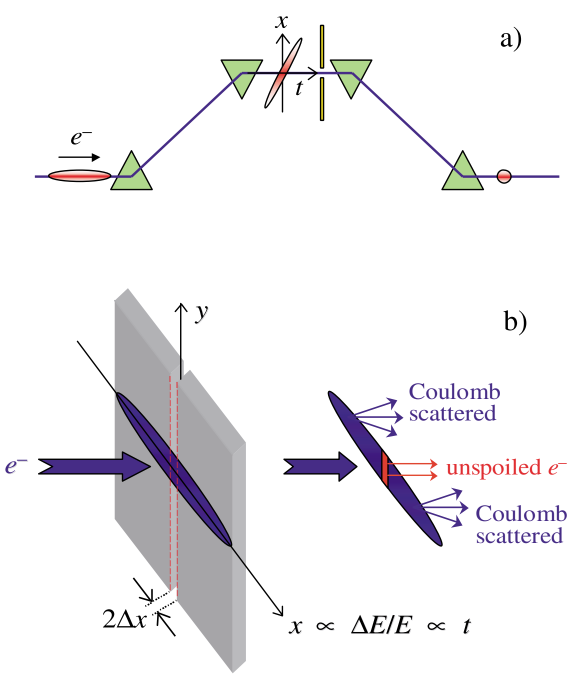
For better performance of SASE FELs

- For shorter photon pulse length.
  Emittance spoiler [1], eSASE [2,3], using a few-cycle laser [4-9], multi-stage HGHG [10], low-charge or manipulation [11,12] ...
- For higher photon energy
  Harmonic lasing [13,14]
- For multi-color multi-pulse
  Two-color SASE [15-18], gain-modulated FEL [19]
- For multi-beamline
  Multi-energy operation [20]

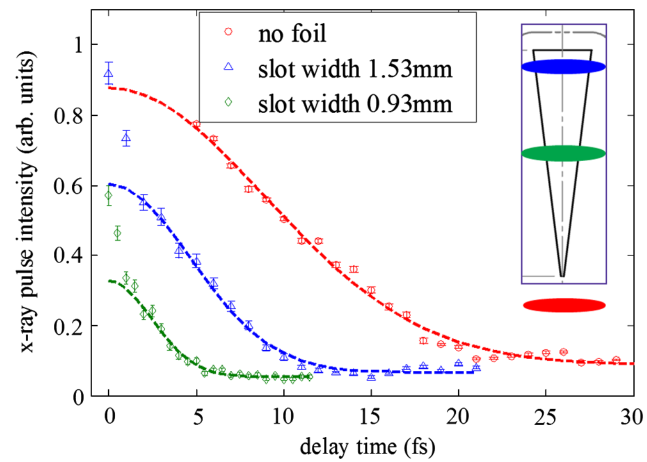
[1] P. Emma et al., PRL 92, 074801 (2004).
[2] A.A. Zholents, PRL 92, 224801 (2004).
[3] Y. Ding et al., PRSTAB 12, 060703 (2009).
[4] E.L. Saldin et al., Opt. Commun. 237, 153 (2004).
[6] E.L. Saldin et al., Opt. Commun. 239, 161 (2004).
[7] A.A. Zholents et al., NJP 10, 025005 (2008).
[8] D. Xiang et al., PRSTAB 12, 060701 (2009).
[9] E.L. Saldin et al., PRSTAB 9, 050702 (2006).
[10] E.L. Saldin et al., Opt. Commun., 377 (2002).
[11] S. Reiche et al., NIMA 593, 45 (2008).
[12] T. Tanaka, PRL 110, 084801 (2013).
[13] B.W.J. McNeil et al., PRL 96, 084801 (2006).
[14] E.A. Schneidmiller et al.,, PRSTAB 15, 084801 (2012).
[15] A.A. Lutman et al., PRL 110, 134801 (2013).
[16] G. De Ninno et al., PRL 110, 064801 (2013).
[17] T. Hara et al., Nat. Commun. 4, 2919 (2013).
[18] E. Allaria et al., Nat. Commun. 4, 2476 (2013).
[19] A. Marinelli et al., PRL 111, 134801 (2013).
[20] T. Hara et al., PRSTAB 16, 080701 (2013).

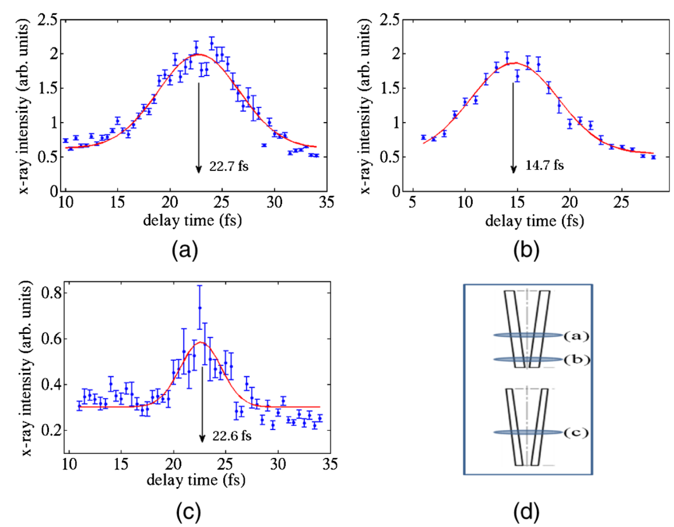
Generation of short pulses

- Slotted foil to limit the lasing portion on the electron bunch.
- X-ray pulse duration confirmed by an autocorrelation technique.



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

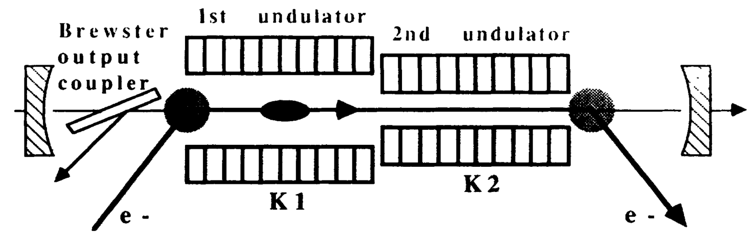




Y. Ding et al., PRL 109, 254802 (2012).

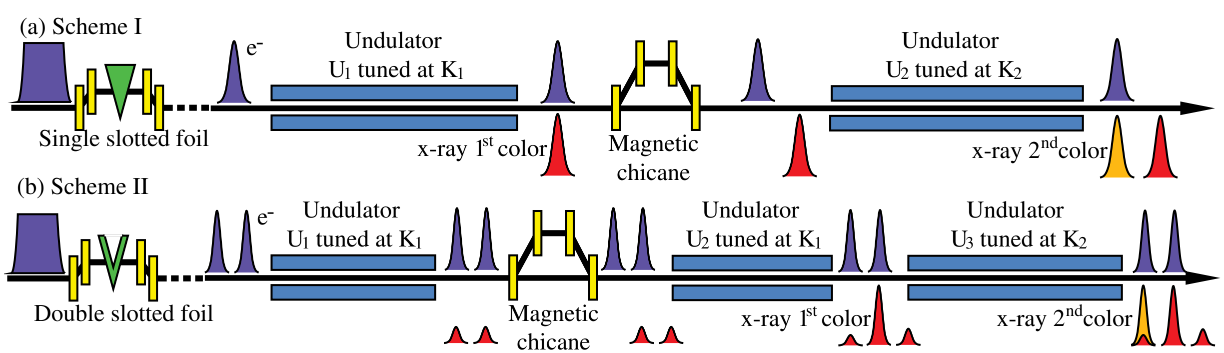
Two-color two-pulse SASE

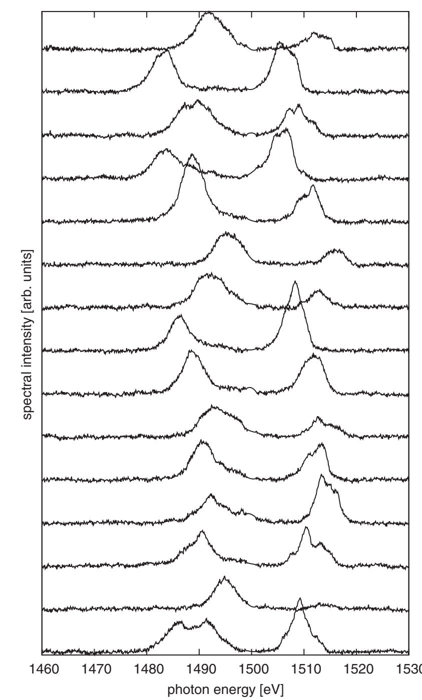
- First two-color FEL was demonstrated on an IR cavity-type FEL at CLIO.



D.A. Jaroszynski et al., PRL 72, 2387 (1994).

- In soft X-rays, LCLS achieved the first two-color SASE operation.



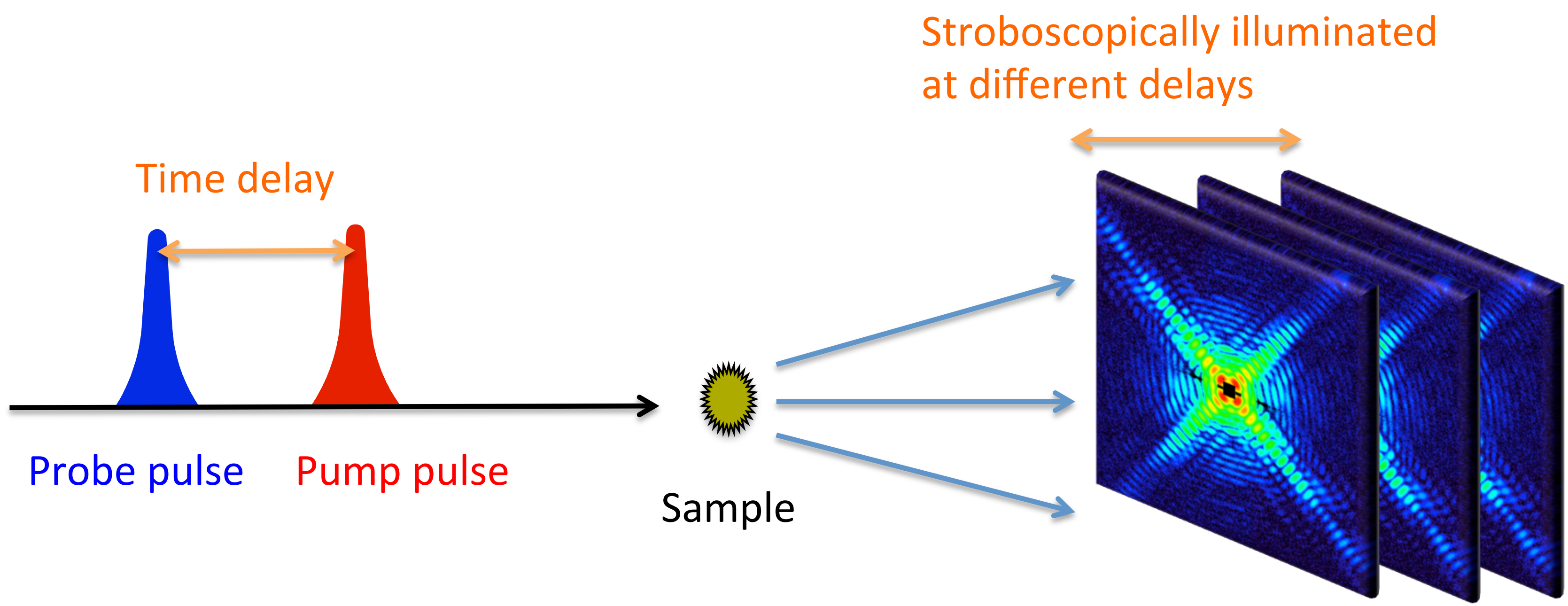


A.A. Lutman et al., PRL 110, 134801 (2013).

Why two-color two-pulse SASE?

Strong demands from users.

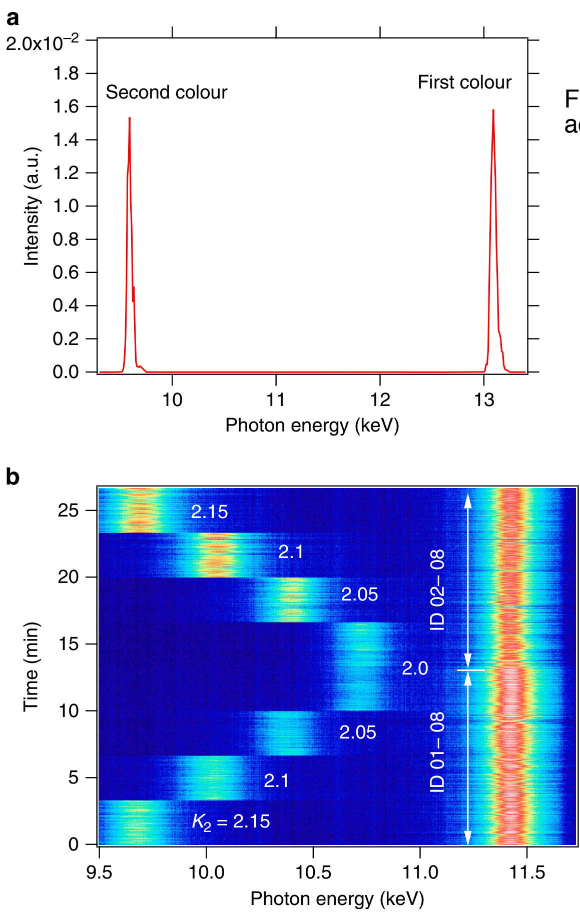
Pump-probe technique to dynamically observe phenomena.

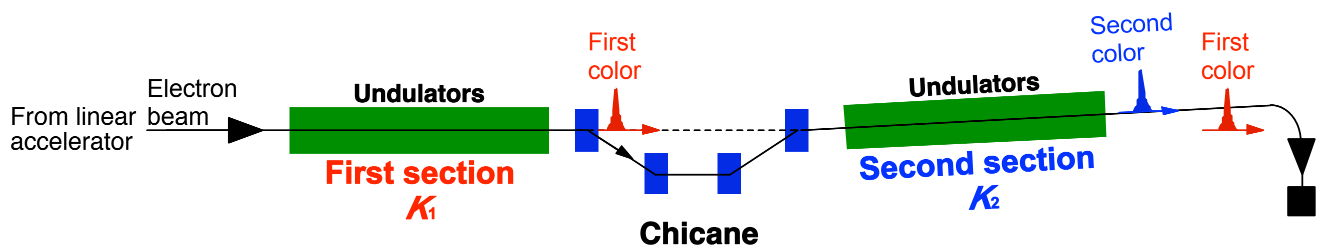


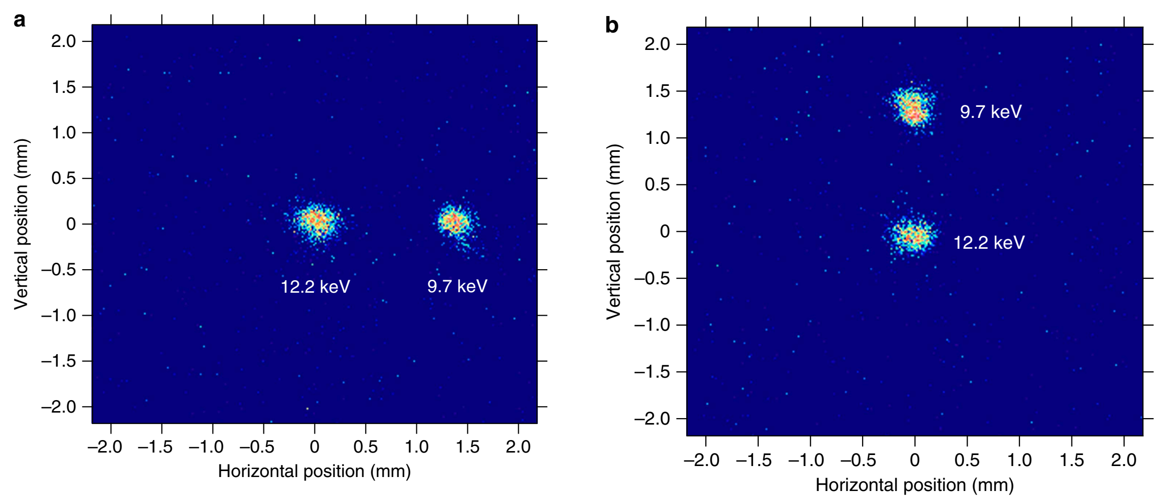
- Conventionally combining SASE and a synchronized laser.
- Several tens of fs temporal jitter between the pulses.
- A big difference of the two wavelengths.

Two-color two-pulse SASE

- In SACLA, the photon energy range is extended to hard X-rays, and the wavelength separation of more than 30 % is obtained by using variable gap undulators.

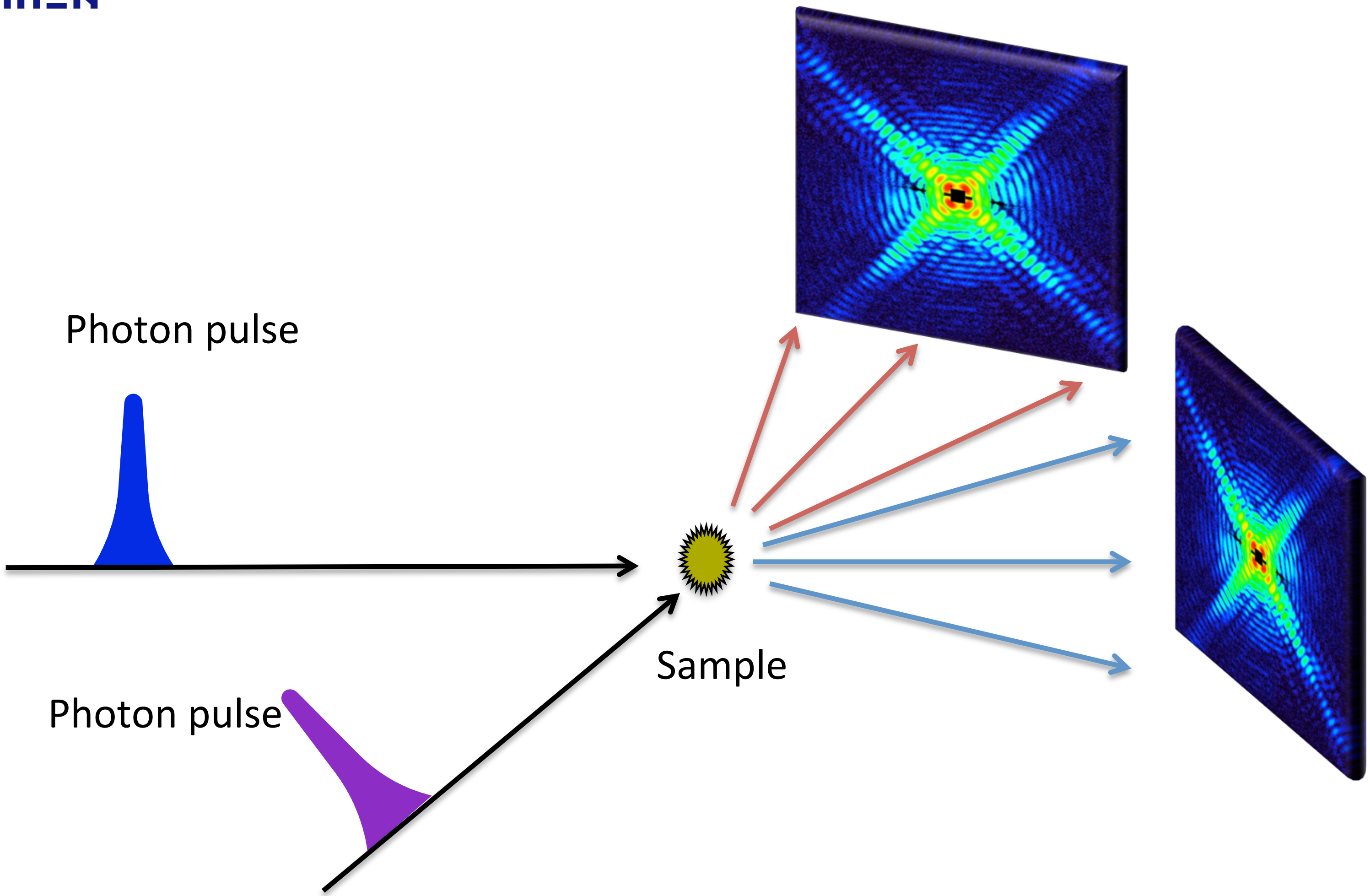






T. Hara et al., Nat. Commun. 4, 2919 (2013).

Why two-color two-pulse SASE?

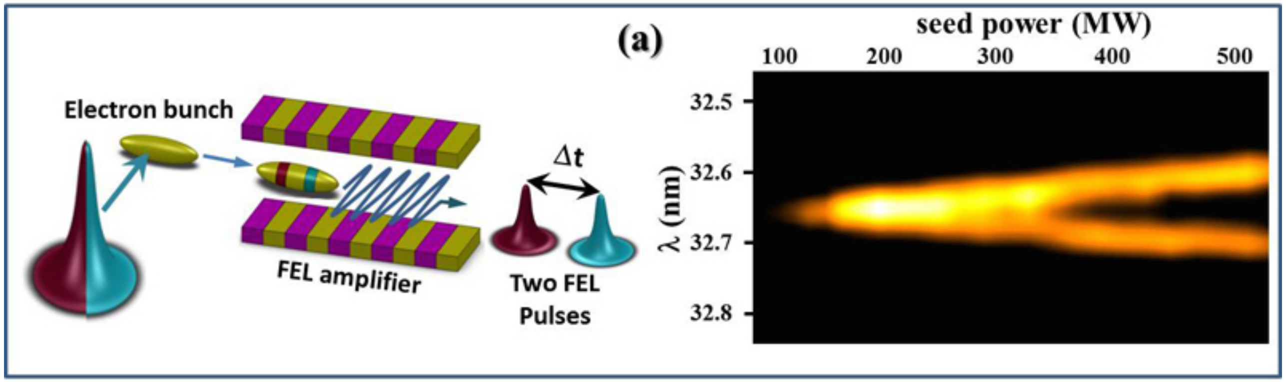


- Simultaneous illumination and diffraction from different angles.

Two-color seeded FEL with HGHG

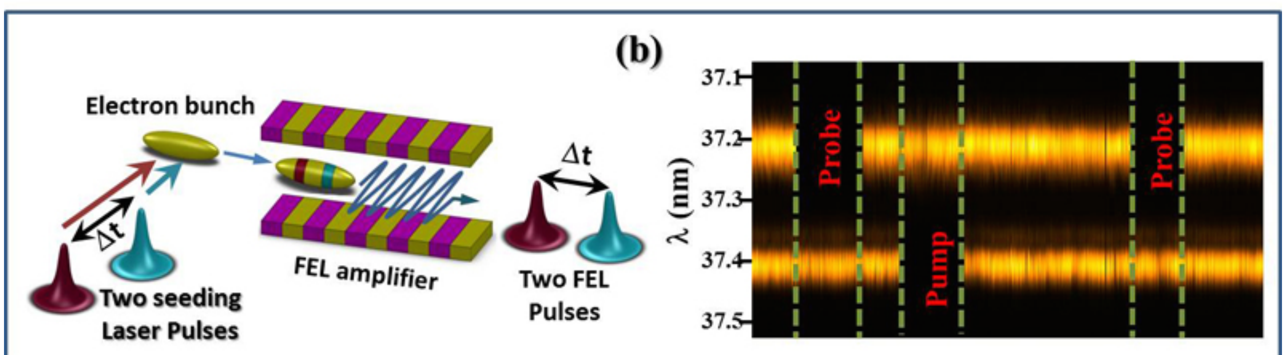
- Two types of methods have been proposed and demonstrated at FERMI.

1. Use of intense chirped seed laser pulses and pulse splitting.



G. De Ninno et al., PRL 110, 064801 (2013).
M. Labat et al., PRL 103, 264801 (2009).

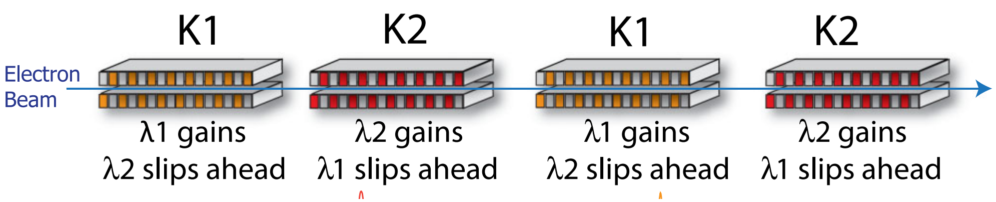
2. Two-color seed injection.

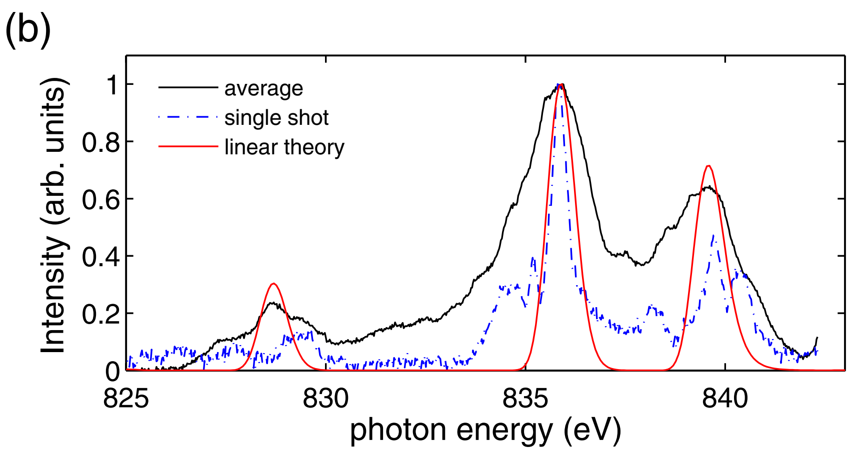


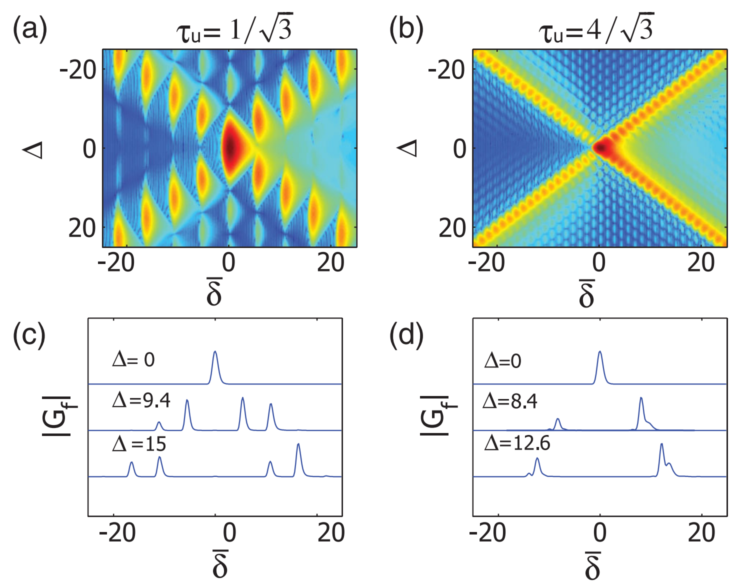
E. Allaria et al., Nat. Commun. 4, 2476 (2013).

Multi-color gain modulated FEL

- The undulator parameters can be alternately changed to obtain quasi-simultaneous multicolor radiation.
- Experimental demonstration performed at LCLS.



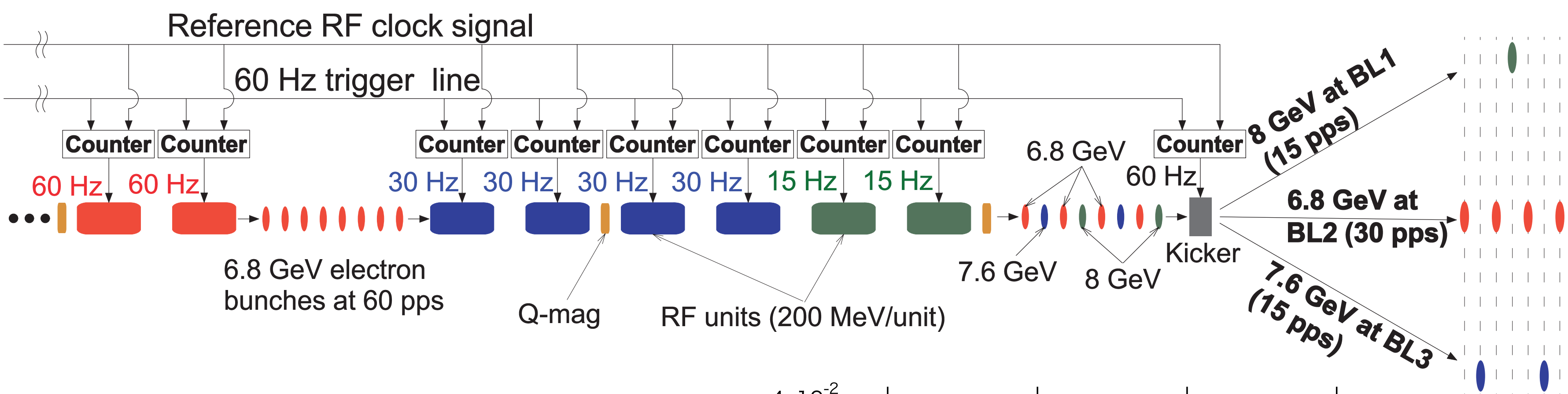


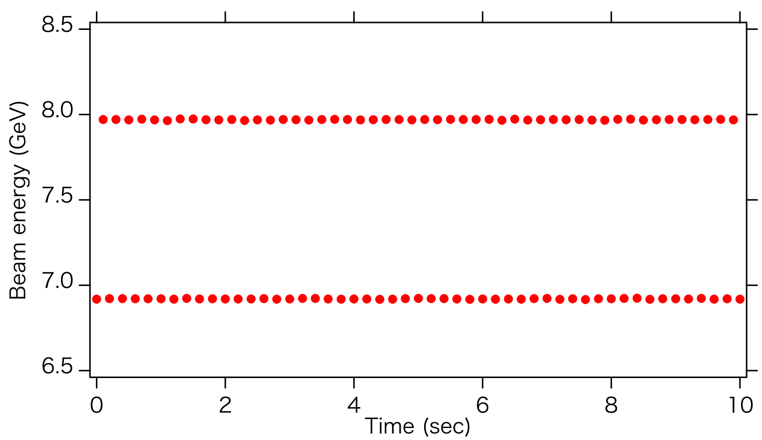


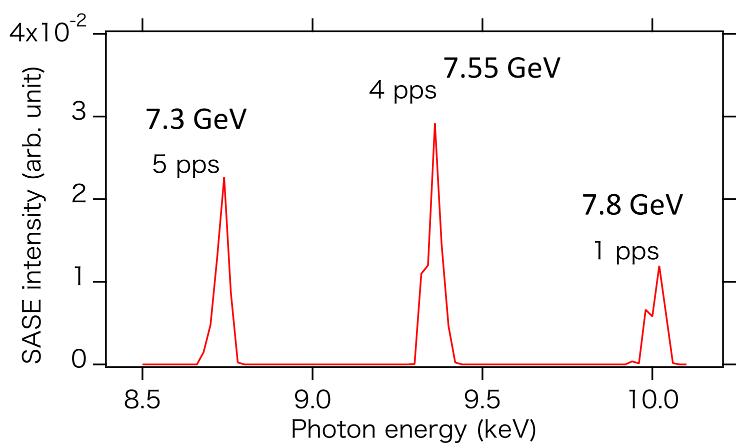
A. Marinelli et al., PRL 111, 134801 (2013).

Multi-energy operation for multi-beamline

- Multi-beamline is planned at most of XFEL facilities.
- Optimize the beam energy for each beamline on a bunch-to-bunch basis.







T. Hara et al., PRSTAB 16, 080701 (2013).

Summary

- So many innovative and unique ideas have been proposed, and some of them have been experimentally demonstrated.
- Combination of plural schemes can further improve the performance, like double-bunch two-color self-seeding demonstrated at LCLS.
- FEL is a tool to investigate phenomena or structures of matters, and the implementation of new ideas should match the demands of users.
- New ideas mostly require ultimate stability of the accelerator, and the progress of the accelerator technology is a key issue for the future FELs.