Capabilities for Ultrafast Pump/Probe Experiments

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Two-Color FELs

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X-ray Pump/X-ray Probe

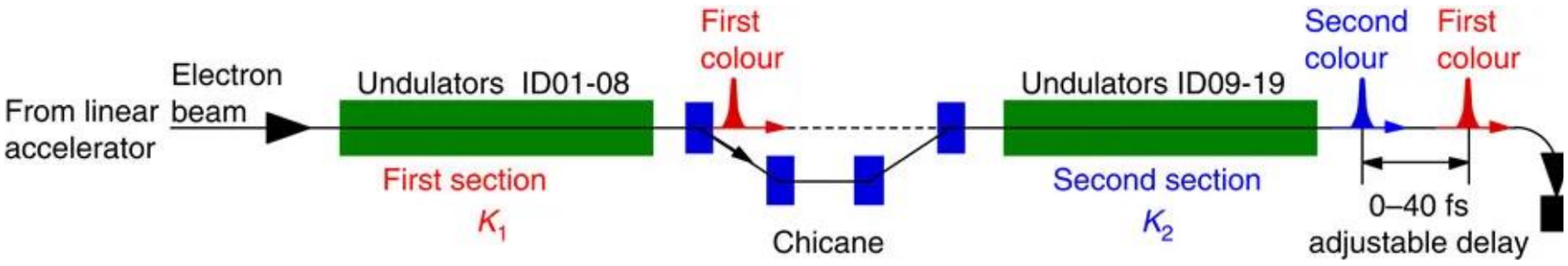
$$\lambda_{1,2} = \lambda_w \frac{1 + K_{1,2}^2}{2\gamma^2}$$

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.

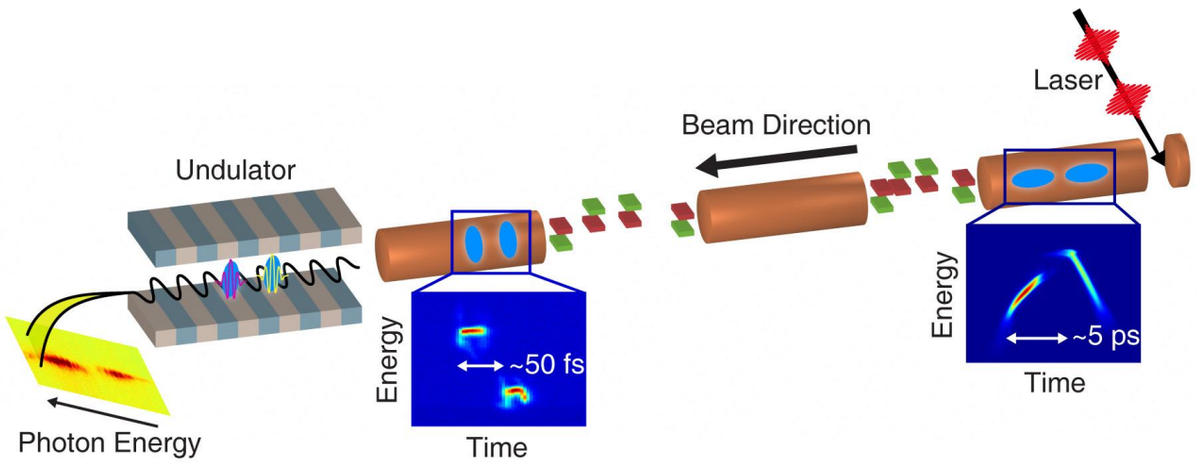


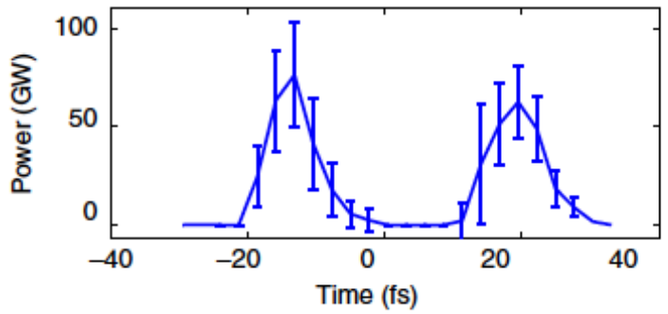
$$\lambda_{1,2} = \lambda_w \frac{1 + K^2}{2\gamma_{1,2}^2}$$

Allaria, E., et al. *Nature communications* 4 (2013): 2476.

Marinelli, A., et al. *Nature communications* 6 (2015): 6369.

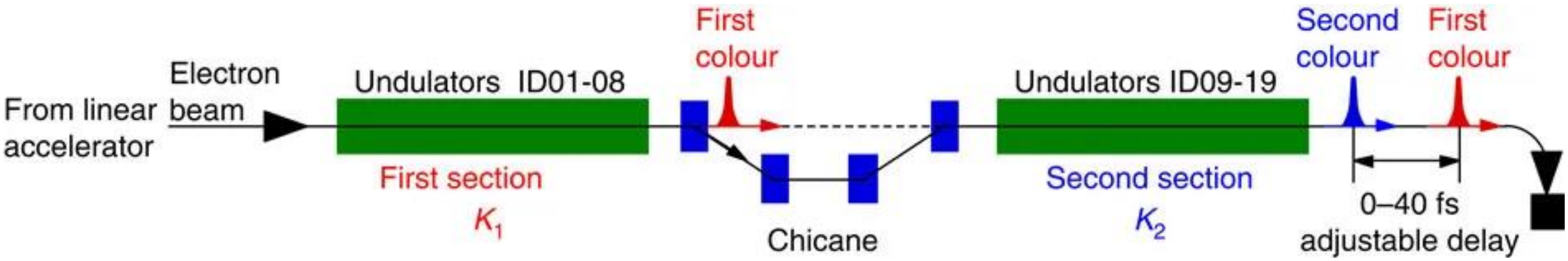
Petralia, A., et al. *Physical review letters* 115.1 (2015): 014801.



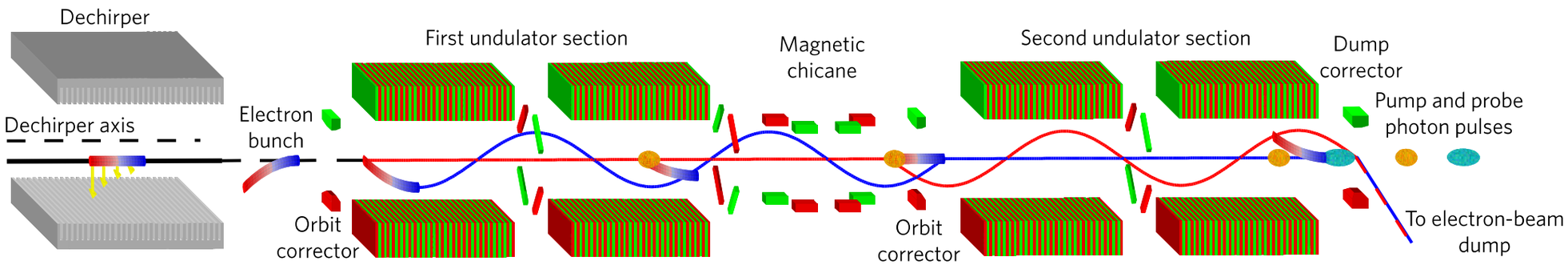


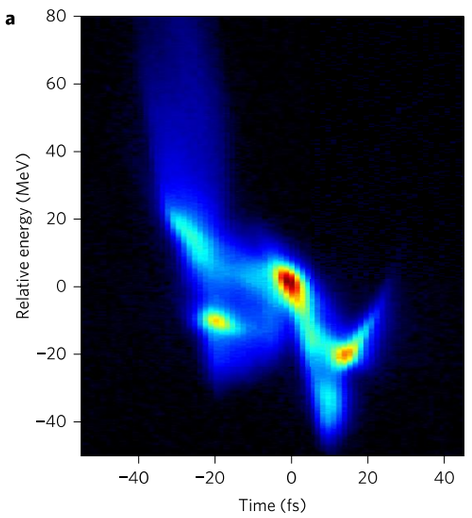
Nat. Comm. Vol 6, 6369 (2015)

Split Undulator/Fresh Slice



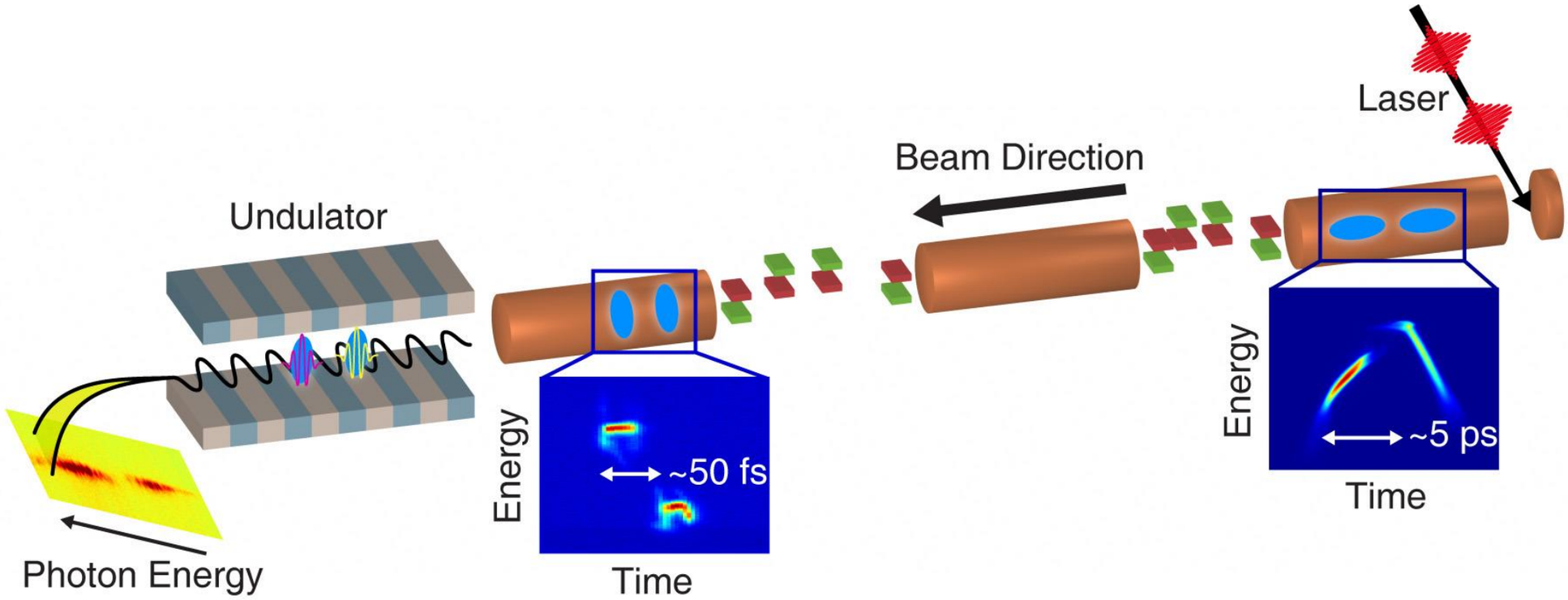
Use same electrons twice.
Limited to ~10-20% of saturation power (few GW)
Minimum delay ~ slippage in 2nd undulator (~5 fs)
Energy separation limited by undulator tuning (250 eV to 1.2 keV at LCLS-II!)

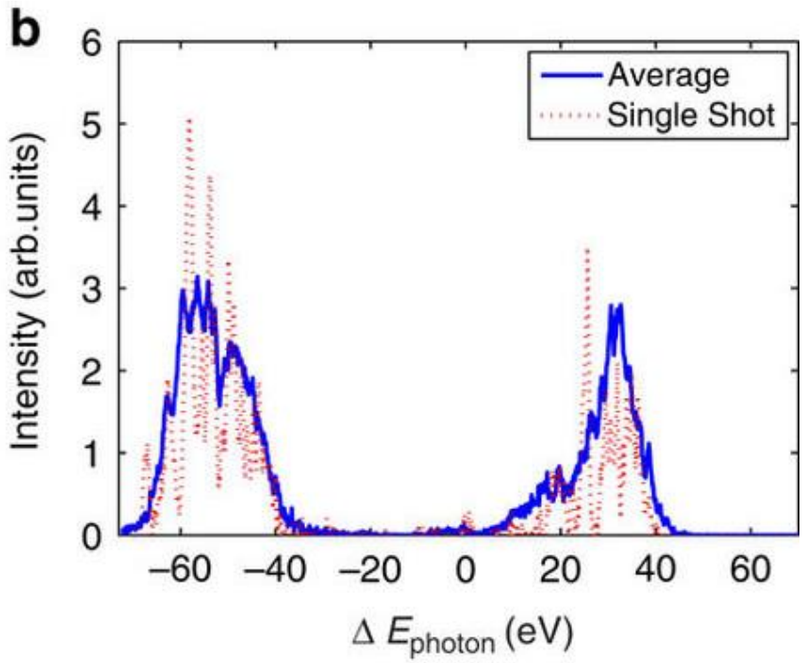


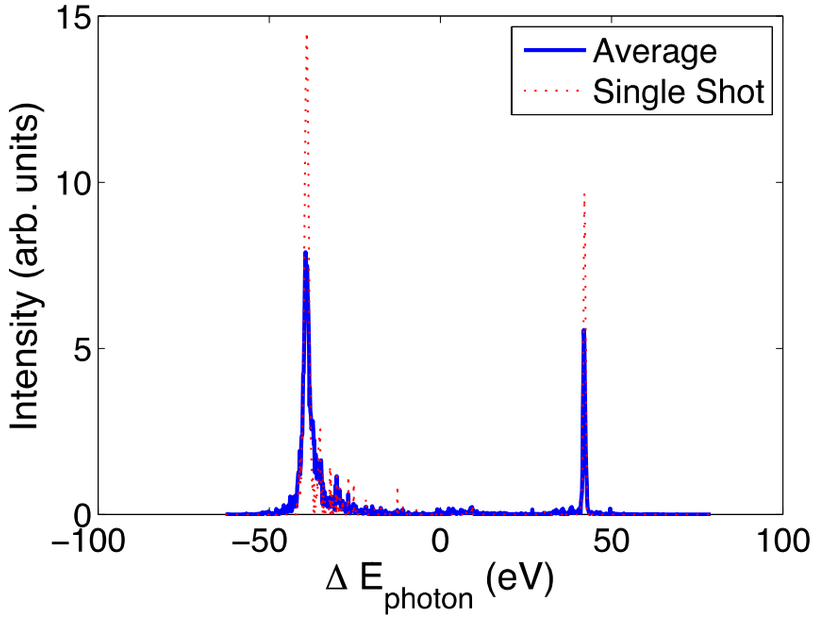


Use two different parts of e-beam.
Full saturation power (tens of GW)
Delay fully tunable through 0
Energy separation limited by undulator tuning (250 eV to 1.2 keV at LCLS-II!)
Best observed time resolution ~3 fs RMS

Twin-Bunch FEL







1.3 mJ two-color pulses
Up to 1% separation
Allows two-color seeding

Preferred method for HXR

A . Marinelli et al. Nature Communications
***vol. 6**, Article number: 6369 (2015)*

XLEAP: Attosecond Pulses at LCLS

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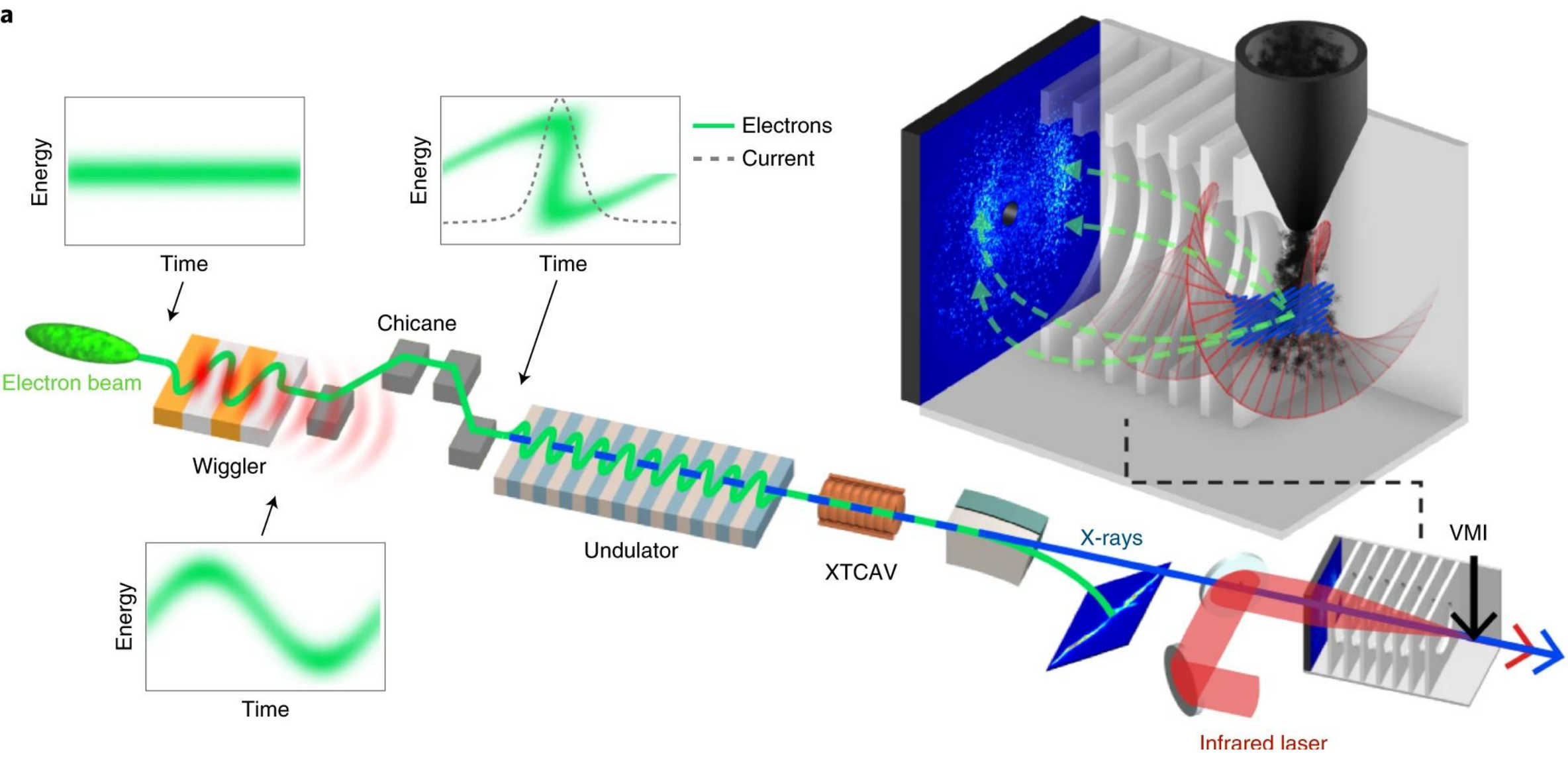
XLEAP: X-ray Laser-Enhanced Attosecond Pulse Generation

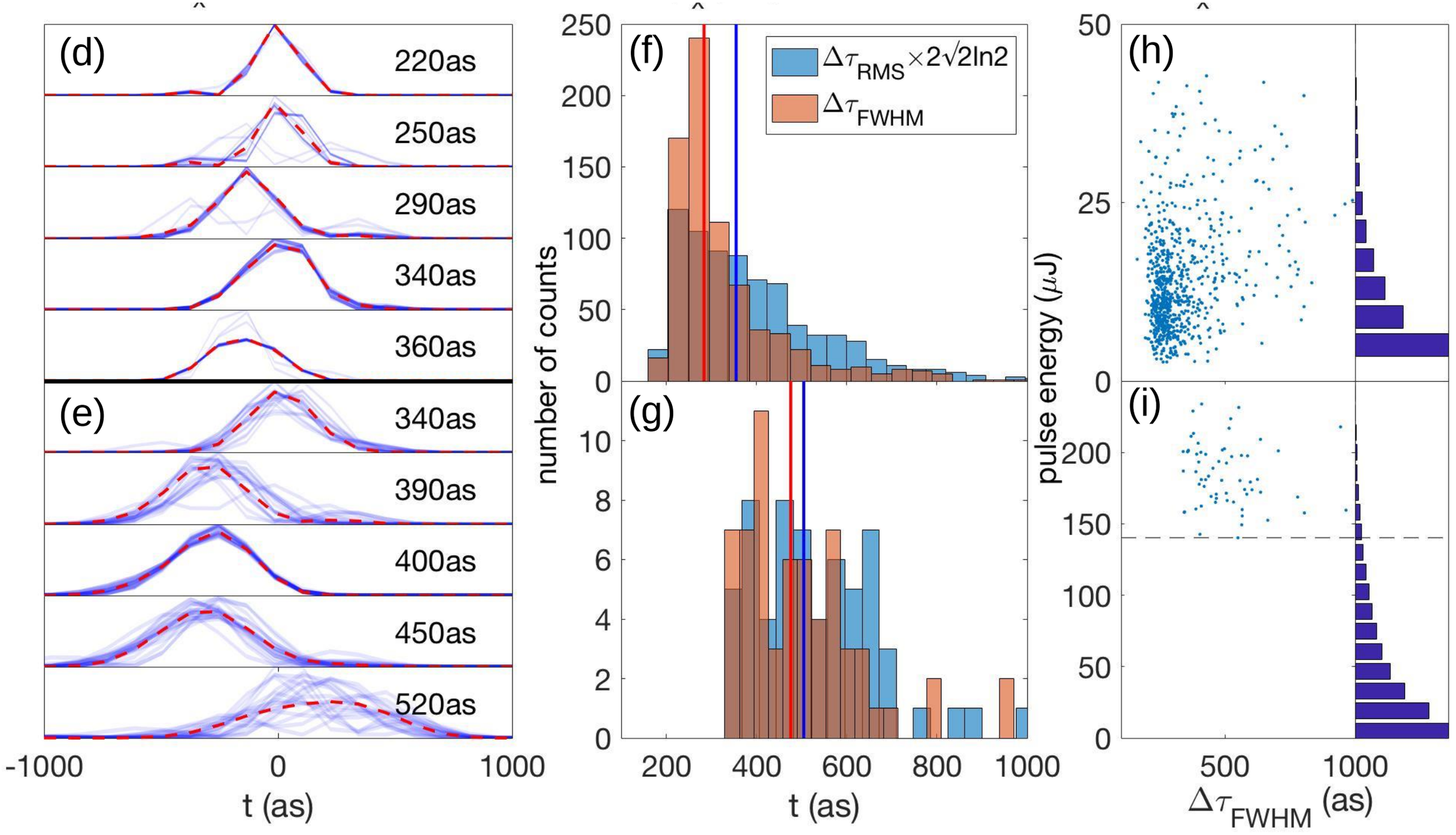
SLAC

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

MacArthur, James P., et al. *Physical Review Letters* 123.21 (2019): 214801.



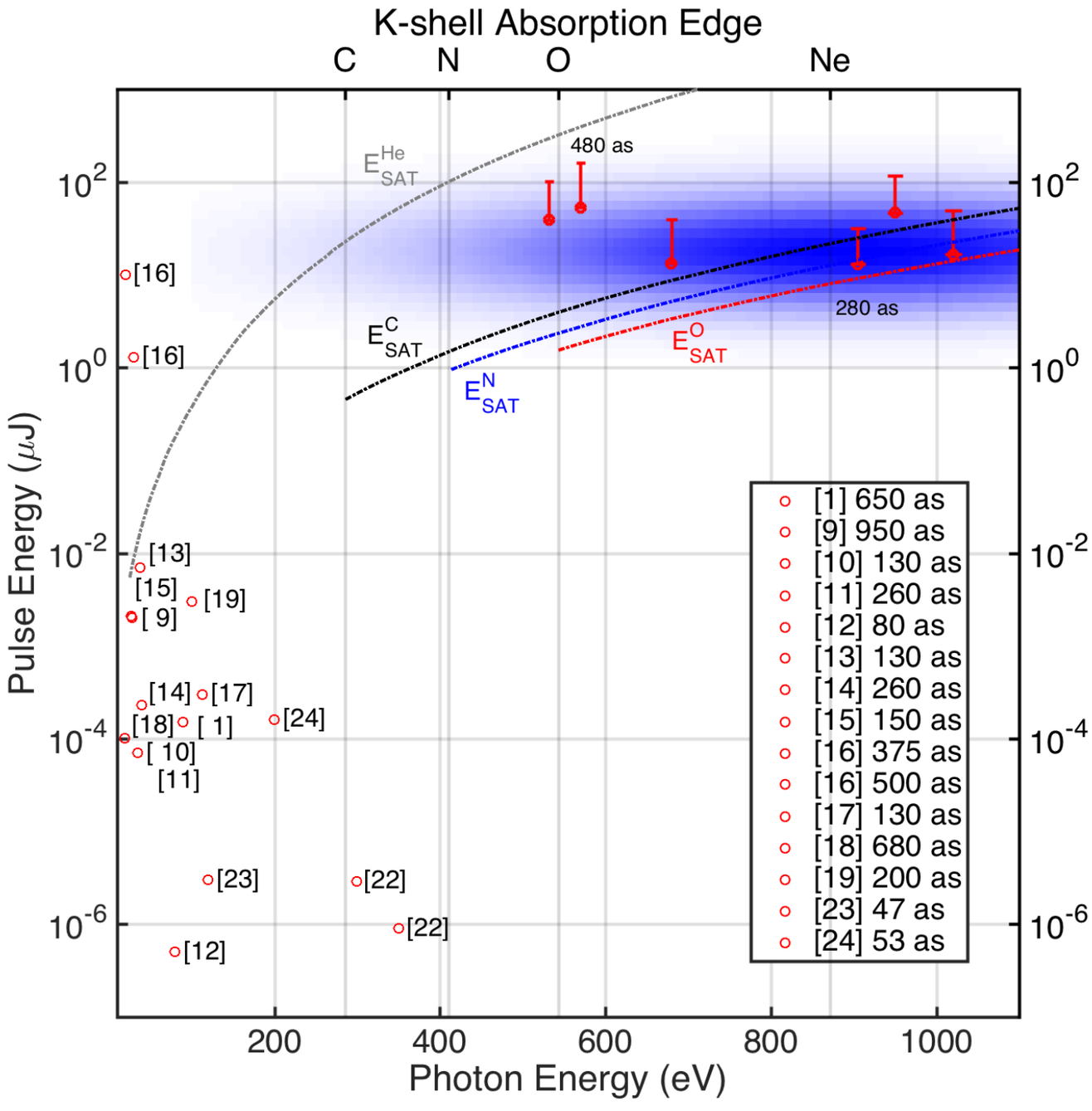
Results



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

Reconstruction Algorithm: S. Li et al. Optics Express Vol. 26, *Issue 4, pp. 4531-4547 (2018)*

Scientific Impact



>10^6 increase in pulse energy at SXR compared to other attosecond sources!

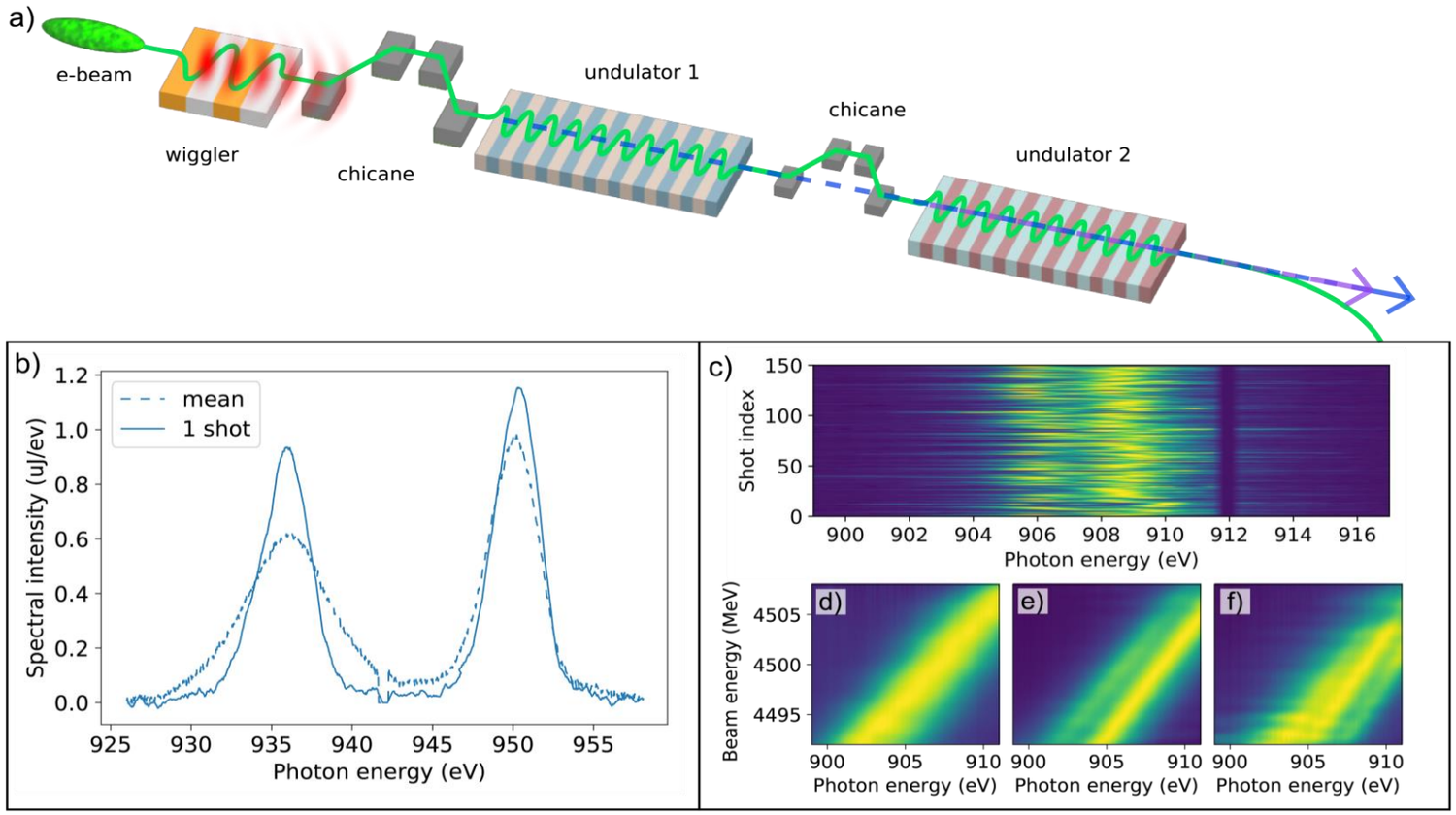
Where do we win?

-Non-linear interactions (pump-probe, impulsive Raman etc..)

-Single-shot X-ray imaging

-Wide tunability

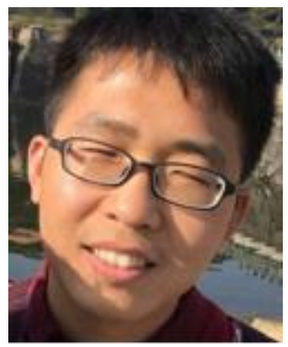
Two-Color Attosecond Pulses: Split Undulators



6 uJ per color
Delay up to ~ 50 fs
Temporal jitter < duration

Re-use microbunching:
Phase stable pulse-pair!

Tuning delay down to ~100 as minimum delay using harmonic radiation (pump ω - probe 2 ω)
(Z. Guo)



Z. Guo
Physics

The Future: High Repetition Rate Attosecond XFEL

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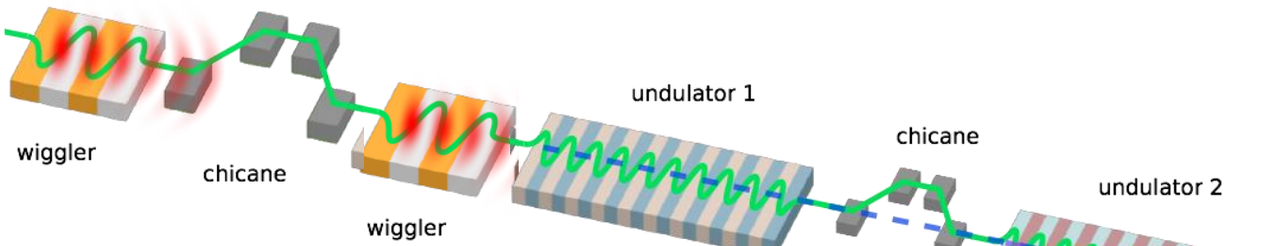
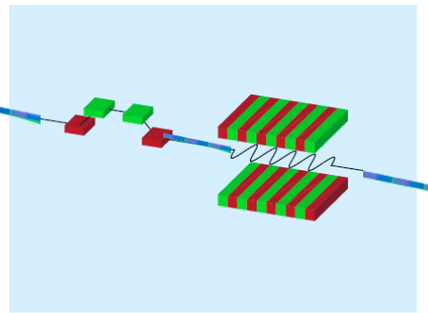
Where do We Want to Be?

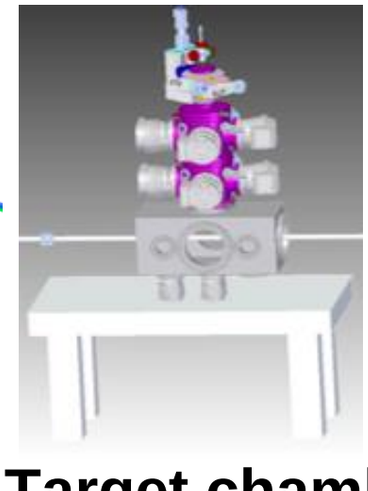


Modulator

2-color SXR FEL



EM-wiggler



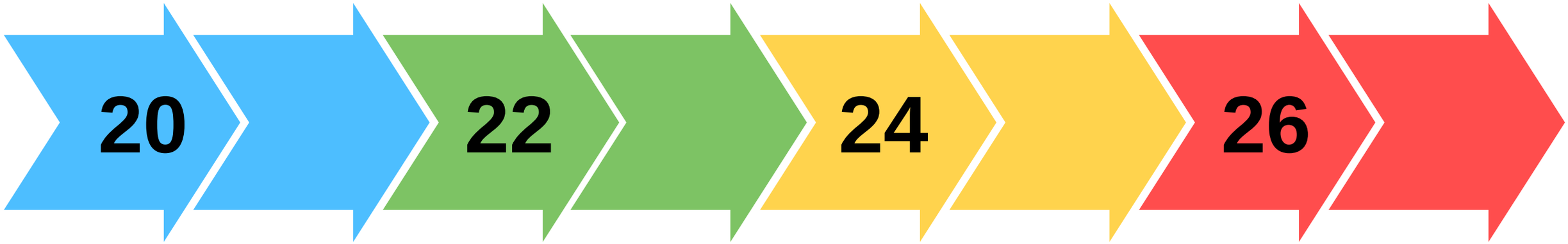
Target chamber (PEPPEx)

Beamline capable of PUMP/PROBE experiments with sub-fs resolution OVER WIDE RANGE OF PHOTON ENERGIES AND HIGH REPETITION RATE

- X-ray pump/X-ray probe experiments
- Visible/UV pump/X-ray probe and strong-field

100-200 as resolution
High intensity (tens of uJ)
High repetition rate (100 kHz or more)

Timeline



RESEARCH

HIGH REP-RATE ATTOSECOND PULSES

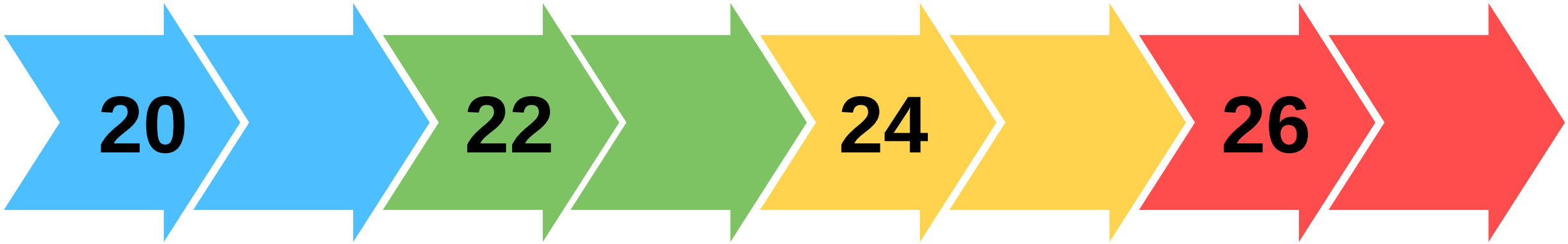
SXR/HXR PUMP/PROBE

X-RAY/OPTICAL/UV CAPABILITIES??

ATTOSECOND PUMP/PROBE DOUBLE CHIRP-TAPER DELAY LINE

FEW CYCLE PULSES??

Timeline



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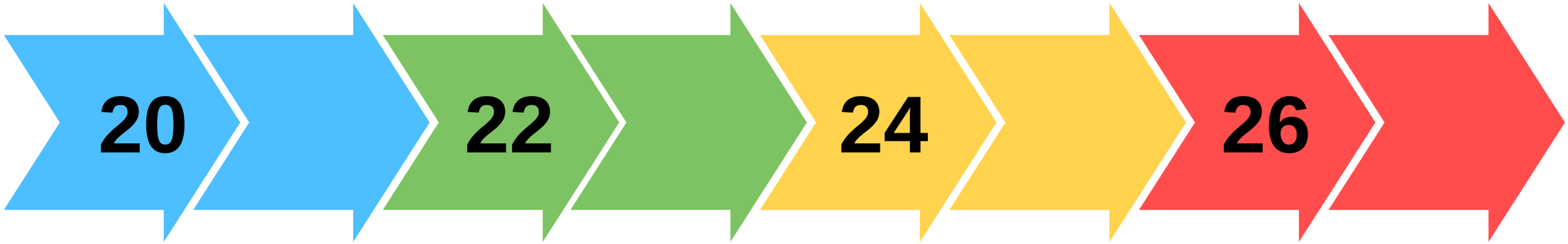

RESEARCH

HIGH REP-RATE ATTOSECOND PULSES

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EARLY ATTOSECOND CAPABILITIES

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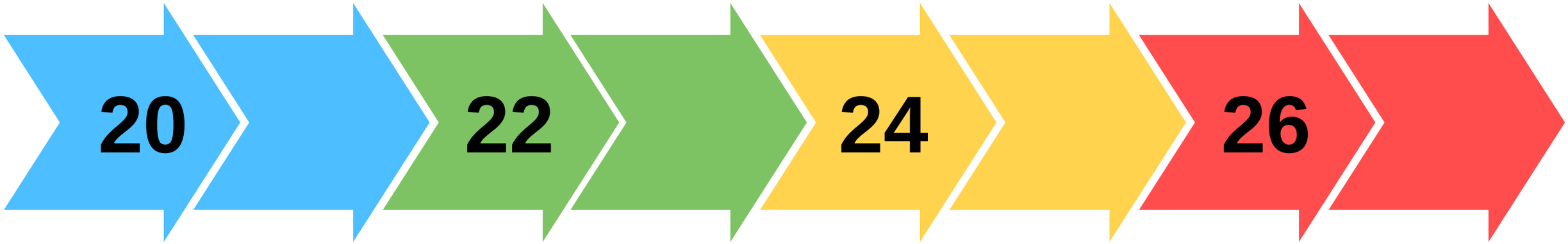
FEW CYCLE PULSES??

Timeline



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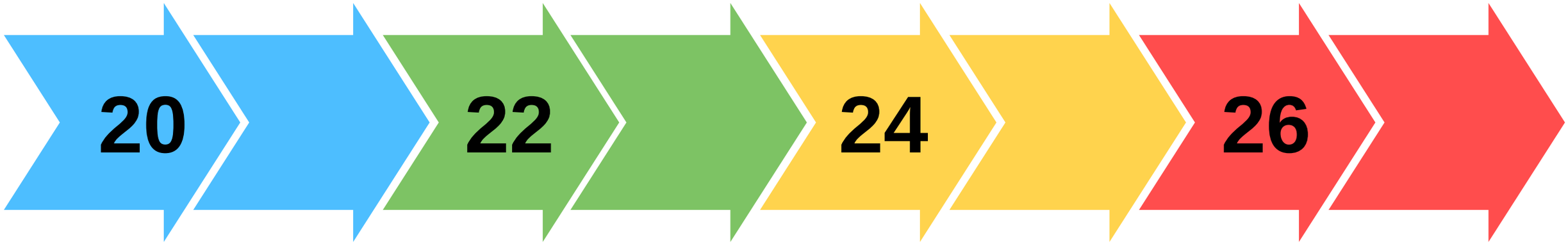
ATTOSECOND PUMP/PROBE DOUBLE CHIRP-TAPER DELAY LINE

FEW CYCLE PULSES??

ONGOING R&D

Timeline



RESEARCH

HIGH REP-RATE ATTOSECOND PULSES

SXR/HXR PUMP/PROBE

X-RAY/OPTICAL/UV CAPABILITIES??

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ATTOSECOND PUMP/PROBE DOUBLE CHIRP-TAPER DELAY LINE

FEW CYCLE PULSES??

ONGOING R&D

FUTURE R&D

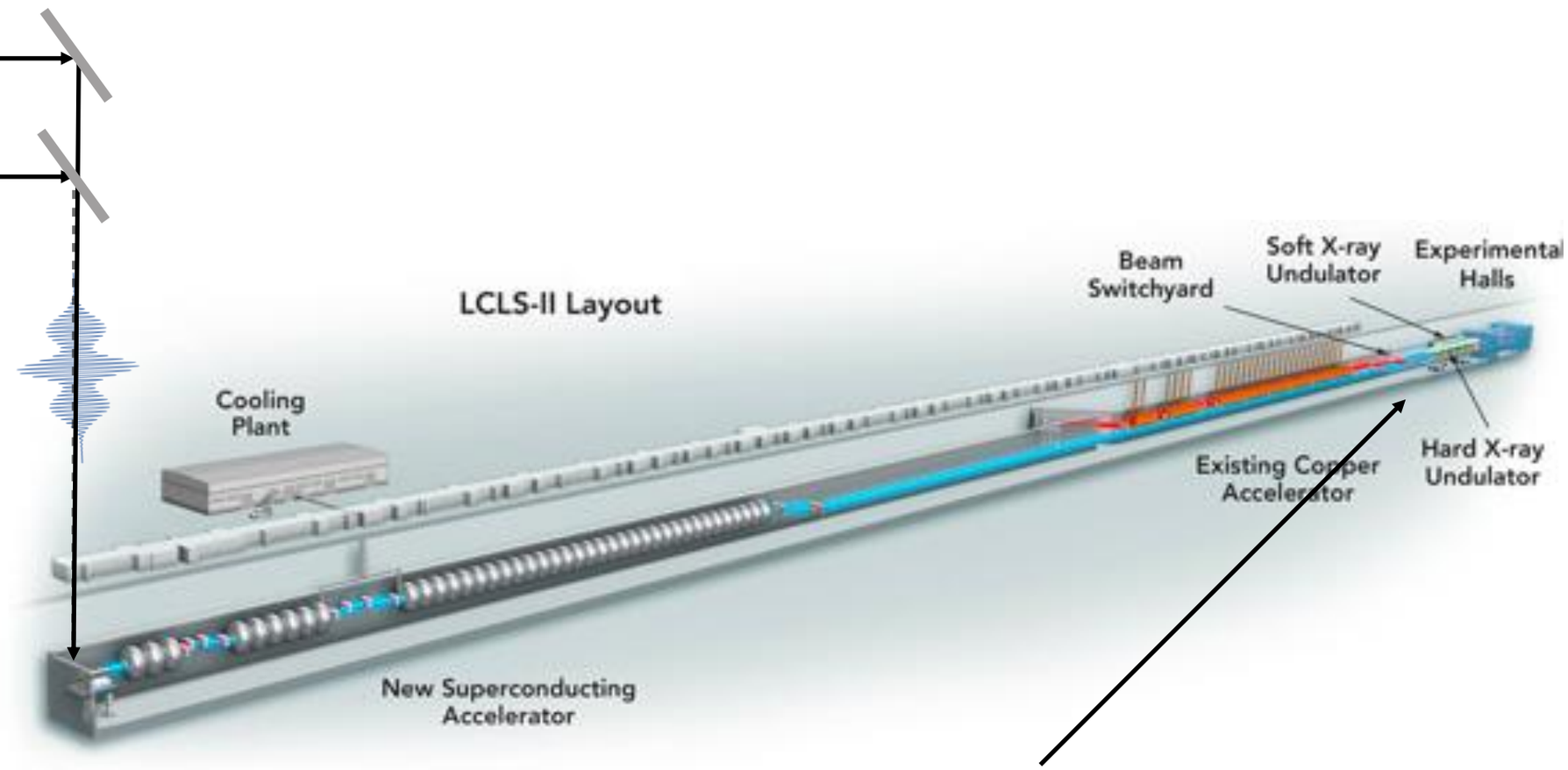
Beam Shaping for Attosecond Pulses at LCLS-II

SLAC

Shaping laser

Cathode laser

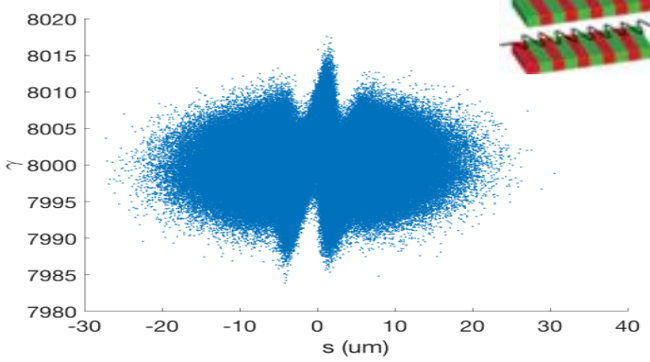
Shaped Laser

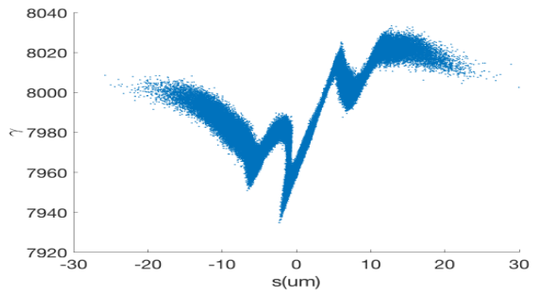


P. Franz
Applied Physics

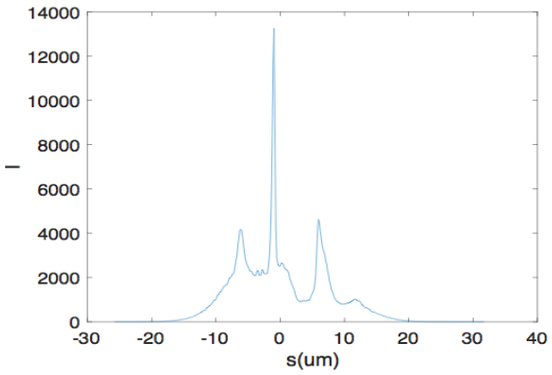
XLEAP-II Modulators

Input





Output



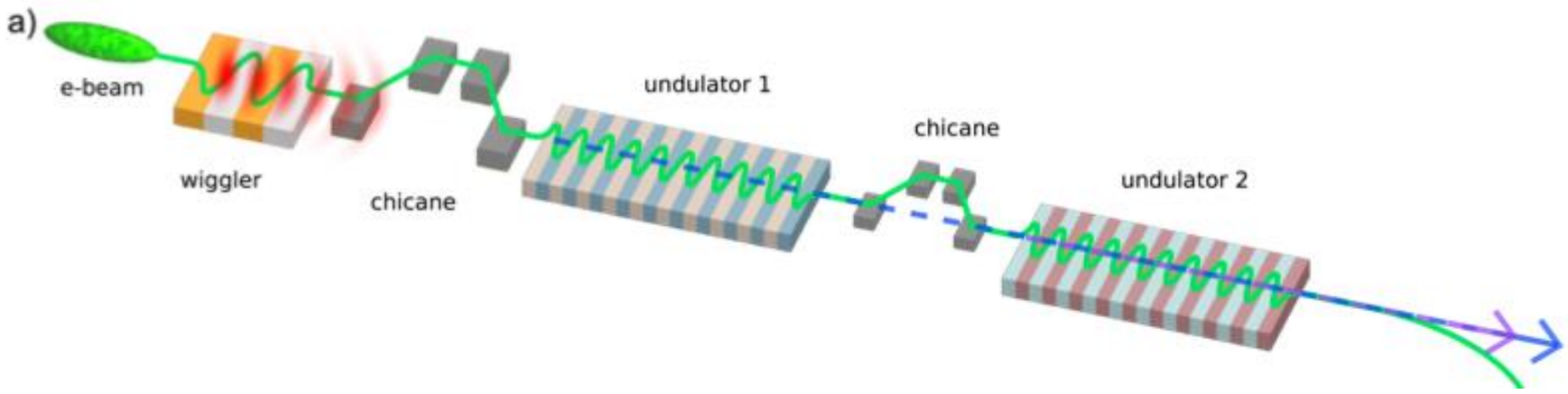
Early Attosecond Capabilities with Superconducting Linac

Isolated attosecond pulses from ESASE (2022)

- Heater/cathode laser shaping, work our way up to 100 kHz
- Can we reach ~ 1 MHz at low charge?
- Simultaneous operation of two beam lines

Early two-color experiments (2022)

- Two-pulse generation using split undulator

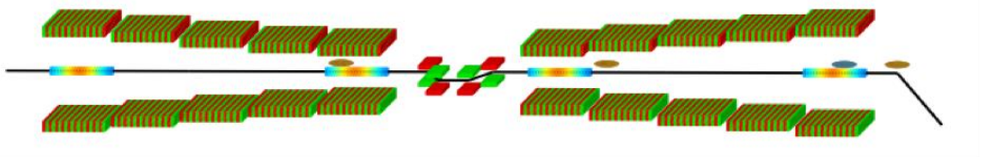


We expect similar single-shot performance as LCLS-I
~10s of uJ, 200-500 as duration (depending on energy)

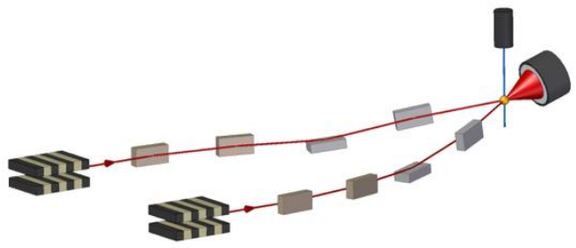
What's Next?

Attosecond pump/probe capabilities AT HIGH REPETITION RATE

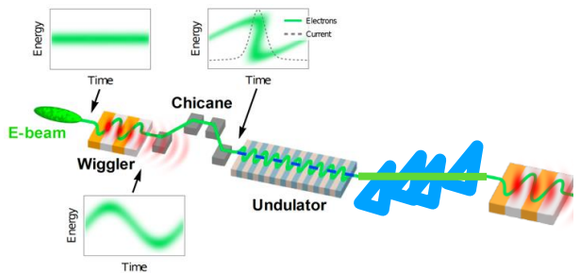
Two-color SXR pump/probe



Soft-Hard X-ray pump/probe

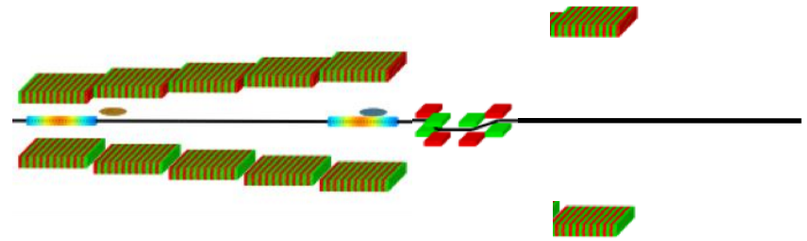


X-ray - UV/Optical pump/probe

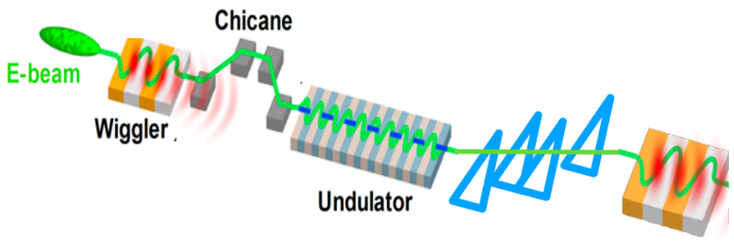


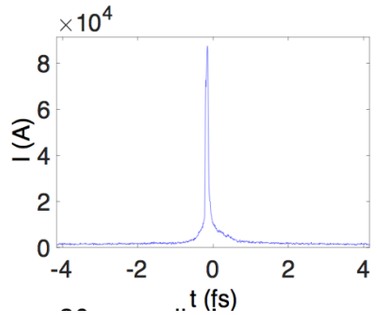
Shorter pulses

Harmonic generation/ Superradiance



Single-microbunch FEL (CONCEPTUAL STUDIES)

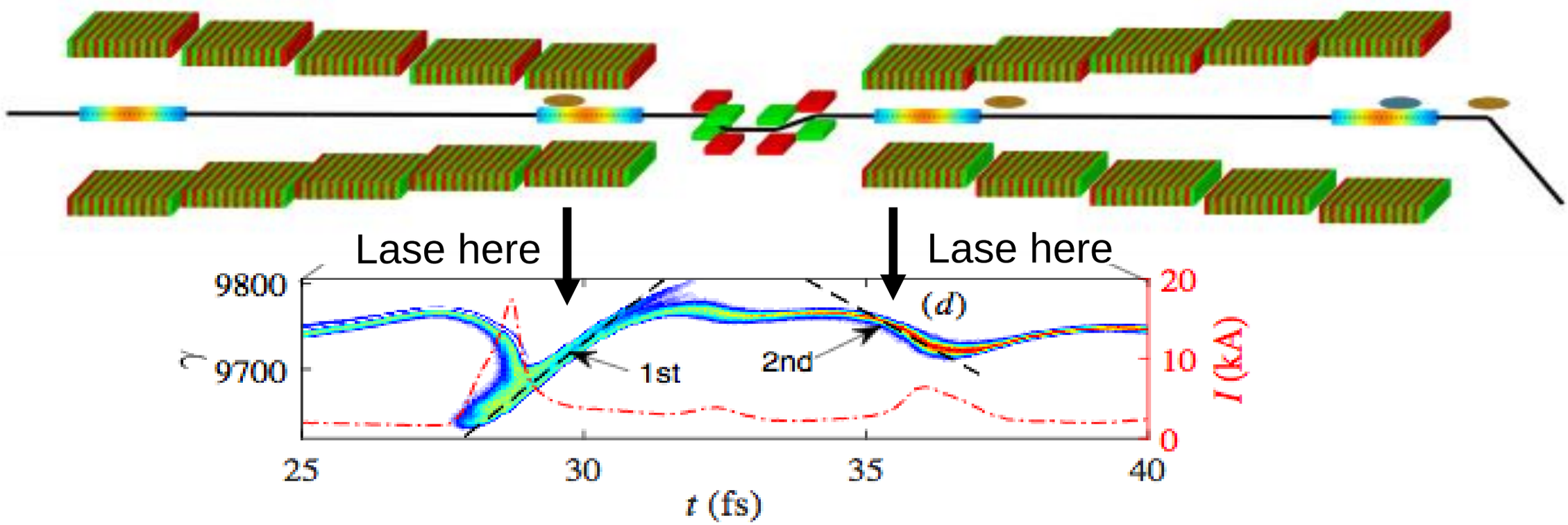


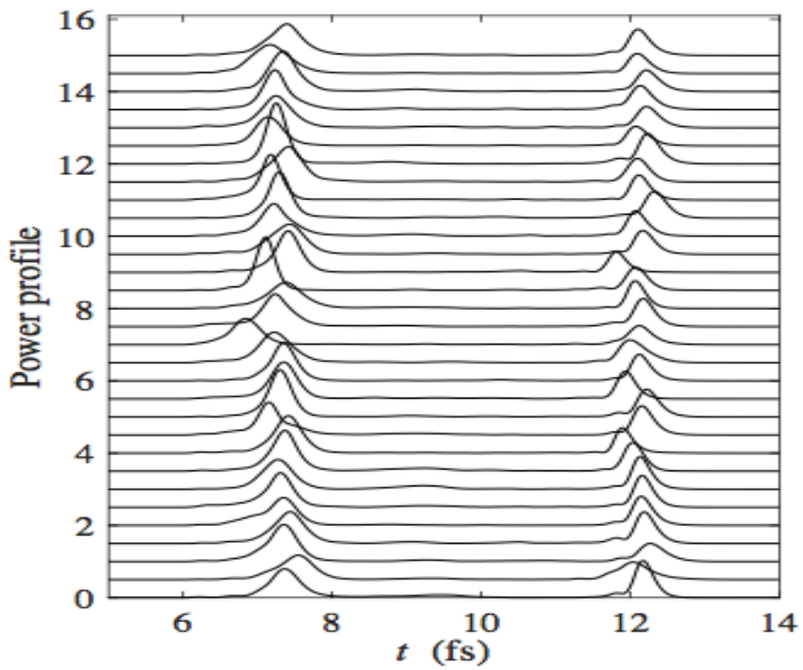


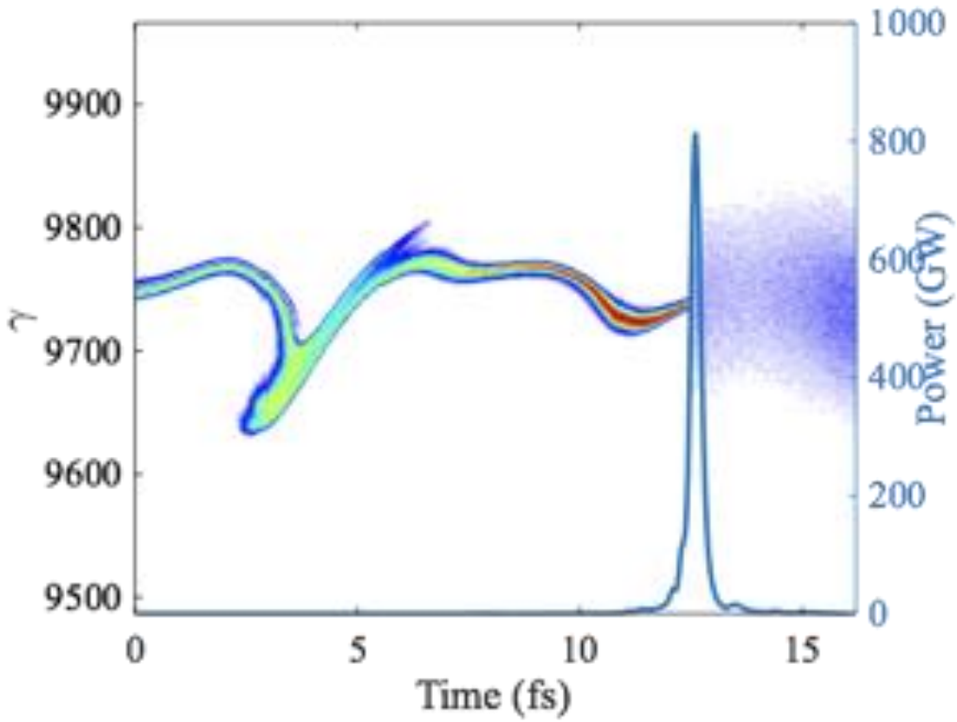
Can we reach soft X-ray regime?

~20 nm spike

Double Chirp-Taper Scheme

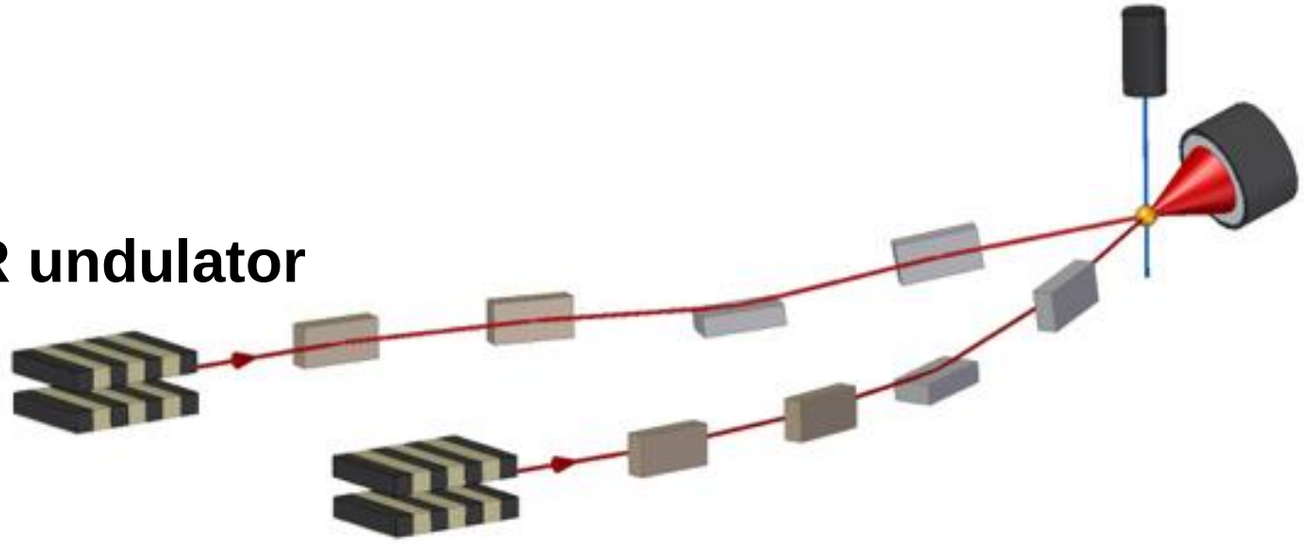






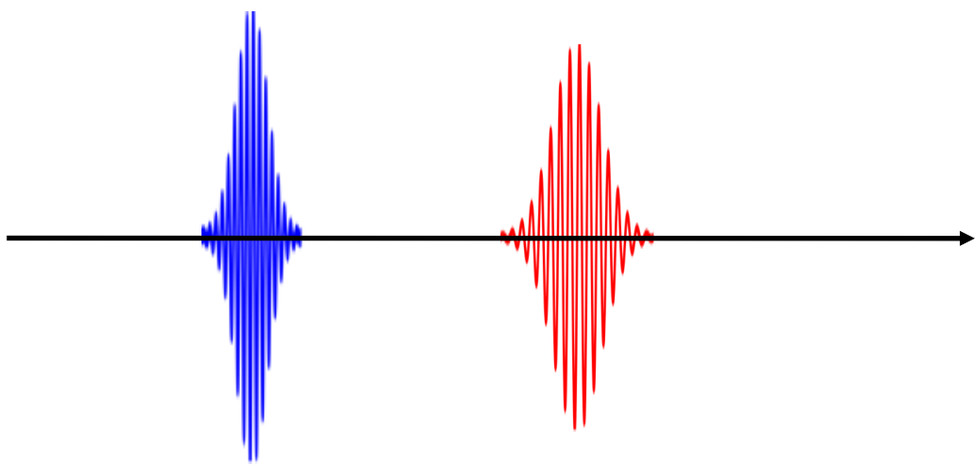
Z. Zhang et al. Phys. Rev. Accel. Beams **22**, 050701

Soft/Hard X-ray Pump/Probe

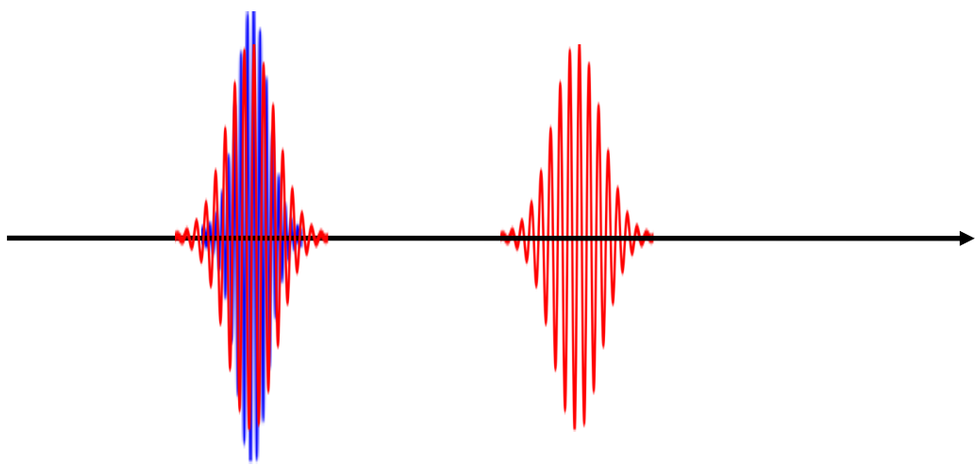


Kicker and X-ray delay line currently being developed for simultaneous soft/hard X-ray operation in TXI.
(A. Aquila, T. Beuker)

Future direction:
-HXR/SXR simultaneous attosecond Operation (or attosecond/few fs)
(A. Aquila, A. Marinelli)

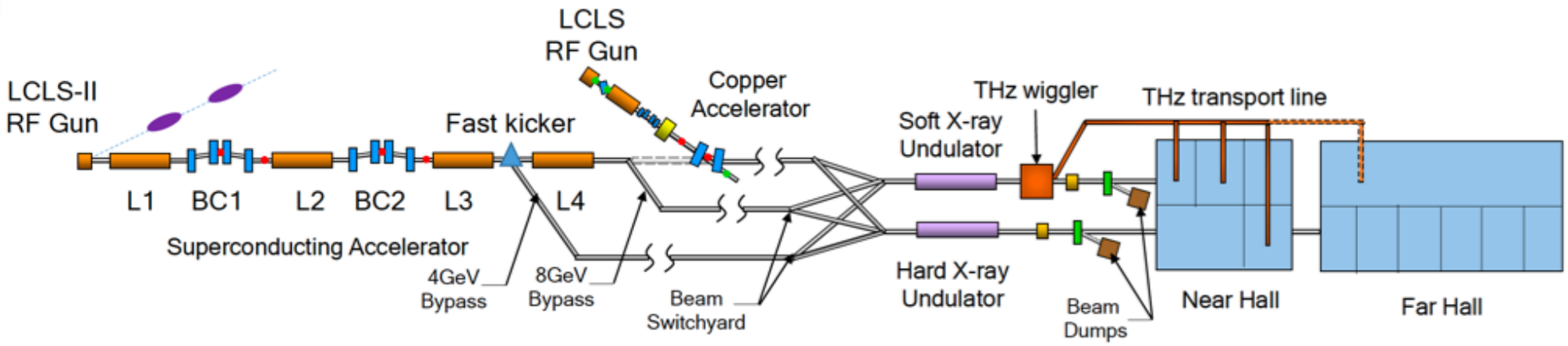


SXR pump/HXR probe



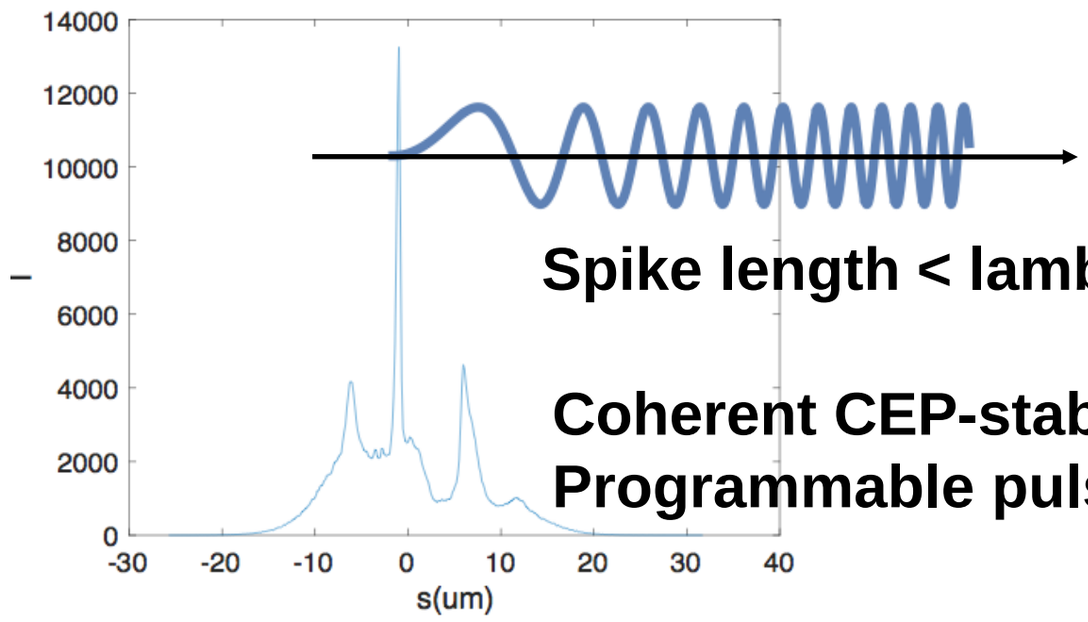
SXR pump/HXR+SXR probe

NEW RESEARCH DIRECTION:
Optical-UV/X-ray Attosecond Pump/Probe



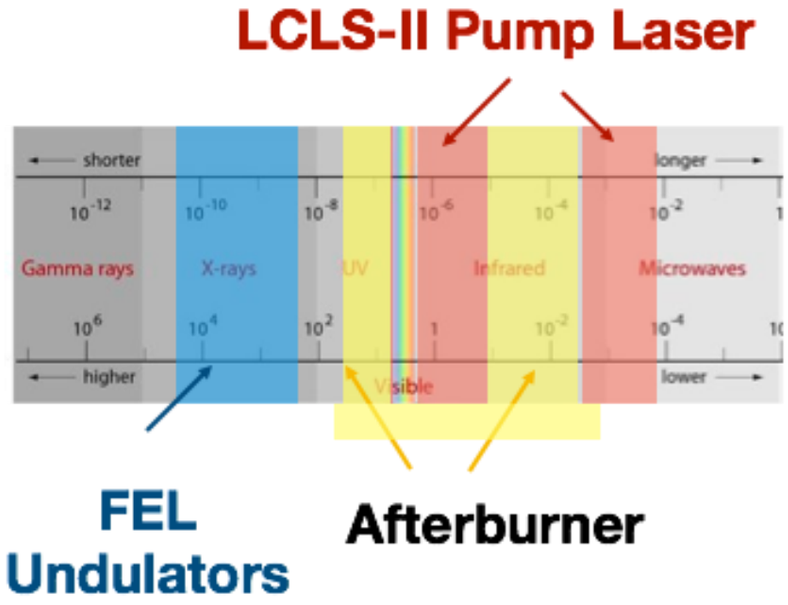
Z. Zhang et al. A High-Power, High-Repetition Rate THz Source for Pump-Probe Experiments at Linac Coherent Light Source II

THz wiggler + XLEAP can be used for CEP stable programmable pulses down to 100 nm (shorter wavelength with upgraded optics…)



Spike length < lambda

Coherent CEP-stable Programmable pulse!



Proof of principle experiments[23]
Could be performed with XLEAP
Variable gap wiggler…

Summary

-Two-color FELs well established method for pump/probe experiment with ~10 fs resolution.

-Attosecond science is very active area of research at LCLS and in the FEL community.

-Working on high repetition rate attosecond pump/probe capabilities:

SXR two-color

HXR-SXR two-color

UV/X-ray