Future perspectives on short wavelength FELs

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SLAC National Accelerator Laboratory

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

Intro on FEL physics and FEL R&D

Attosecond pulses

Seeded FELs

Future R&D

Opportunities for advanced accelerators

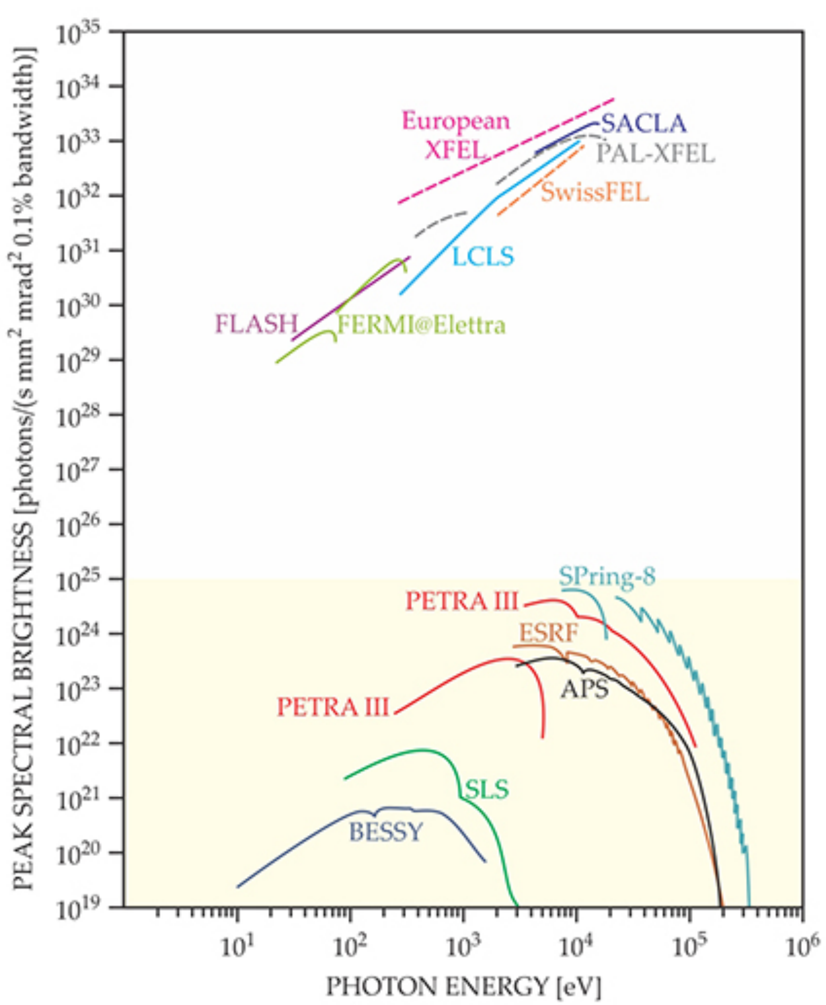
DISCLAIMER:
A lot of work being done, can't possibly include everything…
I will focus on experimental progress.
I am not immune to bias…

The X-Ray Free-Electron Laser

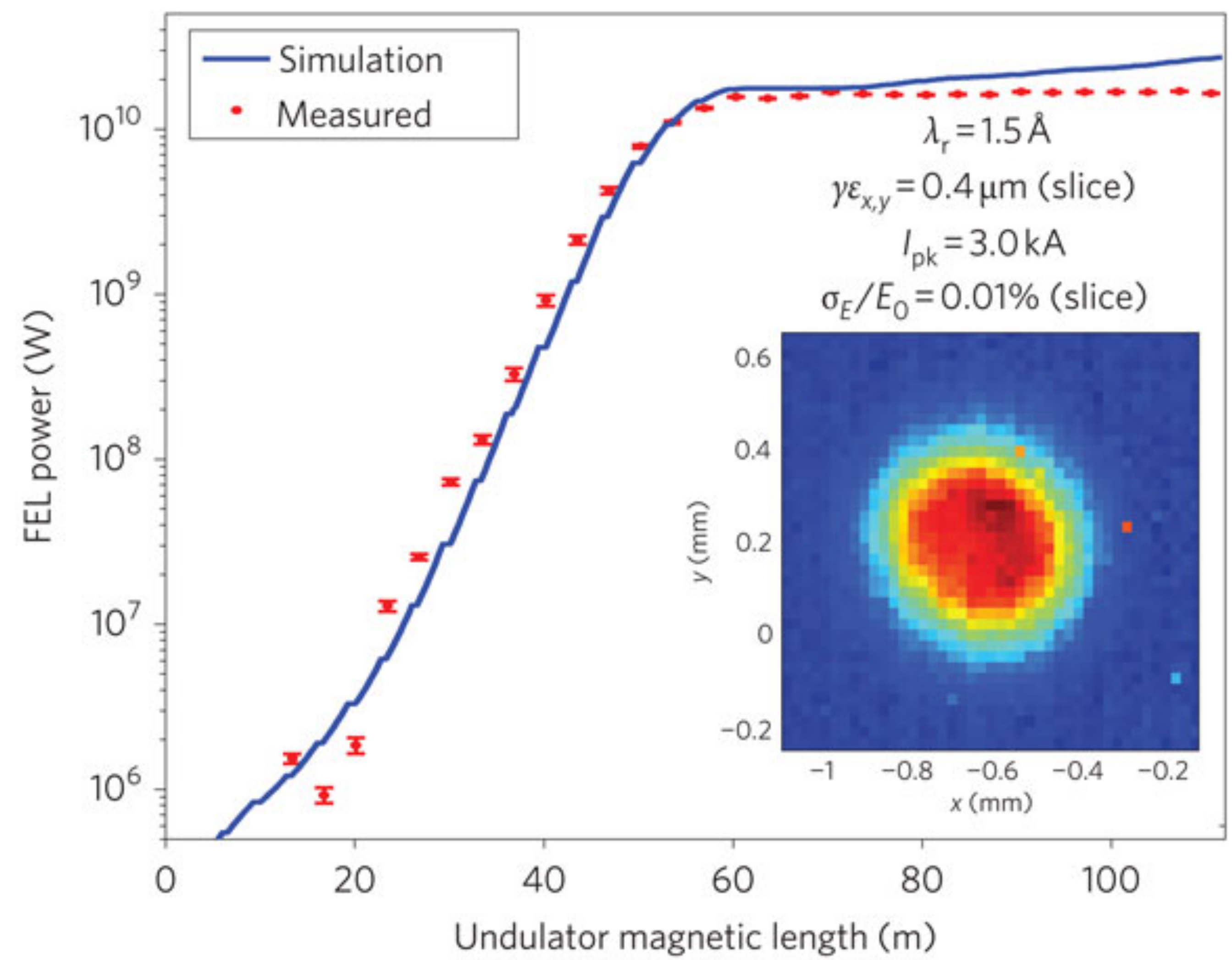
SLAC

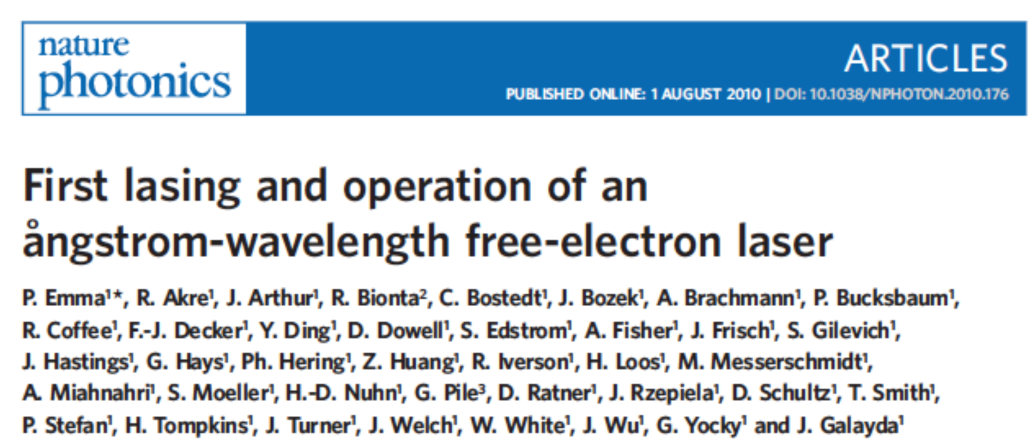
X-FEL shares properties of conventional lasers:

-High Power (up to 100s GW)
-Short Pulse (0.2-100 fs)
-Narrow Bandwidth (~0.1% to 0.005%)
-Transverse Coherence



Philip H. Bucksbaum; Nora Berrah; *Physics Today* **68,** 26-32 (2015)




nature photonics

ARTICLES

PUBLISHED ONLINE: 1 AUGUST 2010 | DOI: 10.1038/NPHOTON.2010.176

First lasing and operation of an ångstrom-wavelength free-electron laser

P. Emma[1*], R. Akre[1], J. Arthur[1], R. Bionta[2], C. Bostedt[1], J. Bozek[1], A. Brachmann[1], P. Bucksbaum[1], R. Coffee[1], F.-J. Decker[1], Y. Ding[1], D. Dowell[1], S. Edstrom[1], A. Fisher[1], J. Frisch[1], S. Gilevich[1], J. Hastings[1], G. Hays[1], Ph. Hering[1], Z. Huang[1], R. Iverson[1], H. Loos[1], M. Messerschmidt[1], A. Miahnahri[1], S. Moeller[1], H.-D. Nuhn[1], G. Pile[3], D. Ratner[1], J. Rzepiela[1], D. Schultz[1], T. Smith[1], P. Stefan[1], H. Tompkins[1], J. Turner[1], J. Welch[1], W. White[1], J. Wu[1], G. Yocky[1] and J. Galayda[1]

Working Principle

Resonant Interaction

↓

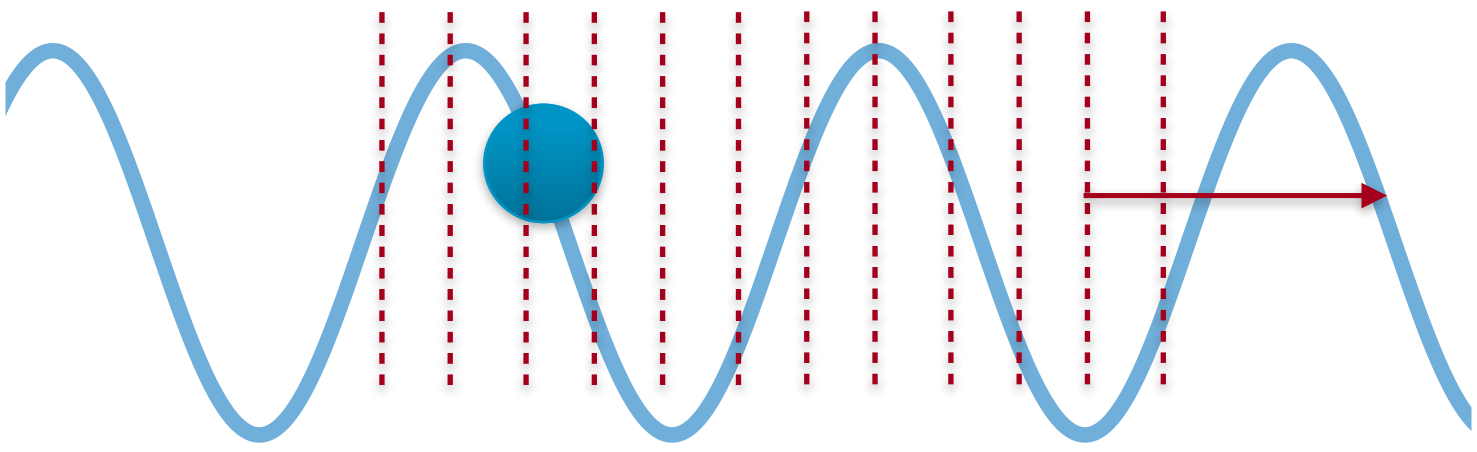
Energy Modulation

↓

Density Modulation

↓

Coherent Radiation



Net energy exchange between electron and wave

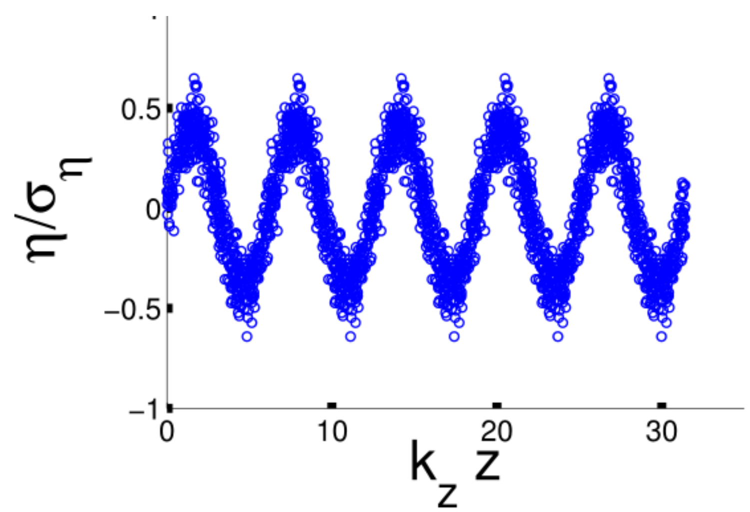
Working Principle

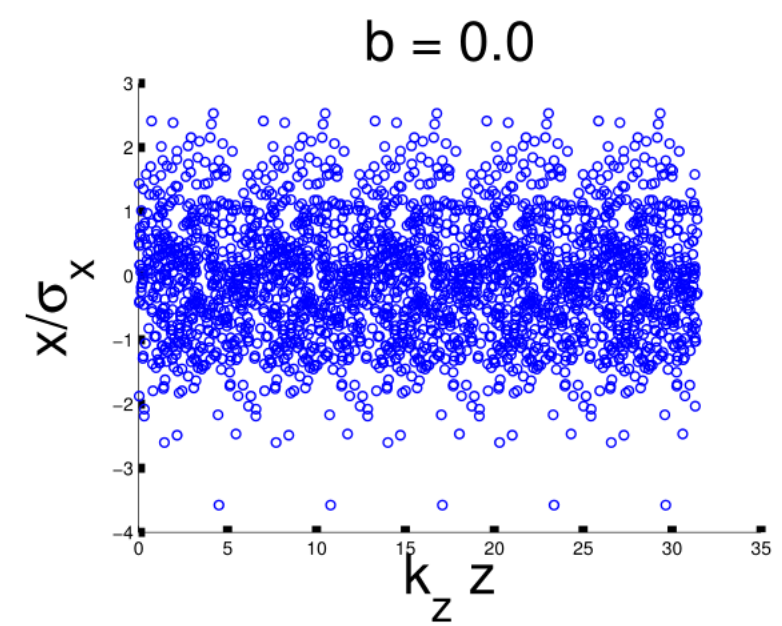
Resonant Interaction

Energy Modulation

Density Modulation

Coherent Radiation





Working Principle

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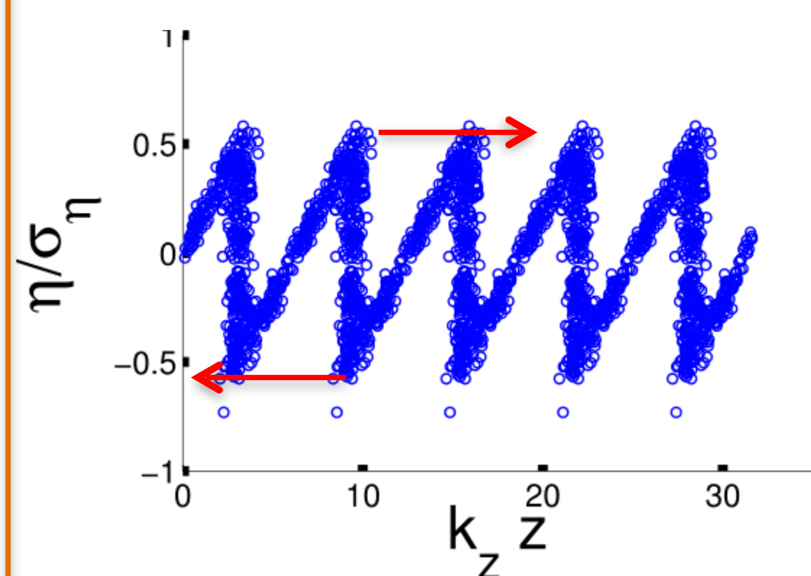

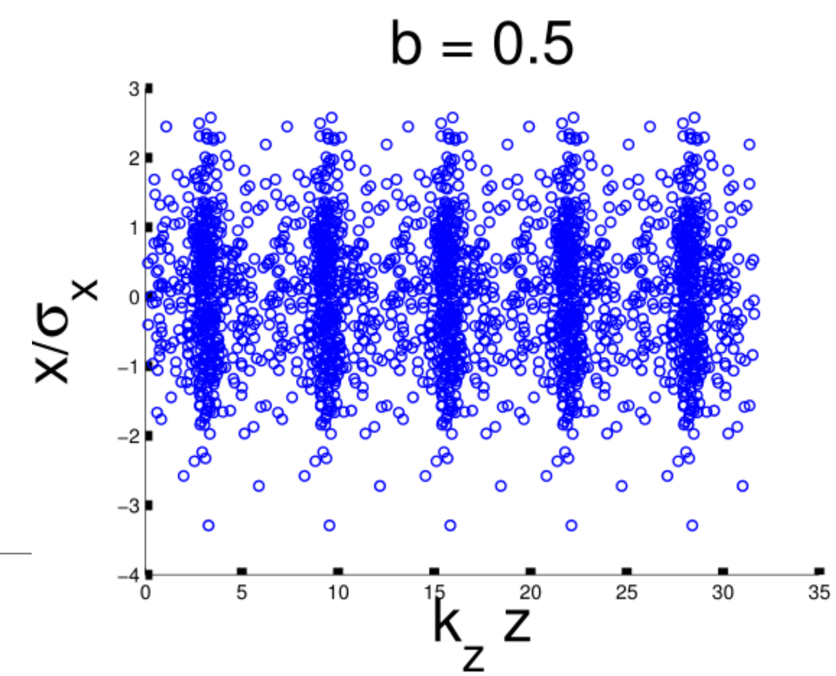

Working Principle

Resonant Interaction

↓

Energy Modulation

↓

Density Modulation

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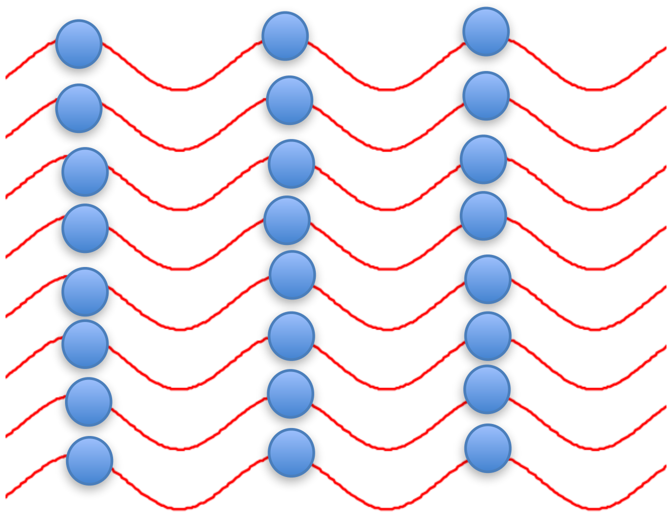
Coherent Radiation



Working Principle

Resonant Interaction

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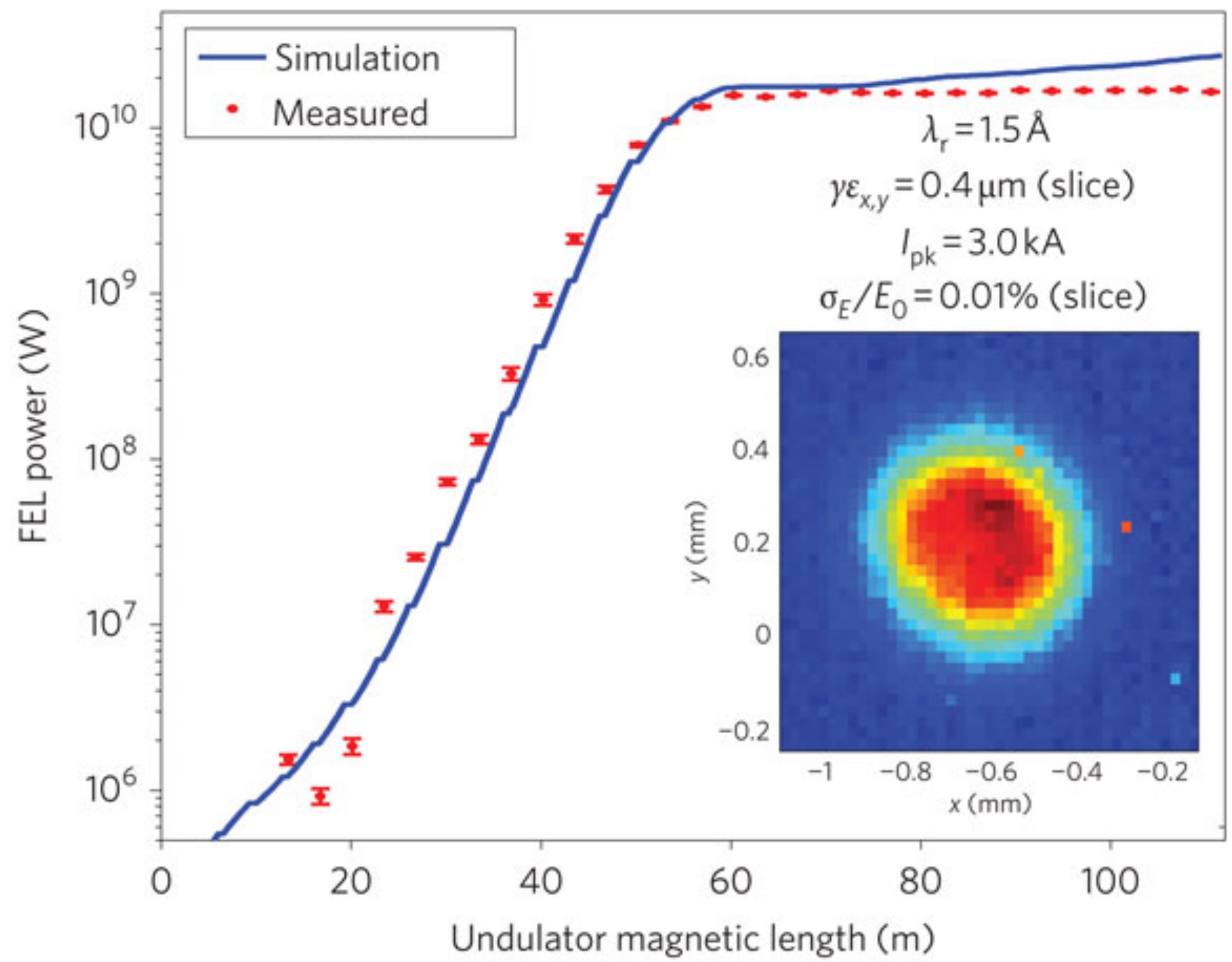
Coherent Radiation



COLLECTIVE INSTABILITIES AND HIGH-GAIN REGIME IN A FREE ELECTRON LASER

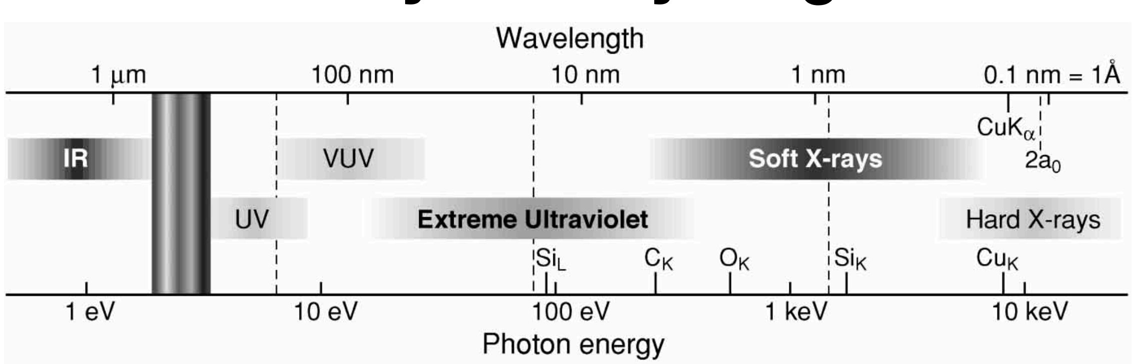
R. BONIFACIO *, C. PELLEGRINI
National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY 11973, USA

and

L.M. NARDUCCI
Physics Department, Drexel University, Philadelphia, PA 19104, USA

XFELs of the World

We define X-rays as anything around or above carbon K-edge (280 eV)

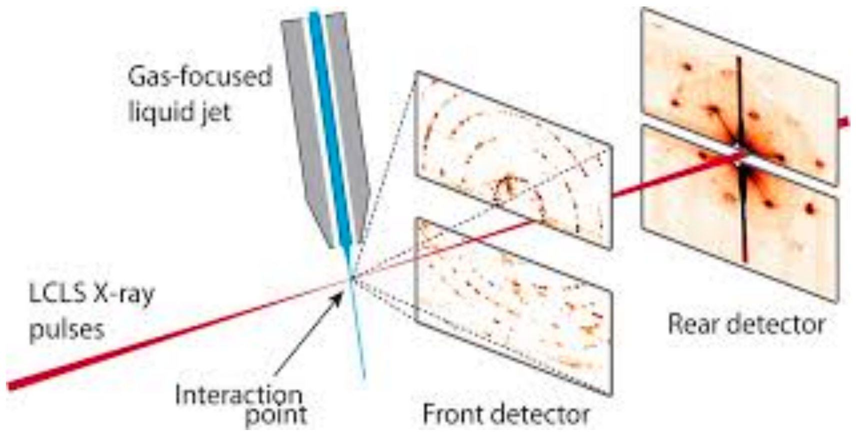


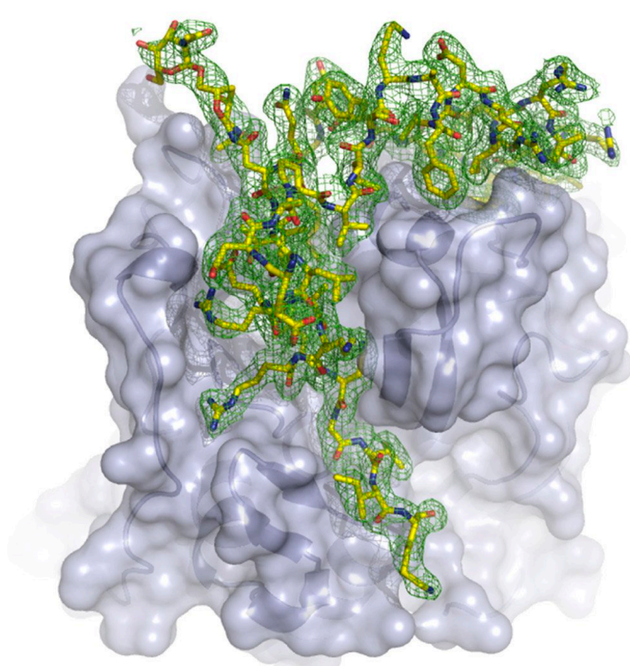
David Attwood
Soft X-Rays and Extreme Ultraviolet Radiation
Cambridge University Press 1999

Why X-Rays?

X-ray diffraction imaging

Resolution limited by wavelength
1 Angstrom ~ size of an atom

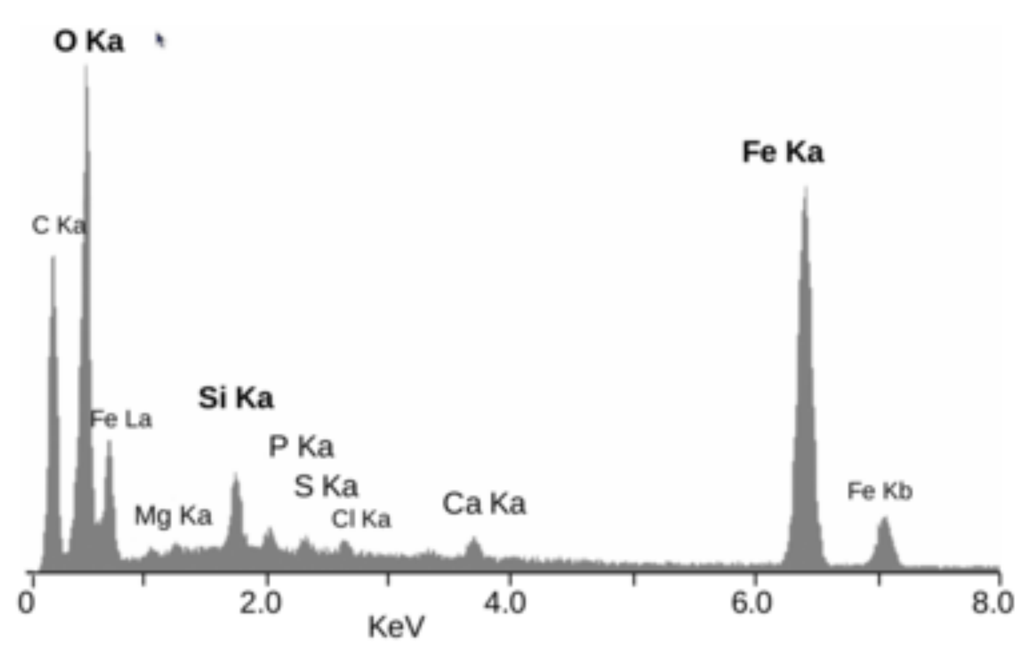




21 February 2013, SPIE Newsroom. DOI: 10.1117/2.1201302.004713

X-ray spectroscopy

Core electron energies are
Element specific!



FEL R&D: A few Thoughts

X-ray FELs are a revolutionary technology.
We are still learning how to best use them.

FEL R&D is geared towards:

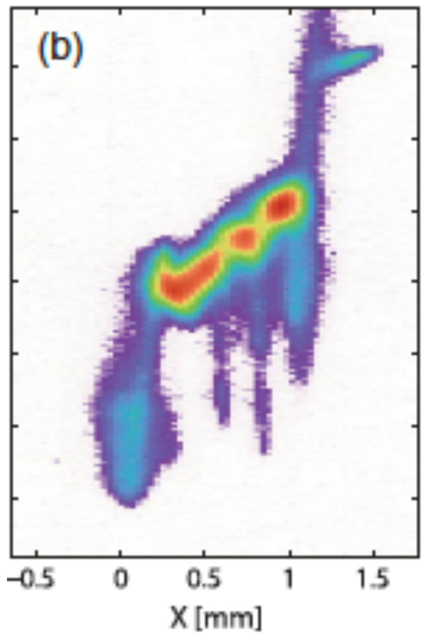
1) **Making things a little better for everyone**
   (i.e. improve spectral brightness, peak power)
2) **Making things a lot better for a few people**
   (targeted R&D: attosecond FELs, two-colors, polarization control)

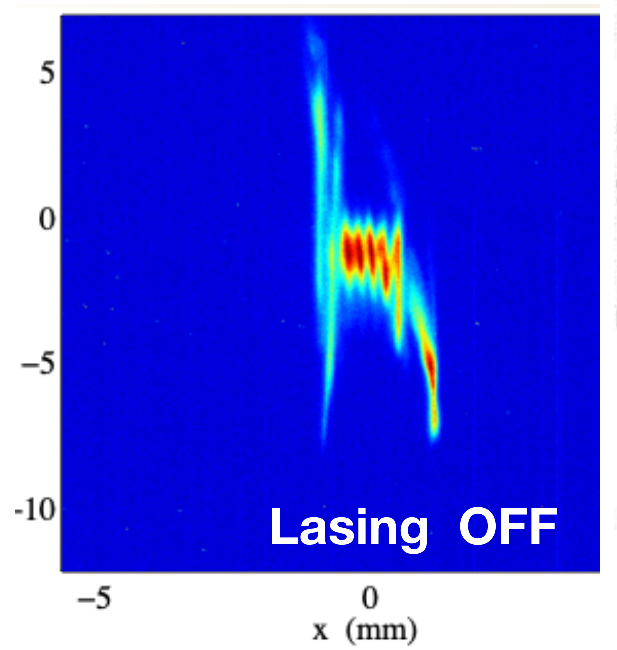
In my experience doing something new is easier than doing something better…

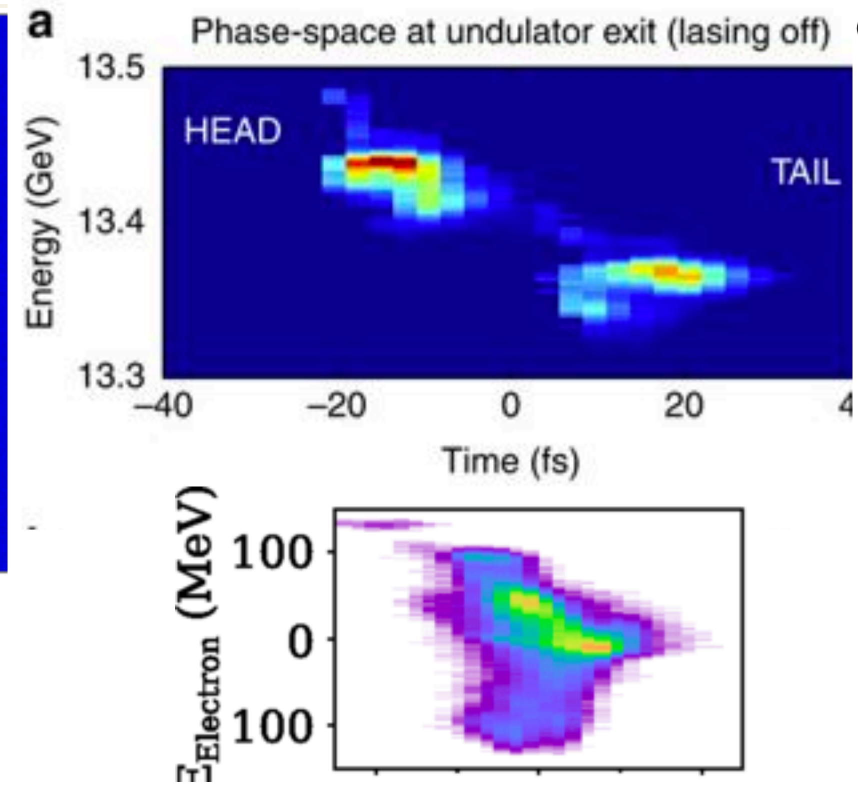
Recent breakthroughs have come through strong collaboration between users and accelerator experts.

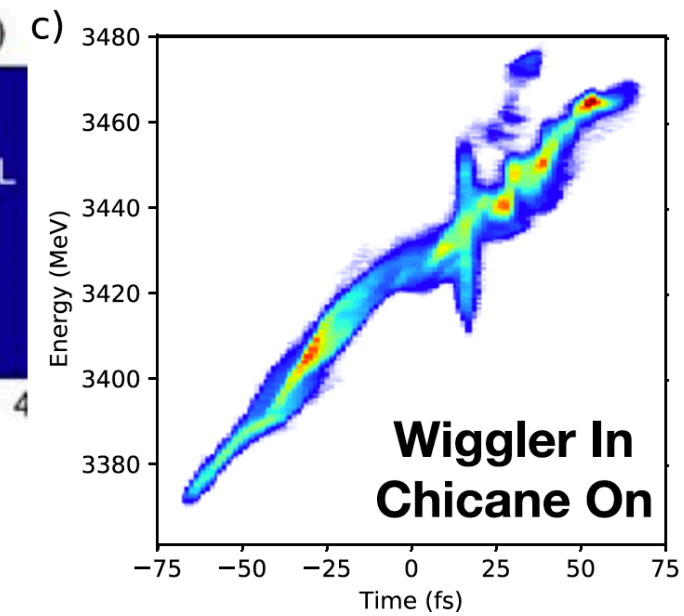
My dream: educating the next generation of FEL physicists to be users AND machine experts.

One Machine, Many FELs!

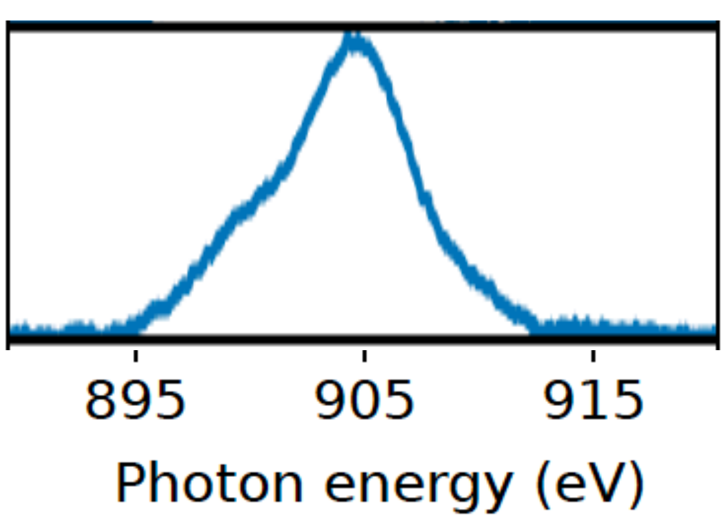


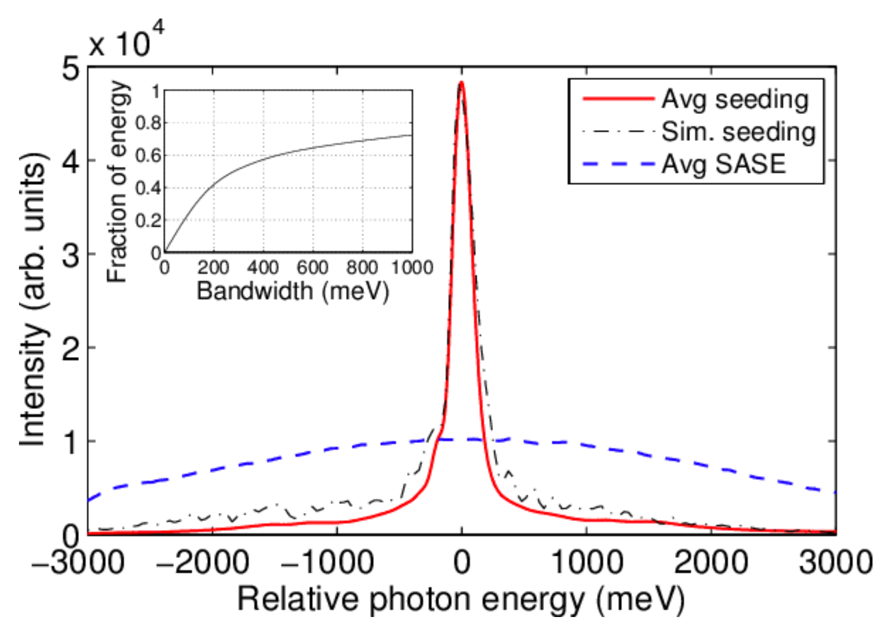


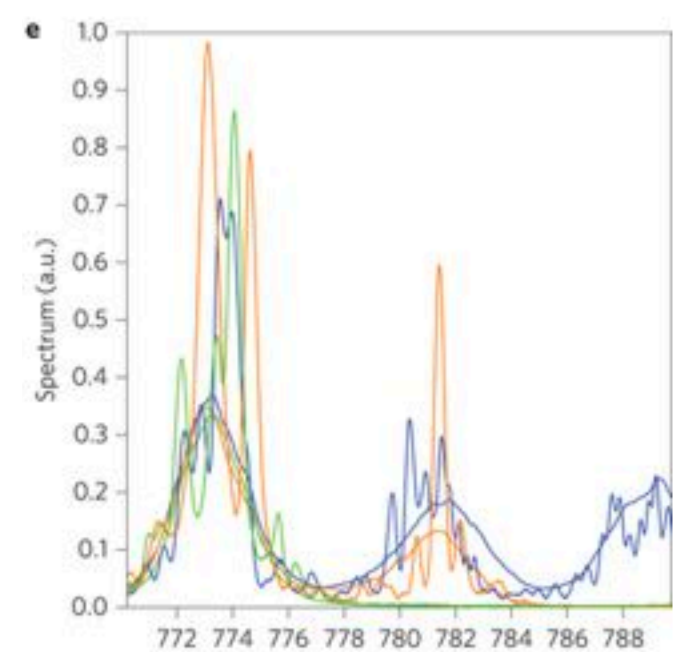




Accelerator is the most flexible device used in the experiment!
Accelerator physicist in an excellent position to drive new science…



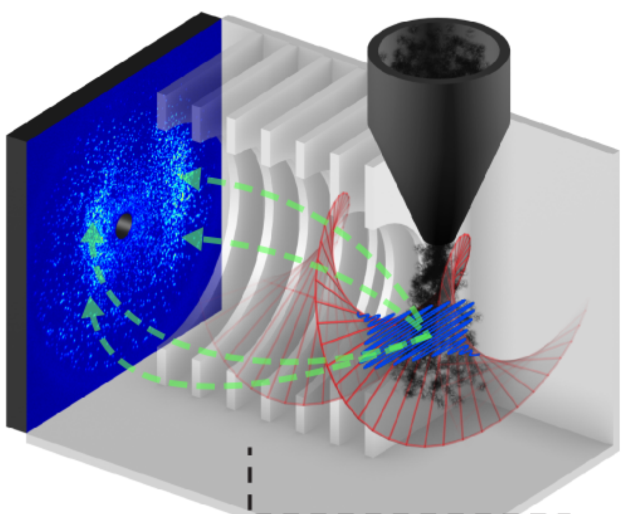


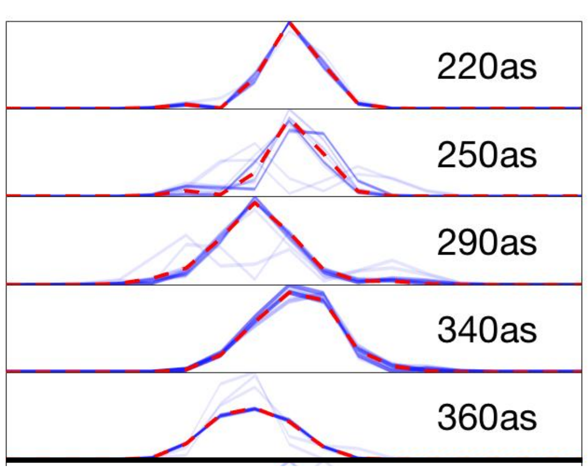


Status of FEL R&D

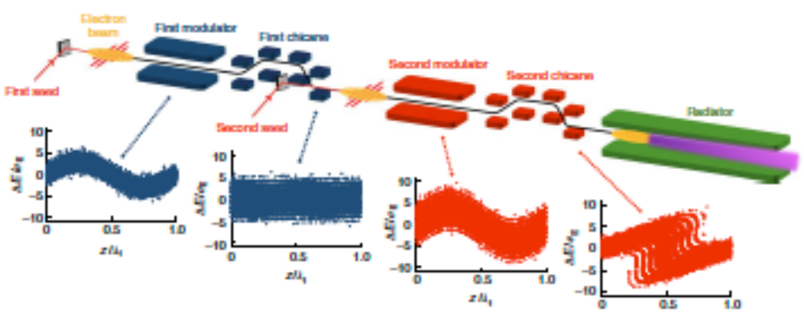
3 AREAS OF FOCUS

Attosecond Science

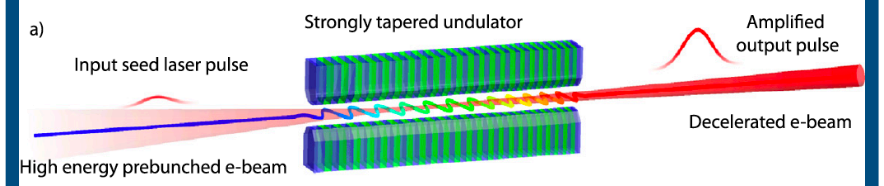


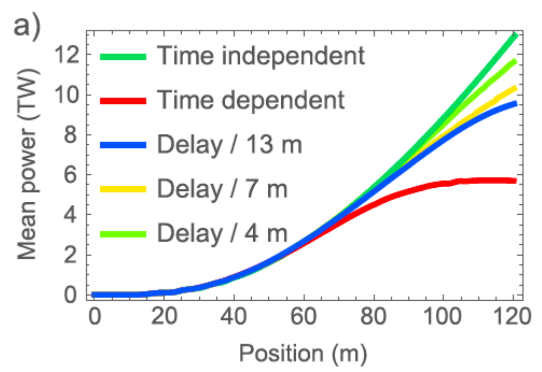


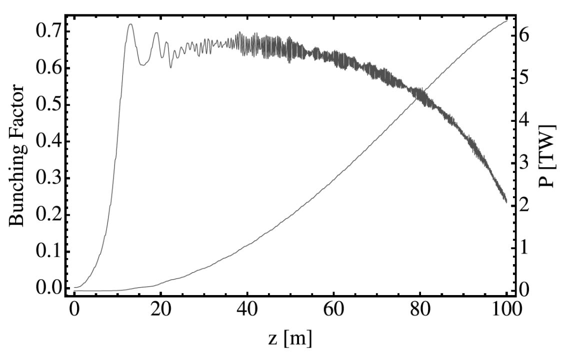
Femtosecond Shaping/ Seeding



Higher Power







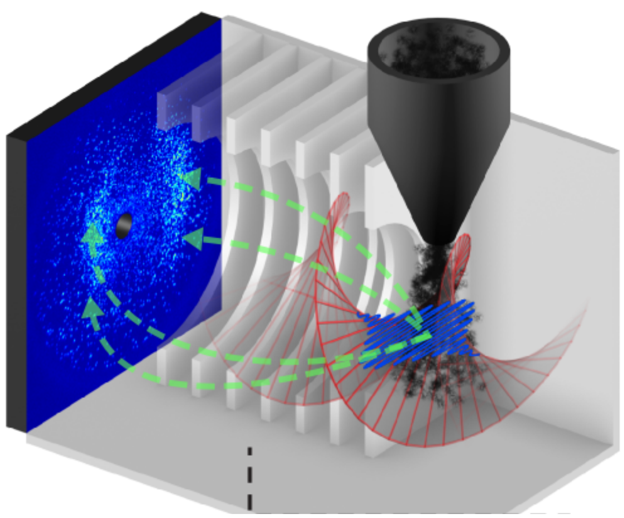
Tapering enhanced stimulated superradiant amplification
J Duris[1], A Murokh[2] and P Musumeci[1]

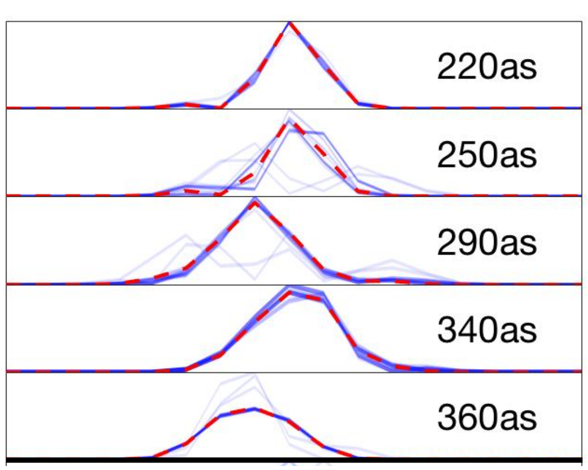
Status of FEL R&D

SLAC

3 AREAS OF FOCUS

Attosecond Science





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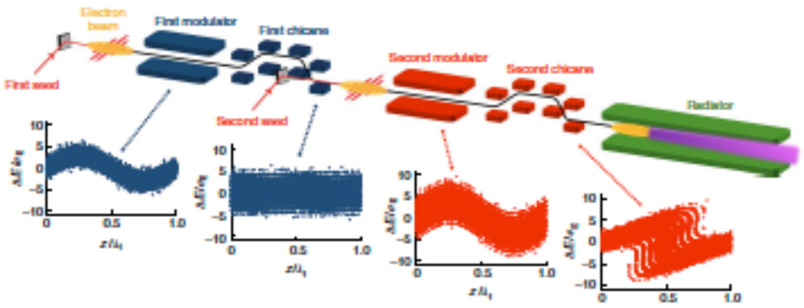
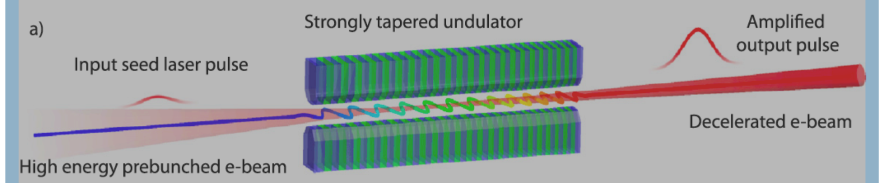
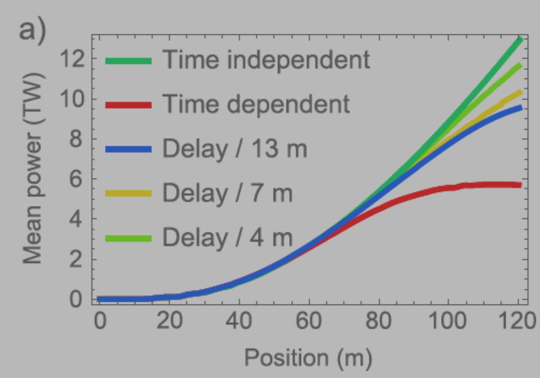
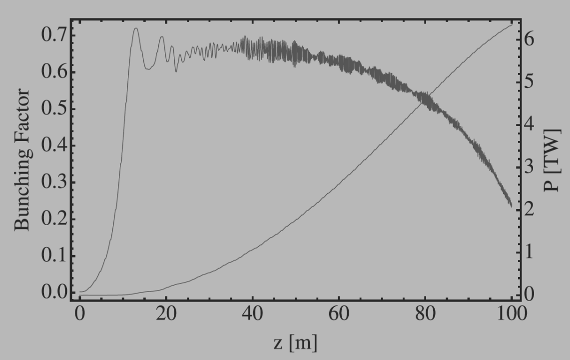


Higher Power





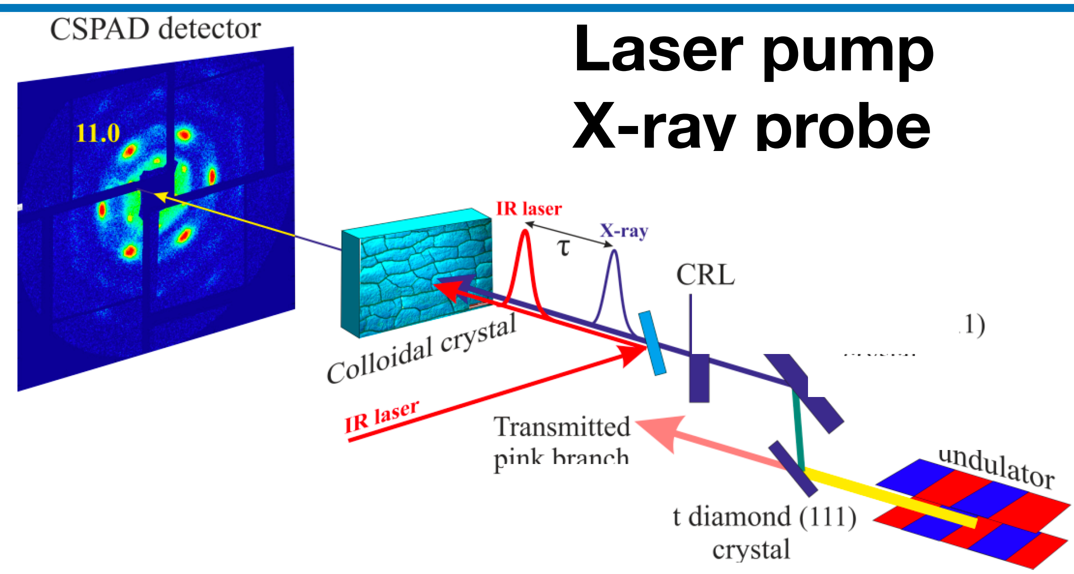


Tapering enhanced stimulated superradiant amplification
J Duris[1], A Murokh[2] and P Musumeci[1]

Attosecond Pulse

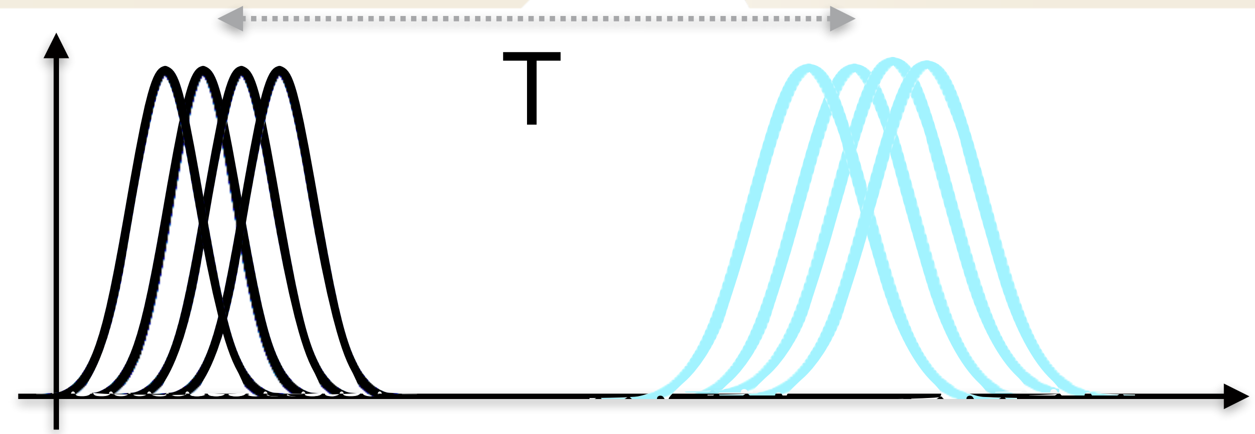
Laser Pump-X-ray Probe Experiments

SLAC



Laser pump
X-ray probe

Appl. Sci. , 7(5), 519 (2017)

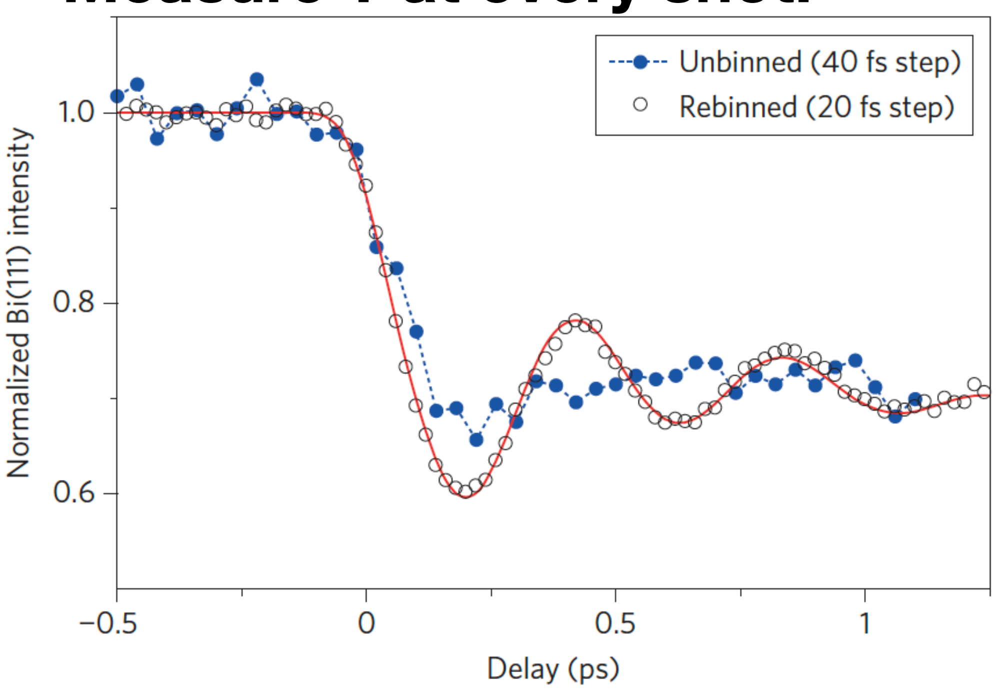


Time resolution

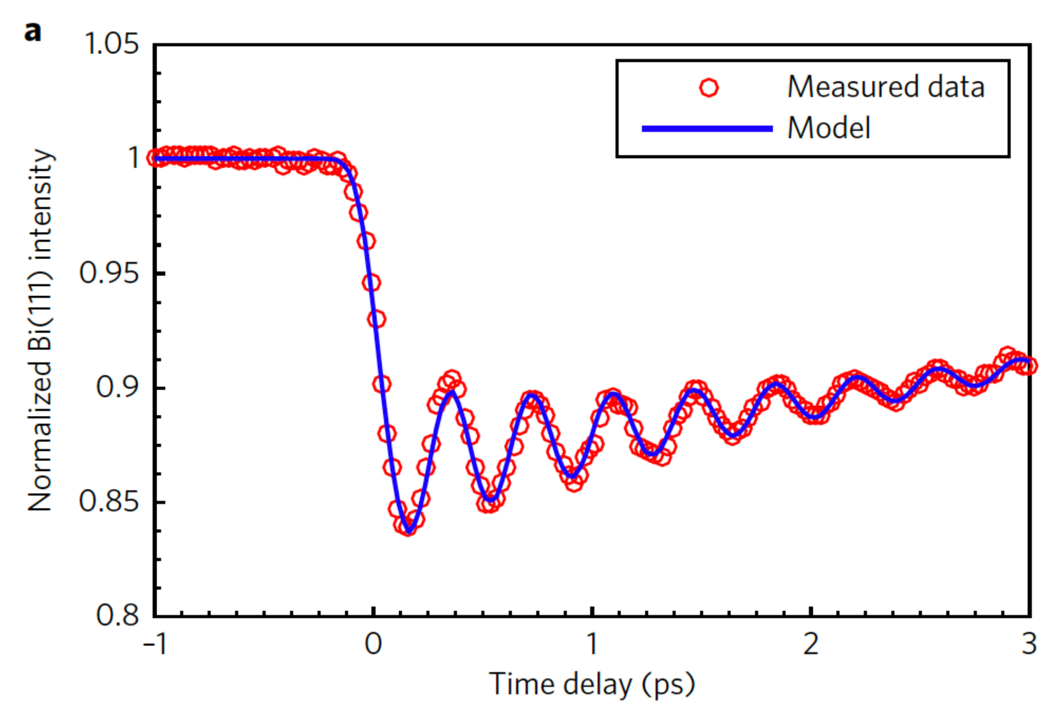
$$\sqrt{\Delta t_1^{\,2} + \Delta t_2^{\,2} + \sigma_T^{\,2}}$$

Jitter is dominant contribution at LCLS (150 fs rms jitter)
Measure T at every shot!

New FELs showing ~10-20 fs jitter with no time-sorting (PAL and XFEL)



Harmand, M., et al. *Nature Photonics* 7.3 (2013): 215



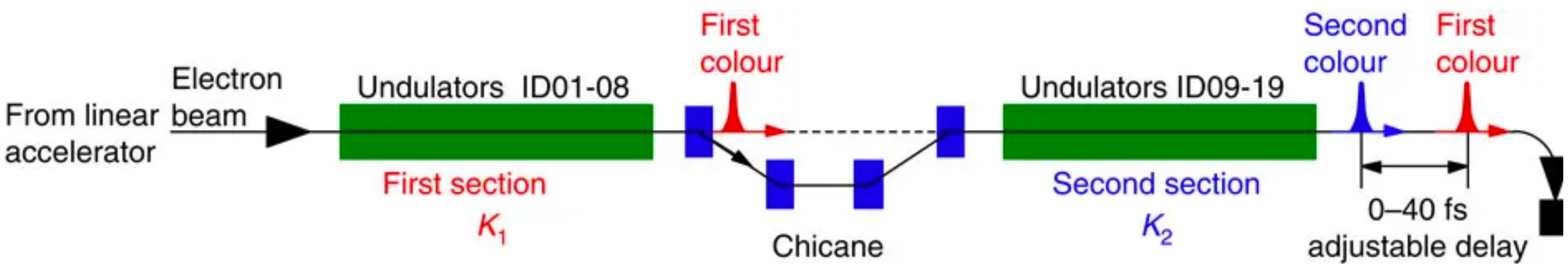
Kang, Heung-Sik, et al. *Nature Photonics* 11.11 (2017): 708.

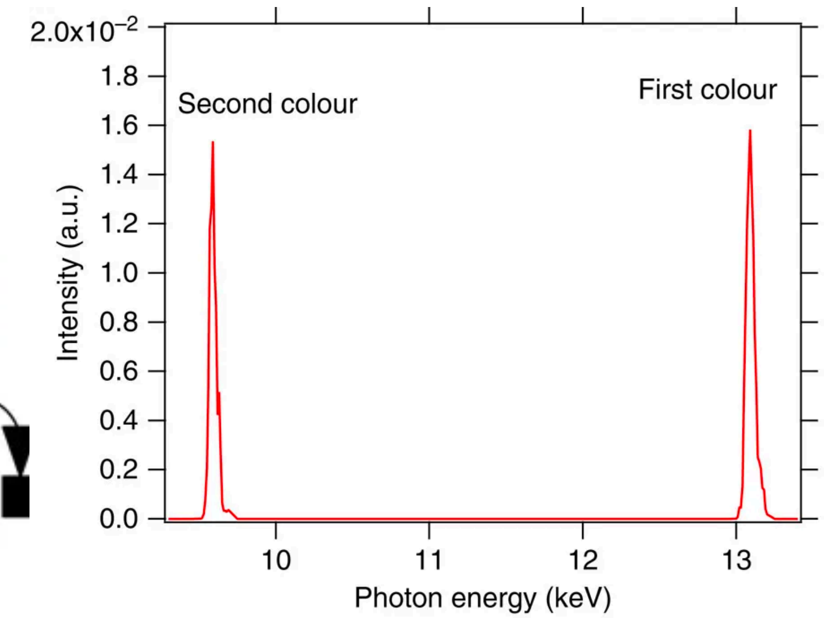
X-ray Pump/X-ray Probe

SLAC

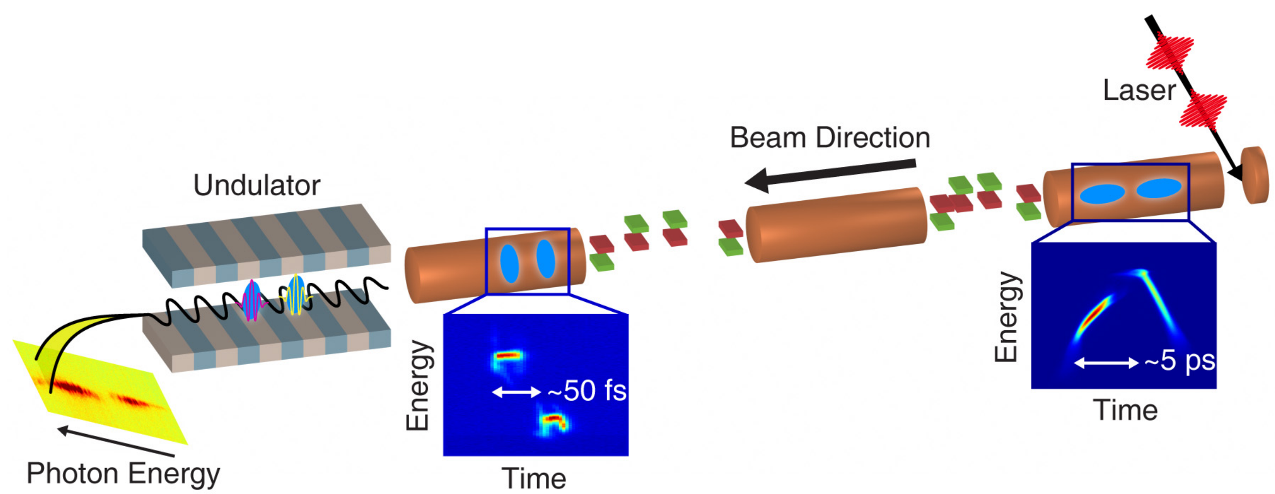
$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$

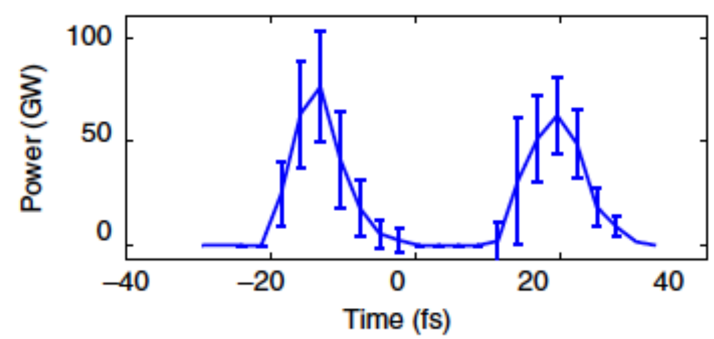
Lutman, A. A., et al. *Physical review letters* 110.13 (2013): 134801.
Hara, Toru, et al. *Nature communications* 4 (2013): 2919.
Marinelli, A., et al. *Physical review letters* 111.13 (2013): 134801.
Lutman, Alberto A., et al. *Nature Photonics* 10.11 (2016): 745.
Ferrari, Eugenio, et al. *Nature Communications* 7 (2016): 10343.





$$\lambda_{1,2} = \lambda_w \frac{1+K^2}{2\gamma_{1,2}^2}$$





Nat. Comm. Vol 6, 6369 (2015)

Allaria, E., et al. *Nature communications* 4 (2013): 2476.
Marinelli, A., et al. *Nature communications* 6 (2015): 6369.
Petralia, A., et al. *Physical review letters* 115.1 (2015): 014801.

Ultrafast Timescales

10 ps

1 ps

100 fs

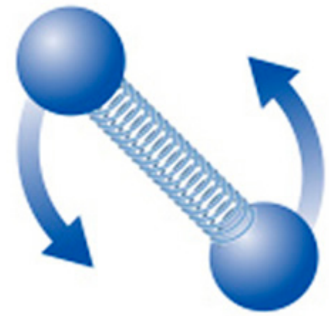
10 fs

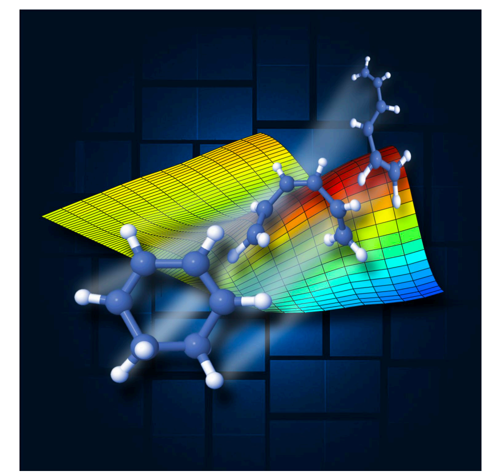
1 fs

Our goal

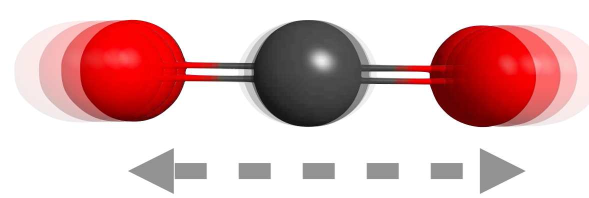
0.1 fs

Molecular rotation ~ ps

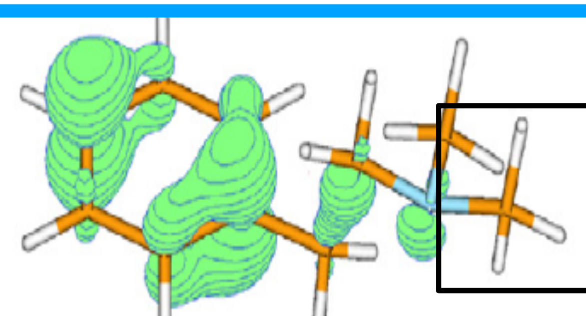




Molecular rearrangement ~100s fs



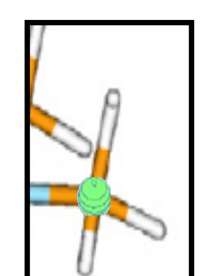
Molecular vibration ~10s fs



Valence electron motion ~ 100s as

[J. Chem Phys. 8 129(10):104305 (2008)]

Inner electron motion ~ 10 as



XLEAP: X-ray Laser-Enhanced Attosecond Pulse Generation

J. Duris, S. Li et al. to be published in Nature Photonics

Collaboration:
SLAC (AD, LCLS, PULSE), ANL
LMU, Imperial, Max Planck, U. Kassel, TU Dortmund, TU Munich

-Energy modulation from resonant radiation-electron interaction

-Compression with small chicane~10 kA in 1 fs

-Sub-fs X-ray pulse in undulator

Original concept using laser: Zholents PRSTAB 8, 040701 (2005).

XLEAP Streaking Measurements

Scientific Impact

J. O'Neil, J. Cryan, In Preparation

Scientific Impact

COST PER PHOTON 1000 TIMES CHEAPER FOR FELS!!

J. O'Neil, J. Cryan, In Preparation

Seeded FELs

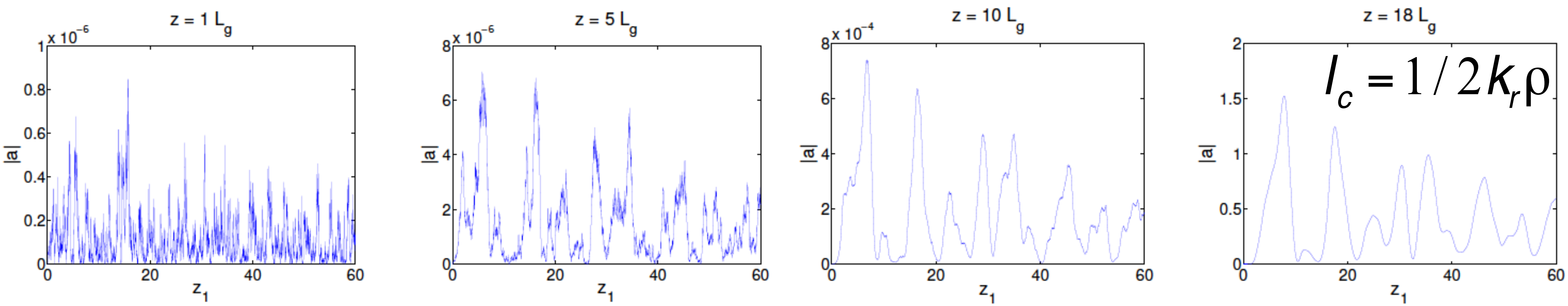
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Temporal Coherence of SASE (or Lack Thereof…)

SLAC

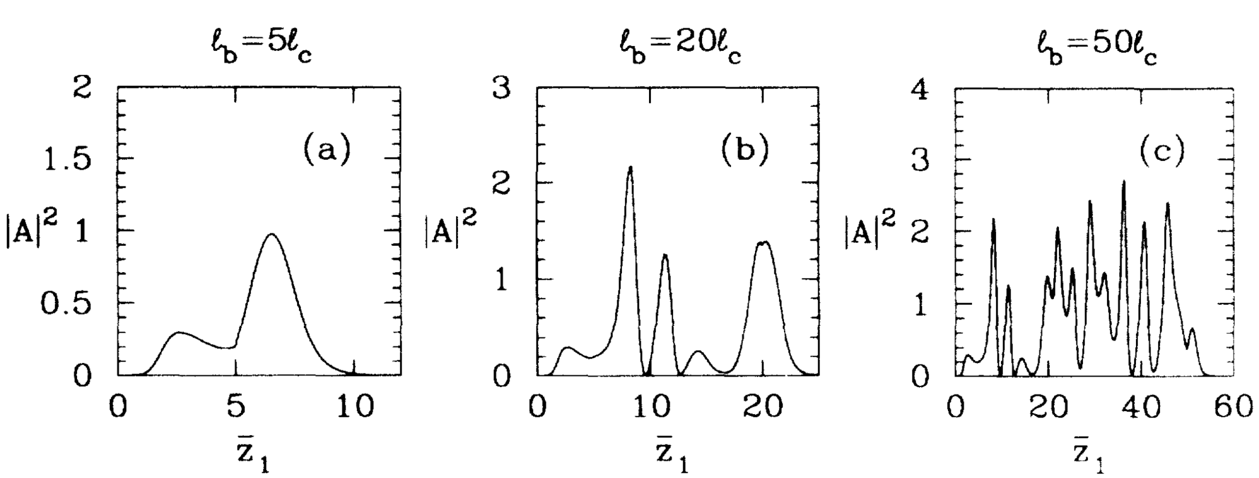
Signal starts from noise (totally uncorrelated) → **Correlation grows due to slippage** → **At saturation Coherence length~lc**



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

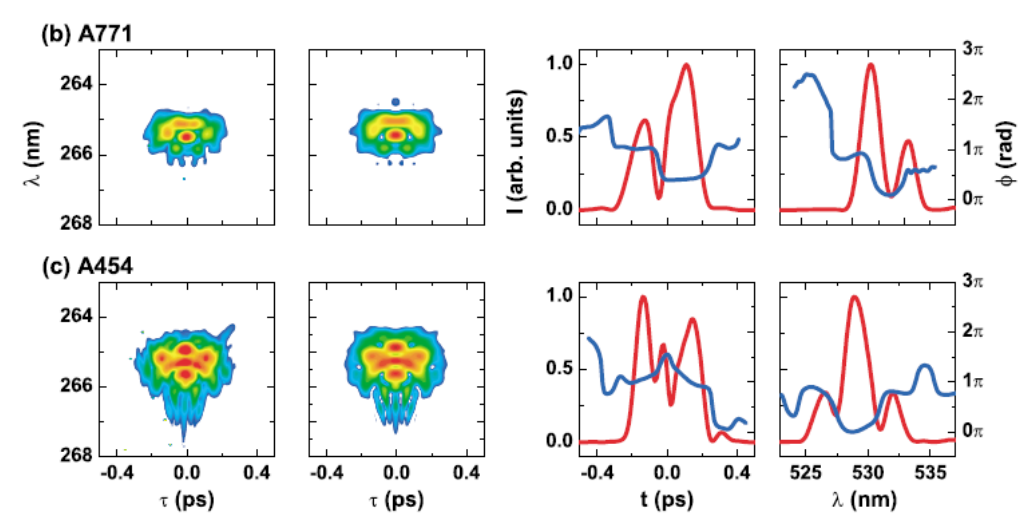
R. Bonifacio,[1,2] L. De Salvo,[1] P. Pierini,[2] N. Piovella,[1] and C. Pellegrini[3]



VOLUME 91, NUMBER 24 PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2003

Characterization of a Chaotic Optical Field Using a High-Gain, Self-Amplified Free-Electron Laser

Yuelin Li,[1,*] Samuel Krinsky,[2] John W. Lewellen,[1] Kwang-Je Kim,[1] Vadim Sajaev,[1] and Stephen V. Milton[1]



Solutions

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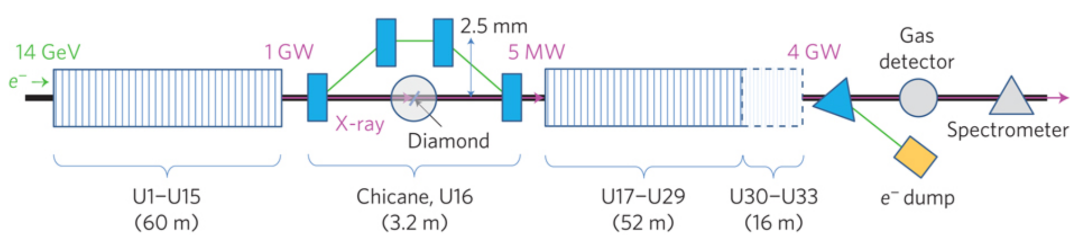
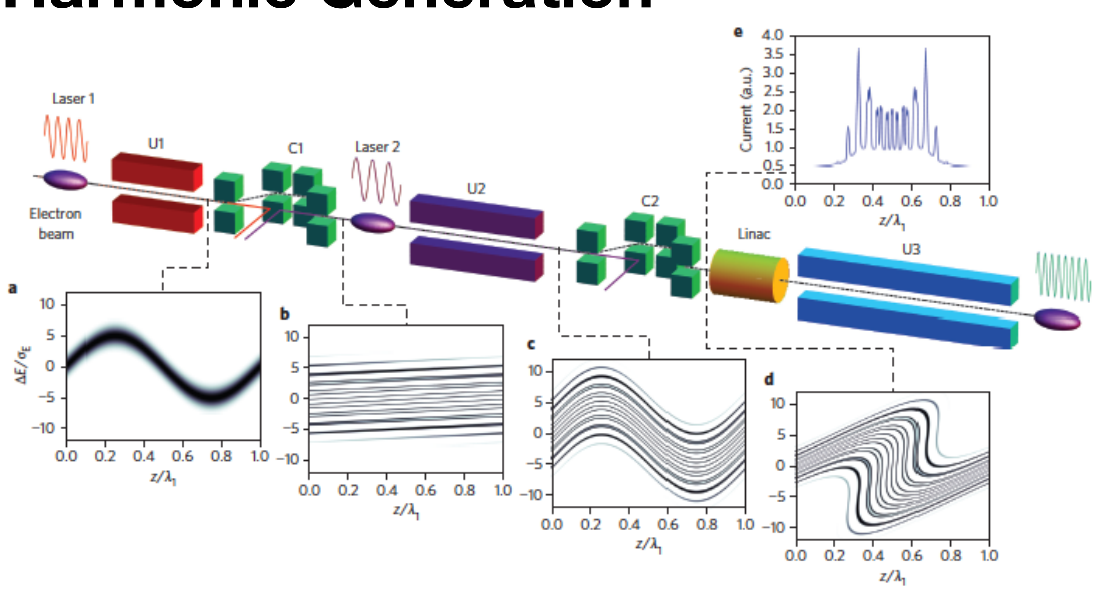
Seeding: Establish phase coherence by triggering instability with a coherent pulse.

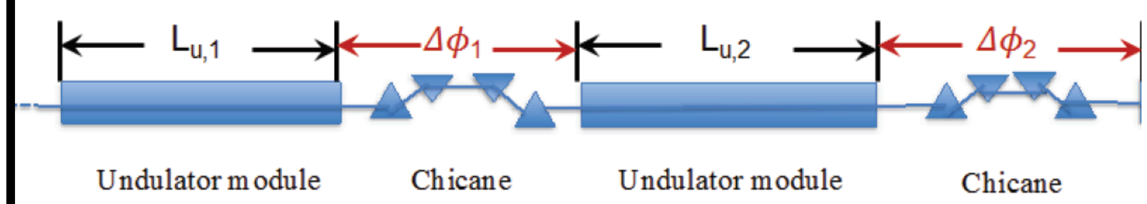
Self-Seeding



Harmonic Generation



Slippage boosting: Establish phase coherence by enhancing slippage.



Schneidmiller, E. A., and M. V. Yurkov. "Harmonic lasing in x-ray free electron lasers." *Physical Review Special Topics-Accelerators and Beams* 15.8 (2012): 080702.

Wu, Juhao, et al. "X-ray spectra and peak power control with iSASE." (IPAC 2013): WEODB101.

McNeil, B. W. J., N. R. Thompson, and D. J. Dunning. "Transform-limited X-ray pulse generation from a high-brightness self-amplified spontaneous-emission free-electron laser." *Physical review letters* 110.13 (2013): 134802.

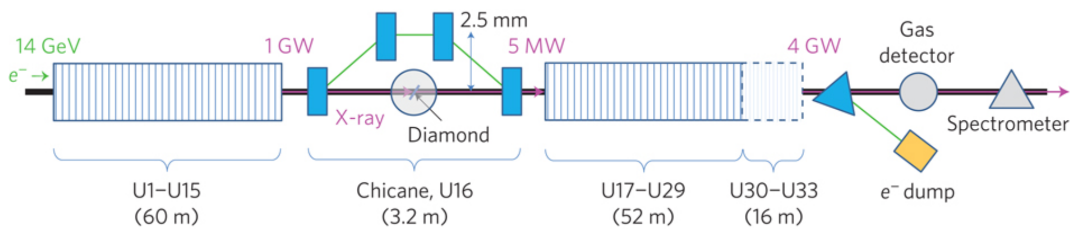
Xiang, Dao, et al. "Purified self-amplified spontaneous emission free-electron lasers with slippage-boosted filtering." *Physical Review Special Topics-Accelerators and Beams* 16.1 (2013): 010703.

Schneidmiller, E. A., et al. "First operation of a harmonic lasing self-seeded free electron laser." *Physical Review Accelerators and Beams* 20.2 (2017): 020705.

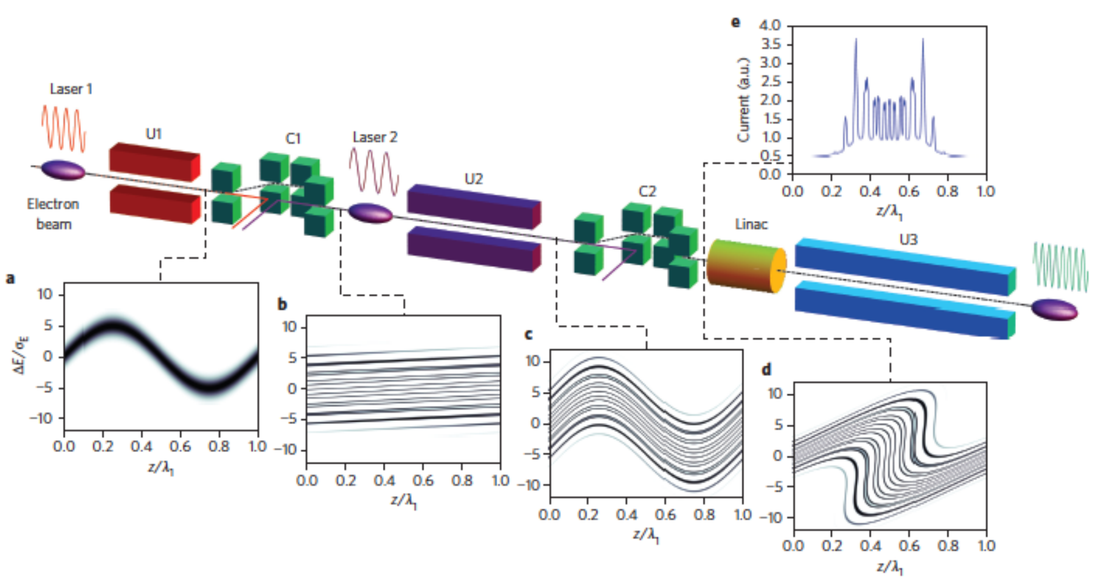
Solutions

Seeding:
Establish phase coherence by triggering instability with a coherent pulse.

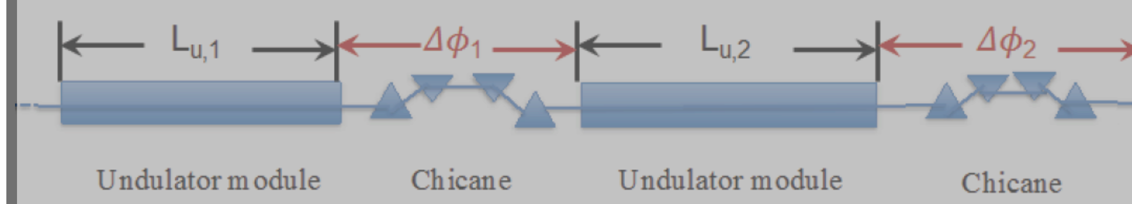
Self-Seeding



Harmonic Generation



Slippage boosting:
Establish phase coherence by enhancing slippage.



Schneidmiller, E. A., and M. V. Yurkov. "Harmonic lasing in x-ray free electron lasers." *Physical Review Special Topics-Accelerators and Beams* 15.8 (2012): 080702.

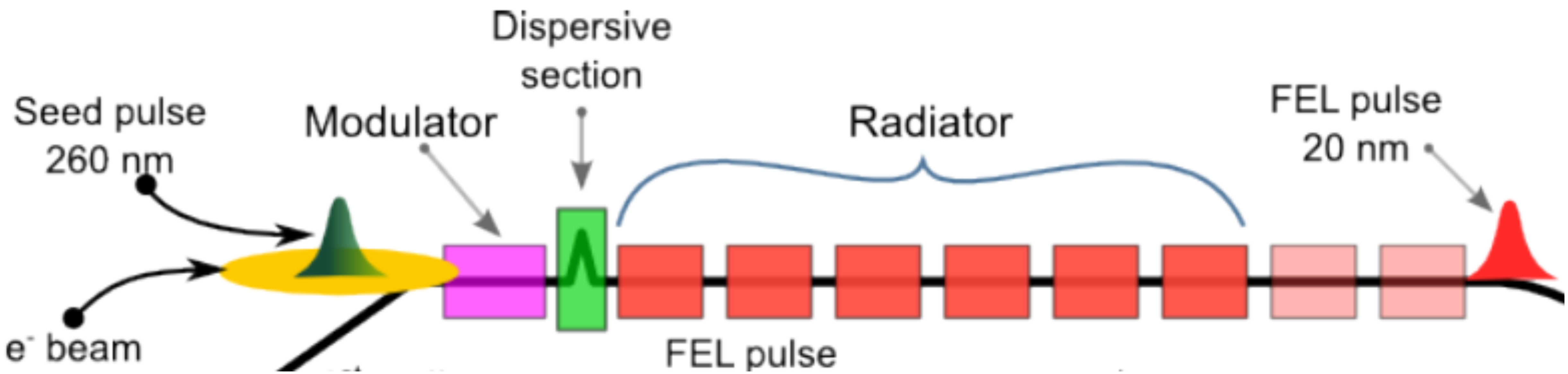
Wu, Juhao, et al. "X-ray spectra and peak power control with iSASE." (IPAC 2013): WEODB101.

McNeil, B. W. J., N. R. Thompson, and D. J. Dunning. "Transform-limited X-ray pulse generation from a high-brightness self-amplified spontaneous-emission free-electron laser." *Physical review letters* 110.13 (2013): 134802.

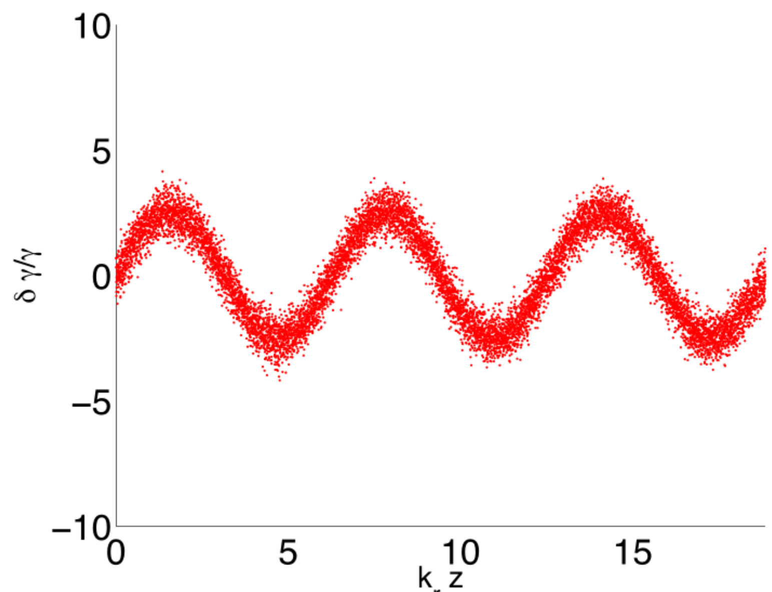
Xiang, Dao, et al. "Purified self-amplified spontaneous emission free-electron lasers with slippage-boosted filtering." *Physical Review Special Topics-Accelerators and Beams* 16.1 (2013): 010703.

Schneidmiller, E. A., et al. "First operation of a harmonic lasing self-seeded free electron laser." *Physical Review Accelerators and Beams* 20.2 (2017): 020705.

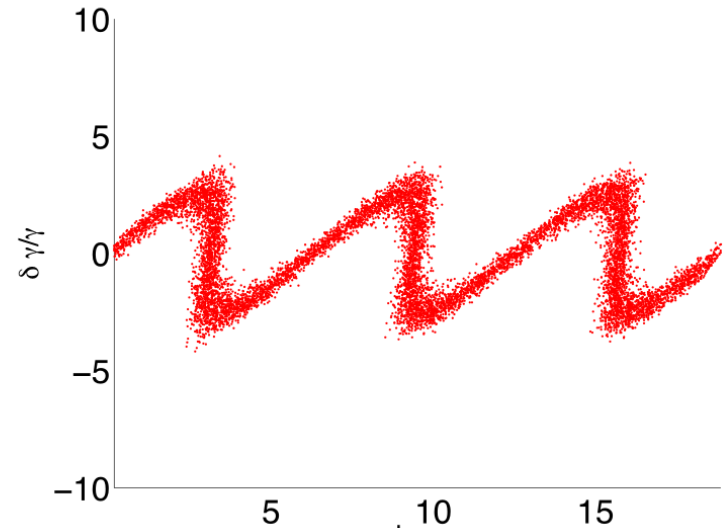
Externally Seeded FELs



First undulator tuned at λ



Second undulator tuned at λ/n



Proposed and demonstrated by L.H. Yu at BNL

High-Gain Harmonic-Generation Free-Electron Laser

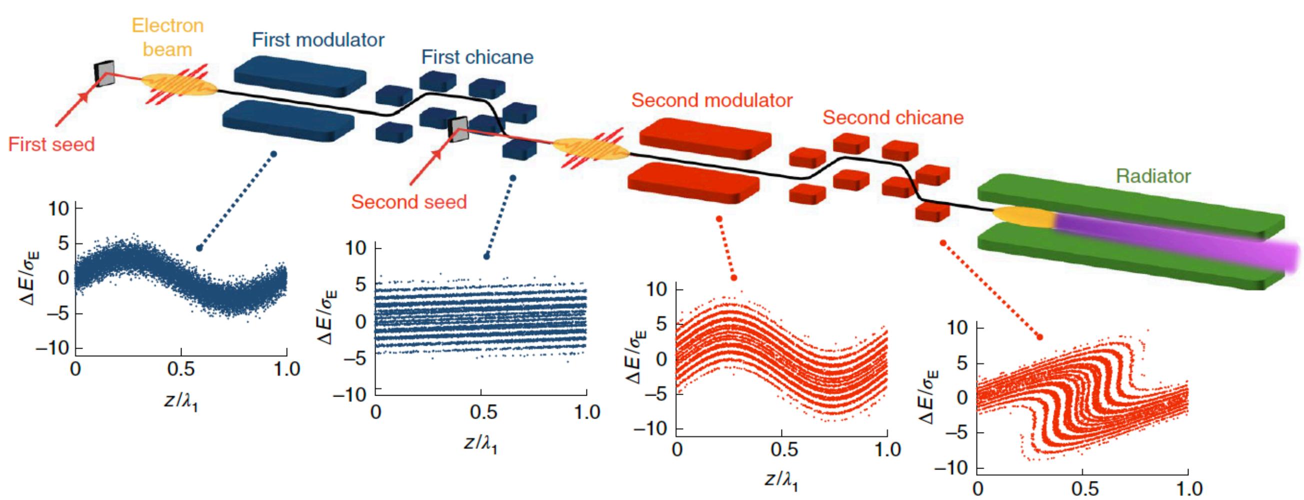
L.-H. Yu[1,*], M. Babzien[1], I. Ben-Zvi[1], L. F. DiMauro[1], A. Doyuran[1], W. Graves[1], E. Johnson[1], S. ...

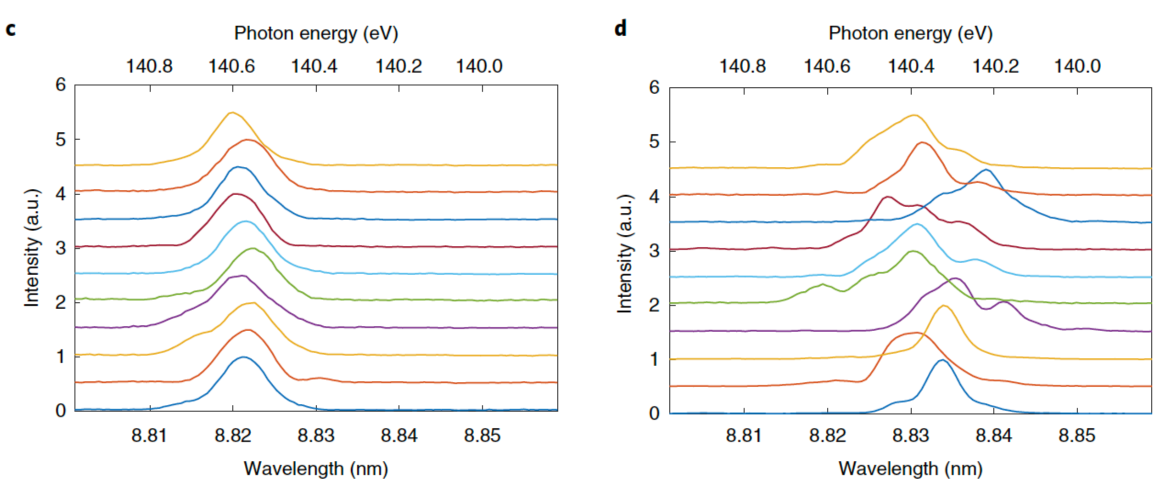
+ See all authors and affiliations

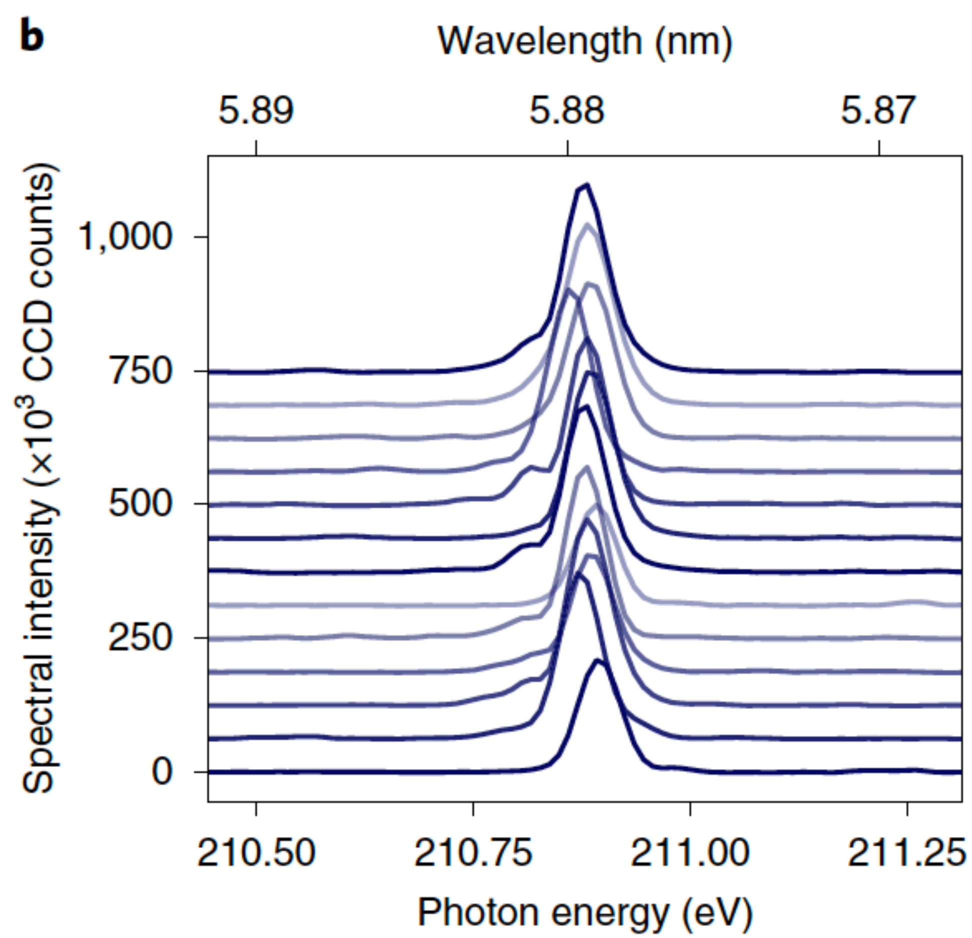
External Seeding

1) Yu, L-H., et al. "High-gain harmonic-generation free-electron laser." *Science* 289.5481 (2000): 932-934.
2) Lambert, G., et al. "Injection of harmonics generated in gas in a free-electron laser providing intense and coherent extreme-ultraviolet light." *Nature physics* 4.4 (2008): 296
3) Stupakov, Gennady. "Using the beam-echo effect for generation of short-wavelength radiation." *Physical review letters* 102.7 (2009): 074801.
4) Xiang, D., et al. "Demonstration of the echo-enabled harmonic generation technique for short-wavelength seeded free electron lasers." *Physical review letters* 105.11 (2010): 114801
5) Allaria, E., et al. "Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet." *Nature Photonics* 6.10 (2012): 699.
6) Allaria, E., et al. "Two-stage seeded soft-X-ray free-electron laser." *Nature Photonics* 7.11 (2013): 913.
7) Zhao, Z. T., et al. "First lasing of an echo-enabled harmonic generation free-electron laser." *Nature Photonics* 6.6 (2012): 360.
8) Hemsing, E., et al. "Echo-enabled harmonics up to the 75th order from precisely tailored electron beams." *Nature Photonics* 10.8 (2016): 512.
9) Grattoni, Vanessa, et al. "Status of Seeding Development at sFLASH." (2018): MOP042.
10) Ribič, Primož Rebernik, et al. "Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser." *Nature Photonics* (2019): 1.

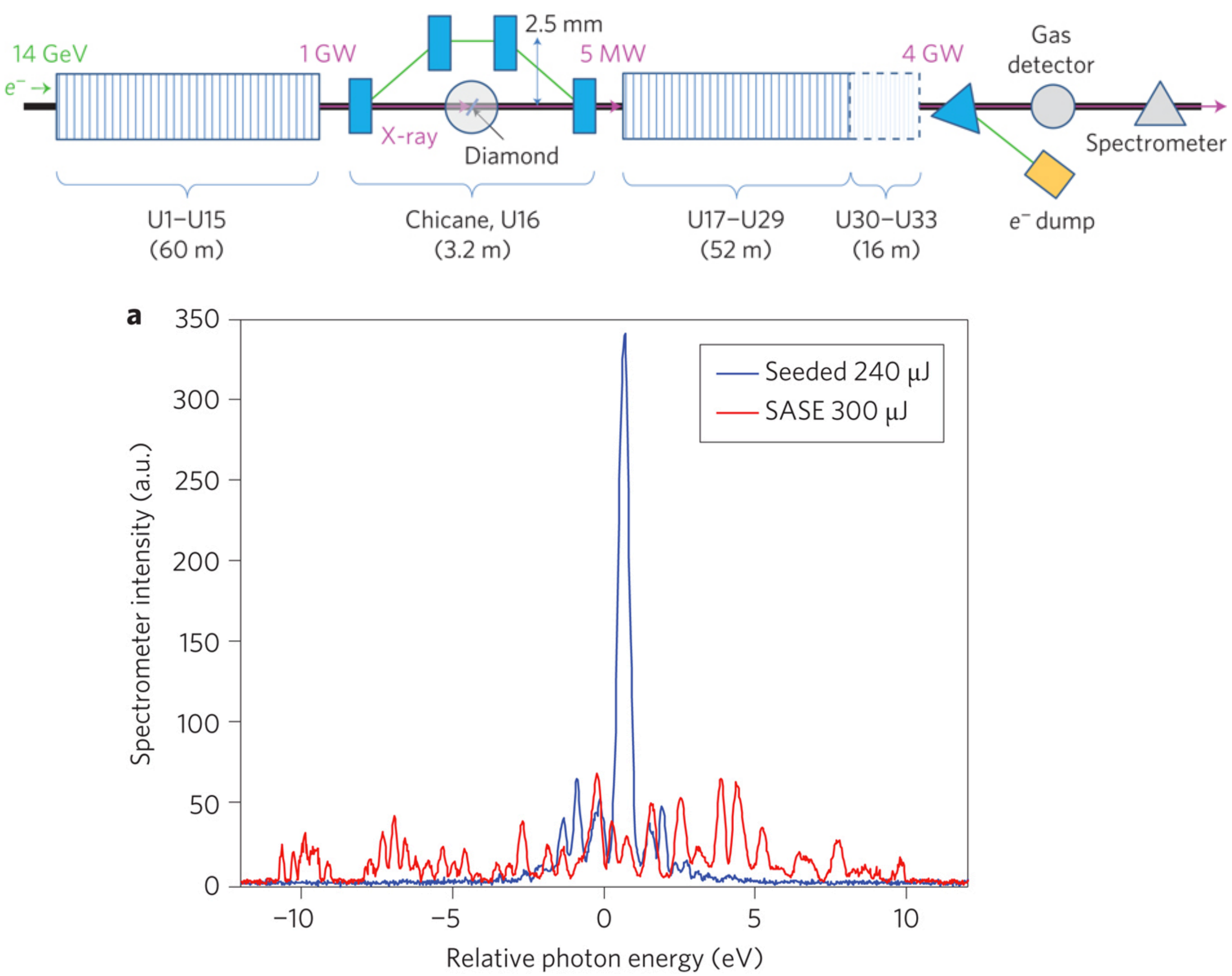
MORE EXPERIMENTS COMING FROM FLASH!!







Self-Seeding



Seeding vs Self-seeding

Seeding	Self-seeding
Synchronization with pump lasers	Shorter wavelength
Exotic intra-pulse phase control	Higher spectral brightness
	Less sensitive To non-linear beams

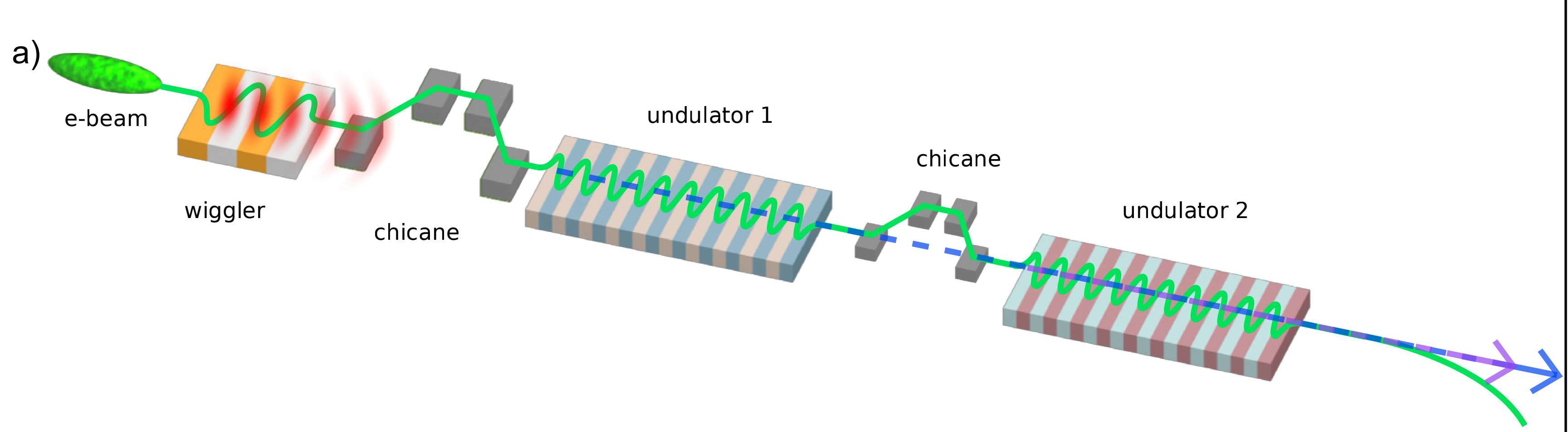
Marinelli, Agostino, et al. "Comparative study of nonideal beam effects in high gain harmonic generation and self-seeded free electron lasers." *Physical Review Special Topics-Accelerators and Beams* 13.7 (2010): 070701.

Hemsing, Erik. "Minimum Spectral Bandwidth in Echo Seeded Free Electron Lasers." *Frontiers in Physics* 7 (2019).

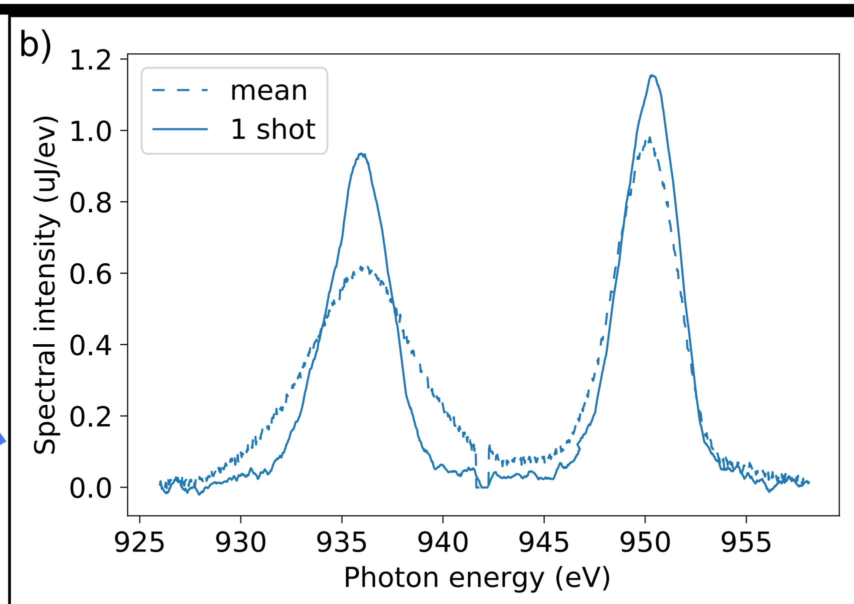
1) Feldhaus, J., et al. "Possible application of X-ray optical elements for reducing the spectral bandwidth of an X-ray SASE FEL." *Optics Communications* 140.4-6 (1997): 341-352.
2) Geloni, Gianluca, Vitali Kocharyan, and Evgeni Saldin. "A novel self-seeding scheme for hard X-ray FELs." *Journal of Modern Optics* 58.16 (2011): 1391-1403
3) Amann, J., et al. "Demonstration of self-seeding in a hard-X-ray free-electron laser." *Nature photonics* 6.10 (2012): 693.
4) Ratner, Daniel, et al. "Experimental demonstration of a soft x-ray self-seeded free-electron laser." *Physical review letters* 114.5 (2015): 054801.
5) Inoue, Ichiro, et al. "Generation of narrow-band X-ray free-electron laser via reflection self-seeding." *Nature Photonics* 13.5 (2019): 319.

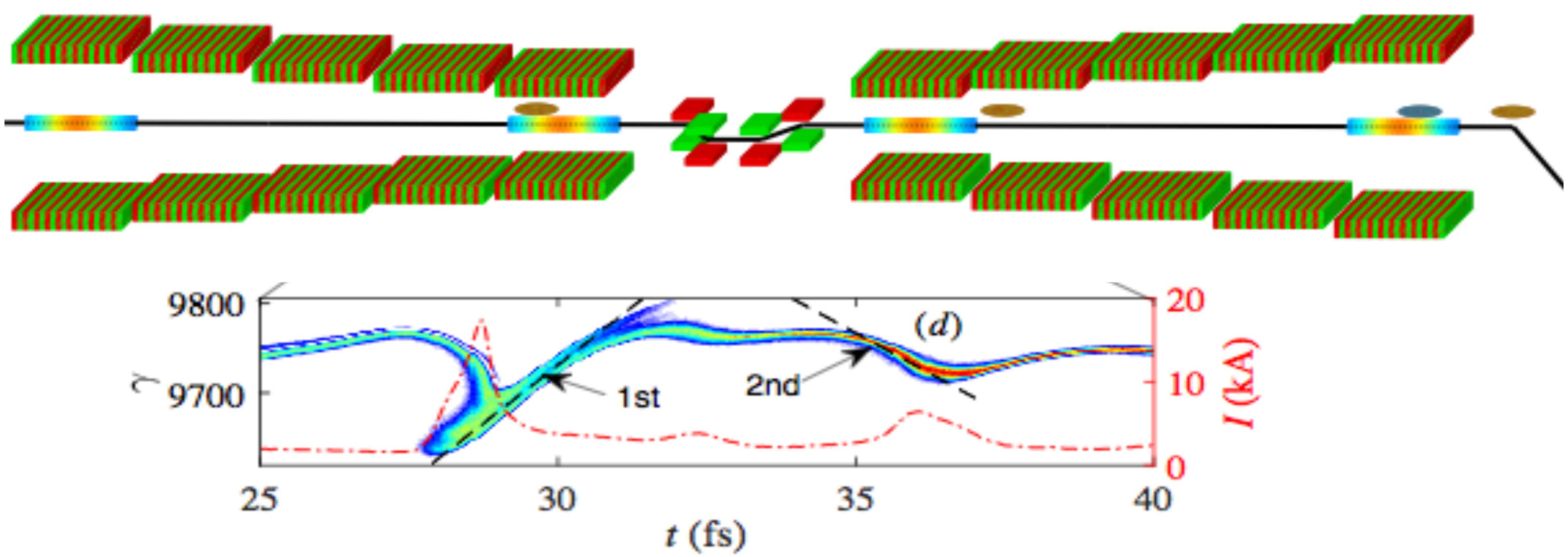
Future R&D

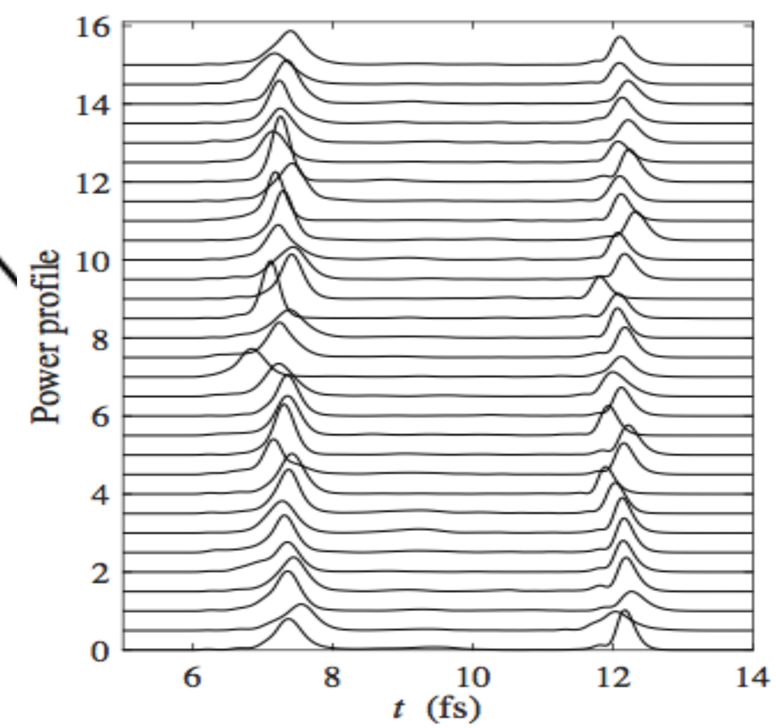
Attosecond Pump/Probe



Demonstrated 2-color attosecond operation



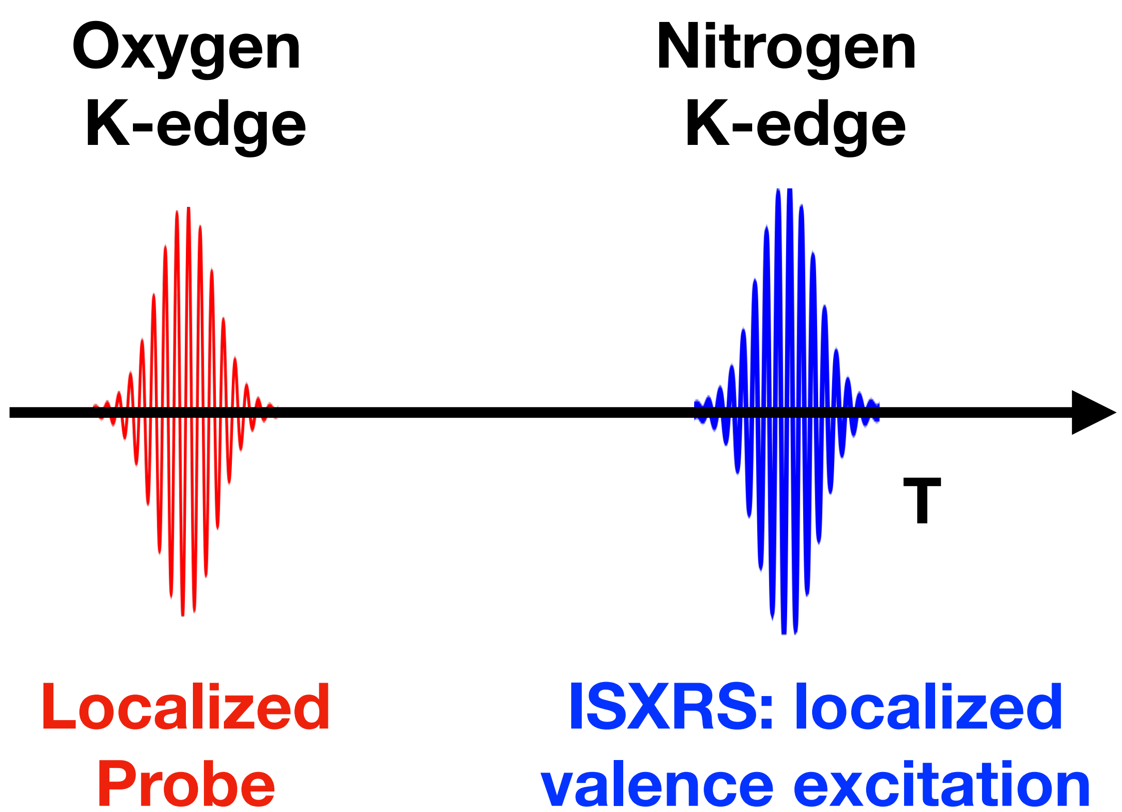


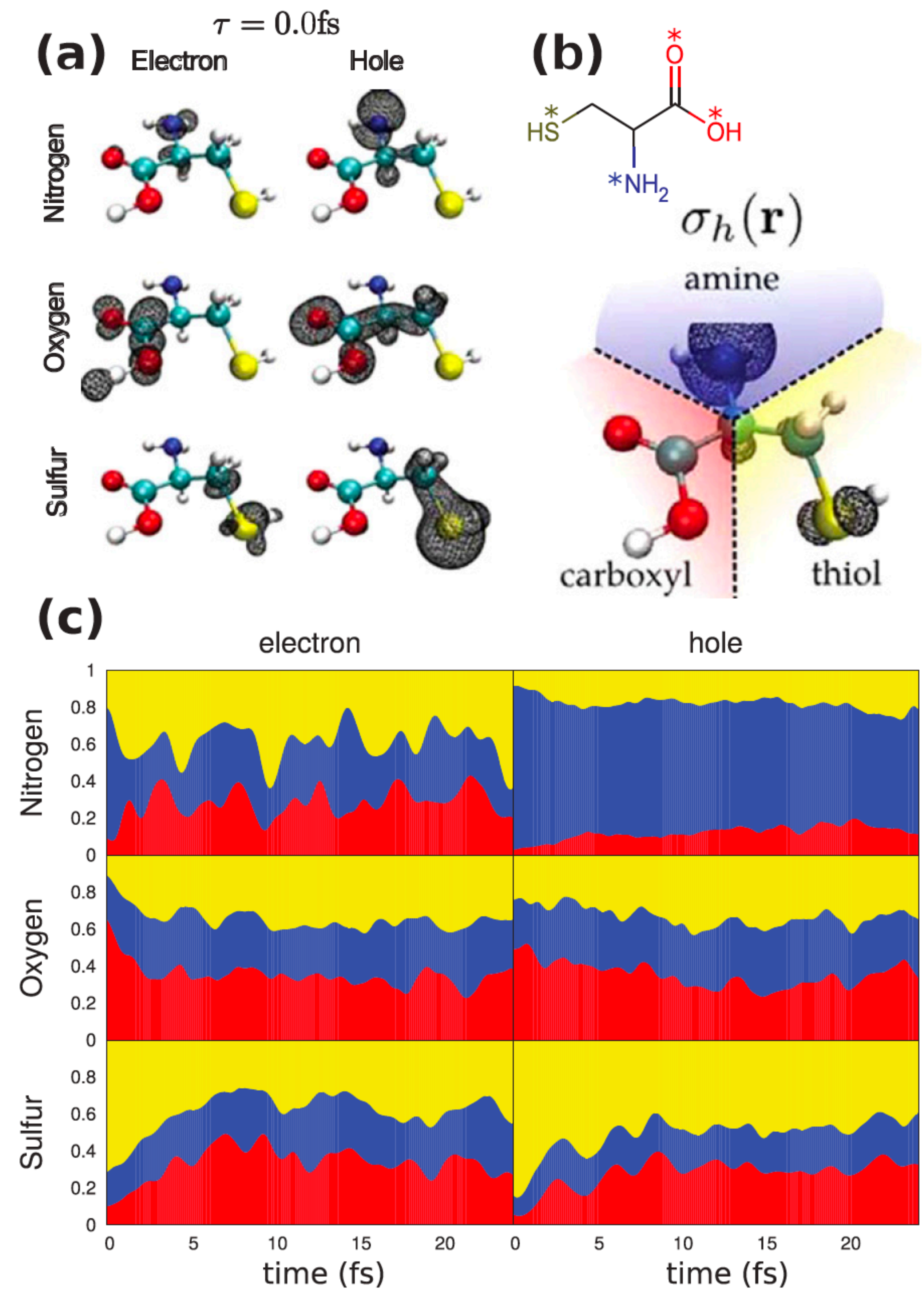


Z. Zhang et al. Phys. Rev. Accel. Beams **22**, 050701

The Dream Attosecond Experiment

SLAC





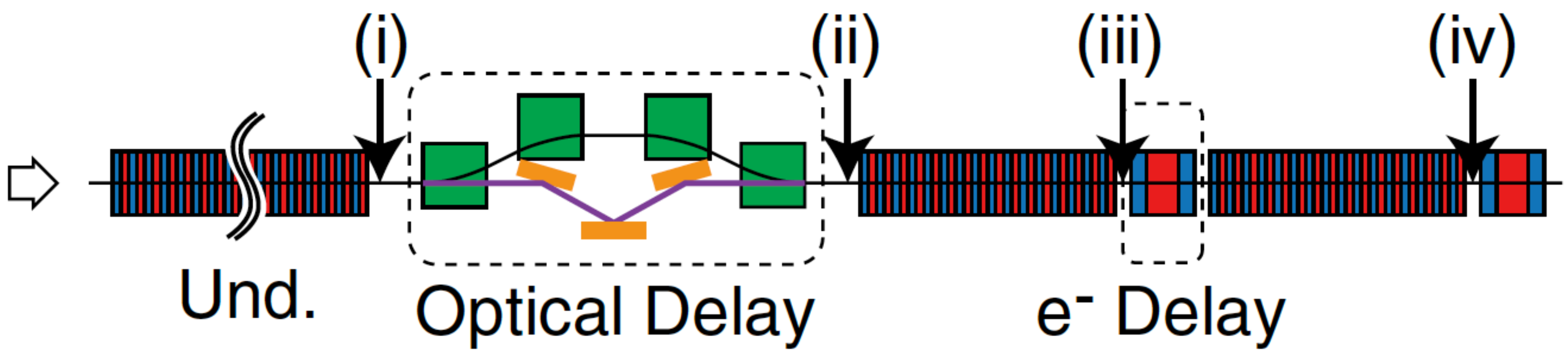
Probe coupled electron/nuclear dynamics
Currently beyond theoretical and numerical models!

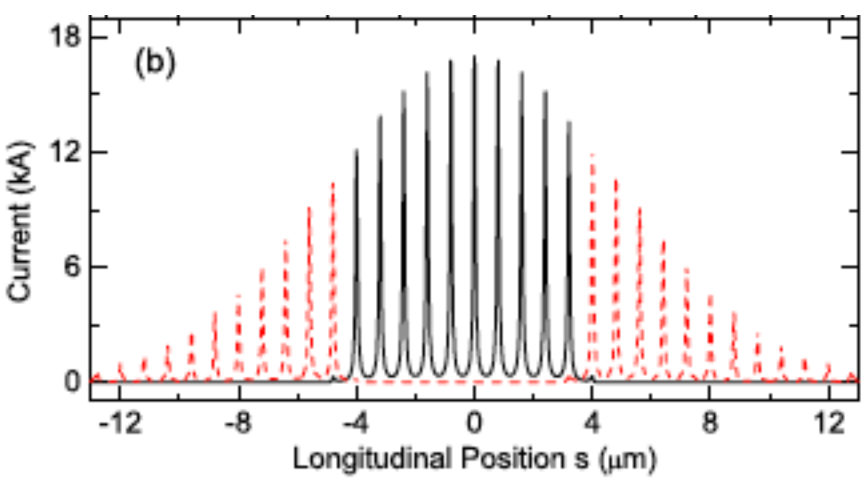
IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta
Phys. Scr. T169 (2016) 014002 (15pp) doi:10.1088/0031-8949/T169/1/014002

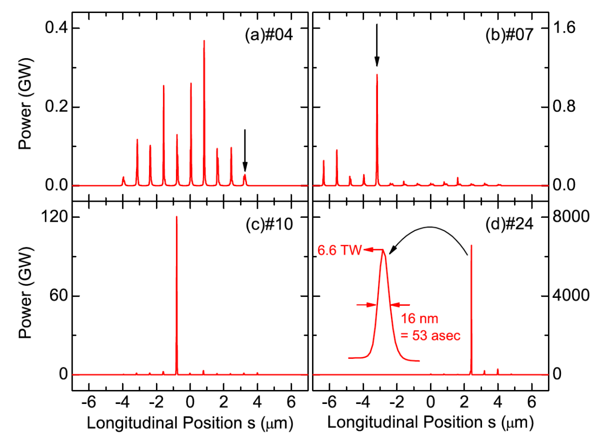
Multidimensional resonant nonlinear spectroscopy with coherent broadband x-ray pulses

Kochise Bennett[1,2], Yu Zhang[1], Markus Kowalewski[1], Weijie Hua[1,3] and Shaul Mukamel[1,2,4,5]

TW-Scale Attosecond Pulses

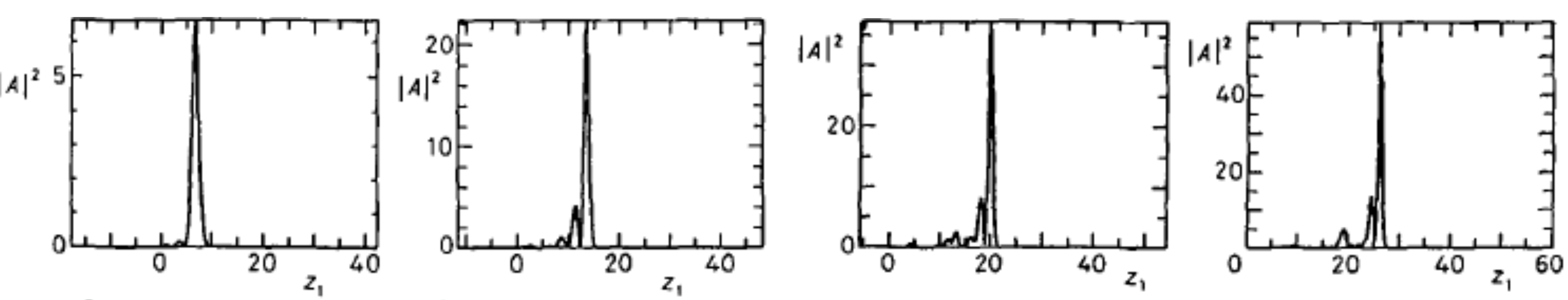






Multi-stage amplification leads
To superradiant regime:
Power grows ~ z2
Pulse duration ~z-1/2
Multi-TW 50 as pulse

Tanaka, Takashi. "Proposal for a pulse-compression scheme in X-ray free-electron lasers to generate a multiterawatt, attosecond X-ray pulse." *Physical review letters* 110.8 (2013): 084801.



Bonifacio, R., et al. "Physics of the high-gain FEL and superradiance." *La Rivista del Nuovo Cimento (1978-1999)* 13.9 (1990): 1-69.

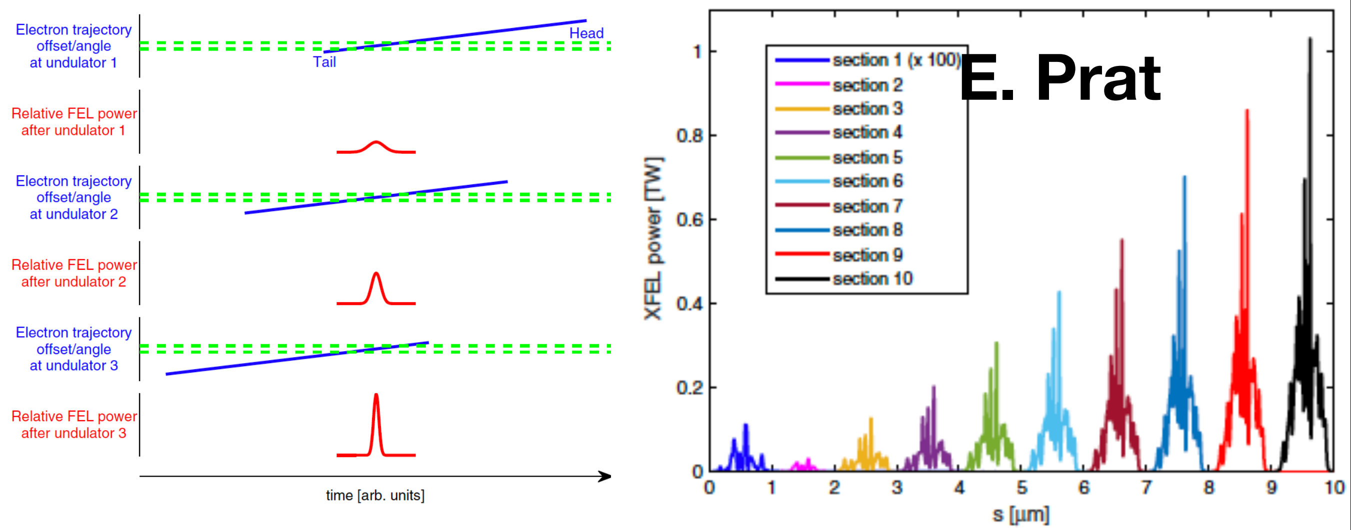
TW-Scale Attosecond Pulses: Simplified Approaches

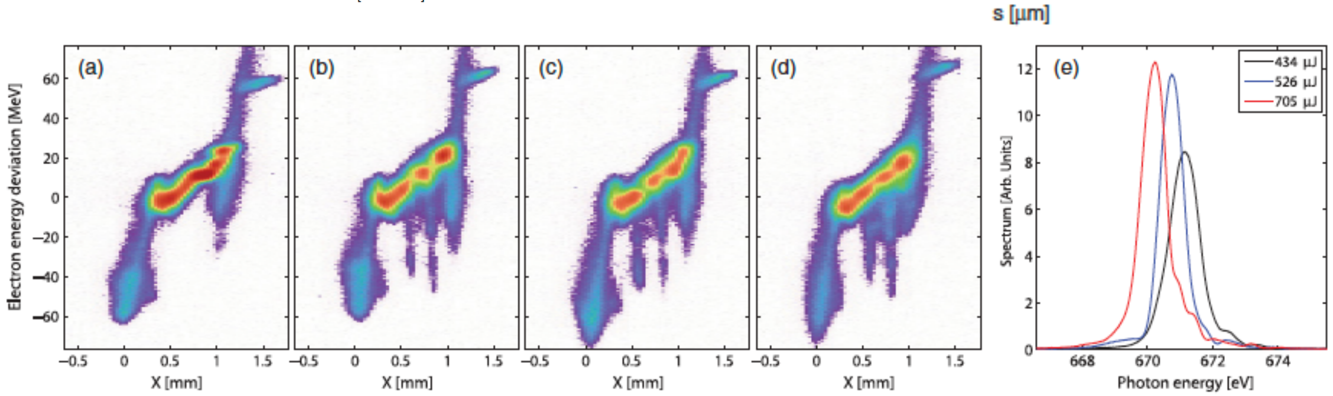
“In comparison with a similar scheme proposed in a previous paper … **simplifies the accelerator layout.”**
(T. Tanaka et al. J Synchrotron Radiat. 2016 Nov 1; 23(Pt 6): 1273–1281.)

1) Prat, Eduard, and Sven Reiche. *Physical review letters* 114.24 (2015): 244801.
2) Prat, Eduard, Florian Löhl, and Sven Reiche. *Physical Review Special Topics-Accelerators and Beams* 18.10 (2015): 100701.
3) Kumar, Sandeep, et al. *Scientific reports* 6 (2016): 37700.
4) Huang, Senlin, et al. *Physical Review Accelerators and Beams* 19.8 (2016): 080702.
5) Wang, Zhen, Chao Feng, and Zhentang Zhao. *Physical Review Accelerators and Beams* 20.4 (2017): 040701.

Transverse tilt

E. Prat

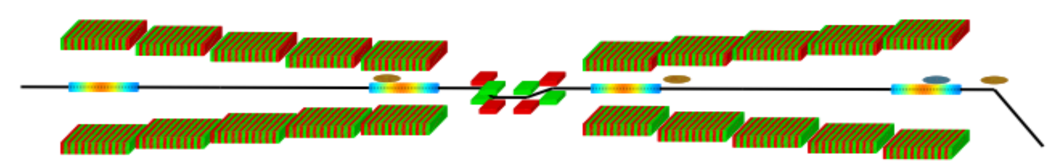


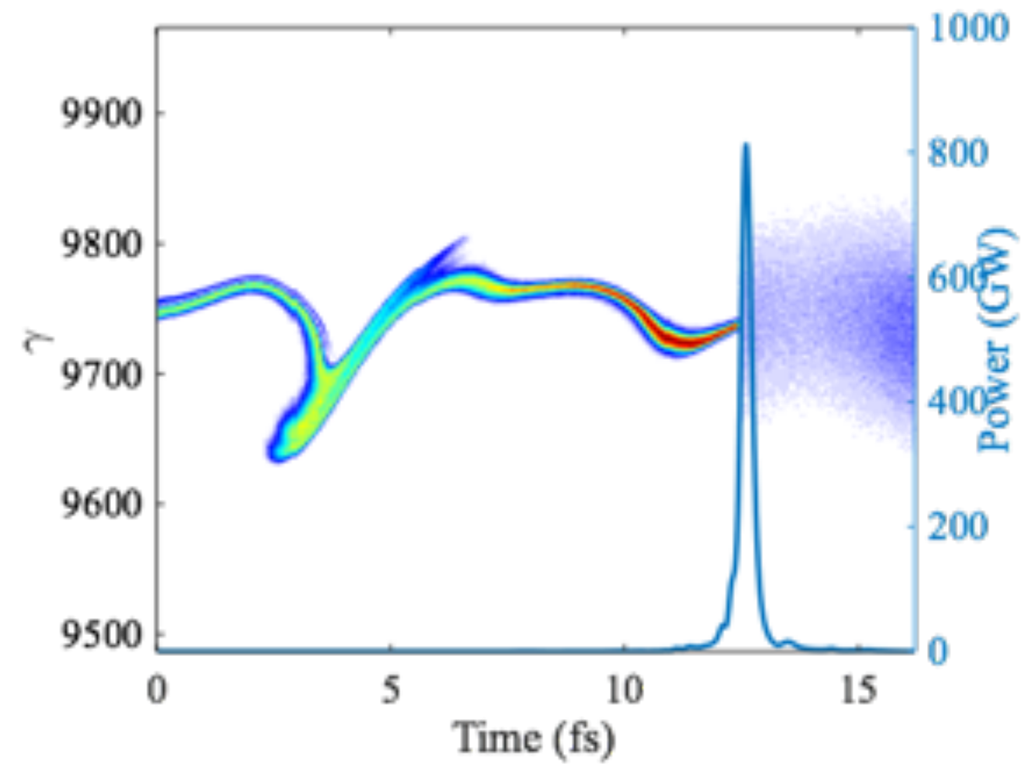


Experiment at LCLS ~3 fs ~200 GW

Lutman, Alberto A., et al. *Physical review letters* 120.26 (2018): 264801.

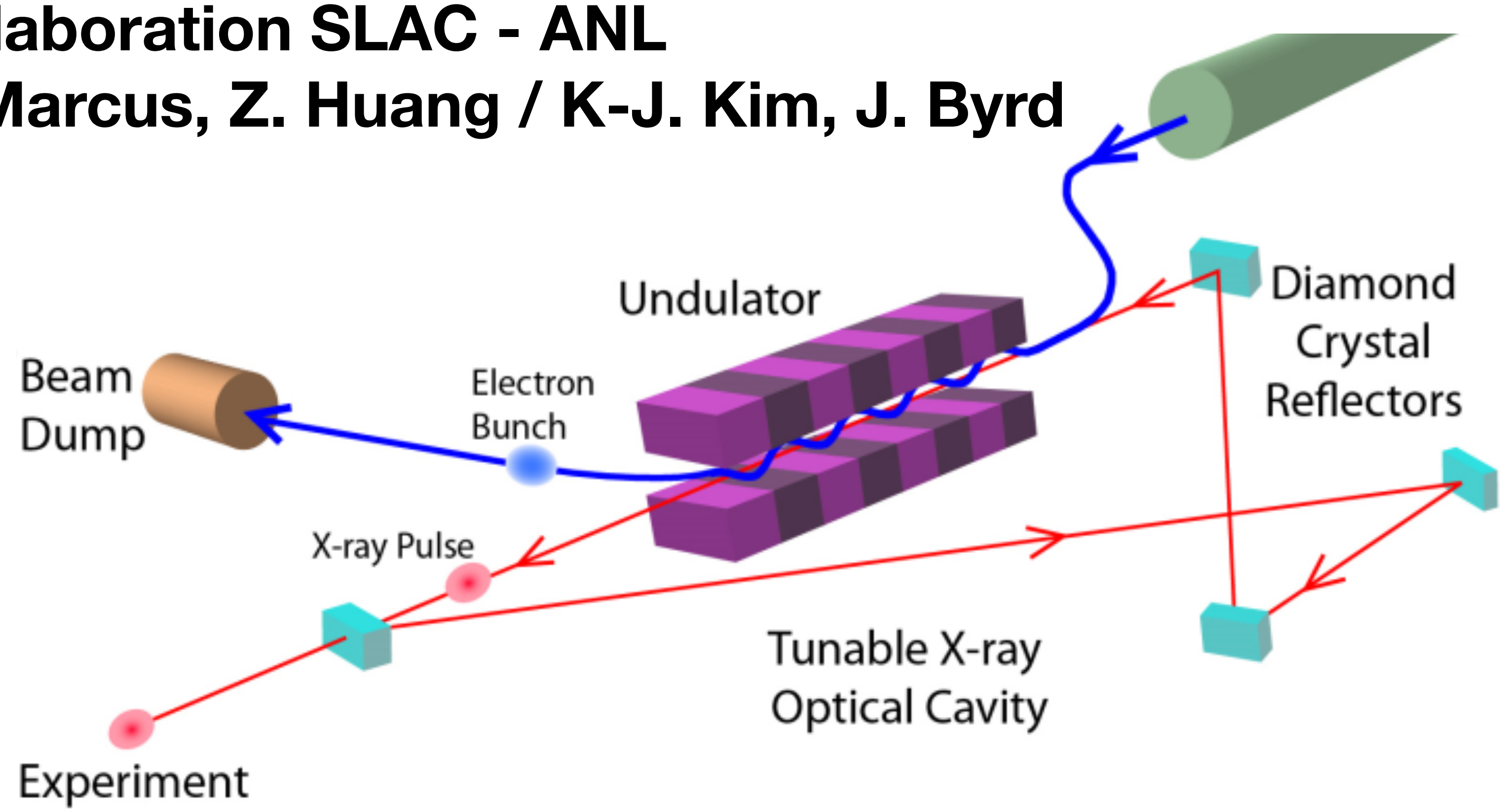
Double chirp-taper



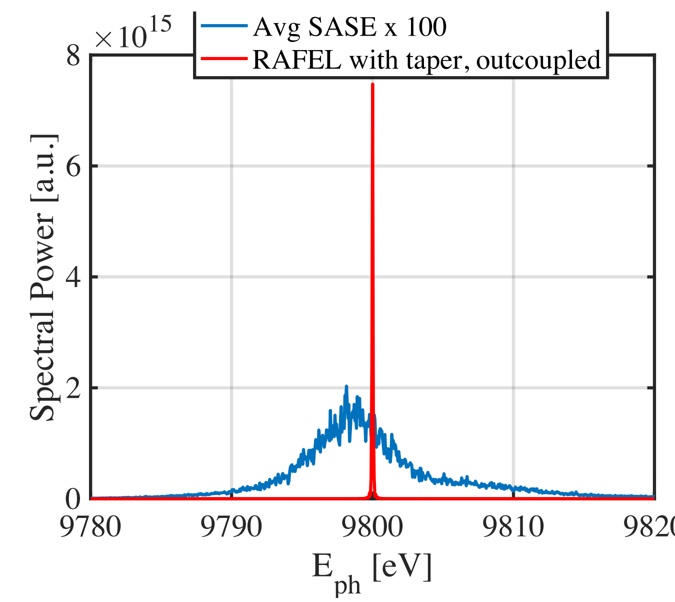


The Brightness Frontier: Cavity-Based FELs

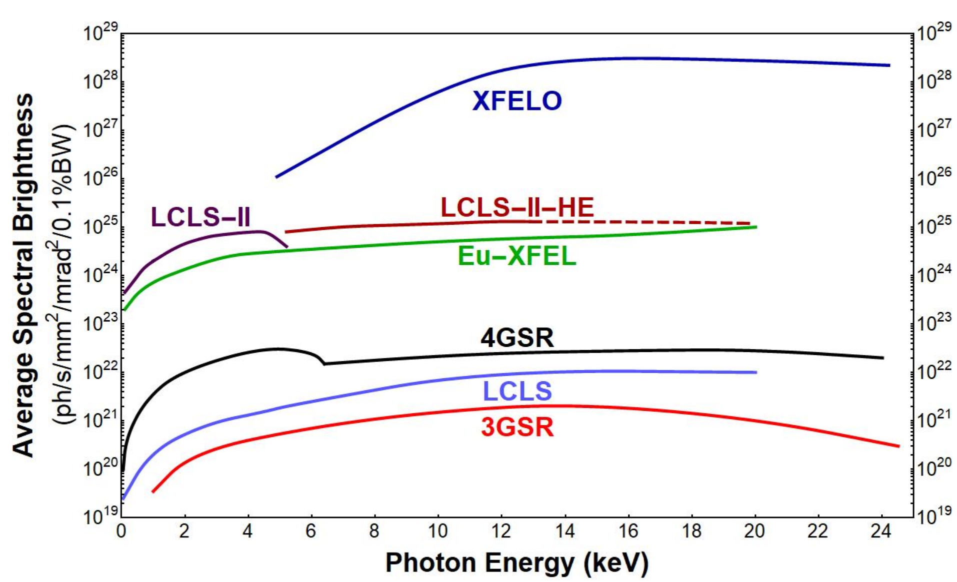
Collaboration SLAC - ANL
G. Marcus, Z. Huang / K-J. Kim, J. Byrd



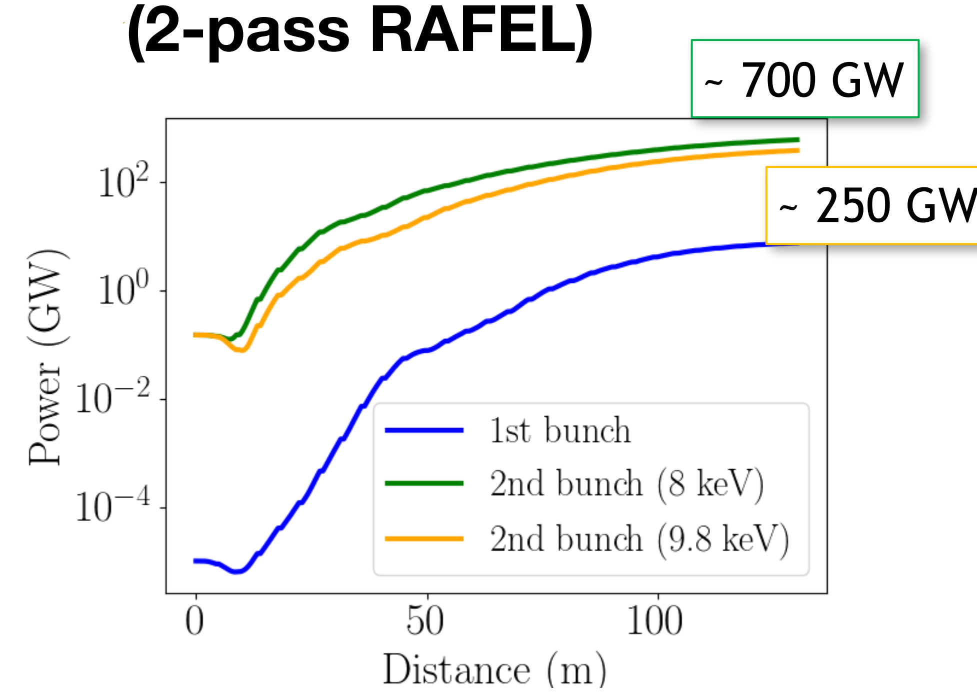
Improve peak brightness by 2 orders of magnitude For LCLS-II HE



Oscillator with superconducting linac: Increased spectral brightness



TW Pulses with copper linac (2-pass RAFEL)

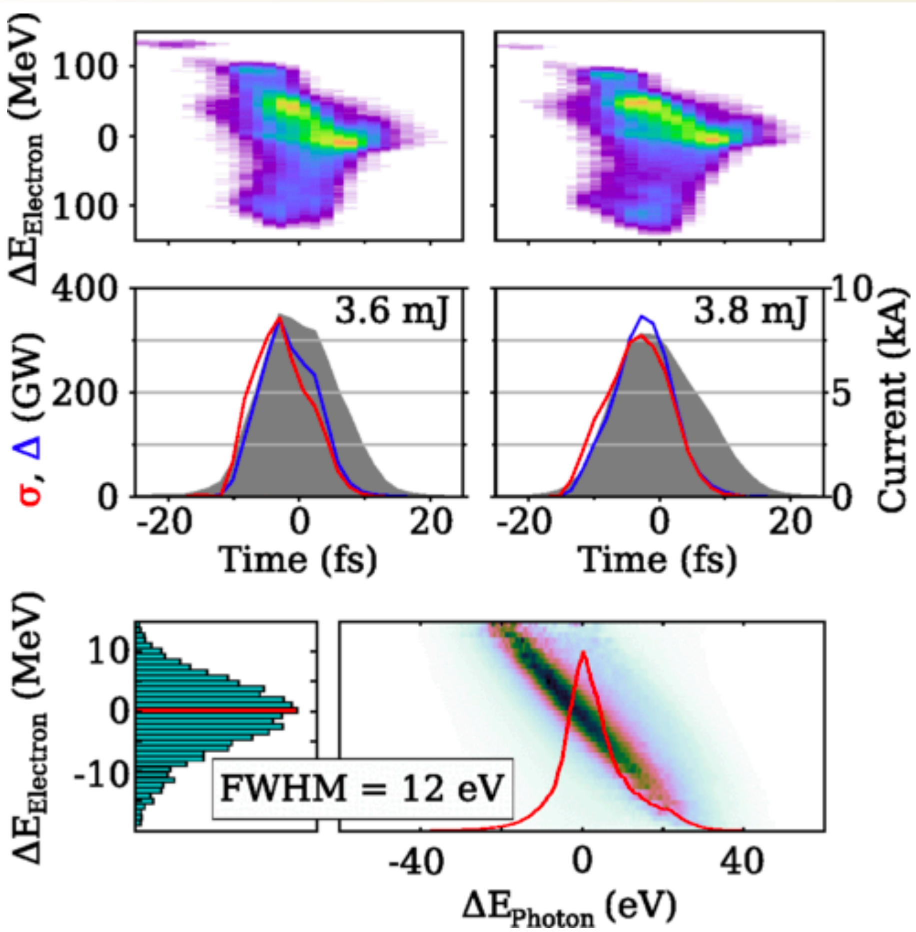


Opportunities for Advanced Accelerators

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

How Much FEL Power Actually Used



High-energy FEL facilities can generate
Few mJ of pulse energy.

Tall order for compact machines!
Convert energy from laser to electrons to x-rays, small chance you find a mJ at the other end…

However:
XFELs ~10^{10} x brighter than synchrotrons…
Surely 10^{8} is still revolutionary!

~50% HXR beamtimes use beam-sharing mode -> ~1% of pulse energy
~35% of SXR beamtime uses 90% attenuation or more

(underestimate of actual use of attenuators since HXR attenuators are not archived…)

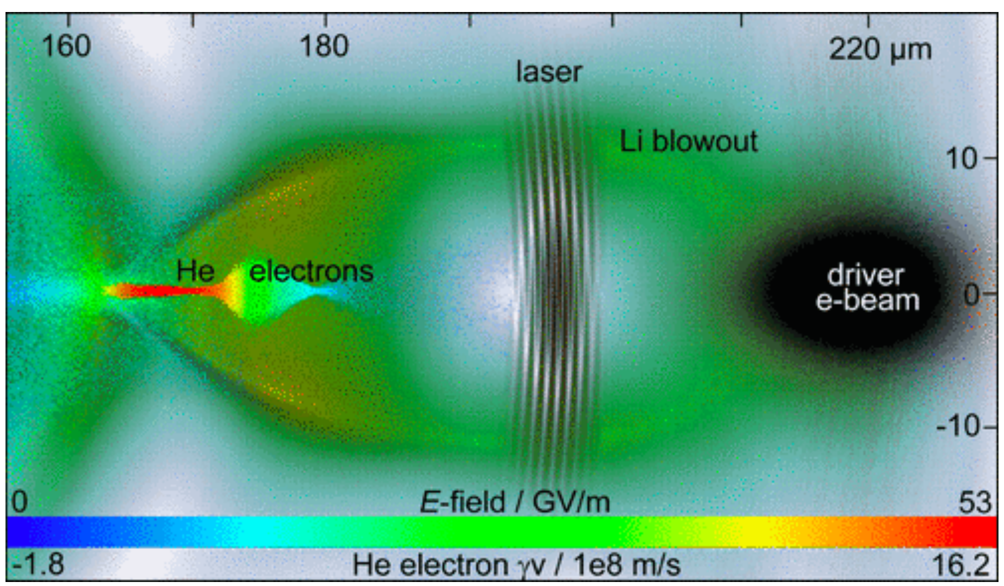
Zhu, Diling, et al. "Performance of a beam-multiplexing diamond crystal monochromator at the Linac Coherent Light Source." *Review of Scientific Instruments* 85.6 (2014): 063106.

Opportunities in Attosecond Science

Saldin, Evgeny L., Evgeny A. Schneidmiller, and Mikhail V. Yurkov.
"Design formulas for short-wavelength FELs." *Optics communications* 235.4-6 (2004): 415-420.

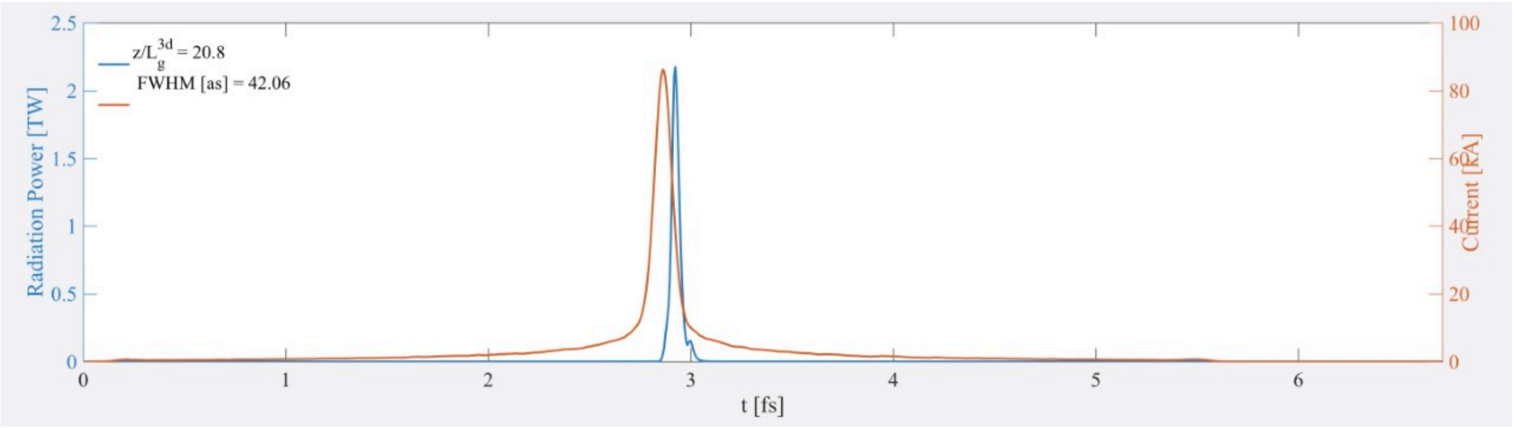
$$L_g \propto \epsilon_n^{5/6} \rightarrow \Delta t_{min} \propto \epsilon_n^{5/6}$$

After optimizing all parameters cooperation length almost proportional to 1/emittance.
Attosecond pulses from plasma photo-injectors!



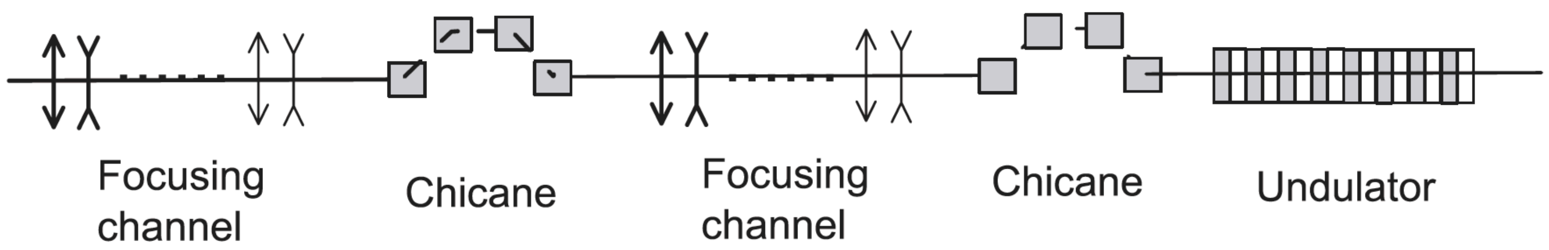
B. Hidding, G. Pretzler, J. B. Rosenzweig, T. Königstein, D. Schiller, and D. L. Bruhwiler Phys. Rev. Lett. **108**, 035001

Beam from FACET-II plasma photo-injector sim.
Assuming transport and ESASE compression
are feasible ~5-10 times shorter pulses than LCLS:
42 as - 2 TW at 1 nm



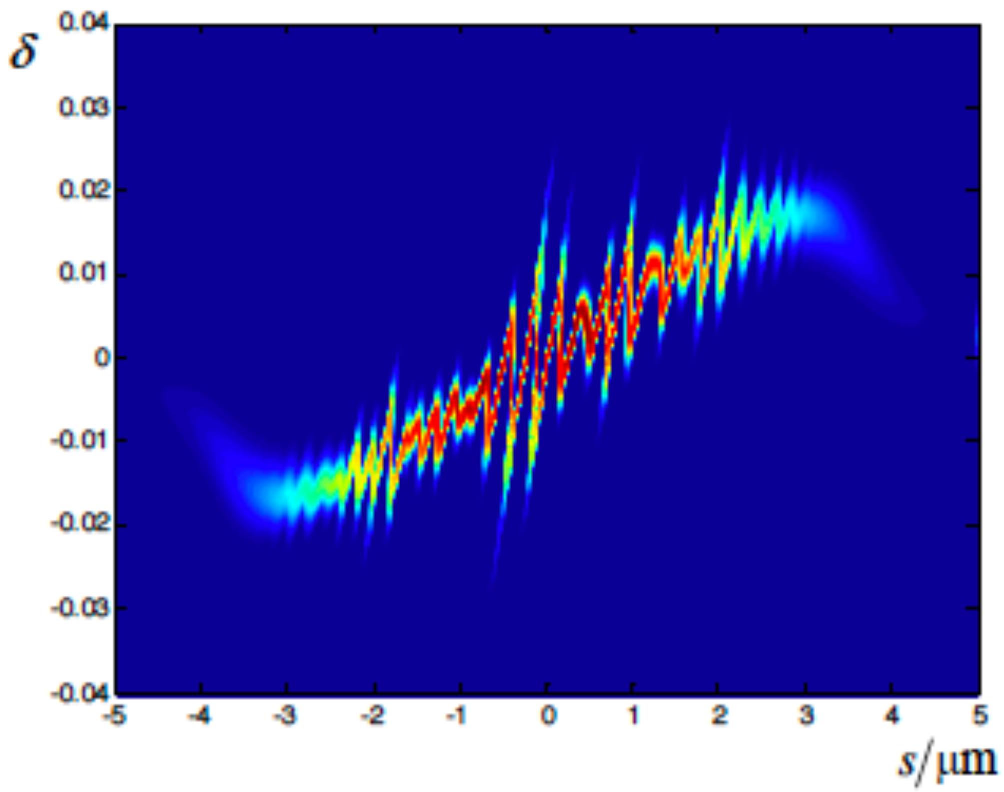
Courtesy C. Emma

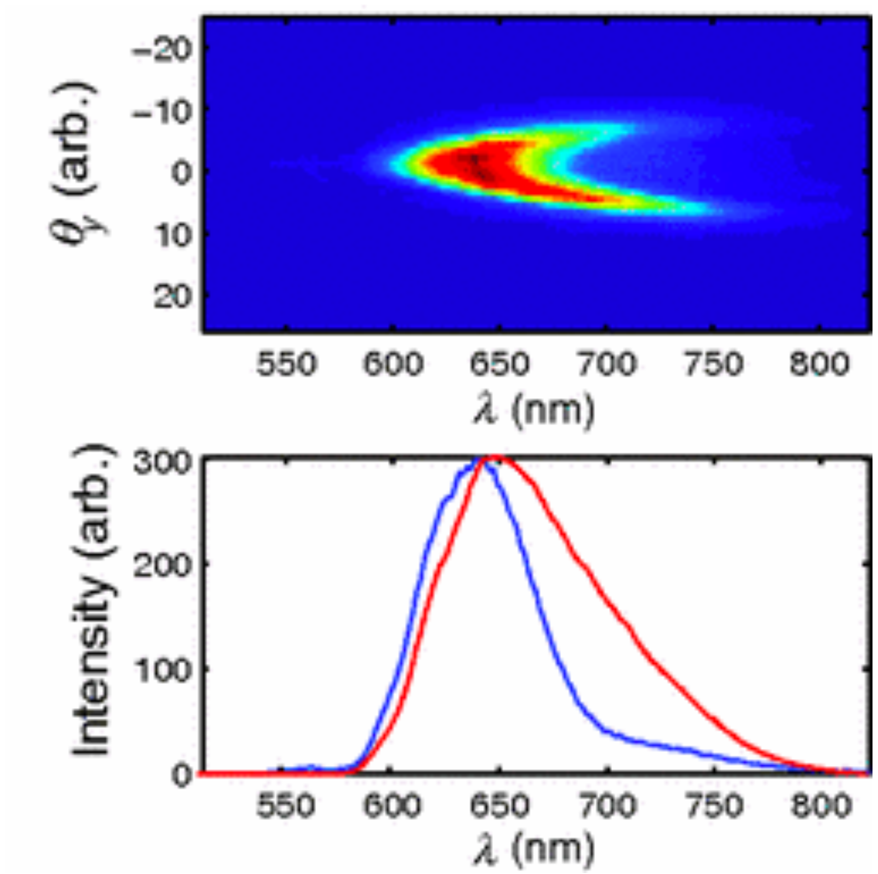
Does it Have to be an FEL?



- -Insensitive to pointing instability
- -Insensitive to correlated e-spread
- -Scalable to XUV

E. A. Schneidmiller and M. V. Yurkov
Phys. Rev. ST Accel. Beams **13**, 110701 (2010) - Published 13 November 2010

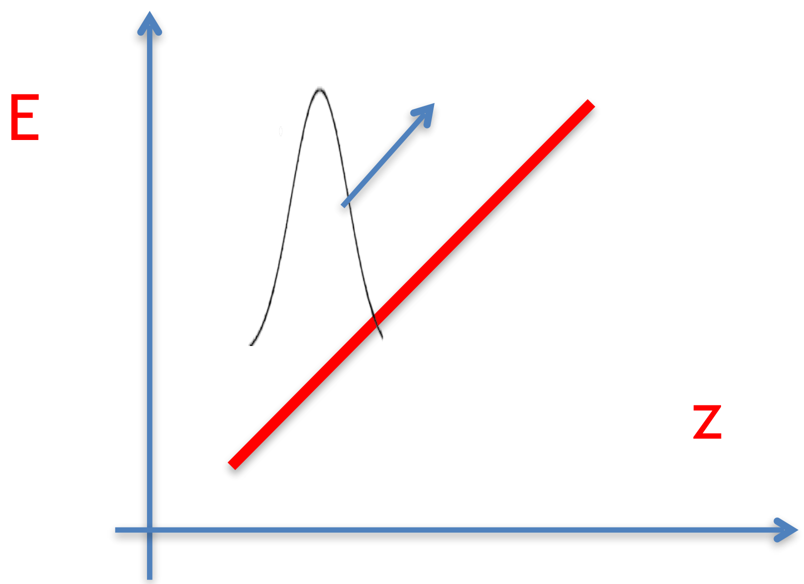




Longitudinal Space Charge Amplifier driven by a Laser-Plasma Accelerator
Martin Dohlus[a], Evgeny Schneidmiller[a], Mikhail V. Yurkov[a], Christoph Henning[a] and Florian J. Gruner[b]

Marinelli, A., et al. *Physical review letters* 110.26 (2013): 264802

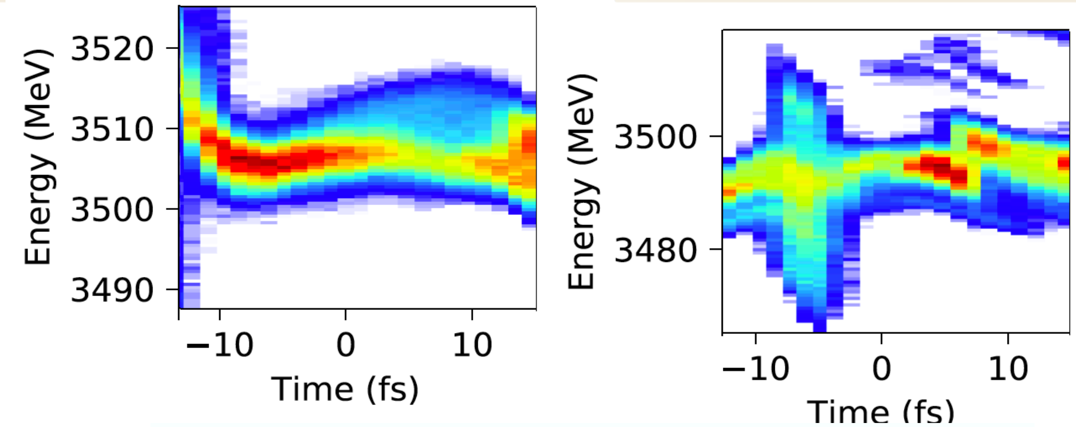
Chirp-Tapered FEL

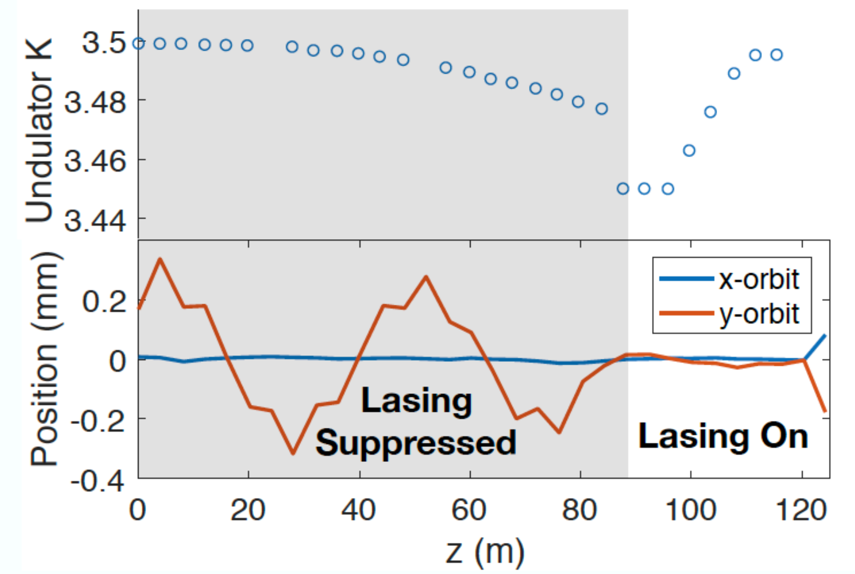


Radiation slips forward
Photons move to electrons with different energy.

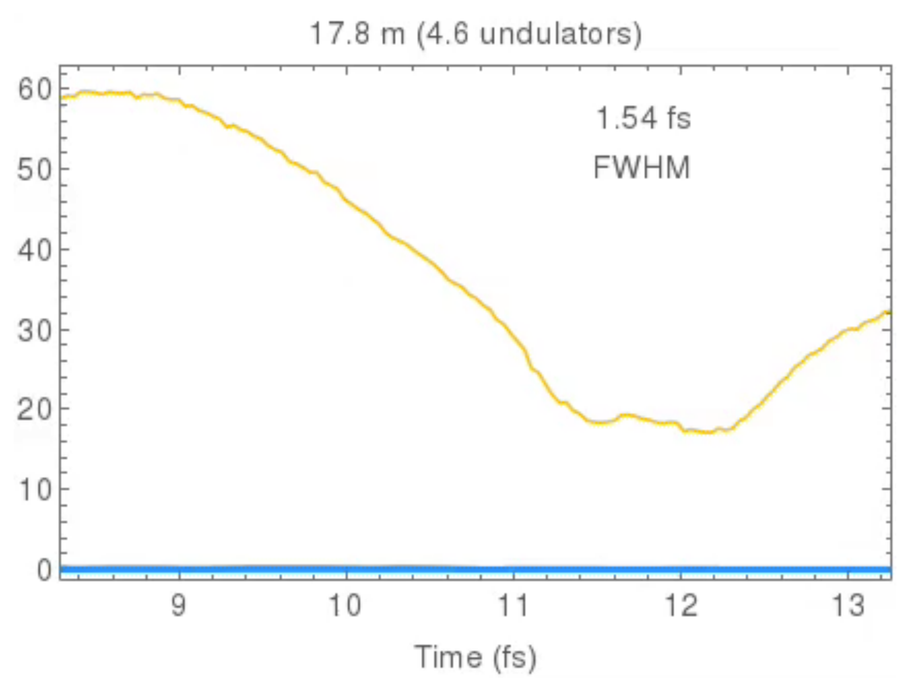
Change undulator K to keep resonance

$$\frac{1}{\gamma}\frac{\Delta\gamma}{c\Delta t}\lambda_r = \frac{\Delta K}{\Delta z}\frac{K}{1+K^2}\lambda_w$$





Chirp-taper compensation allows preserving gain while increasing bandwidth



Saldin, Evgenij L., Evgeny A. Schneidmiller, and Mikhail V. Yurkov. *Physical Review Special Topics-Accelerators and Beams* 9.5 (2006): 050702.

Giannessi, L., et al. *Physical review letters* 106.14 (2011): 144801.

Couprie, Marie-Emmanuelle, et al. "Towards a free electron laser based on laser plasma accelerators." *Journal of Physics B: Atomic, Molecular and Optical Physics* 47.23 (2014): 234001.

Summary

- Advanced X-ray FEL modes subject of intense investigation at XFEL facilities worldwide

- Accelerator physicist driving new science by accessing more extreme Parameters

- Things to look forward to:

  Attosecond pump/probe
  Cavity based FELs (RAFEL, XFELO)
  TW attosecond pulses with superradiant operation

- Advanced accelerators present unique opportunities (and lots of challenges…)

QUESTIONS?

Terawatt X-ray FELs

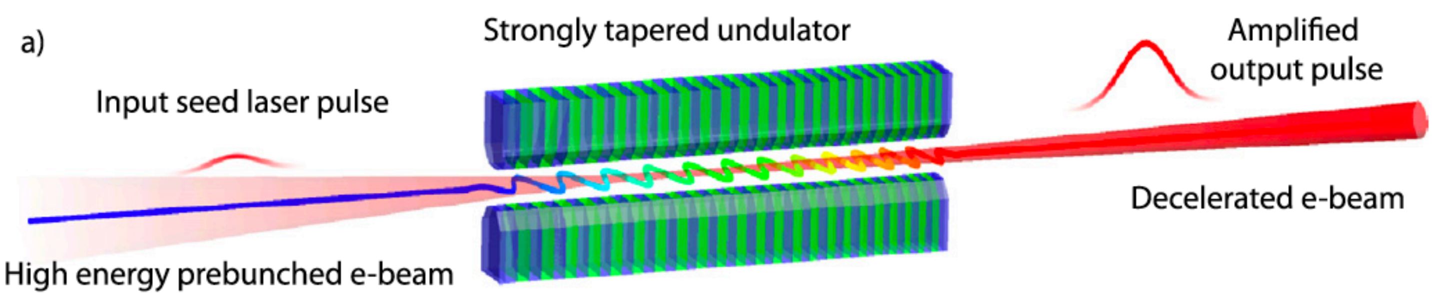
STRUCTURAL DYNAMICS 2, 041701 (2015)

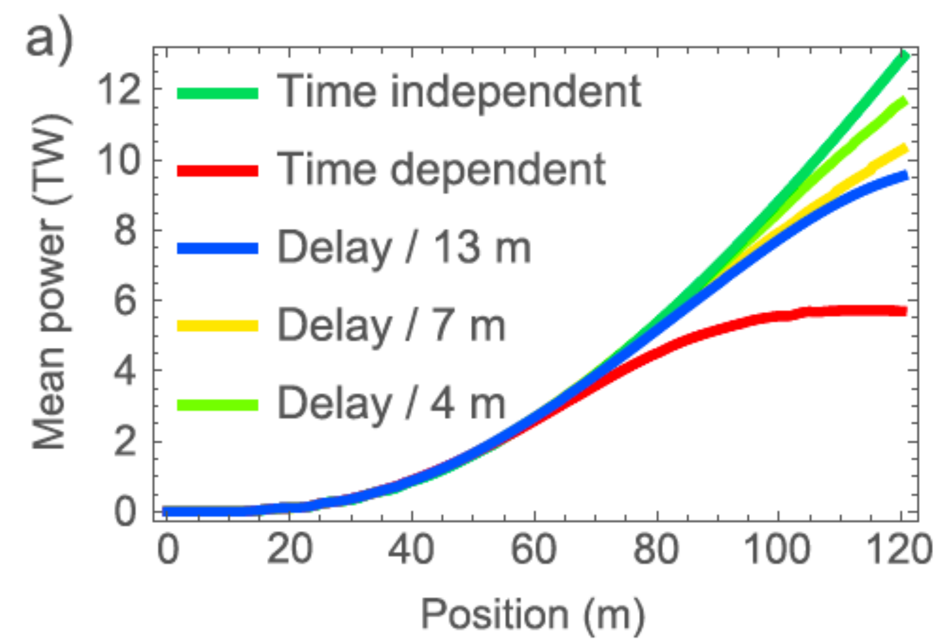
The linac coherent light source single particle imaging road map

A. Aquila,[1,2] A. Barty,[3] C. Bostedt,[1,a)] S. Boutet,[1] G. Carini,[1] D. dePonte,[1] P. Drell,[1,4,5] S. Doniach,[1,5] K. H. Downing,[6] T. Earnest,[7,8] H. Elmlund,[9,10] V. Elser,[1,11] M. Gühr,[12] J. Hajdu,[13,2] J. Hastings,[1] S. P. Hau-Riege,[14] Z. Huang,[1] E. E. Lattman,[15,16] F. R. N. C. Maia,[13,6] S. Marchesini,[6] A. Ourmazd,[17] C. Pellegrini,[1,18] R. Santra,[3,19] I. Schlichting,[20] C. Schroer,[21] J. C. H. Spence,[22] I. A. Vartanyants,[21,23] S. Wakatsuki,[1,24] W. I. Weis,[24] and G. J. Williams[1,25]

e.g. diffraction signal from crystal ~Intensity x (#cells)²
Single molecule image requires large Intensity!

Pulse requirements: 1 TW - 10 fs

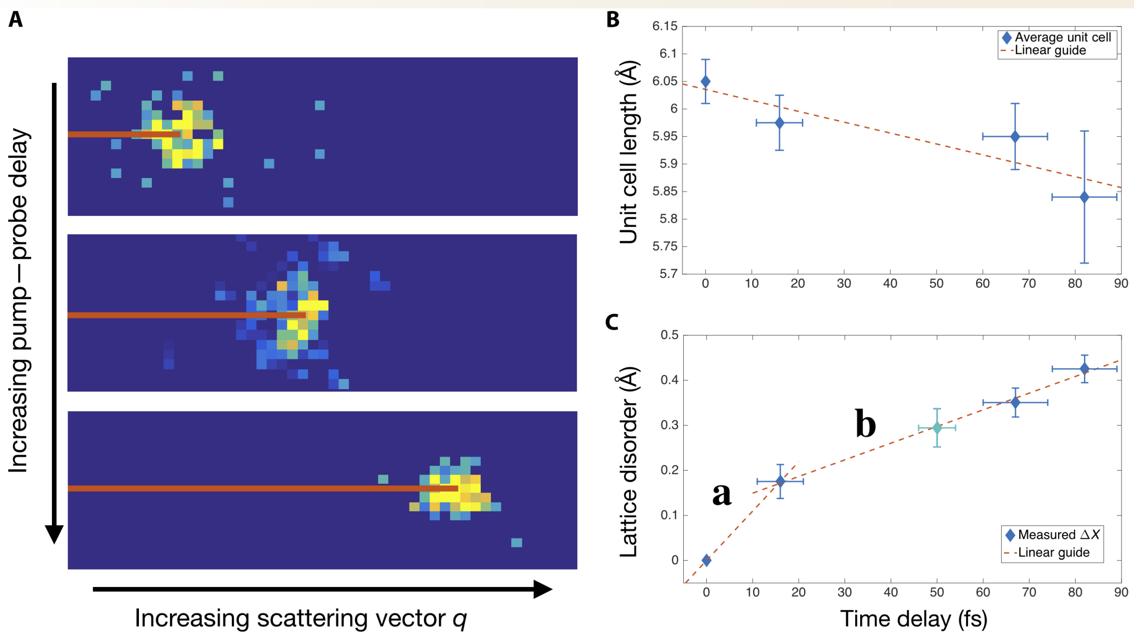




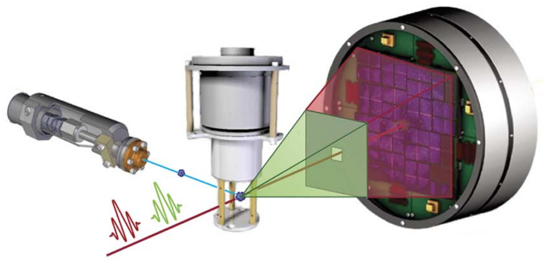
Duris, Joseph, Alex Murokh, and Pietro Musumeci. "Tapering enhanced stimulated superradiant amplification." *New Journal of Physics* 17.6 (2015): 063036.

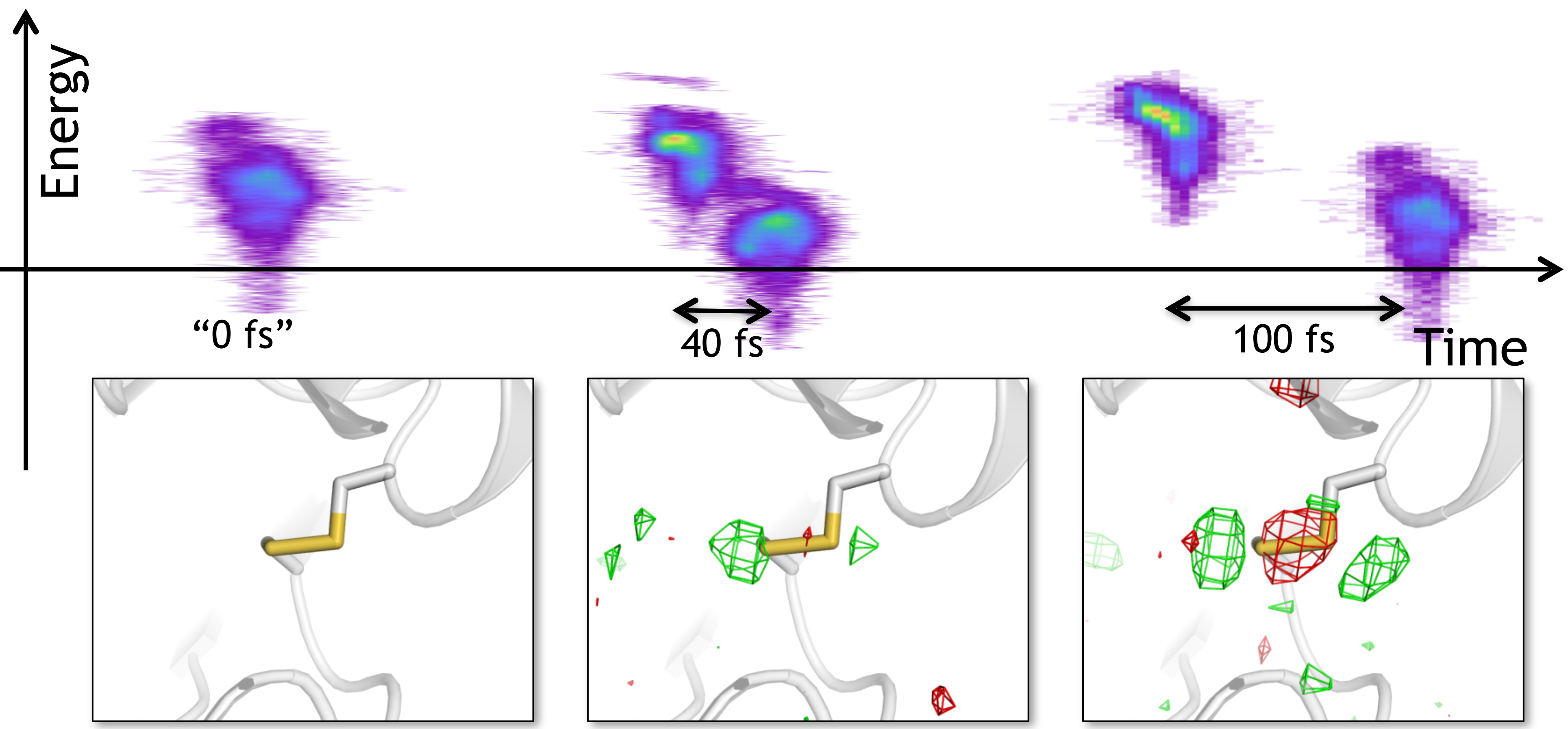
Emma, Claudio, et al. "High efficiency, multiterawatt x-ray free electron lasers." *Physical Review Accelerators and Beams* 19.2 (2016): 020705.

Femtosecond X-ray Pump/X-ray Probe



X-ray induced cluster dynamics.
K. Ferguson et al.
Science Advances 29 Jan 2016:
Vol. 2, no. 1, e1500837





Courtesy of S. Boutet
And I. Schlichting