Towards Attosecond Science at LCLS and LCLS-II

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Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

Introduction: ultrafast time-scales and attosecond dynamics in molecules

Single-spike SASE FELs

The XLEAP experiment at SLAC:

-IR laser modulation

-self-modulation

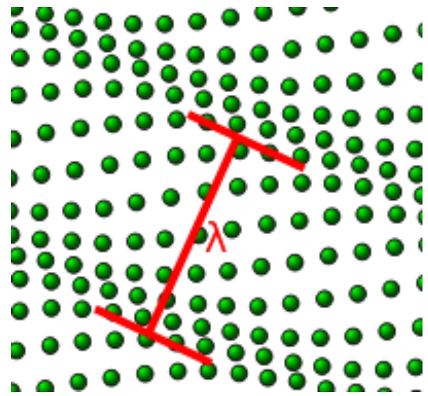
Conclusions

XLEAP Team:
SLAC
AD: A. Marinelli (project lead), J. Duris, J. MacArthur, S. Li, J. Welch, E. Kraft, M. Carrasco, A. Cedillos, K. Luchini, J. Amann, P. Krejcik, A. Fisher, A. A. Lutman, D. Bohler, M. Guetg, T. Maxwell, P. Baxevanis, Z. Huang
LCLS: M. Glownia, A. Fry, S. Vetter, P. Hering, D. Ray, T. Osipov, R. Coffee, A. Miahanari, B. Smith, J. Hastings
PULSE: J. Cryan, P. Bucksbaum

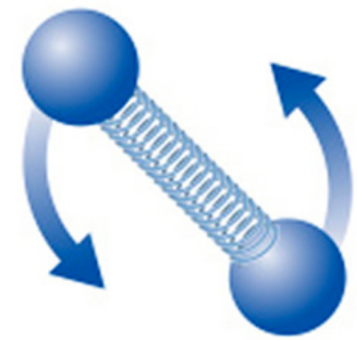
ANL
A. Zholents, J. Xu

Ultrafast Timescales

SLAC



Lattice Vibrations



Molecular Rotations

10 ps

1 ps

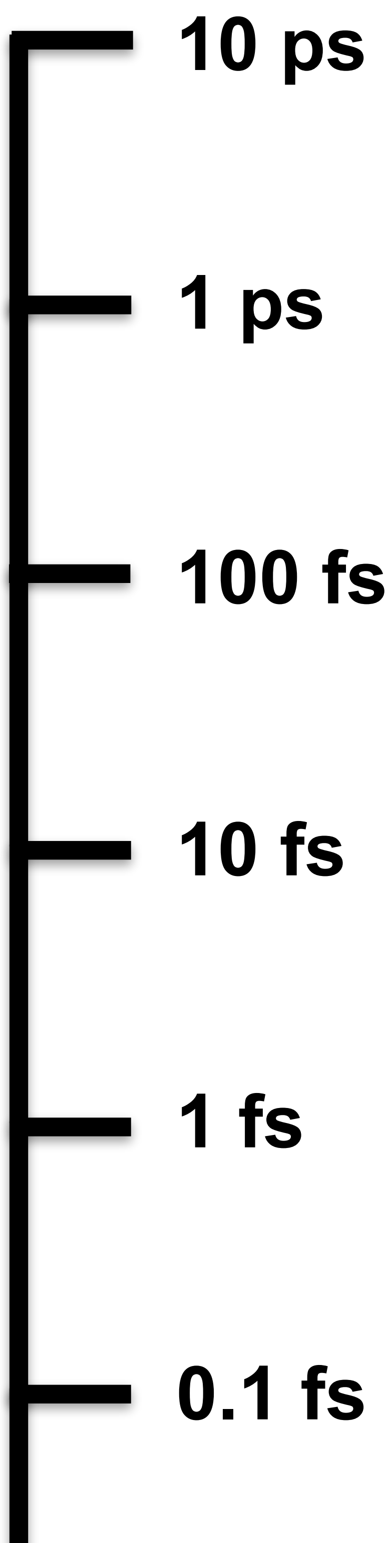
100 fs

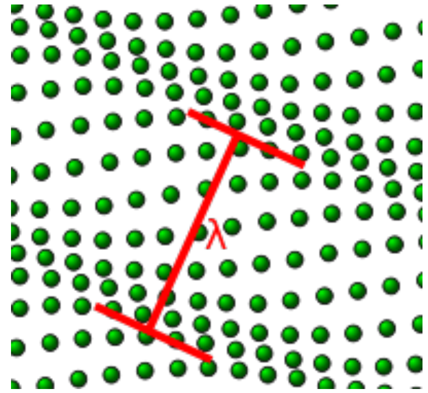
10 fs

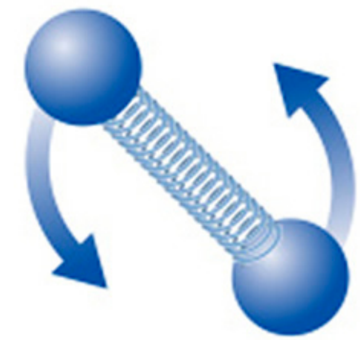
1 fs

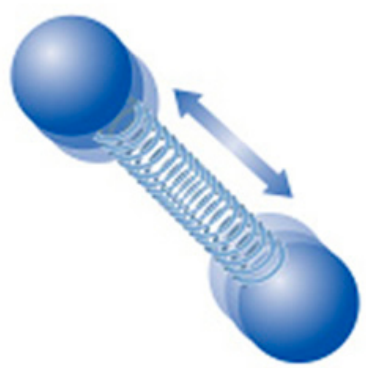
0.1 fs

Ultrafast Timescales

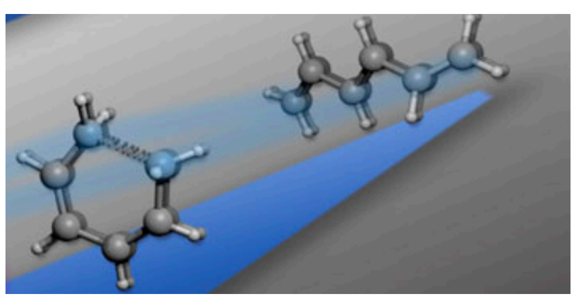








Molecular Vibrations

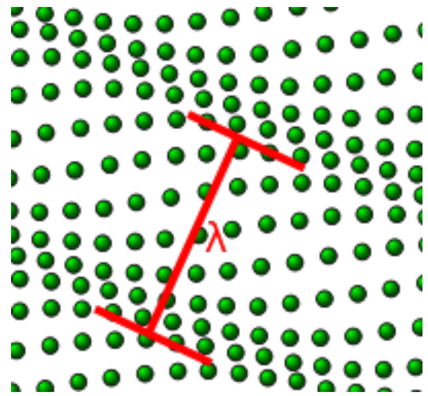


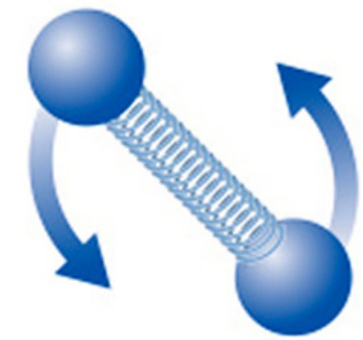
Molecular Rearrangement

Ultrafast Timescales

SLAC

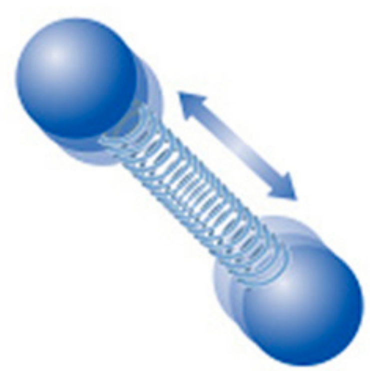
10 ps

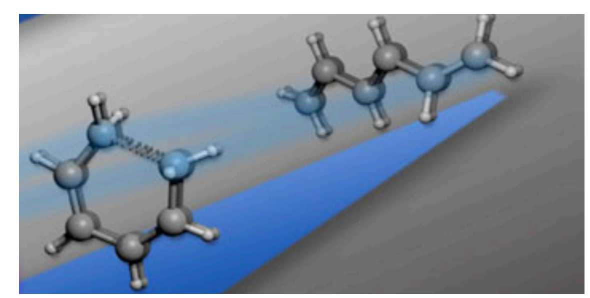




1 ps

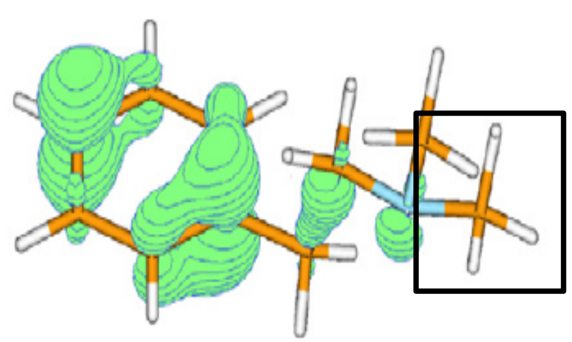
100 fs





10 fs

1 fs



0.1 fs

Valence electron motion

Ultrafast Timescales

10 ps

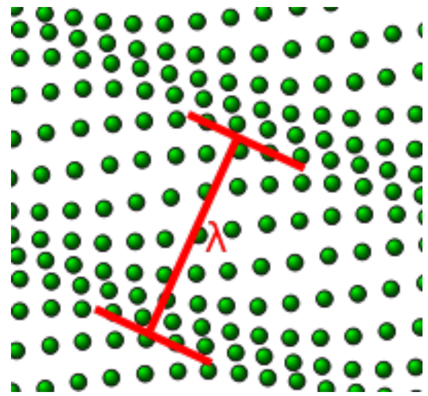
1 ps

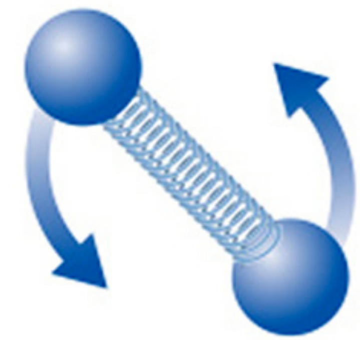
100 fs

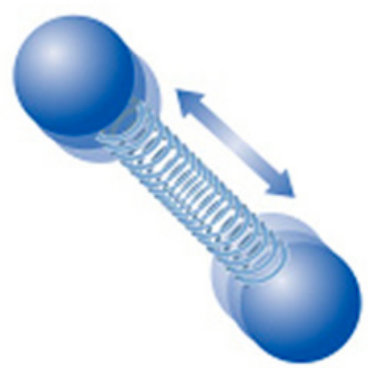
10 fs

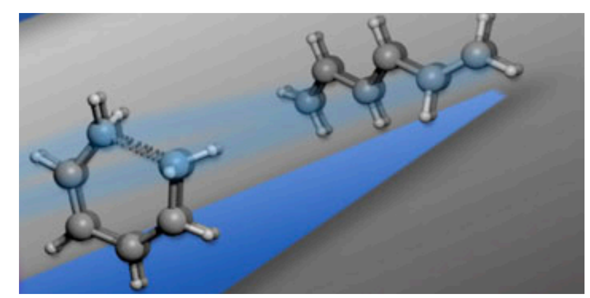
1 fs

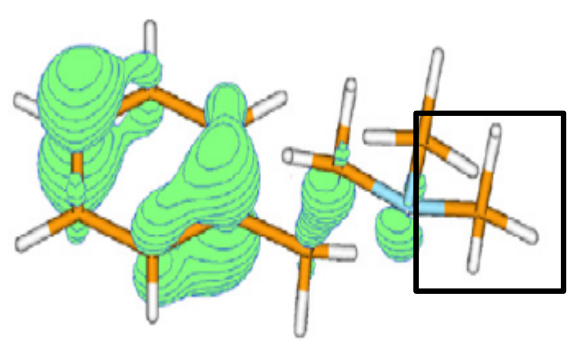
0.1 fs



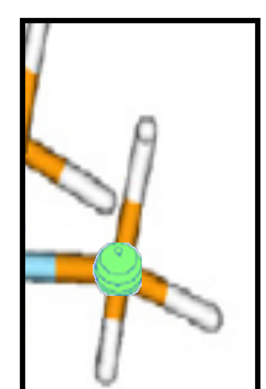








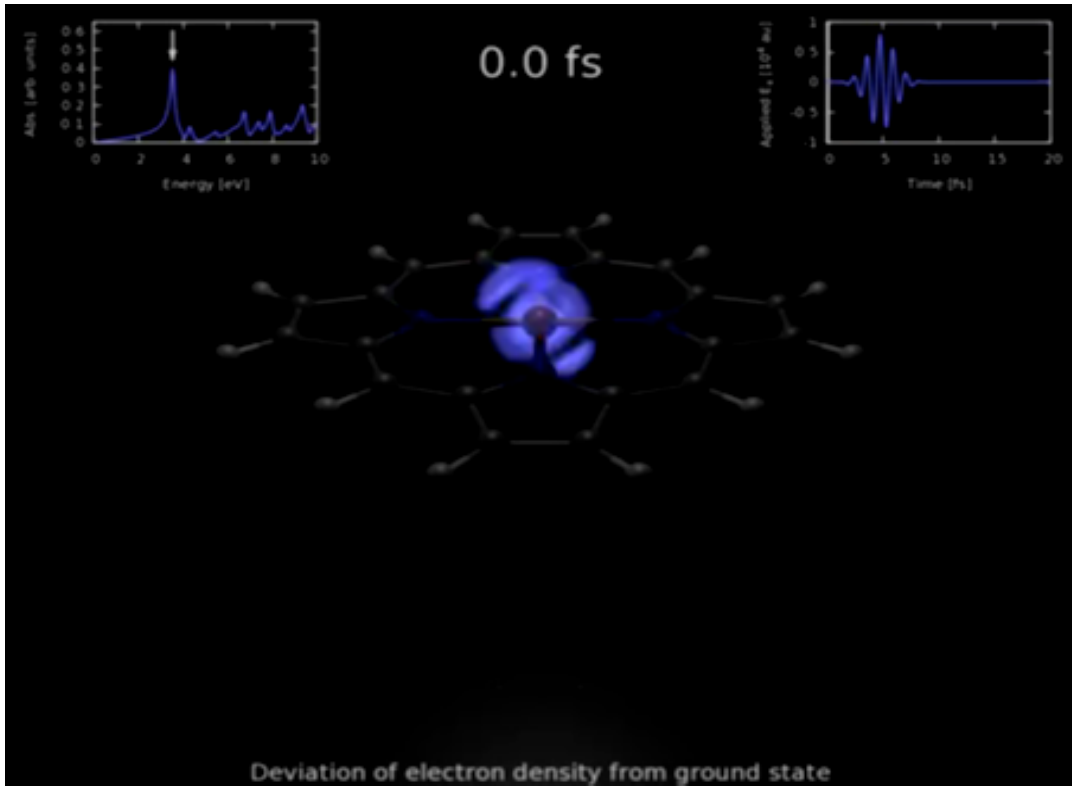
Inner electron motion



Attosecond Dynamics

Uncertainty principle

$$\sigma_E \times \sigma_T \geq \frac{\hbar}{2}$$



Important numbers:

$$\Delta E_{FWHM} = 1.9eV / \Delta T_{FWHM}(fs)$$

$$Ry \approx 13eV$$

Pulse Duration Limit in an FEL

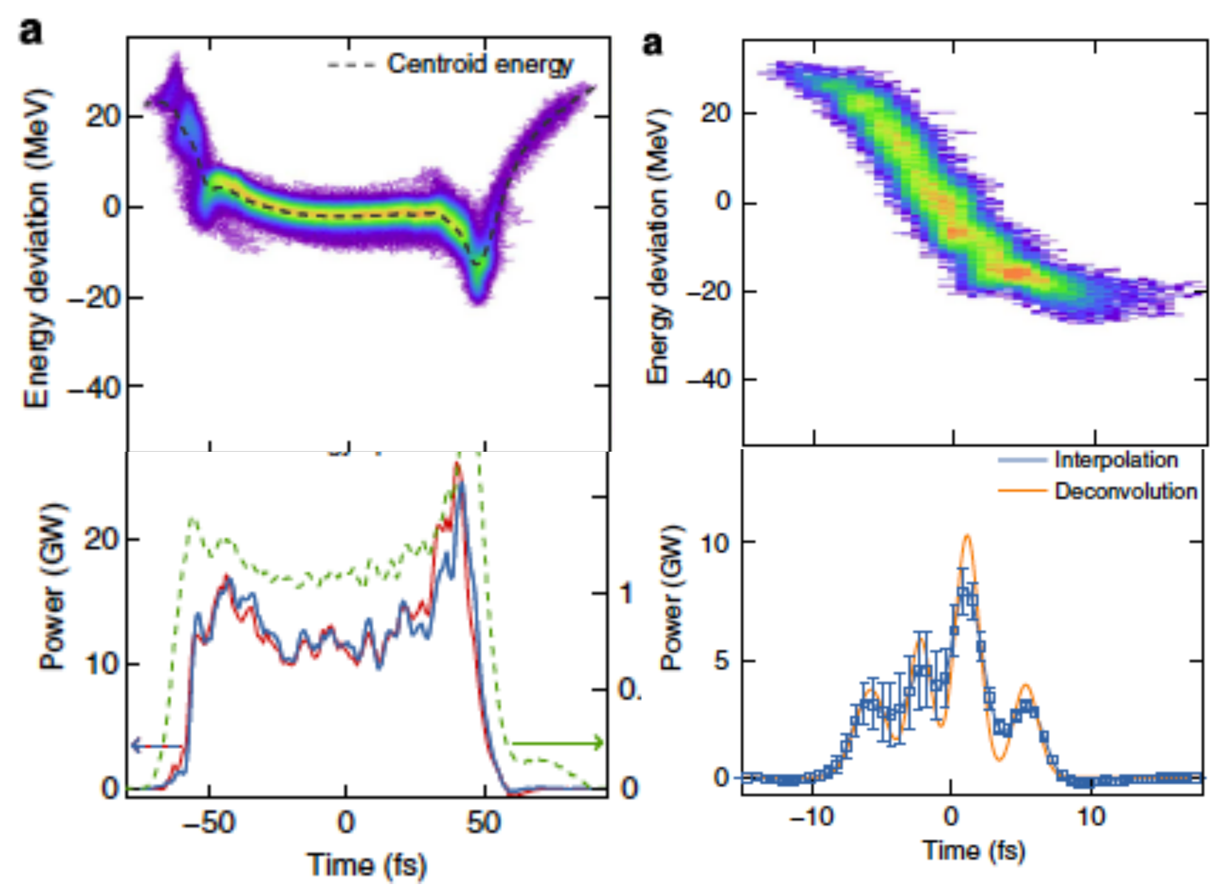
- FEL bandwidth:

$$\frac{\Delta\omega}{\omega} \approx \rho = \frac{\lambda_w}{4\pi L_g}$$

- Lower limit on pulse duration given by slippage in a gain-length:

$$L_{min} \approx \lambda_r \frac{L_g}{\lambda_w}$$

- Shortening the electron bunch decreases pulse length, but only if associated bandwidth doesn't exceed ρ.



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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]

ARTICLE

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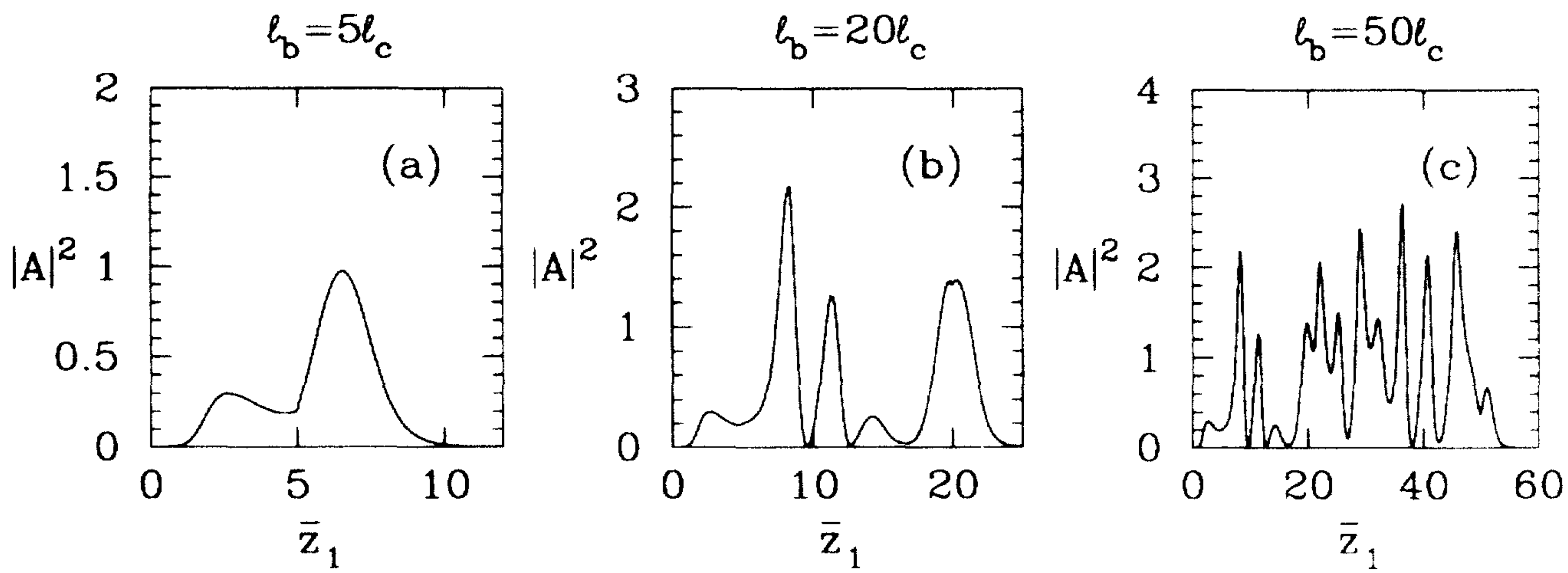
Few-femtosecond time-resolved measurements of X-ray free-electron lasers

C. Behrens[1,2], F.-J. Decker[1], Y. Ding[1], V.A. Dolgashev[1], J. Frisch[1], Z. Huang[1], P. Krejcik[1], H. Loos[1], A. Lutman[1], T.J. Maxwell[1], J. Turner[1], J. Wang[1], M.-H. Wang[1], J. Welch[1] & J. Wu[1]

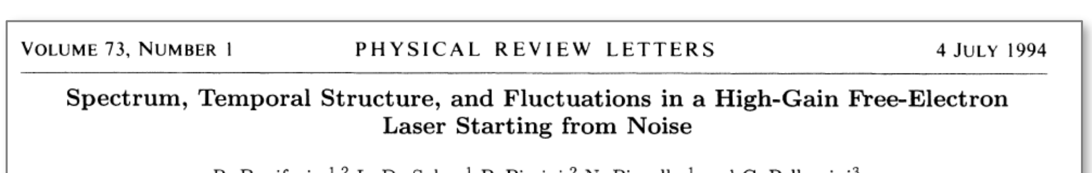
Temporal Structure of SASE FELs



FEL pulse starting from noise composed of many uncorrelated spikes

Spike duration ~ $l_c = \lambda_r \frac{L_g}{\lambda_w}$

Single-spike limit is shortest pulse achievable with SASE FELs.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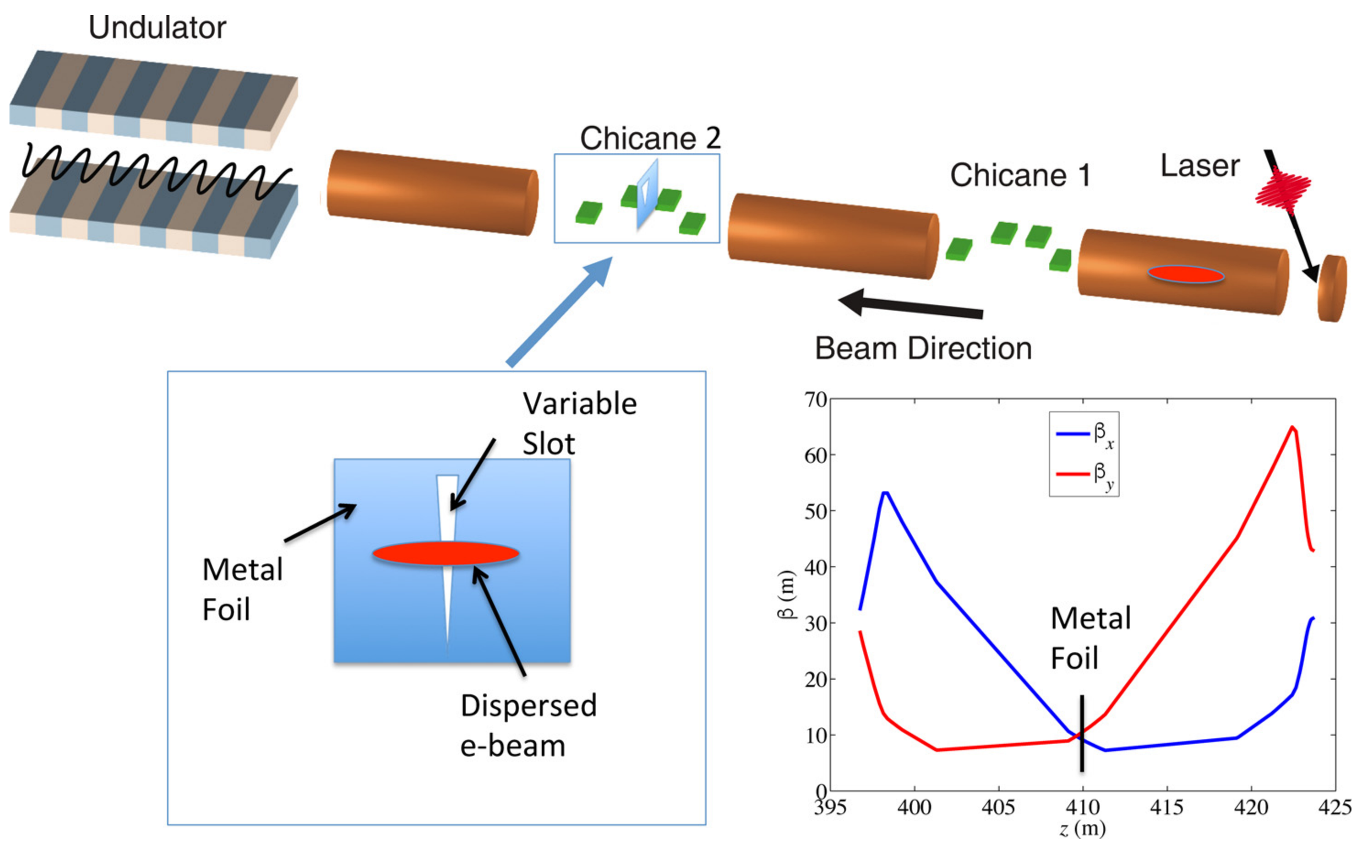
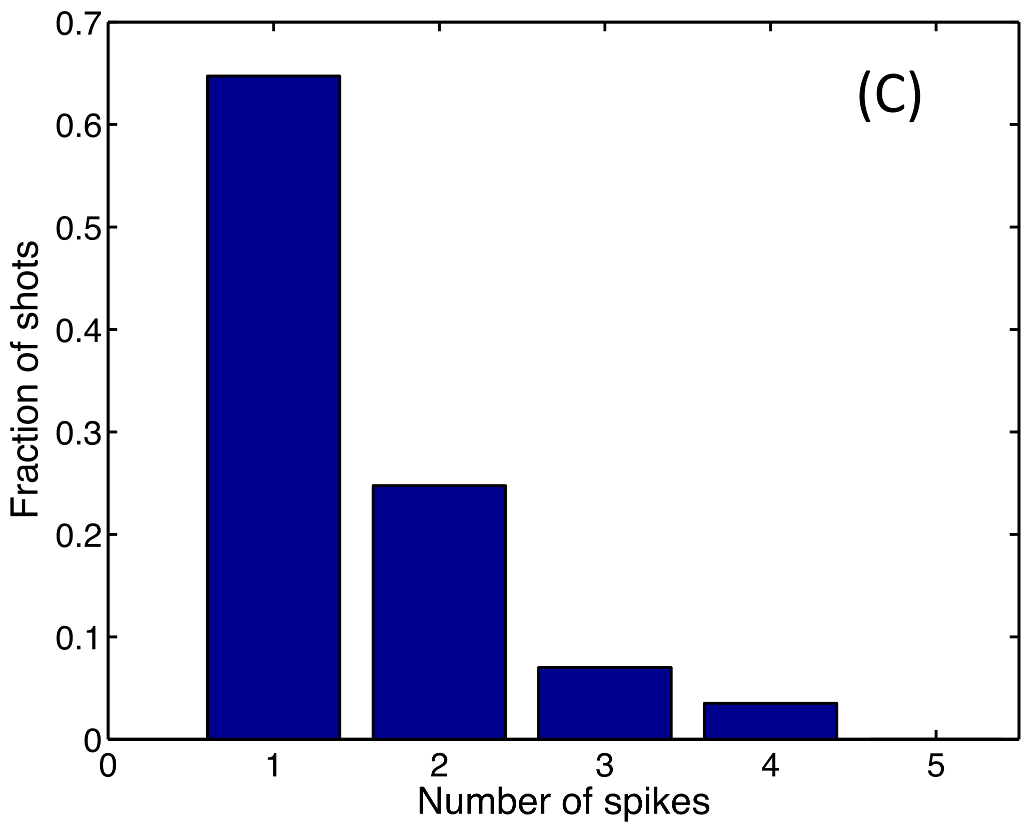
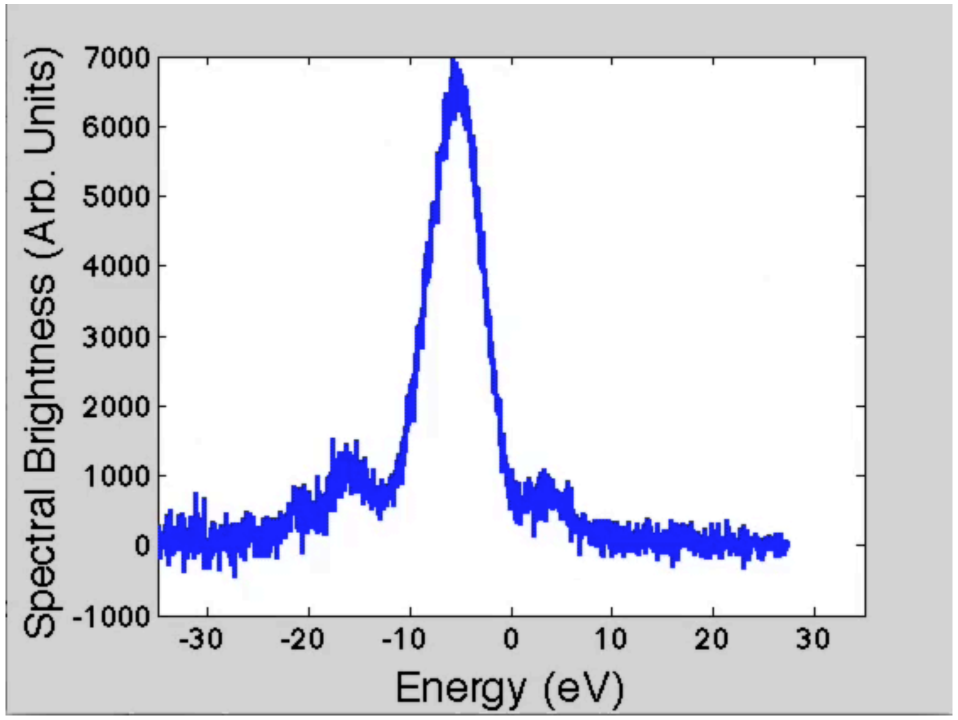
R. Bonifacio,[1,2] L. De Salvo,[1] P. Pierini,[2] N. Piovella,[1] and C. Pellegrini[3]

Single Spike Operation at 6keV



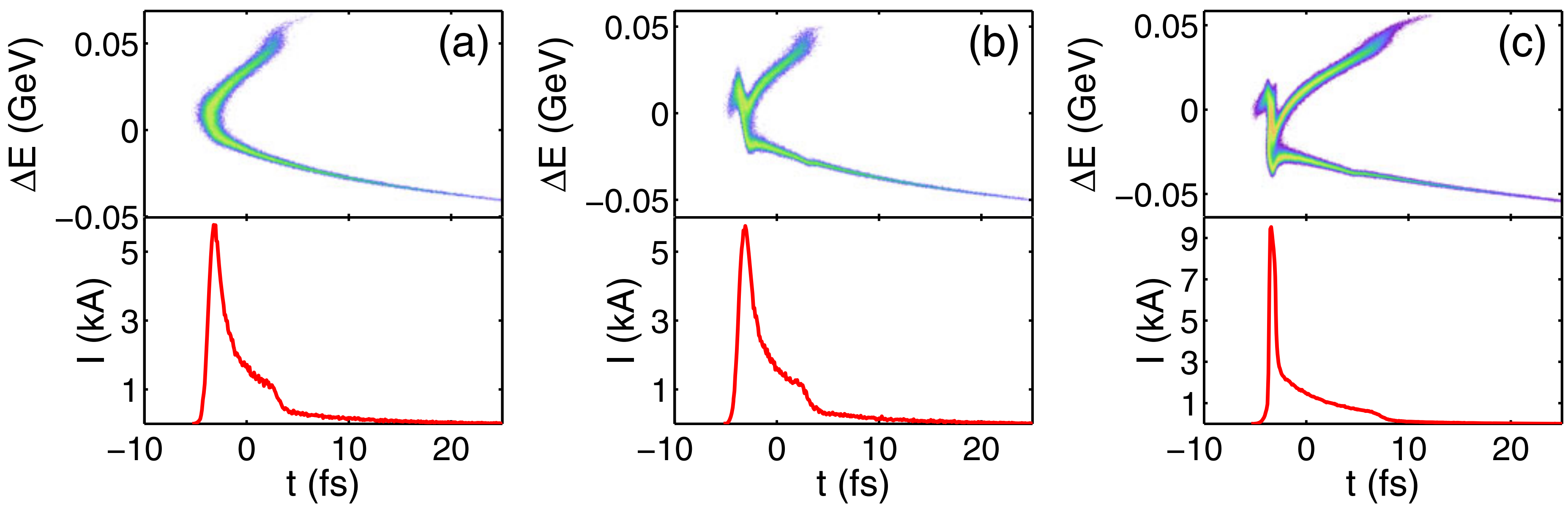


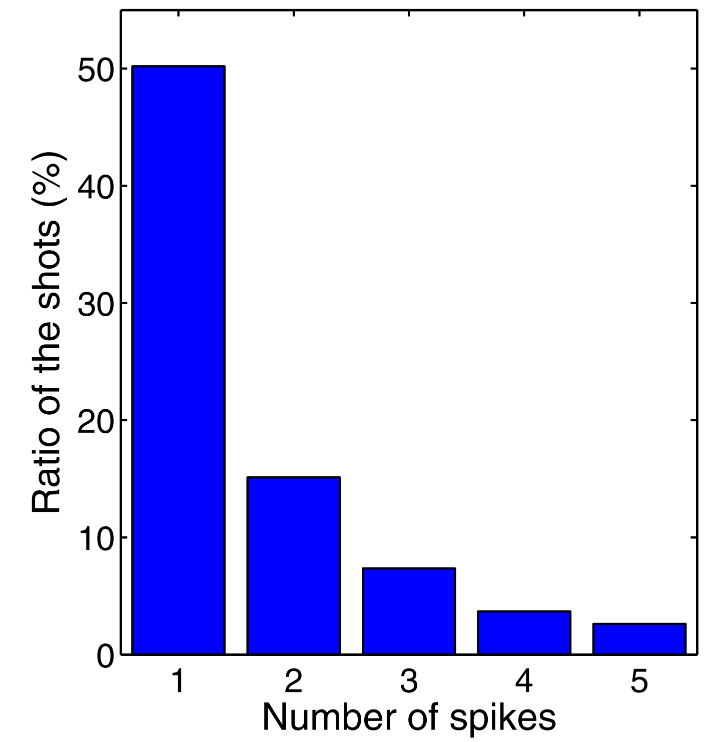


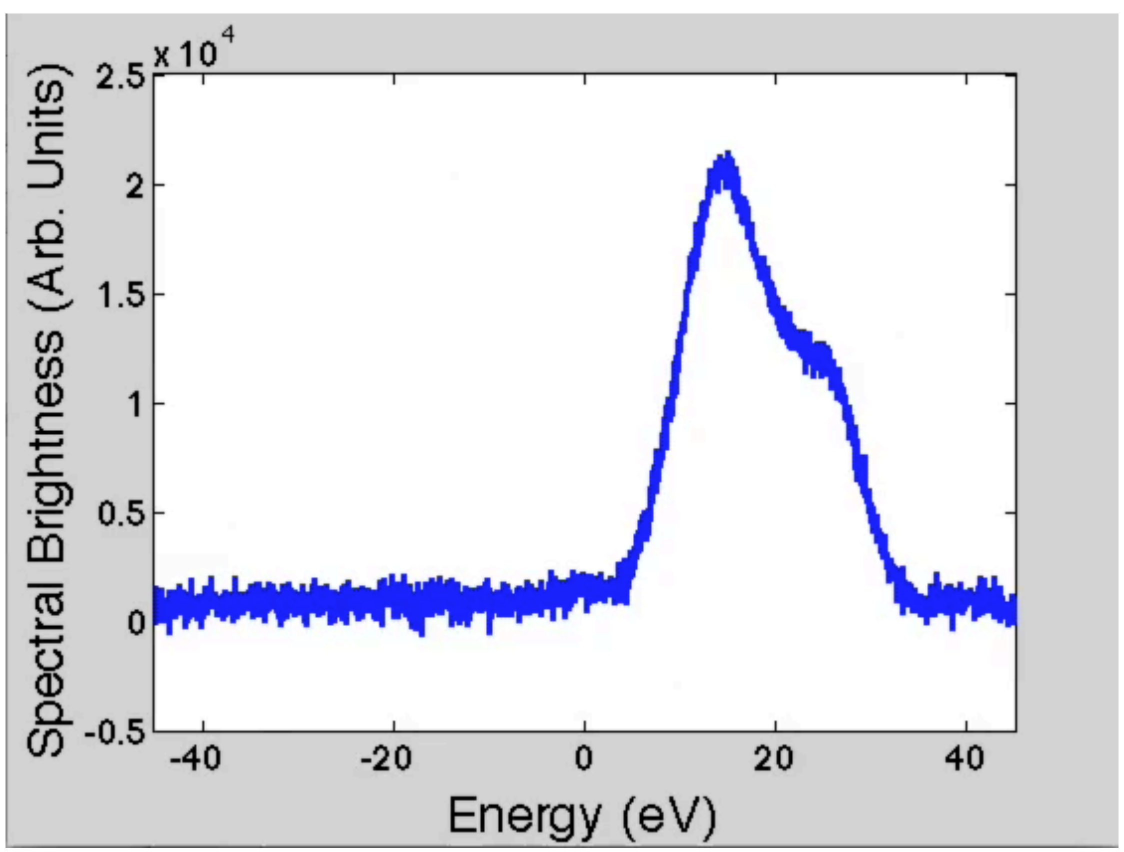
4.5 eV Bandwidth FWHM
DT ~ 400 as (estimated)
Pulse Energy ~ 10 uJ

A. Marinelli et al. Appl. Phys. Lett. ***111****, 151101 (2017)*

Single Spike Operation at 6keV



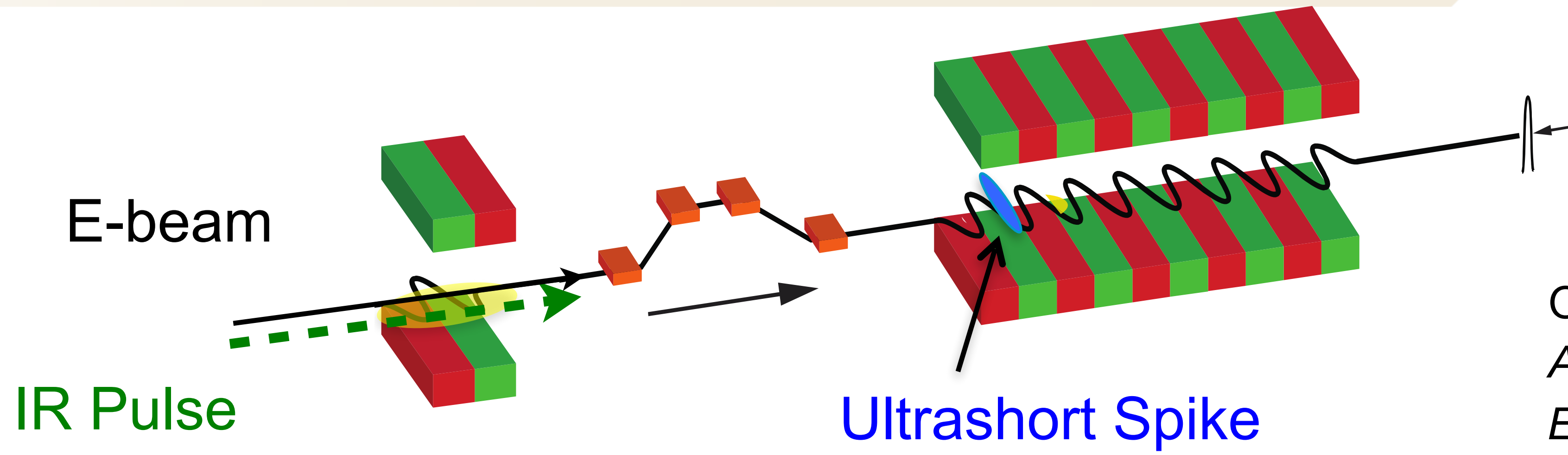




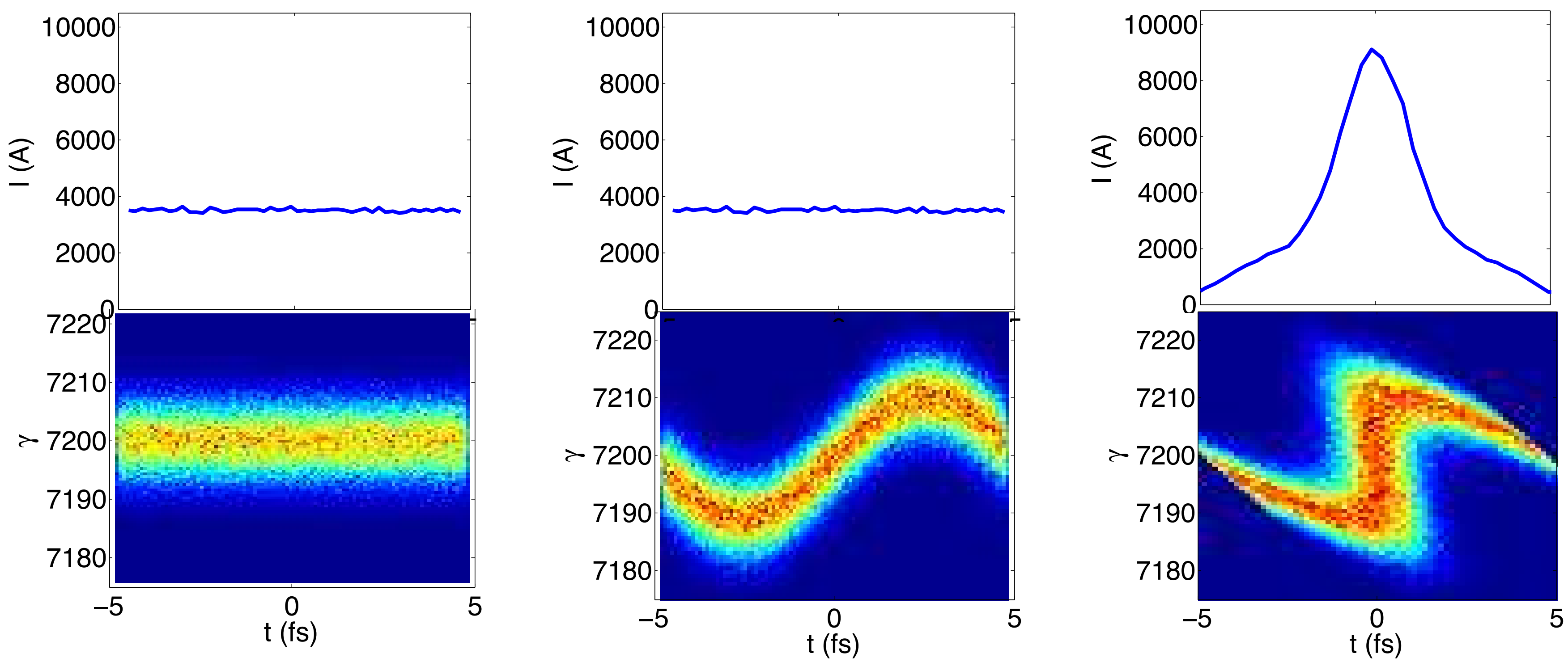
7 eV Bandwidth (FWHM)
DT ~ 250 as (estimated)
Pulse Energy ~ 10 uJ

S. Huang et al. Phys. Rev. Lett. ***119****, 154801 (2017)*

XLEAP: X-Ray Laser-Enhanced Attosecond Pulse Generation



Original concept:
A. Zholents PRSTAB (2005)
E. Saldin PRSTAB (2006)



IR pulse compression -> High current, beam quality preserved
Short cooperation length

Bandwidth Broadening

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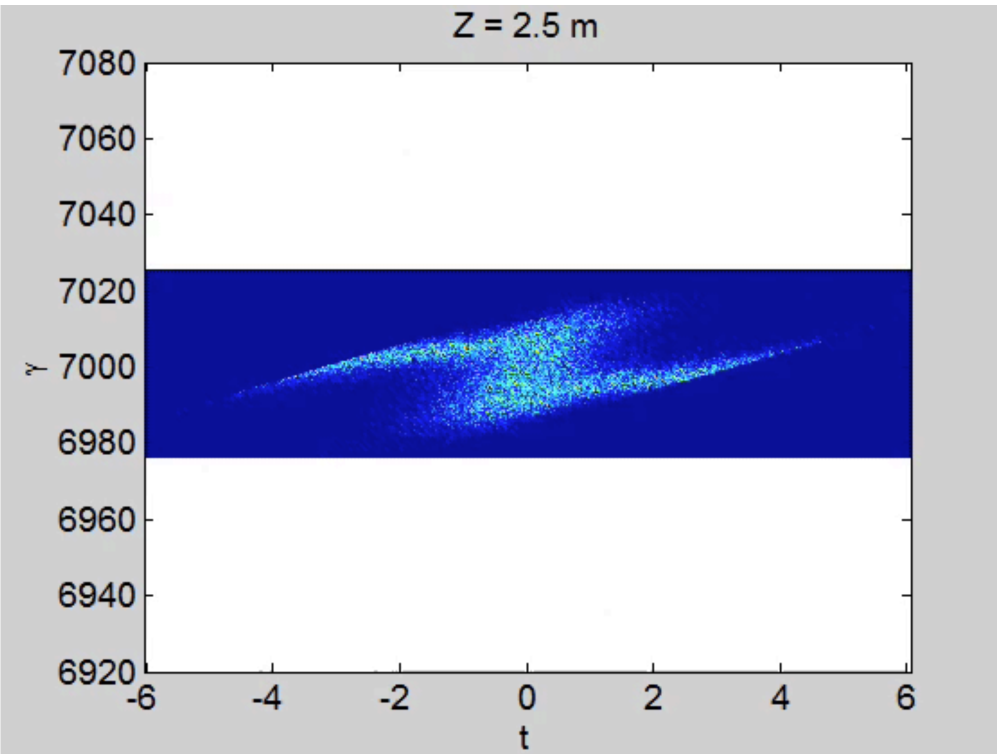
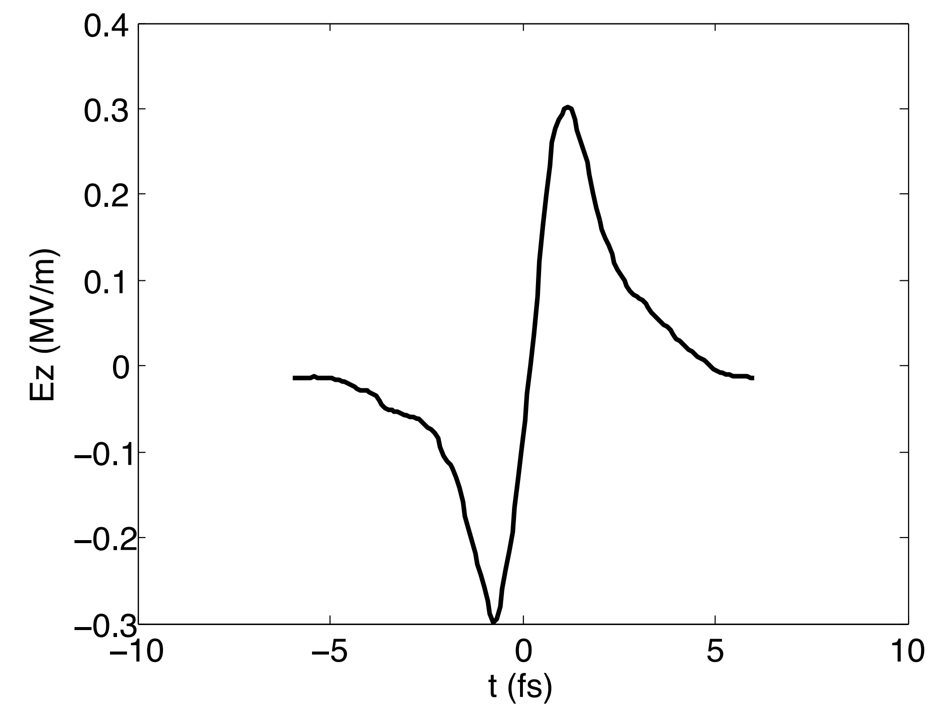
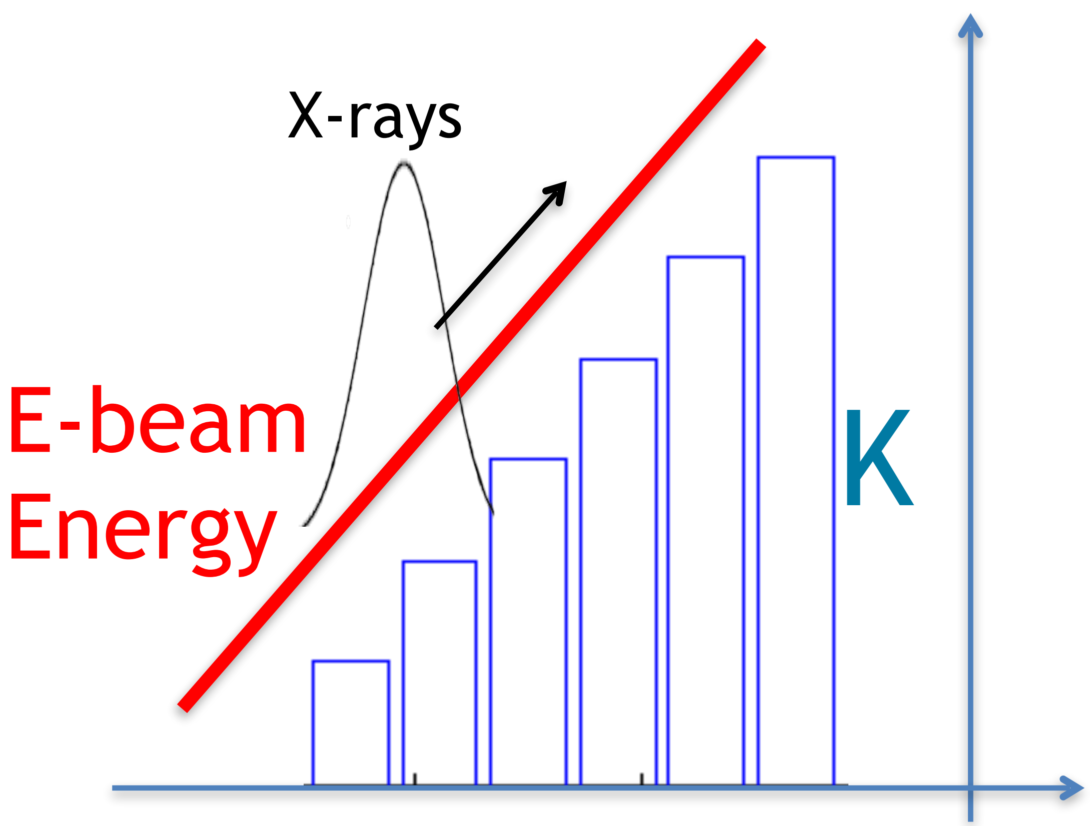


$$E_z \propto I' \frac{K^2}{\gamma^2}$$

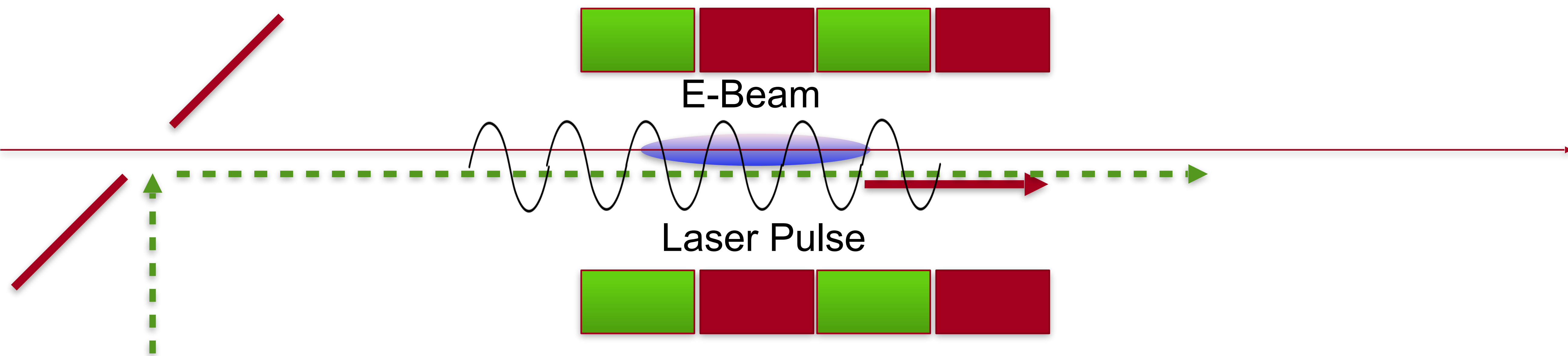


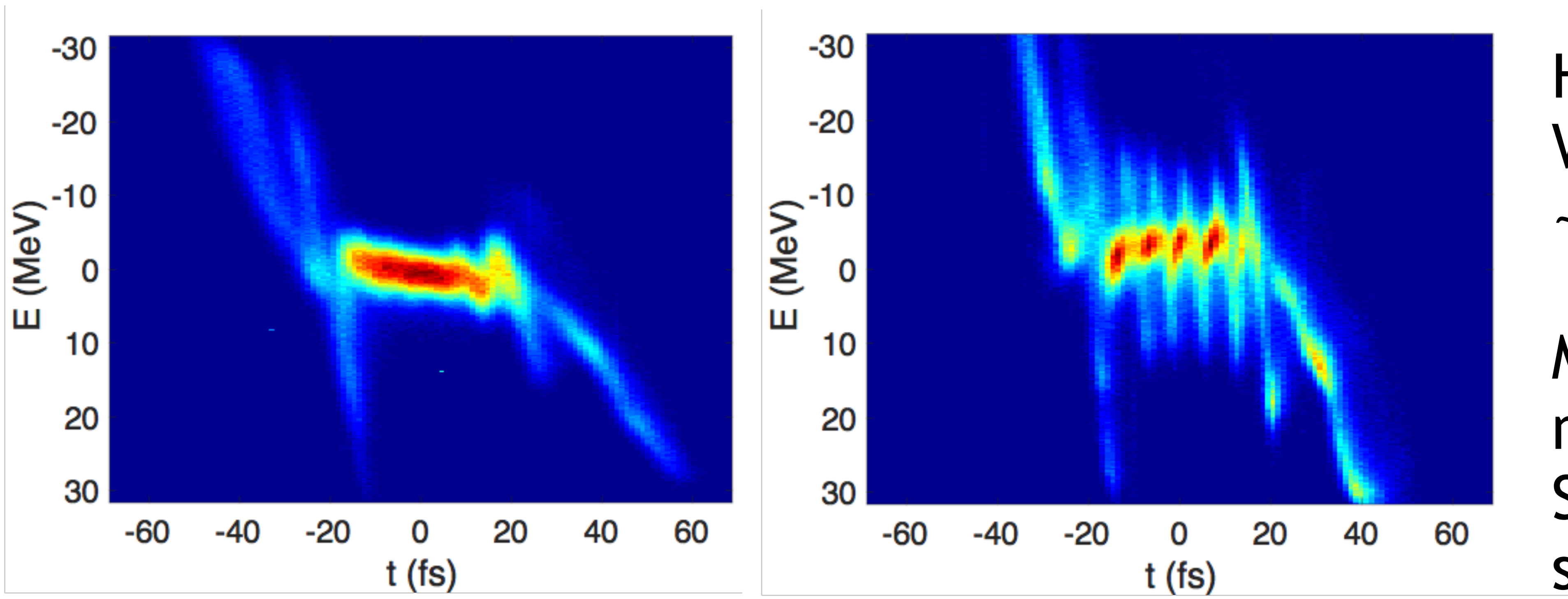


Linear chirp compensated by taper: chirped X-rays broad bandwidth.
(Z. Huang et al.)

Third order chirp contributes to pulse shortening…
(P. Baxevanis, Z. Huang and A. Marinelli, in preparation)

Laser Modulation

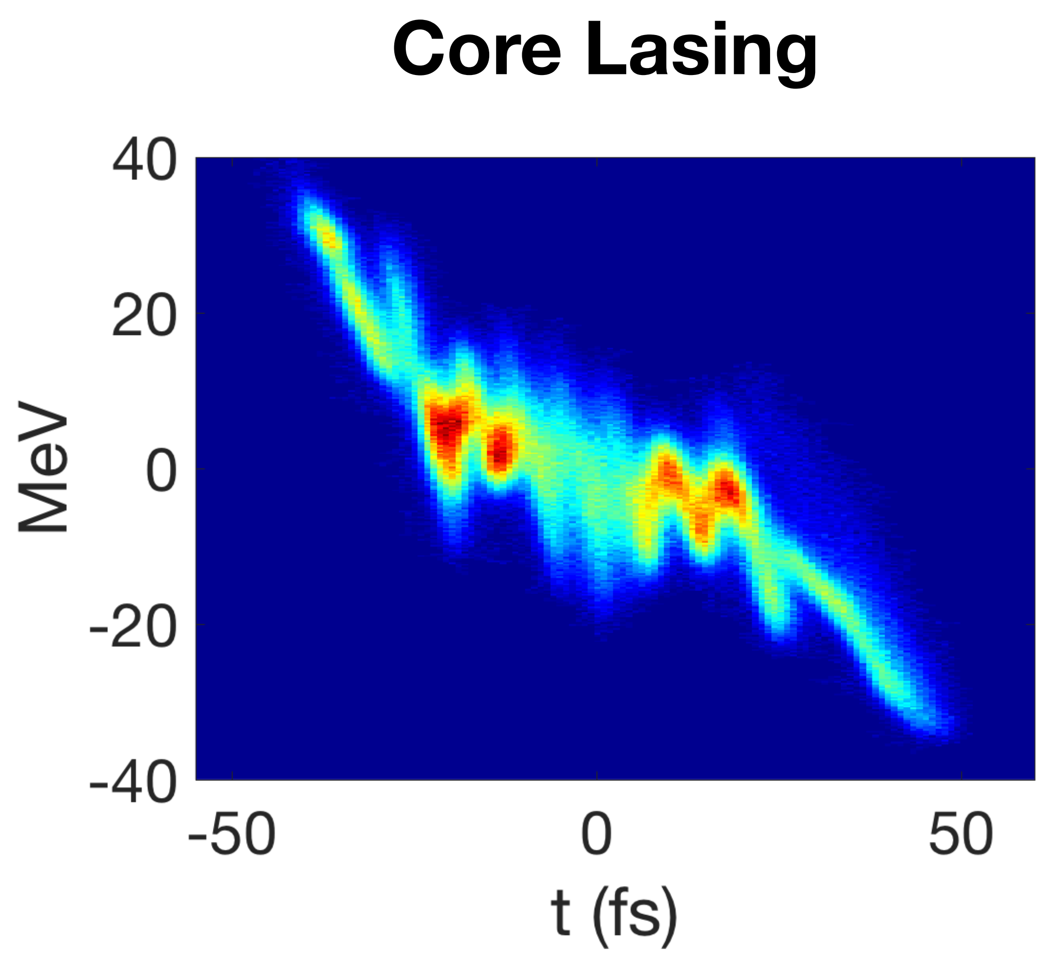


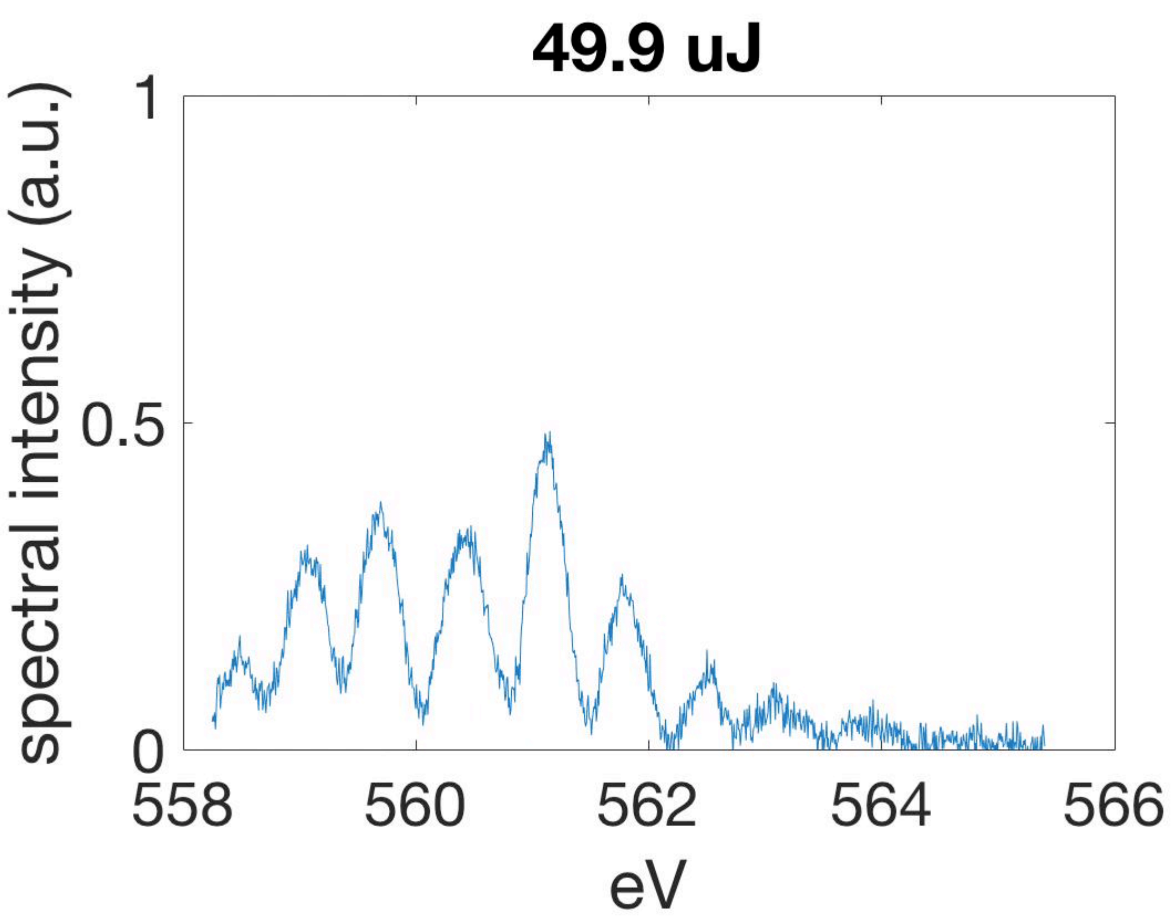


Ho:YLF laser
Wavelength = 2 um
~20 mJ in 3 ps

Multi-cycle modulation.
Several high-current spikes

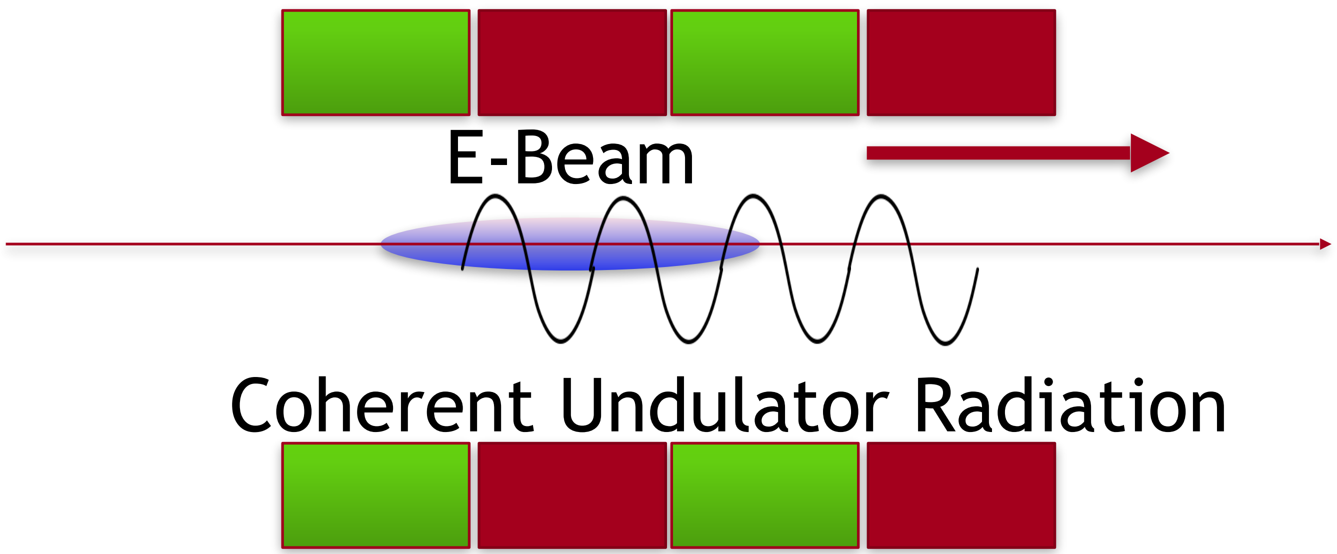
Broad, 560 eV Spectra From Laser Modulation





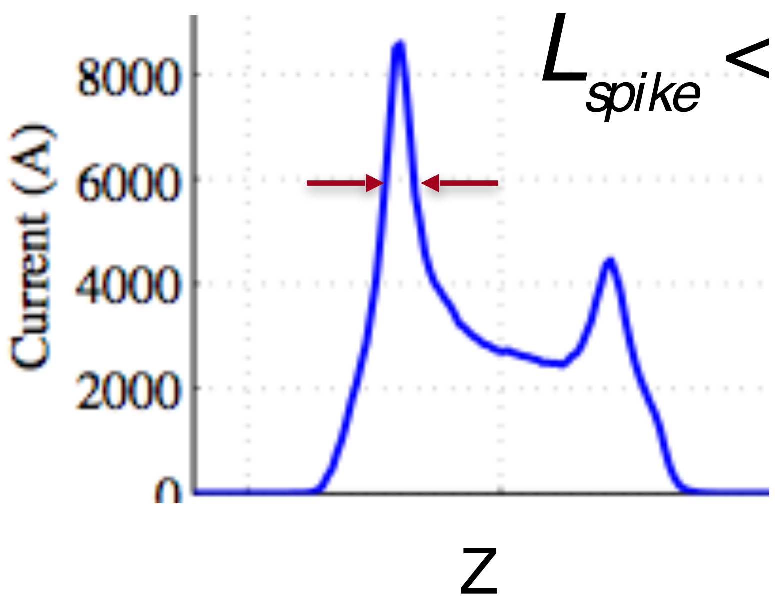
- Spectra show wide 2-4 eV shape. Up to 50 uJ per pulse (50 uJ / 1 fs = 50 GW)
- Periodic modulation at ~ 0.6 eV indicates 2 adjacent pulses are interfering

Self-Modulation

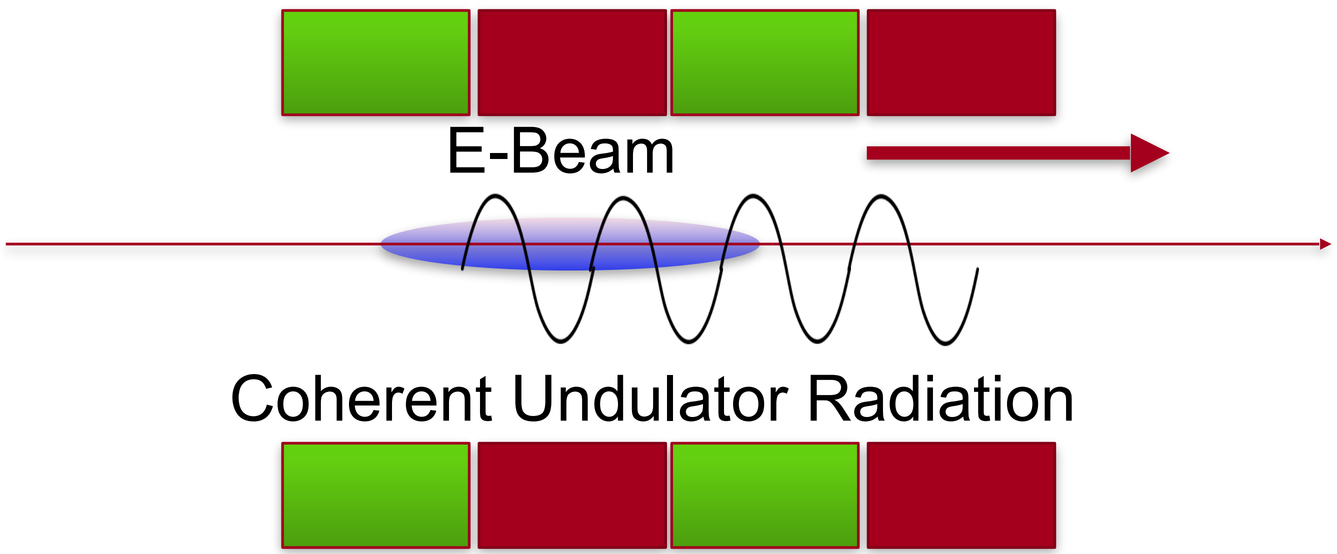


Tail spike

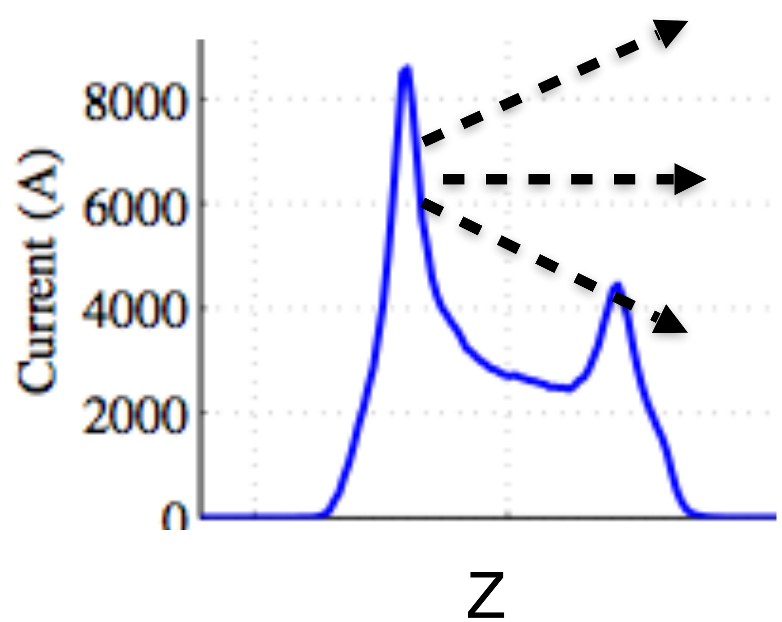
$L_{spike} << \lambda_{rad}$



Self-Modulation



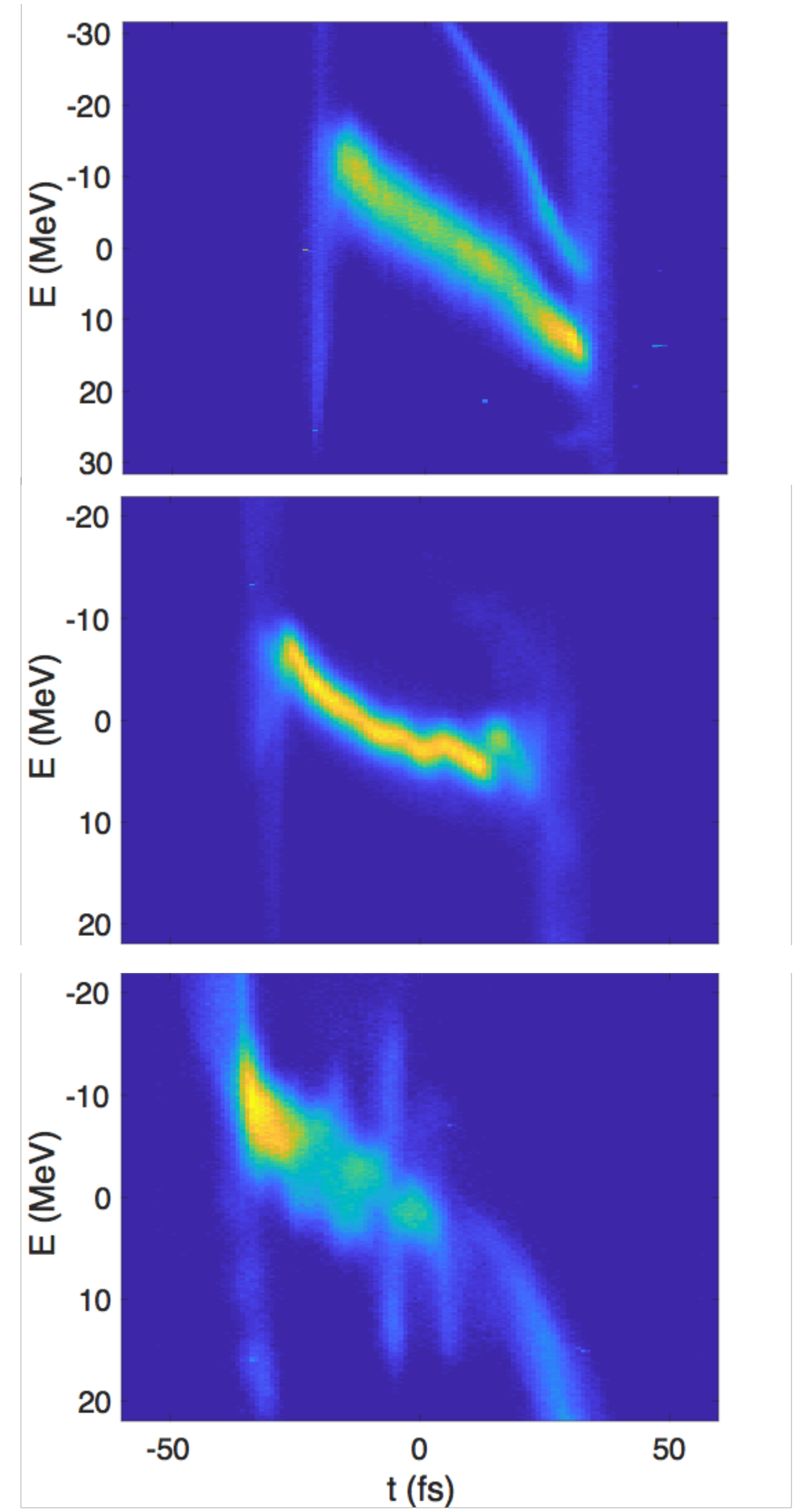
Coherent Undulator Radiation



Wiggler OUT
Chicane OFF

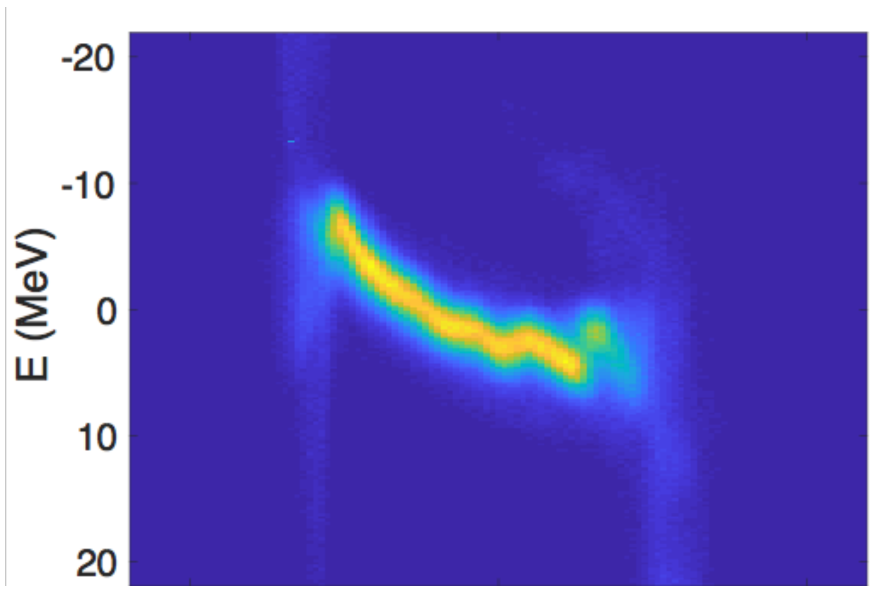
Wiggler IN
Chicane OFF

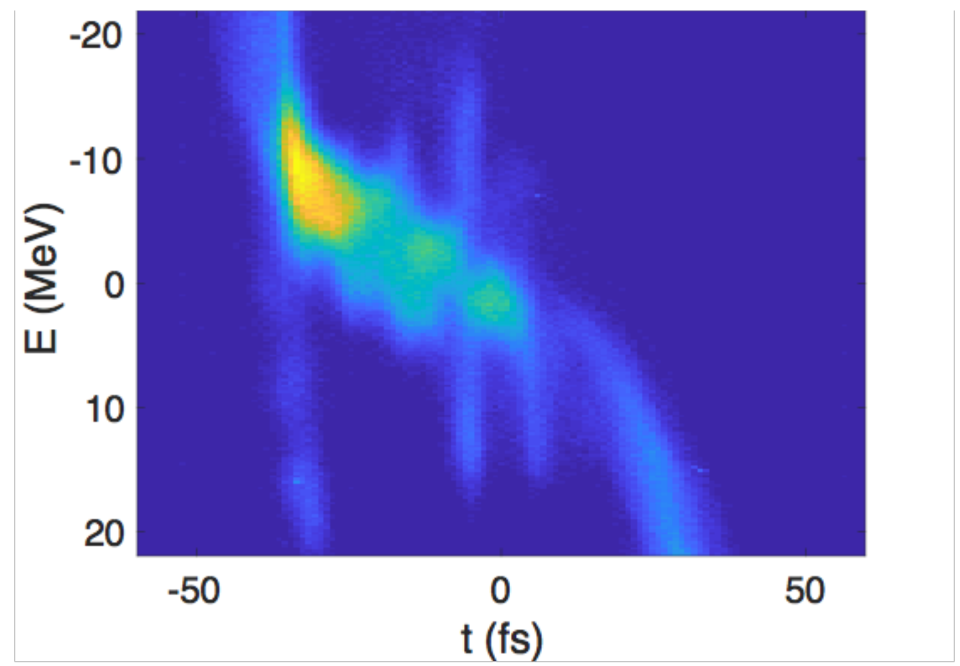
Wiggler IN
Chicane ON



$L_{RAYLEIG} << \lambda_{WIGGLER}$ -> Quasi single-cycle modulation

Self-Modulation





Emission from current horn: CEP stable modulation!

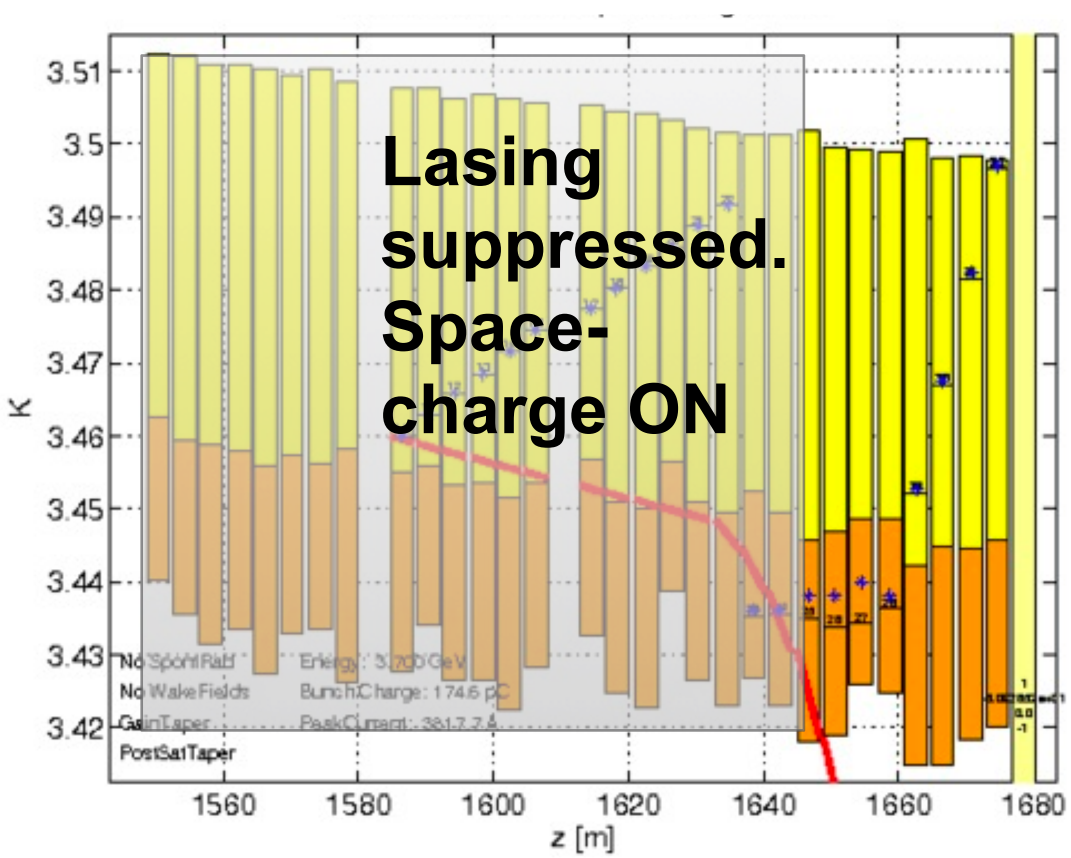
Diffraction dominated emission: Quasi single-cycle modulation!

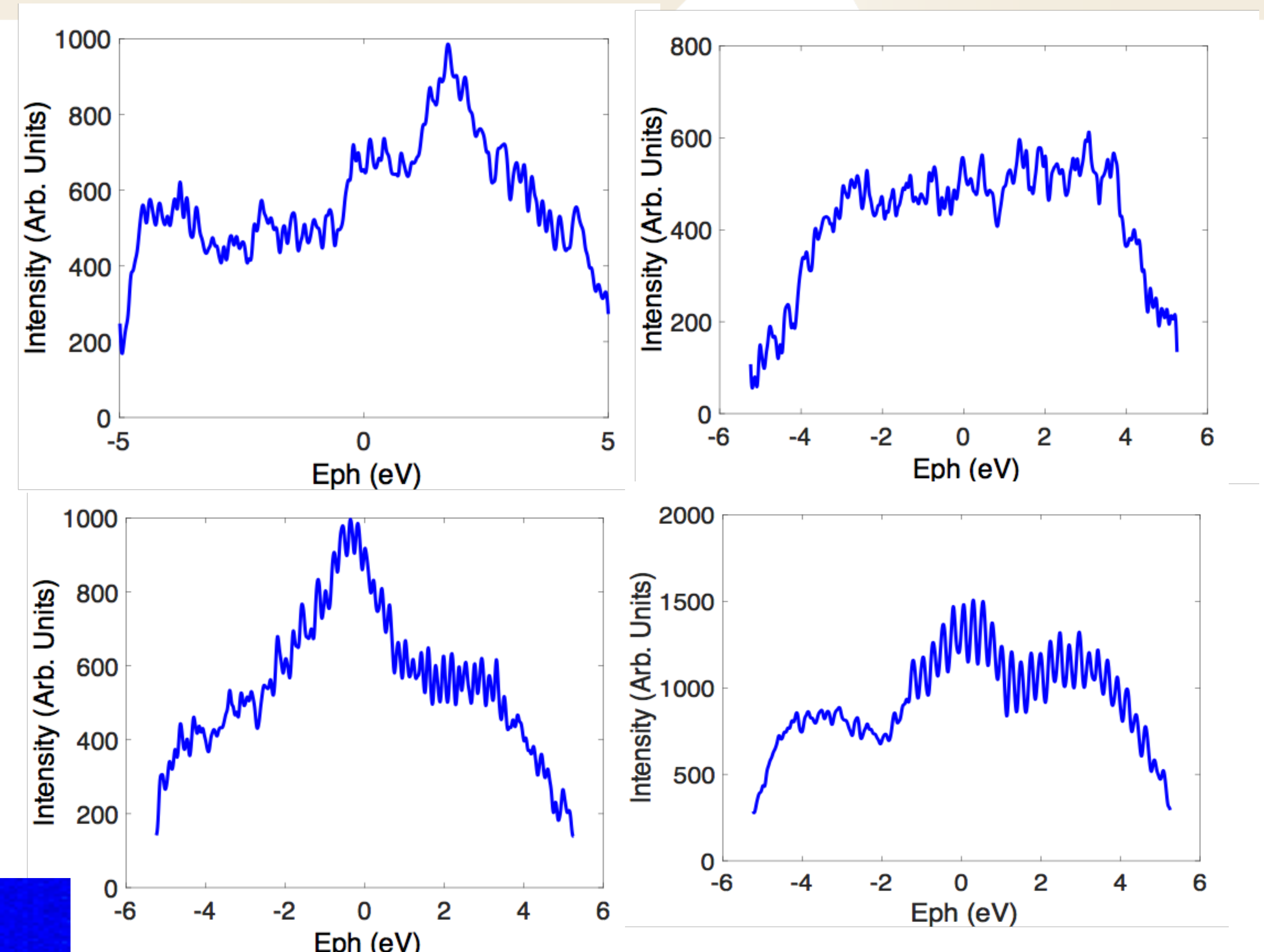
Easily scalable to LCLS-II rep rate.

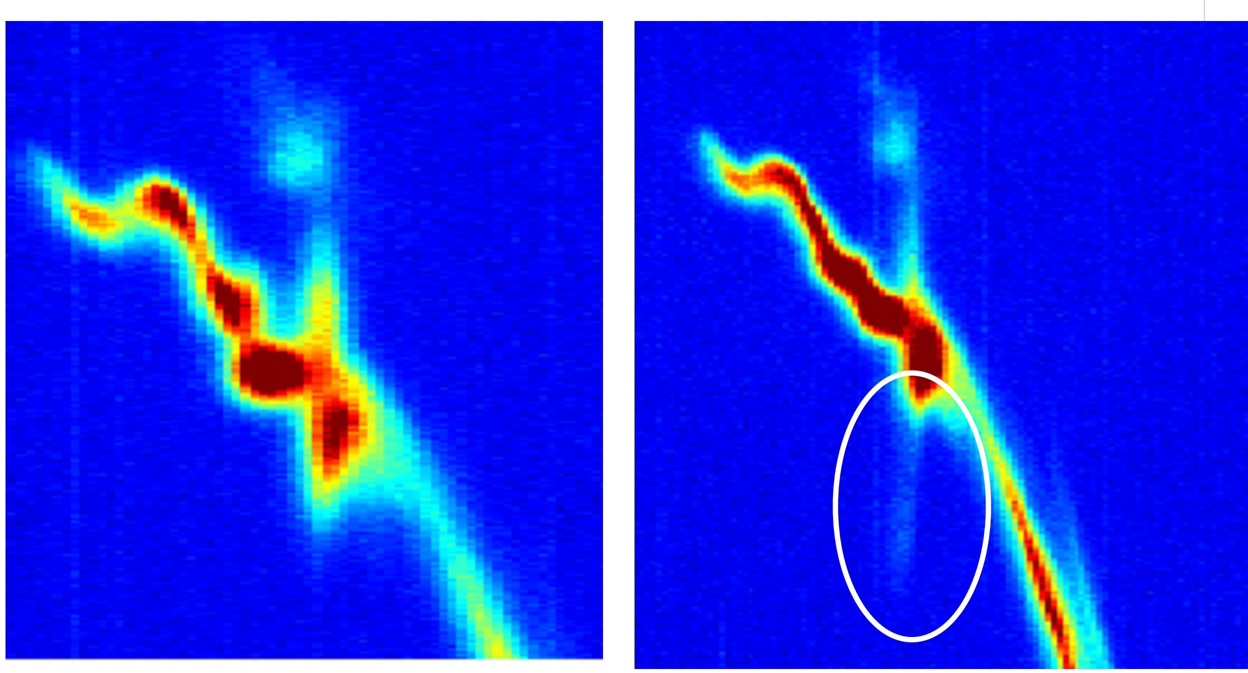
Naturally aligned and timed to e-beam!

MOST IMPORTANT RESULT FROM THIS PROJECT!

650 eV Spectra







25 uJ Average Pulse Energy
5.5 eV Average BW

Bandwidth, pulse energy and saturation length constistent with start-to-end simulations giving 0.5 fs duration

Comparison With Single-Spike SASE

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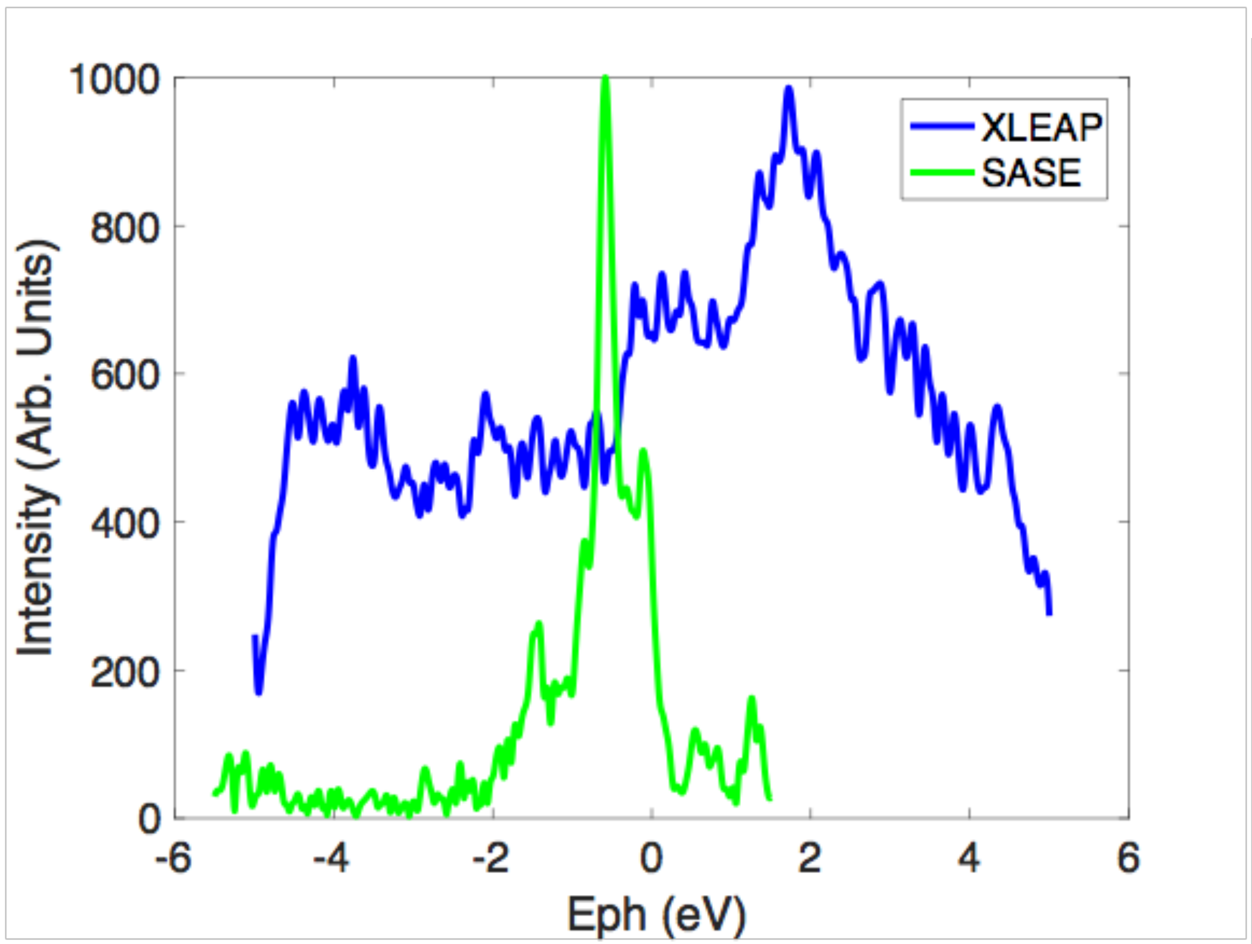
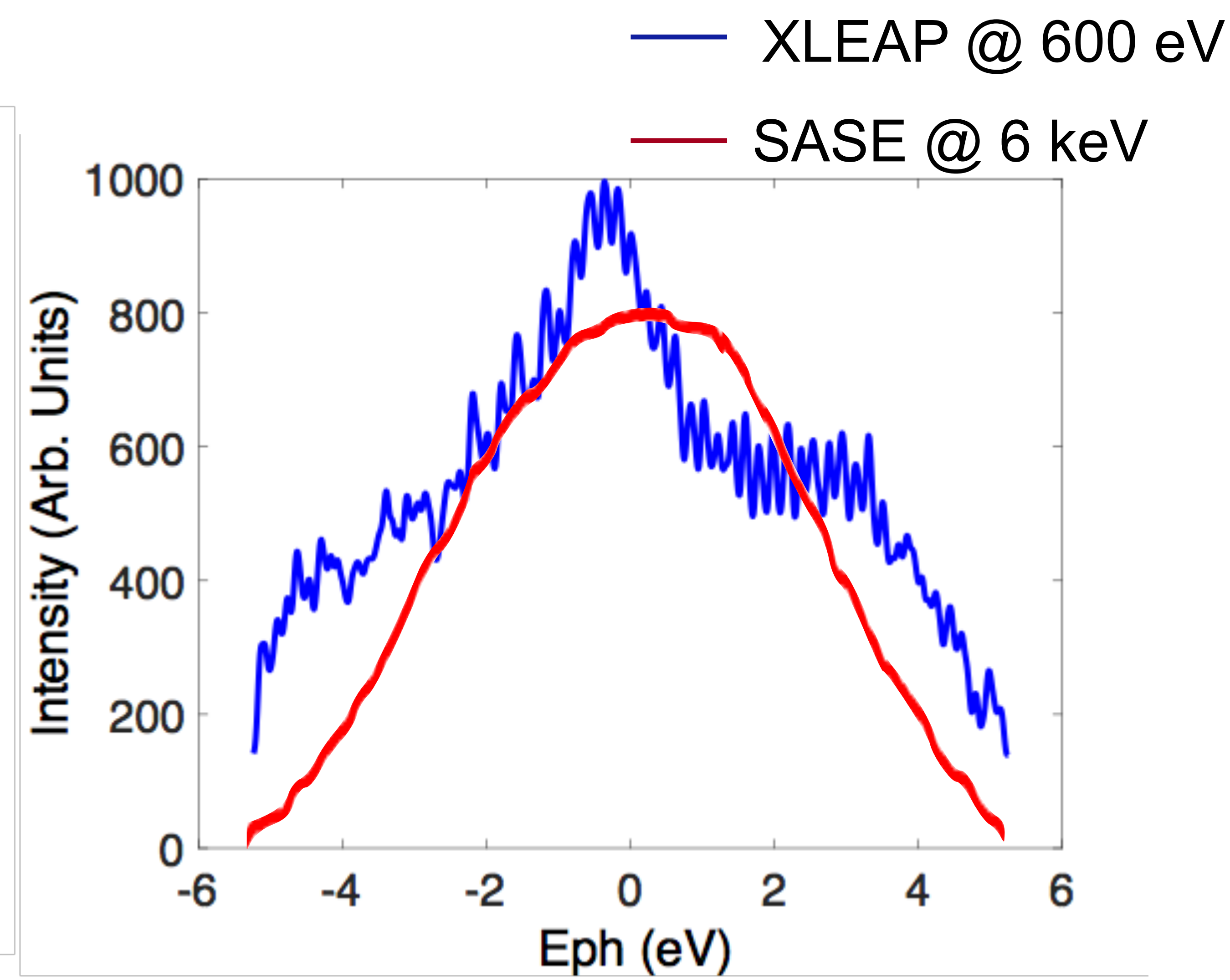
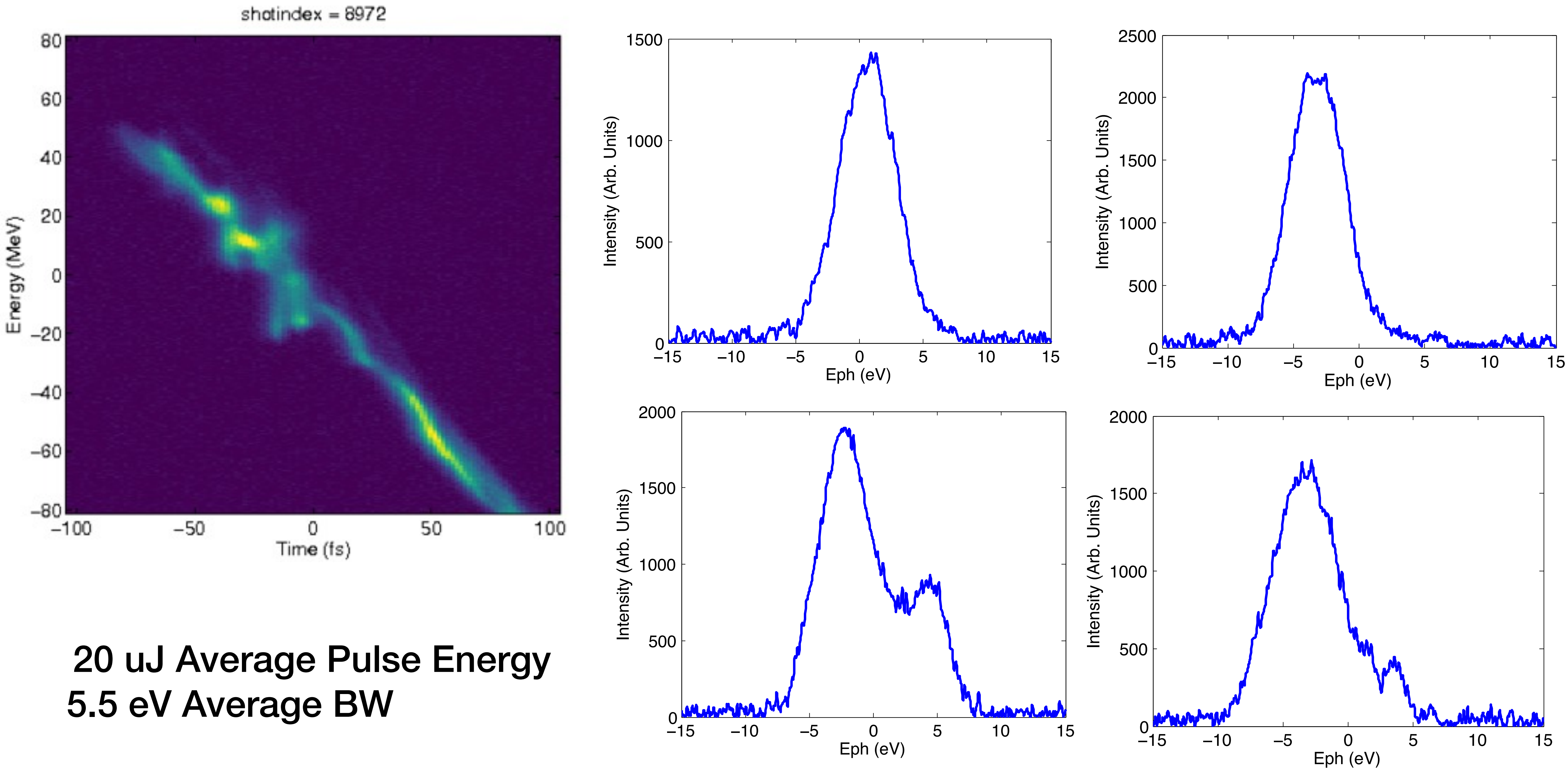




- ~ 6 times broader than single-spike SASE at similar energy

- Broader than SASE bandwidth at HXR!

900 eV Spectra

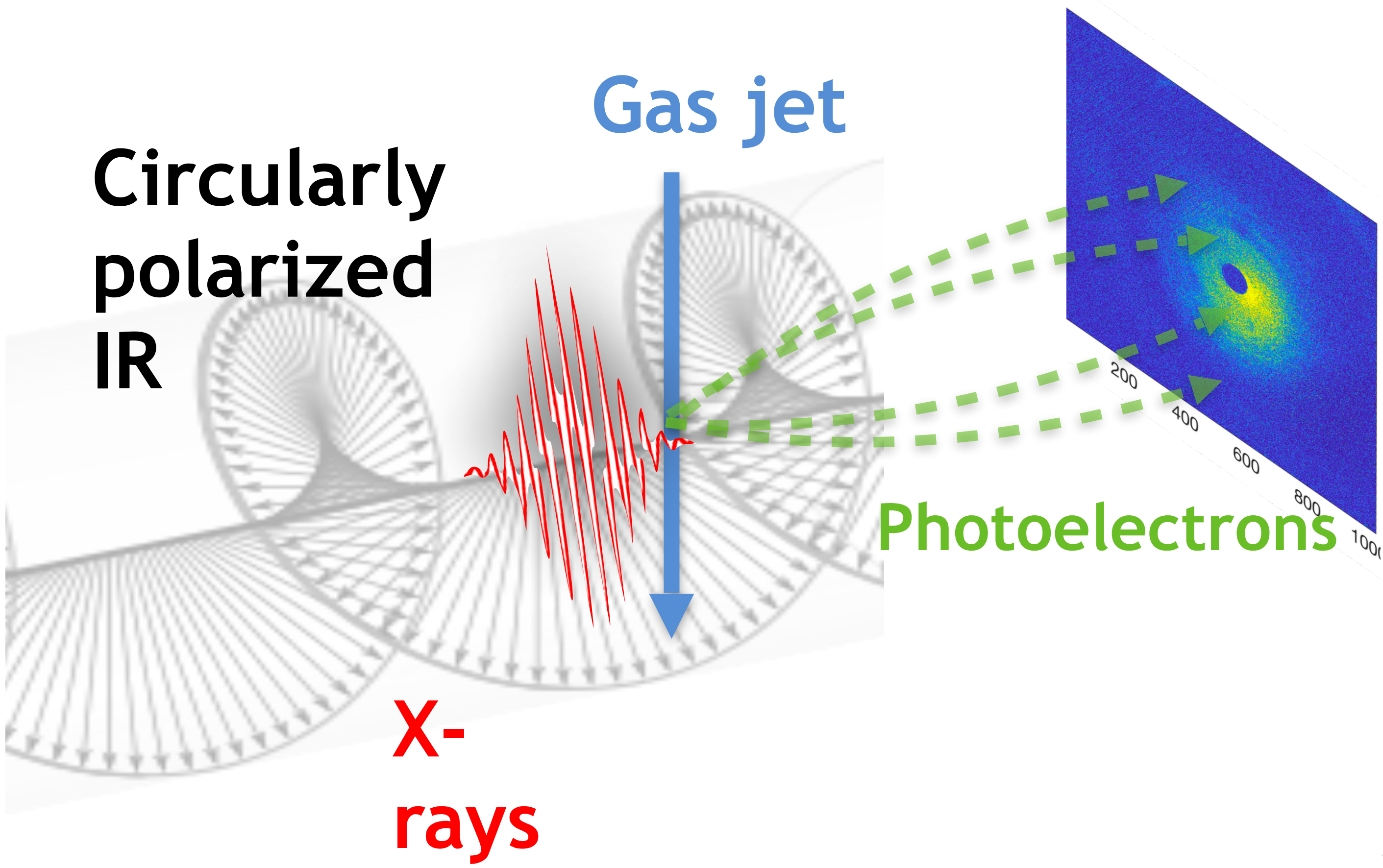


20 uJ Average Pulse Energy
5.5 eV Average BW

Results vs Photon Energy

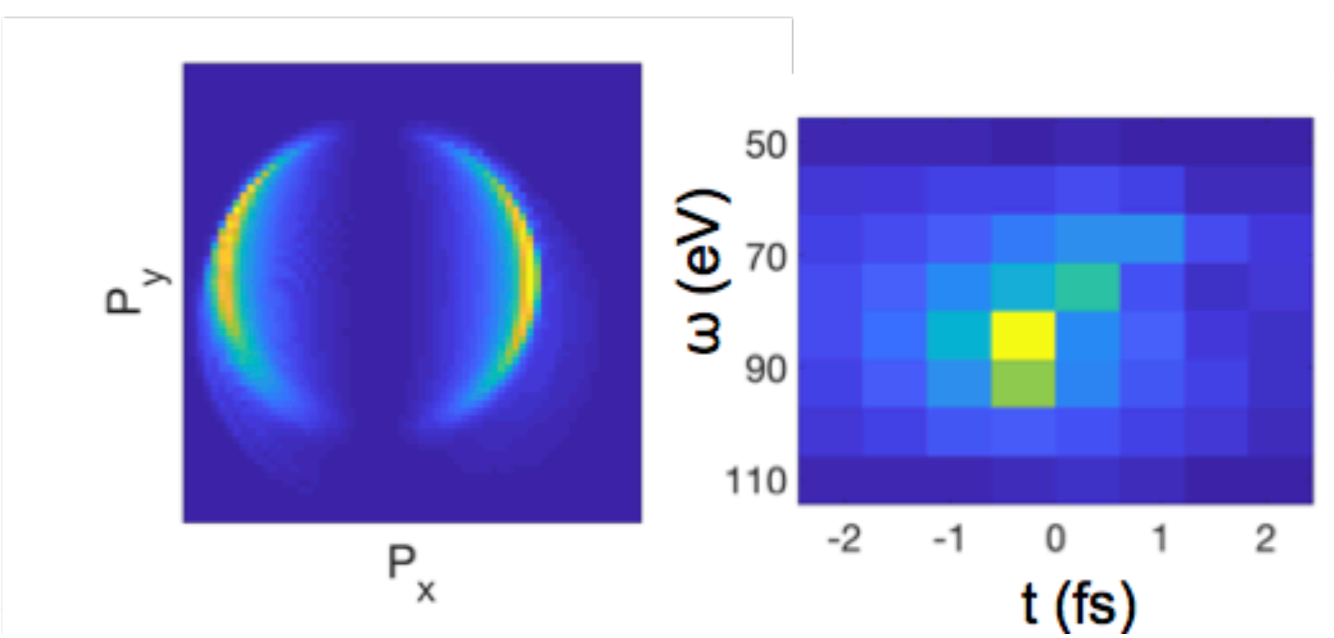
	Bandwidth	Pulse Energy
650 eV	5.5 eV	25 uJ
820 eV	4.3 eV	20 uJ
900 eV	5.5 eV	25 uJ
1050 eV	6 eV	25 uJ

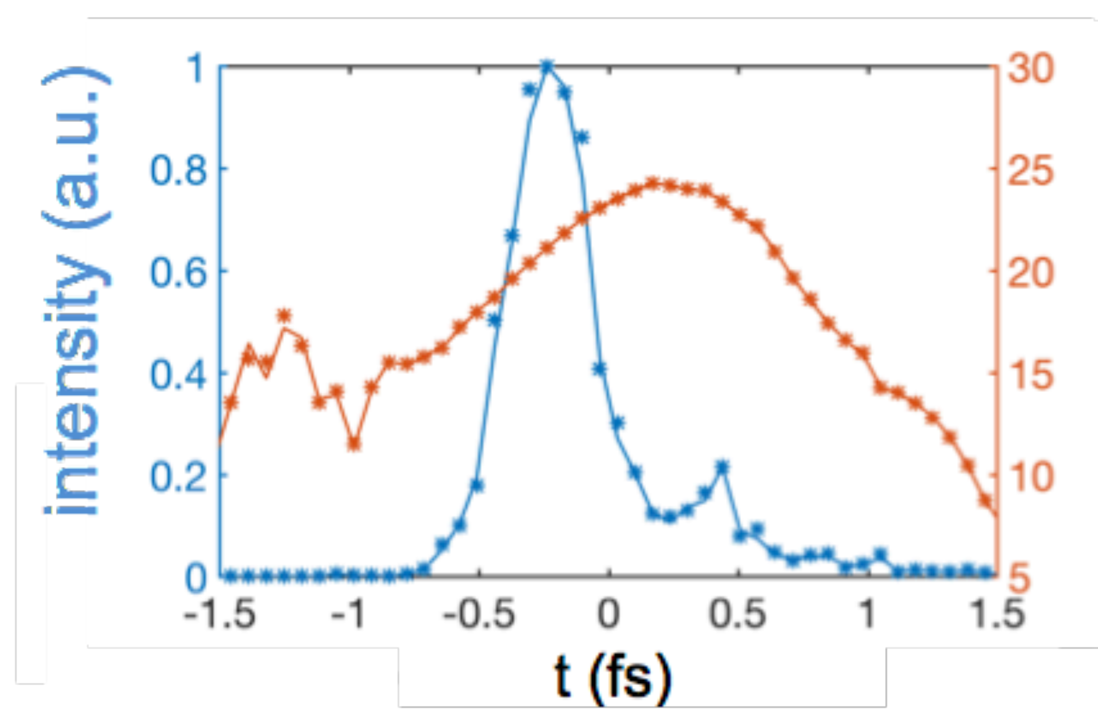
Angular Streaking Experiment



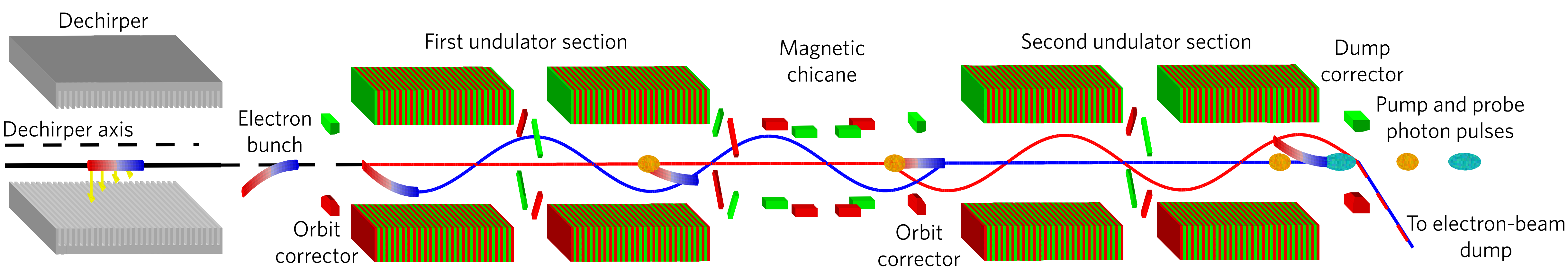
N. Hartmann et al. Nature Photonics ***12****, pages 215-220 (2018)*

S. Li et al. Optics Express Vol. 26, [Issue 4](), pp. 4531-4547 (2018)





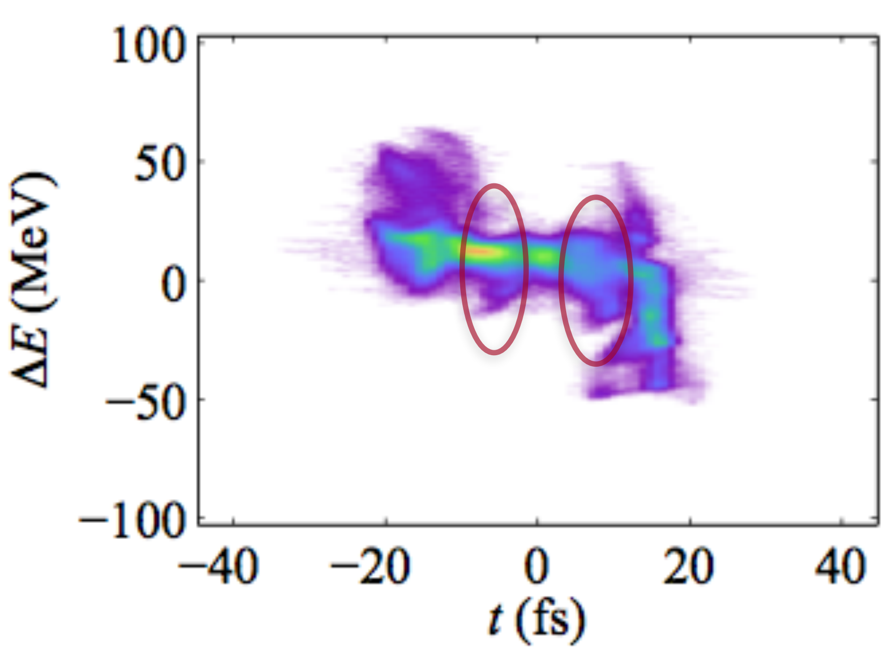
Two-Color Attosecond Pulses

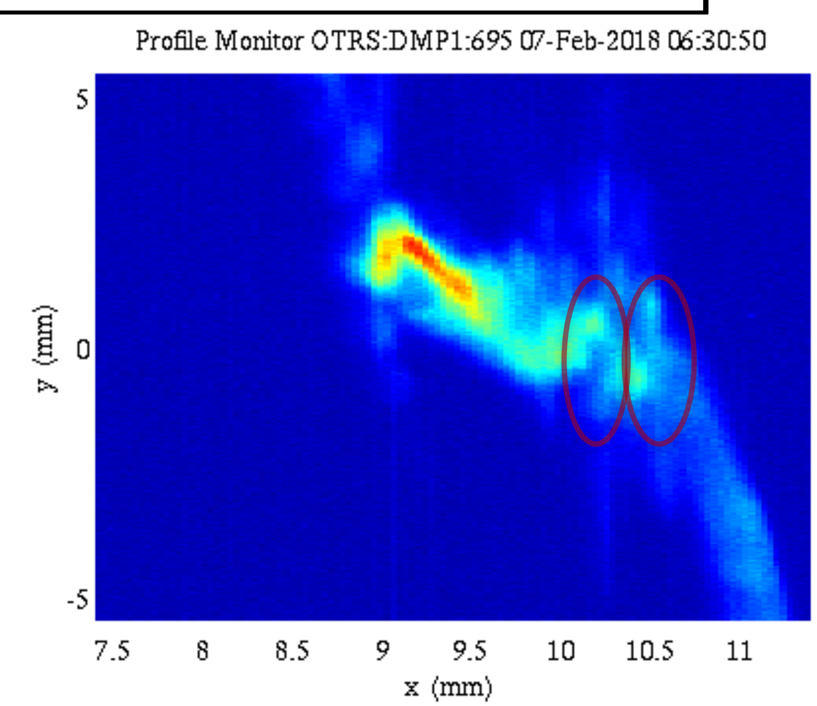


*A. Lutman et al. Nature Photonics **vol.10**, 745–750 (2016)*

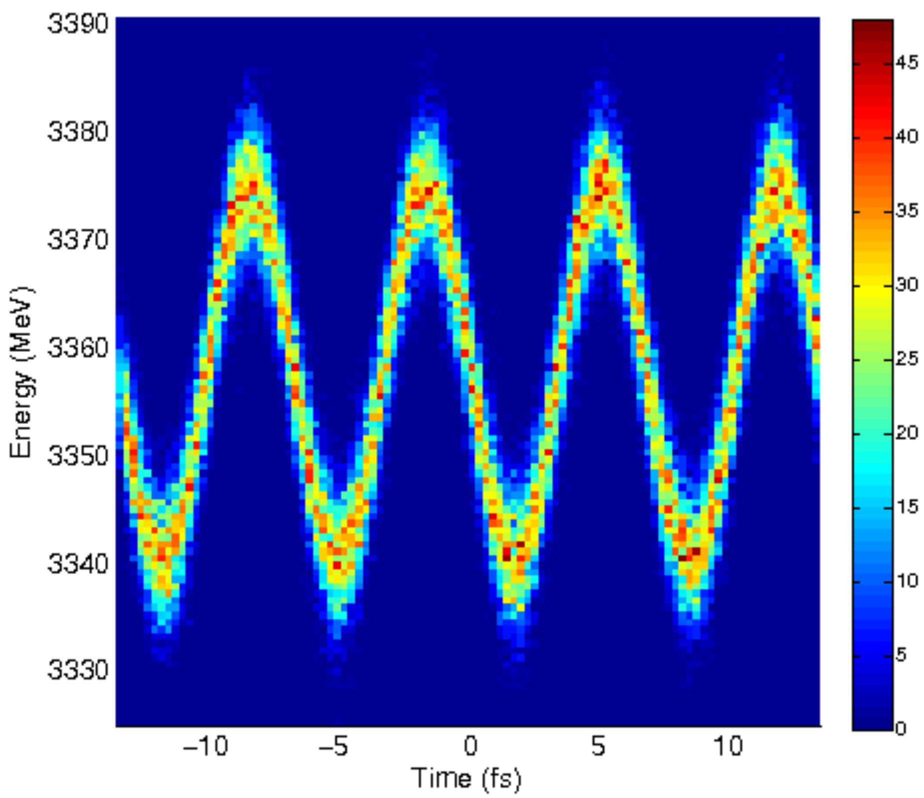
Pump/Probe with sub-fs stability

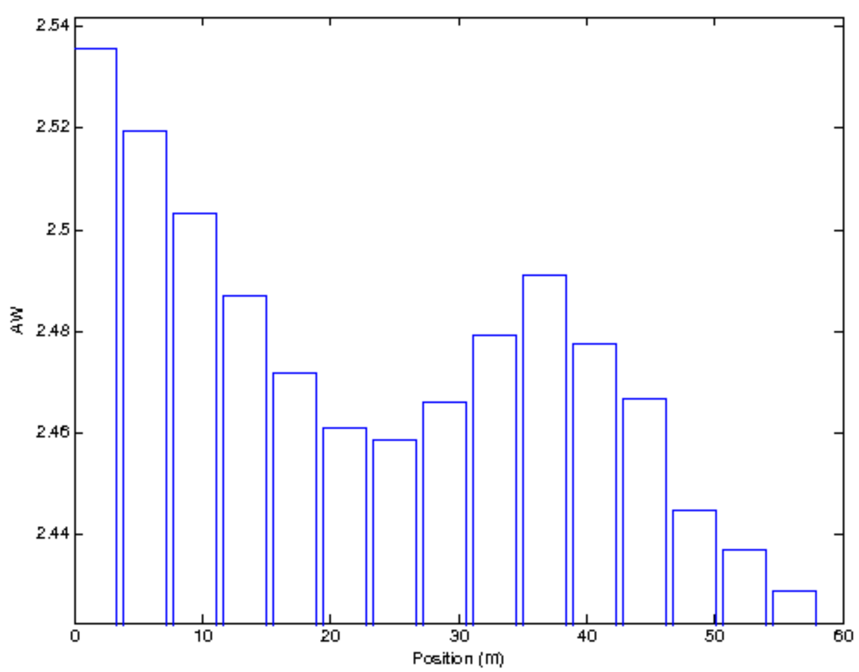
$$\Delta T = \Delta T_{CHICANE} + N\lambda_{RES} + \text{Slippage}$$

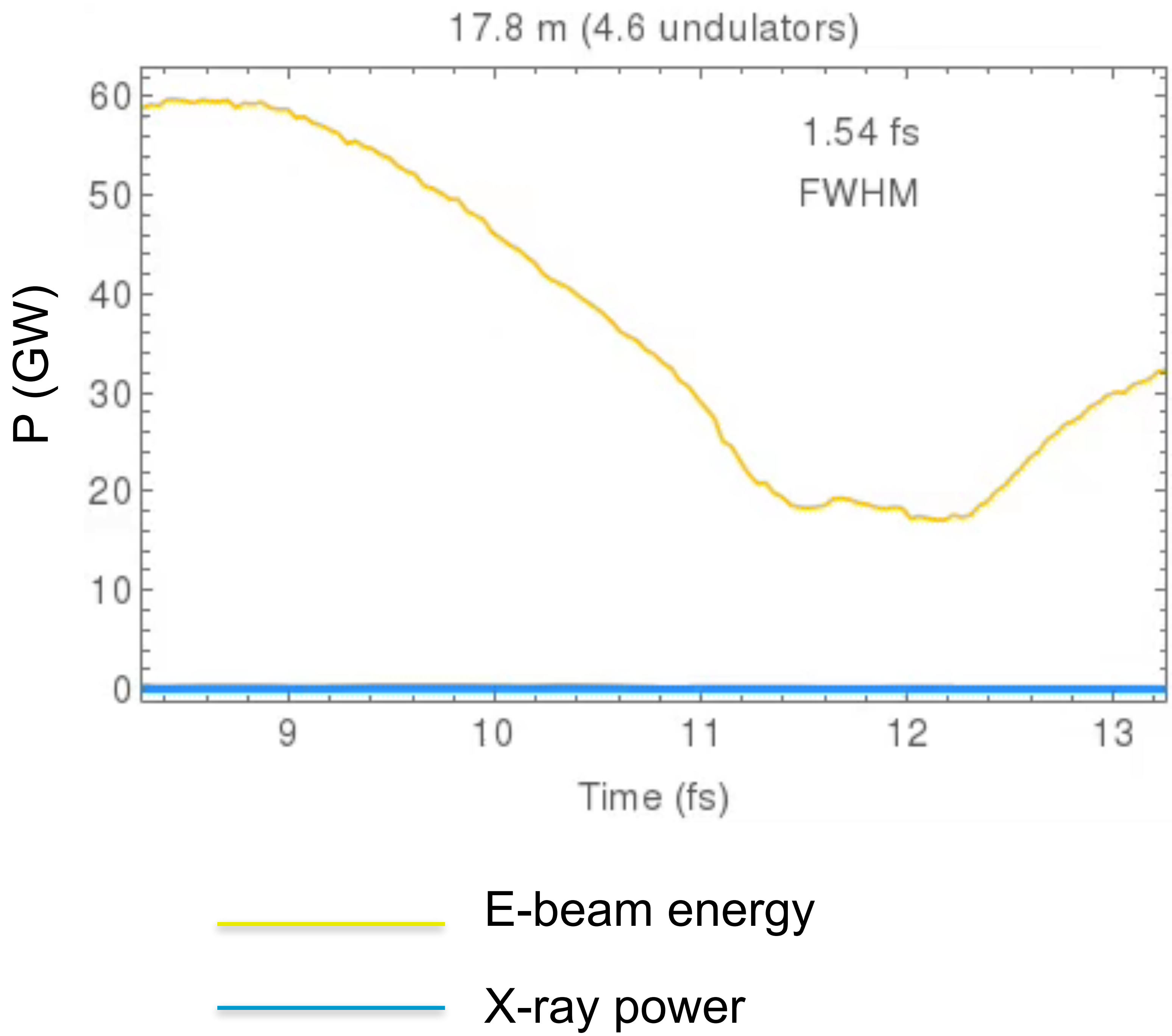




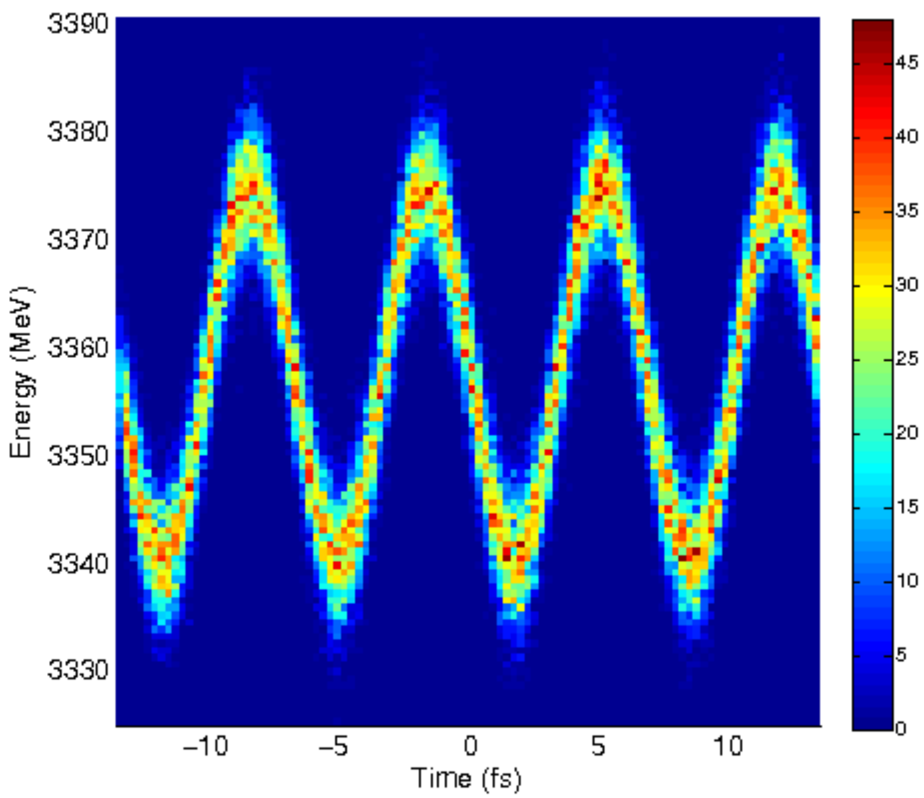
Terawatt Attosecond Pulses

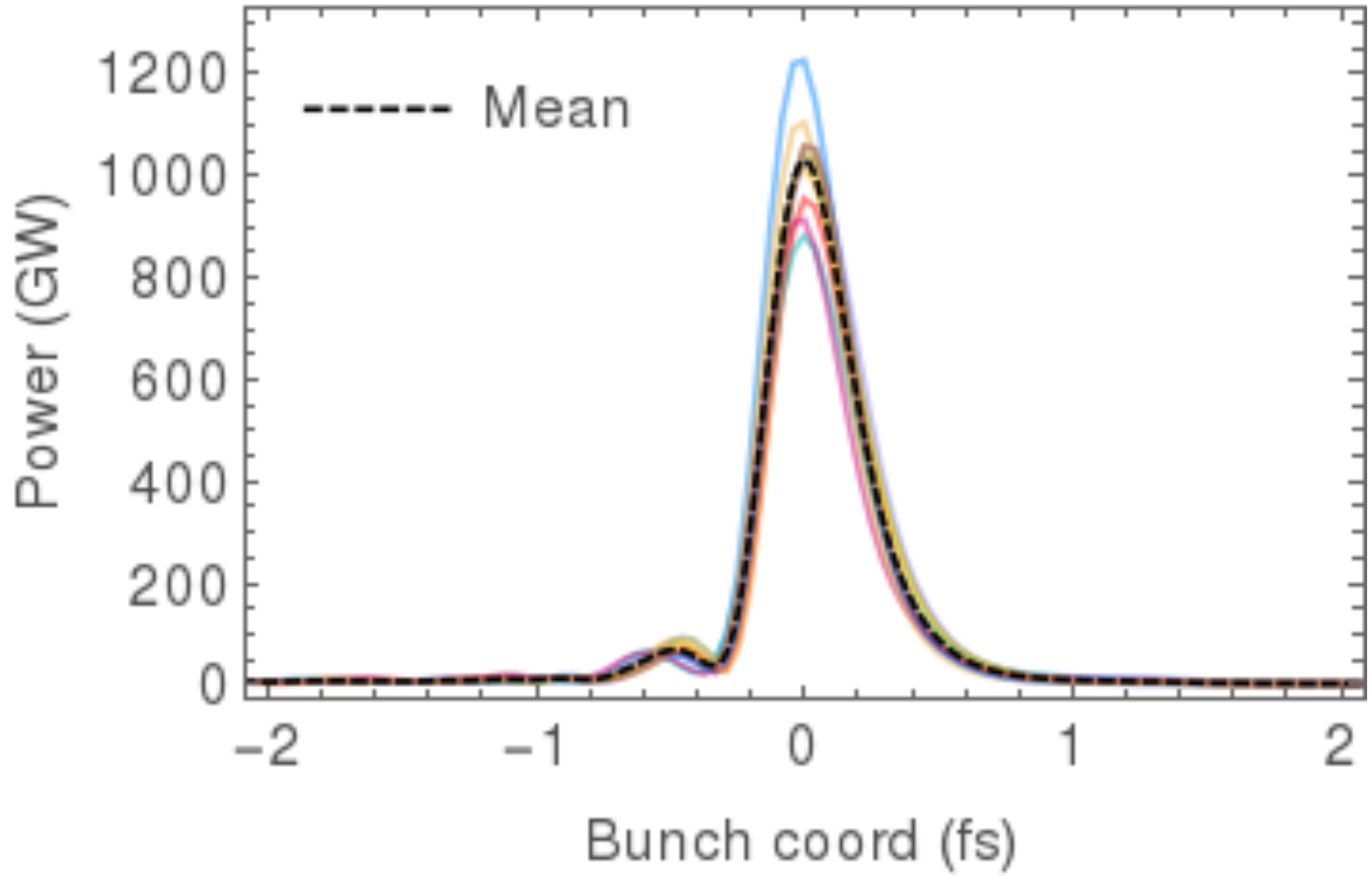


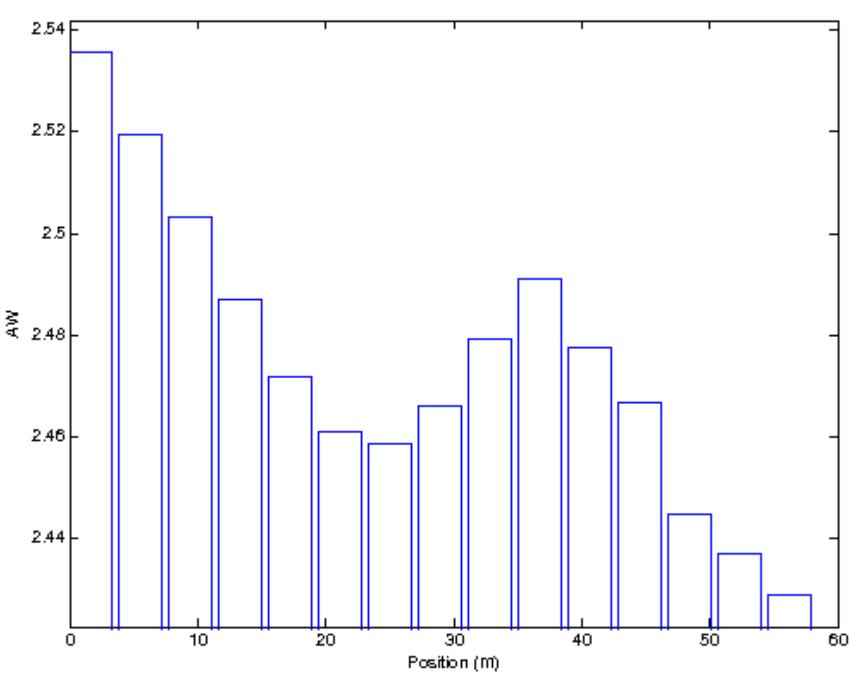




Terawatt Attosecond Pulses



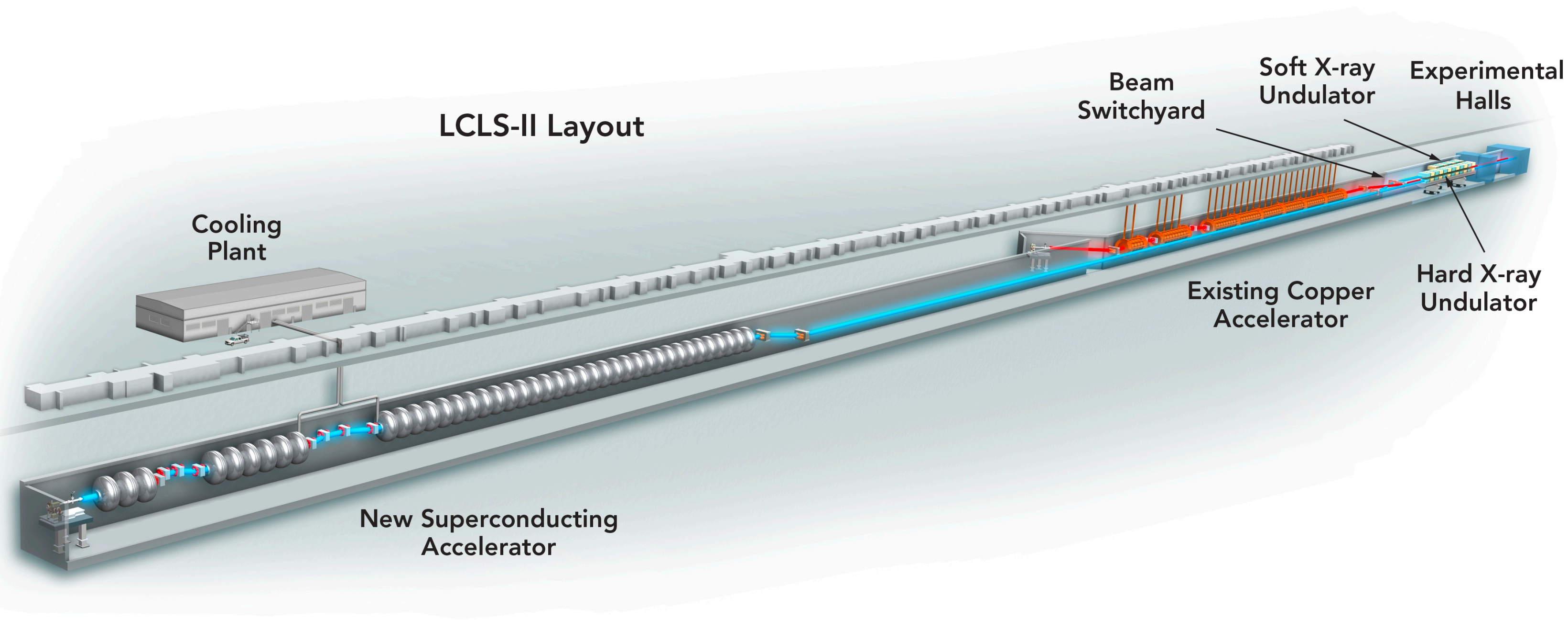


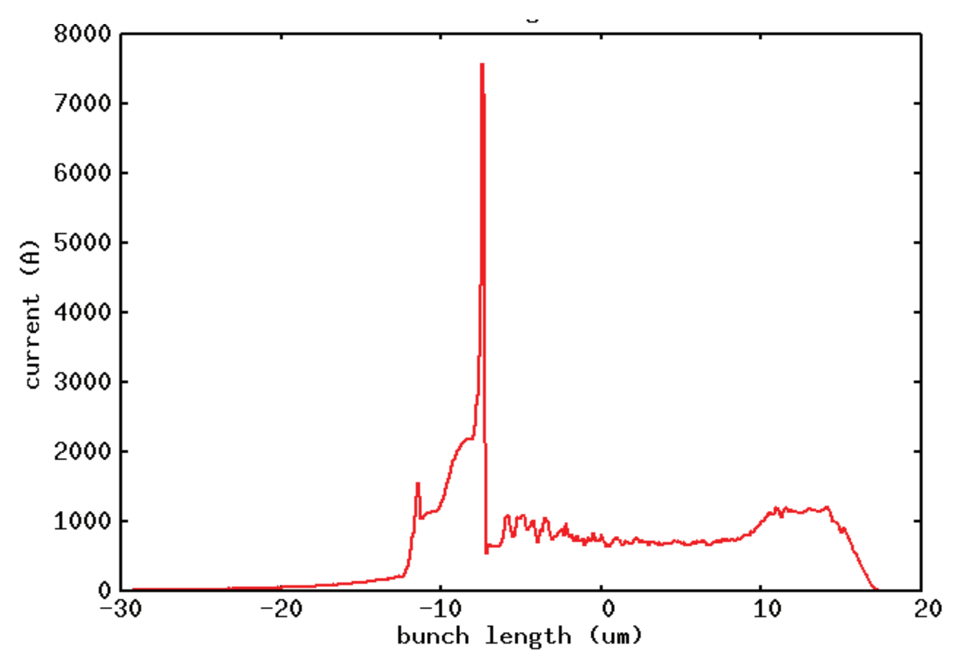


1 TW in 300 as
Requires large modulation > 10 MeV

J. Duris, In preparation

Towards LCLS-II

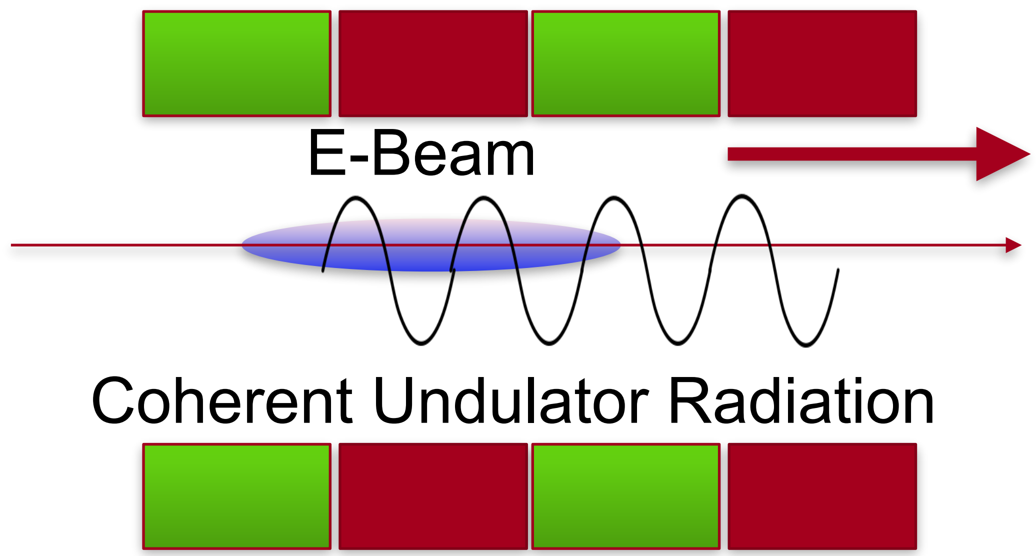




High repetition rate (up to 1 MHz)
High energy and timing stability
Ideal playground for attosecond science!

XLEAP at LCLS-II
Challenging laser system ~ 1 kW
Self-modulation easy option for baseline ESASE

Use 4 wigglers for < 10 MeV modulation…



Summary

-Attosecond X-ray FELs subject of intense investigation at LCLS. Strong interest from the scientific user community and funding agencies

-XLEAP commissioning results show single spike spectra with 5.5 eV average BW, estimated pulse duration < 0.7 fs

-Upcoming work

Angular streaking measurement

Two-color attosecond pulses

-Present XLEAP scheme is scalable to LCLS-II repetition rate.

The Project Formerly Known as XLEAP

Since no laser is necessary, do we need the L in XLEAP?

Open to suggestions for new name, so far favorites are:

X-ray Current Horn Enhanced Attosecond Pulse generation (XCHEAP)

THE PROJECT FORMERLY KNOWN AS XLEAP

Questions?


I CAN THINK AT THE SPEED OF LIGHT. I CAN PERCEIVE EVENTS THAT LAST FOR LESS THAN AN ATTOSECOND. I CAN RUN FASTER THAN TIME.
WHAT DO I SEE WHEN I RUN ACROSS THE COUNTRY, SUPERMAN? I SEE EVERYTHING. AND EVERYONE.