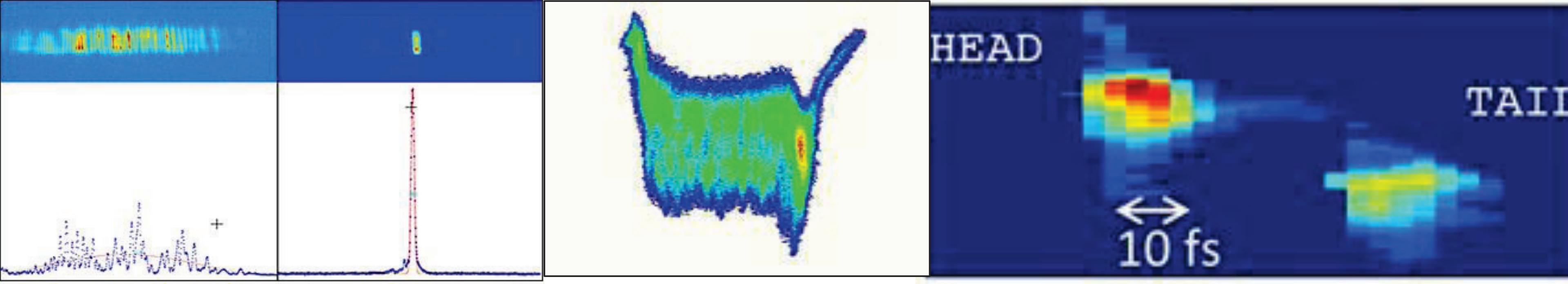
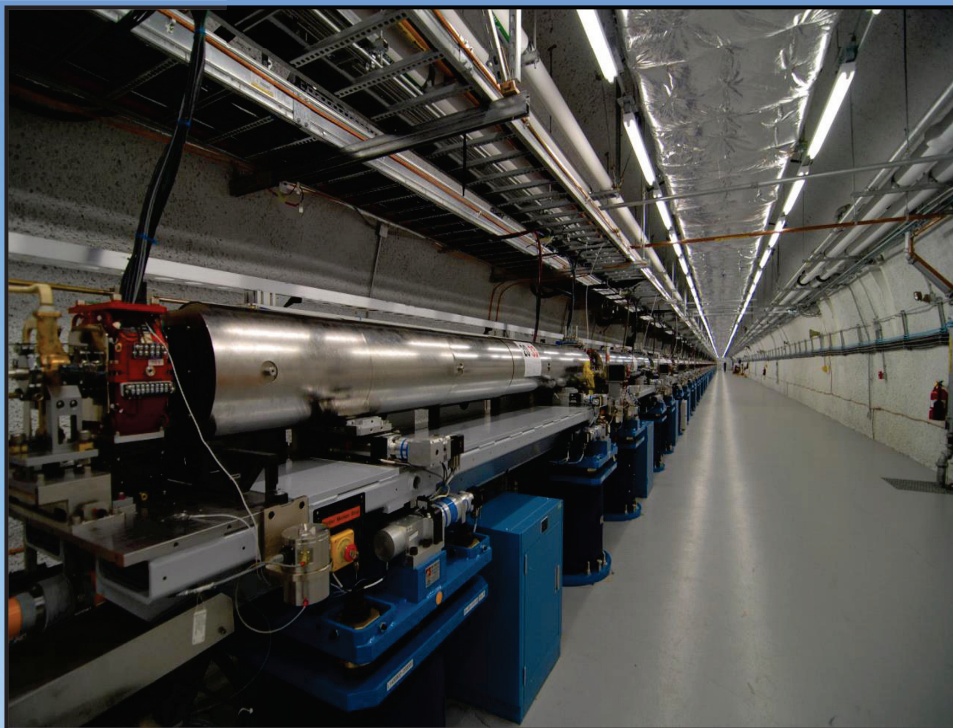


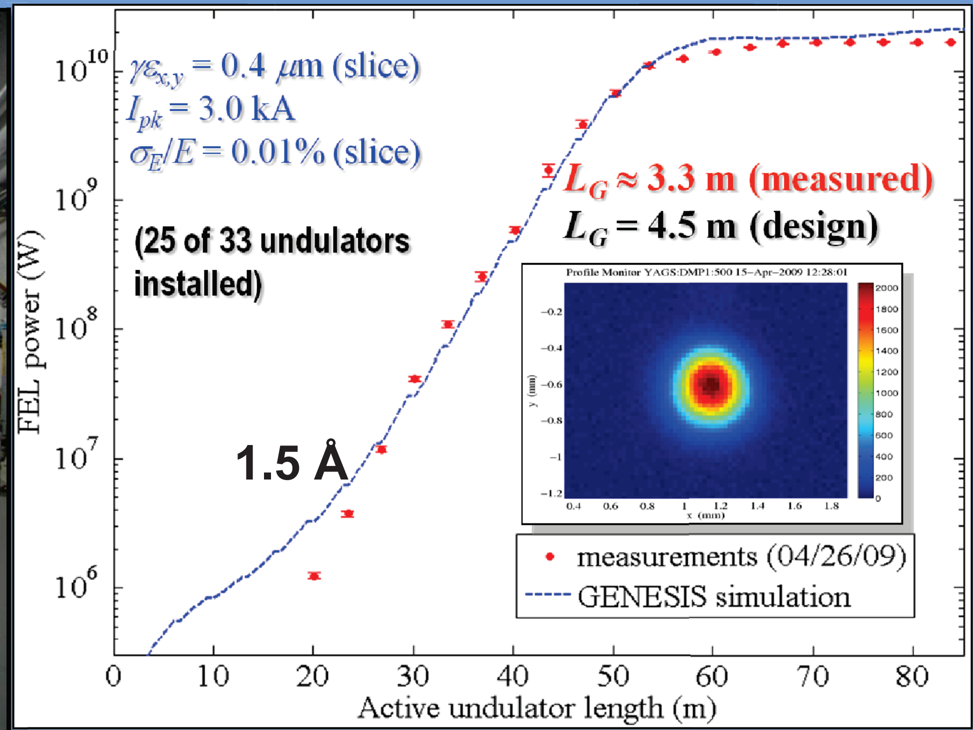
X-Ray FEL R&D
Brighter, Better, Cheaper

Zhirong Huang

NATIONAL ACCELERATOR LABORATORY

LCLS: A new era of x-ray sources





- SASE wavelength range: **40 – 1** Å
- Photon energy range: **0.3 – 12.8** keV *F.-J. Decker, WEP022*
- Pulse length FWHM **5 - 500** fs (SXR only)
- Pulse energy up to **5** mJ, rep. rate **120 Hz**
- User operation since **2010**

A growth spurt in XFELs

- EUV/soft X-rays: FLASH (2005), FERMI (2012), SXFEL (2017)
- LCLS-II (2020): a new SC CW FEL at 1 MHz rep. rate

Introduction

- Despite the early success, it is widely recognized that XFELs continue to have significant potential for improvement.

- New methods have been rapidly developing to provide FEL seeding, extremely short x-ray pulses, variable double pulses, two-color FEL generation, and polarization control.

- Many of the proposals were implemented in the LCLS since 2011 through FEL R&D program that I have the privilege to contribute. Here I present a personal (incomplete) overview.

- I also like to discuss dreams/progress towards compact XFELs and conclude with some final remarks.

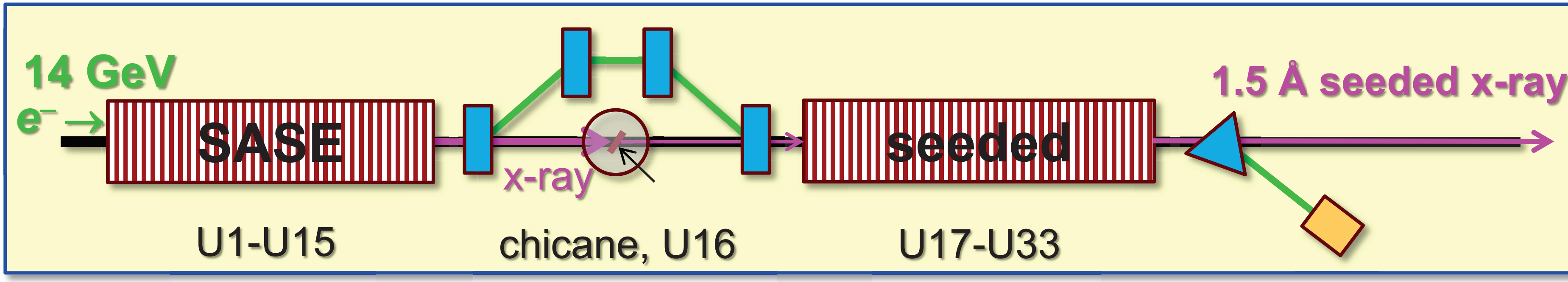
Outline

- *Introduction*
- *Improving temporal coherence ("**brighter**")*
- *X-ray pulse controls ("**better**")*
- *Compact coherent sources ("**cheaper**")*
- *Summary*

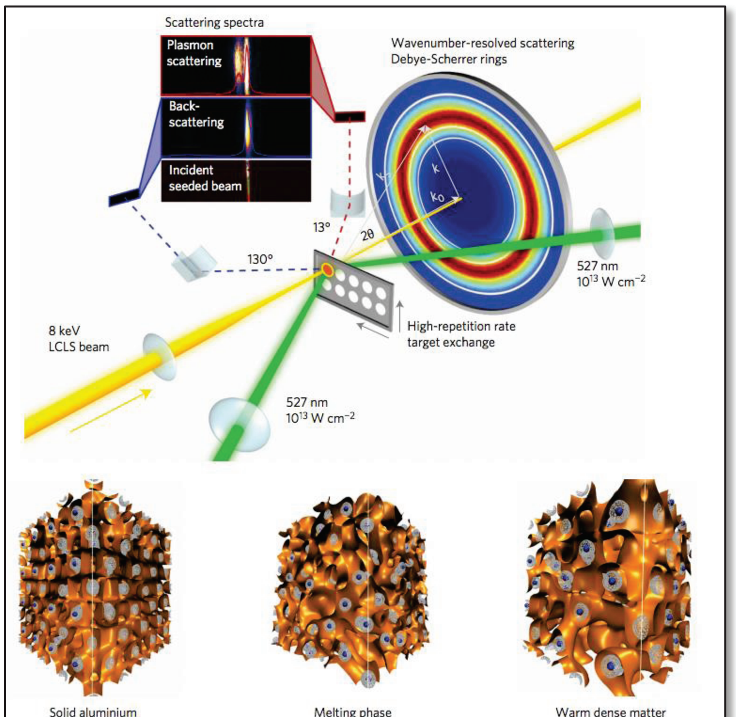
Hard x-ray self-seeding @ *LCLS*

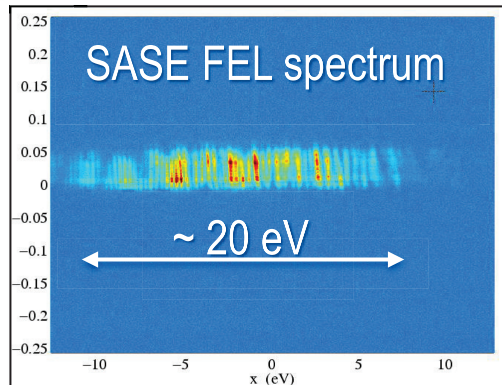
J. Amann et al., Nature Photon. 6, 693 (2012)

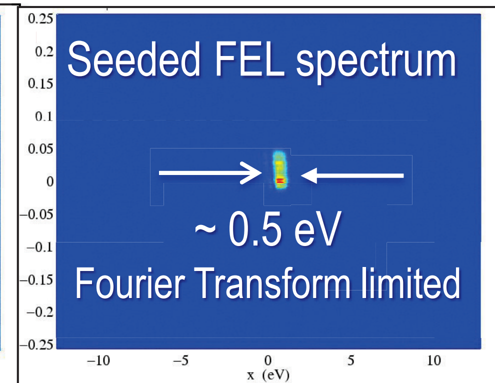
G. Geloni et al., DESY 10-133, 2010.

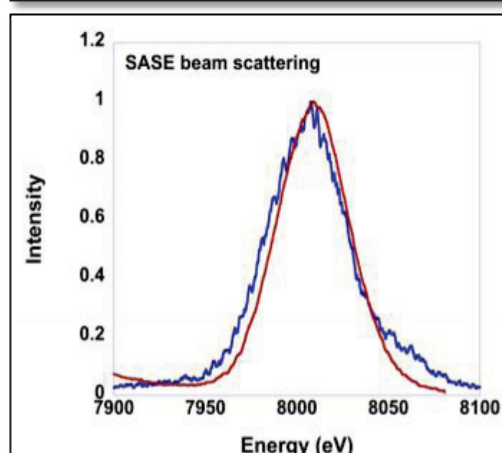


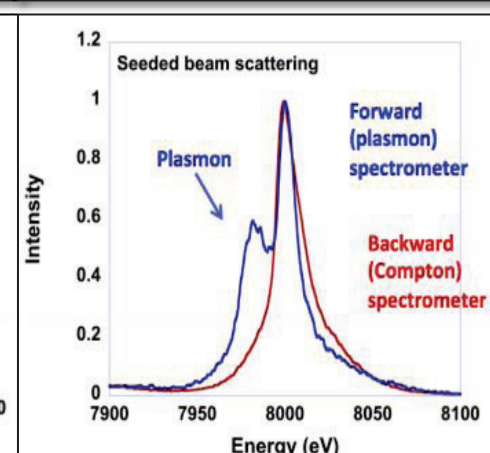
- User operation started in 2013







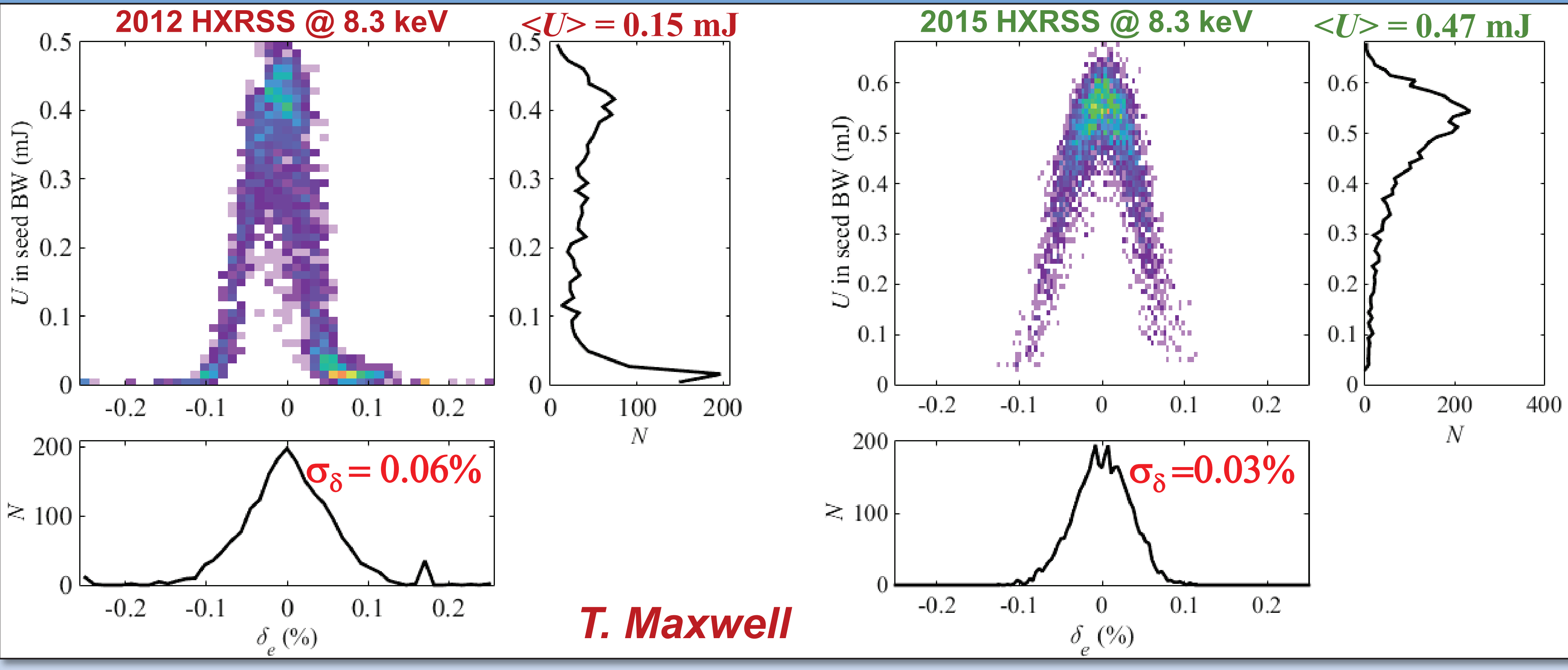




L. Fletcher et al., J. Instrum. 8, C11014 (2013); Nature Photon. 9, 274 (2015)

Improving energy jitter for seeding

- Seeded FEL intensity is sensitive to beam energy jitters (need $\sigma_\delta < \rho/2$).



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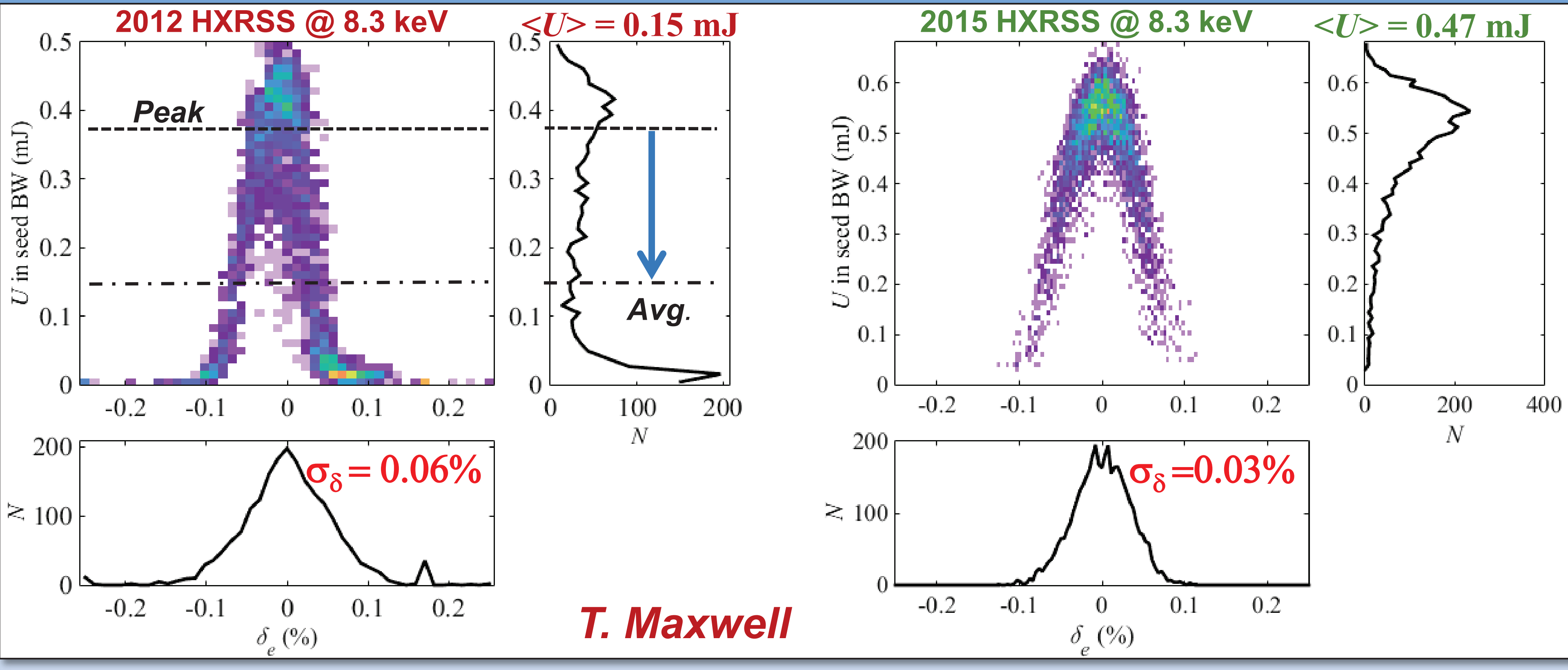

- HXR and SXR *E* jitter reduced by factor 2 since 2012
  - Injector RF tuned up, compression scheme optimized

L. Wang, TUP070

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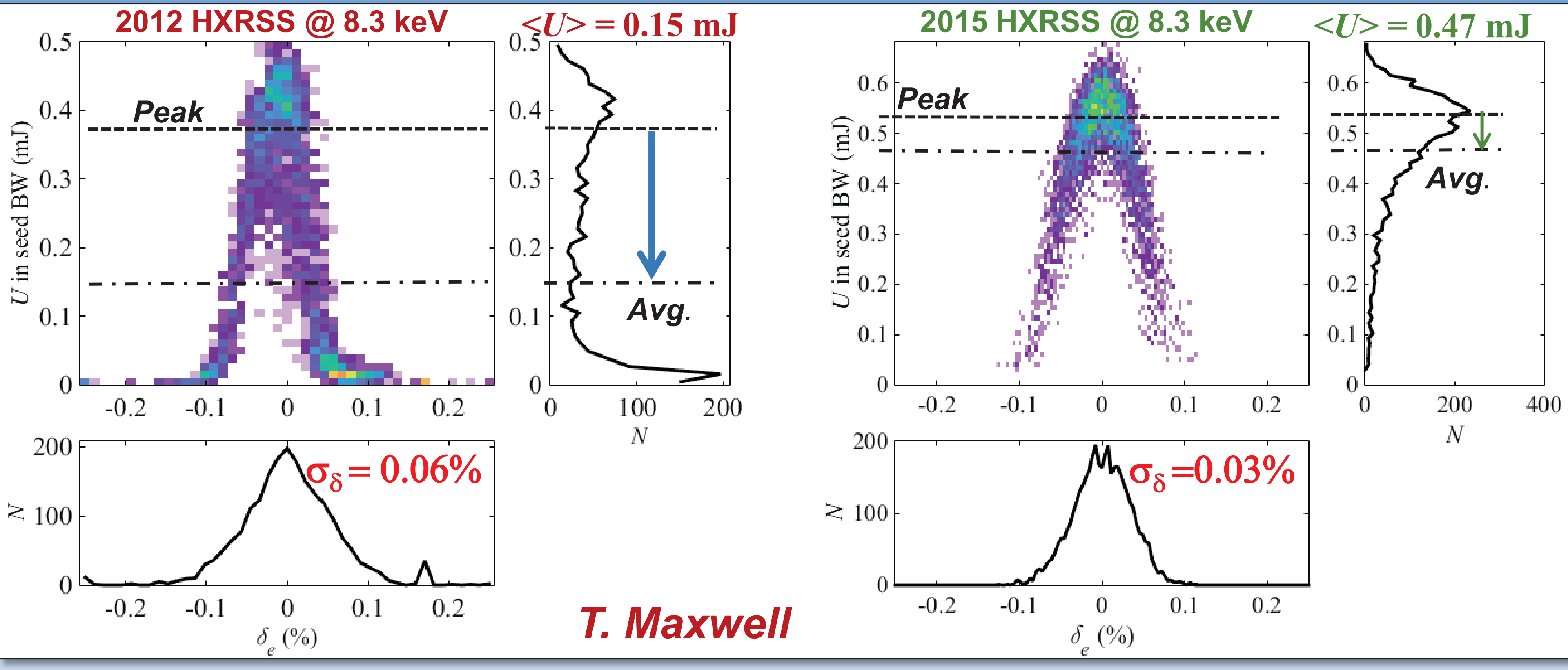
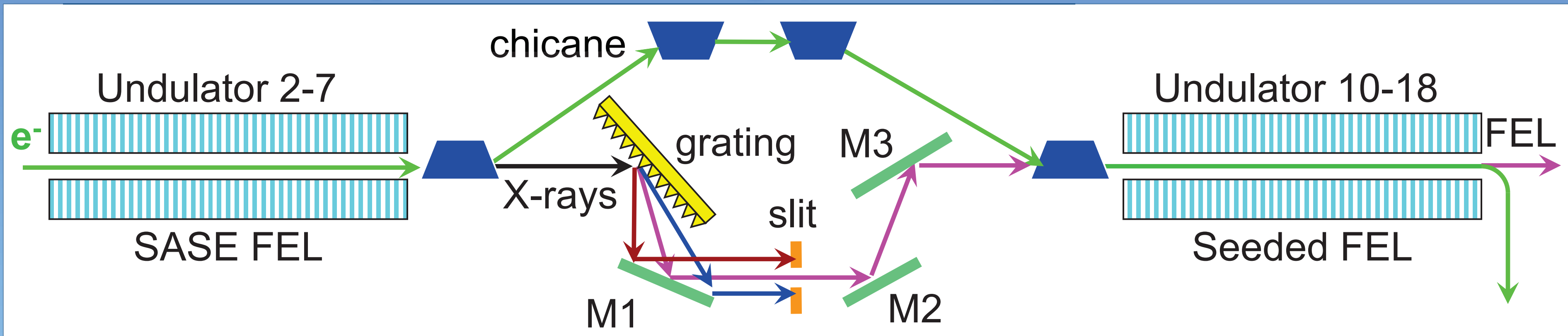
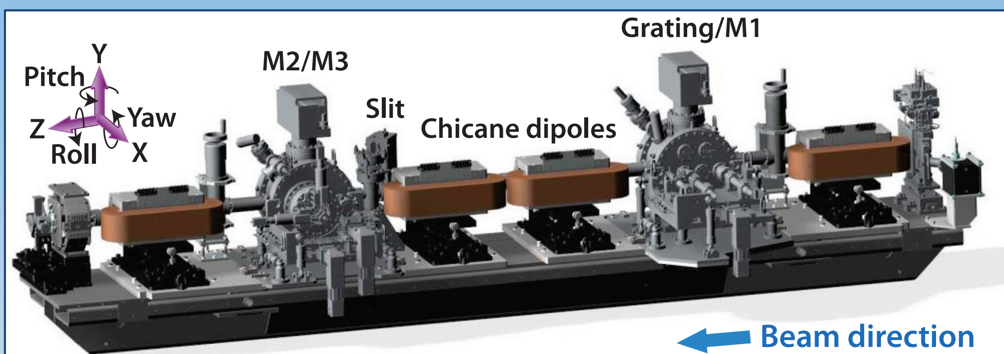


- HXR and SXR *E* jitter reduced by factor 2 since 2012
  - Injector RF tuned up, compression scheme optimized
- Hardware improvements incoming for further reduction
  - High-power RF terminating loads + higher-rated deuterium thyratrons

L. Wang, TUP070

Soft X-ray Self-Seeding (SXRSS)





D. Ratner et al., PRL 114, 054801 (2015) Y. Feng, TUP026, LCLS-II SXRSS design

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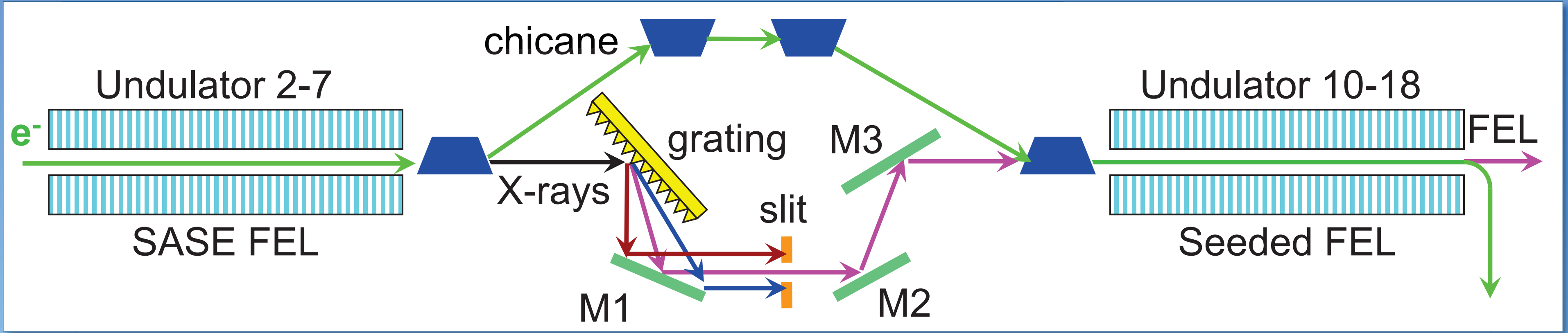

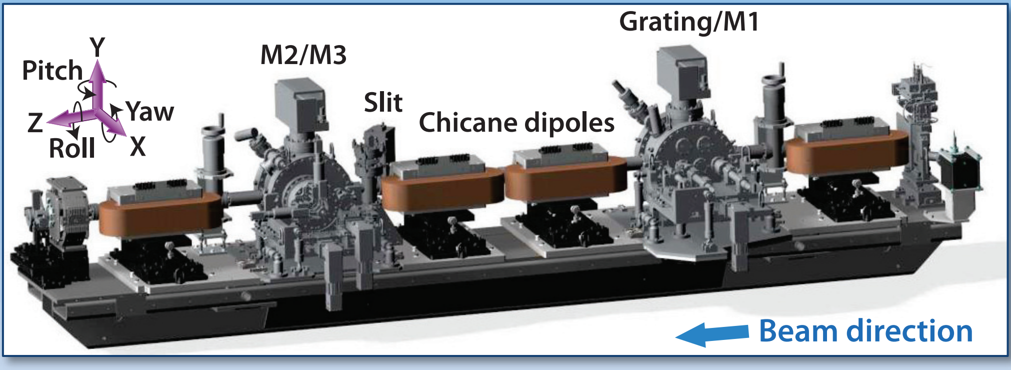

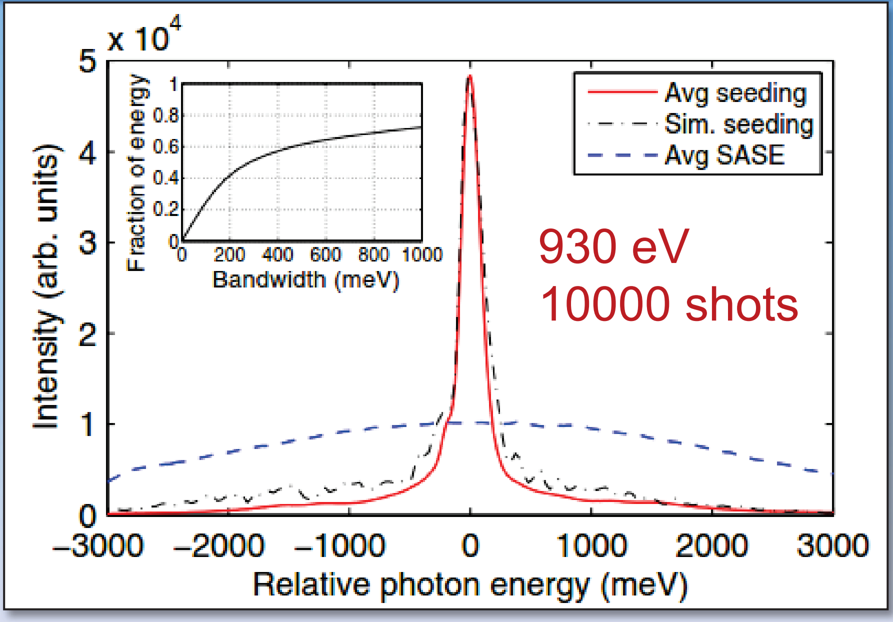

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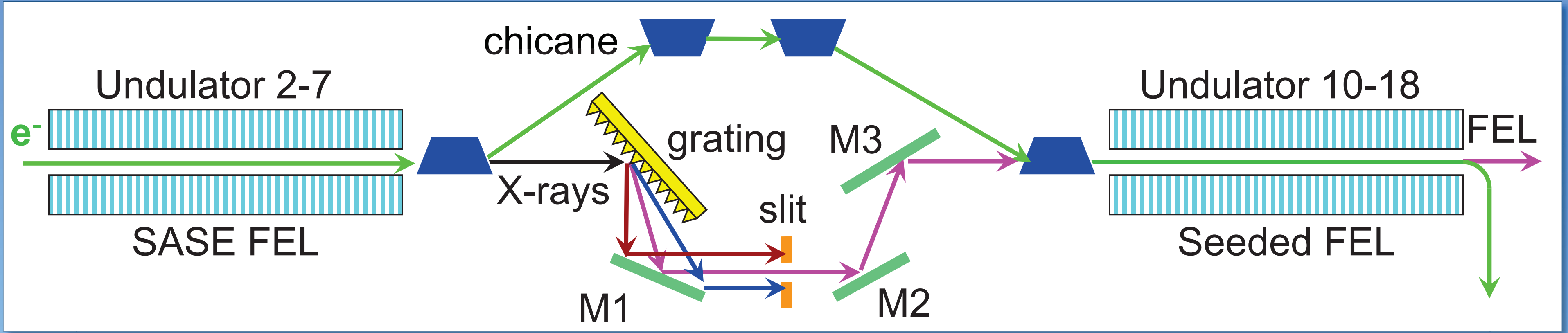
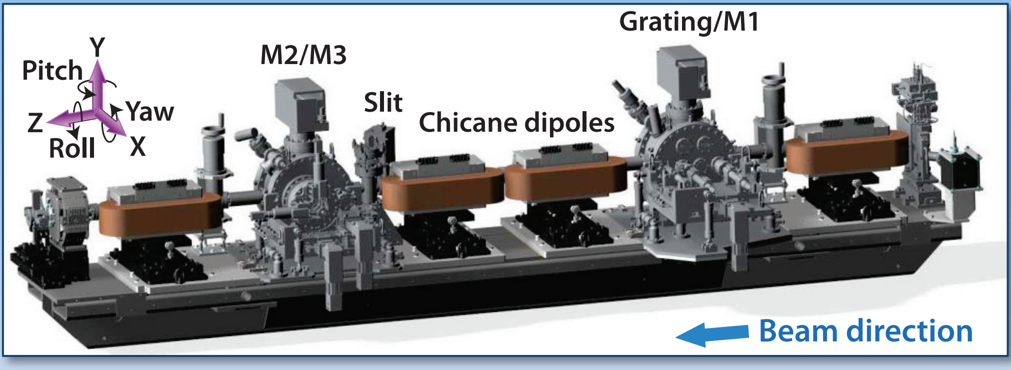
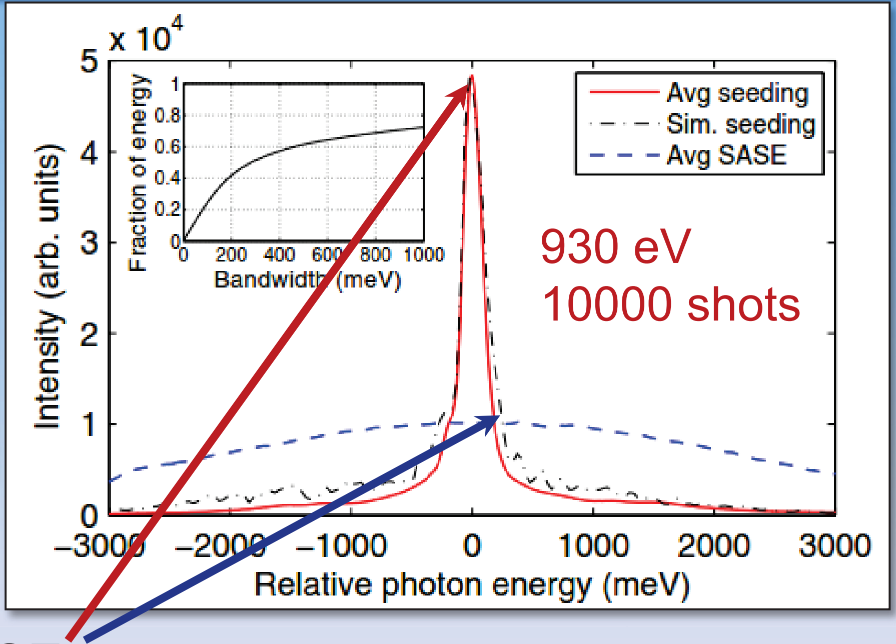


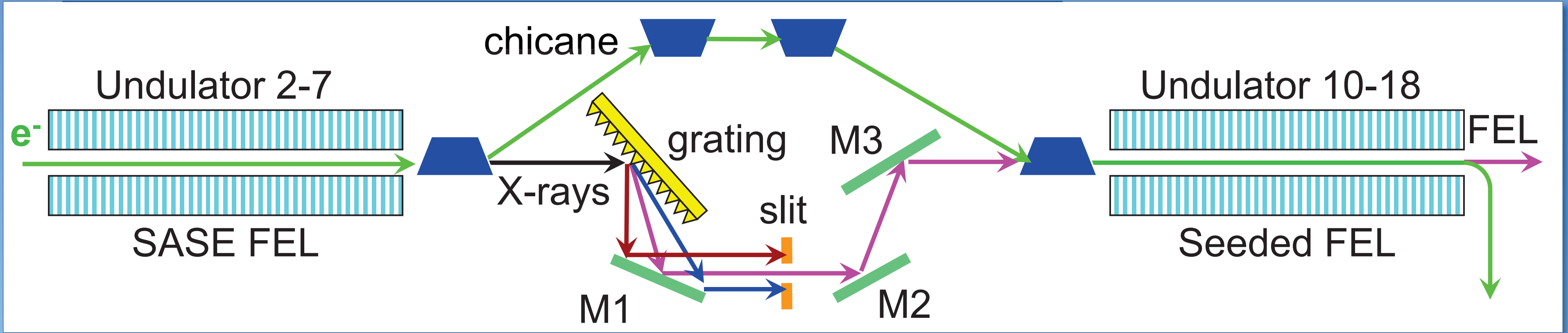


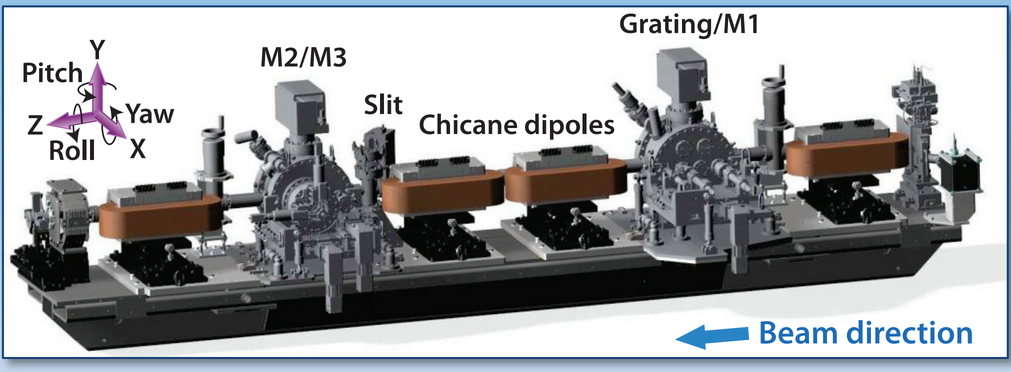


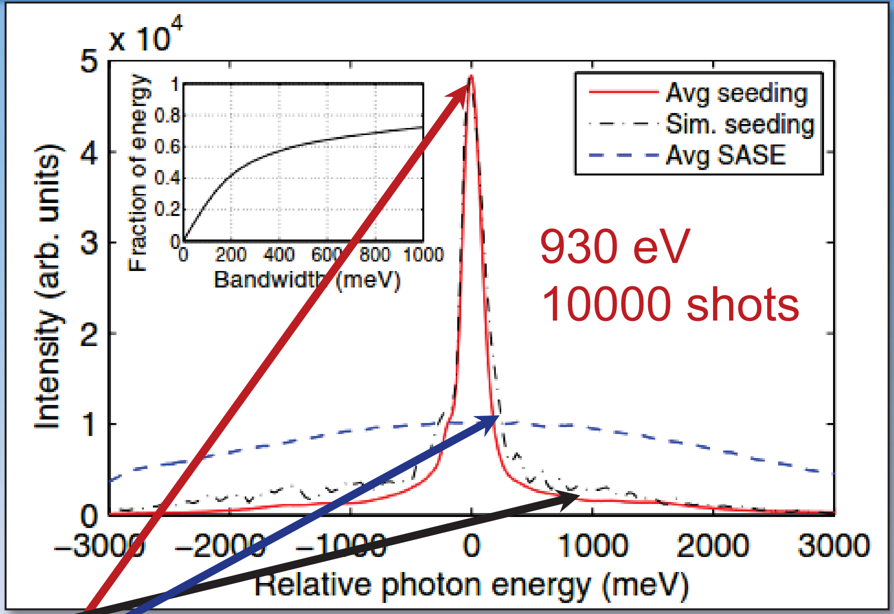
- Spectral brightness ~5x higher than SASE

D. Ratner et al., PRL 114, 054801 (2015) *Y. Feng, TUP026, LCLS-II SXRSS design*

Soft X-ray Self-Seeding (SXRSS)





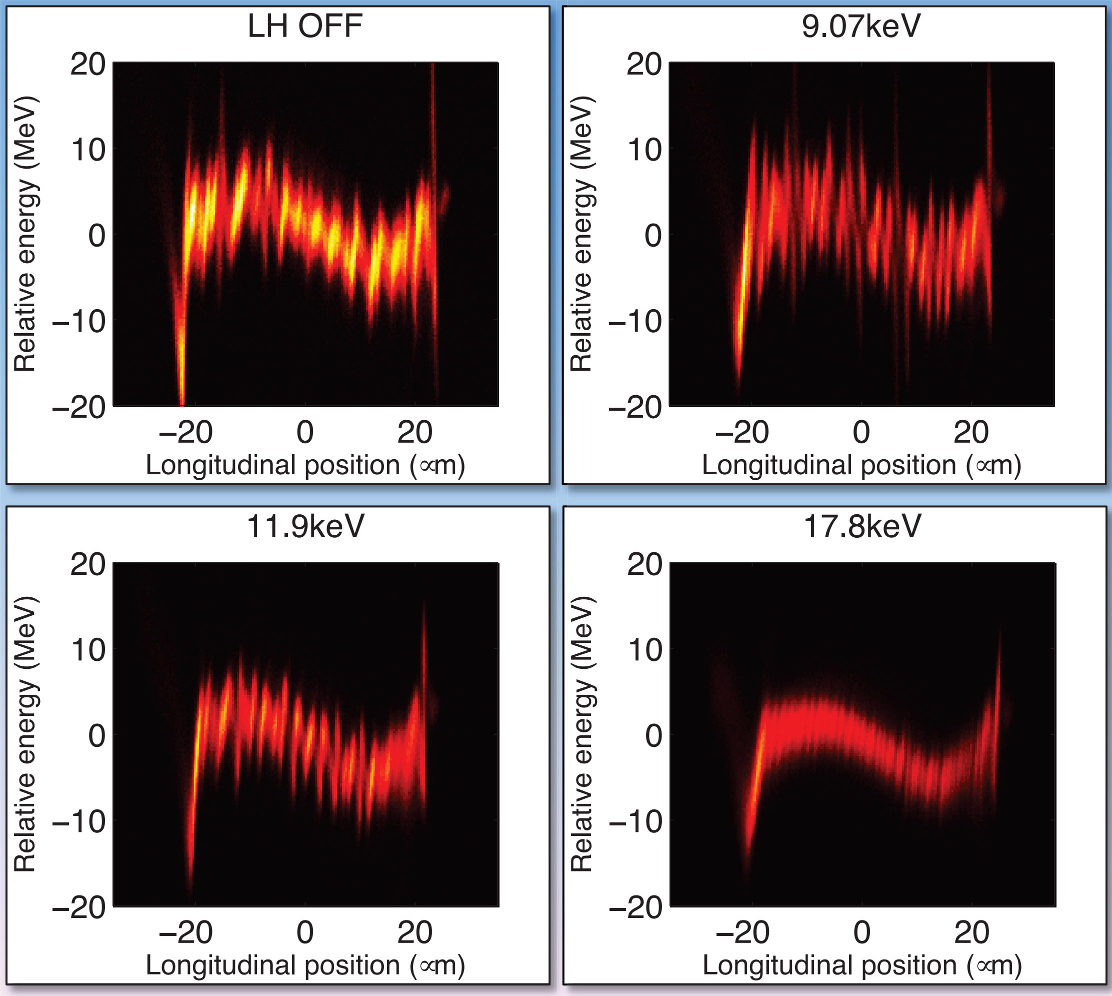


- Spectral brightness ~5x higher than SASE
- Observe spectral pedestals (may degrade certain applications w/o a mono).

D. Ratner et al., PRL 114, 054801 (2015) *Y. Feng, TUP026, LCLS-II SXRSS design*

Where are SXRSS pedestals from?

- Studies ruled out various sources (spectrometer noise, seeding monochromator optics)
- Focus on beam microbunching instability (μBI) that drives sideband growth



Observation of μBI at 4 GeV with X-band Transverse Deflector

D. Ratner et al., PRST-AB 18,030704 (2015), MOP058

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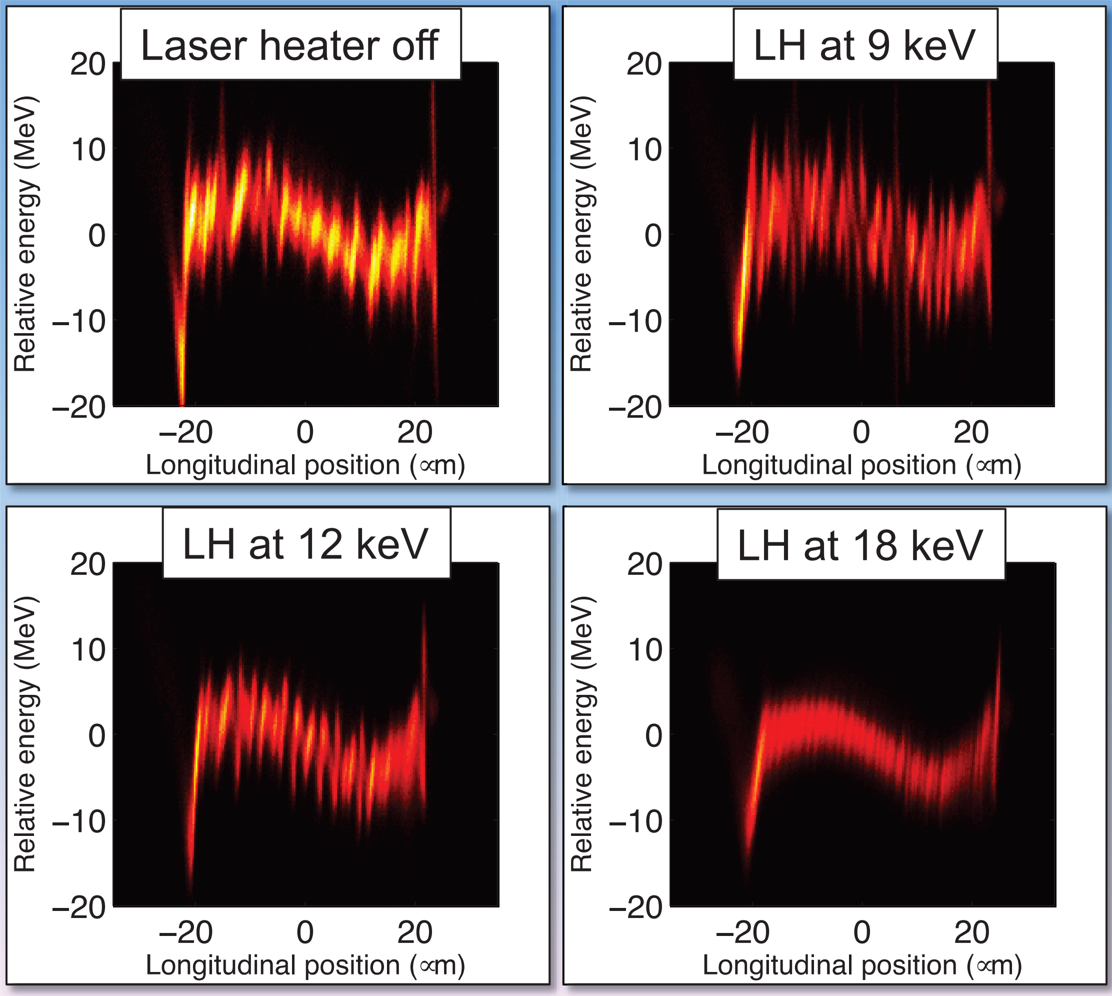

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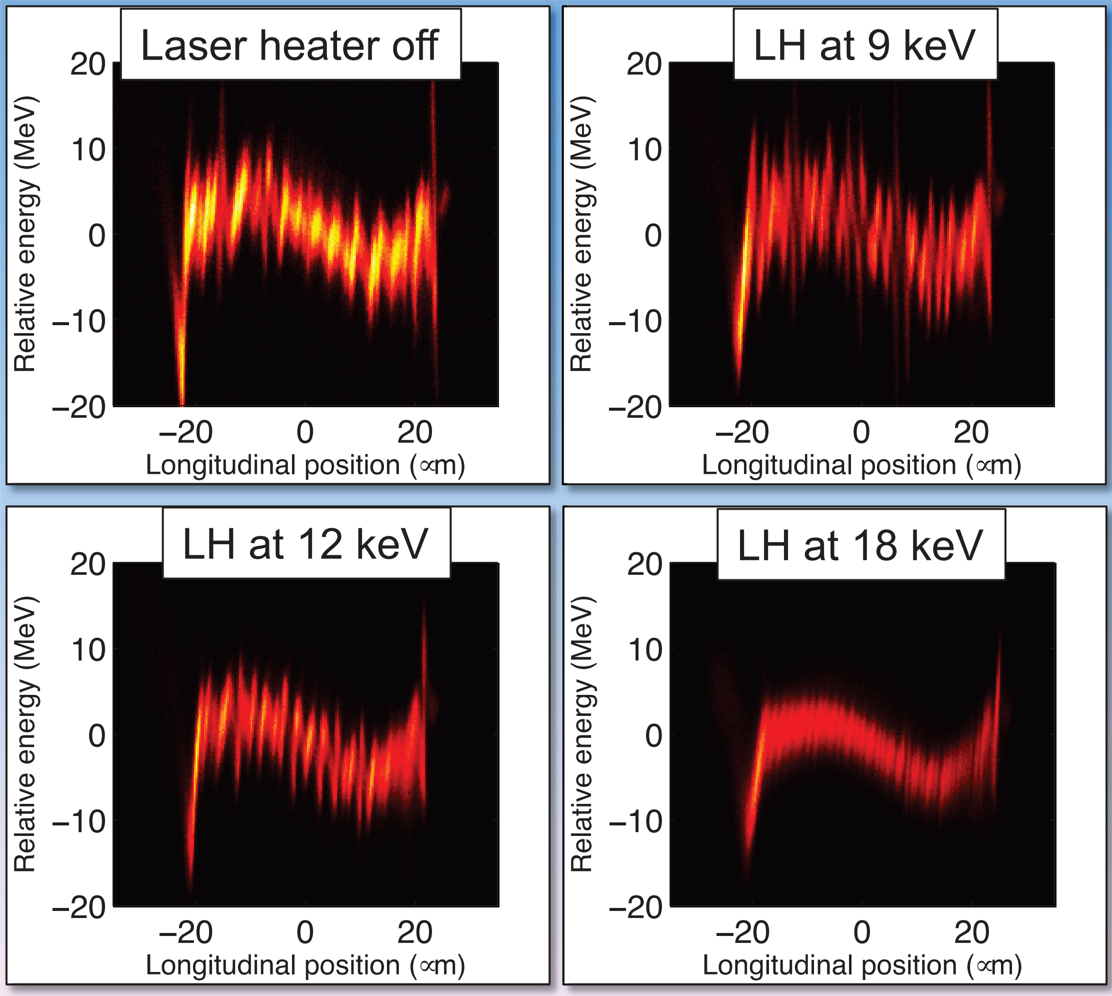

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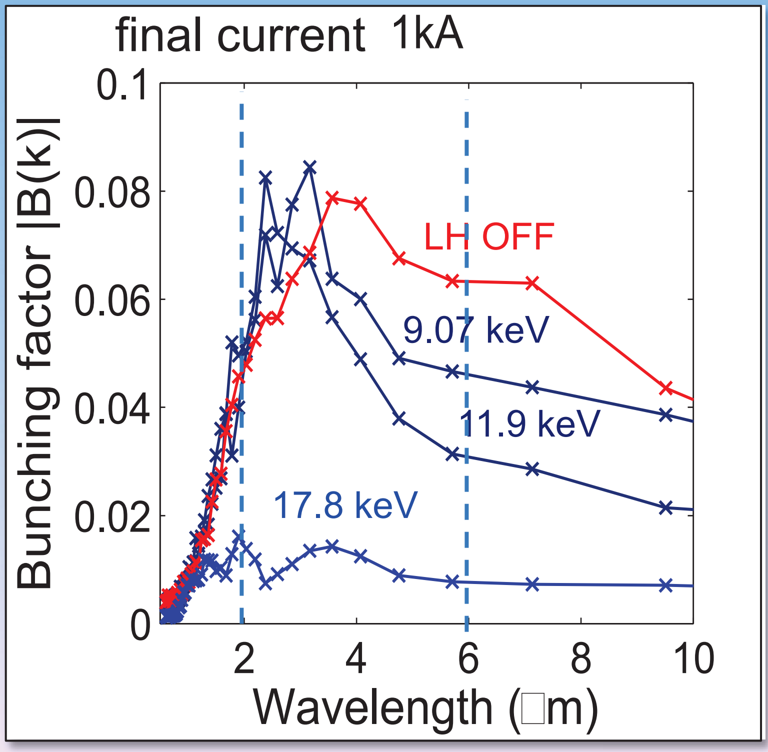


D. Ratner et al., PRST-AB 18,030704 (2015), MOP058

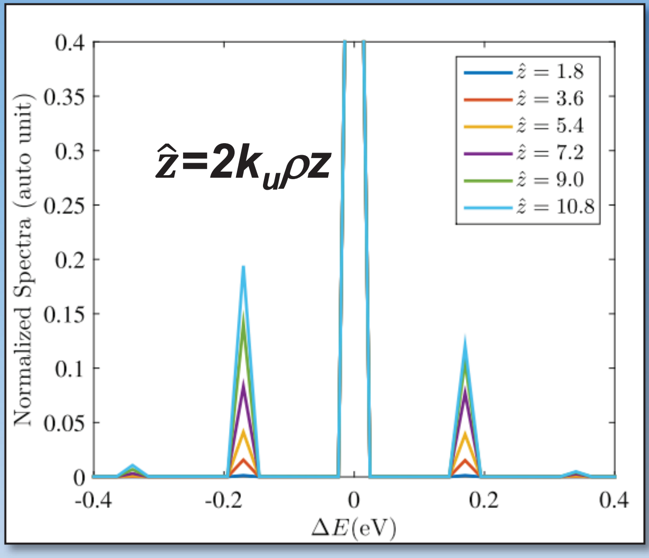
μBI-induced sidebands in a seeded FEL

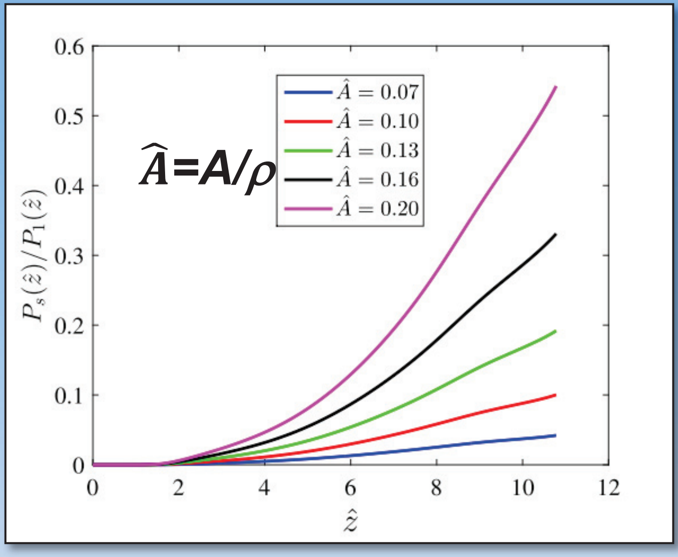
- Sideband (1nm/2μm = 5x10^{-4} within FEL bandwidth)
- Sideband power vs. seed signal power

Z. Zhang, WEP024

$$\frac{P_s(\hat{z})}{P_1(\hat{z})} = \frac{\hat{A}^2}{9}\hat{z}^2 = \frac{(2k_u\rho z)^2}{9}\frac{A^2}{\rho^2}$$

Sideband grows quadratically with undulator length and E mod. amplitude





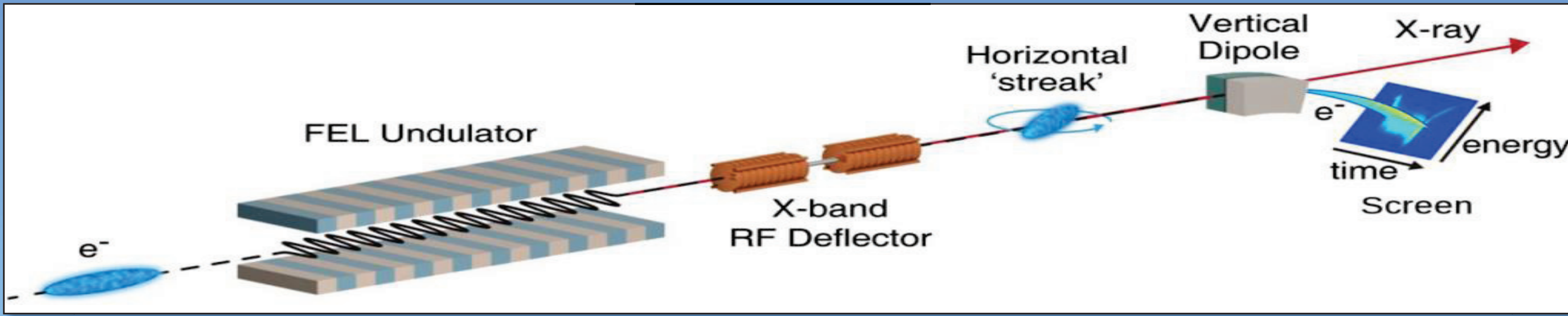
- Take 2$\rho k_u z$ ~ 9 for seeding saturation,

  In order for sideband power < seed power ➔ ***A* < 0.3 ρ**

  Take LCLS E = 4 GeV, $\rho \sim 10^{-3}$, A < 1 MeV (very stringent requirement**!**)

- Needs very uniform beams in longitudinal phase space
  - Laser heater shaping for more effective heating ***S. Li, WEP005***
  - Single BC instead of 2 BCs to reduce μBI (similar to FERMI)

fs X-ray diagnostics with an X-band transverse deflector (XTCAV)



Y. Ding, TUA01

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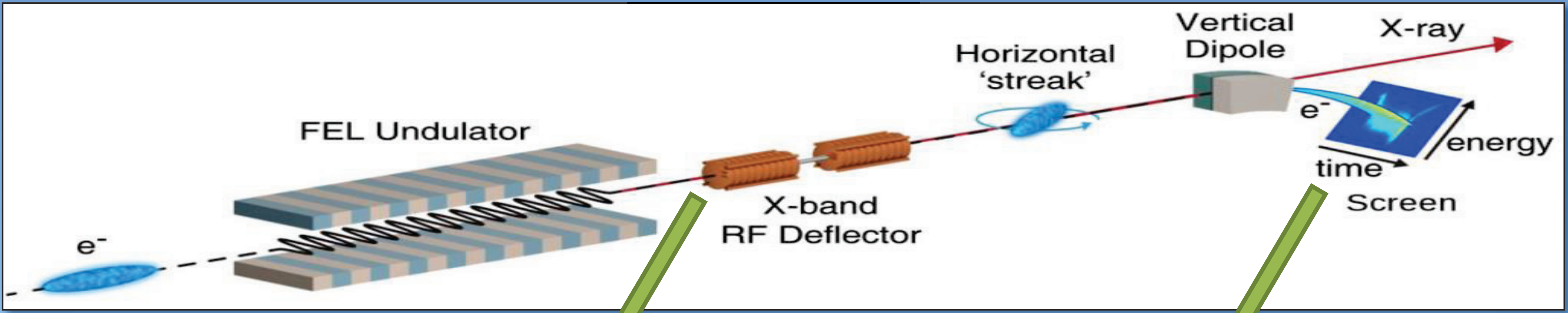

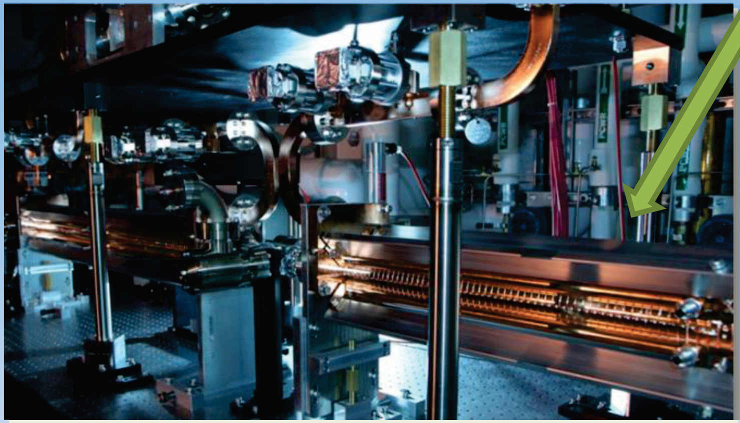

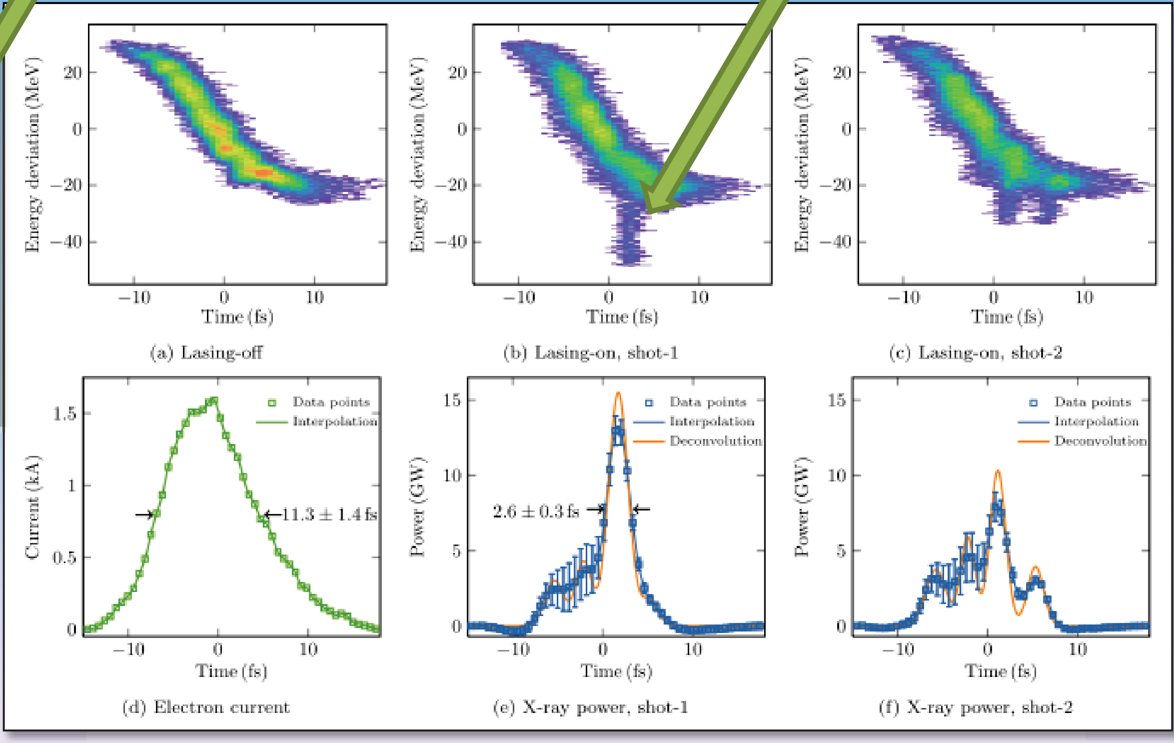

Y. Ding, TUA01

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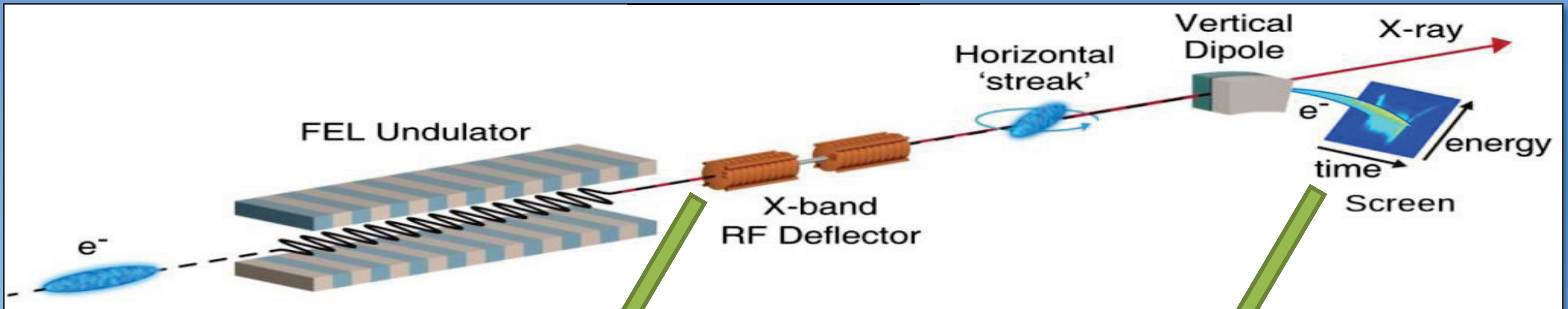
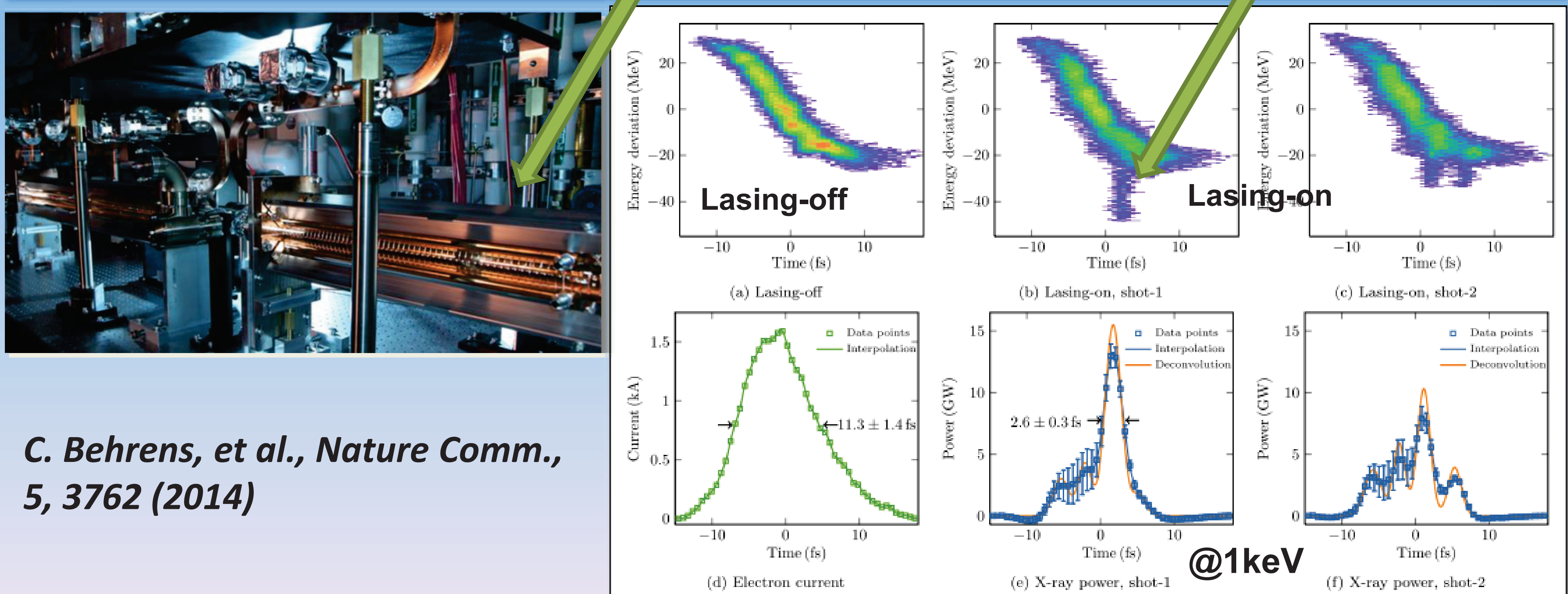


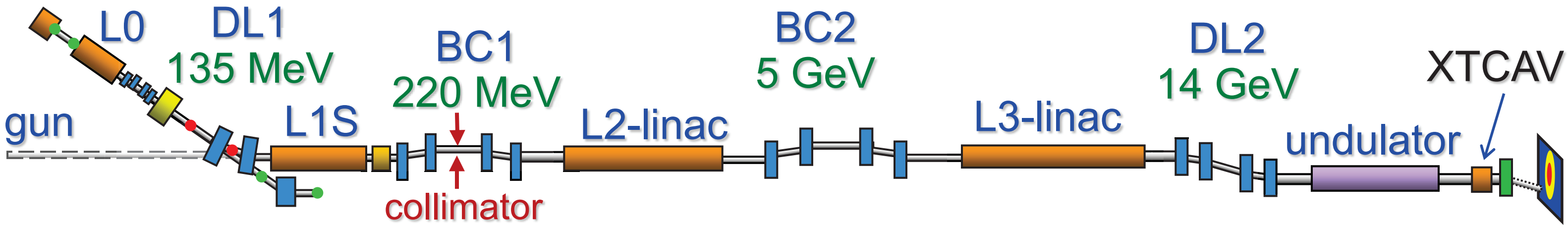


C. Behrens, et al., Nature Comm., 5, 3762 (2014)

Reconstructed X-ray profile 2.6 fs (FWHM)

Y. Ding, TUA01

Generating high power FEL with a horn-collimated beam



Y. Ding, WEP024

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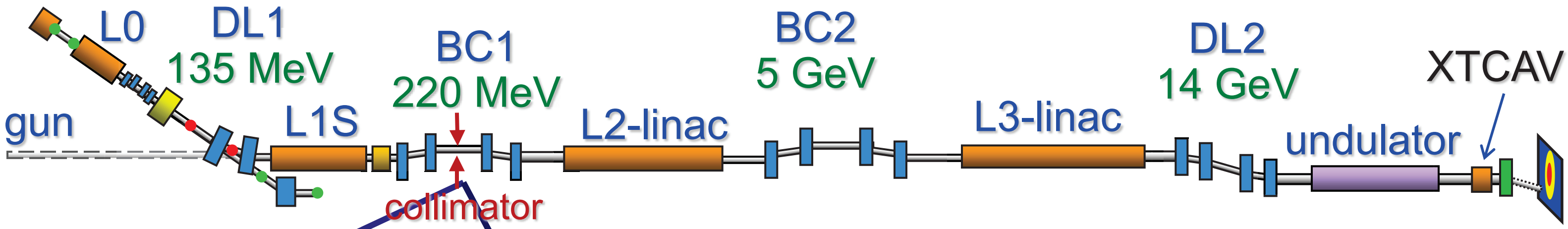

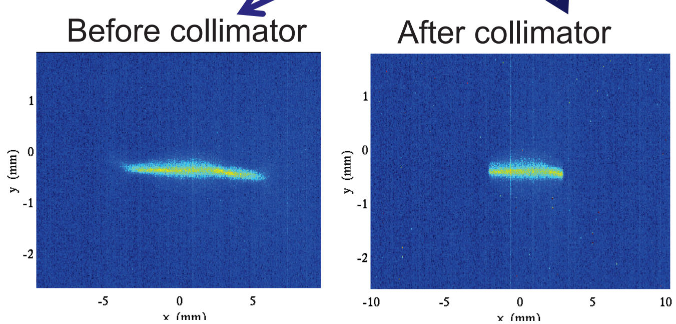

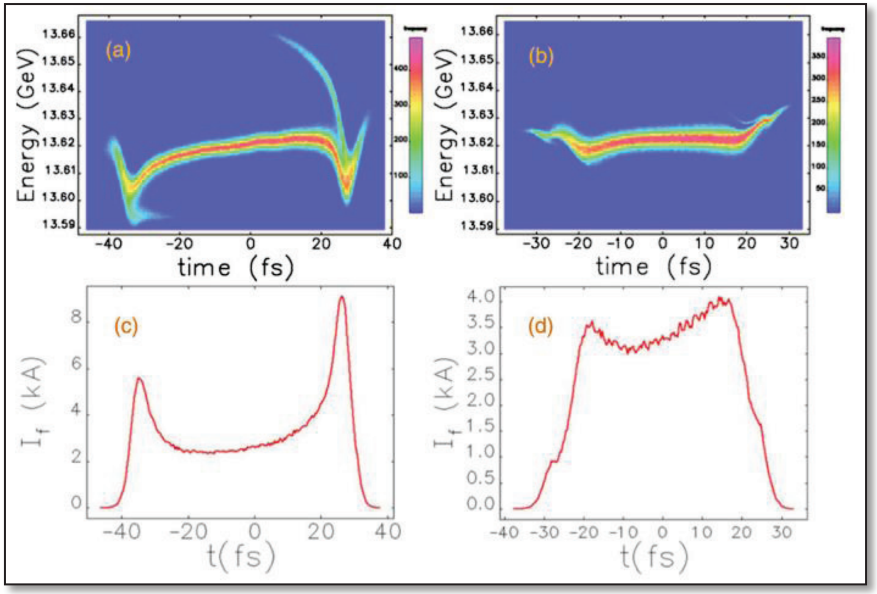

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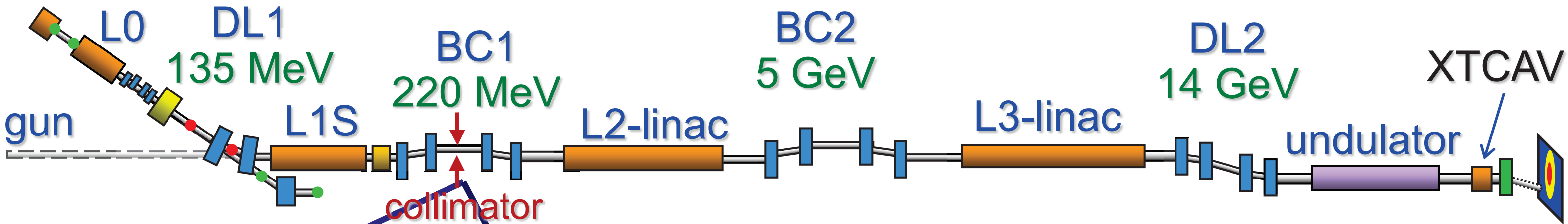
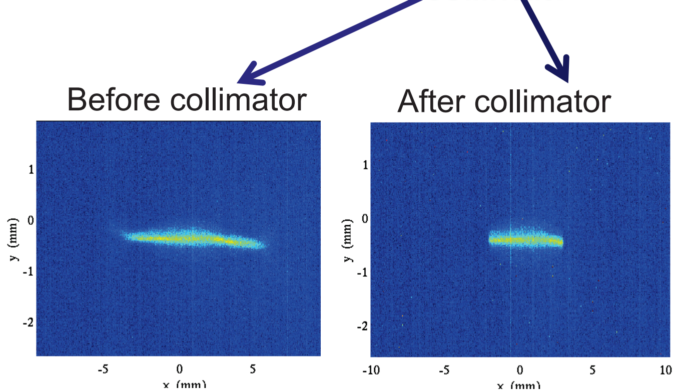
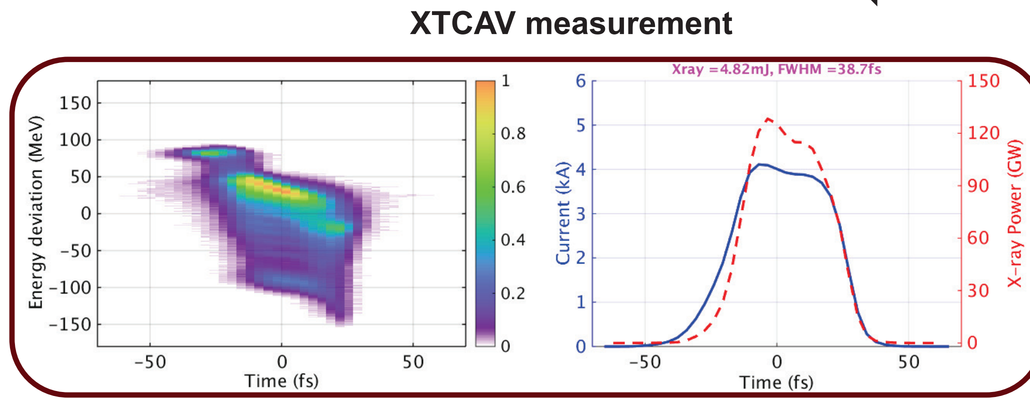


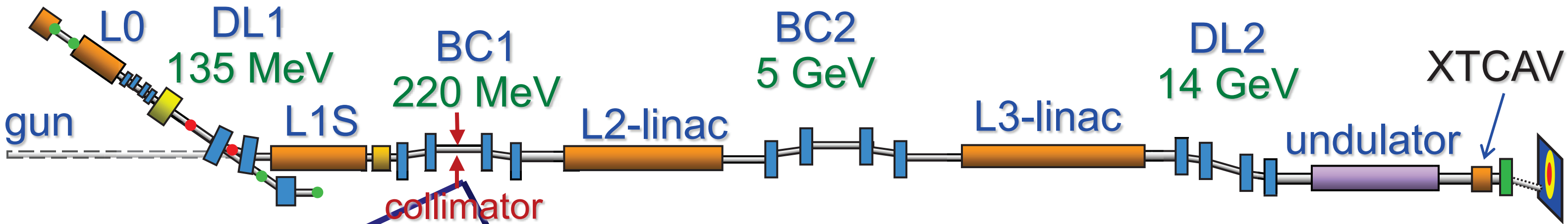


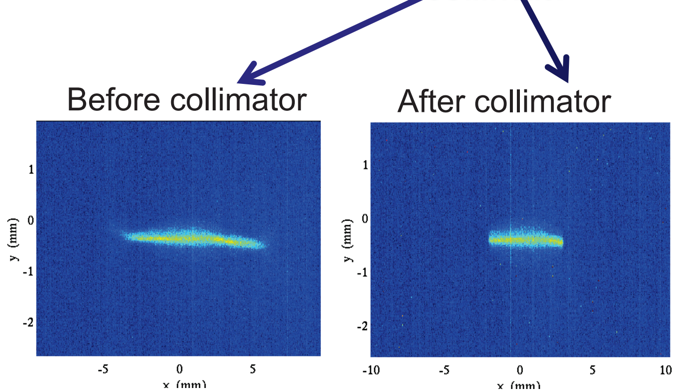


simulations

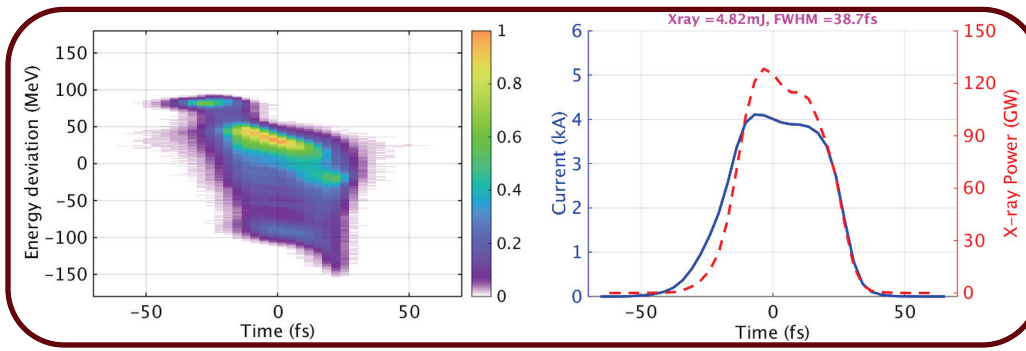
Y. Ding, WEP024

Generating high power FEL with a horn-collimated beam

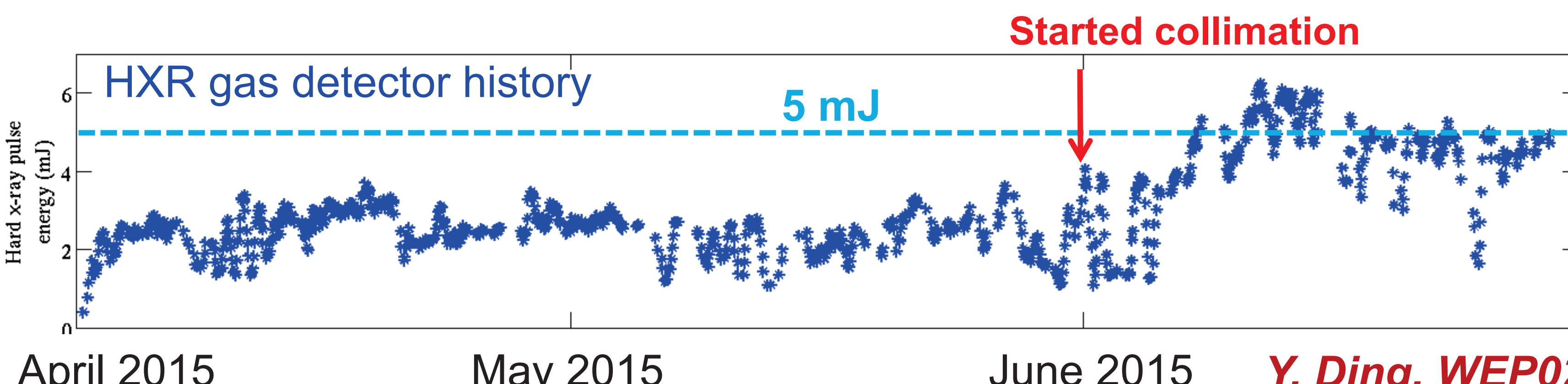




XTCAV measurement



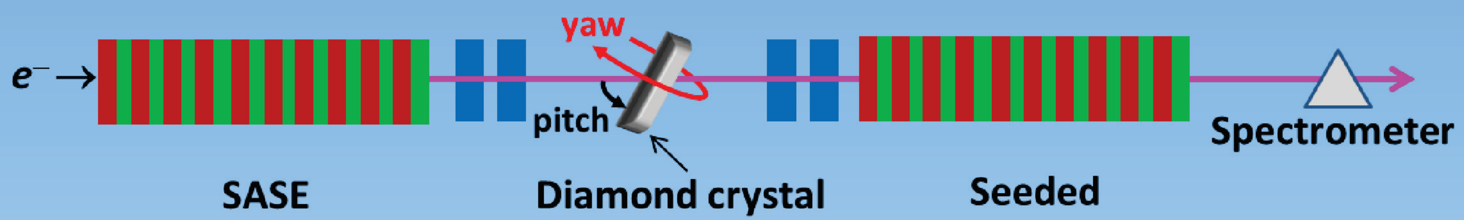
- **Routinely** achieved hard x-ray pulse energy ~4-5 mJ and ~100 GW (from XTCAV).
- Further improvement on this mode, such as compensating BC2 CSR effect for shorter bunches and a few hundred GW power, will be studied.



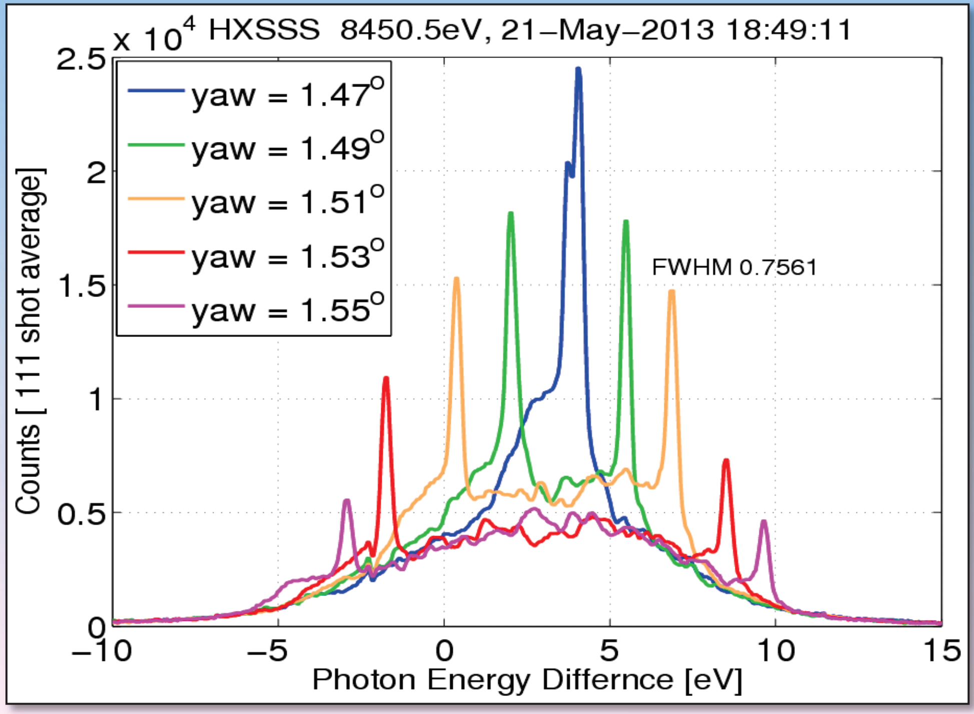
Y. Ding, WEP024

2-color seeded FEL

- Exciting and probing samples above and below absorption edges, imaging at different wavelengths.
- By adjusting the yaw angle in addition to the usual pitch angle of the seeding crystal, two-color hard X-ray self-seeded FEL with two different crystal diffraction planes were demonstrated.

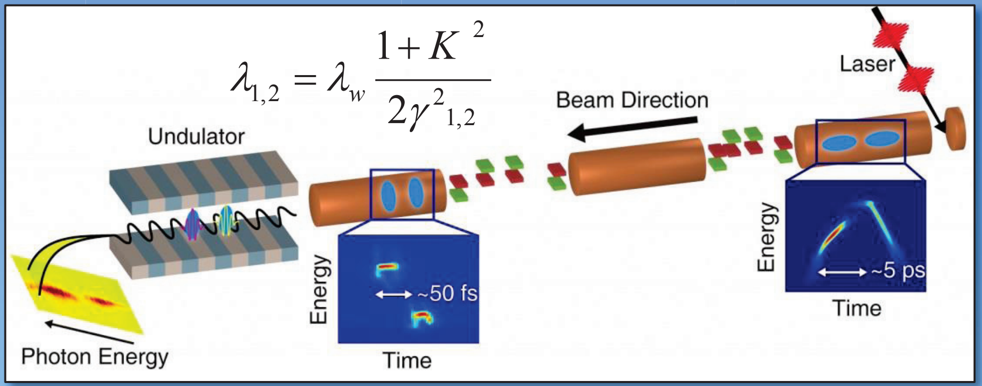


A.A. Lutman et al.
PRL 113, 254801, 2014

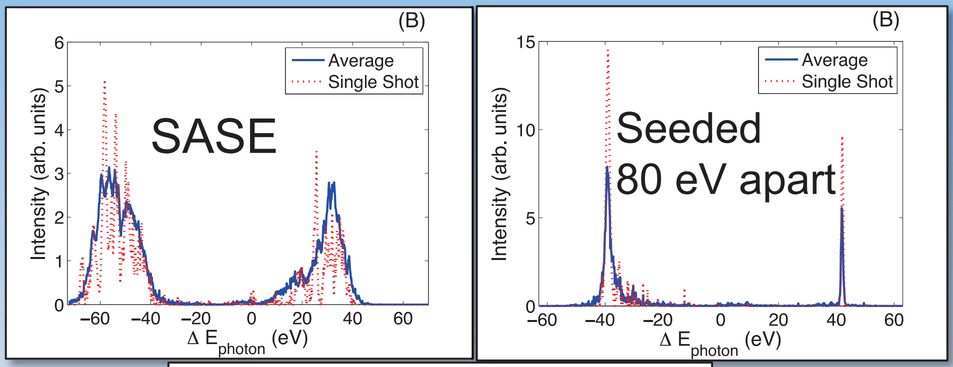


Twin-bunch, high-power 2-color FEL

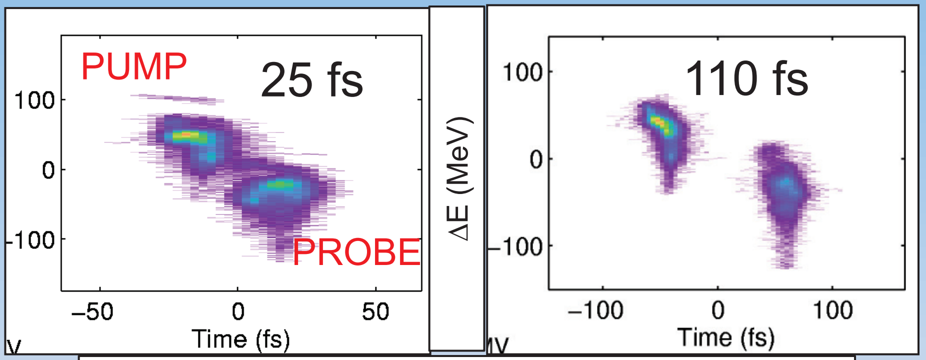
- Two bunches (in same RF bucket) are accelerated and compressed
- Each bunch lases at its own FEL color, hence improving the peak power over previous schemes by one order of magnitude



- Allows for independent control of energy and time delay



Hard X-ray FEL spectra



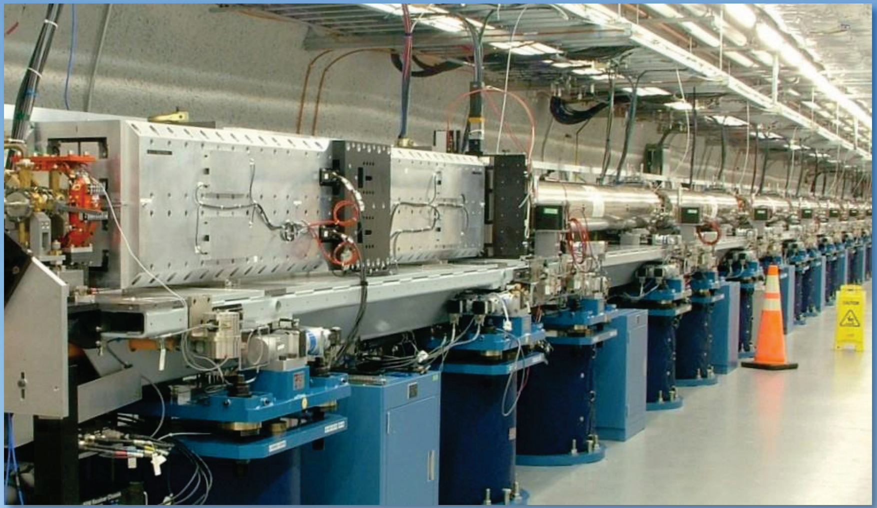
Time delays (measued w/ XTCAV)

- Extend to soft X-rays by combining with double-slotted foil to generate shorter bunches and negative to positive delays *A. Marinelli, WEP080*

A. Marinelli et al., Nature Comm. 6, 6369 (2015); Z. Zhen et al., PRSTAB 18, 030702 (2015)

Novel Undulators

- A new type of undulator ("Delta") has been developed and commissioned at LCLS for polarization control. ***(H.-D. Nuhn, WED01)***



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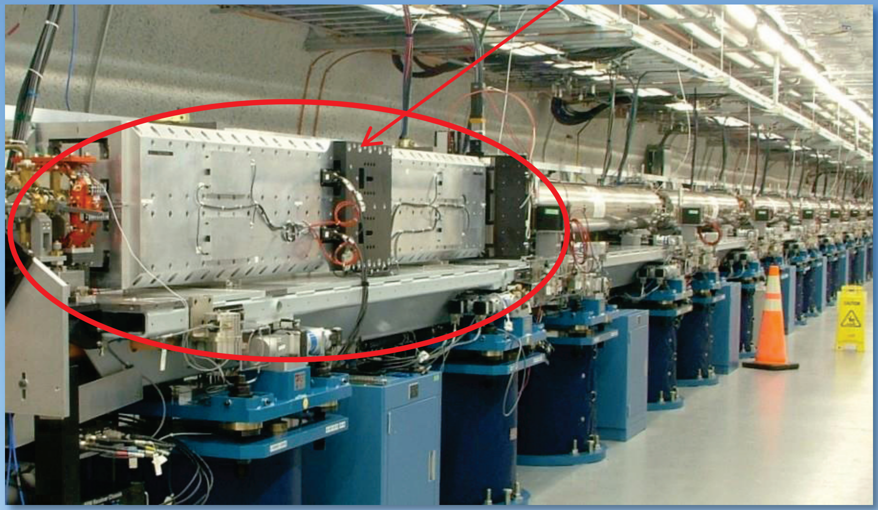

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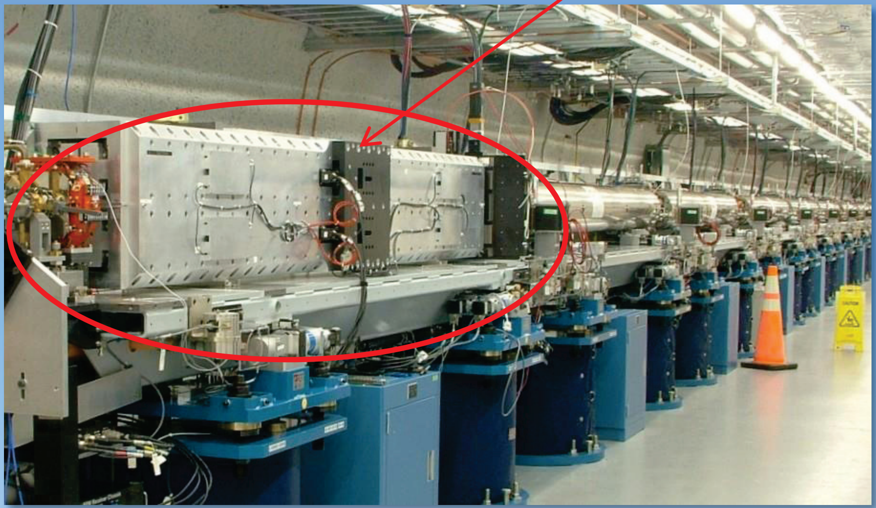
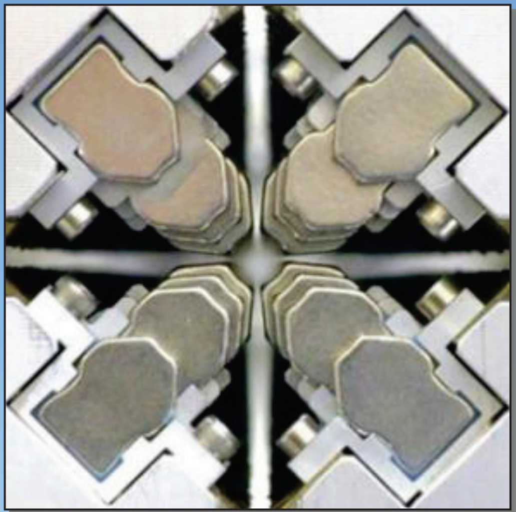
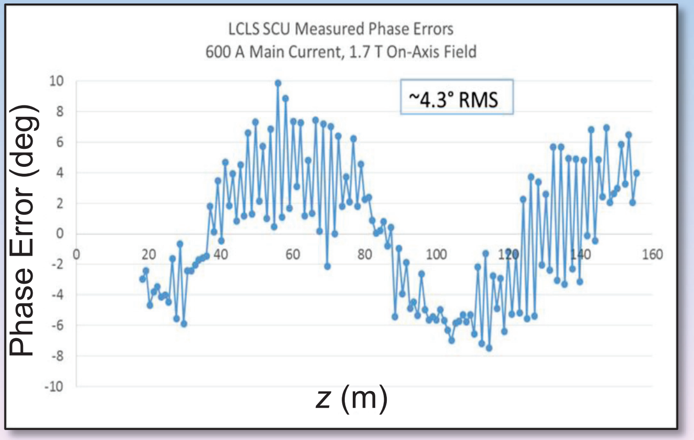




- Superconducting undulator improves FEL efficiency and extends spectral range for LCLS-II (***P. Emma et al., Proc. of FEL 2014***)



ANL prototype (NbTi) phase error controlled to < 5 deg rms

Compact XFELs

- Synchrotrons can provide 30-60 beamlines per machine, much more cost effective than XFELs (1-2 beamlines at present)
- Strong motivation to develop compact coherent x-ray sources at a small fraction of cost and size of big XFELs
- Search "Compact XFEL" on google

- Many ideas exist to make compact coherent sources
  - Some relies on Inverse Compton Scattering (replacing cm-period undulator with μm wavelength laser ➔ lower e-beam energy by 100
  - Some relies on advanced accelerator methods (e.g., plasma accelerator boosts gradient by 100x or more) ***M. Hogan, WEC01***

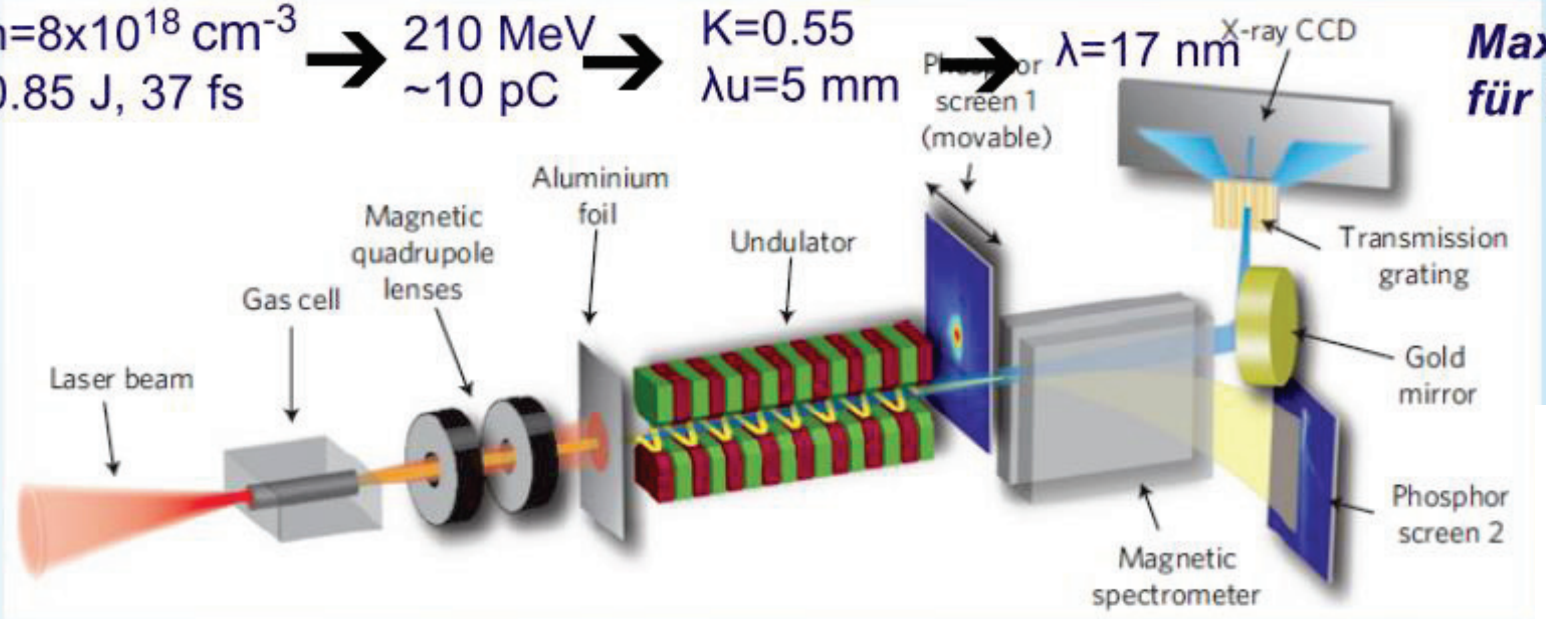
Laser plasma accelerators (LPAs)

C. Schroeder

- Energy: ~ 100 MeV - 4 GeV
  - Obtained 100TW-1PW laser pulses in mm - cm long plasmas
- Charge: ~ 1- 100 pC
  - Depends on tuning, energy spread due to beam loading
- Energy spread: ~ 1 - 10% level
  - Depends on amount of charge, trapping physics
- Normalized Emittance: ~ 0.1 micron
  - Based on divergence measurements (~ 1 mrad) and e-beam spot (~0.1 micron)
  - Improved measurements needed

$n=8\times10^{18}$ cm^{-3} 0.85 J, 37 fs → 210 MeV ~10 pC → K=0.55 λu=5 mm → λ=17 nm

Max-Plank-Institut für Quantenoptik



M. Fuchs et. al., Nature Physics 5, 826 (2009).

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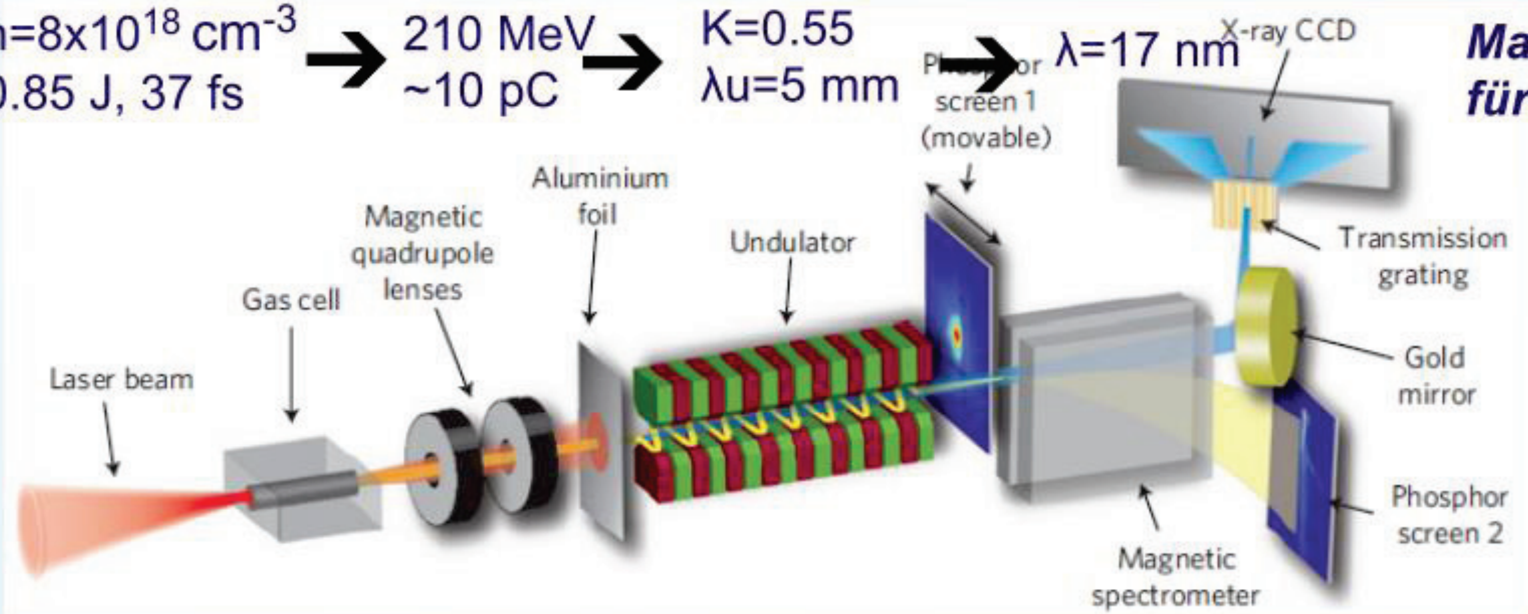
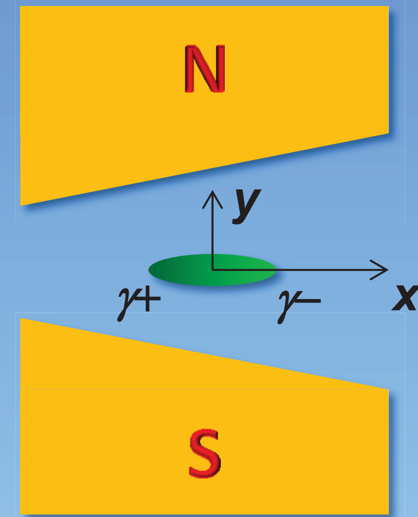


M. Fuchs et. al., Nature Physics 5, 826 (2009).

Compact XFELs using Transverse Gradient Undulator

- TGU can be used to compensate large energy spread of laser plasma accelerator beams for a compact FEL

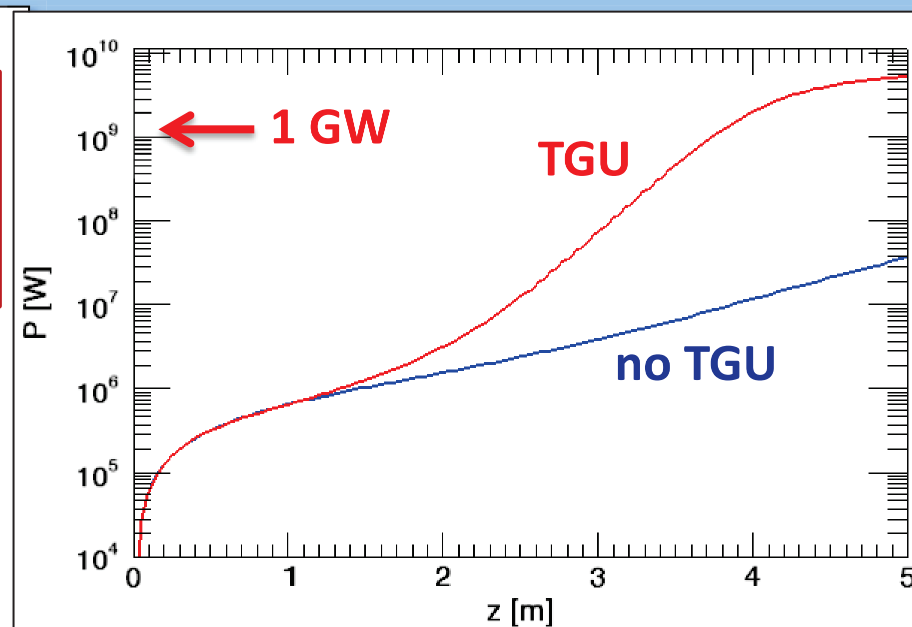
$$\alpha = \frac{dK/K_0}{dx}$$



- FEL resonance can be satisfied for all energies if dispersion at undulator is chosen as $\eta = \frac{2+K_0^2}{\alpha K_0^2}$

T. Smith et al., J. Appl. Phys. 1979

Parameter	Symbol	EUV	X-ray
Beam energy	$\gamma_0 mc^2$	500 MeV	1 GeV
Norm. transv. emittance	$\gamma_0 \varepsilon_x$	0.1 μm	0.1 μm
Peak current	I_0	5 kA	10 kA
Flattop bunch duration	T	10 fs	5 fs
Rel. rms energy spread	σ_δ	2%	1%
Undulator type		Hybrid	SC
Undulator period	λ_u	2.18 cm	1 cm
Undulator length	L_u	5 m	5 m
Undulator parameter	K_0	1.85	2
Transverse gradient	α	43 m^{-1}	150 m^{-1}
Horizontal dispersion	η	3.7 cm	1 cm
Resonant wavelength	λ_r	31 nm	3.9 nm

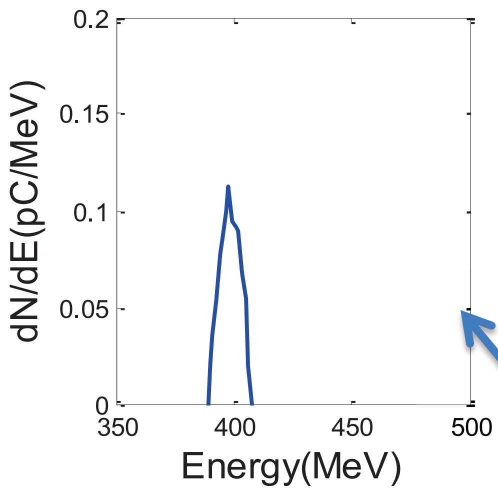


Z. Huang, Y. Ding, C. Schroeder, PRL 109, 204801 (2012)

High-quality high-energy electron beams from a cascaded LPA

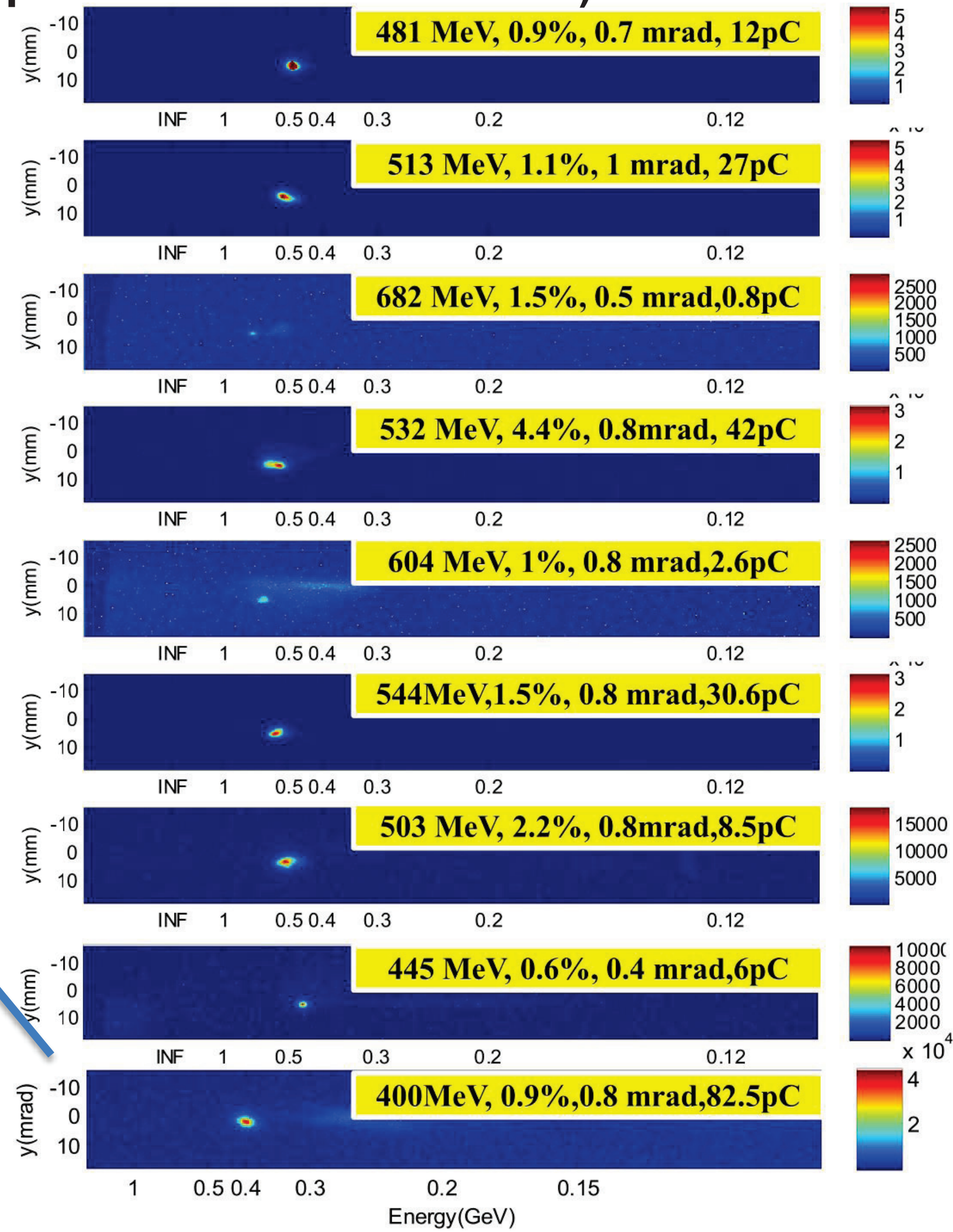
Courtesy J.S. Liu (Shanghai Institute of Optics and Fine Mechanics)

Peak energy: 0.4-0.6 GeV
Energy spread: ~1%
Beam charge : up to 82.5 pC
Divergence: 0.4-1.0 mrad



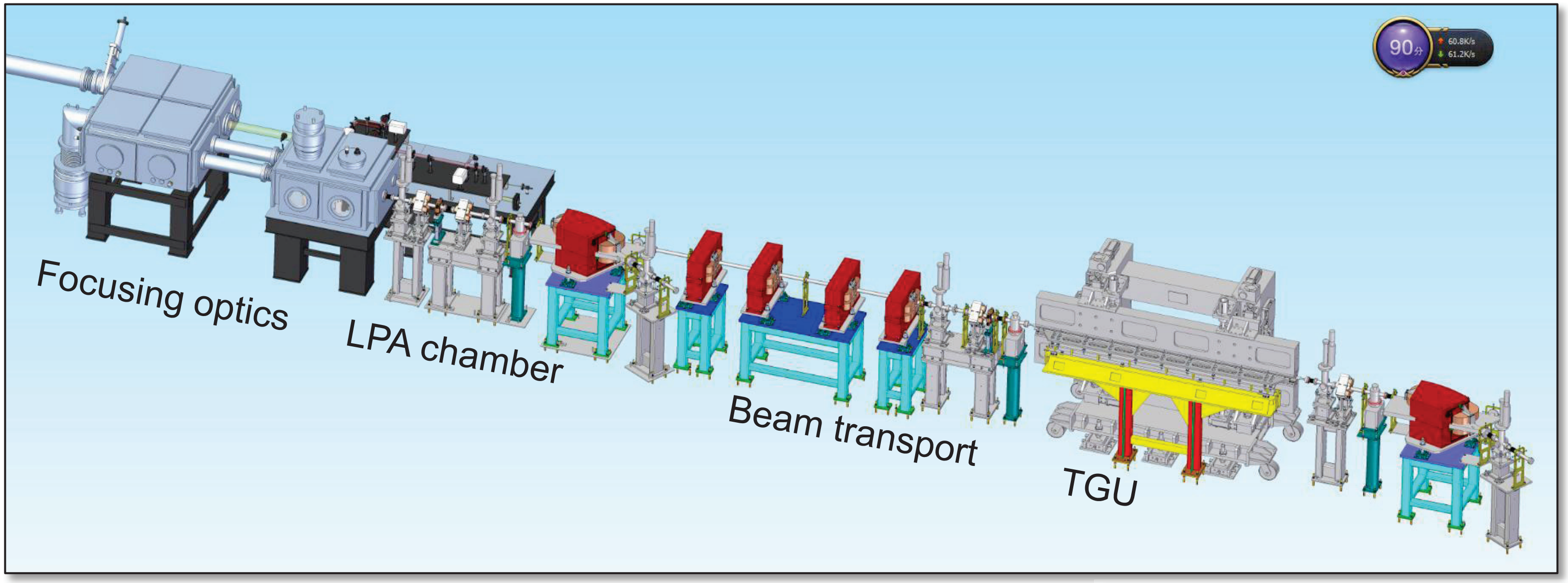
Peak energy	398 MeV
Energy spread (rms)	0.8%
Divergence (rms)	0 .8 mrad
Beam charge	82.5 pC

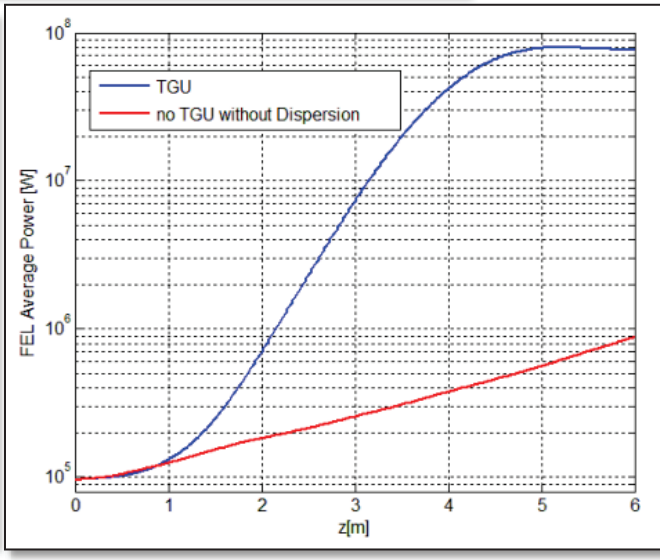
J.S. Liu et al., Phys. Rev. Lett. 107, 035001 (2011).



LPA FEL with TGU (SIOM/SINAP)

- Plan a demonstration experiment at 30 nm (400 MeV, 6 m TGU)





SIOM LPA setup (J.-S. Liu)

SINAP TGU assembly (D. Wang)

Summary

- XFEL is a breakthrough in light source development, enabling atomic-scale imaging at femtosecond time resolution.
- Vigorous accelerator and FEL R&D can drastically improve FEL coherence and brightness, which in turn demands better control of electron beams and advanced diagnostics and undulator development.
- Many challenges exist for realization of compact XFELs, but the efforts are worth pursuing and will be complementary to large facilities.

Acknowledgement

- I would like to thank Kwang-Je Kim, who introduced me to the beautiful and intricate FEL world, and thank Argonne LEUTL team that first demonstrated SASE saturation!
- I wish to thank the entire LCLS team and talented SLAC accelerator research staff and engineers. They made all these possible and are so much fun to work with!
- Thank you all for your attention!