# X-ray FELs:
# State of the Art and Opportunities For Advanced Accelerators

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U.S. DEPARTMENT OF ENERGY

Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

# Outline

## Intro on FEL physics

## FEL R&D

- Attosecond pulses
- Seeded FELs

## 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…**

# Why X-Rays?

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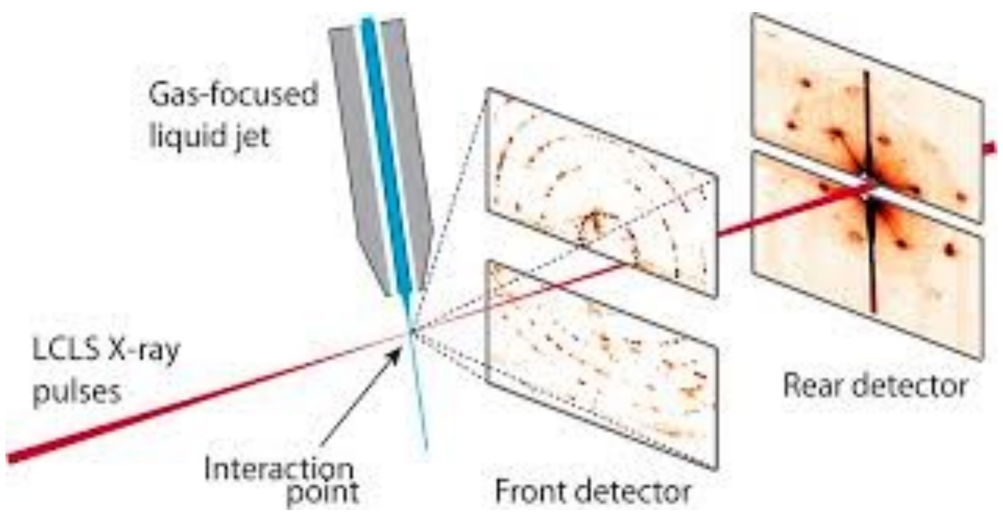
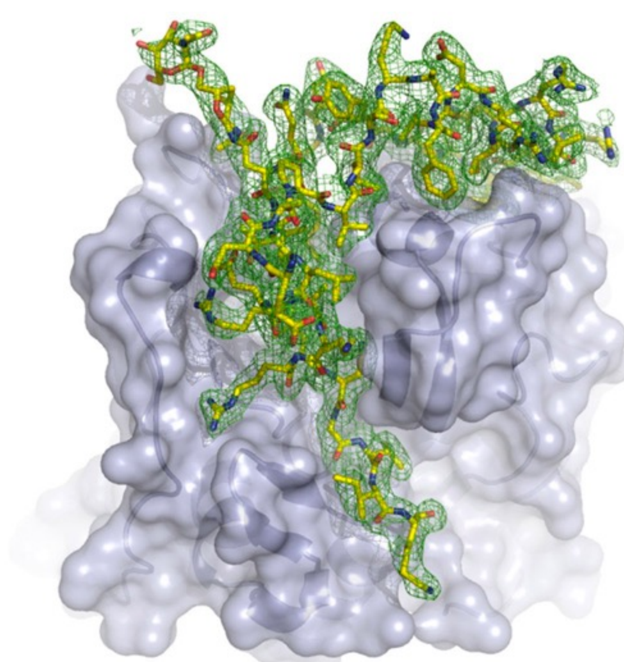
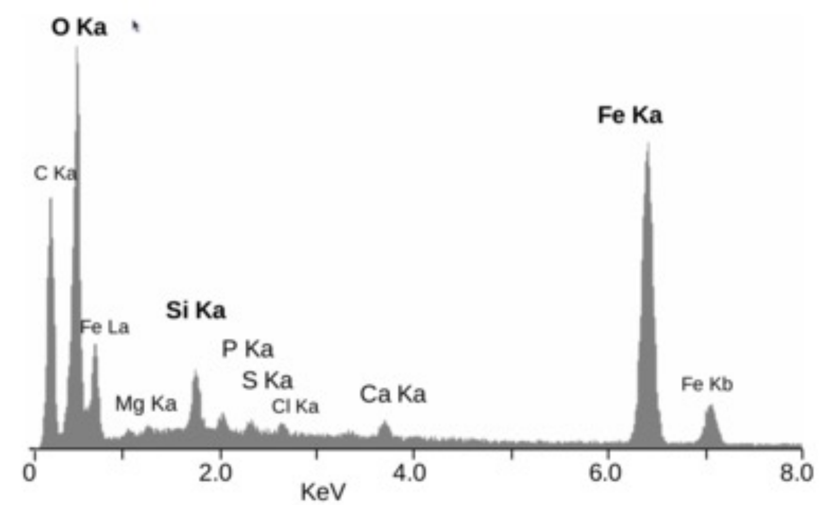
## X-ray diffraction imaging



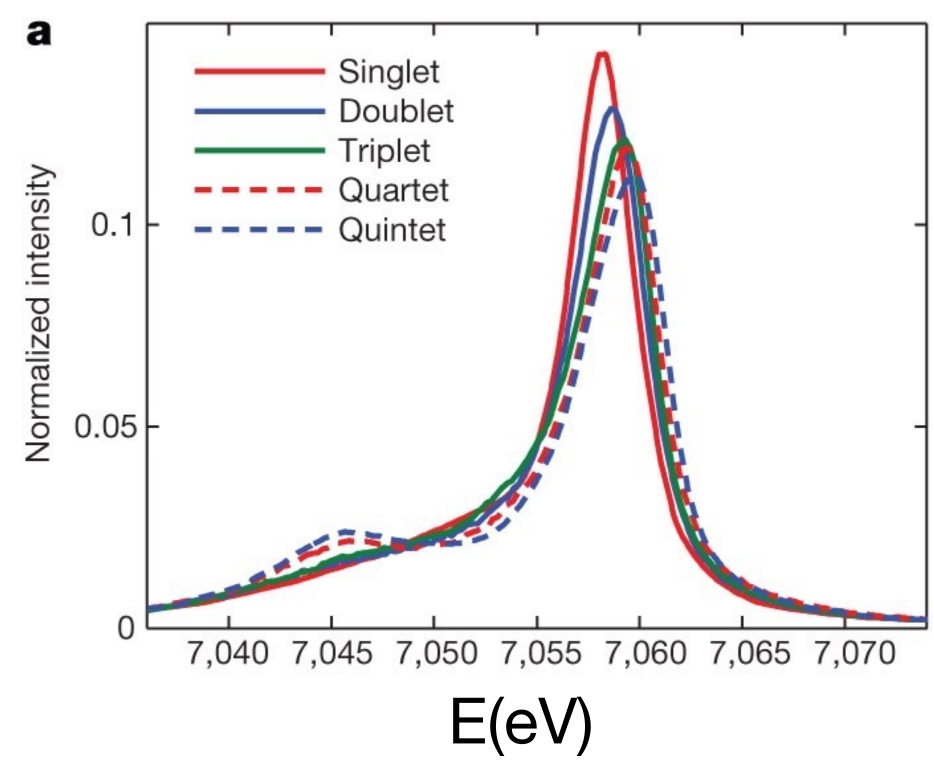



21 February 2013, SPIE Newsroom. DOI: 10.1117/2.1201302.004713

## X-ray spectroscopy




https://en.wikipedia.org/wiki/Energy-dispersive_X-ray_spectroscopy

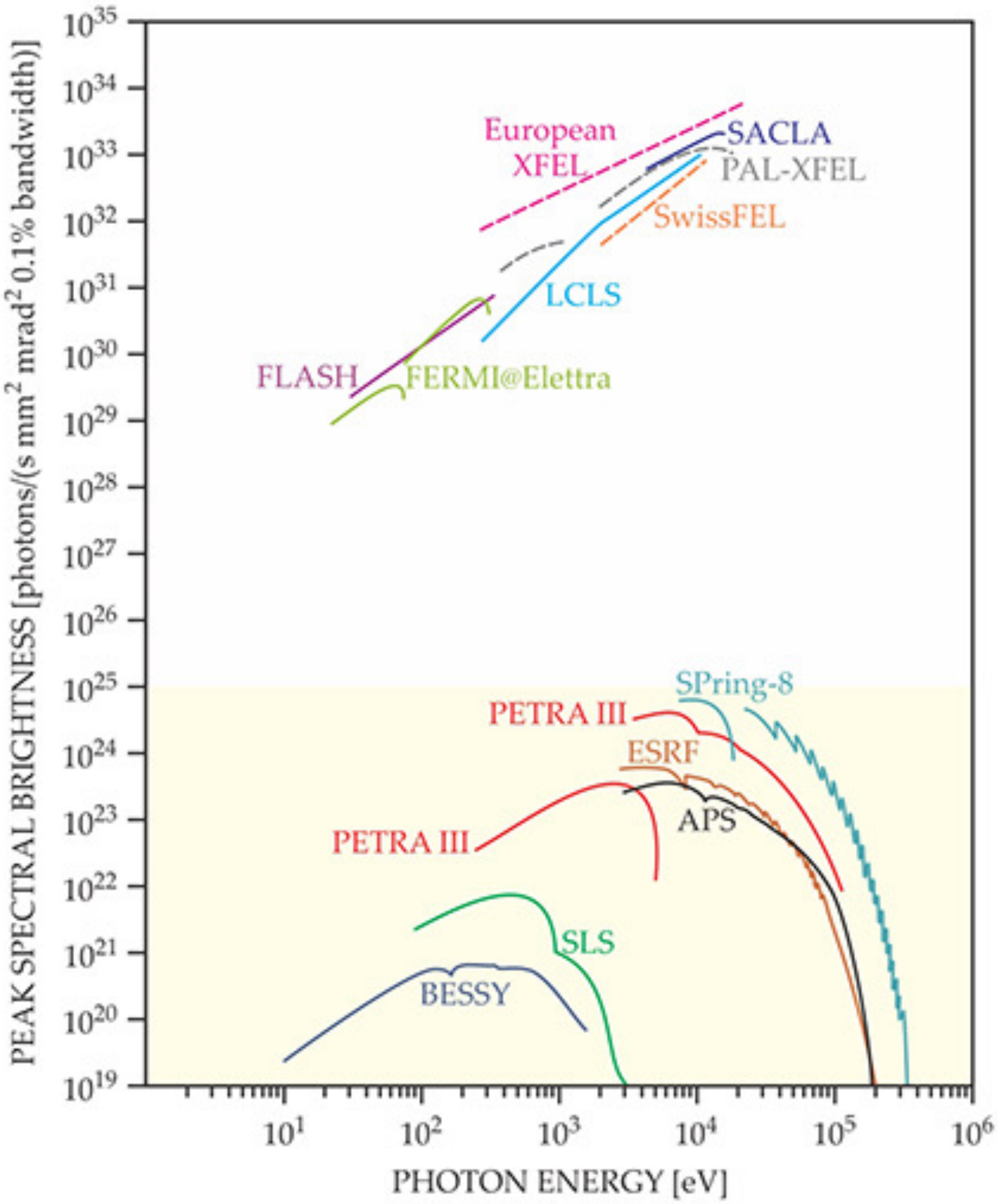



Zhang et al *Nature* **509,** 345–348 (2014)

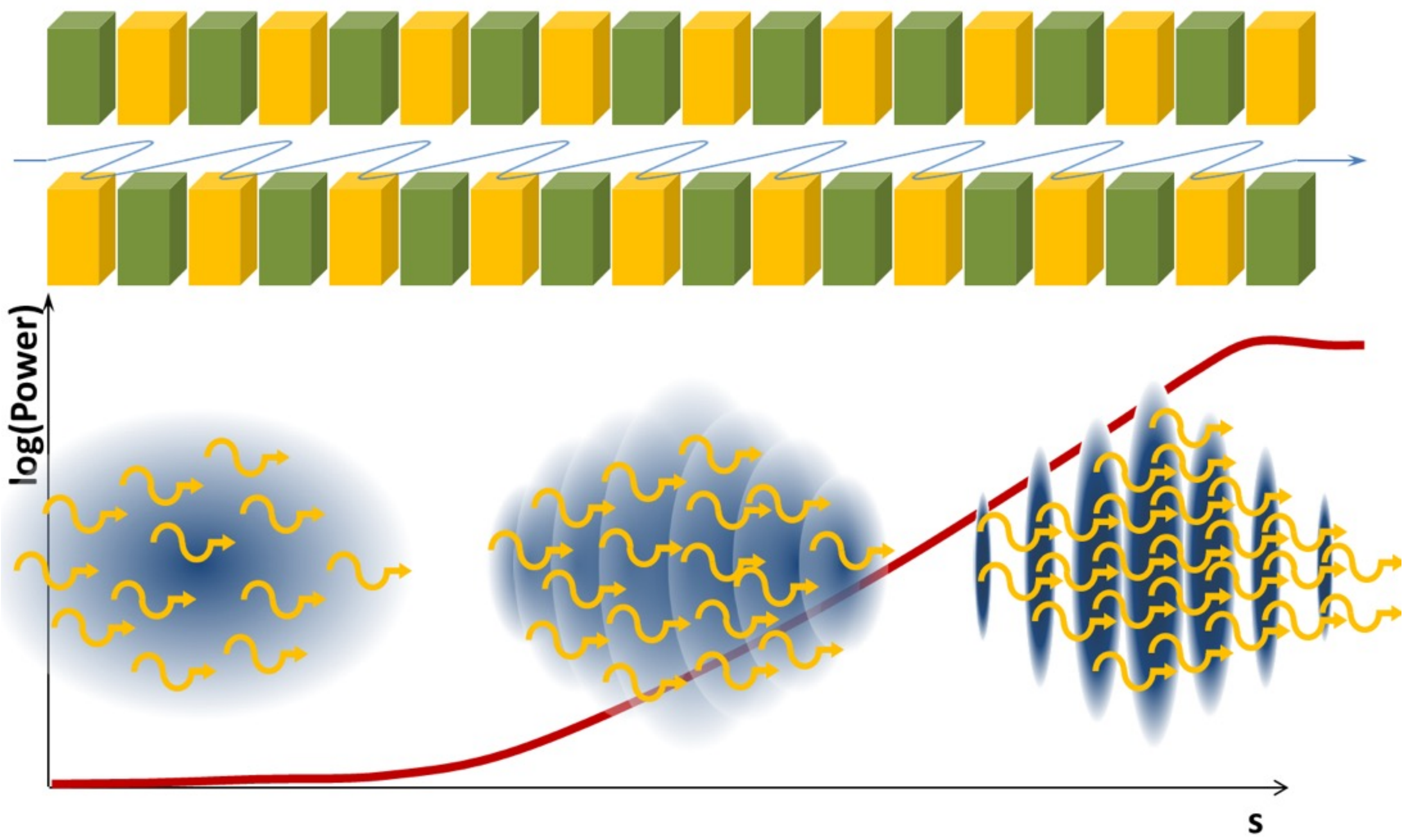
# The X-Ray Free-Electron Laser

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



# Working Principle

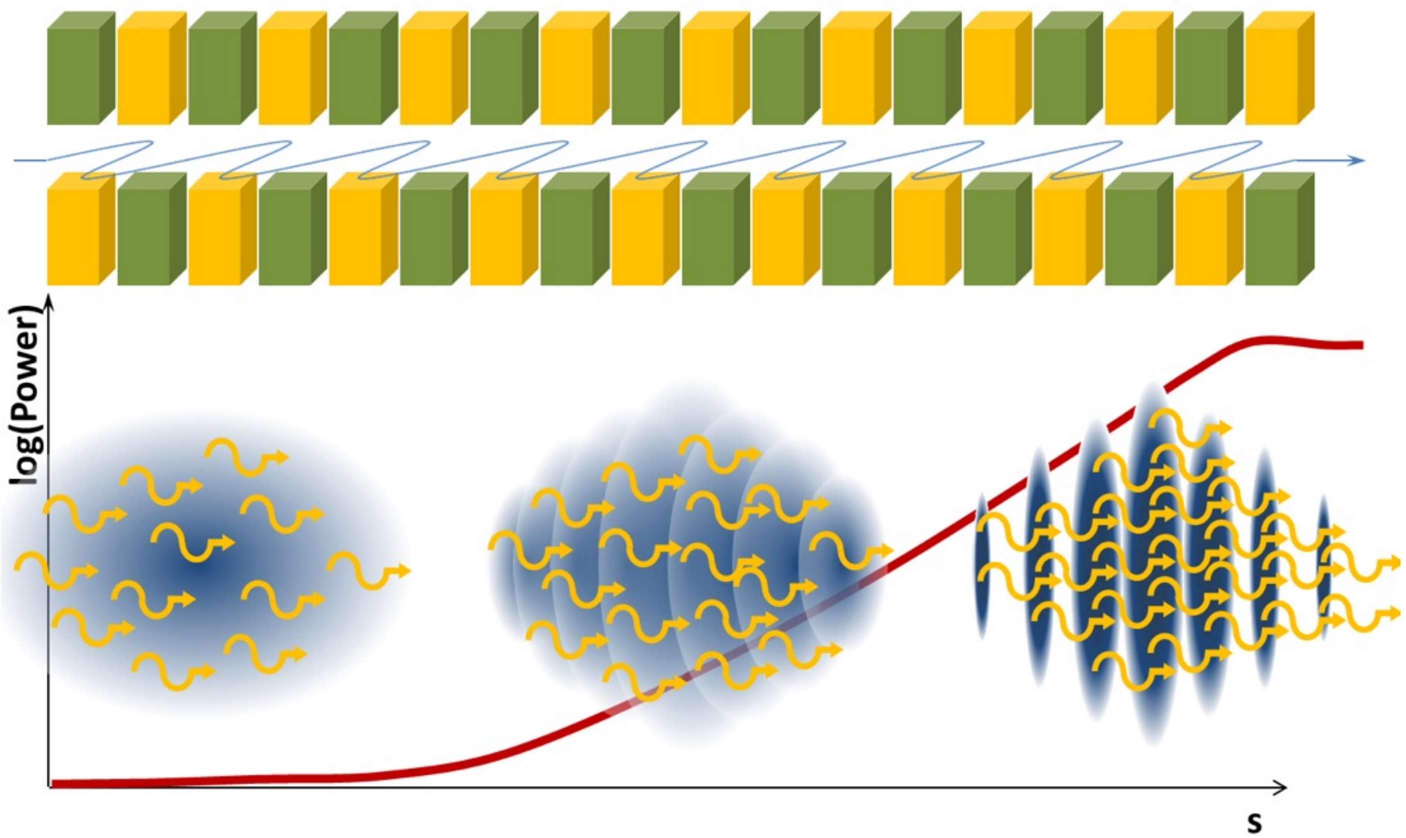



Source: https://www.helmholtz-berlin.de

**Ingredients:**
**Relativistic electrons (~ few GeV)**
**Magnetic undulator**

# Working Principle

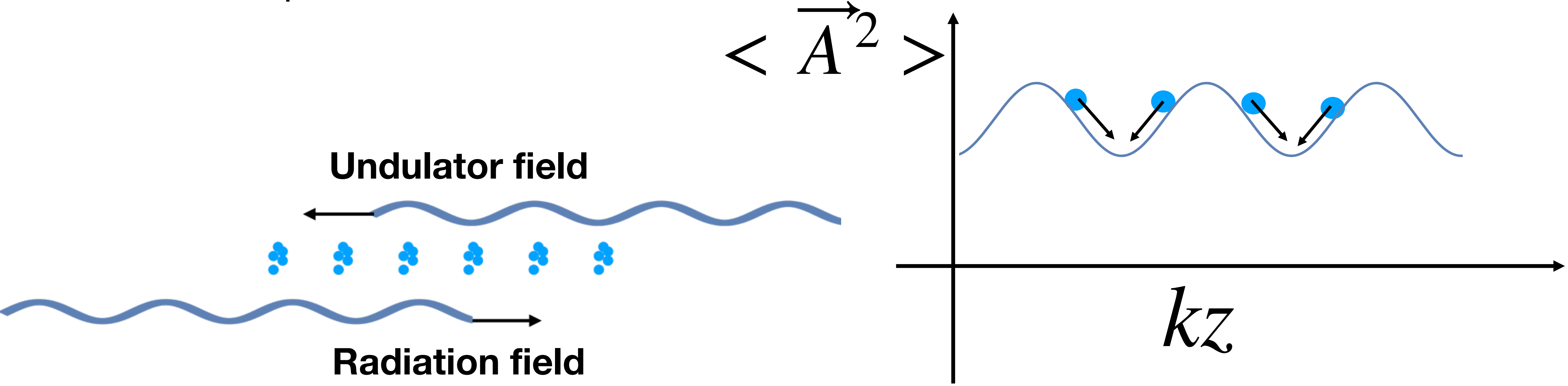





Source: https://www.helmholtz-berlin.de

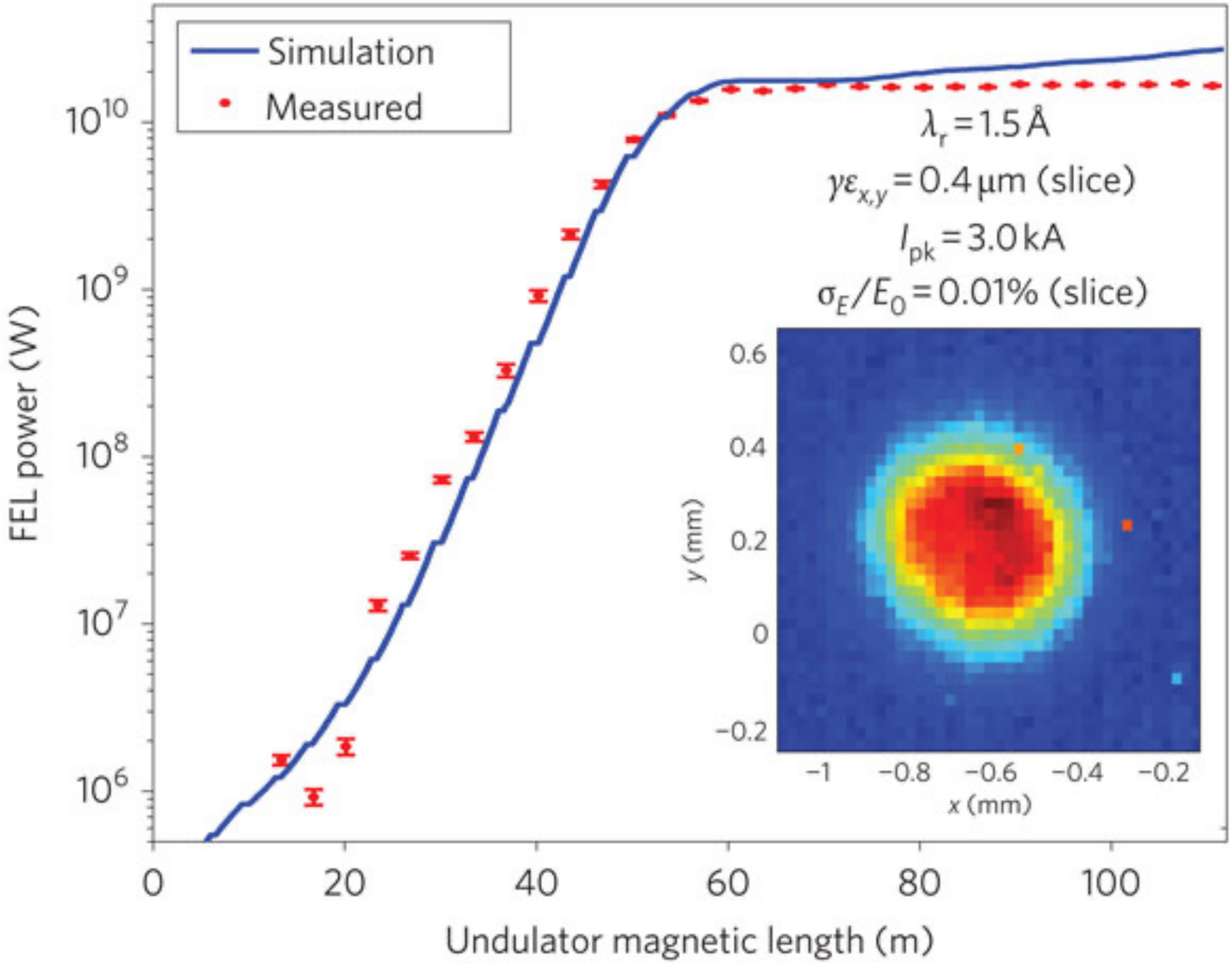
**Ingredients:**
**Relativistic electrons (~ few GeV)**
**Magnetic undulator**

**Ponderomotive force in e-beam frame**




$$< \vec{A}^2 >$$

# FEL Physics in a Nutshell




P. Emma et al. "First lasing and operation of an ångstrom-wavelength free-electron laser." *nature photonics* 4.9 (2010): 641-647.

# Basic XFEL Operation

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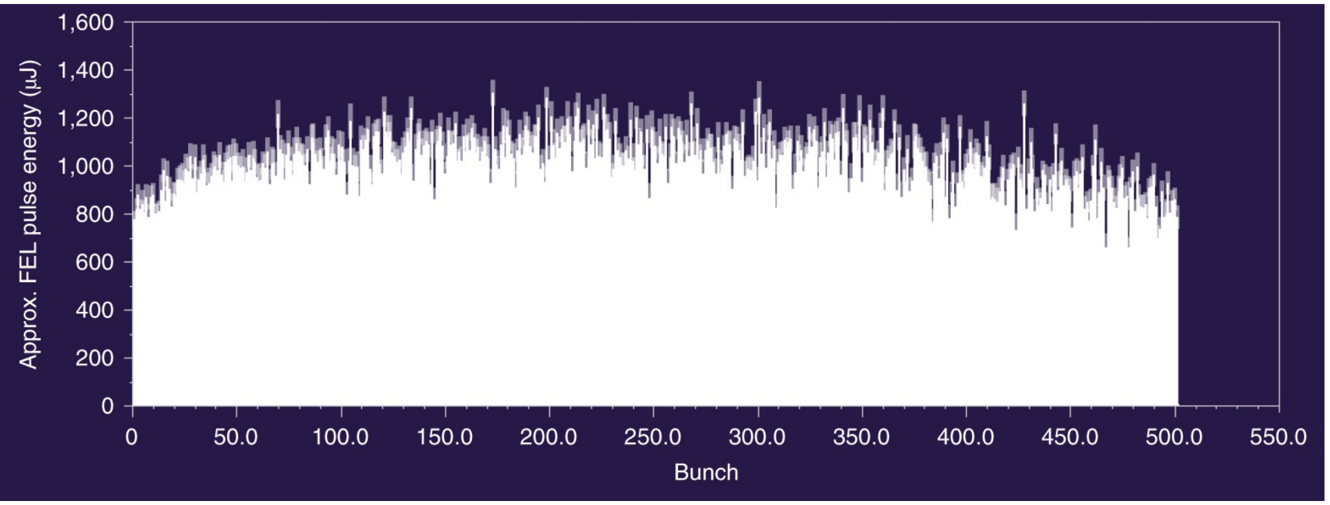
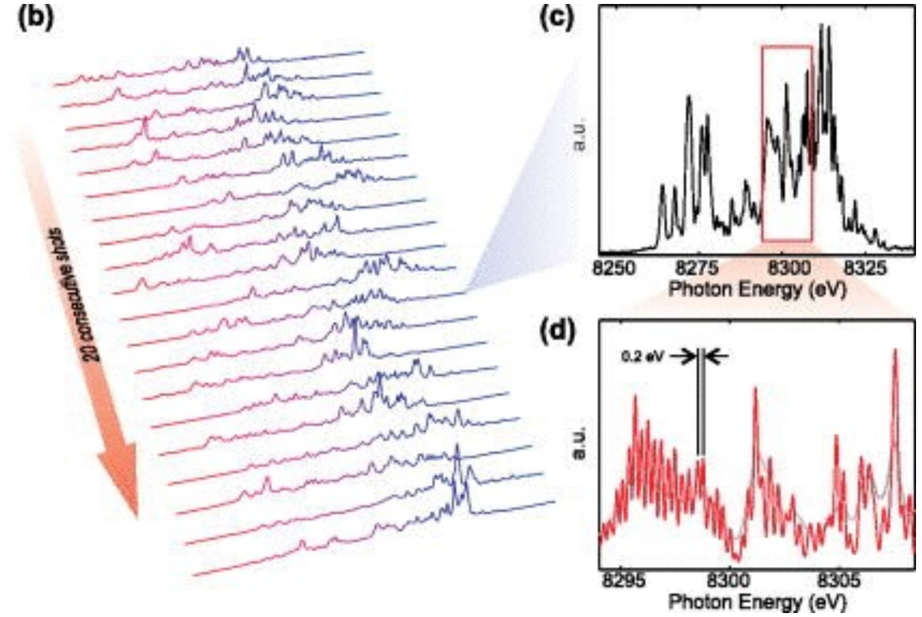
## Pulse energy ~ 0.5 to few mJ



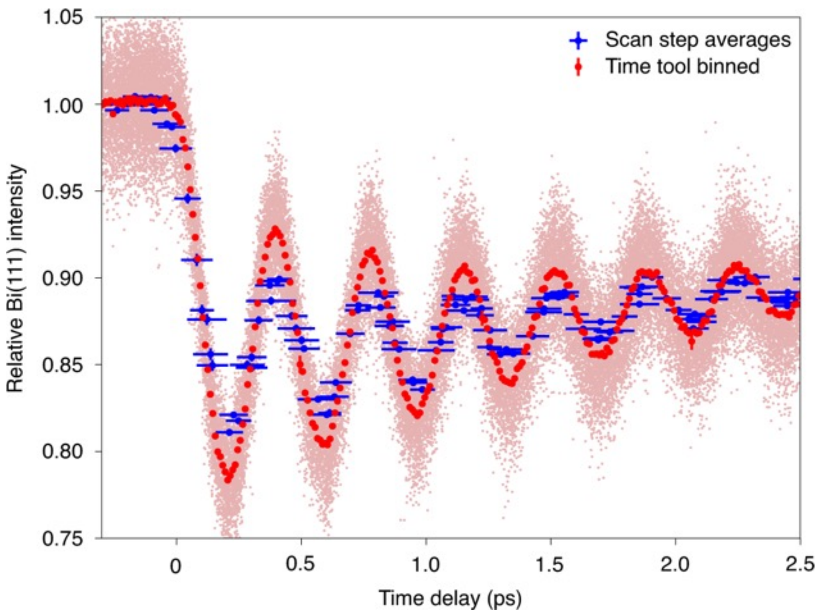

W. Decking et. al.
*Nature photonics* 14.6 (2020): 391-397.

## SASE FEL: partial temporal coherence

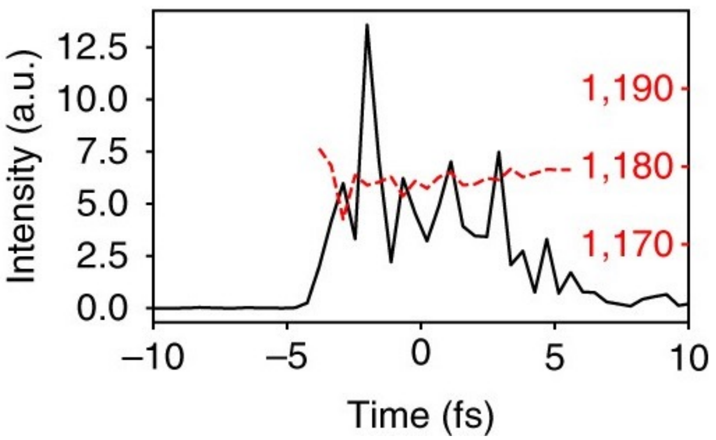



D. Zhu et al.
*Applied Physics Letters* 101.3 (2012): 034103.

## Temporal resolution ~ tens of femtoseconds



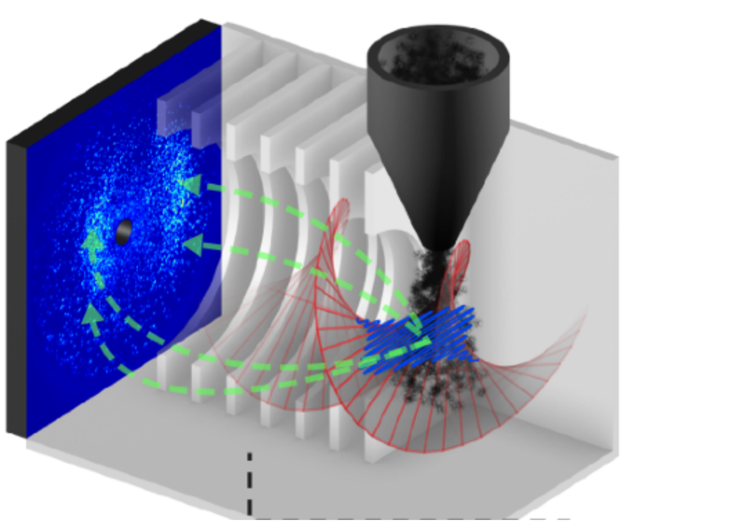

*E. Prat et al. Nature Photonics* 14.12 (2020): 748-754

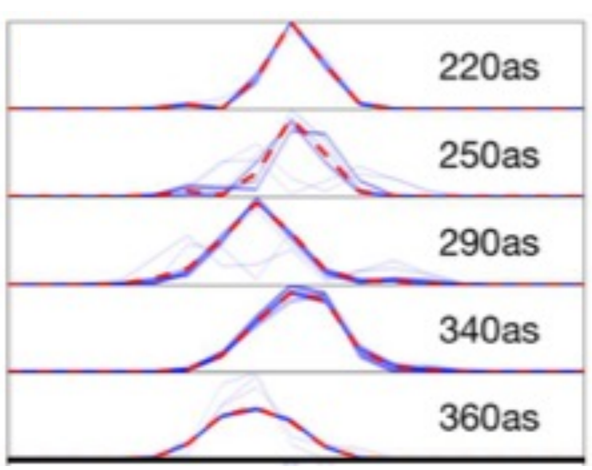



*N. Hartmann et al.*
*Nature Photonics* 12.4 (2018): 215-220.

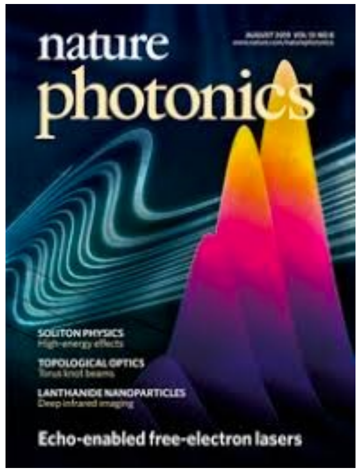
# 3 AREAS OF FOCUS

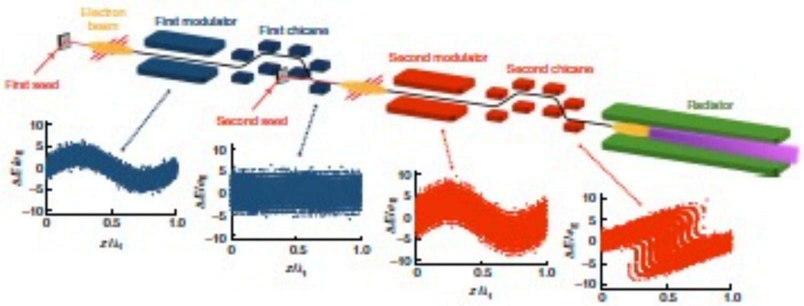
## Attosecond Science



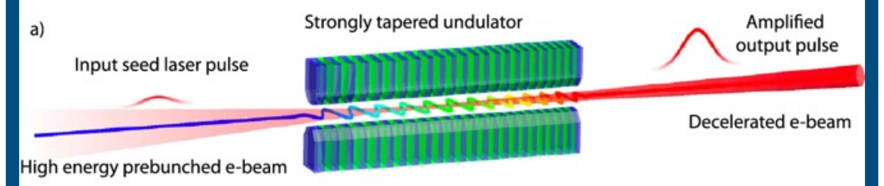


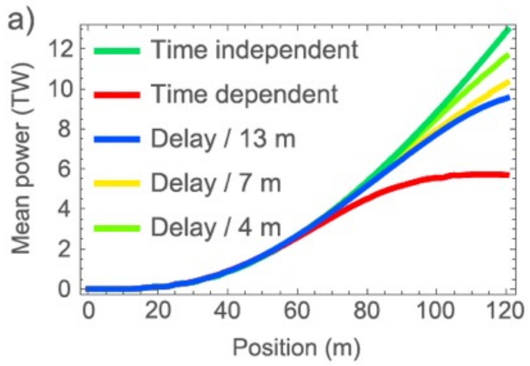

## Femtosecond Shaping/ Seeding

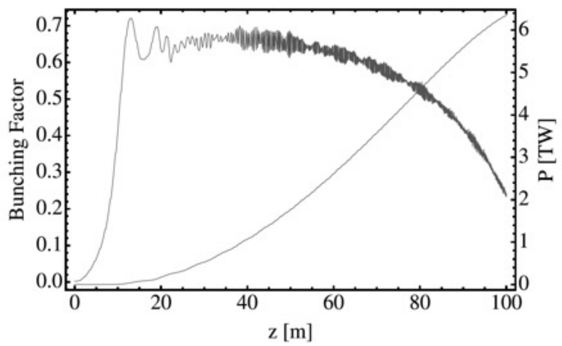


## Higher Power




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

# Status of FEL R&D

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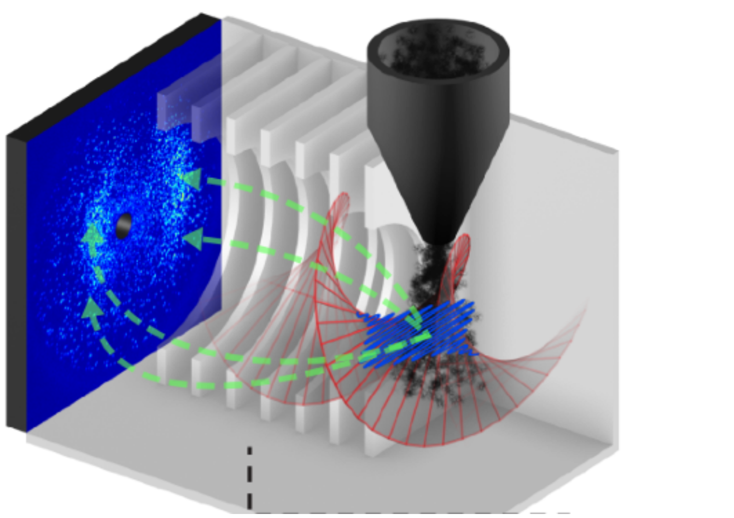
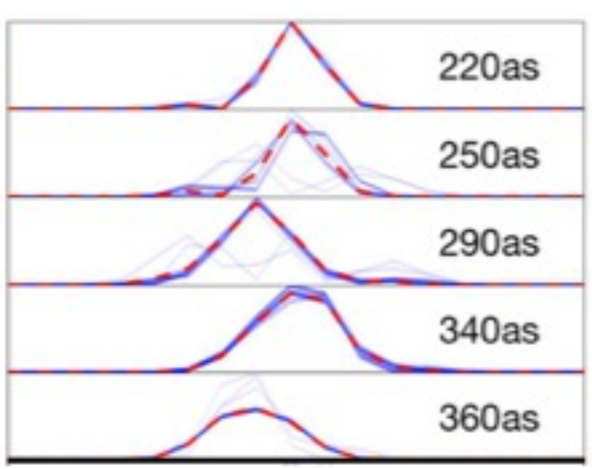
## 3 AREAS OF FOCUS

### Attosecond Science



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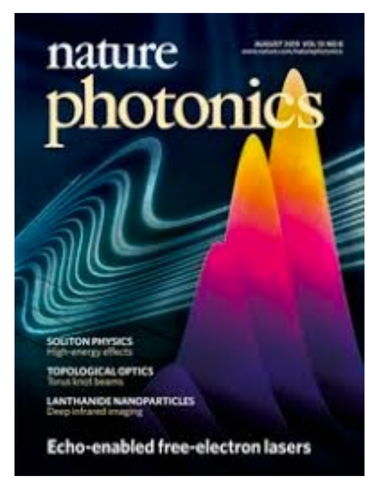


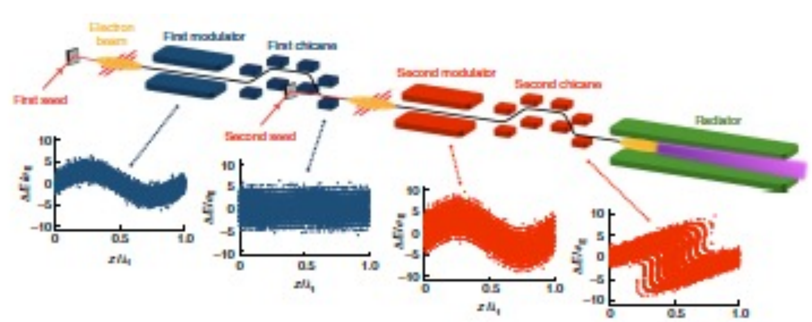


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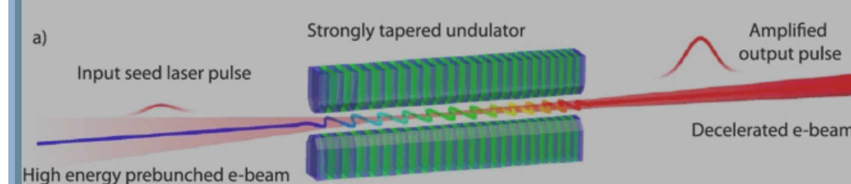


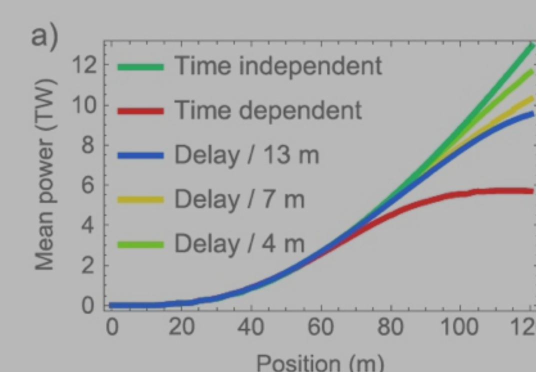


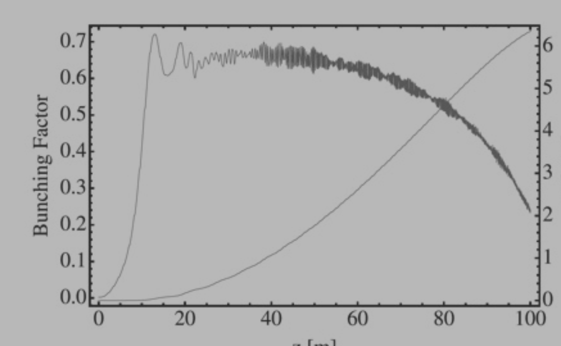


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# Attosecond Science

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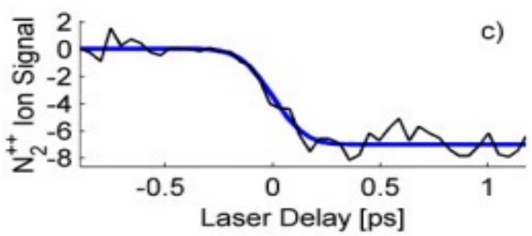
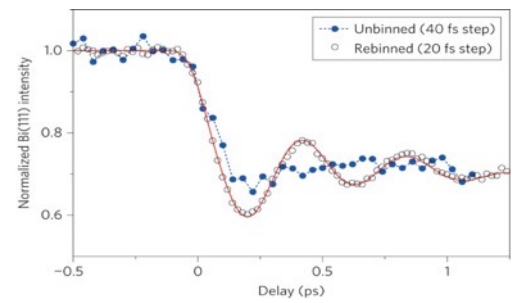
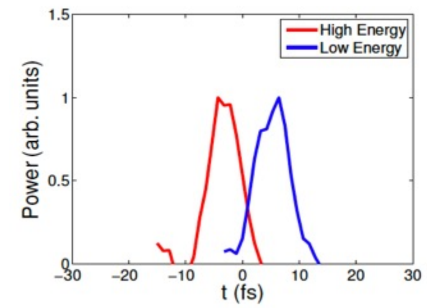
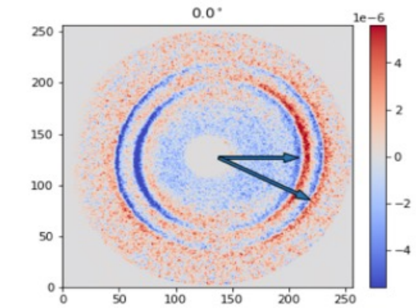
# Time Resolution with X-ray FELs




**Early Experiments**
**2010**
**150 fs**

**Time sorting**
**2013-14**
**~10-30 fs**

**2-Color FELs**
**2013-16**
**3-10 fs**

**Attosecond FELs**
**2017-ongoing**
**< 1 fs**

**1 ps** — **100 fs** — **10 fs** — **1 fs** — **0.1 fs**

**Time Resolution**

# Time Resolution with X-ray FELs

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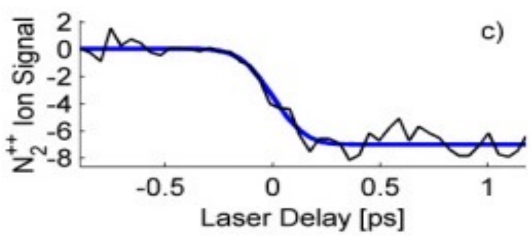


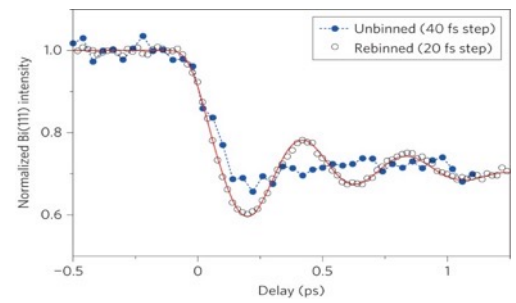


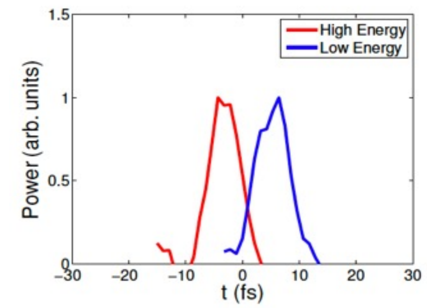


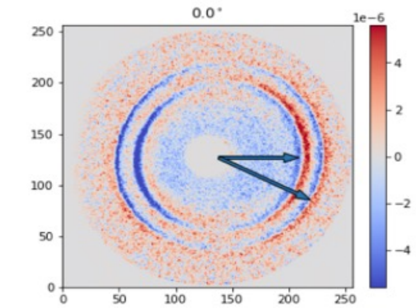


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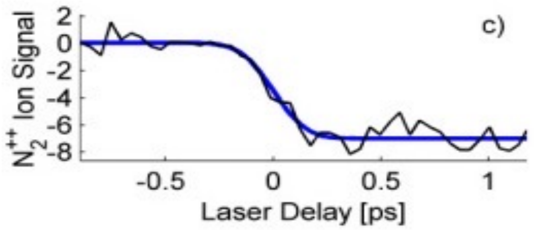
**Time Resolution:** 1 ps — 100 fs — 10 fs — 1 fs — 0.1 fs

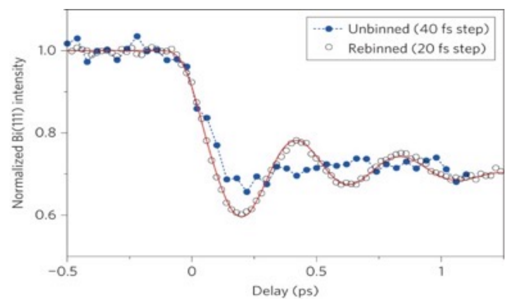
**New FELs (Pohang, EUXFEL, PSI) achieve 10s of fs without time-sorting**

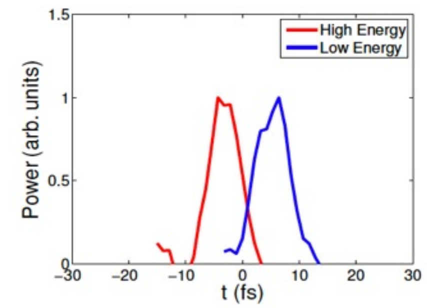
See e.g.: Kang, Heung-Sik, et al *Nature Photonics* 11.11 (2017): 708-713.

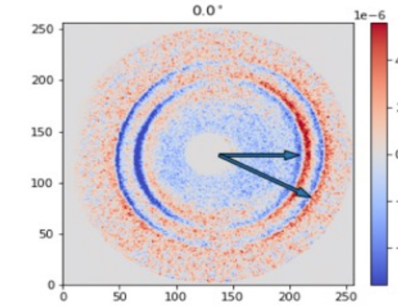
# Time Resolution with X-ray FELs



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**Time Resolution**

Glownia et al. *Opt. express* 18.17 (2010): 17620-17630

*Harmand et al. Nat. Photon.* 7.3 (2013): 215-218

Hartmann et al. *Nat. Photon.* 8.9 (2014): 706-709

Lutman., et al. *PRL* 110.13 (2013): 134801.

Marinelli et al. *PRL* 111.13 (2013): 134801.

Hara, Toru, et al. "*Nat. Comm* 4.1 (2013): 1-5.

Marinelli et al. *Nat. Comm.* 6 (2015): 6369.

Lutman et al. *Nat. Photon.* 10.11 (2016): 745.

Ferrari, Eugenio, et al. *Nat. Comm.* 7.1 (2016): 1-8.

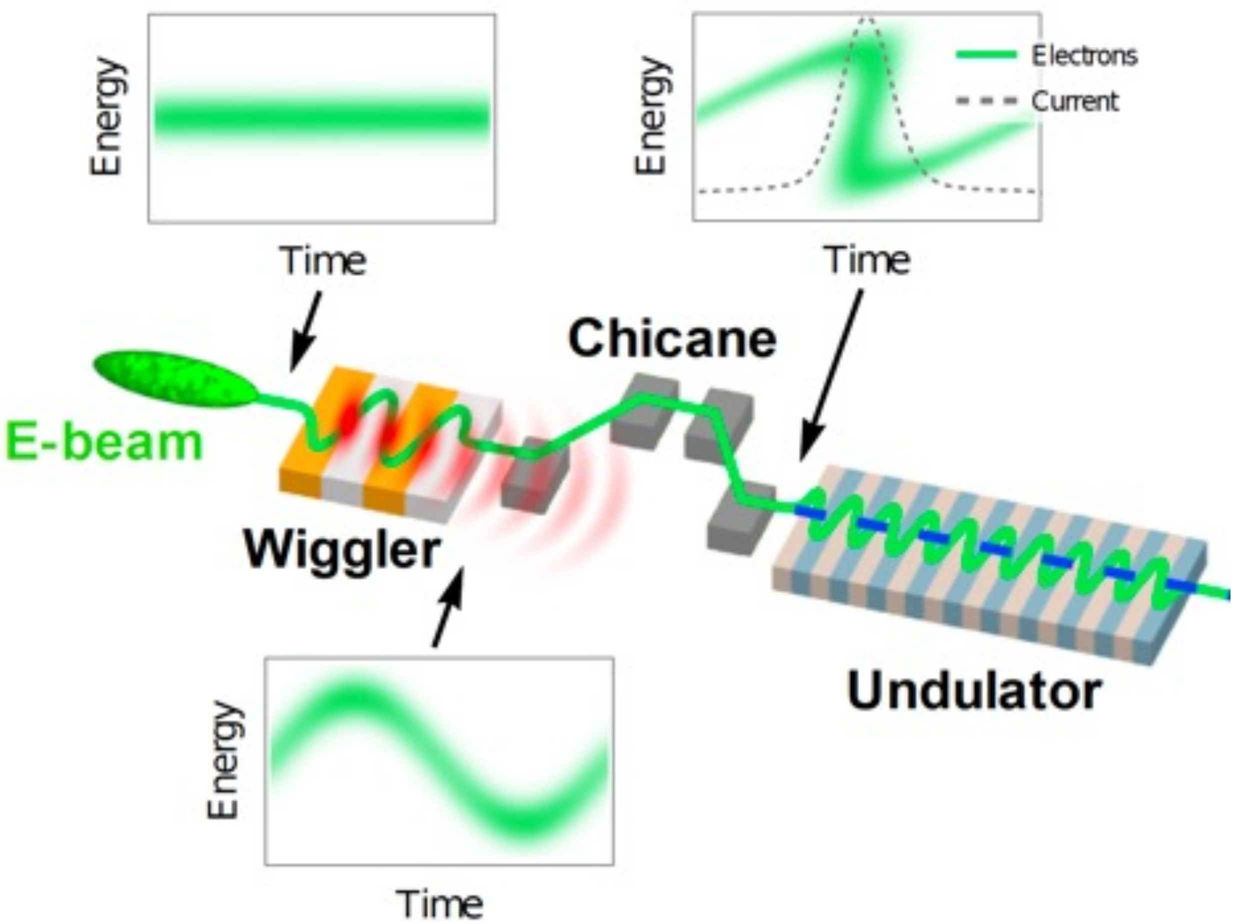
Duris, Li et al. *Nat. Photon.* 14.1 (2020): 30-36.

Huang, S., et al *PRL* 119.15 (2017): 154801.

Malyzhenkov, et al. *PRR* 2.4 (2020): 042018

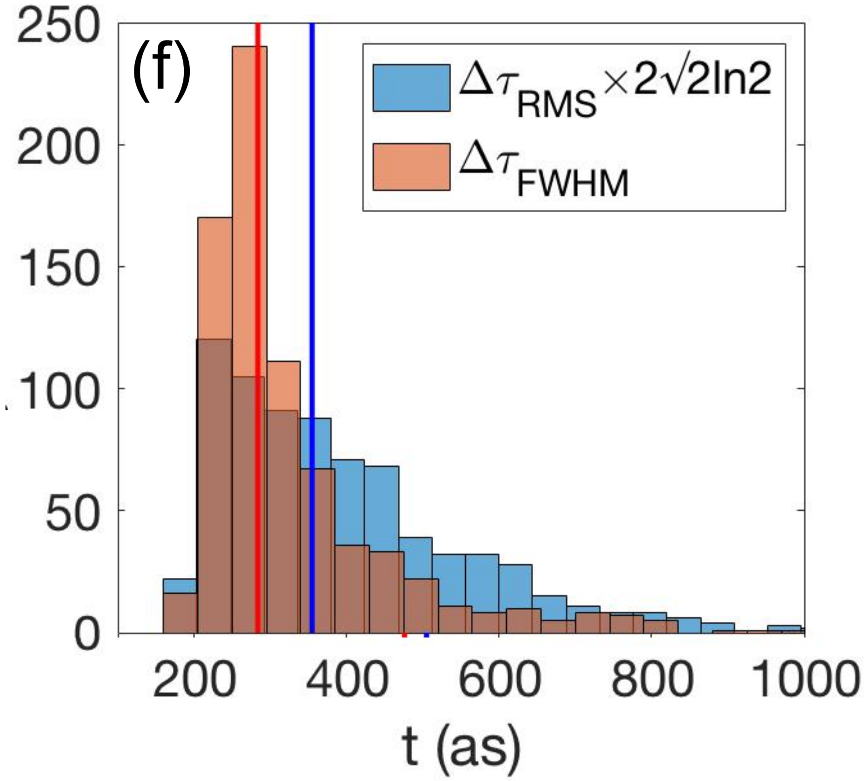
Maroju, et al. *Nature* 578.7795 (2020): 386-391.

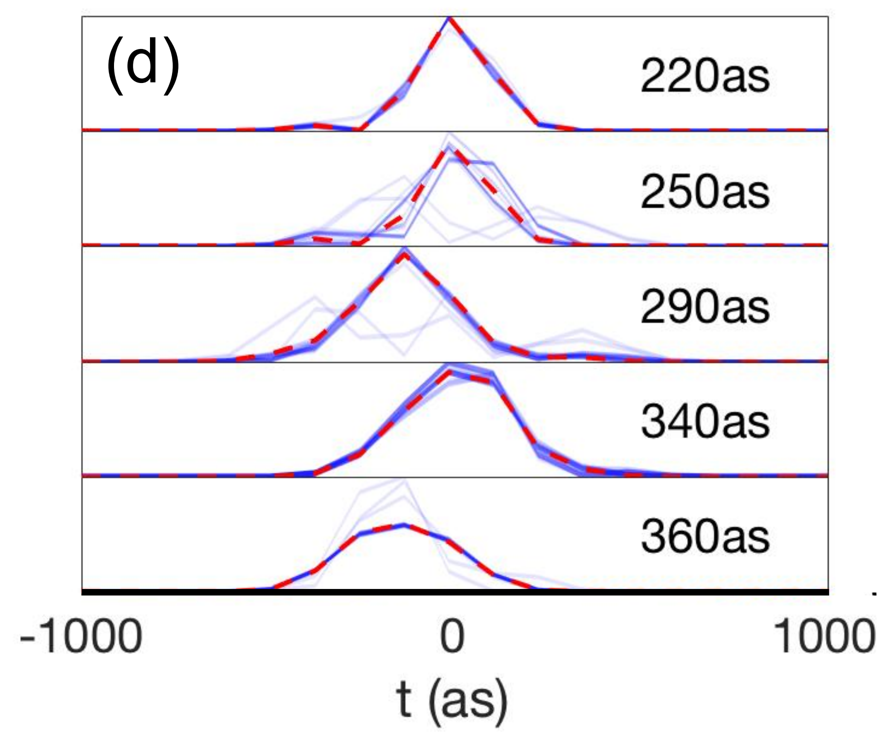
# Attosecond Pulses: Enhanced SASE




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

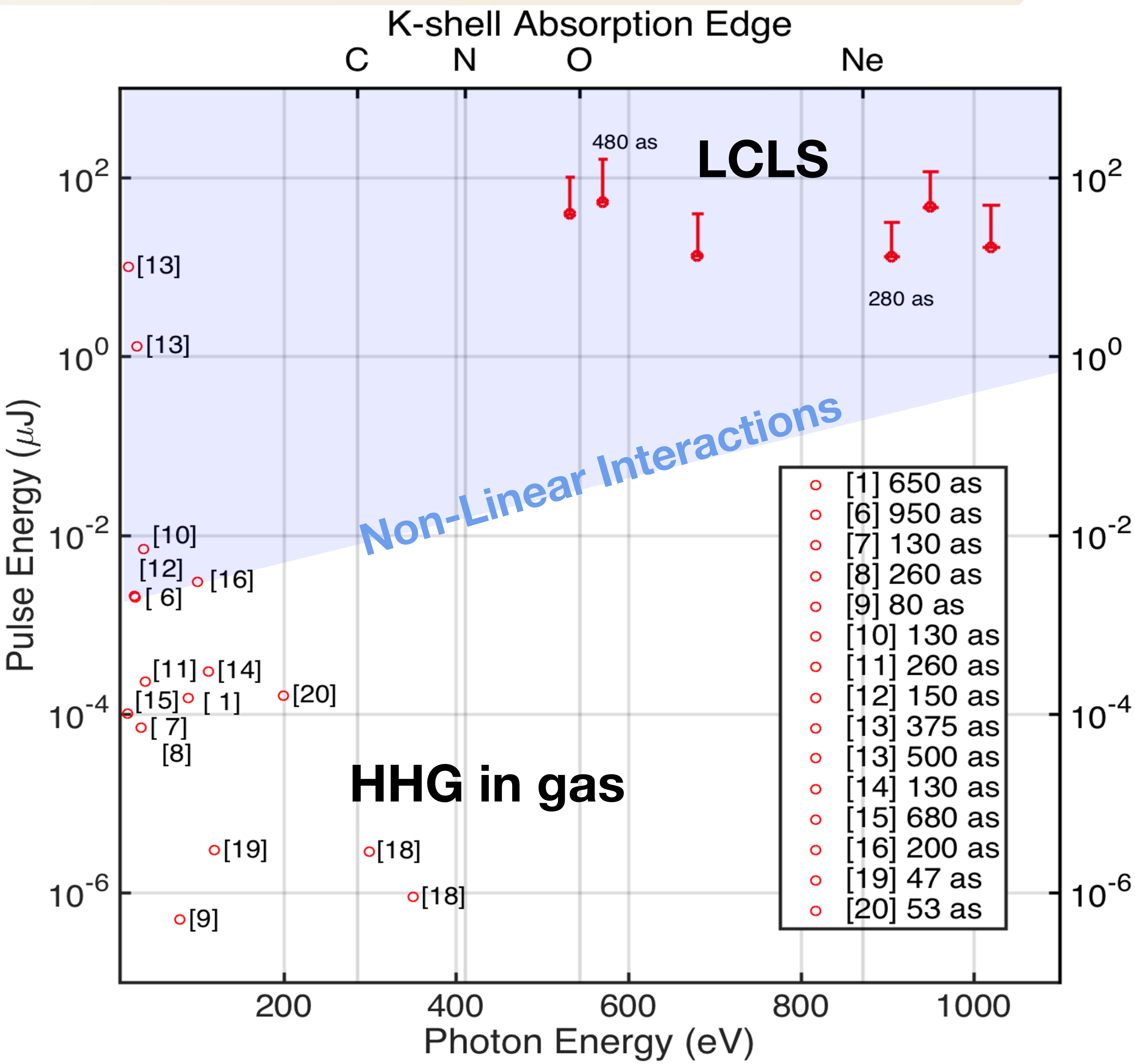
**XLEAP Project**
**SLAC/ANL Collaboration**




J. Duris, S. Li et al. *Nature Photonics* 14.1 (2020): 30-36.
J. Duris et al. Phys. Rev. Lett. **126**, 104802 (2021)
J. MacArthur., et al. *Physical review letters* 123.21 (2019): 214801
Zhang, Zhen, et al. *New Journal of Physics* 22.8 (2020): 083030.

# Scientific Impact

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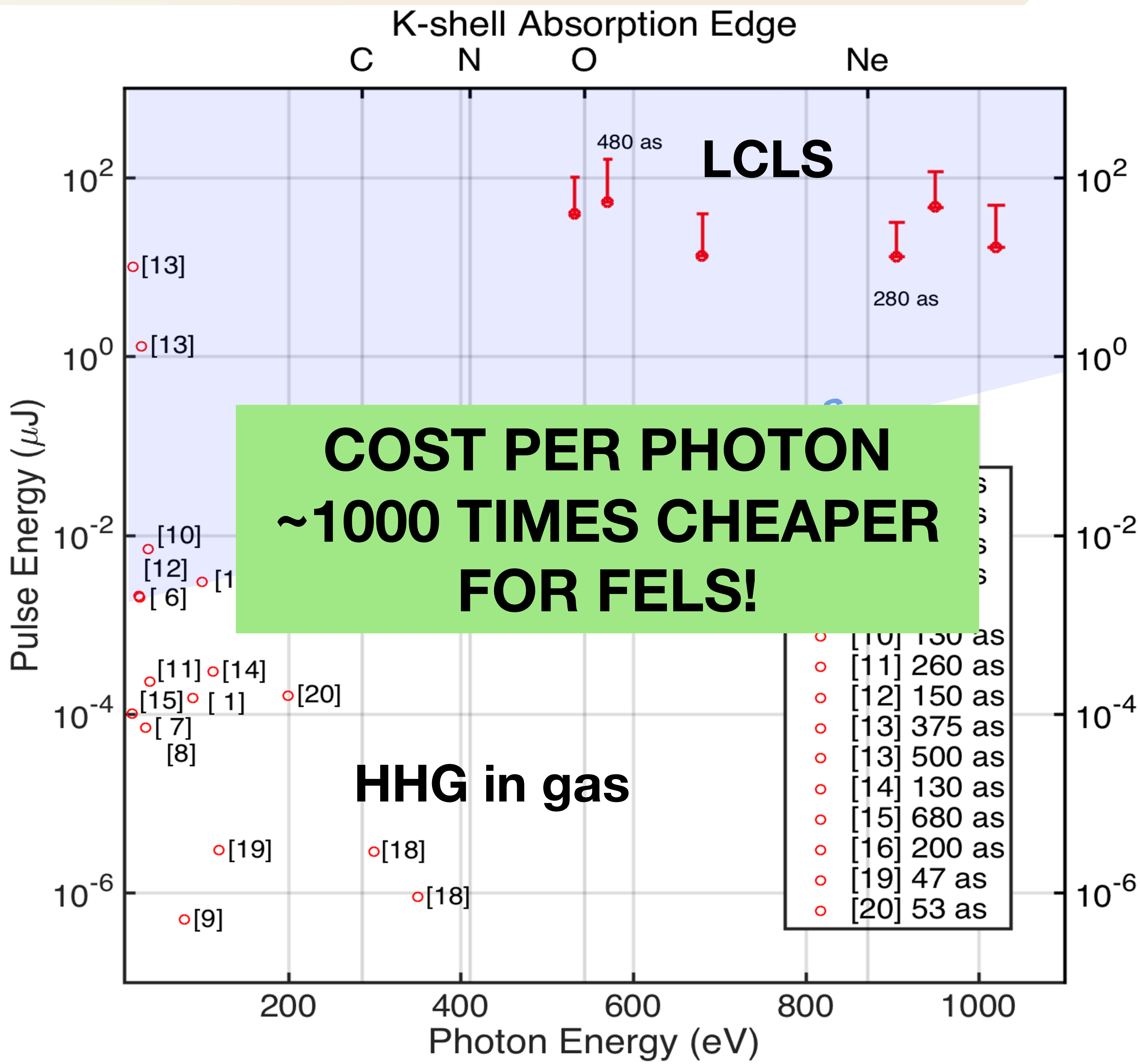
# Scientific Impact




J. Duris, S. Li et al. *Nature Photonics* 14.1 (2020): 30-36.

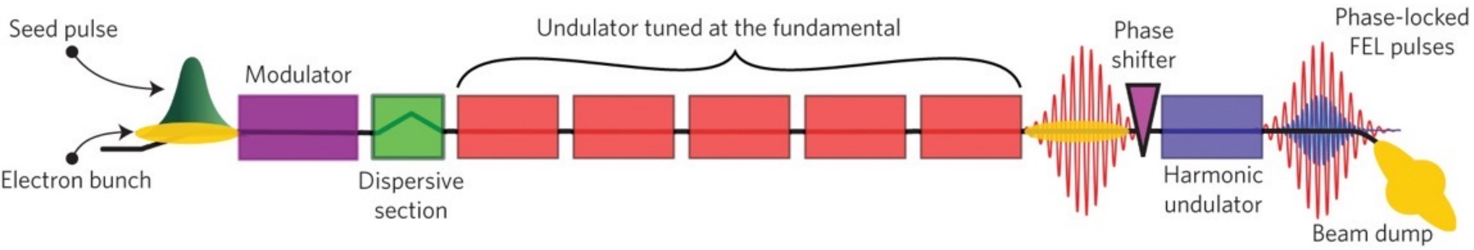
# Science with Attosecond FELs

Simulation: M. Grell (UAM)

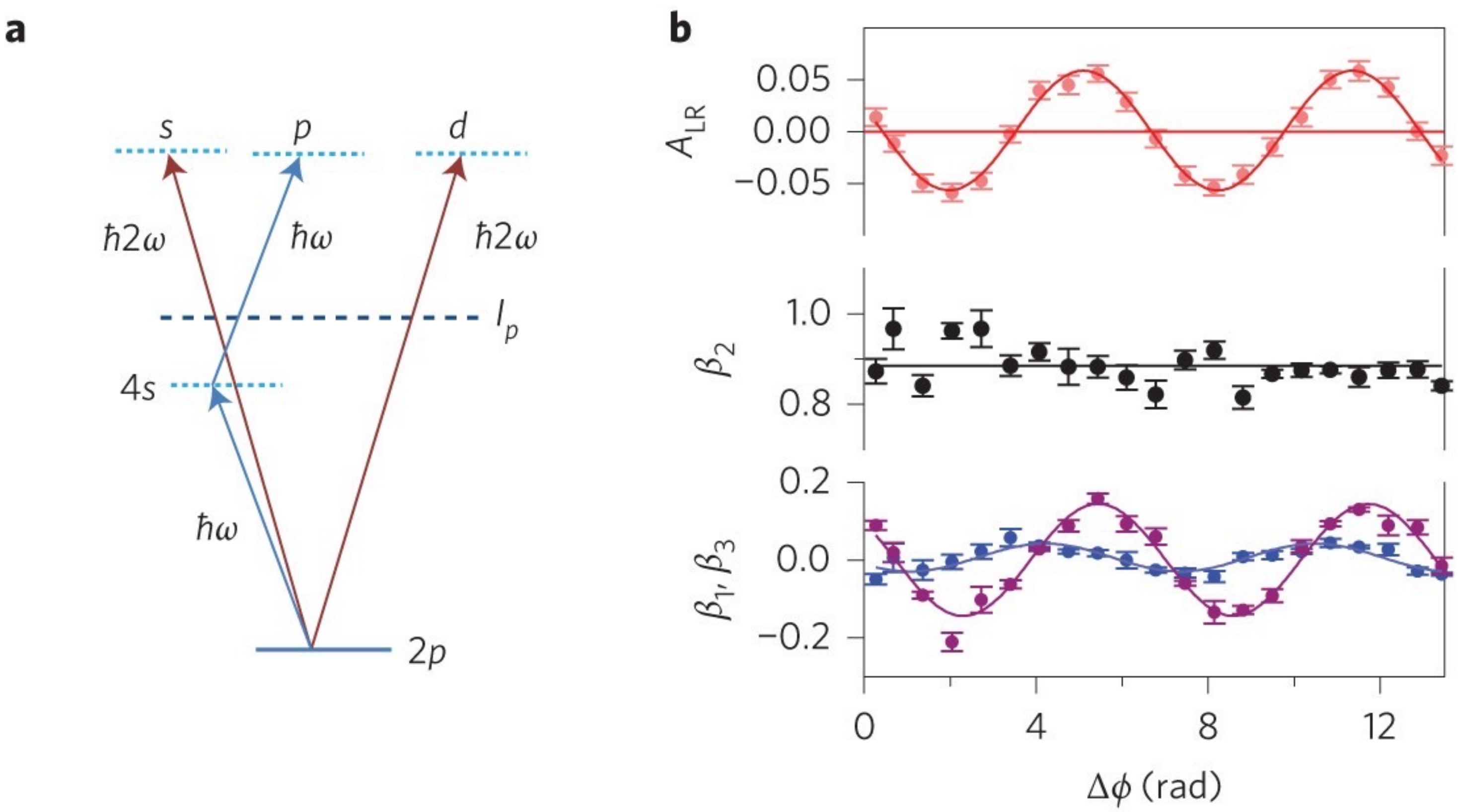
**LCLS Attosecond Campaign:**
**First attosecond pump/attosecond probe experiment (unpublished)**

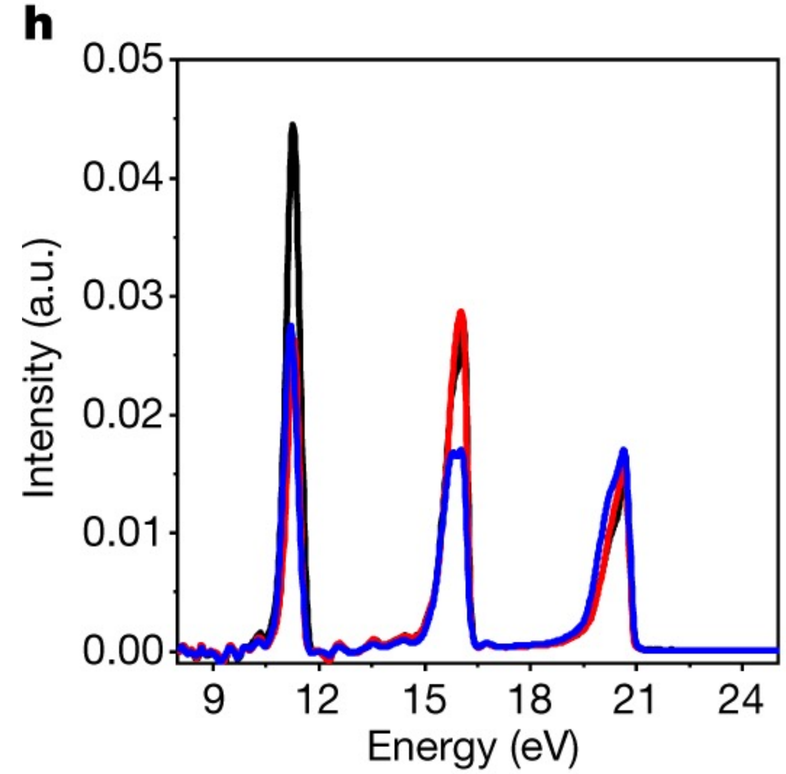
Other highlights:
Mapping coherent electron motion in Auger decay (Siqi Li et al. Science Vol 375, Issue 6578 • pp. 285-290)
Impulsive stimulated X-ray Raman (J. O'Neal *Physical review letters* 125.7 (2020): 073203)

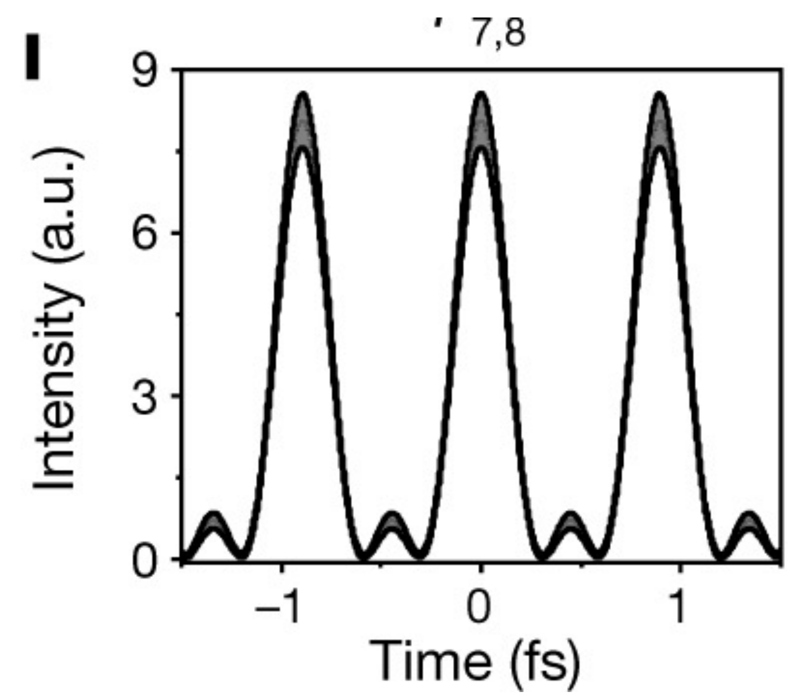
# Attosecond Science with Seeded FELs




Prince, K. C., et al. *Nature Photonics* 10.3 (2016): 176-179



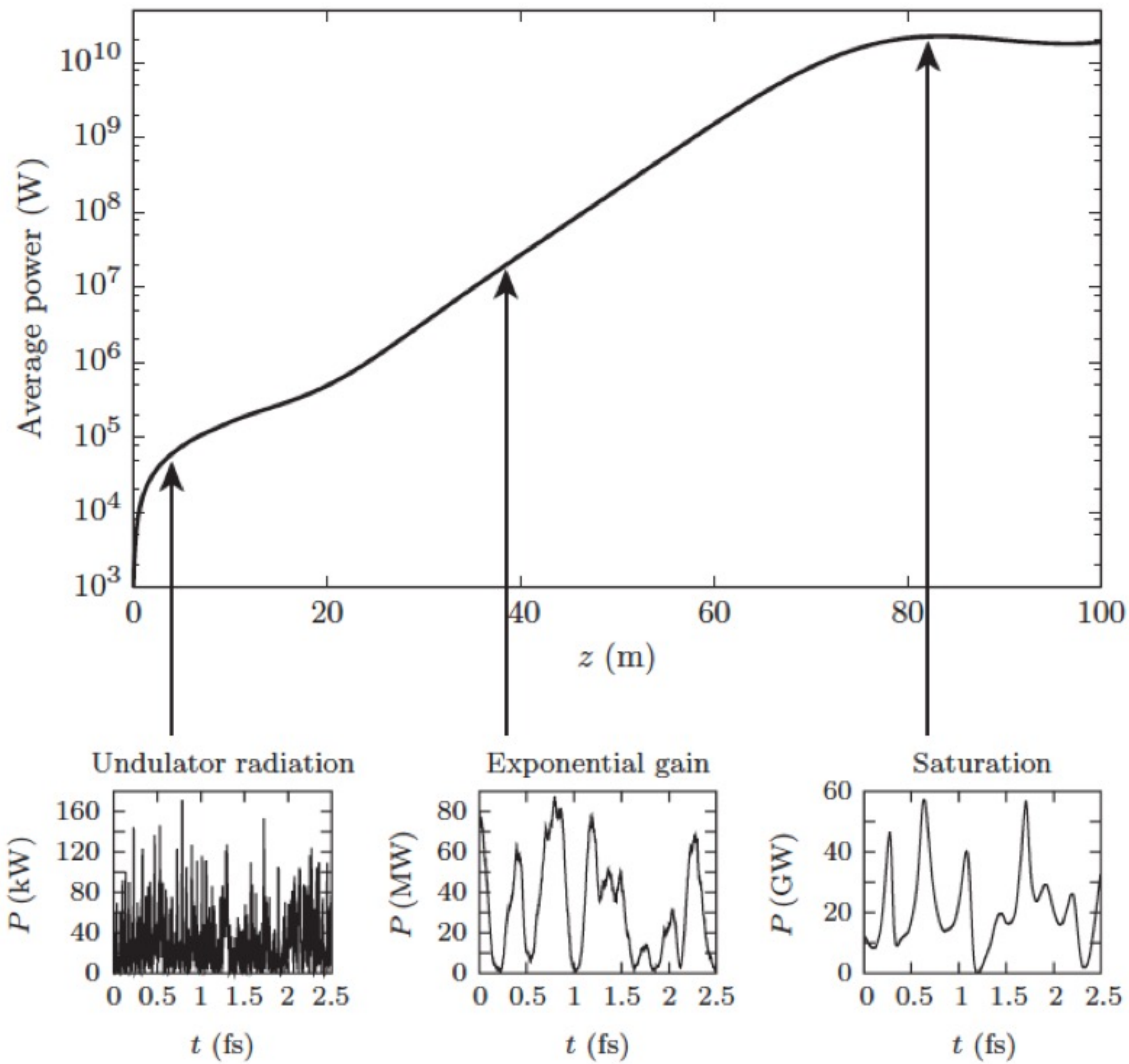



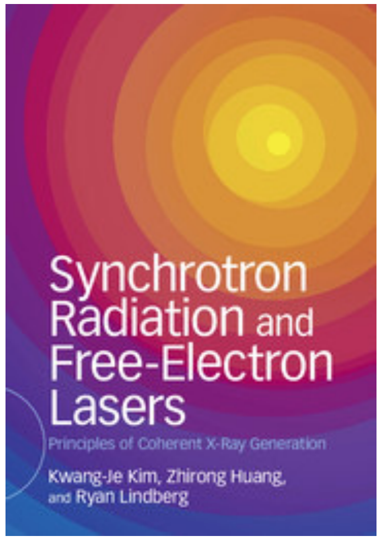

Maroju et al.
*Nature* 578.7795 (2020): 386-391

# SEEDED FELS

# Temporal Coherence of SASE (or lack thereof…)



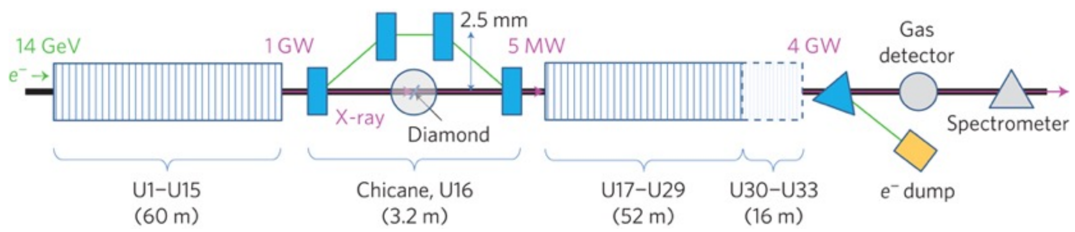


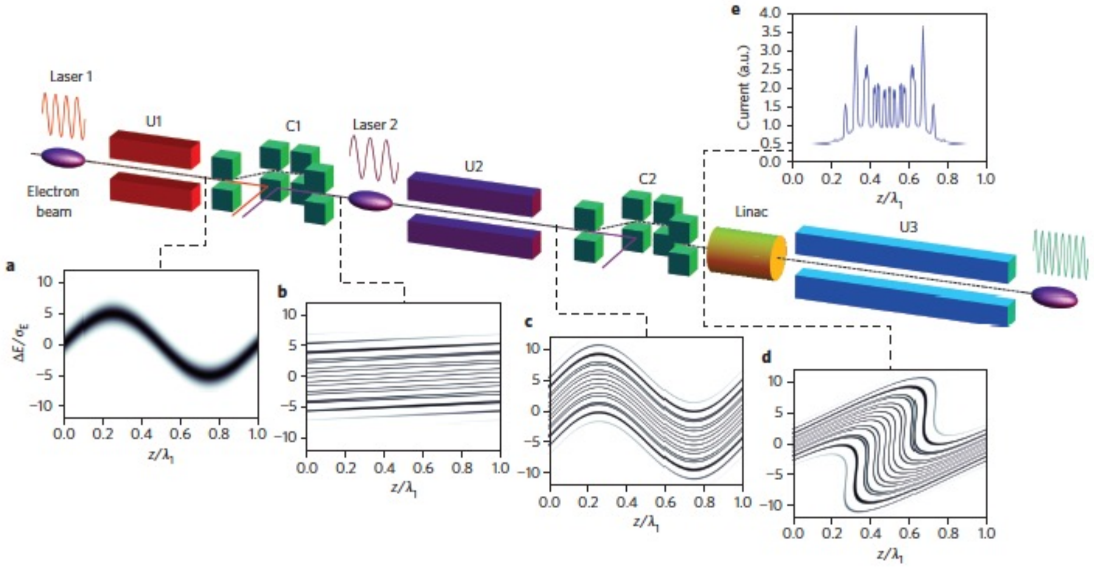
# Solutions

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

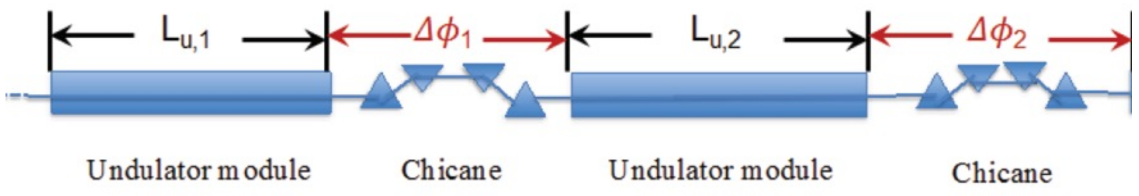
## Self-Seeding




## 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.

# Solutions

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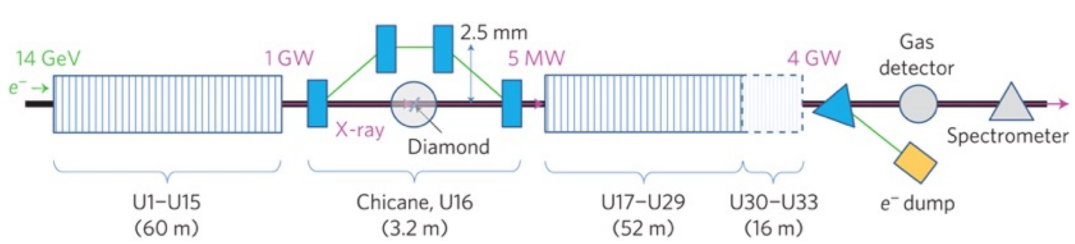
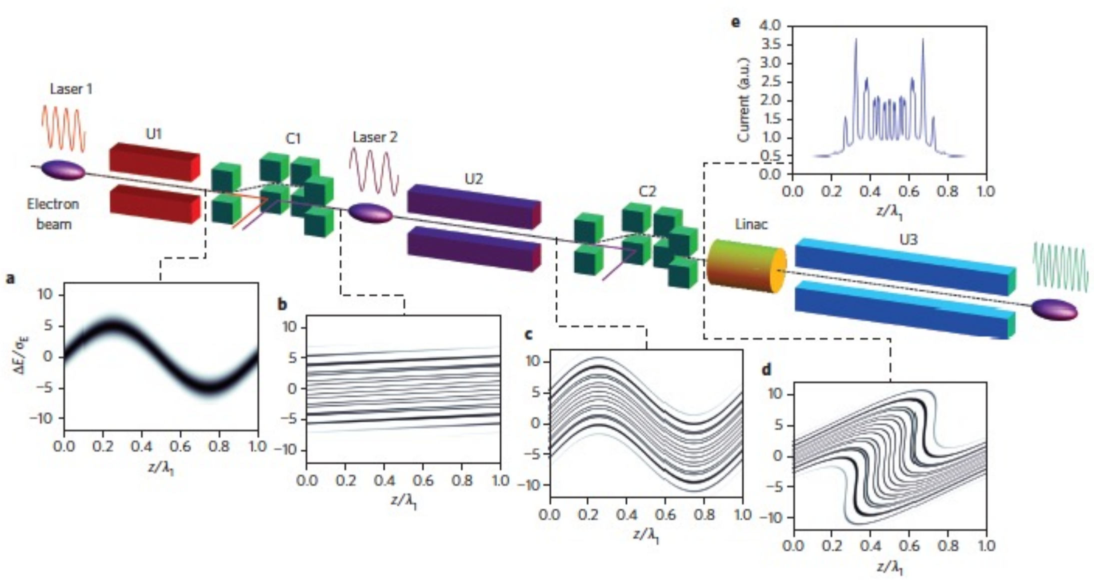
## Seeding:
## Establish phase coherence by triggering instability with a coherent pulse.

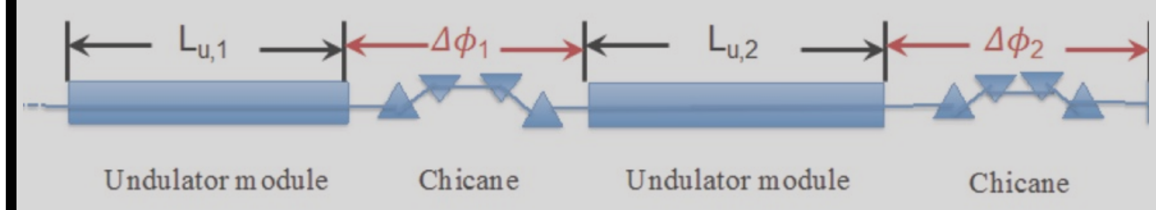
### Self-Seeding




### 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.

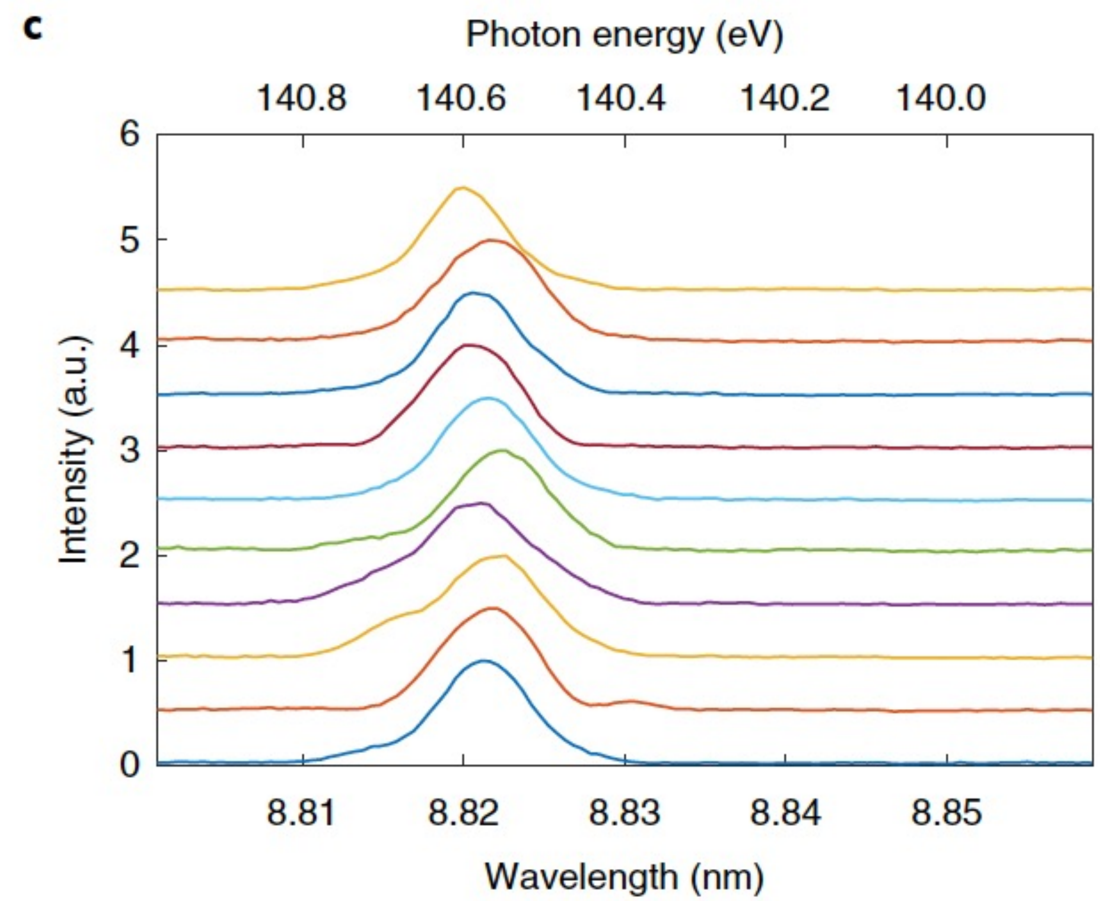
McNeil, B. W. J., N. R. Thompson, and D. J. Dunning. "Transform-limited X-ray pulse generation from a high-brightness self-amplified spontaneous-emission free-electron laser." *Physical review letters* 110.13 (2013): 134802.

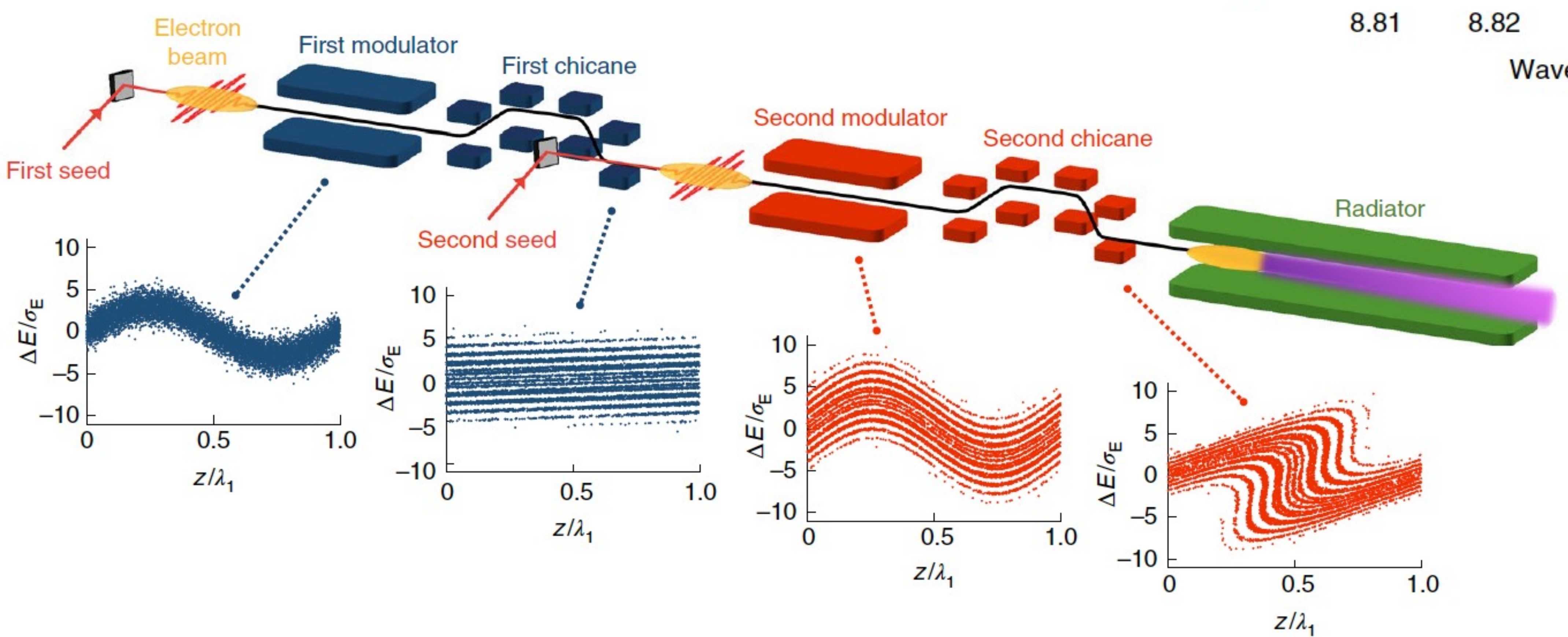
Xiang, Dao, et al. "Purified self-amplified spontaneous emission free-electron lasers with slippage-boosted filtering." *Physical Review Special Topics-Accelerators and Beams* 16.1 (2013): 010703.

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.

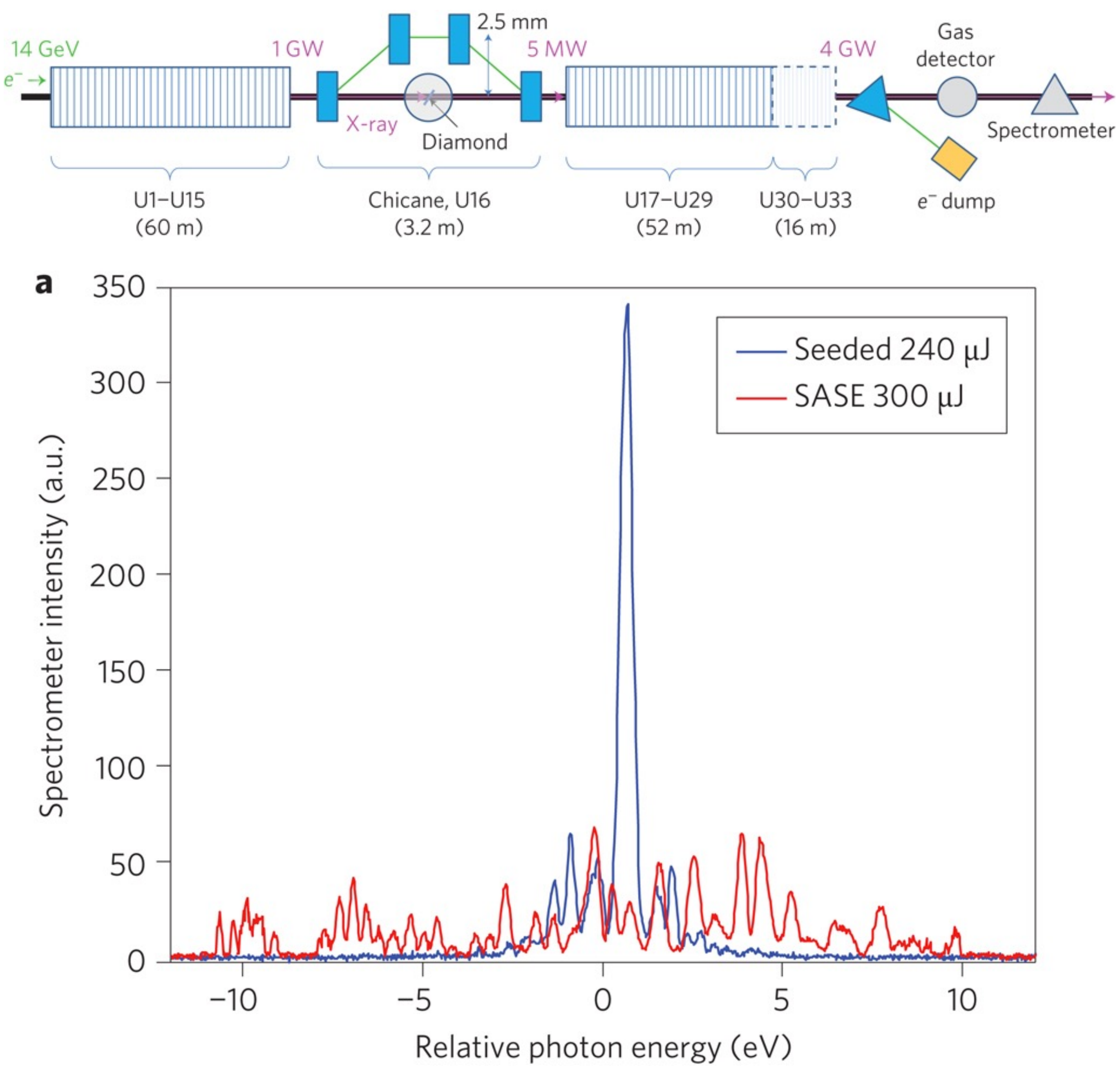
# External Seeding


**1)** Yu, L-H., et al. *Science* 289.5481 (2000): 932-934.
**2)** Lambert, G., et al. *Nature physics* 4.4 (2008): 296
**3)** Stupakov, Gennady *PRL* 102.7 (2009): 074801.
**4)** Xiang, D., et al. *PRL* 105.11 (2010): 114801
**5)** Allaria, E., et al. *Nature Photonics* 6.10 (2012): 699.
**6)** Allaria, E., et al. *Nature Photonics* 7.11 (2013): 913.
7) Zhao, Z. T., et al. *Nature Photonics* 6.6 (2012): 360.
**8)** Hemsing, E., et al. *Nature Photonics* 10.8 (2016): 512.
**9)** Ribič, Primož Rebernik, et al. *Nature Photonics* (2019): 1.


# Self-Seeding




## Seeding vs Self-seeding

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


Marinelli et al. *PRSTAB* 13.7 (2010): 070701.

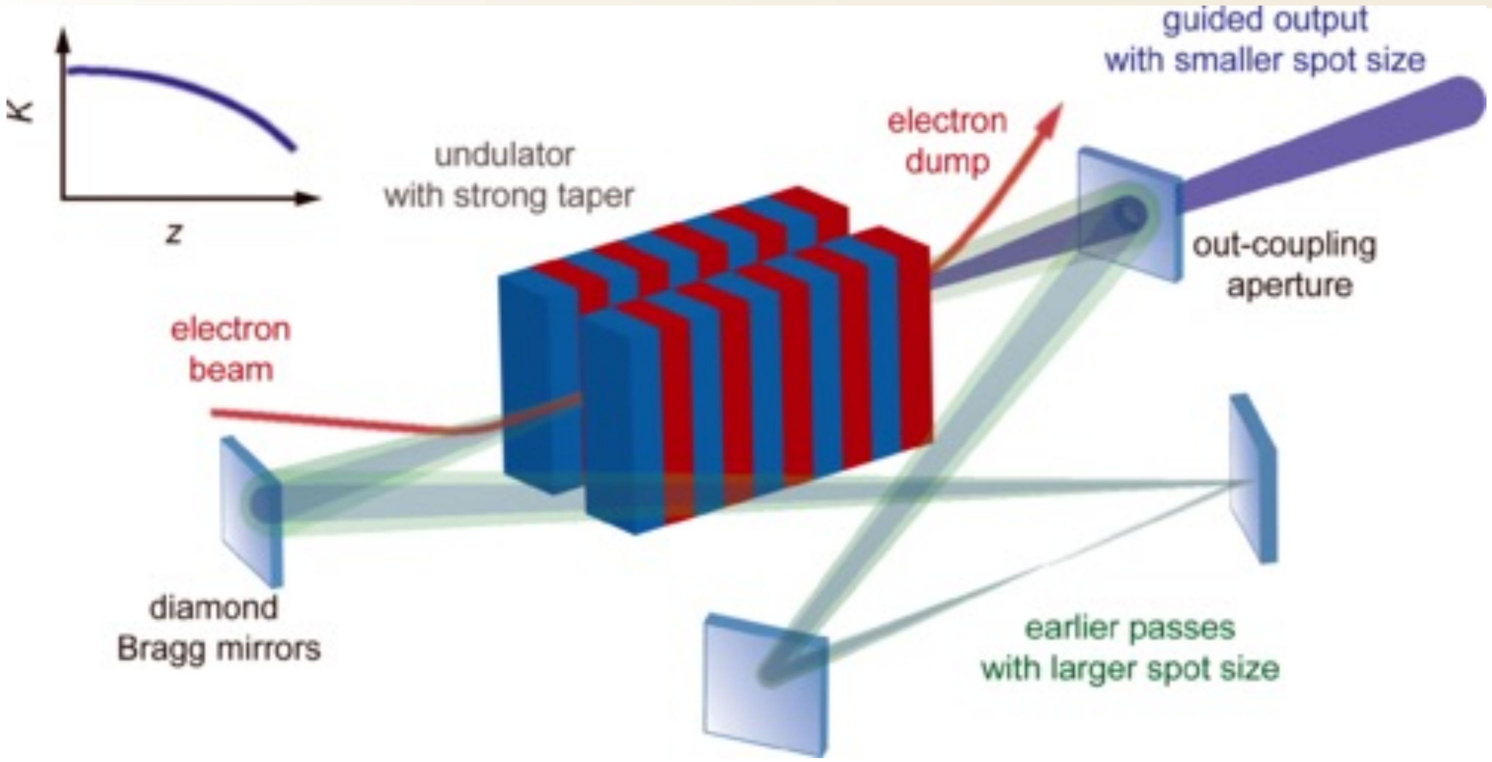
Hemsing, Erik. *Frontiers in Physics* 7 (2019).

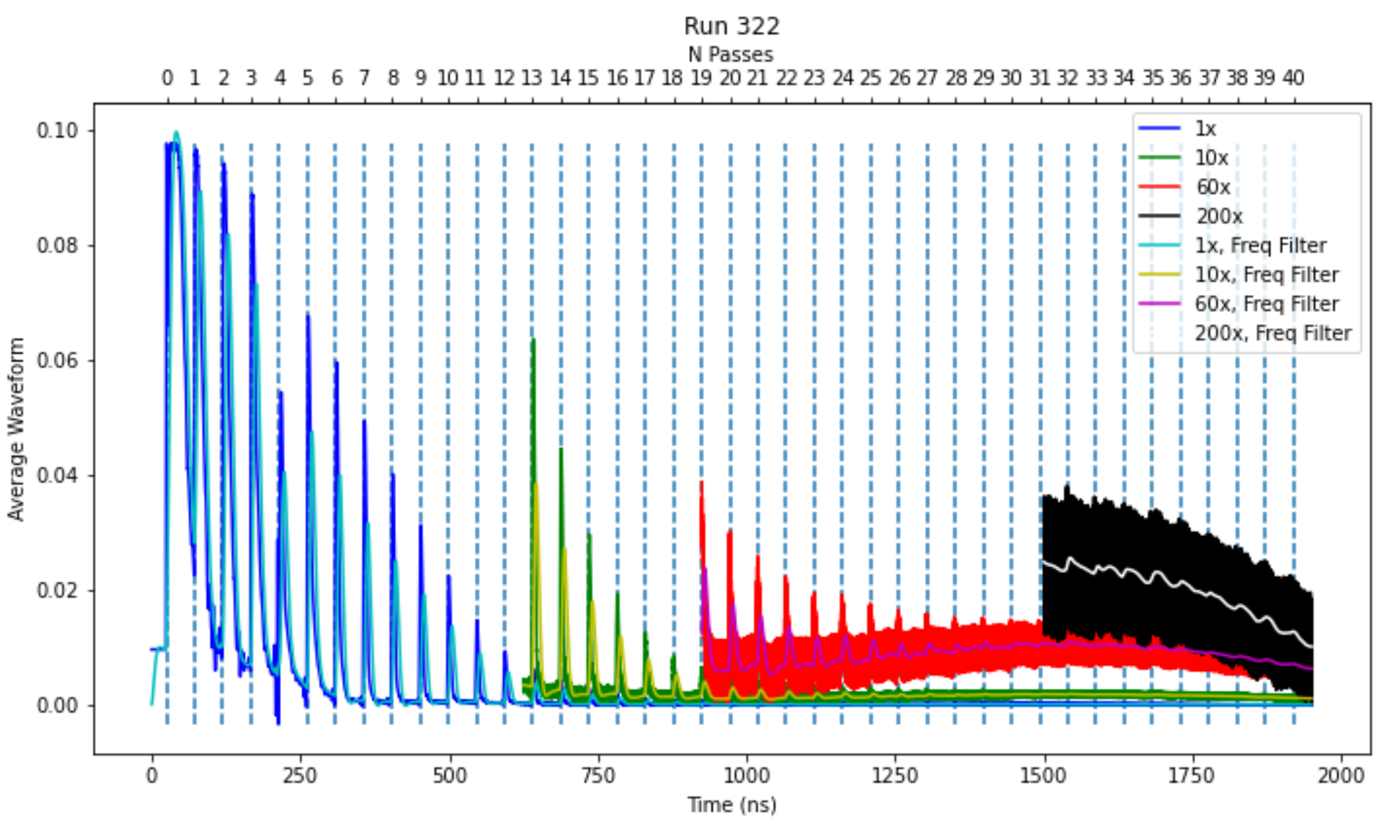
E. Hemsing et *PRAB* 22.11 (2019): 110701.



**1)** Feldhaus, J., et al *Optics Communications* 140.4-6 (1997): 341-352.
**2)** Geloni, Gianluca, Vitali Kocharyan, and Evgeni Saldin. *Journal of Modern Optics* 58.16 (2011): 1391-1403
**3)** Amann, J., et al. *Nature photonics* 6.10 (2012): 693.
**4)** Ratner, Daniel, et al. *Physical review letters* 114.5 (2015): 054801.
**5)** Inoue, Ichiro, et al. *Nature Photonics* 13.5 (2019): 319.

# The Brightness Frontier: Cavity-Based XFELs




**Courtesy G. Marcus, D. Zhu et al.**

**Back to Madey's FEL!**

**Ongoing R&D at LCLS and EUXFEL**

**LCLS:**
**test in FY23-24 (2-bunch mode)**
**Recent highlight:**
**cold-cavity test**

Kwang-Je Kim, Yuri Shvyd'ko, and Sven Reiche
Phys. Rev. Lett. **100**, 244802 (2008)

Zhirong Huang and Ronald D. Ruth
Phys. Rev. Lett. **96**, 144801 (2006)

Marcus, Gabriel, et al.
*Physical Review Letters* 125.25 (2020): 254801

# Opportunities for Advanced Accelerators

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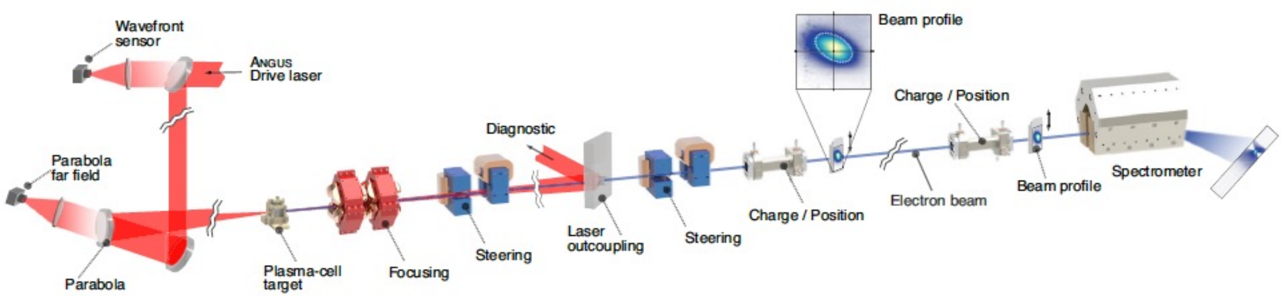
# Plasma-Based FELs: Two Worlds

### Laser-based plasma accelerators



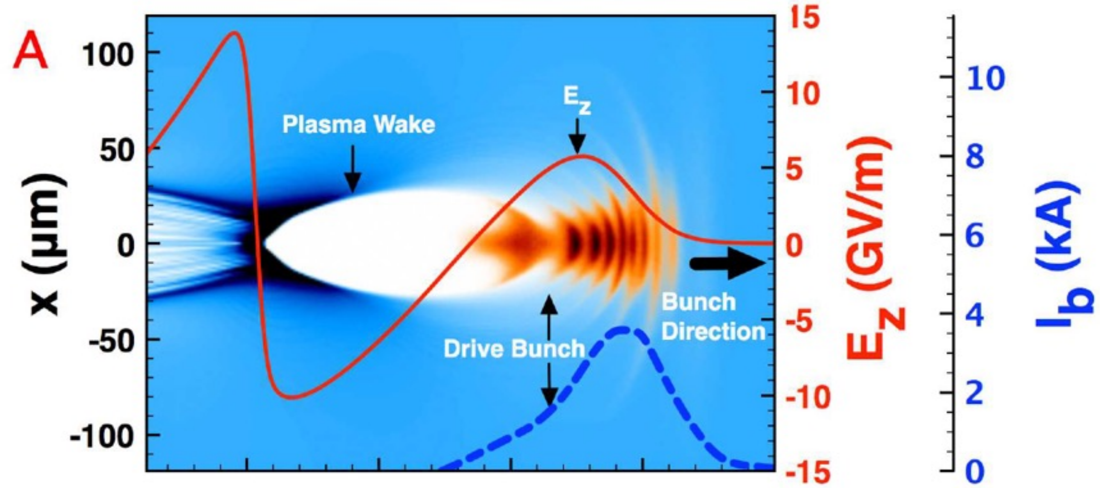

A. Maier et al. Phys. Rev. X **10**, 031039 (2020)

Potentially compact

MANY FELs with lower performance than big machines.

Good opportunity for complementing existing facilities

### Beam-based plasma wakefield




Litos, M., et al. *Nature* 515.7525 (2014): 92-95

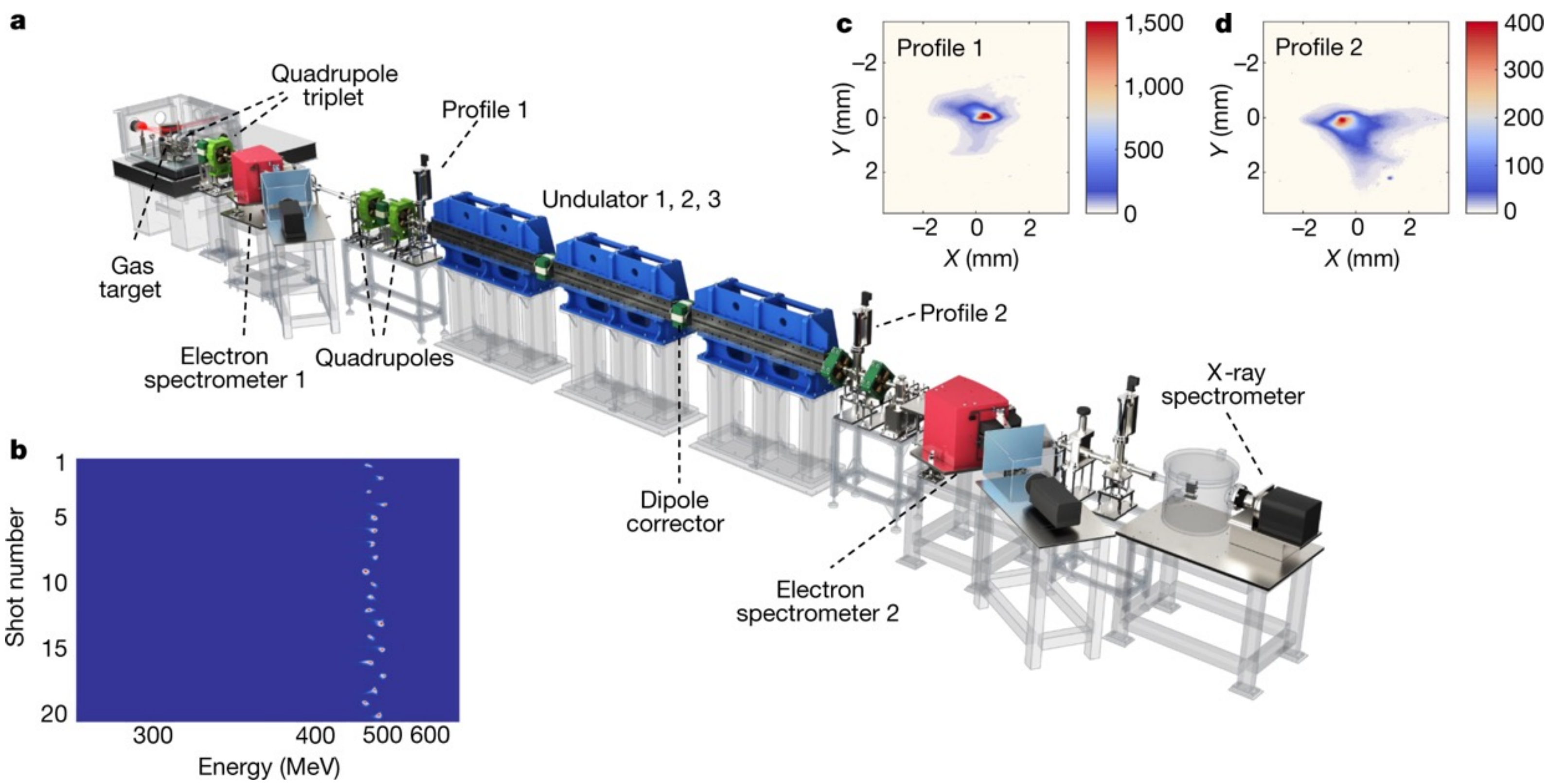
Not exactly compact...

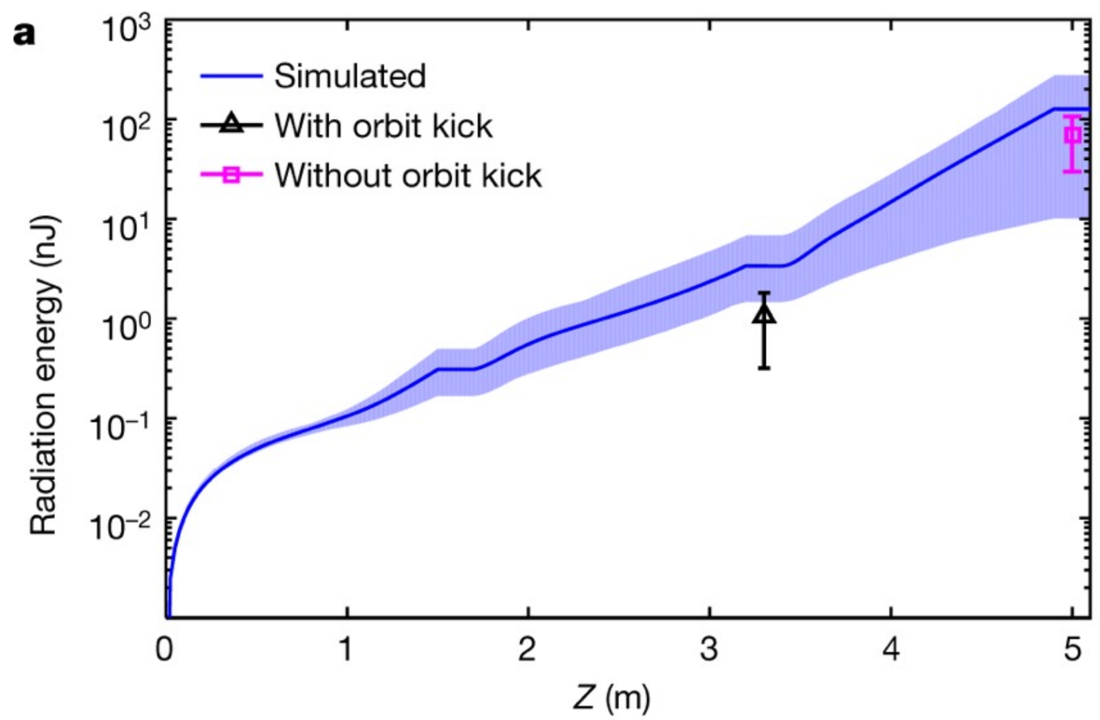
Opportunities arise from doing better than conventional FELs:

-beam “multiplexing”
-ultrahigh brightness injectors
-attosecond science

# Plasma Based FELs ?

Wang, Wentao, et al. *Nature* 595.7868 (2021): 516-520




**Groundbreaking observation of lasing**
**More results coming from SPARC!**

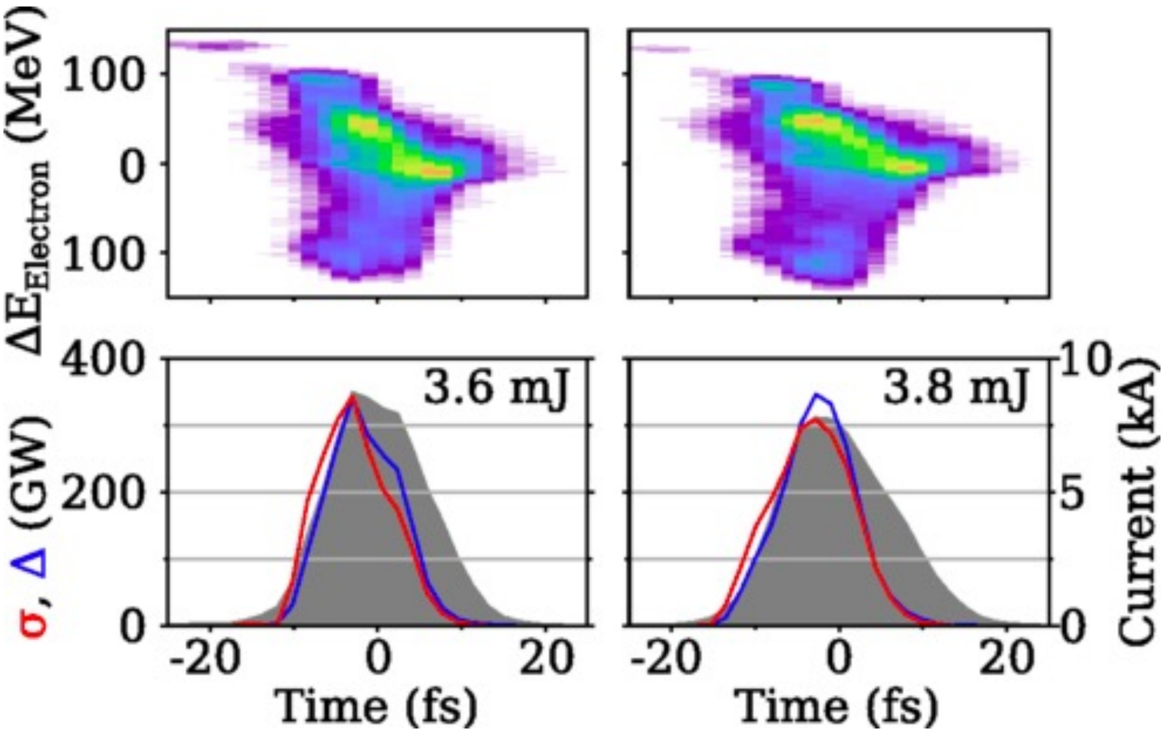
**Still far from usable tool**

**Effort in stable operation of plasma accelerators shows great promise…**

A. Maier et al. Phys. Rev. X **10**, 031039 (2020)
Sören Jalas et al [Phys. Rev. Lett. 126, 104801](Phys. Rev. Lett. 126, 104801) (2021)

# Does It Have to be as Good as LCLS (or other XFELs)?

SLAC




**High-energy FEL facilities: Few mJ pulses.**

**Tall order for compact machines!**

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

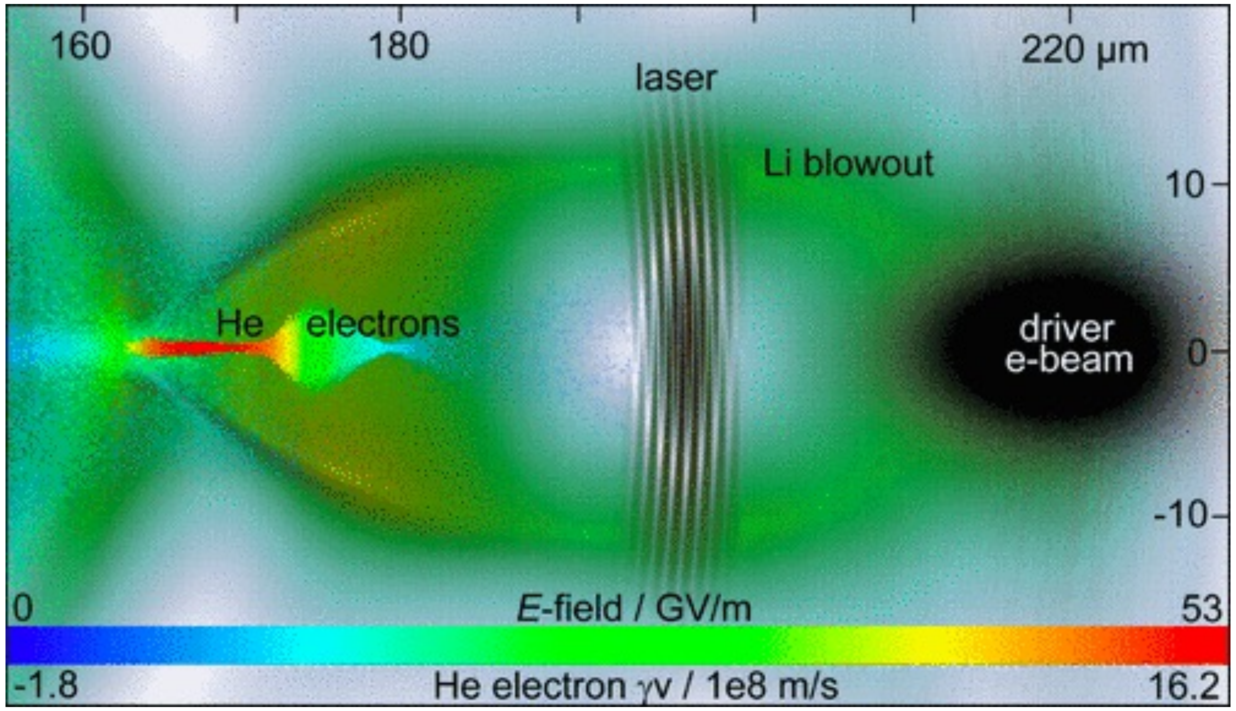
**~25% HXR beamtimes use multiplexing mode -> ~1% of pulse energy**

**Even LCLS doesn't have to be as good as LCLS in many cases!!**

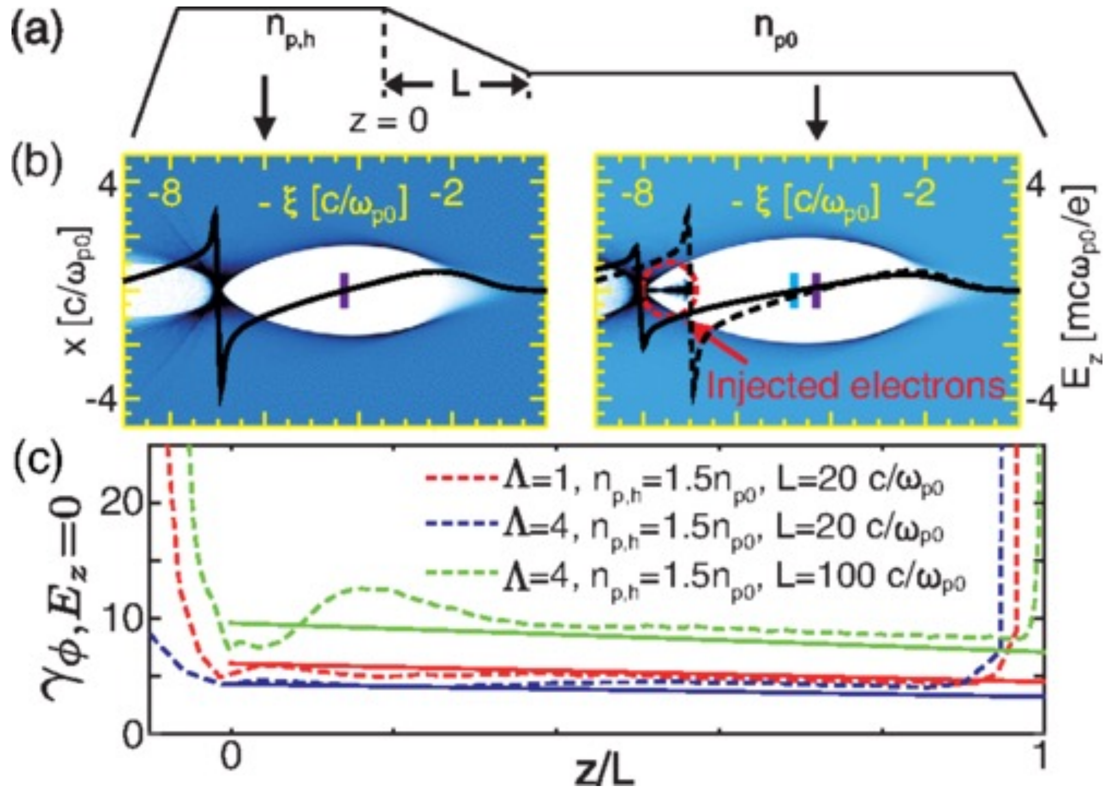
Zhu, Diling, et al. "Performance of a beam-multiplexing diamond crystal monochromator at the Linac Coherent Light Source." *Review of Scientific Instruments* 85.6 (2014): 063106.

# What gets me excited: Opportunities in Attosecond Science

SLAC

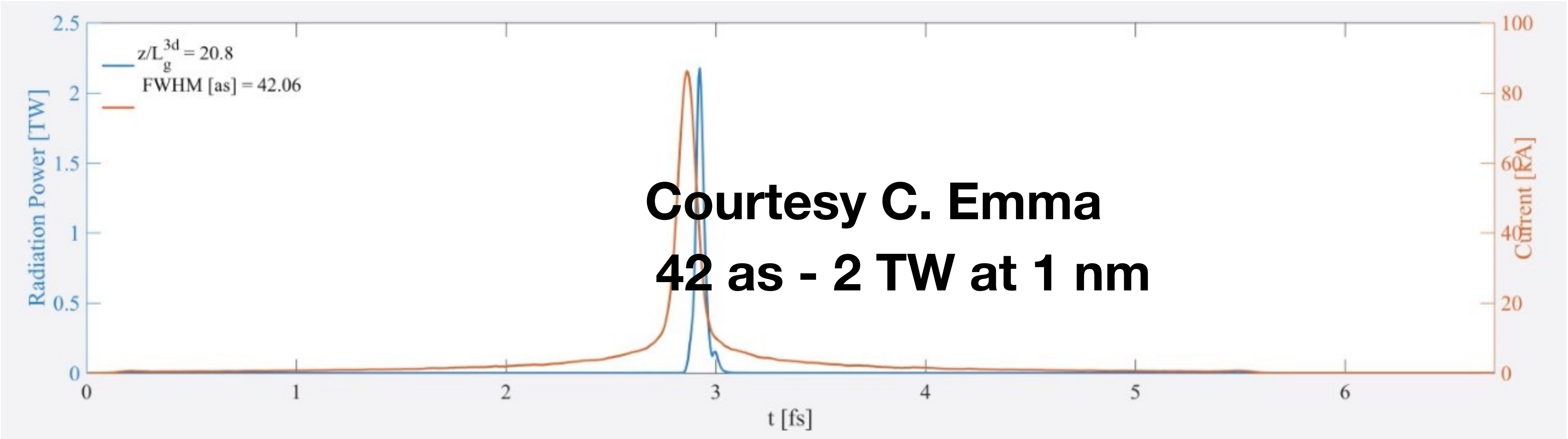



B. Hidding, G. Pretzler, J. B. Rosenzweig, T. Königstein, D. Schiller, and D. L. Bruhwiler Phys. Rev. Lett. **108**, 035001

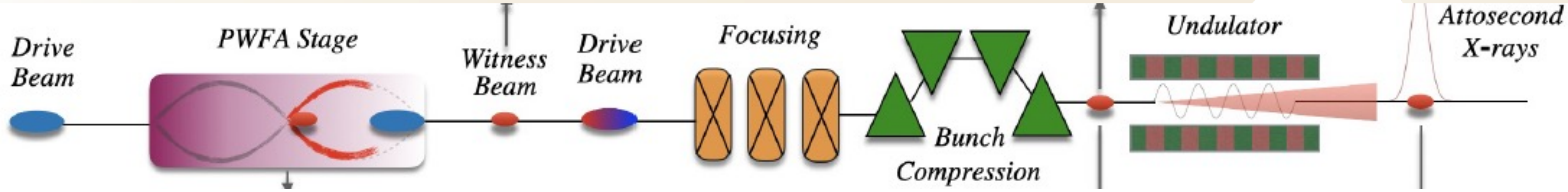


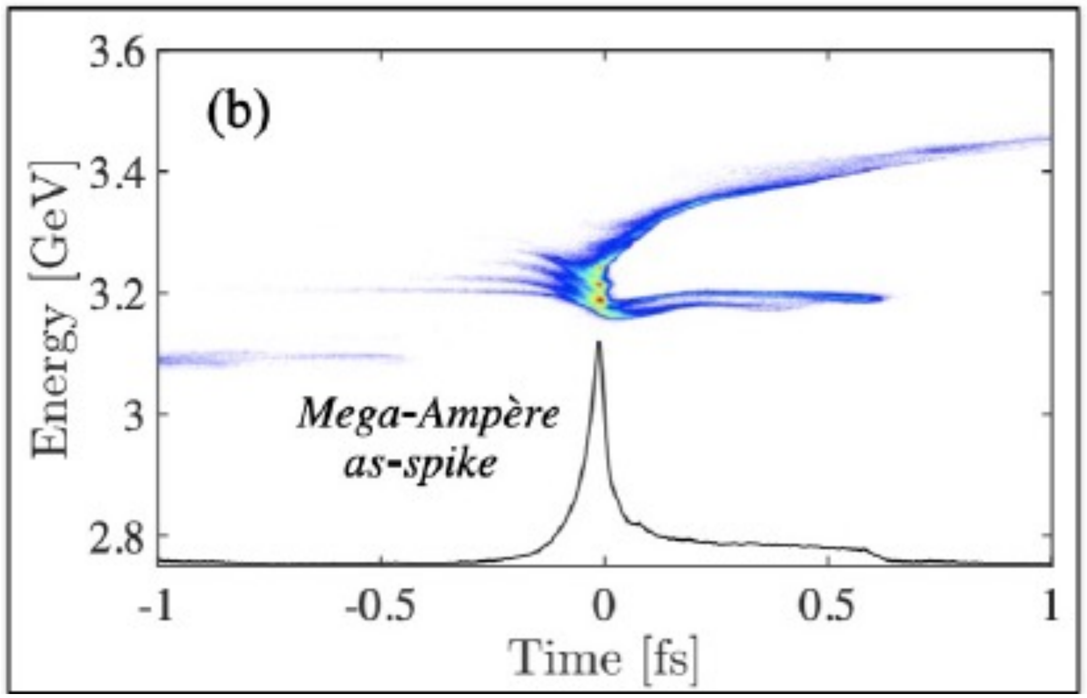

*X. Xu et al. Physical Review Accelerators and Beams* 20.11 (2017): 111303.

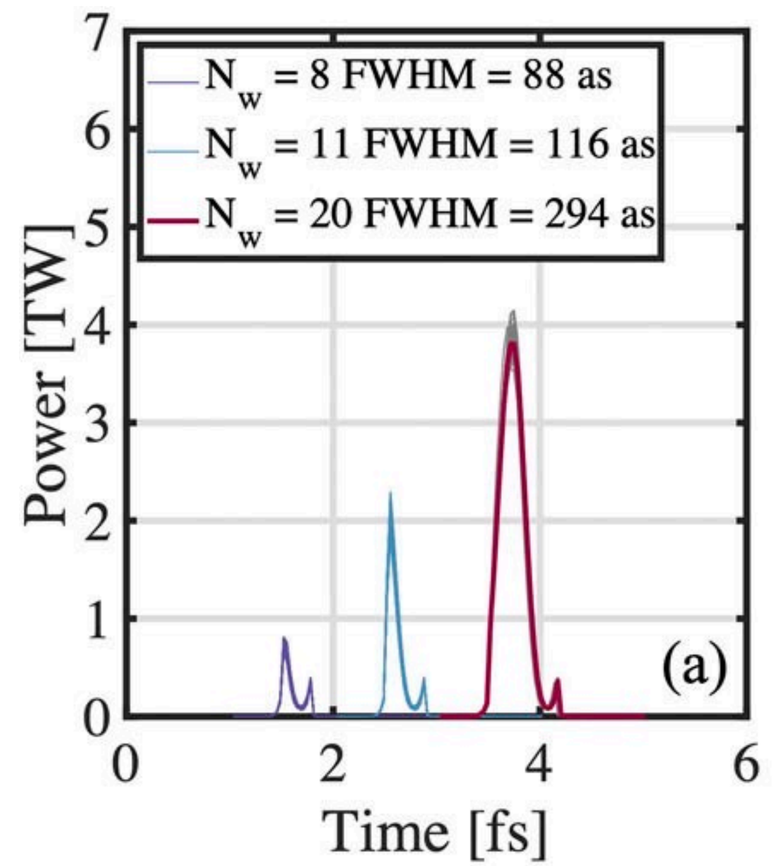
$$L_g \propto \epsilon_n^{5/6} \rightarrow \Delta t_{min} \propto \epsilon_n^{5/6}$$



# Does it Have to be a High-Gain FEL?




*C. Emma et al. APL Photonics* 6.7 (2021): 076107
See also: X. Xu's paper https://arxiv.org/abs/2010.16081

Tolerates what is bad about plasma accelerators (e.g. pointing stability)
Uses features that are unique to plasma accelerators (large chirp, high brightness)

**WE DON'T HAVE TO REPLICATE CONVENTIONAL FELS!**
**THIS IS A NEW TOOL, LET'S DEVELOP NEW APPLICATIONS**

# Summary and Conclusions

**X-ray FELs have become the most prominent tool for ultrafast science**

**X-ray FEL R&D continues pushing the envelope of FEL science:**

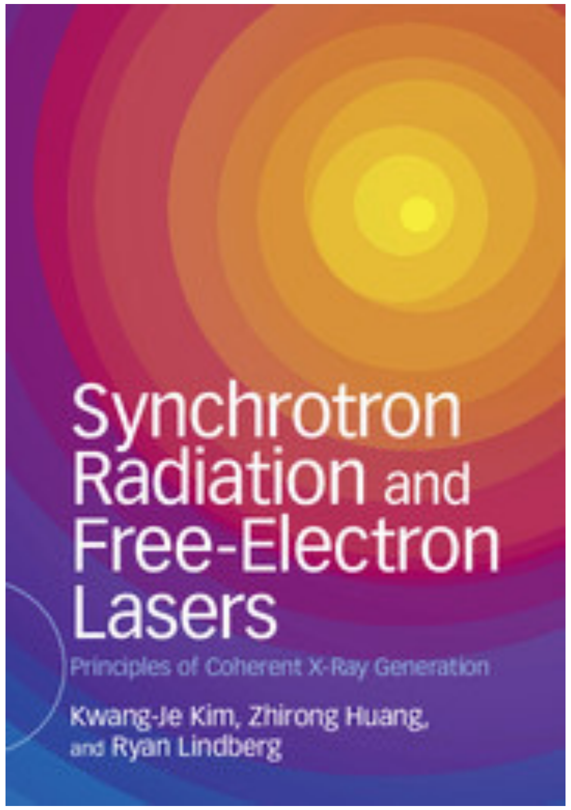
- attosecond pump/probe experiments
- coherent control and narrow bandwidth
- cavity-based X-ray FEL

**Plasma-based sources present many challenges but also unique opportunities**

- plasma-injectors
- attosecond science

**LET'S THINK OUTSIDE THE BOX**

Smaller XFELs are interesting but new technology should create new opportunities




The physics of x-ray free-electron lasers
C. Pellegrini, A. Marinelli, and S. Reiche
Rev. Mod. Phys. **88**, 015006 - 9 March 2016

# Questions?

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