Opportunities for Attosecond Science At FACET-II (and beyond…)

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Collaboration

SLAC

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UCLA

J. B. Rosenzweig
W. Mori

Outline

Science Motivation

Attosecond Light Sources

Opportunities for Advanced Accelerators:

- -Attosecond plasma driven FELs
- -Relativistic Transition Radiation
- -Beam-based Ultrafast Science

Conclusions

Disclaimer: a lot of work in progress!

Ultrafast Timescales

10 ps

1 ps

100 fs

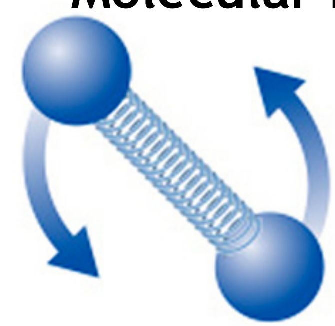
10 fs

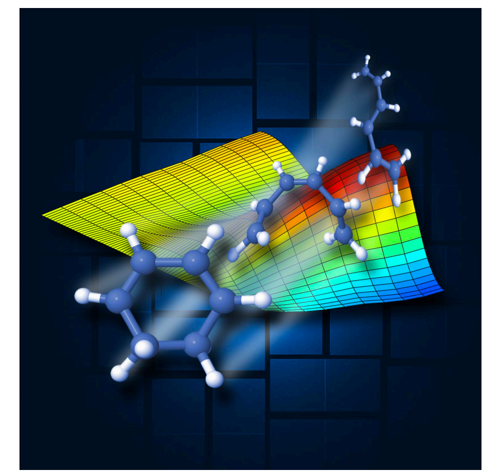
1 fs

Our goal

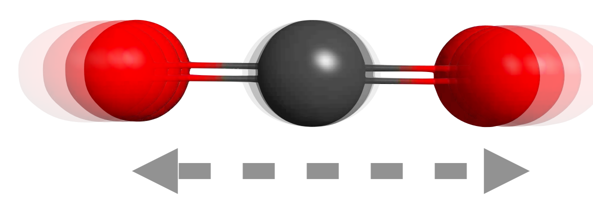
0.1 fs

Molecular rotation ~ ps

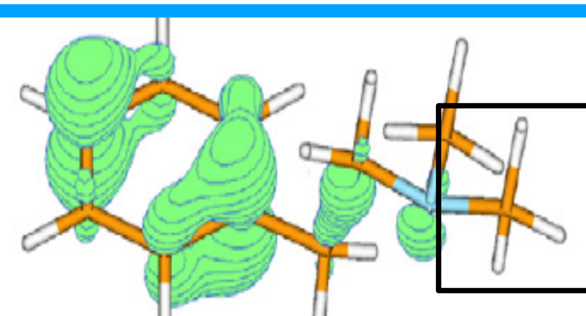




Molecular rearrangement ~100s fs



Molecular vibration ~10s fs



Valence electron motion ~ 100s as

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

Inner electron motion ~ 10 as

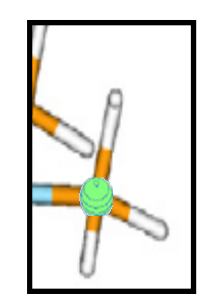
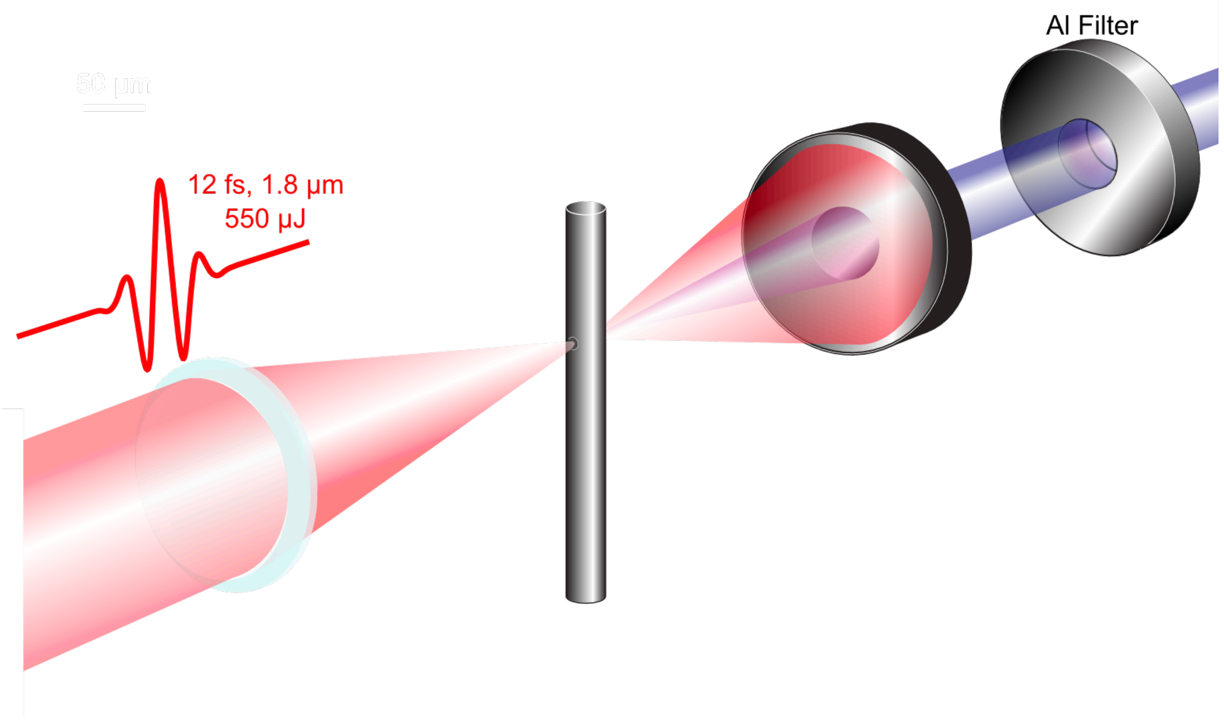
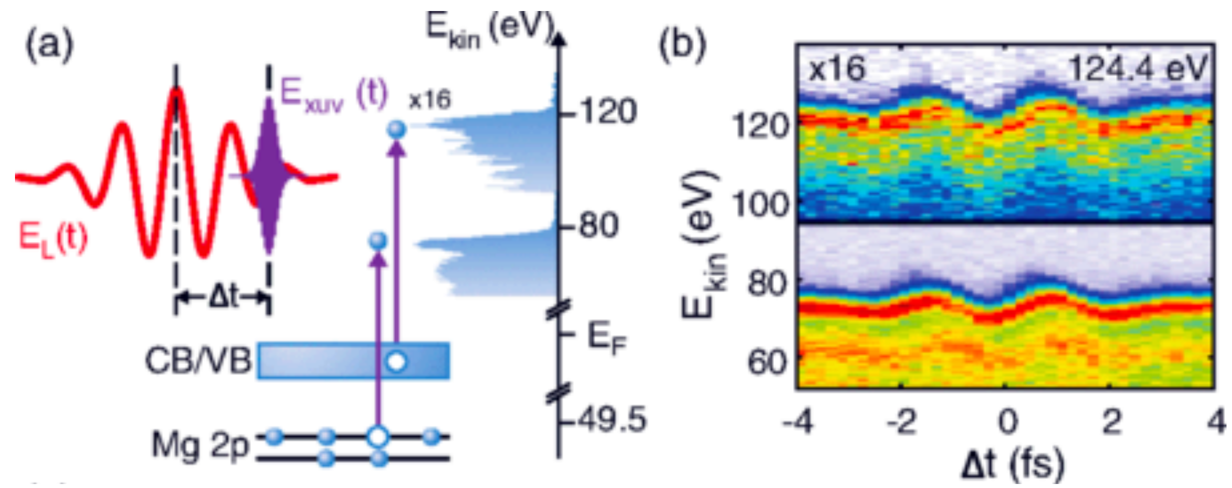


Table-Top Attosecond Light Sources

A.S. Johnson et al. Science Advances Vol. 4, no. 5, 2018





Riemensberger et al. PHYSICAL REVIEW LETTERS 123, 176801 (2019)

-Established technique
(Been around for ~20 years)
Hentschel, M. et al. Attosecond metrology. Nature 414, 509 (2001).
-Isolated pulses down to 50 as
-Scales very poorly to X-ray energies

Typical applications:
Dynamics induced by intense IR fields
Measurement of photoemission delays

XLEAP: X-ray Laser-Enhanced Attosecond Pulse Generation

SLAC

J. Duris, S. Li et al. Nature Photonics (ACCEPTED)

Siqi Li

J. Duris

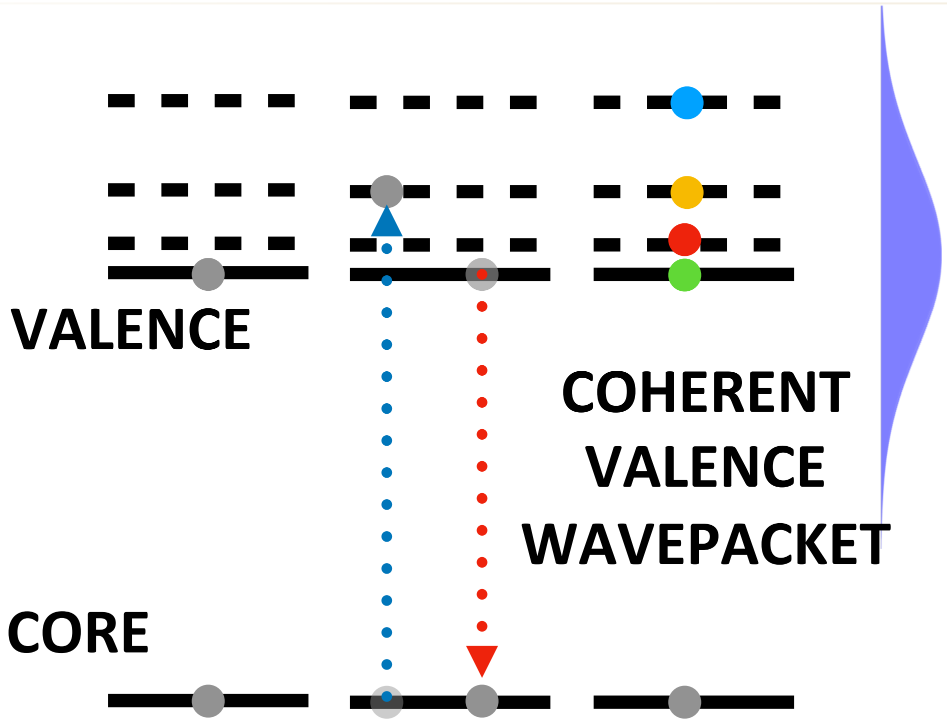
Collaboration:
SLAC (AD, LCLS, PULSE), ANL
LMU, Imperial, Max Planck, U. Kassel,
TU Dortmund, TU Munich

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

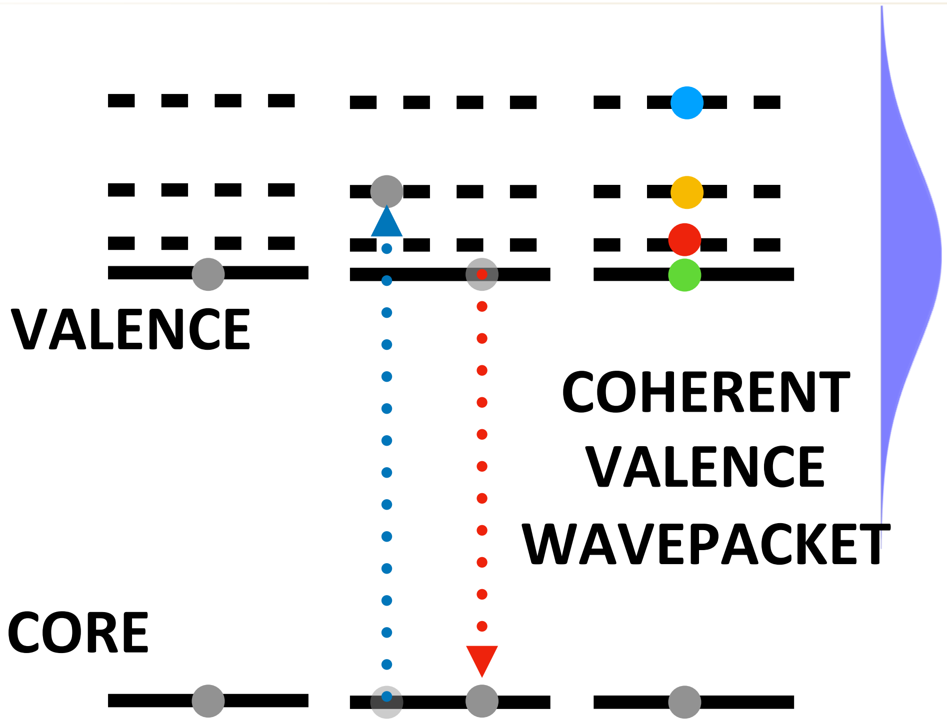
XLEAP Streaking Measurements

Comparison

Comparison



Scientific Impact



Plasma-Based Attosecond FELs

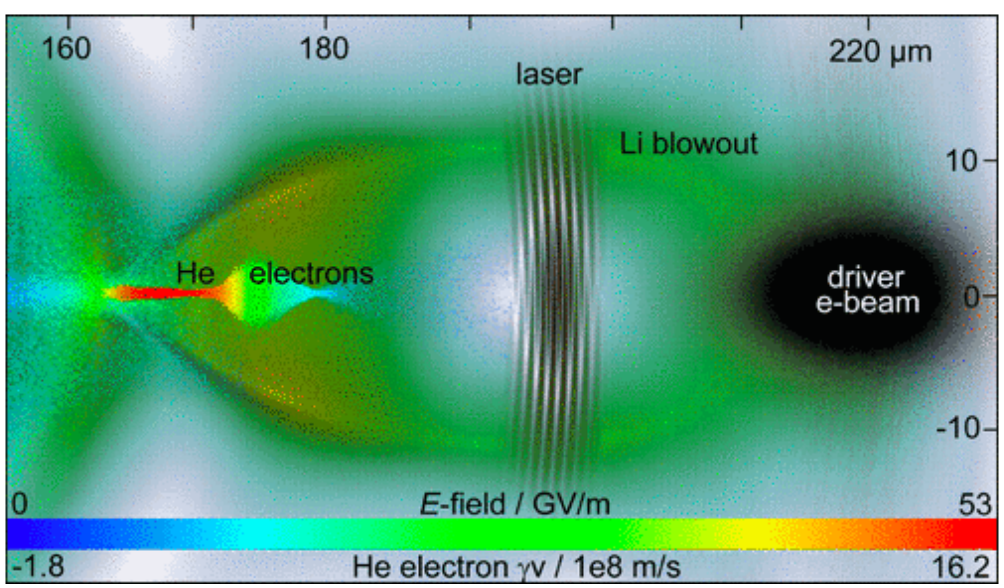
SLAC

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

C. Emma

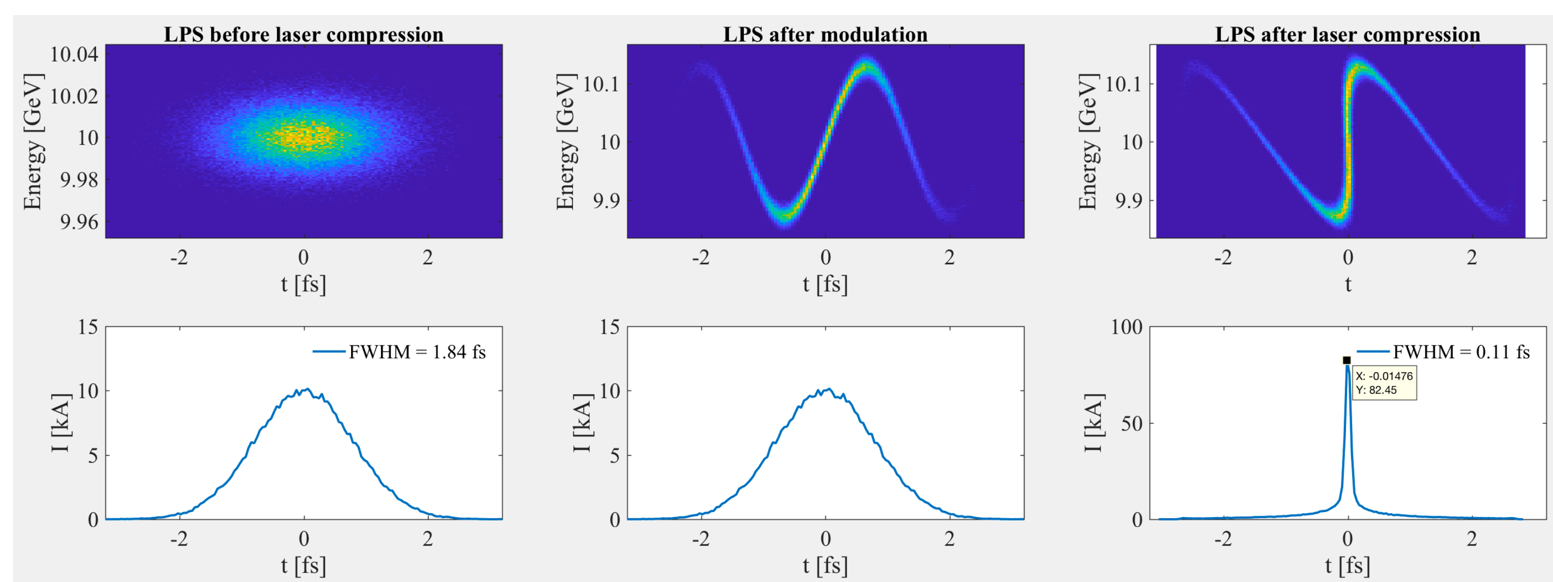
$$L_g \propto \epsilon_n^{5/6} \rightarrow \Delta t_{min} \propto \epsilon_n^{5/6}$$

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



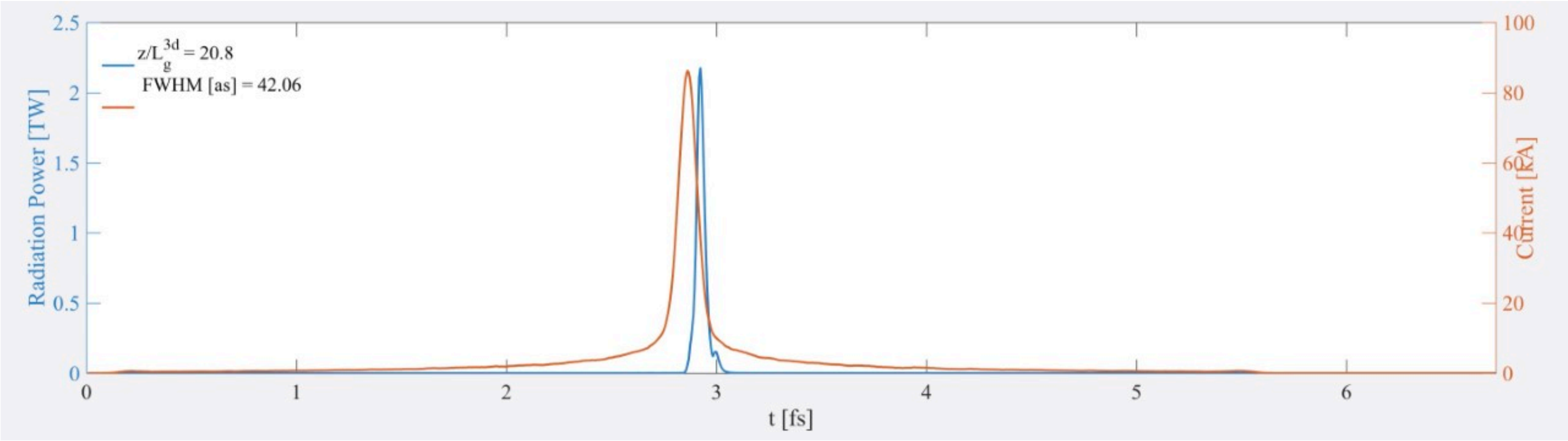
B. Hidding, G. Pretzler, J. B. Rosenzweig, T. Königstein, D. Schiller, and D. L. Bruhwiler Phys. Rev. Lett. **108**, 035001

Beam from FACET-II plasma photo-injector sim.
Assuming transport and ESASE compression

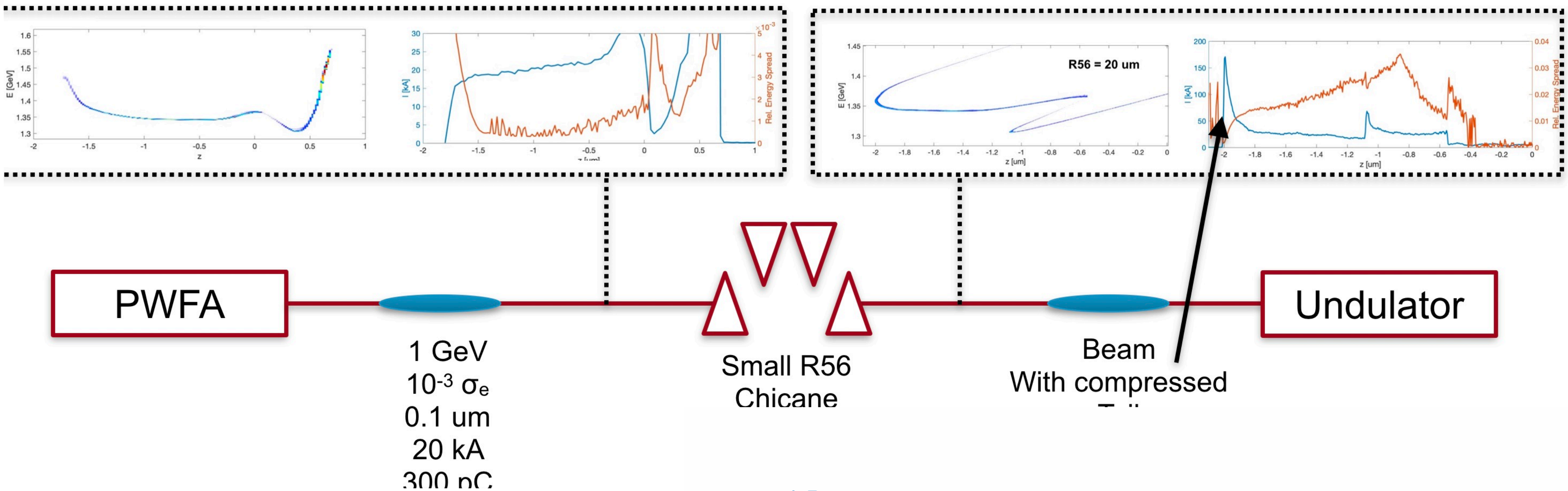


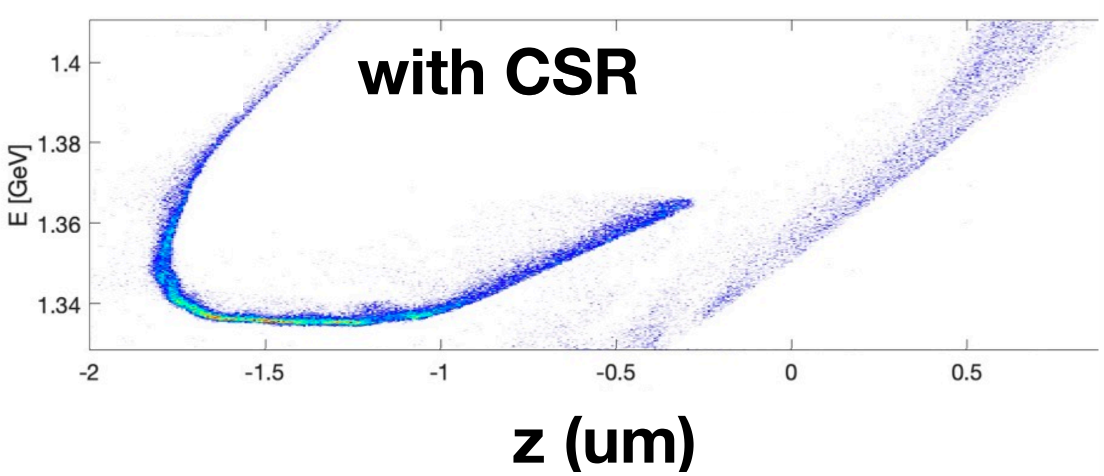
GENESIS SIMULATION - no tapering, with LSC

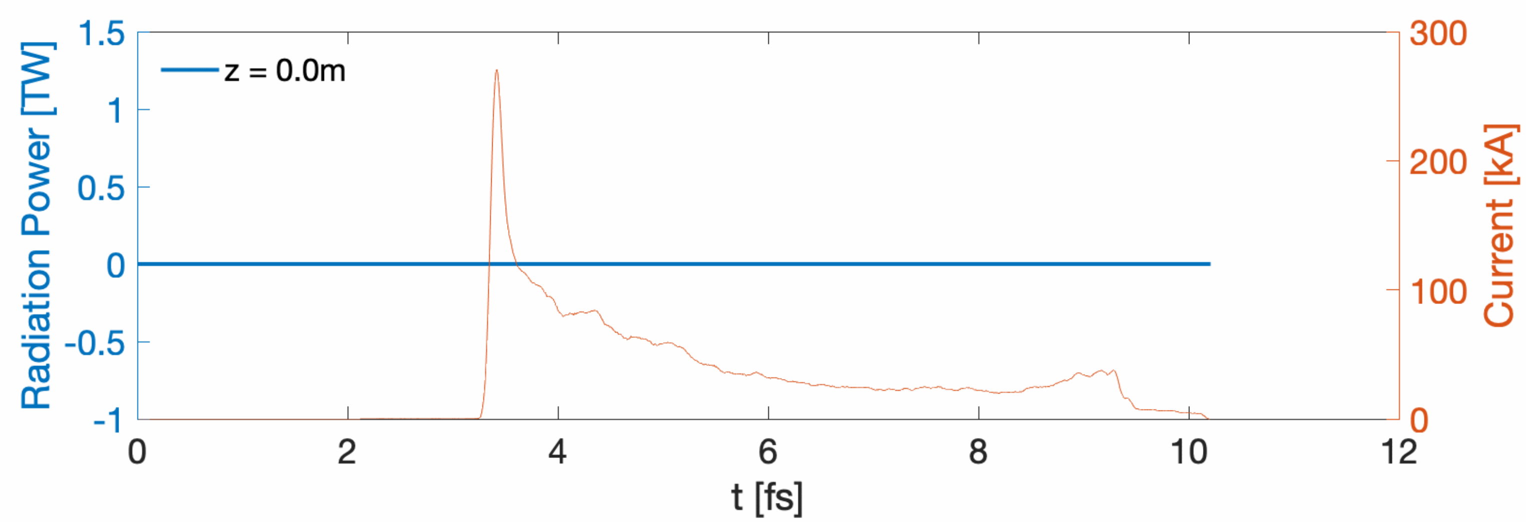
42 as - 2 TW at 1 nm. Factor 5 shorter than LCLS
Comparable to shortest HHG pulse ever (10 M x brighter!)

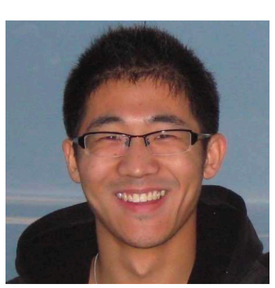


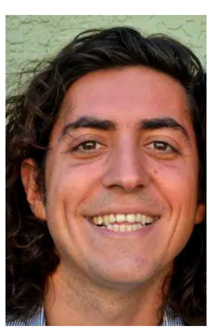
Start-to-End Simulations









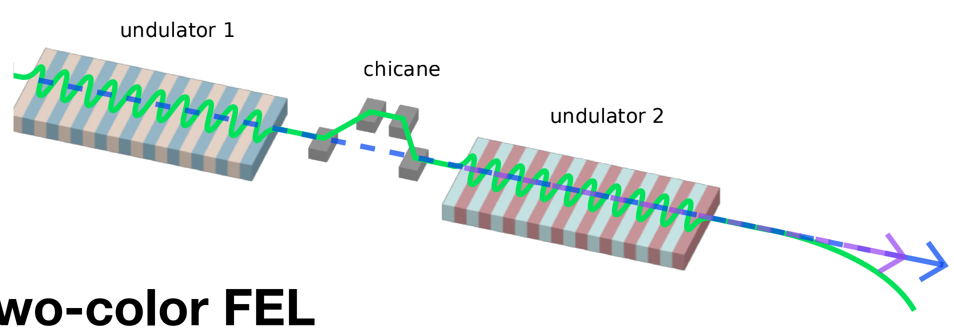


Xinlu Xu **Claudio Emma**

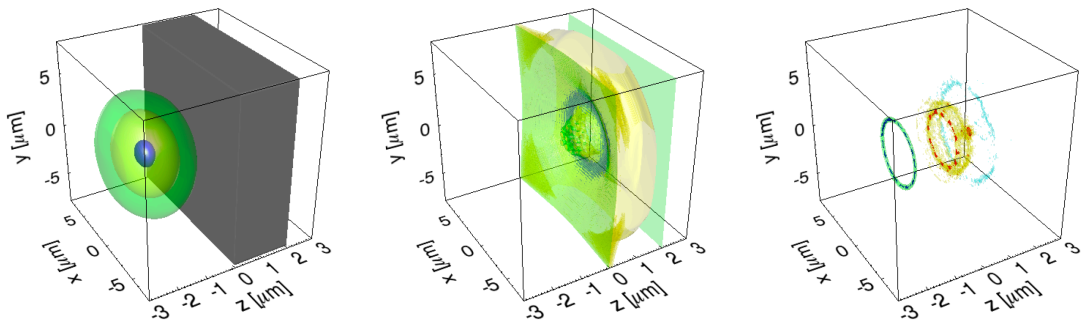
Attosecond Stability For Pump/Probe

SLAC

Use radiation generated by electron bunch

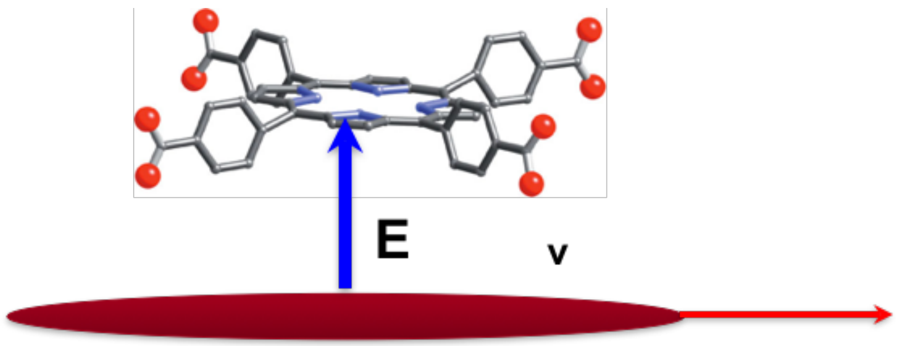


Two-color FEL
UV or Optical afterburner

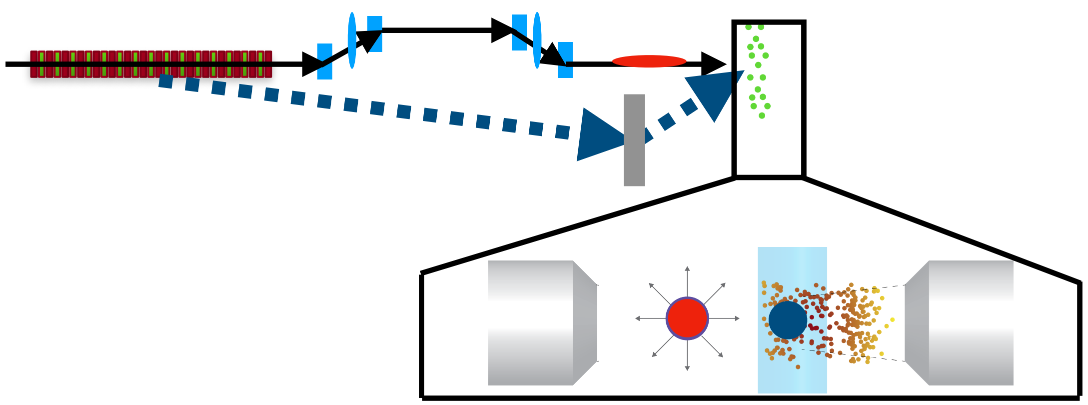


Attosecond relativistic transition radiation

Use field of the electron bunch



$$E_{\perp} \simeq \frac{Z_0 I(s)}{2\pi r}$$



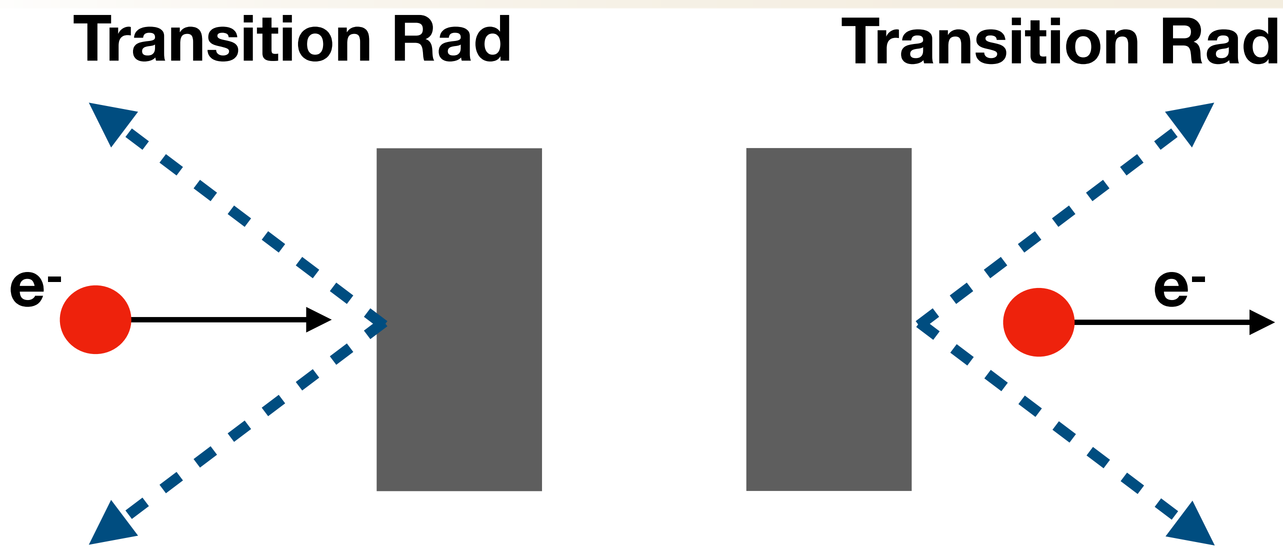
Two-Color Attosecond Pulses

~100 as jitter

< 0.5 as jitter

Stop before saturation to achieve two-color lasing (10-20% saturation)…
With PWFA approach pump/probe with TW peak power!

Relativistic Transition Radiation



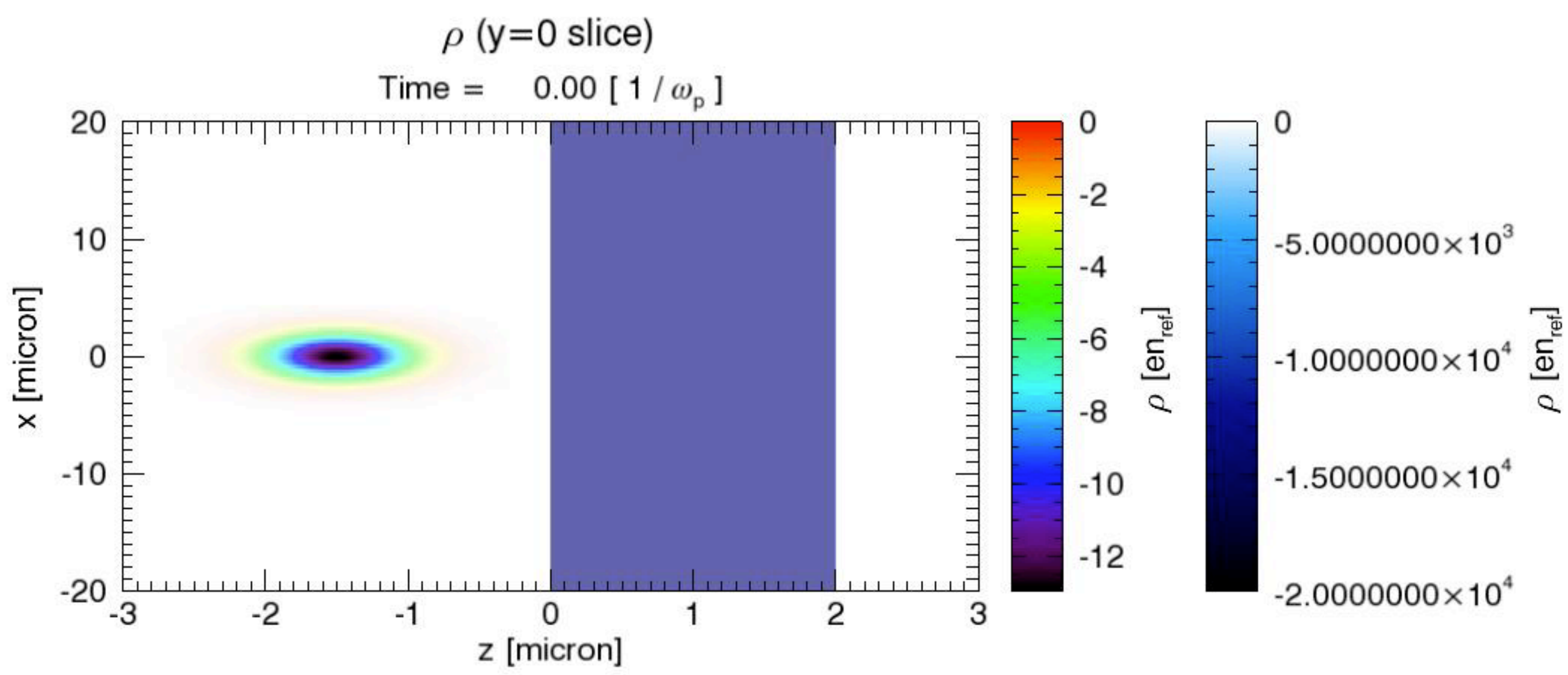
Equivalent to reflection of Transverse Coulomb field…

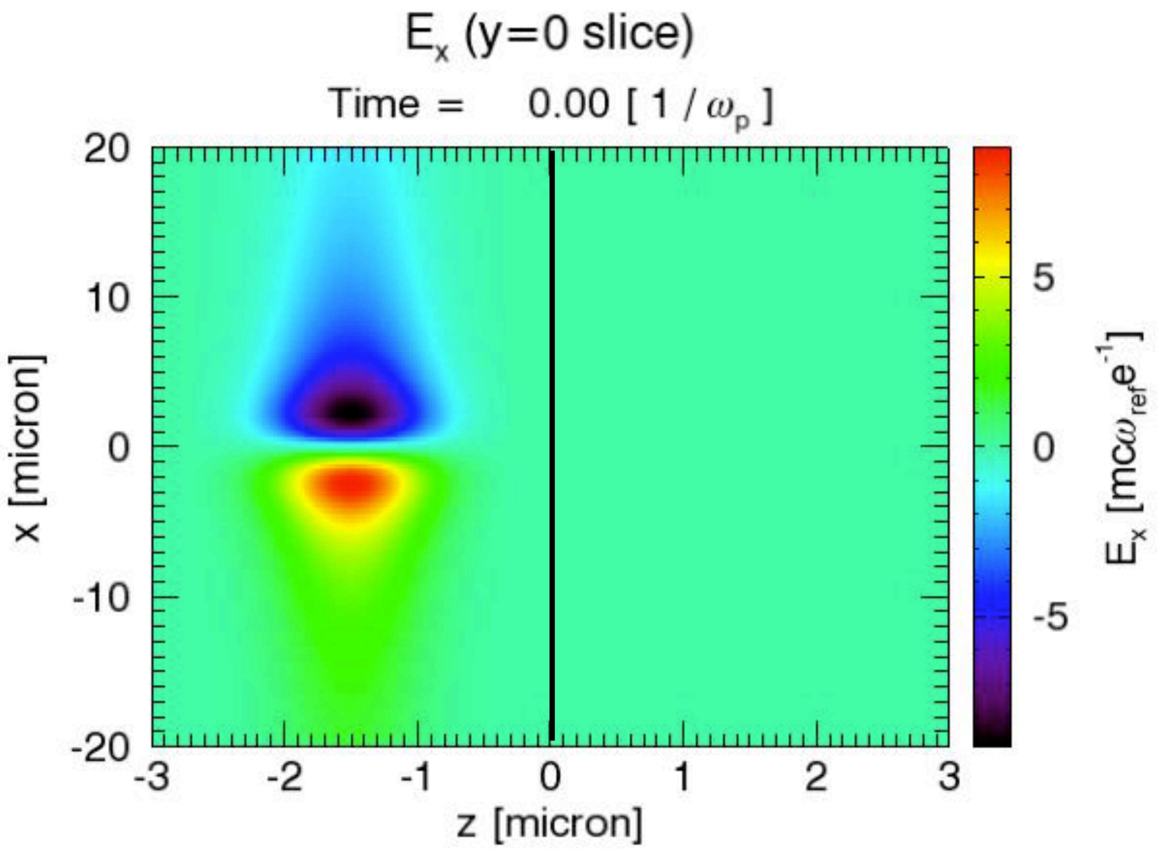
$$E_{\perp} = \frac{Z_0 I}{2\pi r}$$

For FACET or LCLS fields as high as ~TV/m (few atomic units)

HOWEVER field is zero inside plasma due to shielding

Good Old Transition Radiation



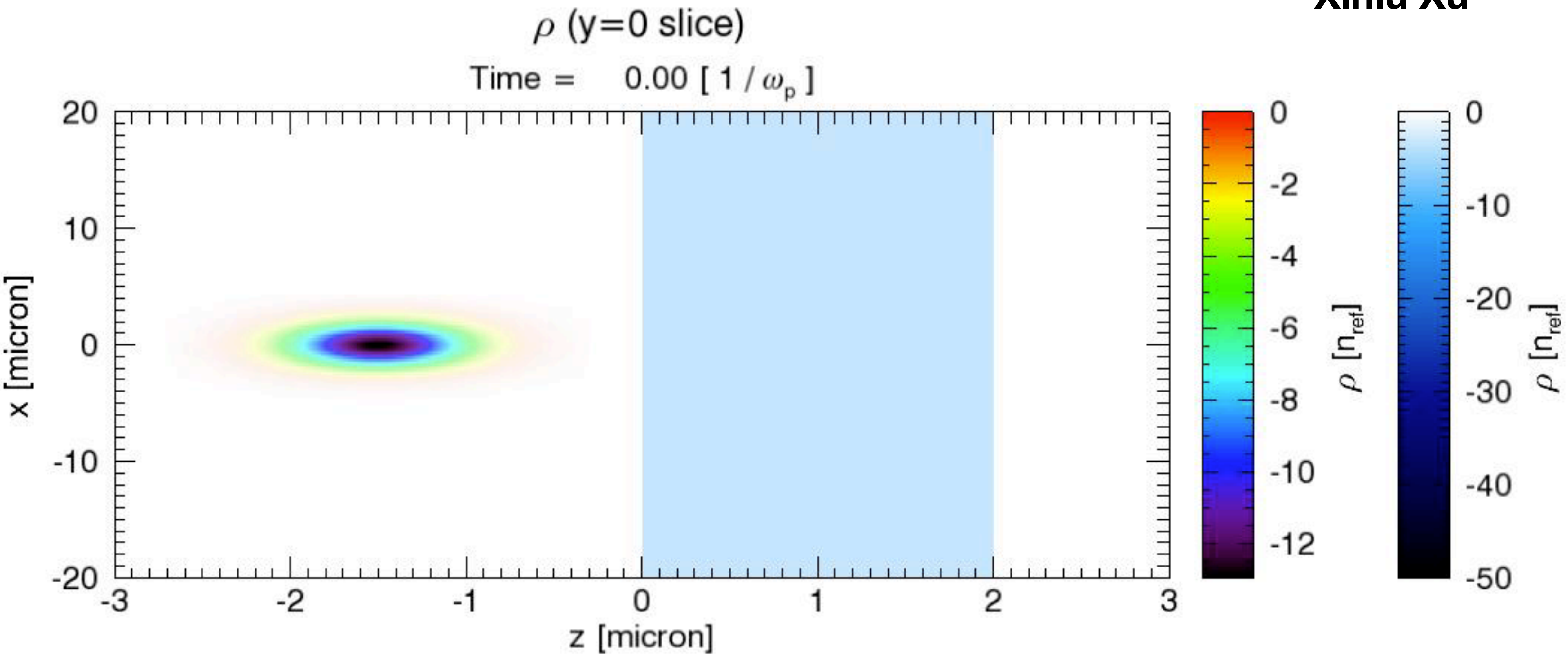


Relativistic Transition Radiation

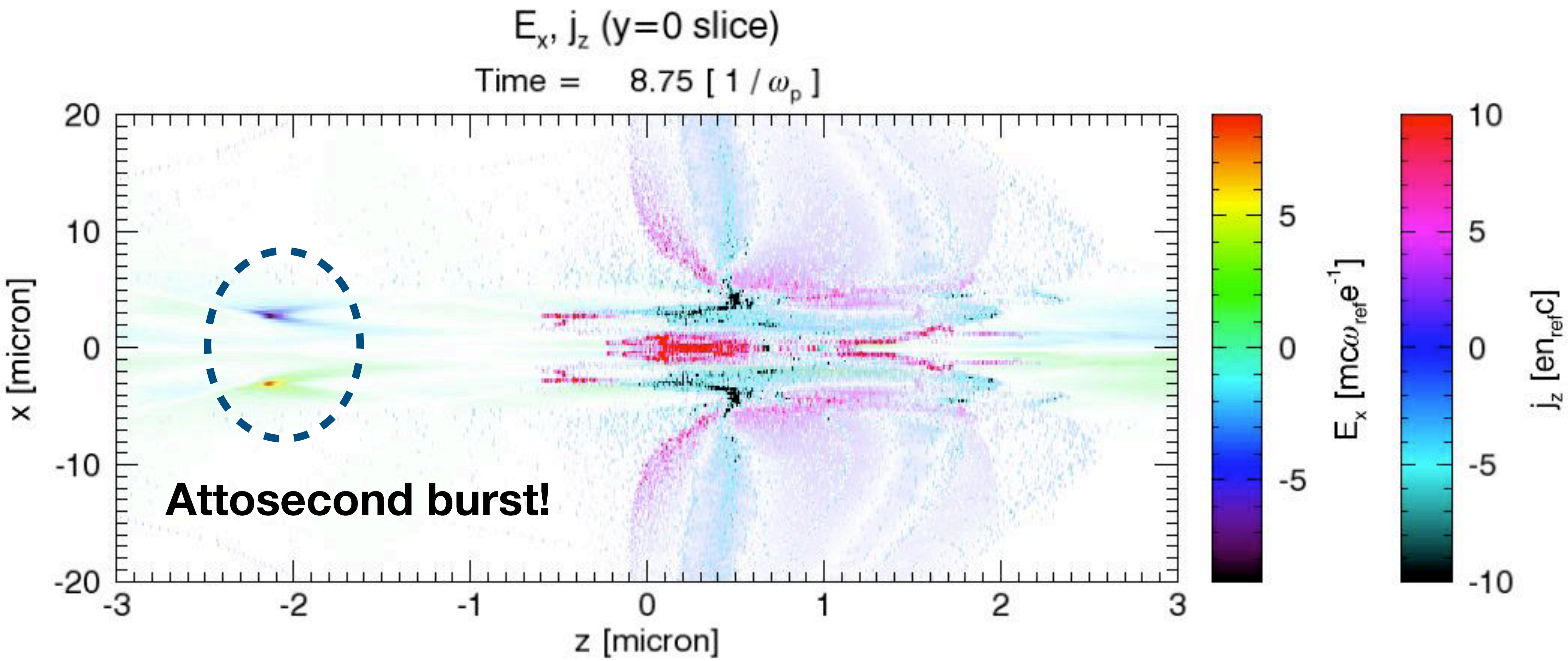
WHAT HAPPENS ABOVE THE WAVE-BREAKING LIMIT?

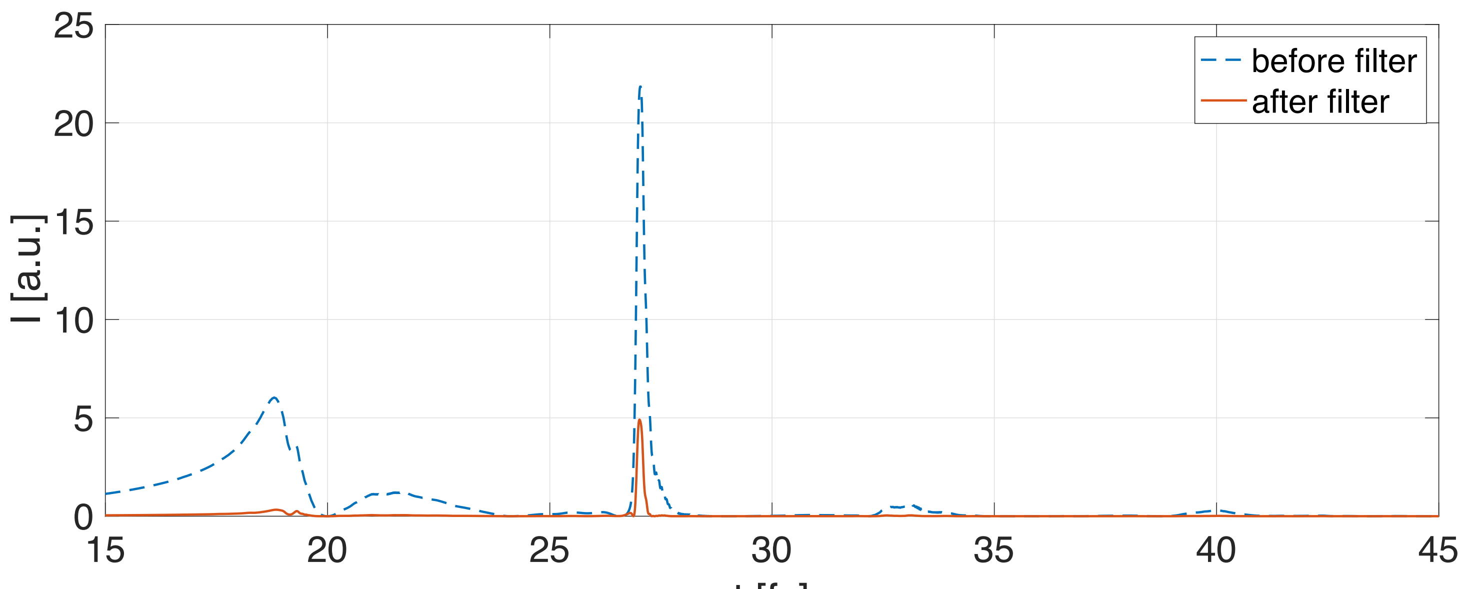
Xinlu Xu

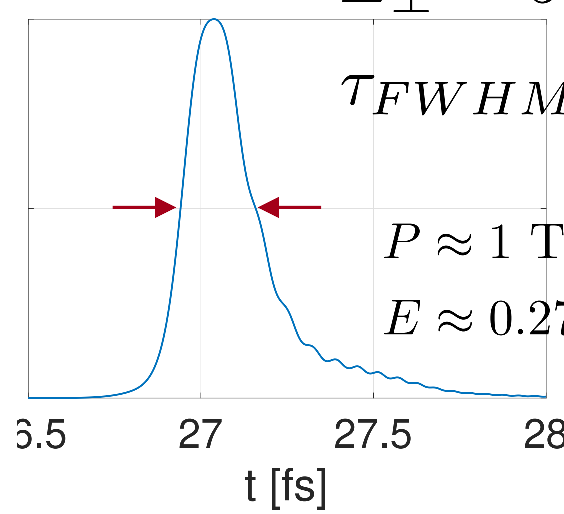
Plasma electrons accelerated to relativistic electrons!!!!



Relativistic Transition Radiation







$$E_\perp \approx 5\ \mathrm{TV/m}$$

$$\tau_{FWHM} \approx 220\ \mathrm{as}$$

$$P \approx 1\ \mathrm{TW}$$

$$E \approx 0.27\ \mathrm{mJ}$$

Relativistic Transition Radiation

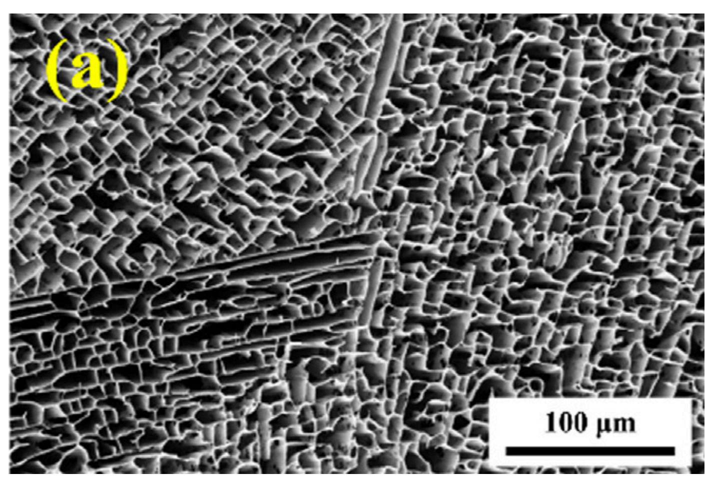
E_x, j_z (y=0 slice)

Time = 0.00 [$1/\omega_p$]

Challenge: What material?

High pressure gas cell?

Carbon nanotube foam (1% solid density) or equivalent (carbon nanotube forest etc…)



Li, Meng-Zhu, et al. *Journal of colloid and interface science* 530 (2018): 113-119

TV/m

≈ 220 as

mJ

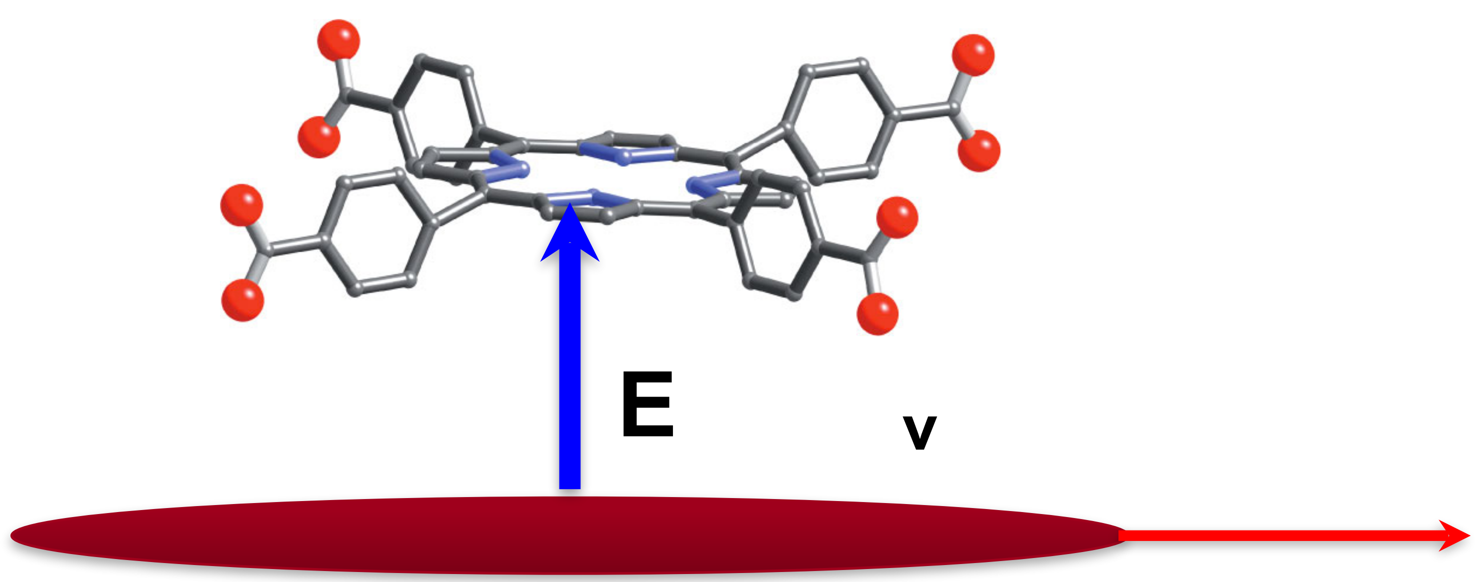
Beam-Based Ultrafast Science

$$E_{\perp} = \frac{Z_0 I(t)}{2\pi r}$$

Why not use Space-charge field?
-High intensity (~10s to 100s GV/m)
-Synchronized to FEL with attosecond precision
-100% bandwidth

$$E_z << E_{\perp}$$

Where do we win?
Attosecond time-scales (high field, good synch.)
THz fields (much larger fields than tabletop)

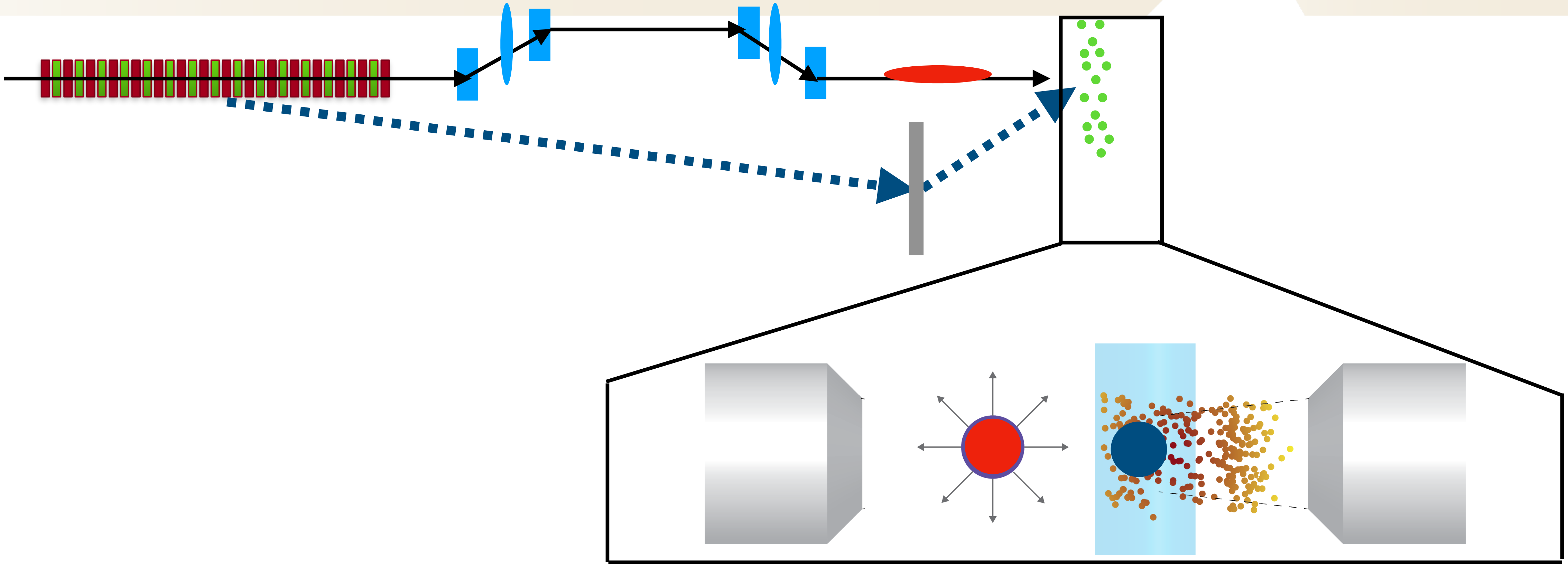


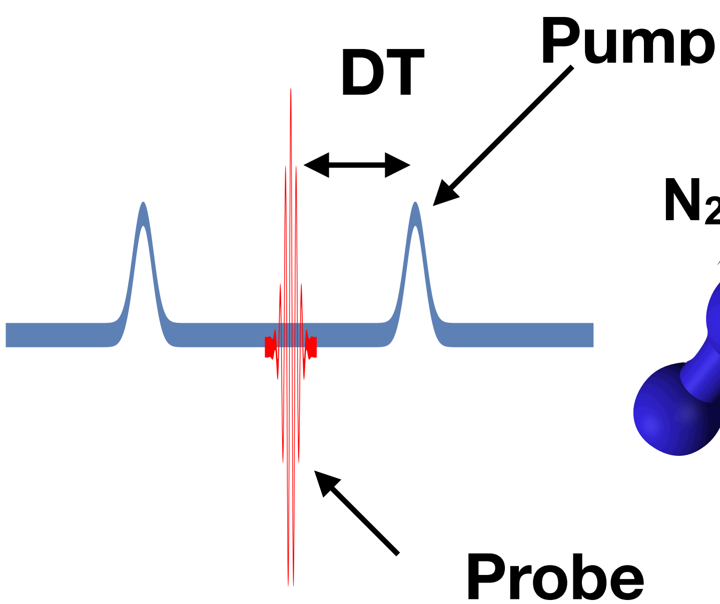
Fields up to TV/m in half-cycle pulse!

J. B. Rosenzweig et al.: Teravolt-per-meter plasma wakefields from low-charge, femtosecond electron beams NIMA 653.1 (2011): 98-102.

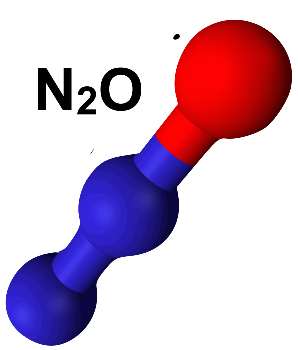
Photon-Electron Pump/Probe Experiment at LCLS

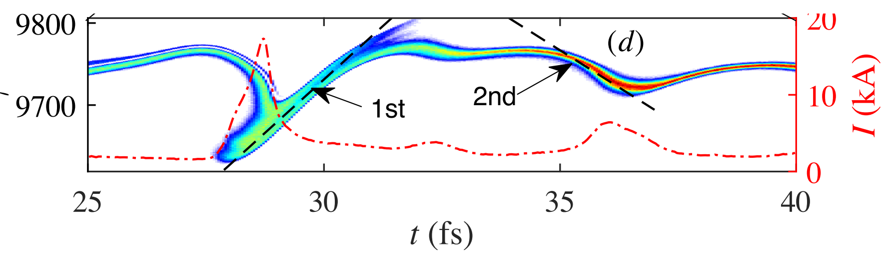
D. Cesar



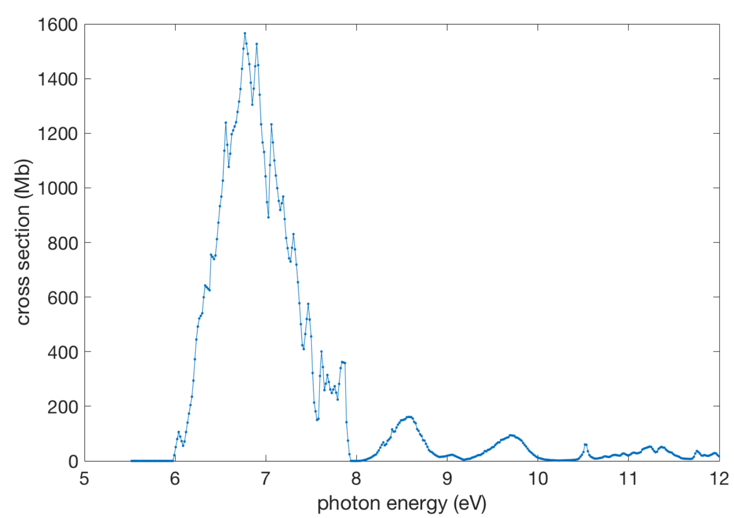


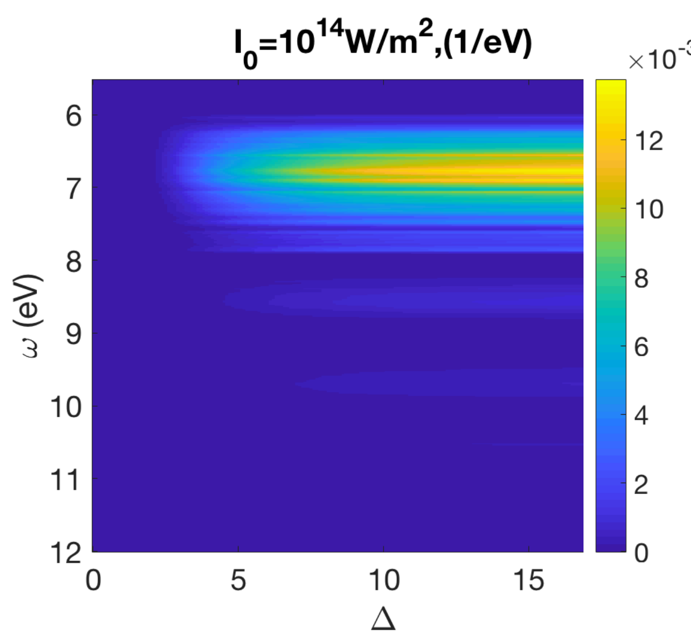
N_2O



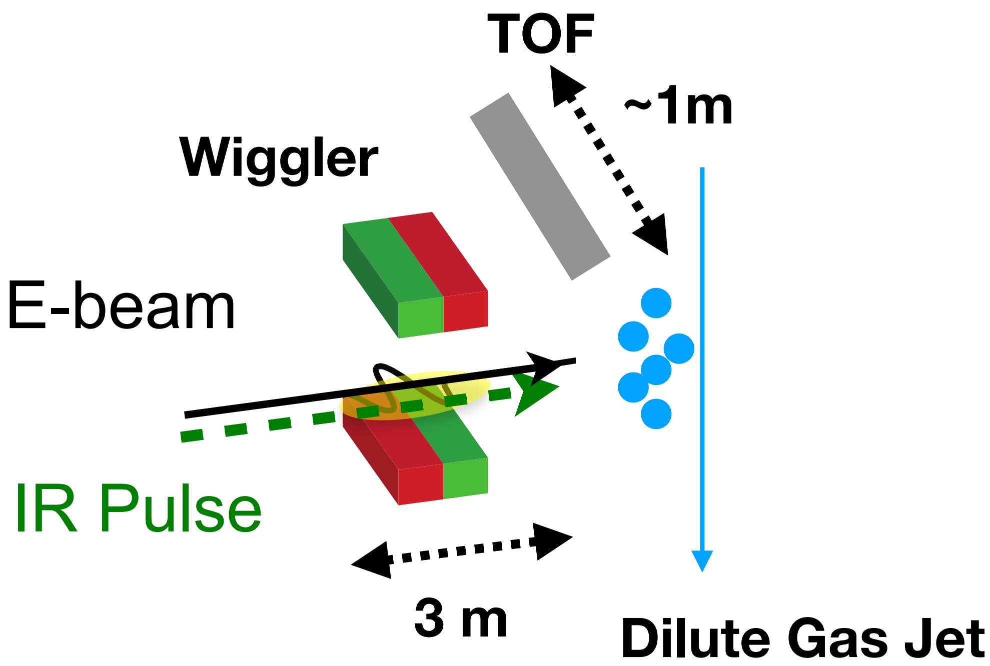


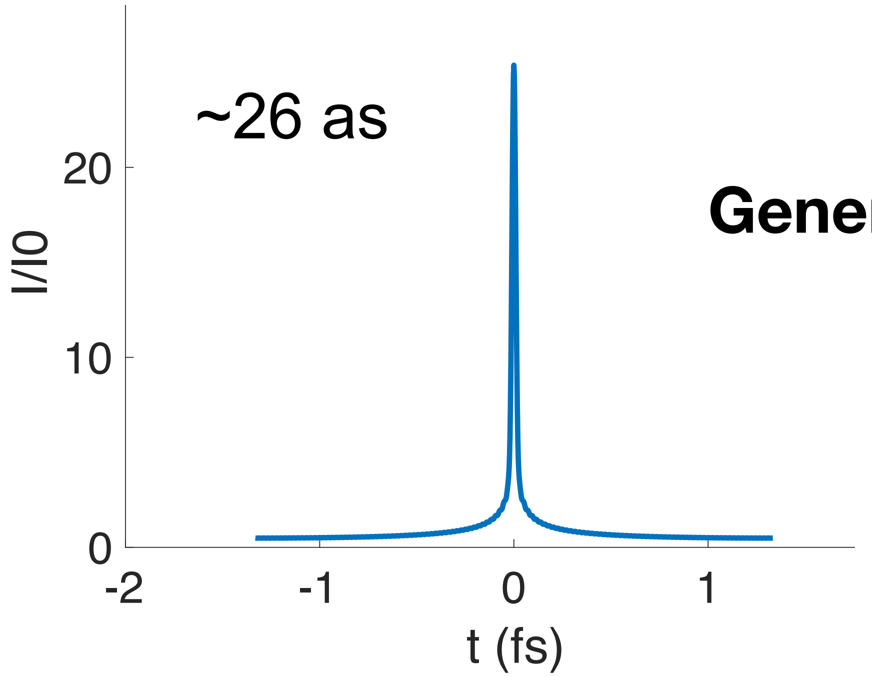
Sub-fs field: impulsively excite valence states





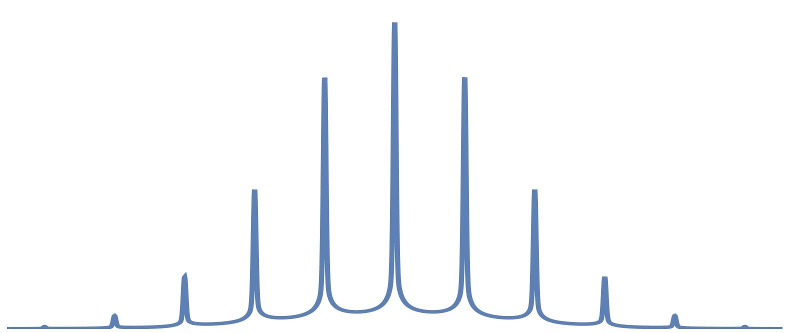
Opportunities with FACET-II Linac Beam





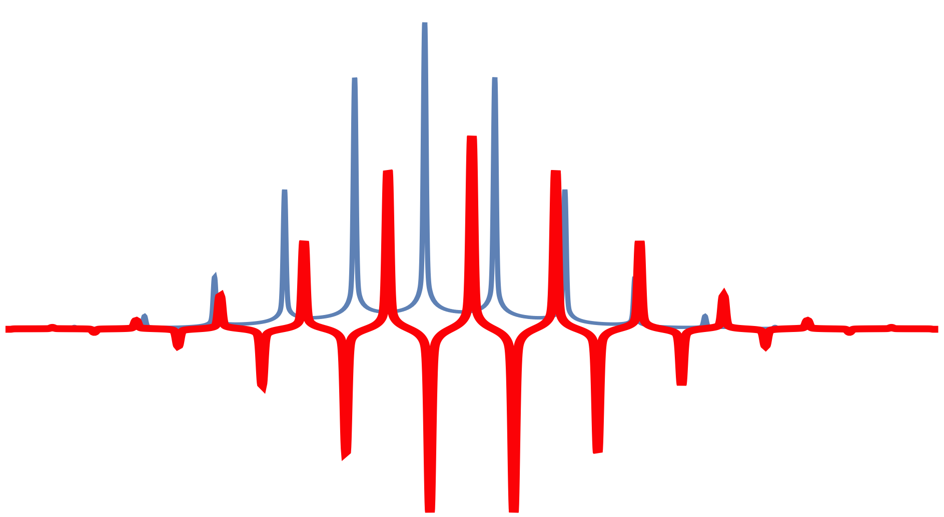
Using FACET-II TW laser
Generate 20 as spikes!

Beam Only



-Impulsive ionization
-Photo-emission delays

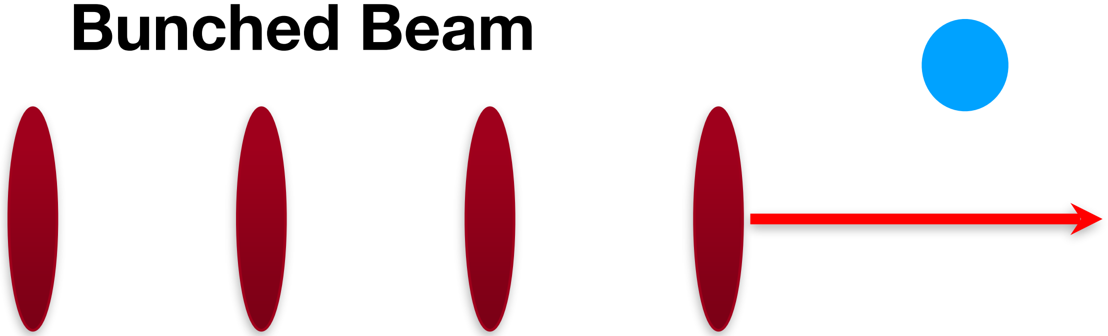
Beam + CSR/CUR



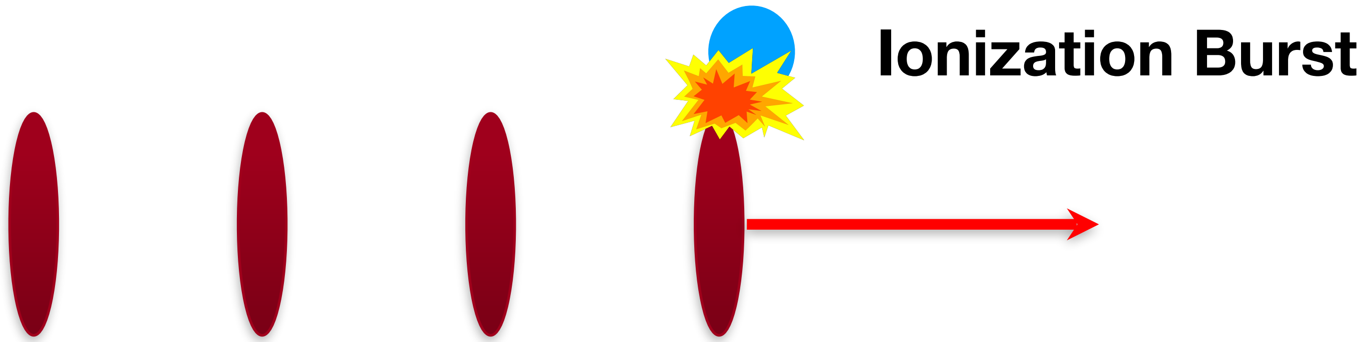
-Probe strong-field induced Electron dynamics

Ongoing FACET-II Proposal: Attoclock Experiment

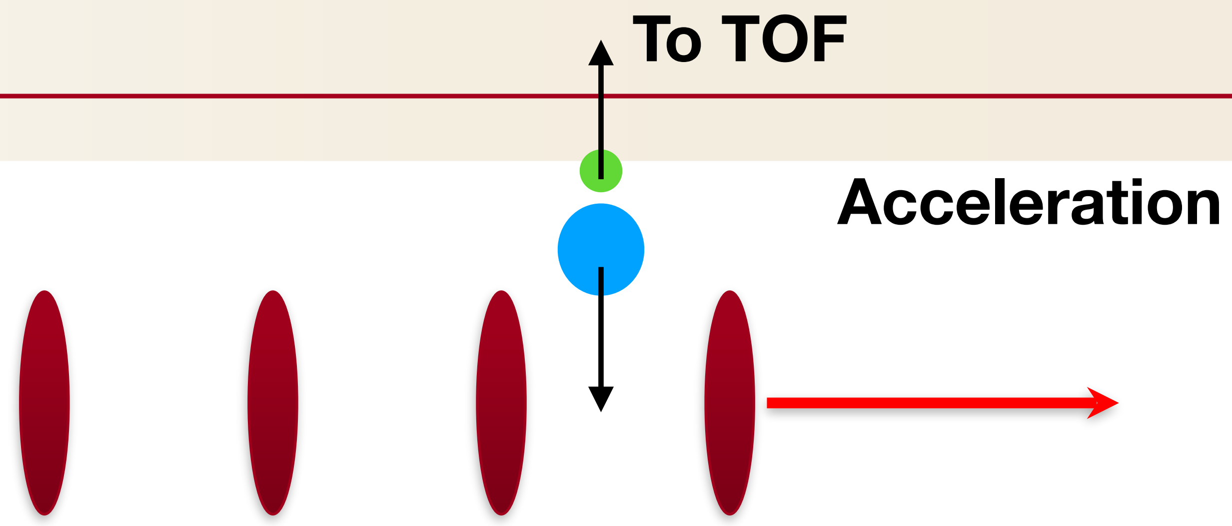
Bunched Beam



Ongoing FACET-II Proposal: Attoclock Experiment

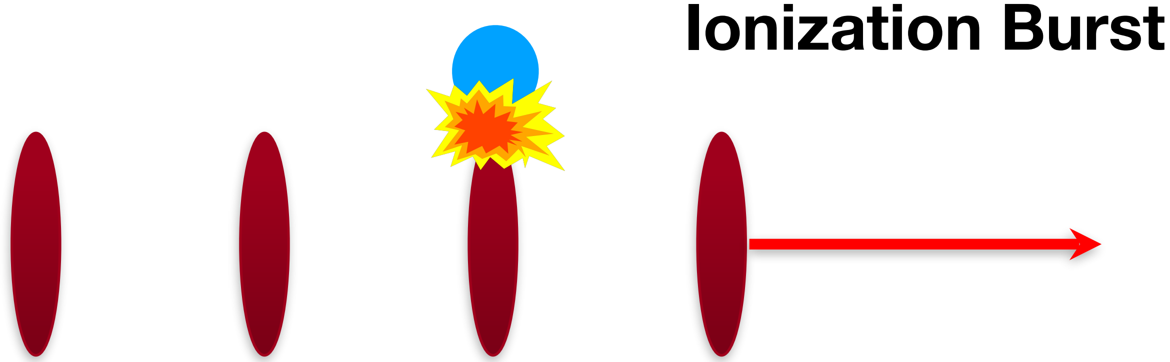


Ongoing FACET-II Proposal: Attoclock Experiment

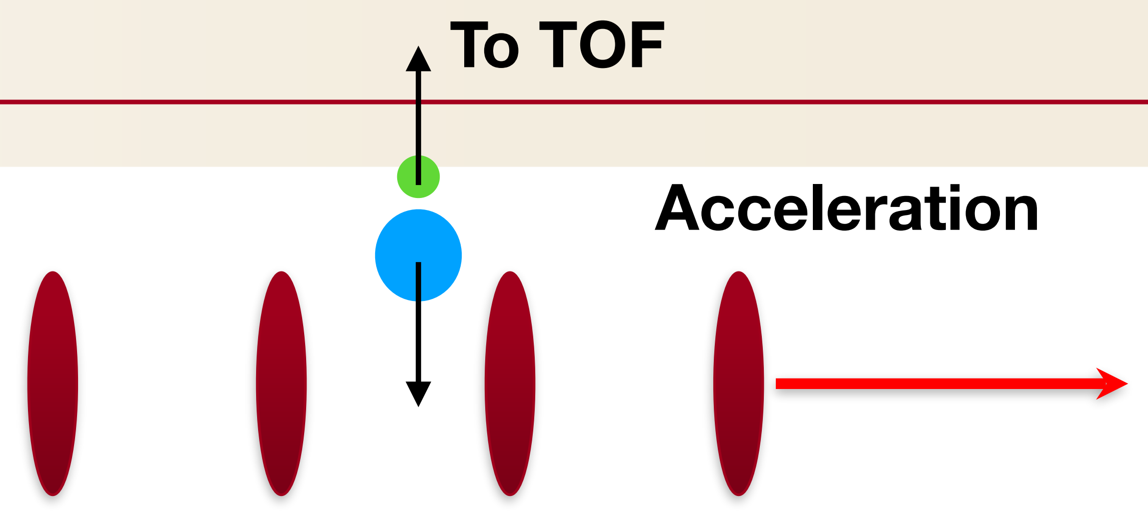


Repeat for following micro-bunches…
Ionization events from different micro bunches mapped onto different momenta!

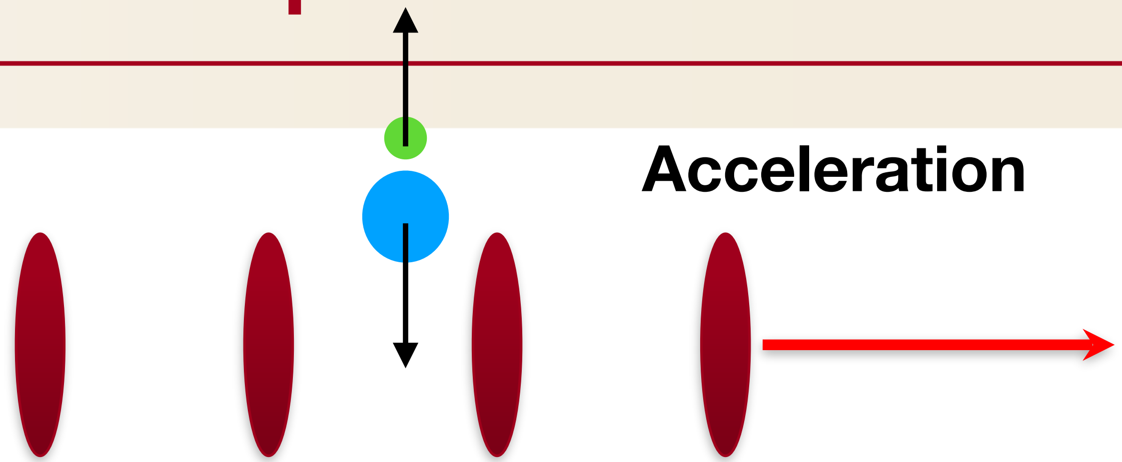
Ongoing FACET-II Proposal: Attoclock Experiment



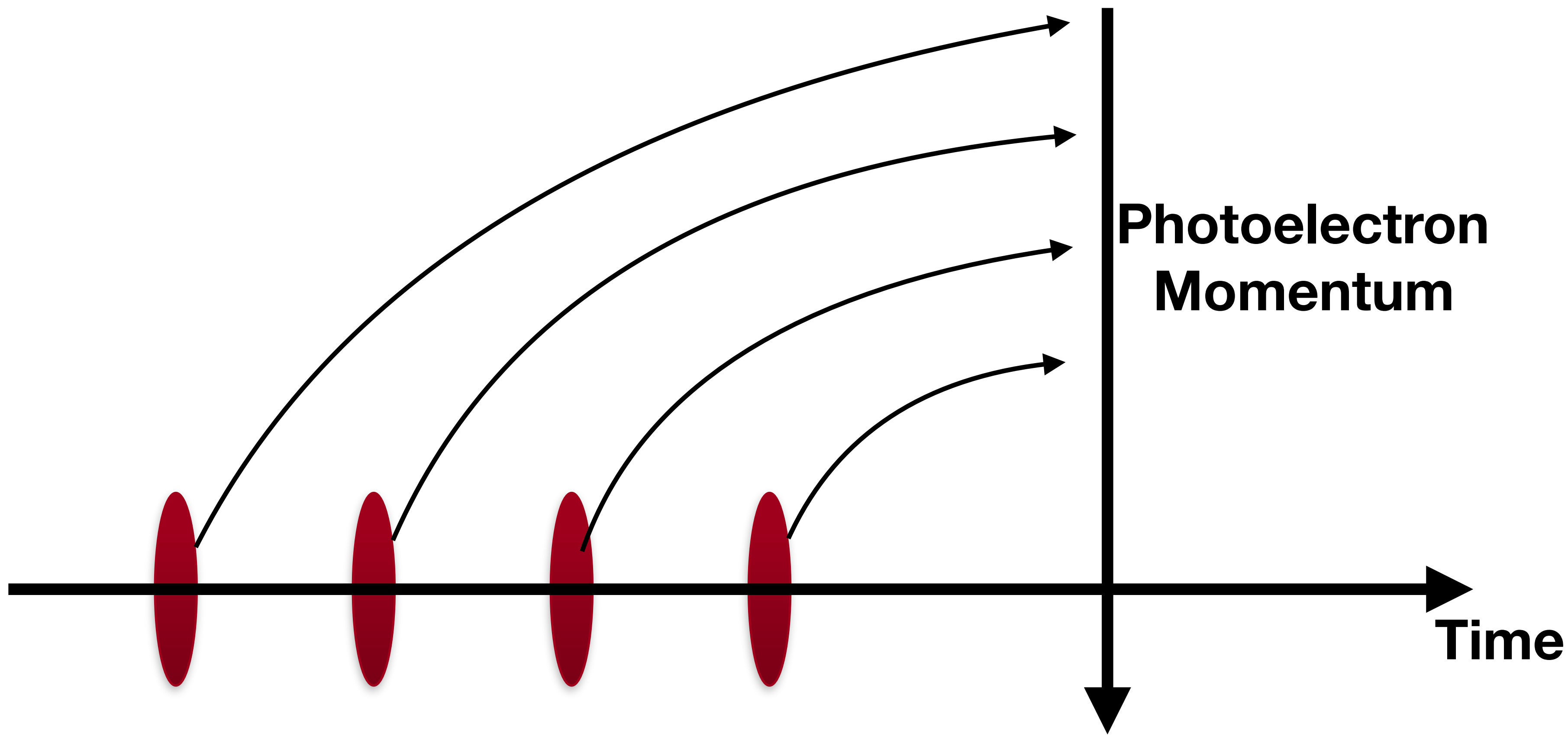
Ongoing FACET-II Proposal: Attoclock Experiment



Ongoing FACET-II Proposal: Attoclock Experiment

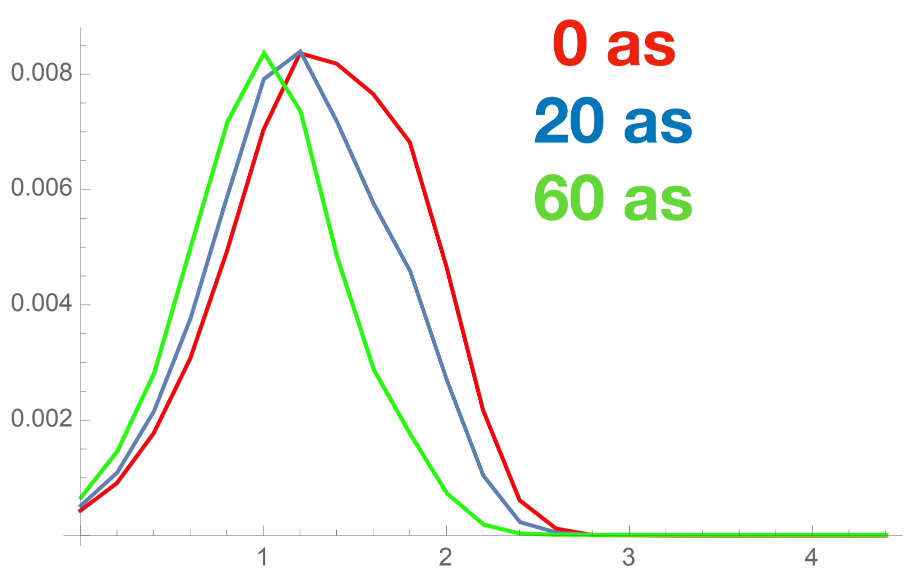


Repeat for following micro-bunches…
Ionization events from different micro bunches mapped onto different momenta
By unipolar E-field!



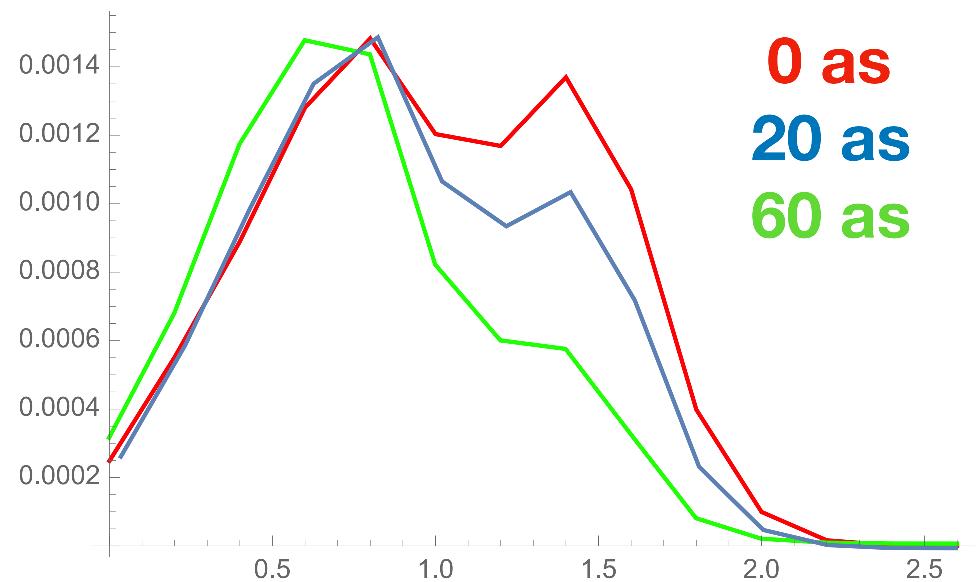
SFA Simulations + Radial Integration

SLAC



p (a.u.)

E = 100 GV/m



p (a.u.)

E = 50 GV/m

Technique sensitive to ~20 as ionization delays
Focal volume averaging kills signal for E > 100 GV/m
Ion microscope for stronger fields?

Summary

-Advanced accelerators offer unique opportunities for attosecond science due to bandwidth scaling of FEL with low emittance!

-X-ray pulses as short as 40 as with multi TW peak power predicted from PWFA beams

Exploring possibilities for attosecond pump/probe

- Two-color
- Relativistic transition radiation
- E-beam space-charge field

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.