Plasma-Based Attosecond X-ray Pulses

Agostino Marinelli
On behalf of the PAX collaboration

Stanford | PULSE INSTITUTE
LCLS

Collaboration

SLAC
C. Emma, R. Hessami, R. Robles, K. Larsen, J. Morgan, G. White, M. Hogan, A. Marinelli

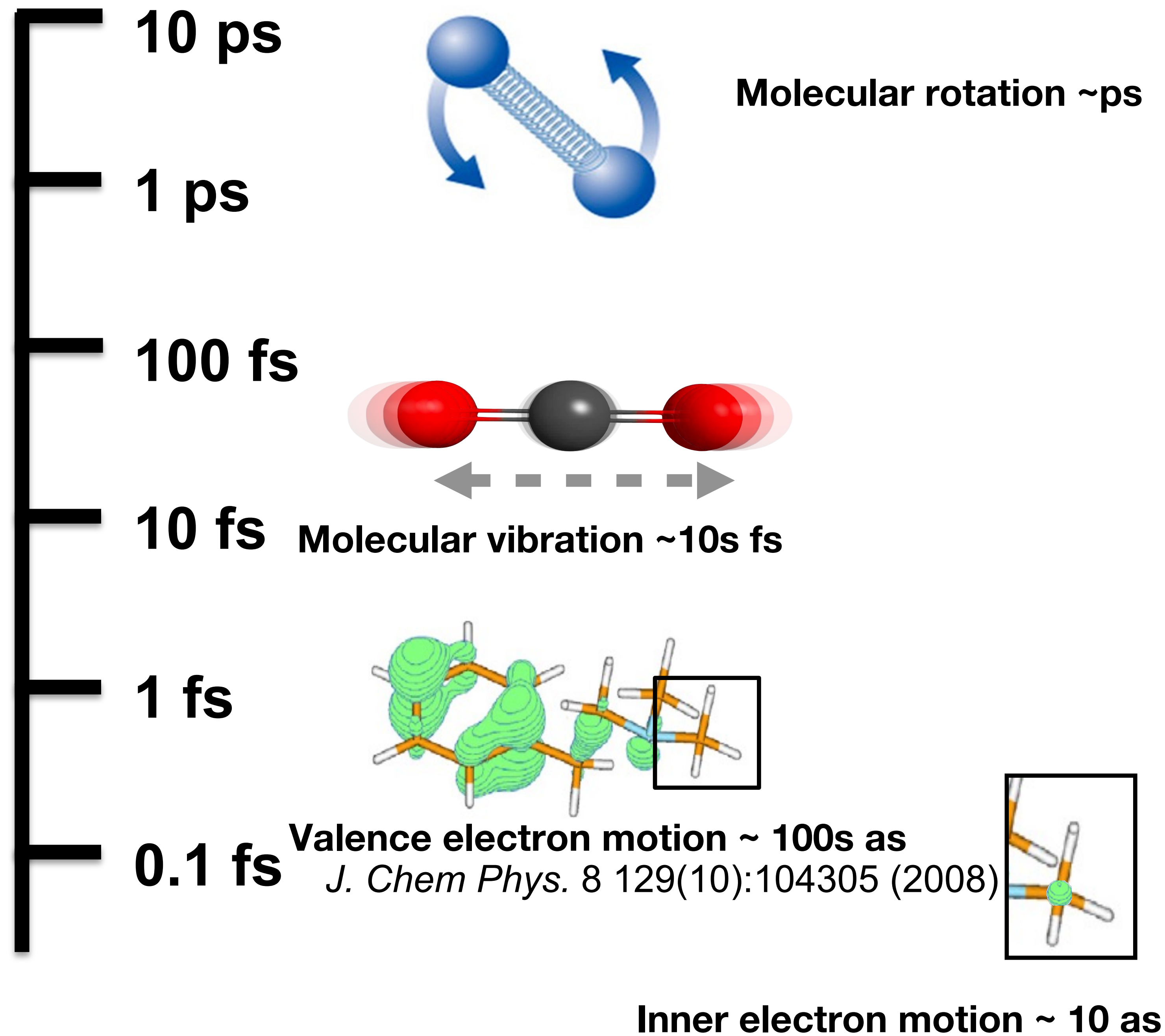
UCLA – EE
C. Zhang, C. Joshi

UCLA - PAB
A.Fisher, P. Musumeci

Synergy with E31X Collaboration
(J. Rosenzweig, B. Hidding and others)

FUNDING:
DOE Office of Science (SLAC LDRD and PD)

Attosecond Timescales



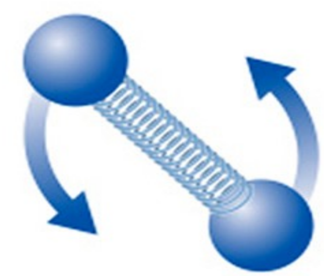
Attosecond Timescales

$$\sum \psi_n(\overrightarrow{x})\exp\left(-i\frac{E_n t}{\hbar}\right)$$

Timescale ~ $\dfrac{\hbar}{\Delta E}$

$$1fsFWHM \rightarrow 1.8eV$$

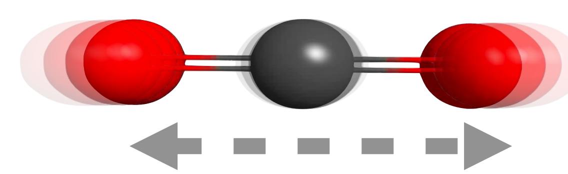
10 ps



Molecular rotation ~ps

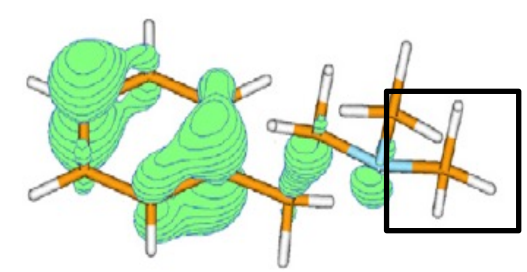
1 ps

100 fs



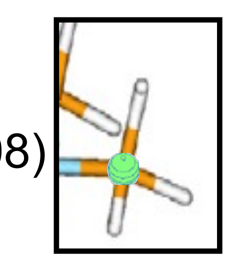
10 fs **Molecular vibration ~10s fs**

1 fs



0.1 fs **Valence electron motion ~ 100s as**

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



Inner electron motion ~ 10 as

Why Attoseconds AND X-rays

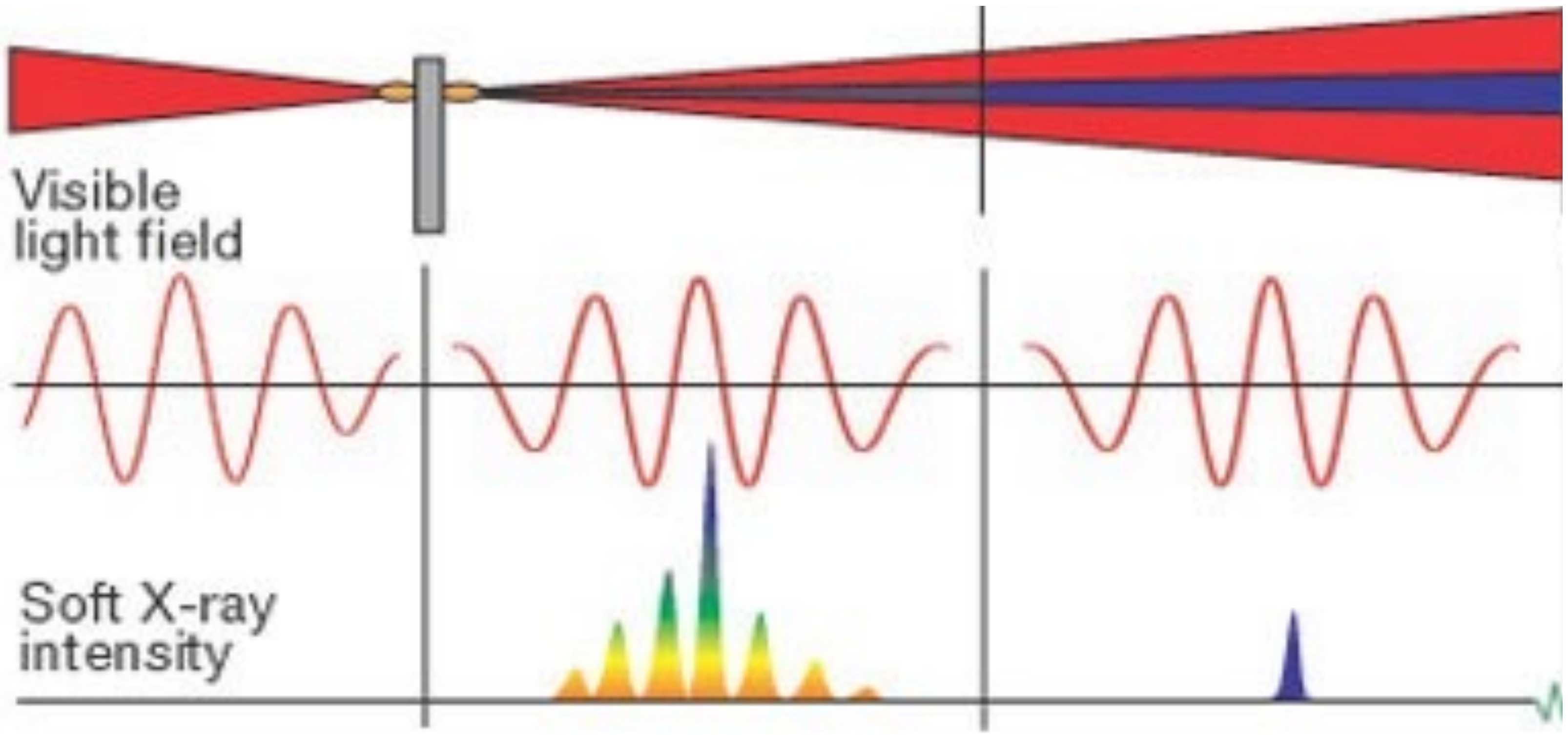
400 eV

280 eV

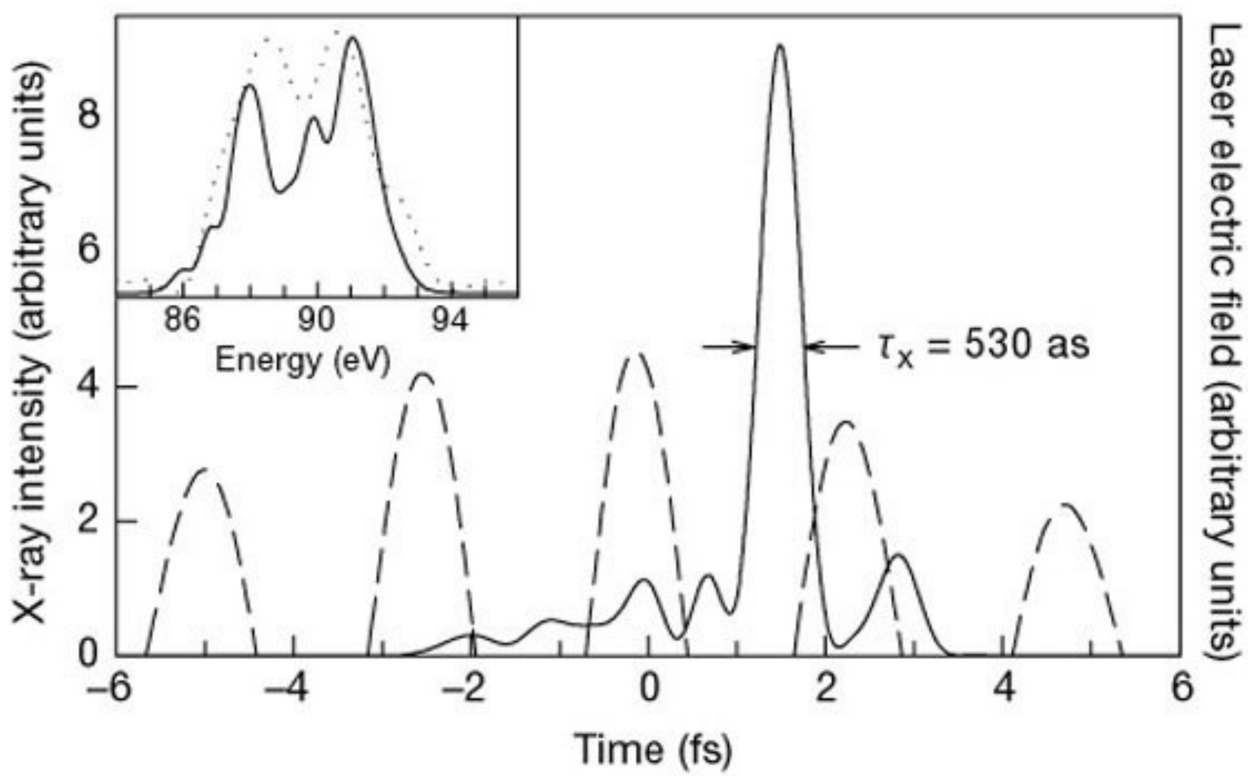
520 eV

Simulation:
G. Grell, J. Gonzalez-Vazquez,
Piero Decleva, A. Palacios and
F. Martín (UAM)

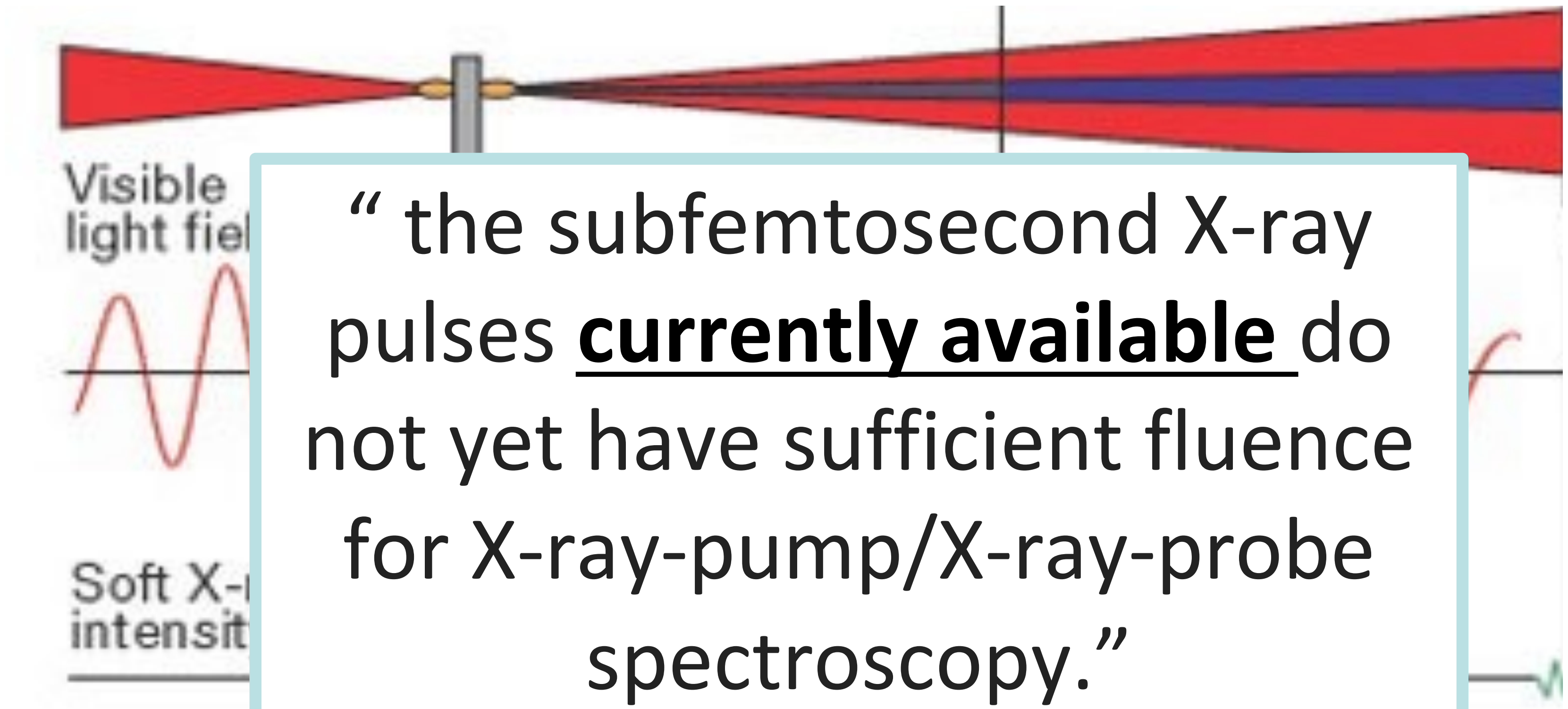
Attosecond Pulses BEFORE FELs



M. Hentschel et al. *Nature* **414**, 509–513 (2001).

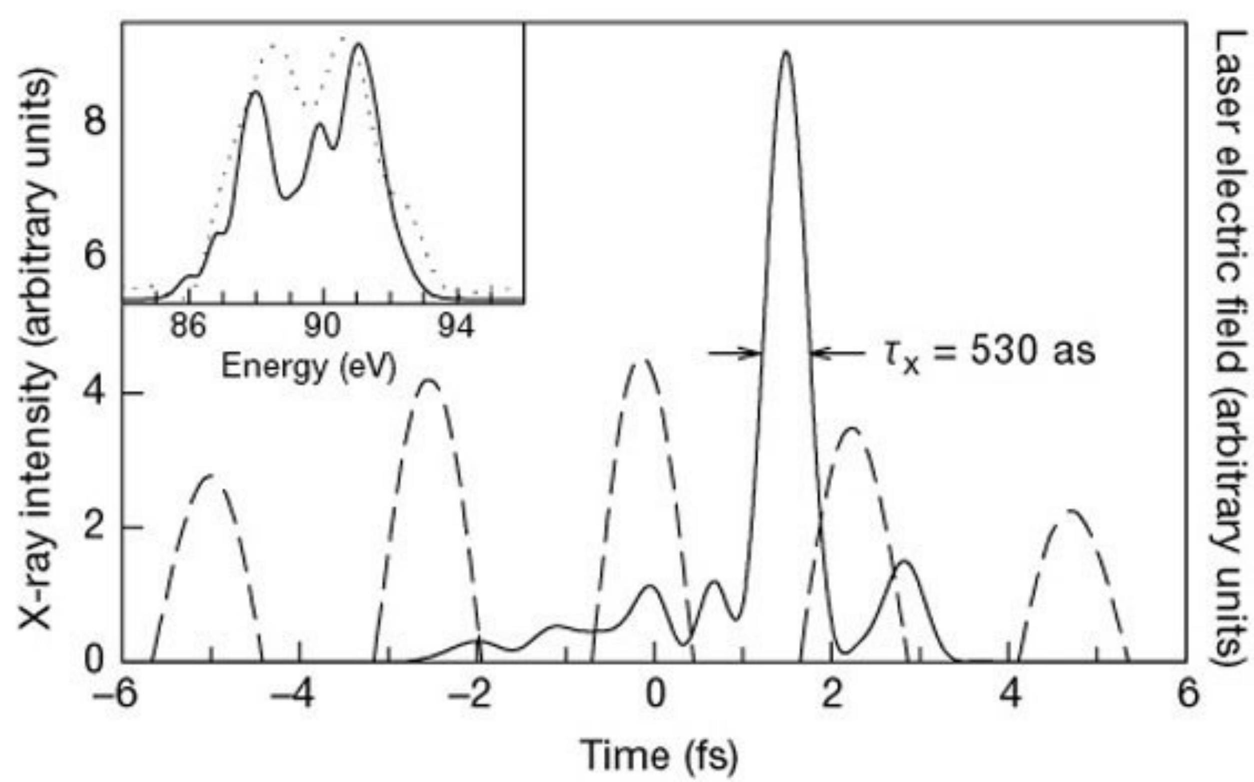


Attosecond Pulses BEFORE FELs

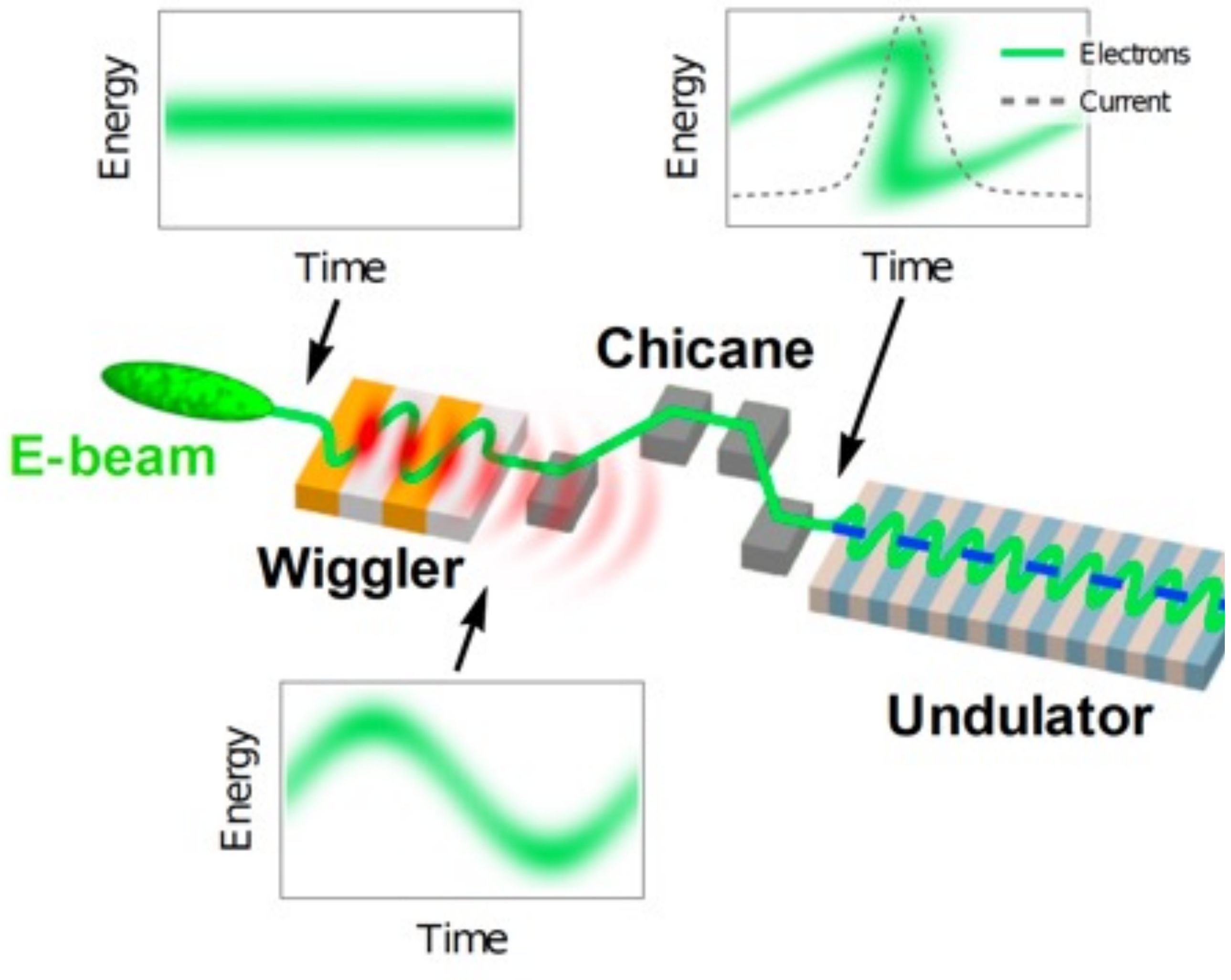


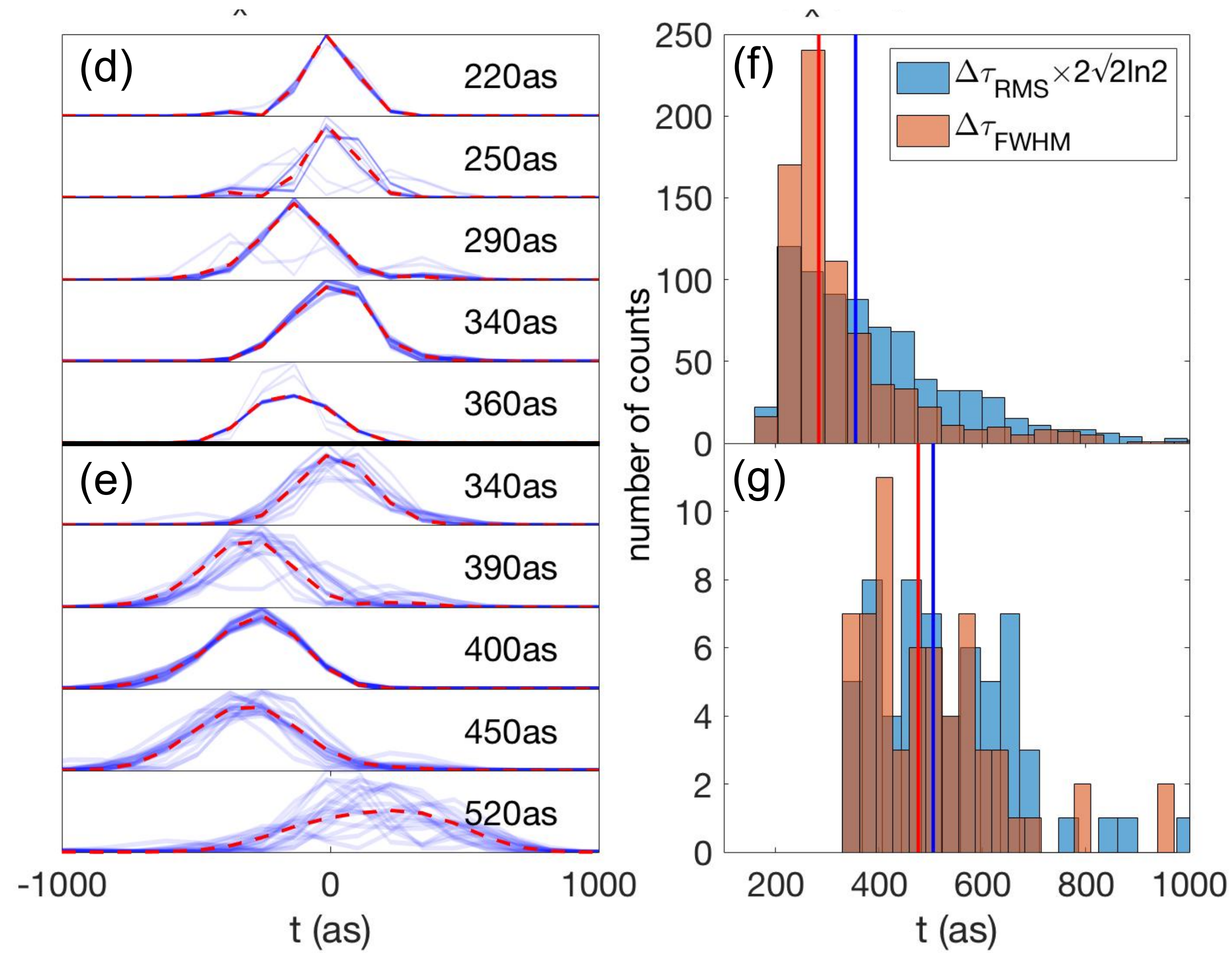
“ the subfemtosecond X-ray pulses **<u>currently available</u>** do not yet have sufficient fluence for X-ray-pump/X-ray-probe spectroscopy.”

M. Hentschel et al. *Nature* **414**, 509–513 (2001).



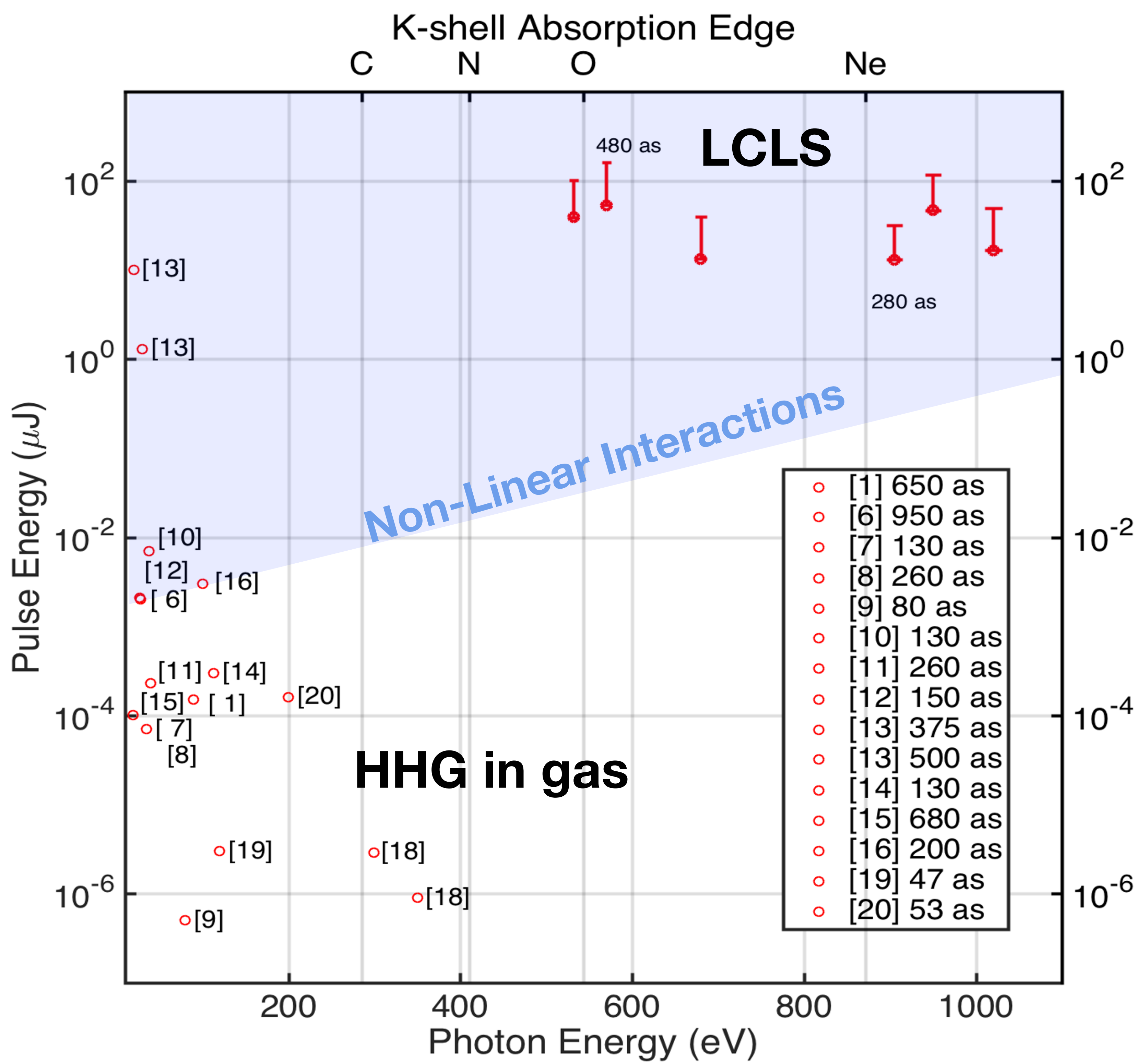
Attosecond Pulses with XFELs





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.
D. Cesar et al. *Physical Review Accelerators and Beams* 24.11 (2021): 110703.

Why Attosecond X-ray FELs?



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

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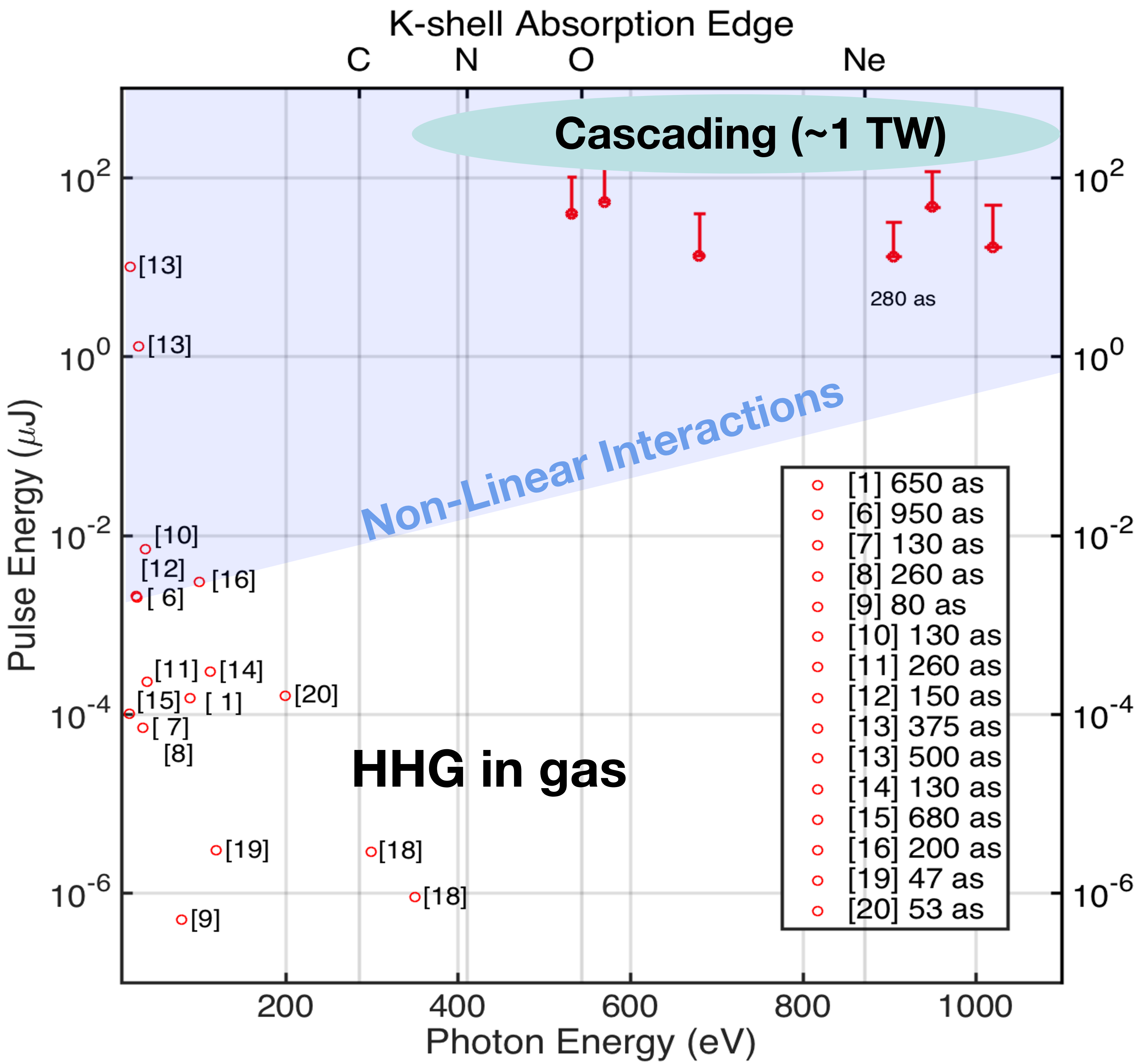


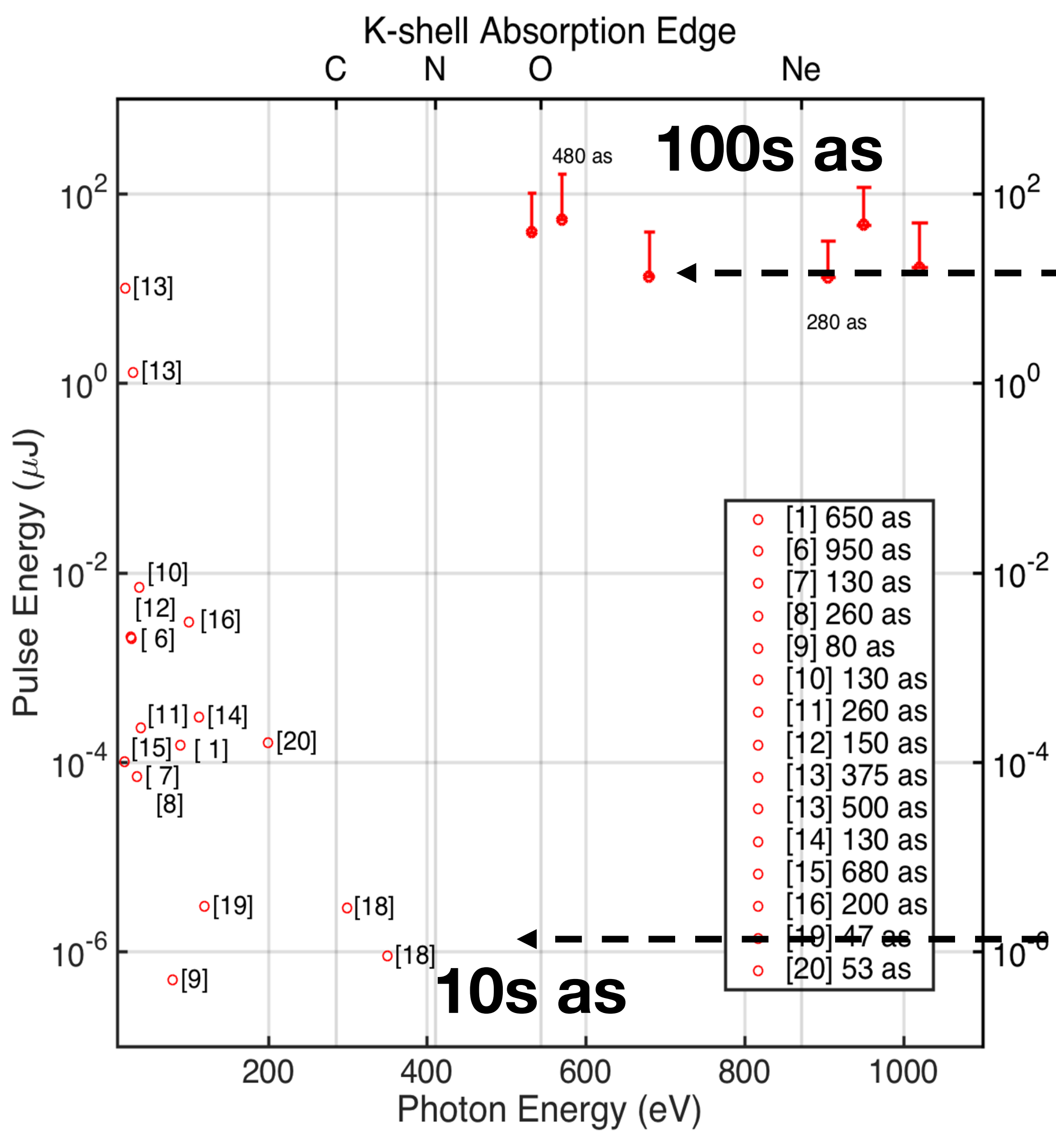
P. Franz
Applied Physics

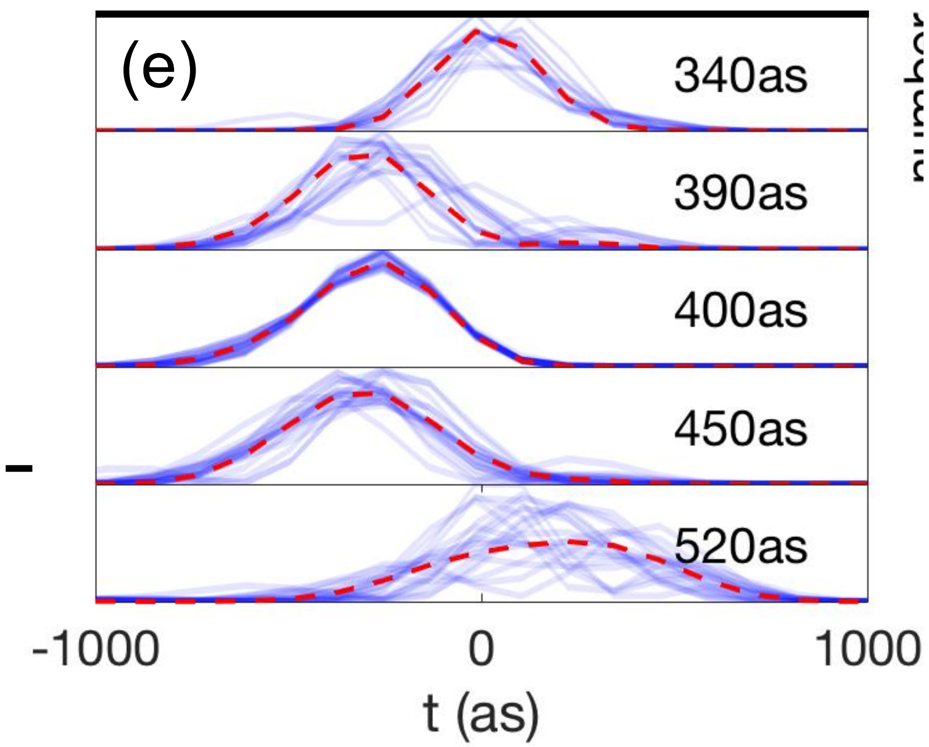
J. Duris, S. Li et al. *Nature Photonics* 14.1 (2020): 30-36.

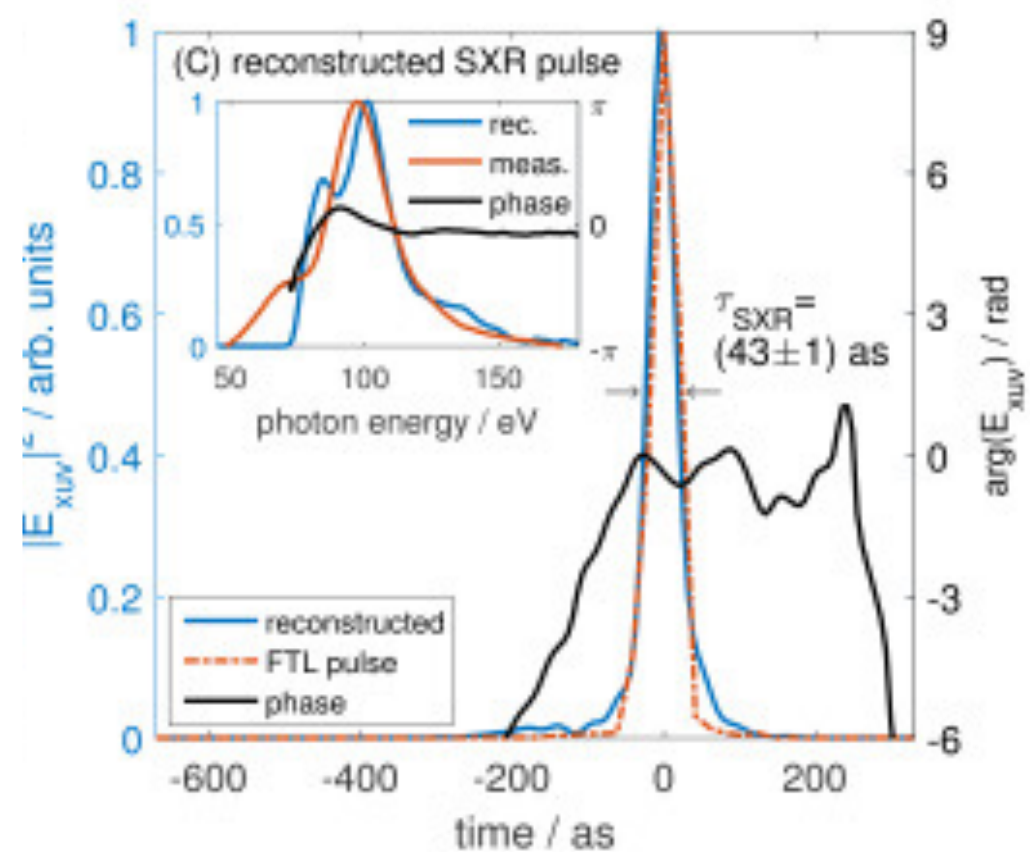
Attosecond Pump/Probe

LCLS Attosecond Campaign

Why Plasma-Based Attosecond Pulses?



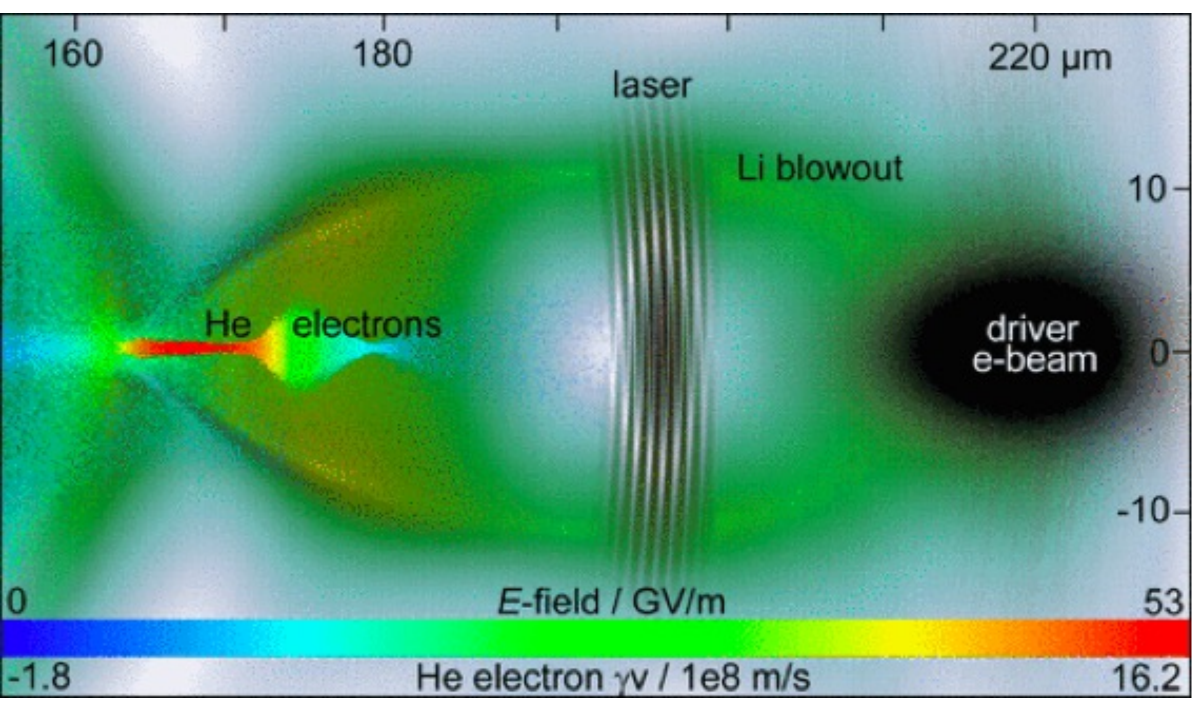


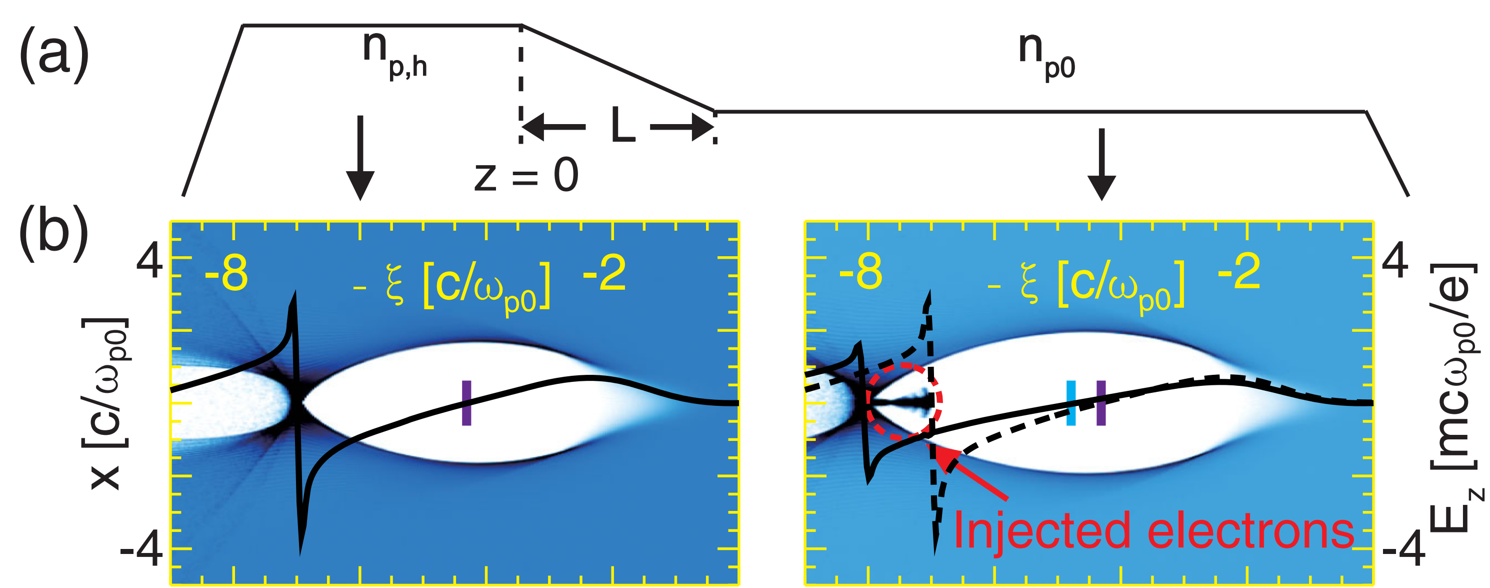


Why Plasma-Based Attosecond Pulses?

$$BW \propto \frac{1}{L_g}$$

$$\Delta t_{min} \propto L_g$$

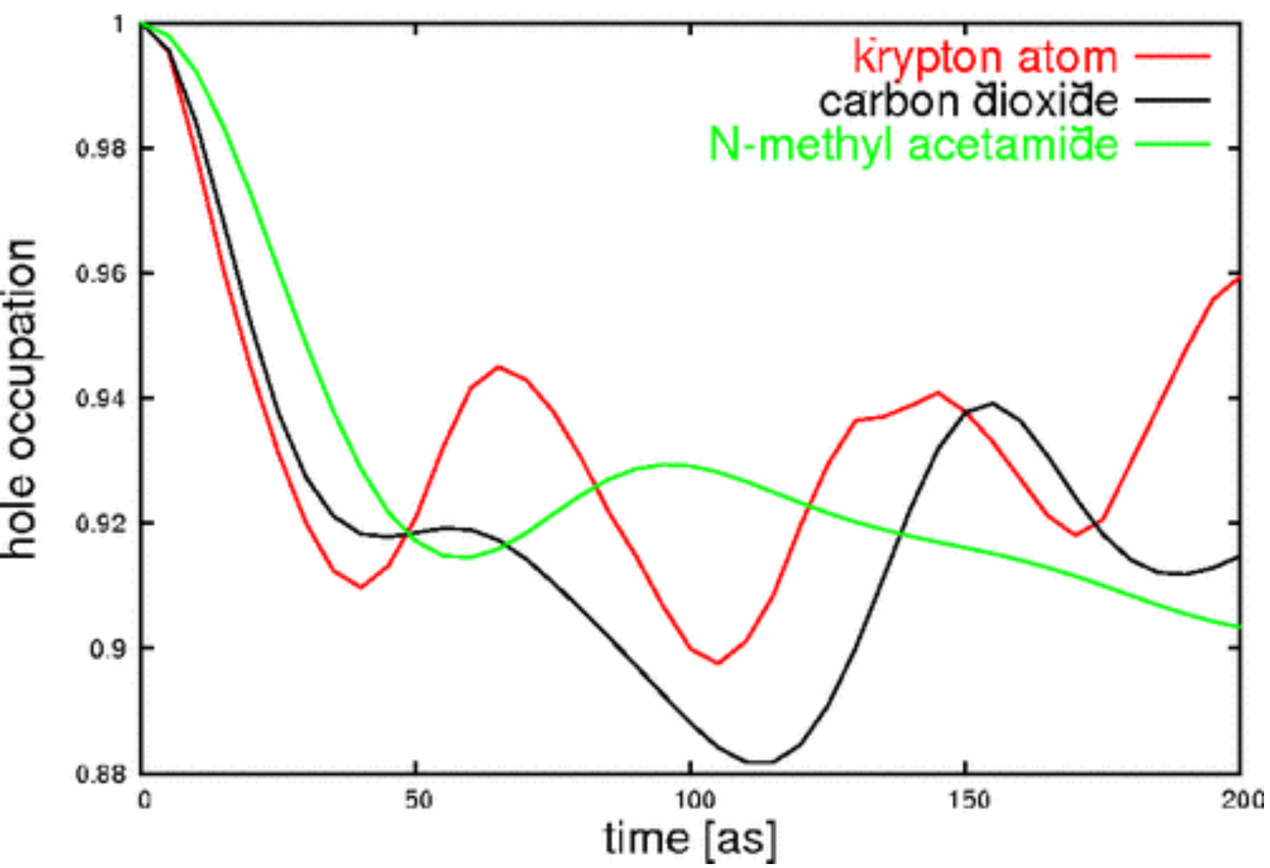




H. Suk et al. Phys. Rev. Lett. 86, 1011 (2001)
B. Hidding et al. Phys. Rev. Lett. 108, 035001
X. Xu et al. PRAB 20, 111303 (2017).

Why Few-Cycle Pulses?

Universal response to electron removal

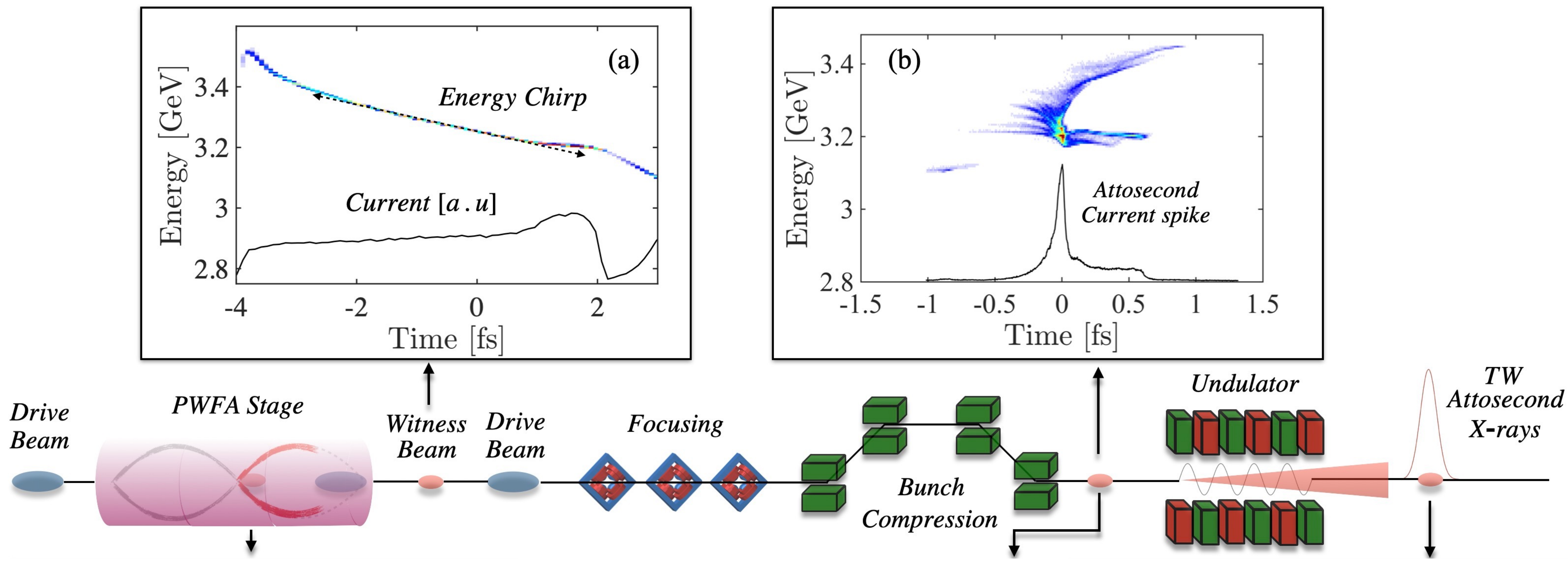


Phys. Rev. Lett. **94**, 033901

More stable pump

M. Grell et al. in preparation

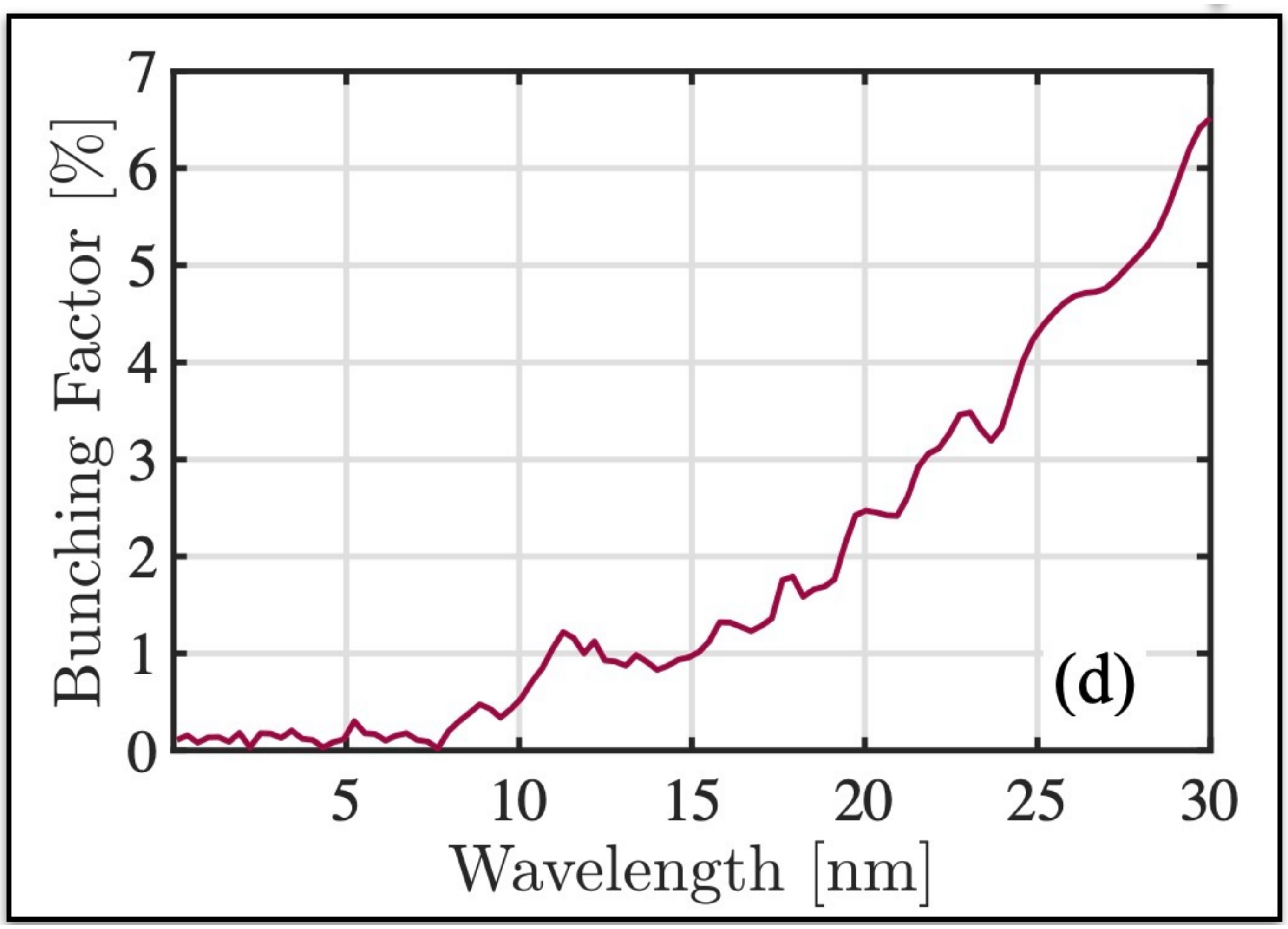
PAX: Plasma-based Attosecond Pulse Generation

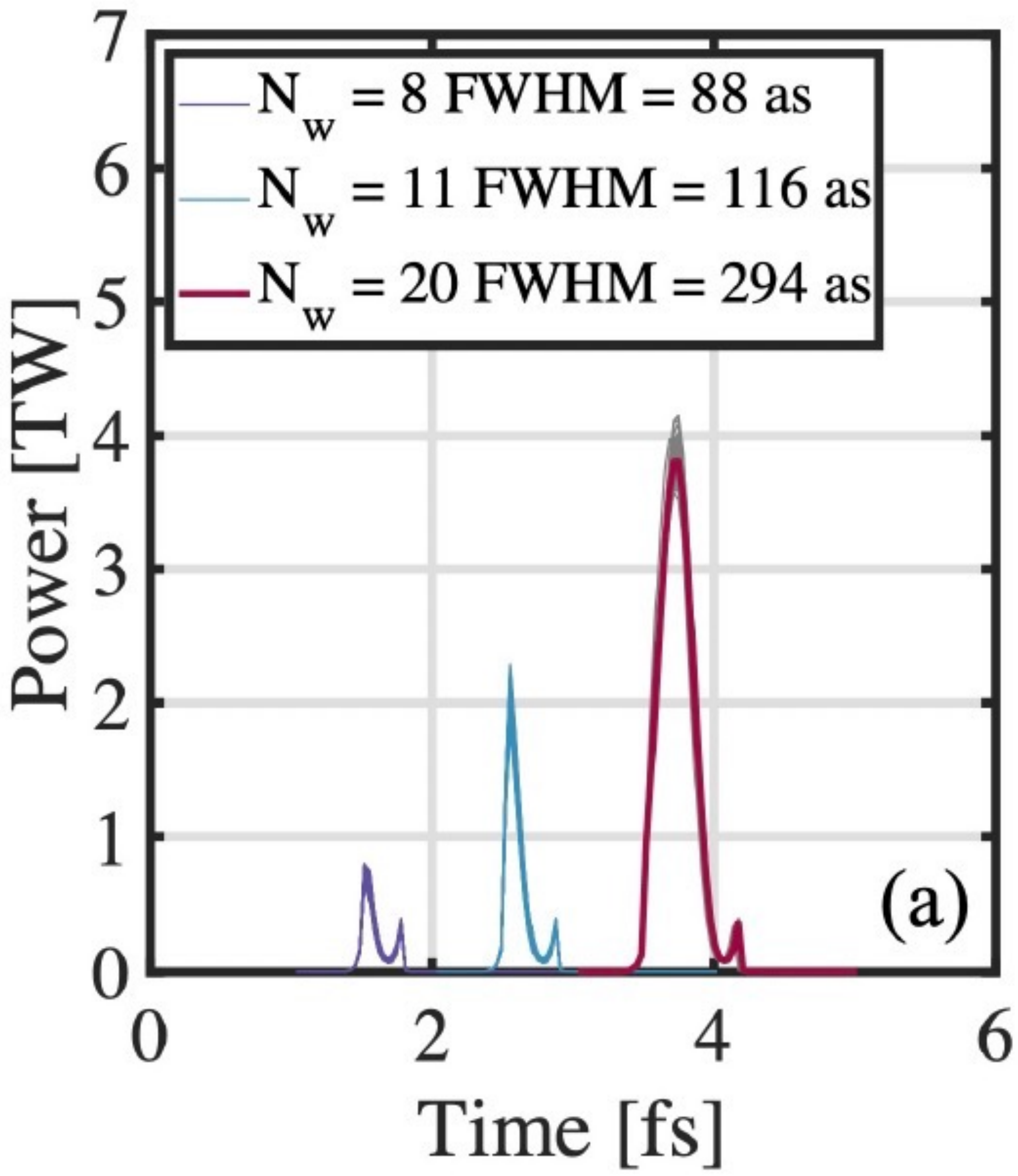


C. Emma et al. APL Photonics 6 (7), 076107

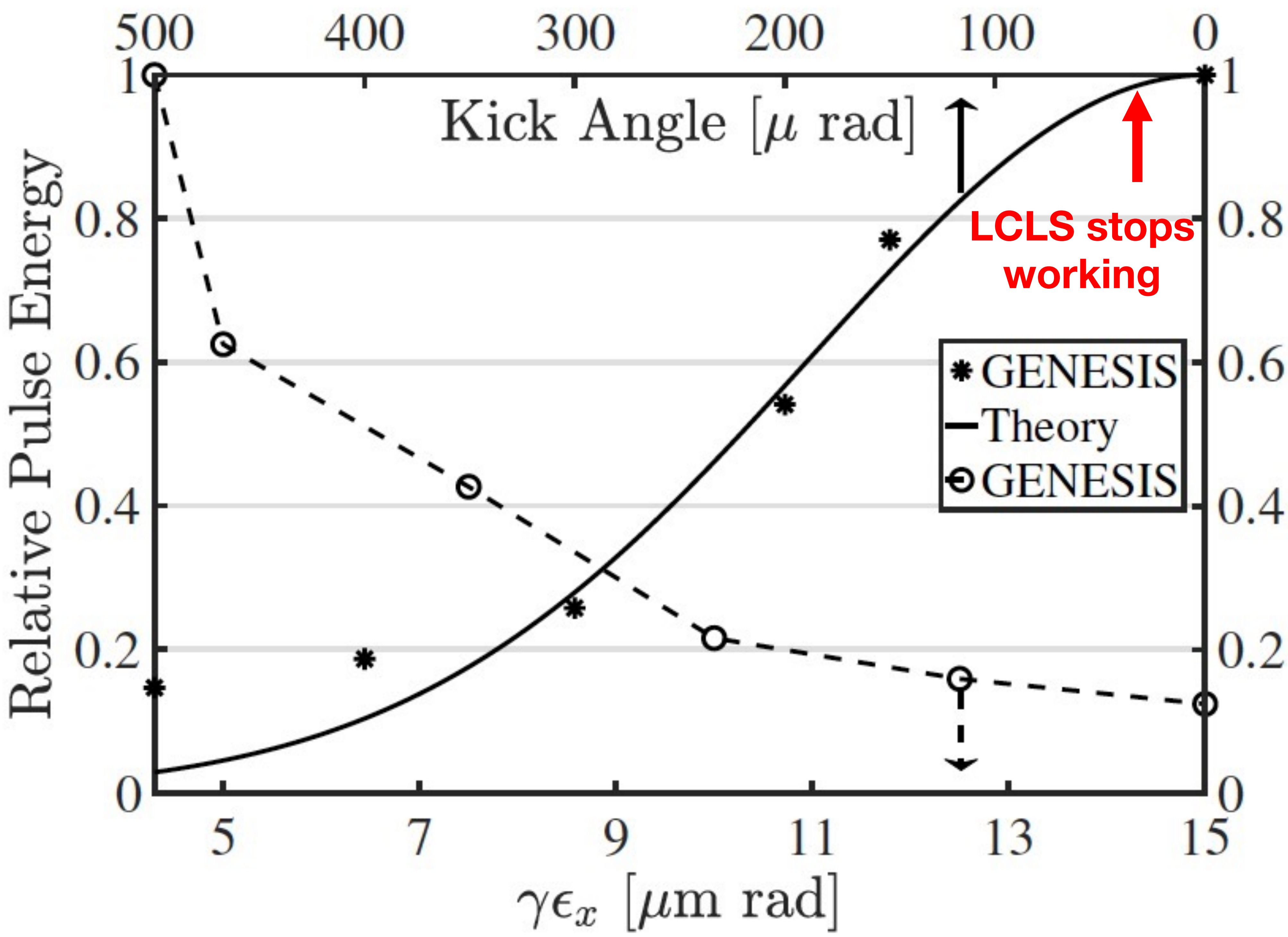
See also X. Xu et al. Nat Commun **13**, 3364 (2022)

Coherent Emission





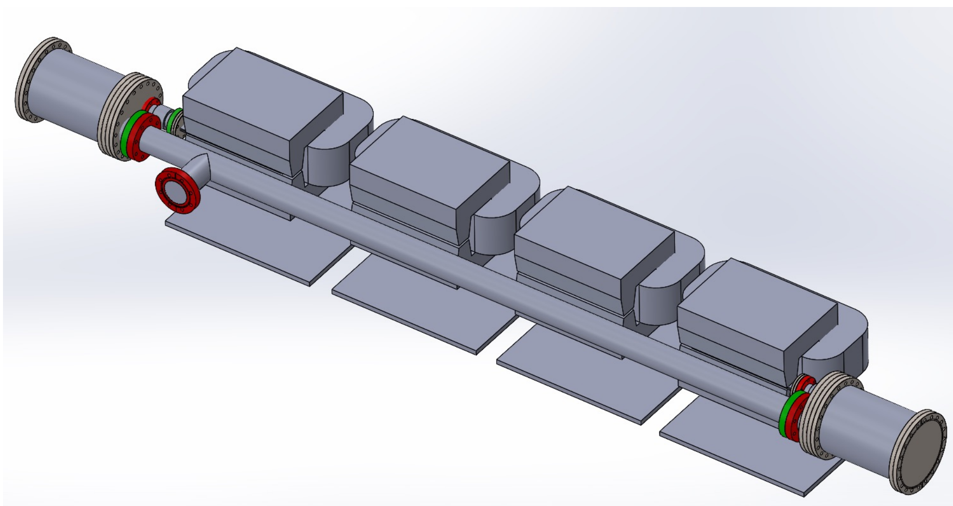
Sensitivity to Pointing Jitter

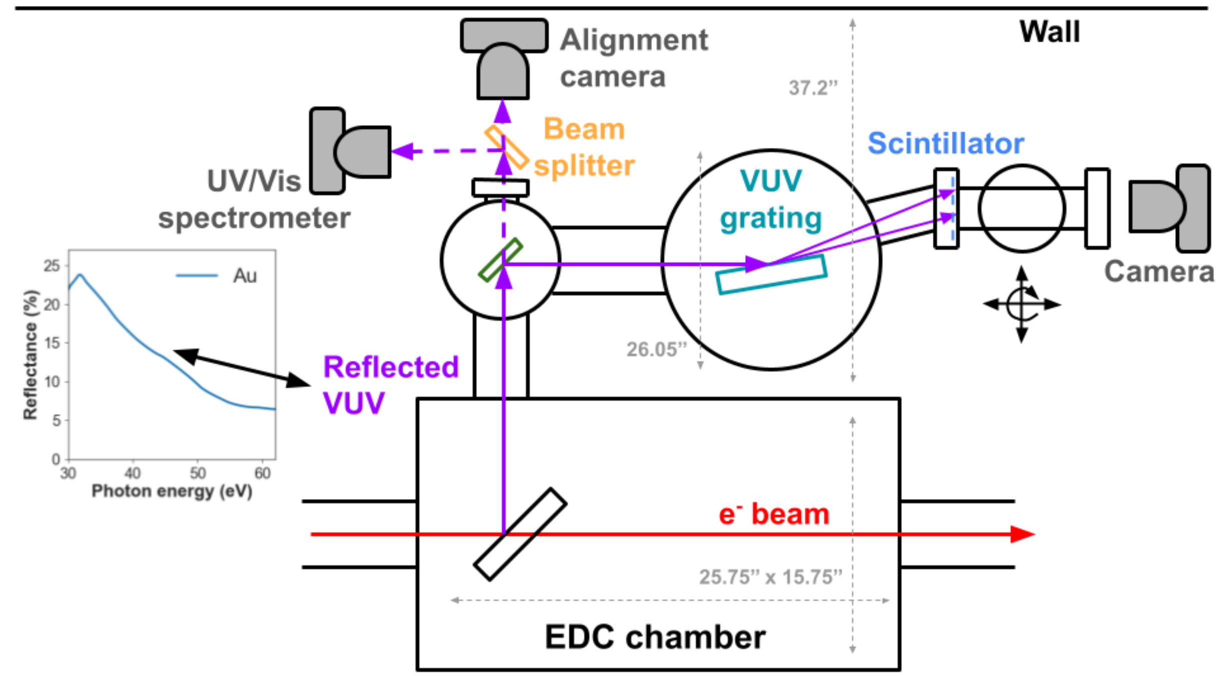


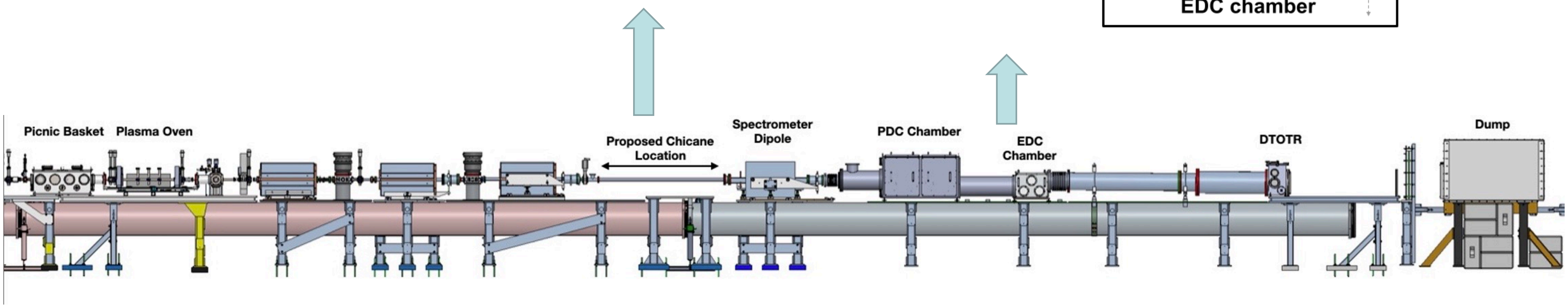
Above the Carbon K-Edge

Harmonic up-conversion of radiation-induced microbunching
Few-cycle soft X-ray pulses
(work in progress)

Proof of Principle Demonstration at FACET-II

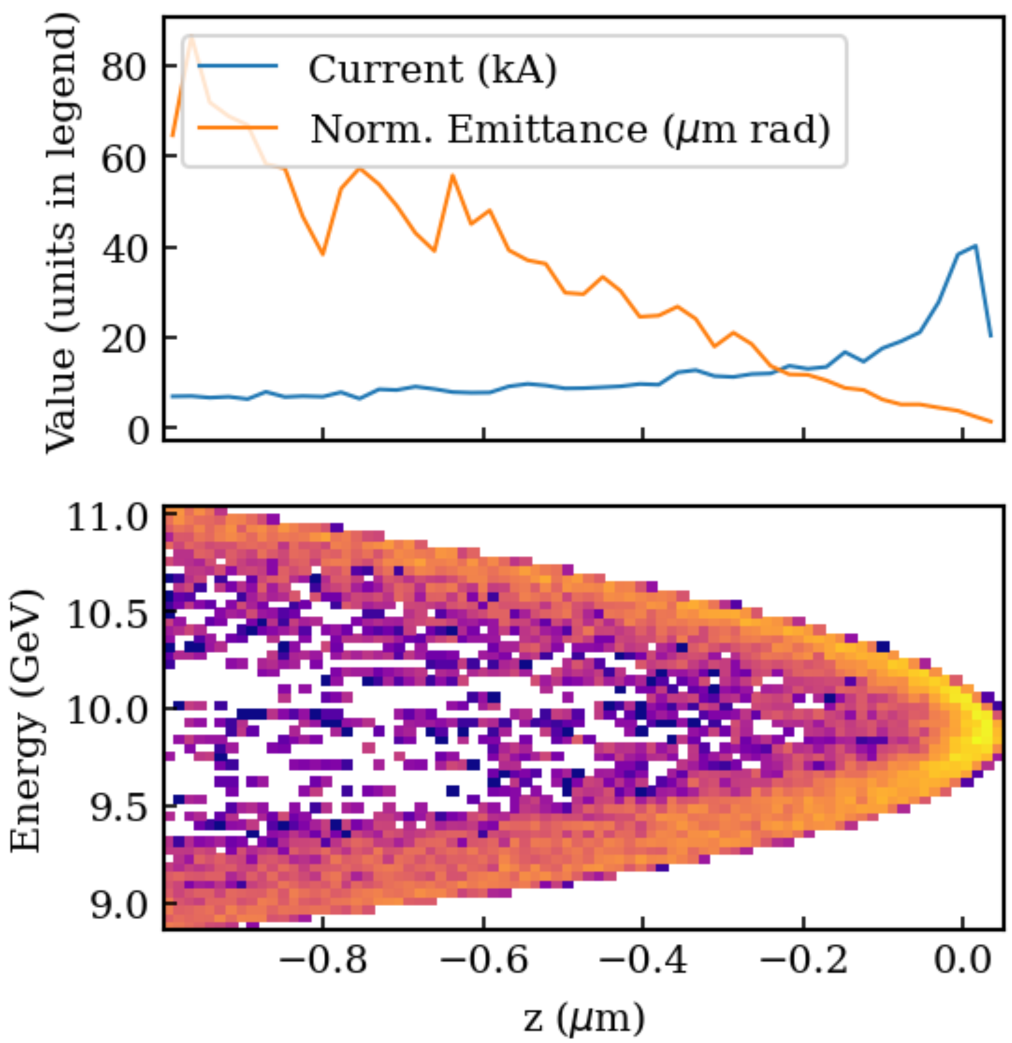


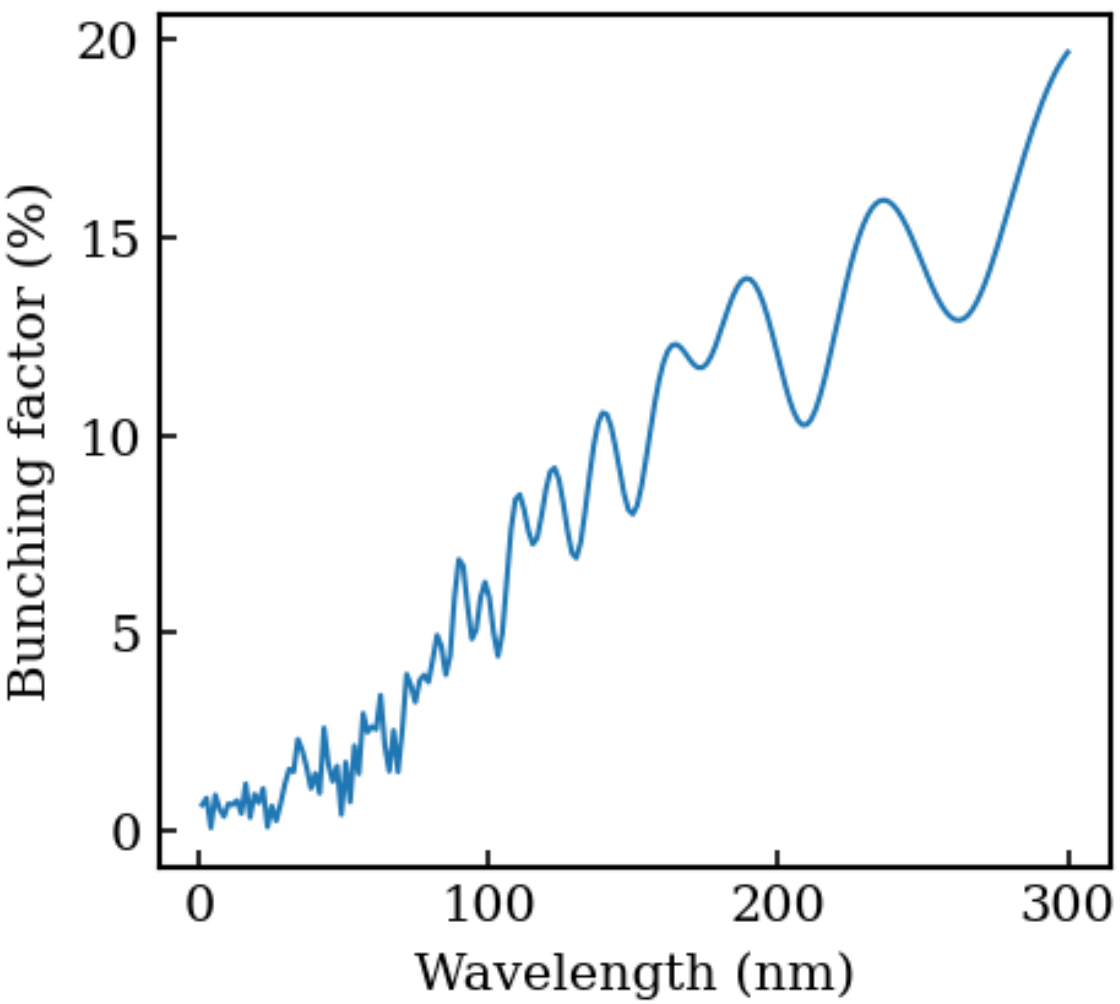




Use linac—generated beam for first demonstration.
Compress with dedicated chicane (R56 = 100 um @ 10 GeV)
Detect dipole radiation from spectrometer bend.

Expected Performance with Linac-Generated Beam

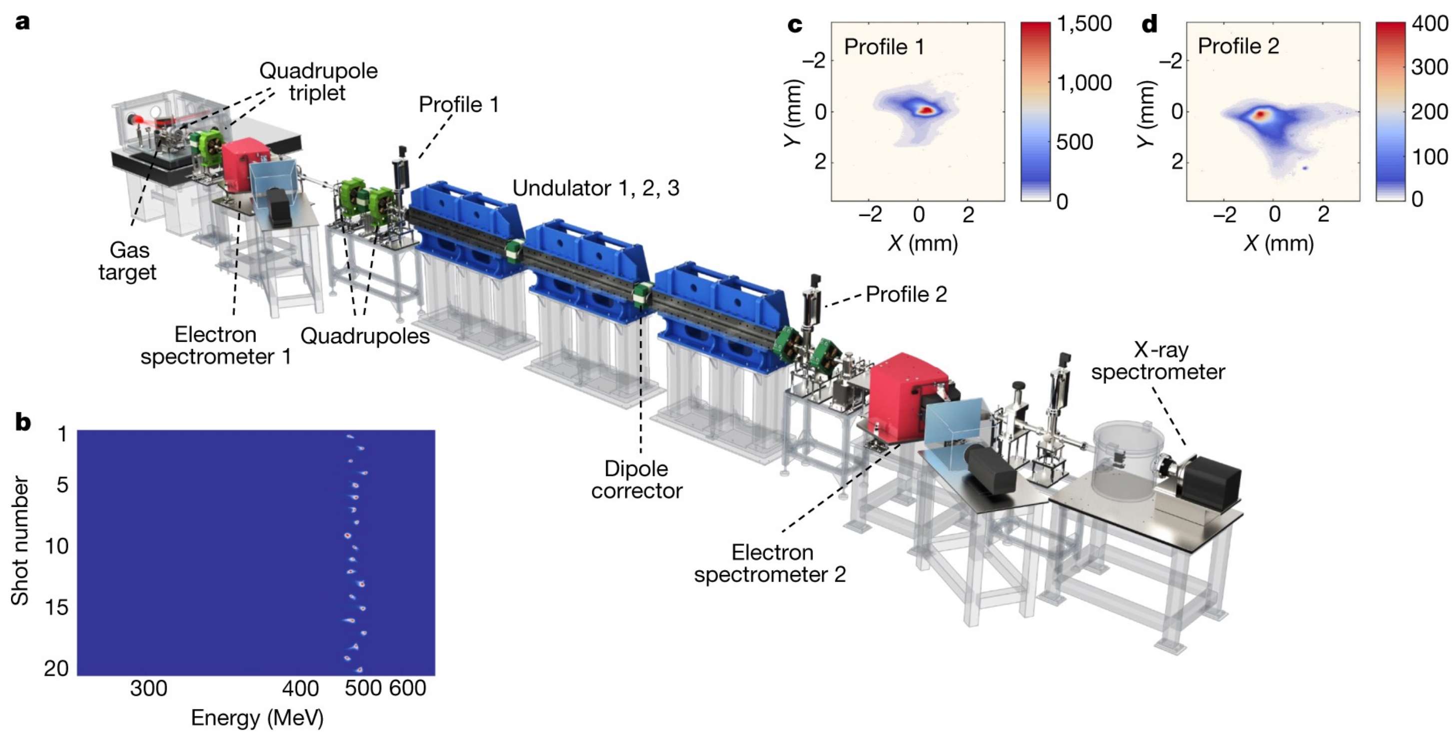




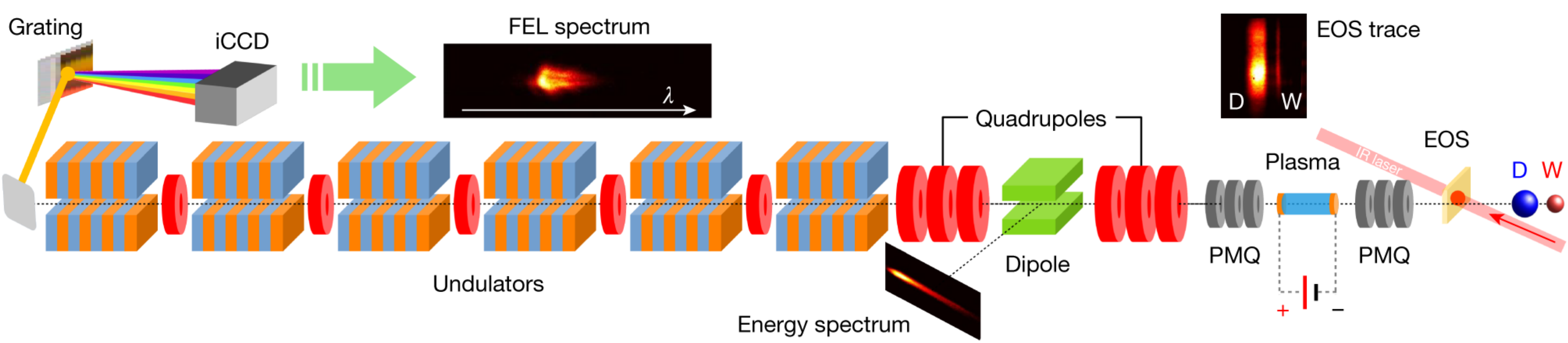
Expect few uJ-scale radiation below 100 nm from spectrometer bend

Plasma-Based FELs

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

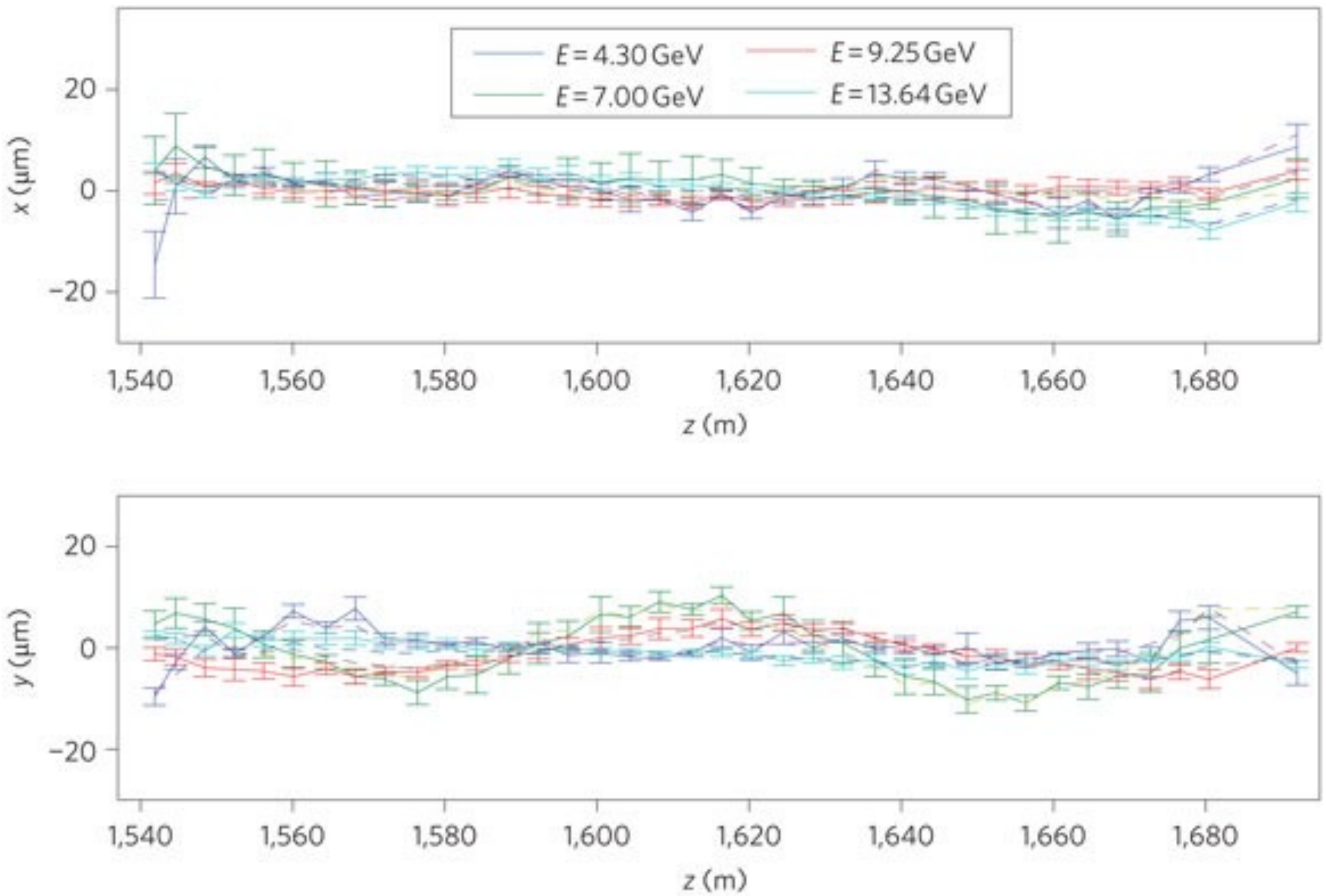


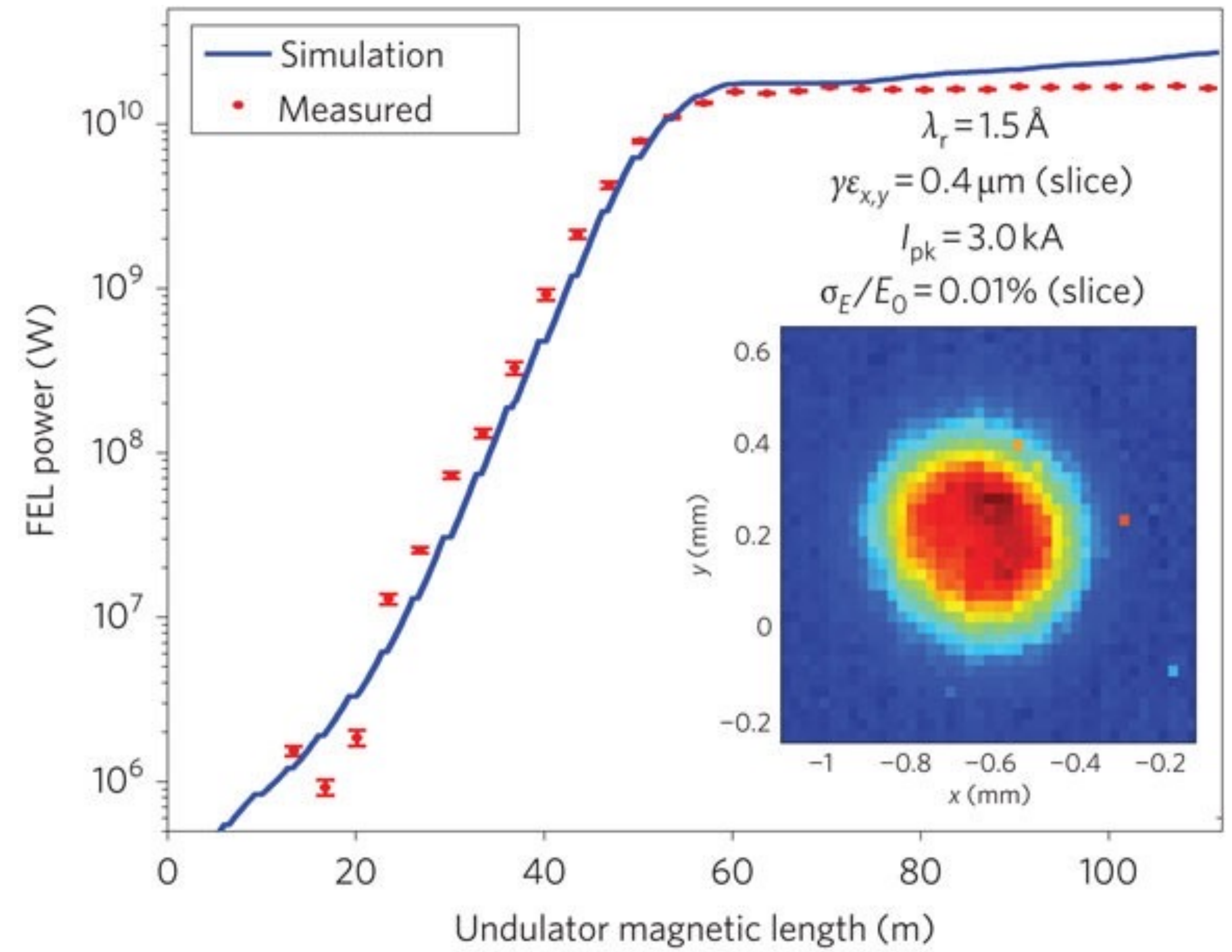
Pompili, R., et al. *Nature* 605.7911 (2022): 659-662.



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

The Problem with Plasma-Based High-Gain FELs

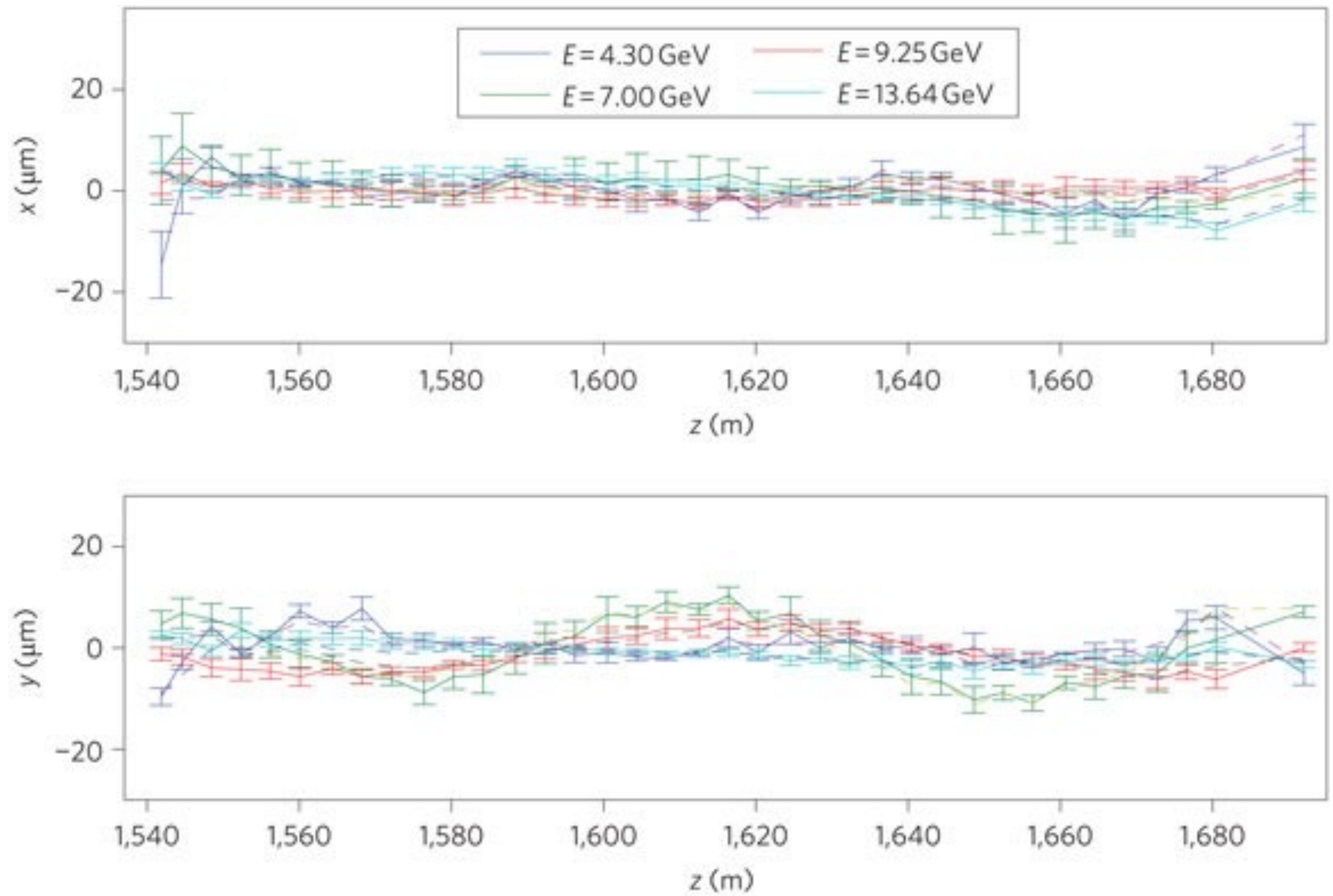


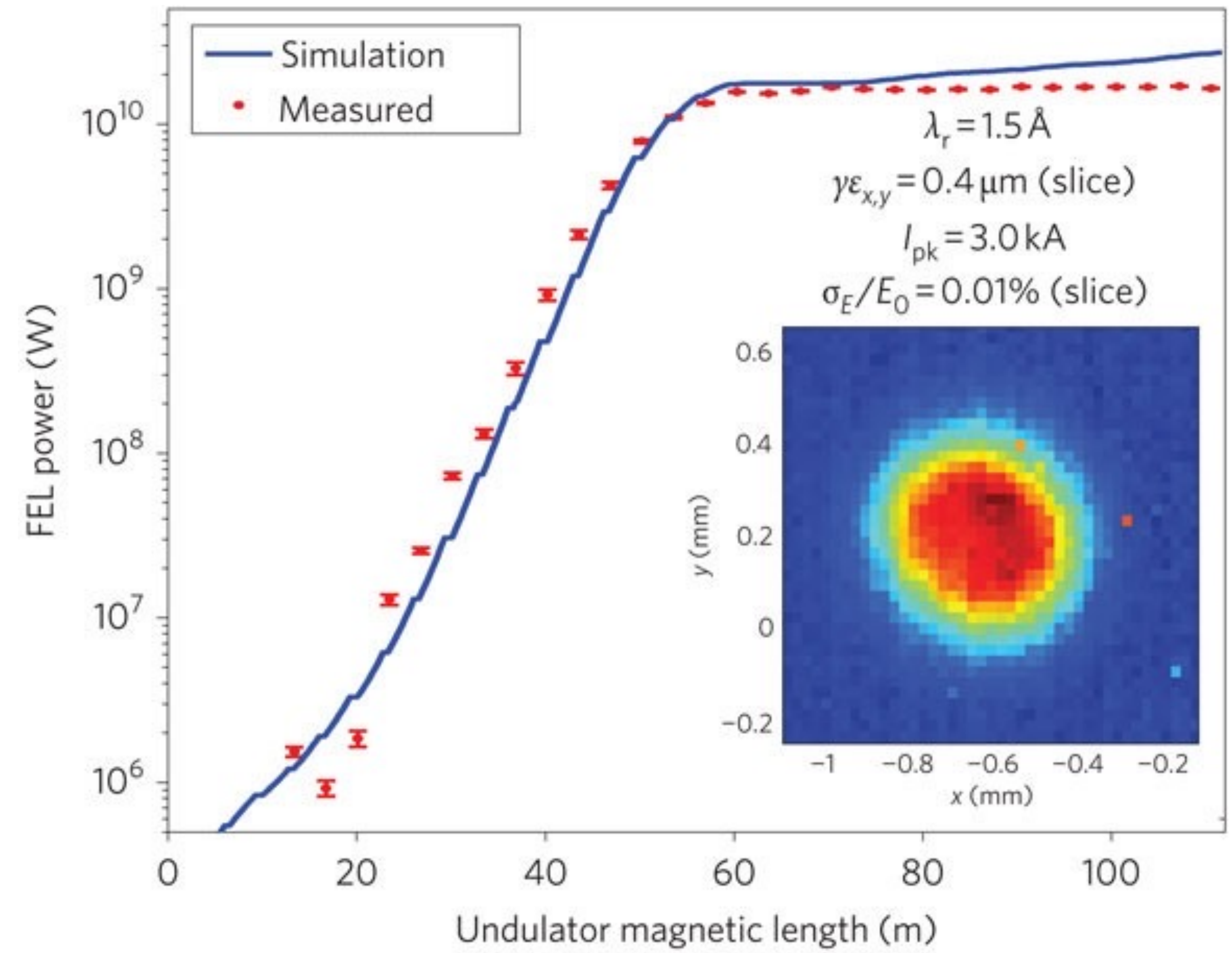


Sub 1% energy jitter
< 10 um orbit jitter

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

The Problem with Plasma-Based High-Gain FELs





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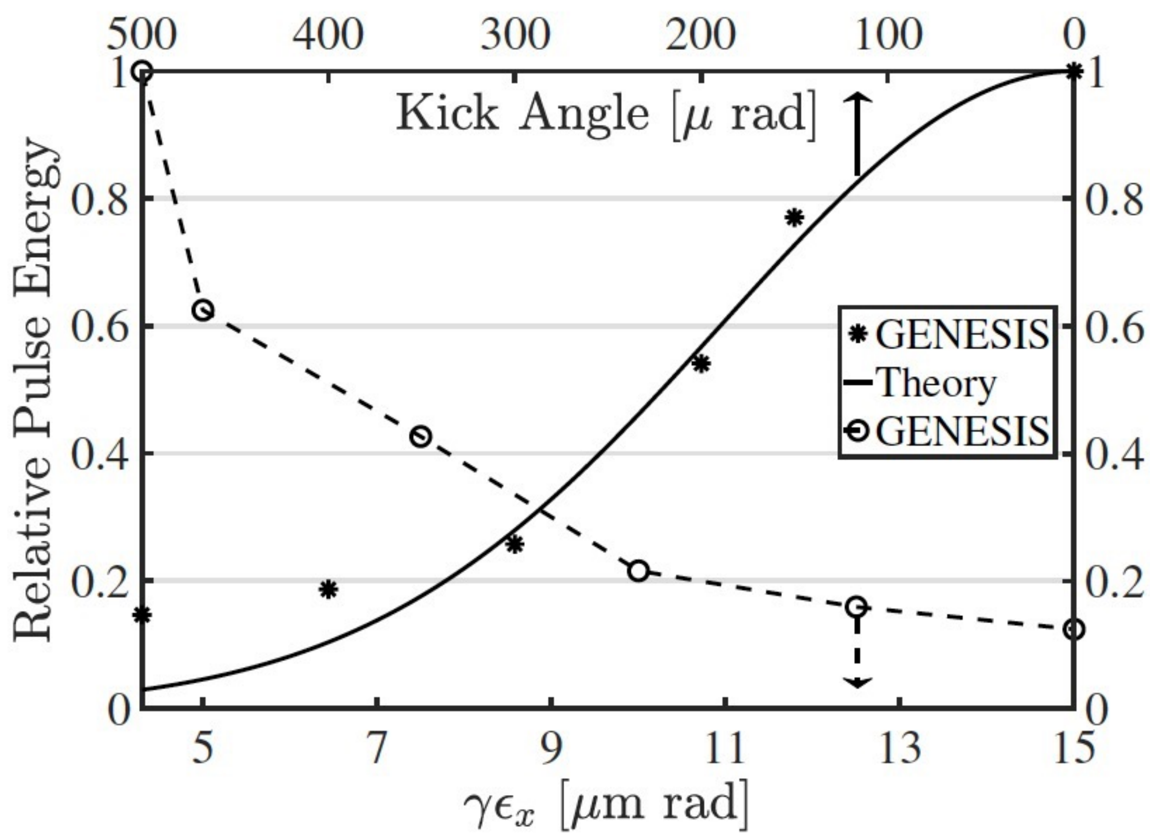
< 10 um orbit jitter

"Our great mistake is to try to exact from each person virtues which he does not possess, and to neglect the cultivation of those which he has."

M. Yourcenar, Memoirs of Hadrian

Why PAX?

1) Tolerates what is bad about plasma accelerators (e.g. pointing stability) thanks to pre-bunching



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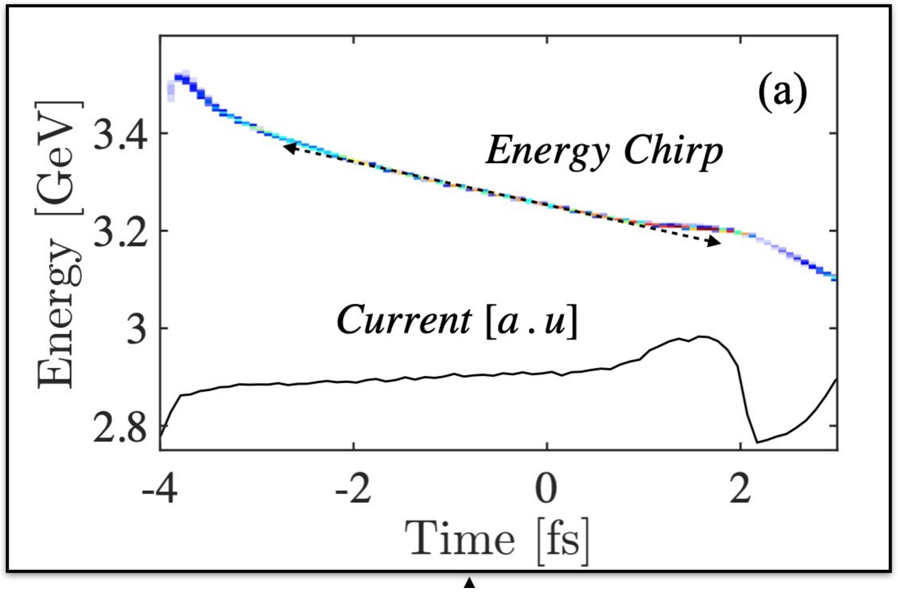
2) Uses features that are unique to plasma accelerators (large chirp, high brightness)



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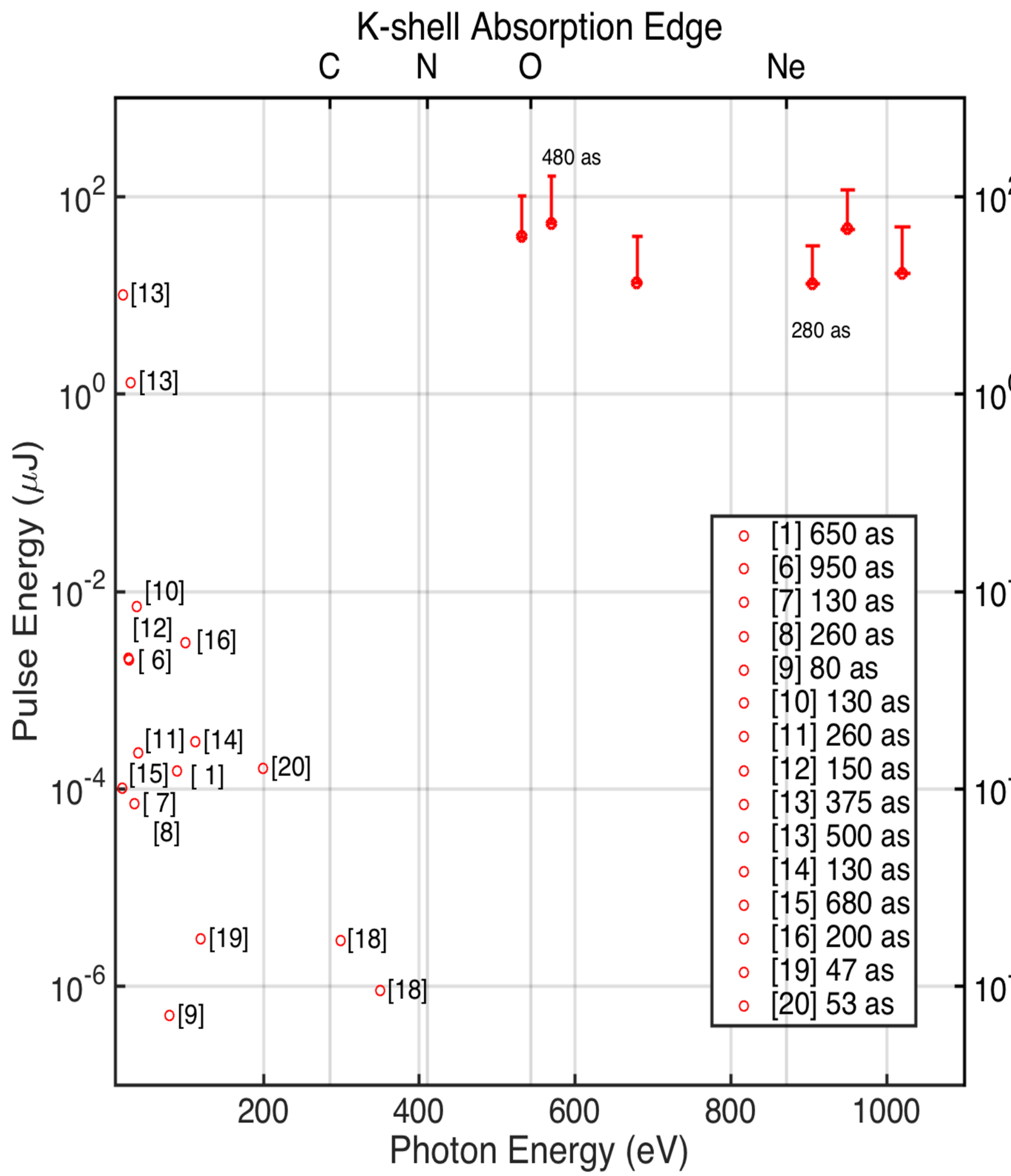

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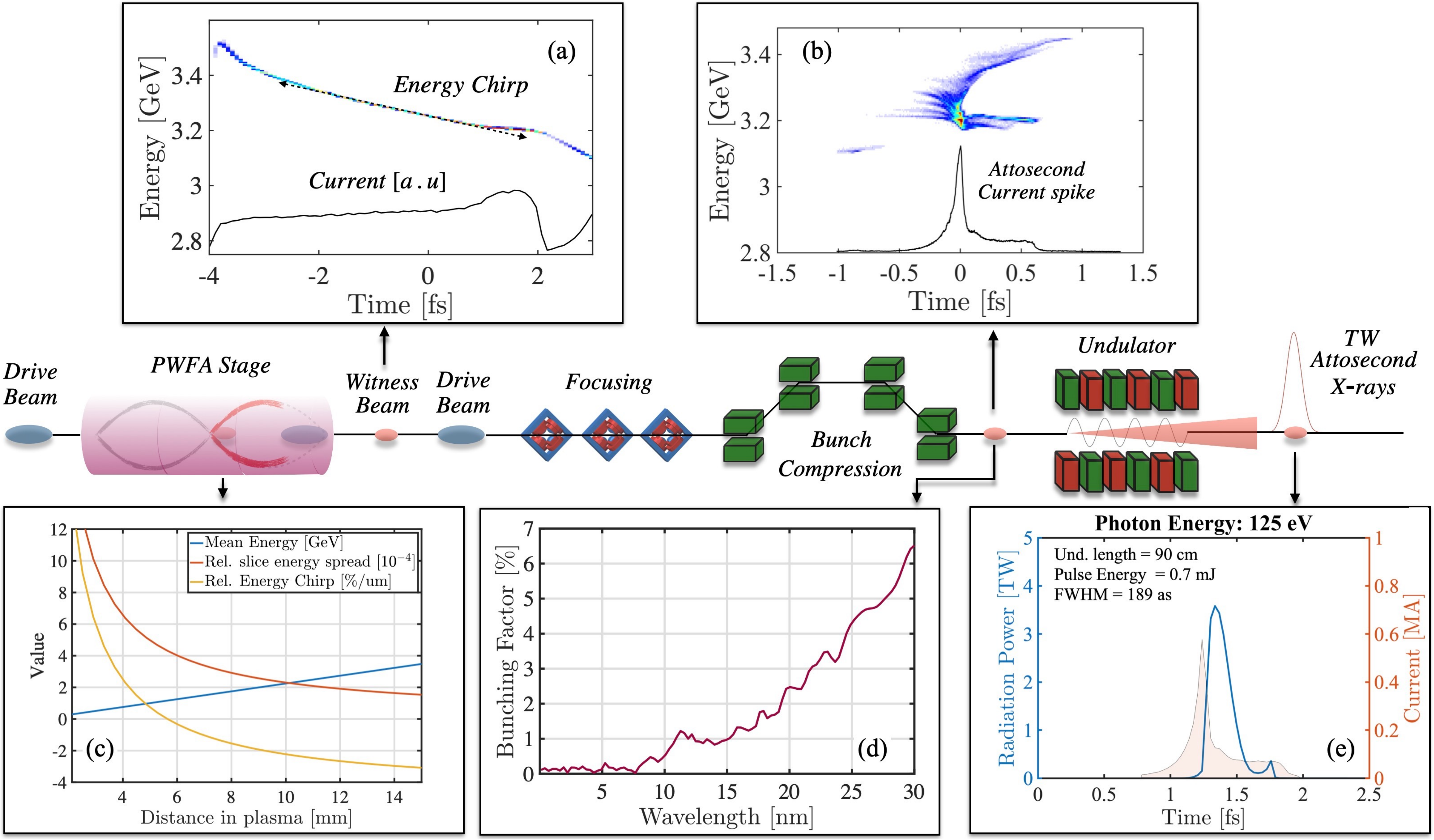
WE DON'T HAVE TO REPLICATE CONVENTIONAL FELS!
THIS IS A NEW TOOL, LET'S DEVELOP NEW APPLICATIONS

Questions?



(a)
Energy Chirp
Current [a . u]
Energy [GeV]
Time [fs]
(b)
Attosecond Current spike
Energy [GeV]
Time [fs]
Drive Beam
PWFA Stage
Witness Beam
Drive Beam
Focusing
Bunch Compression
Undulator
TW Attosecond X-rays
Mean Energy [GeV]
Rel. slice energy spread [10^-4]
Rel. Energy Chirp [%/um]
Value
(c)
Distance in plasma [mm]
Bunching Factor [%]
(d)
Wavelength [nm]
Photon Energy: 125 eV
Und. length = 90 cm
Pulse Energy = 0.7 mJ
FWHM = 189 as
Radiation Power [TW]
Current [MA]
(e)
Time [fs]