



清华大学
Tsinghua University



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ESS
EUROPEAN SPALLATION SOURCE

Malmö, Sweden
8-12 September 2019

THz-based sub-femtosecond metrology of relativistic electron beams

Renkai Li, Tsinghua University

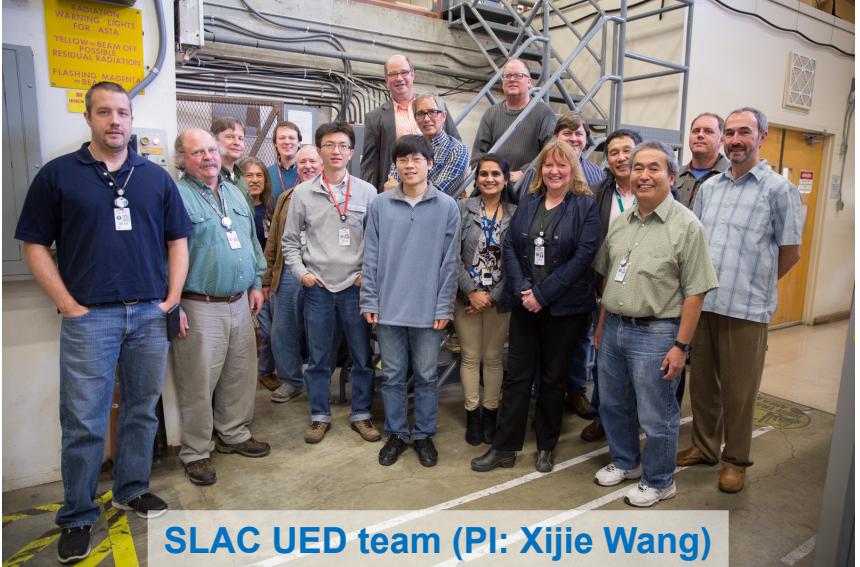
10 September 2019, Malmö, Sweden

* Previously at **SLAC National Accelerator Laboratory**

Team: R. K. Li¹, M. C. Hoffmann¹, E. A. Nanni¹, E. C. Snively¹, M. A. K. Othman¹, M. Kozina¹, B. K. Ofori-Okai¹, S. H. Glenzer^{1,2}, A. M. Lindenberg^{2,3,4}, S. Park^{1,2}, A. H. Reid¹, X. Shen¹, S. P. Weathersby¹, J. Yang¹, M. Zajac¹, X. J. Wang¹
¹ SLAC National Accelerator Laboratory ² PULSE Institute, SLAC National Accelerator Laboratory ³ SIMES, SLAC National Accelerator Laboratory ⁴ Department of Materials Science and Engineering, Stanford University



Team and Acknowledgement



- Strong support from SLAC AD, LCLS and TID
- Work supported in part by the U.S. DOE Contract No. DE-AC02-76SF00515 and the SLAC LDRD and Program Development Fund



Matthias C. Hoffmann



Emilio A. Nanni

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Outline



- Background and Motivation
 - UED, low charge beams, THz manipulation and metrology
- THz streaking of MeV beams
 - direct measurement e-beam-to-optical timing jitter
- THz compression
 - bunch length reduction and intrinsic timing jitter stabilization
- Summary and outlook

Probes into the ultrasmall and ultrafast world

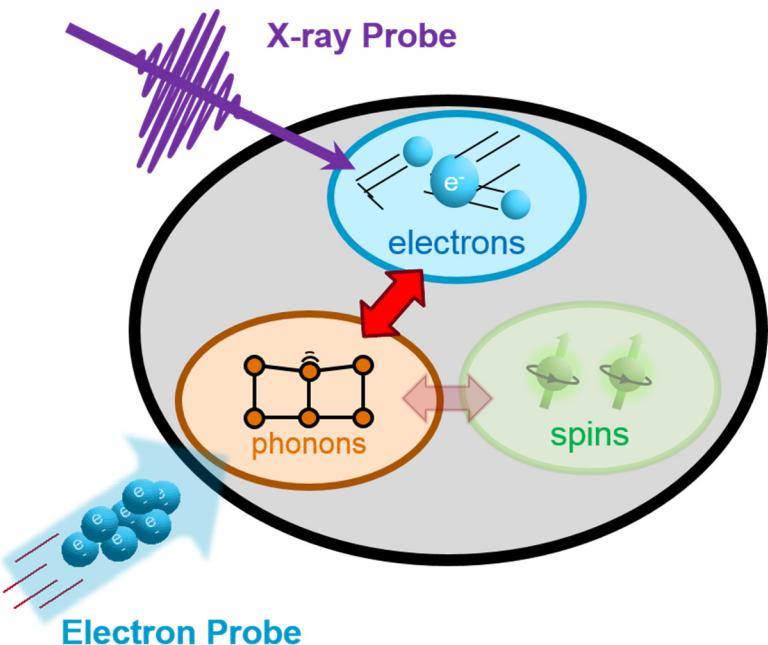
Ultrasmall:

short wavelength

Ultrafast:

short pulse duration

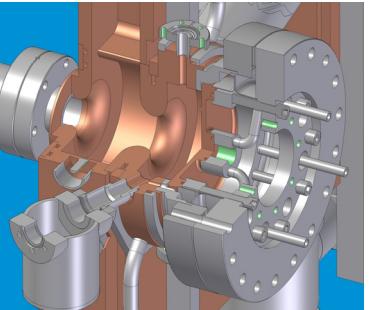
*XFEL & ultrafast electron scattering
are complementary tools towards a
complete picture of dynamics*





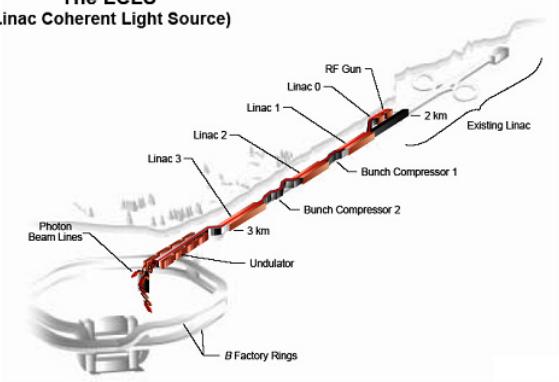
Same source, two machines

LCLS gun

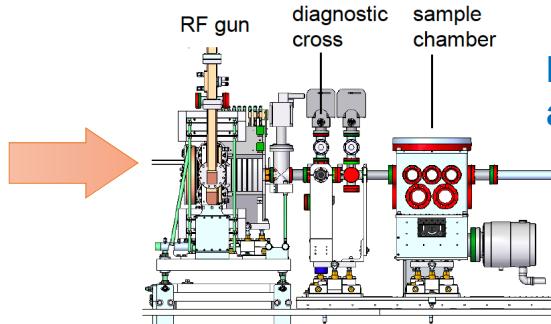
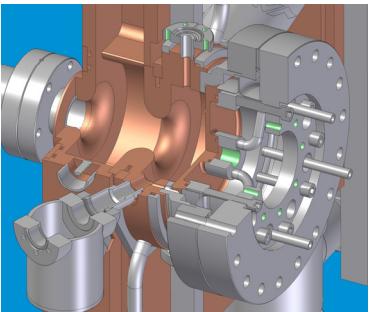


Same source, two machines

The LCLS
(Linac Coherent Light Source)



LCLS gun

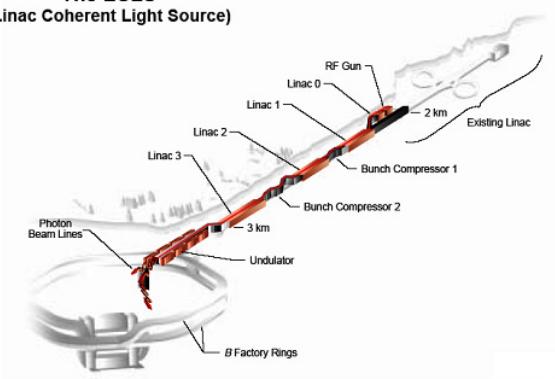


MeV UED
at SLAC

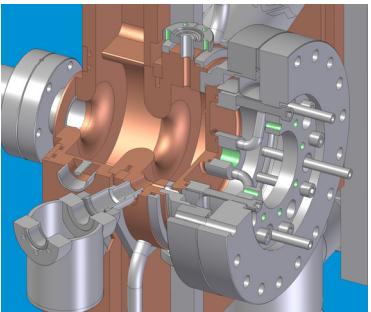
Same source, two machines

XFEL: 100s of pC per bunch

The LCLS
(Linac Coherent Light Source)



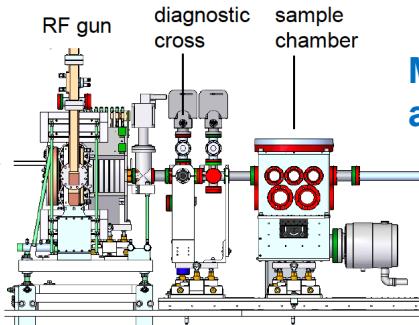
LCLS gun



UED: 10-100 fC per bunch

RF gun
diagnostic cross
sample chamber

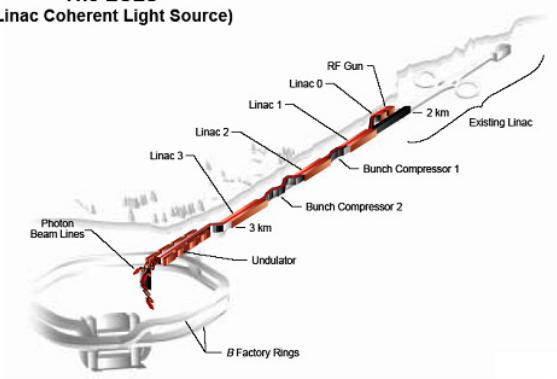
**MeV UED
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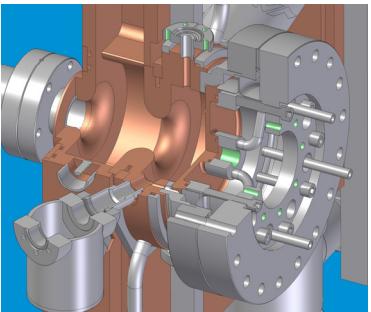
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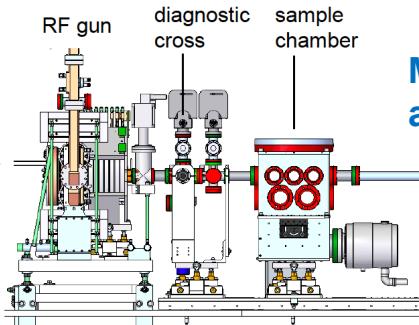
LCLS gun



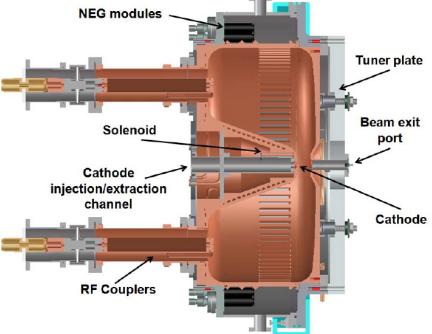
UED: 10-100 fC per bunch

RF gun diagnostic cross sample chamber

**MeV UED
at SLAC**



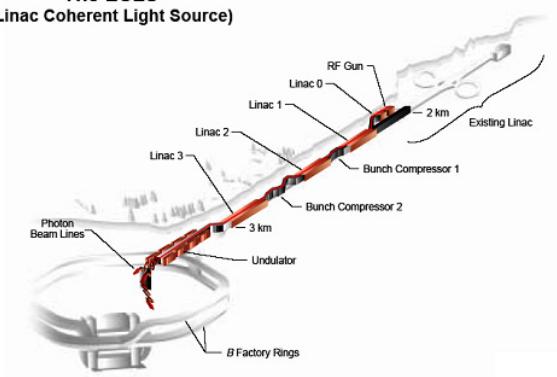
APEX/LCLS-II gun



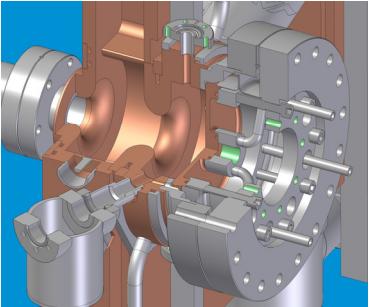
Same source, two machines

XFEL: 100s of pC per bunch

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(Linac Coherent Light Source)



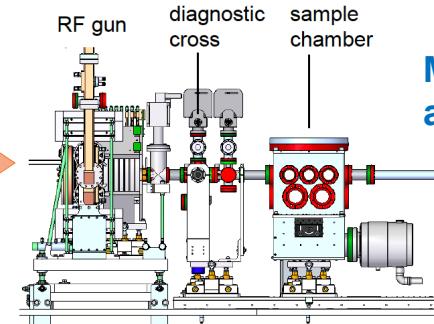
LCLS gun



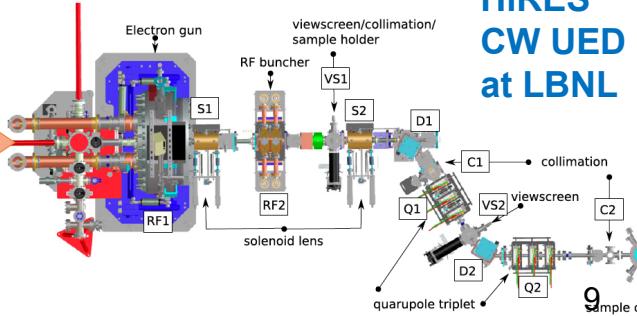
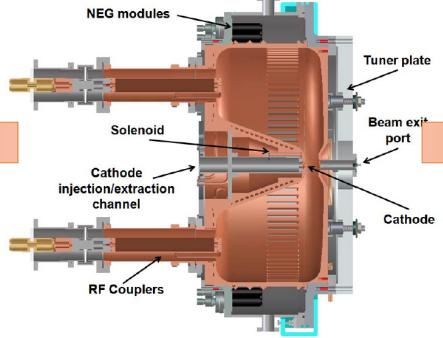
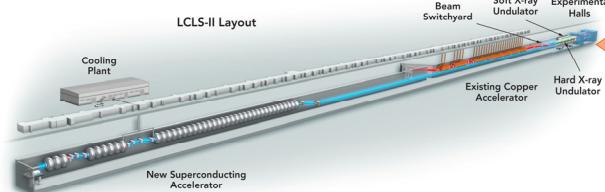
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RF gun
diagnostic cross
sample chamber

**MeV UED
at SLAC**



APEX/LCLS-II gun

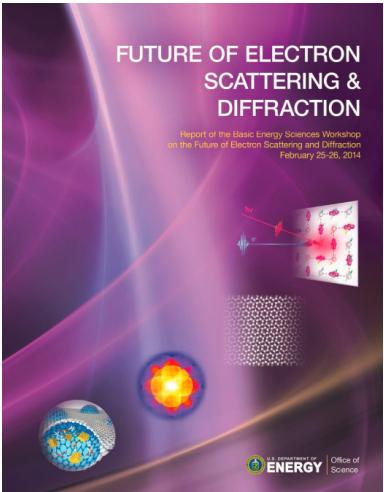
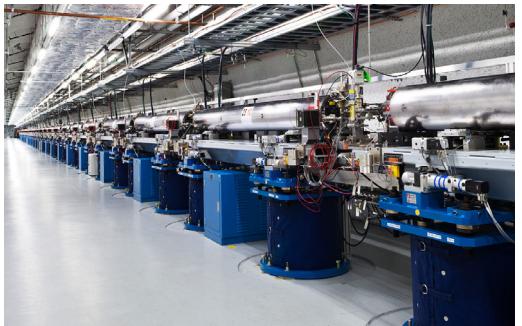


**HiRES
CW UED
at LBNL**

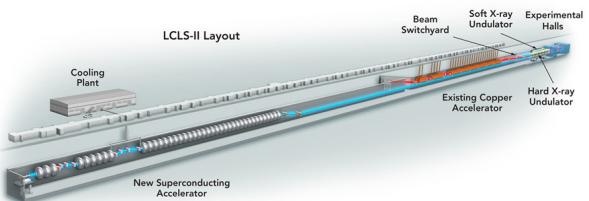


UED/UEM R&D at SLAC

SLAC UED/UEM Initiative:
“... to provide the world’s leading ultrafast electron scattering instrumentation.”



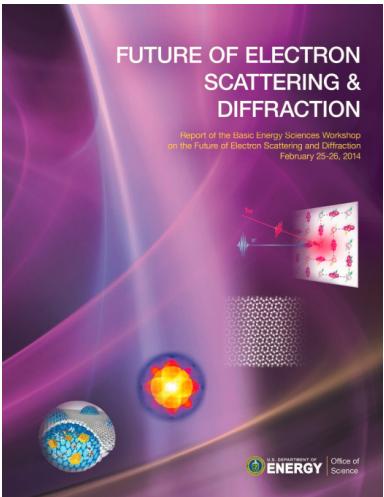
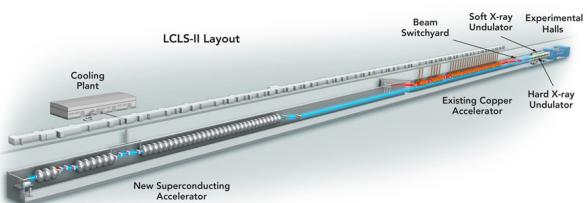
Future of Electron Scattering and Diffraction Workshop
February 25-26, 2014



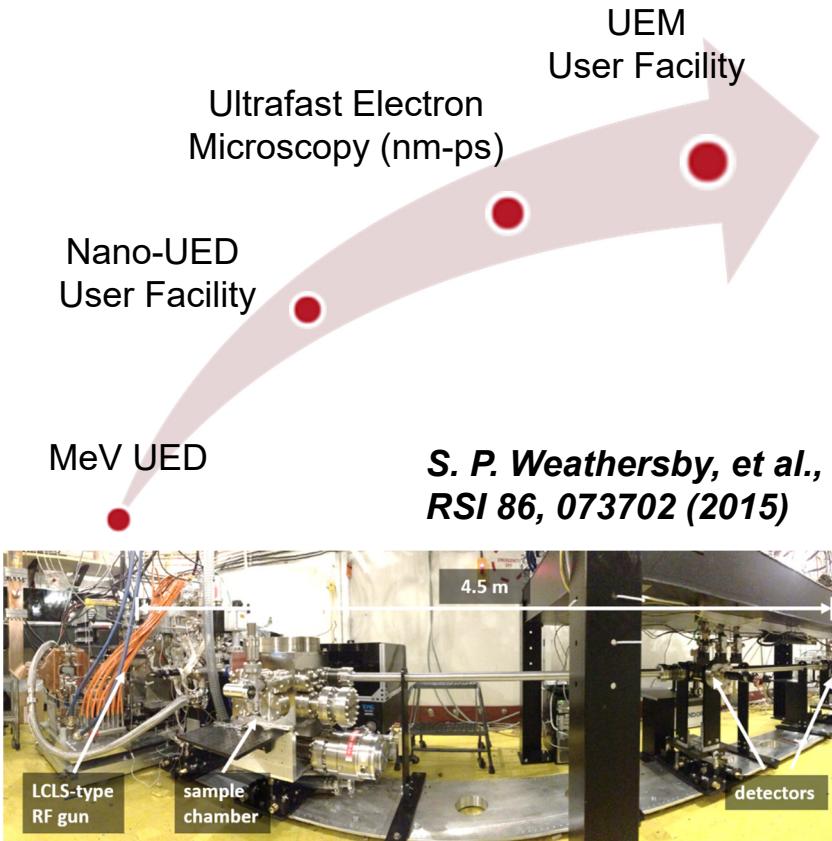


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Scientific output from the SLAC UED machine

30-40 experiments / yr

Solid state: nano-scale,
2D materials, diffuse
scattering, strongly
correlated system,
functional material

Gas-phase: sequential
double-dissociation,
roaming reaction, ring
opening

Liquid-phase



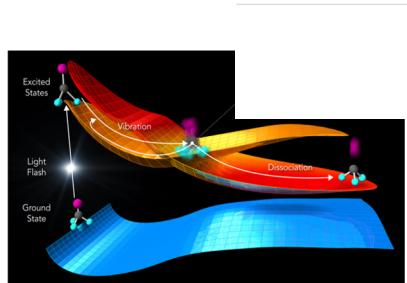
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Liquid-phase



Science 361, 64 (2018)

- First time gas-phase UED with <100 fs temporal resolution (**short pulse, minimal velocity mismatch**)

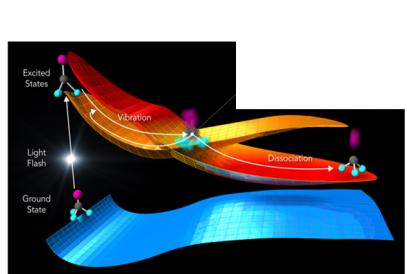
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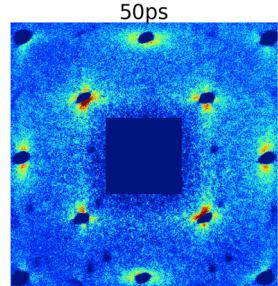
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Science 361, 64 (2018)

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- Diffuse scattering (**large penetration depth, reduced multiple scattering**)

APL 108, 041909 (2016)

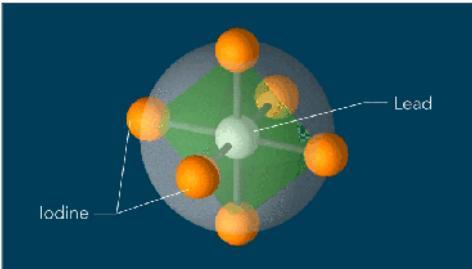
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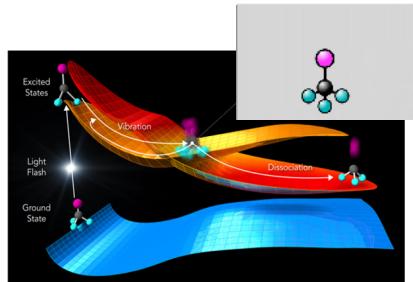
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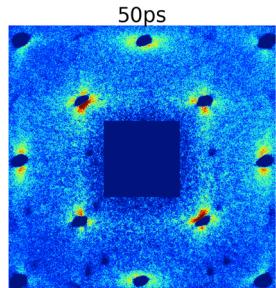
- Lattice distortion in hybrid perovskite (**short wavelength, low radiation damage**)

Sci. Adv. 3, e1602388 (2017)



Science 361, 64 (2018)

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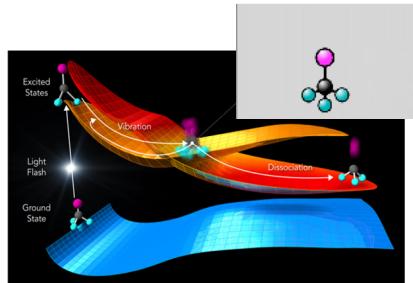
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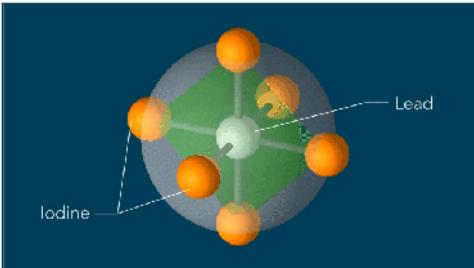
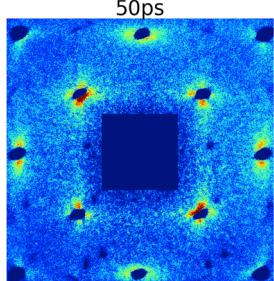
Liquid-phase



Science 361, 64 (2018)

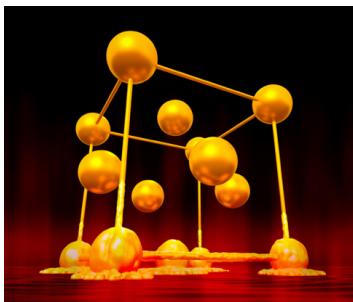
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- Single-shot snapshot of high energy density dynamics (**high beam brightness and density, excellent SNR**)

Science 360, 1451 (2018)

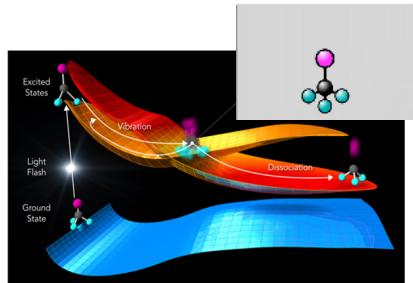
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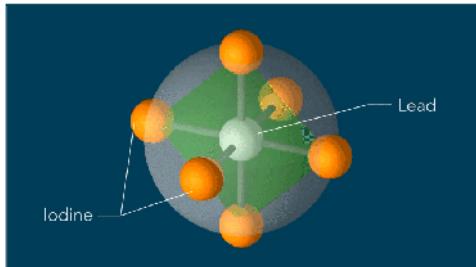
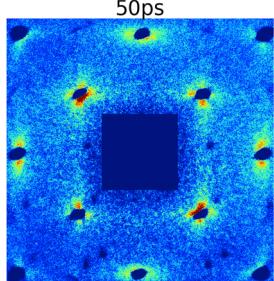
Liquid-phase



Science 361, 64 (2018)

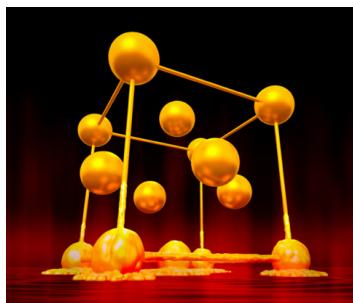
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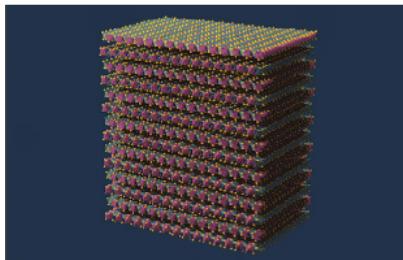
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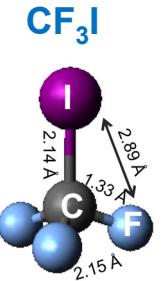
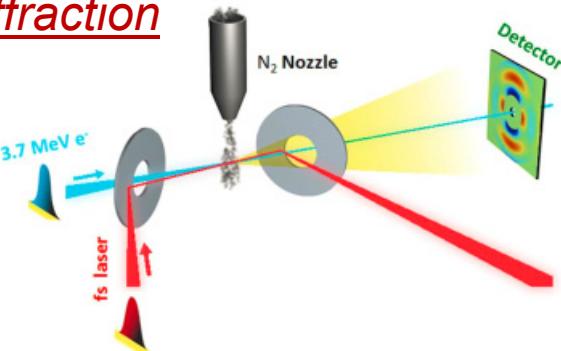
- THz control of material symmetry (**sensitive to EM fields, short wavelength**)

Nature 565, 61 (2019)

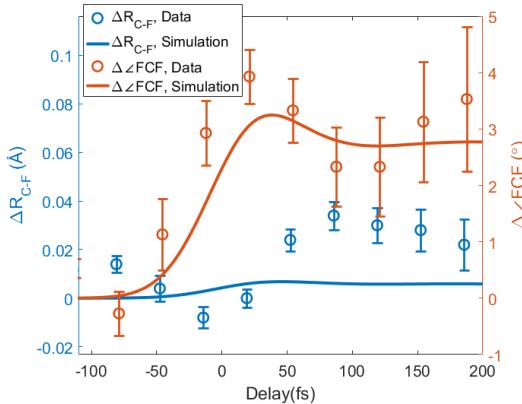
Striving for better temporal resolution

Ultrafast electron diffraction

optical pump
+
electron probe



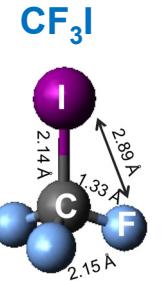
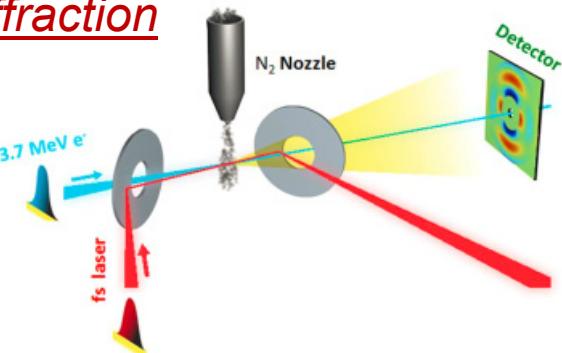
Science 361, 64 (2018)



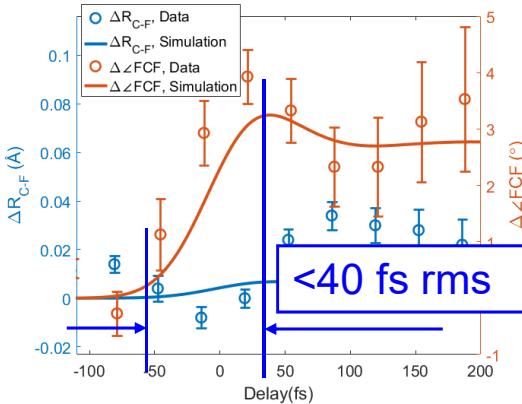
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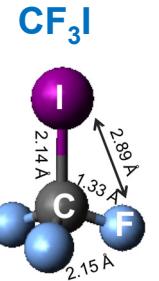
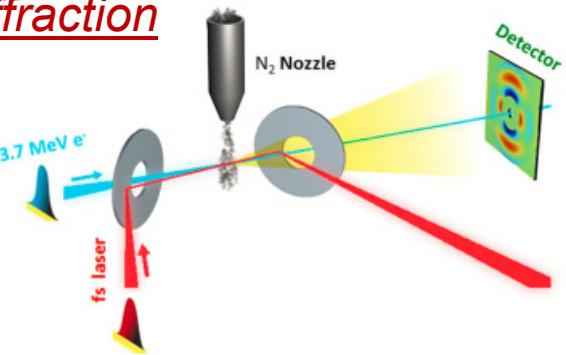
Science 361, 64 (2018)



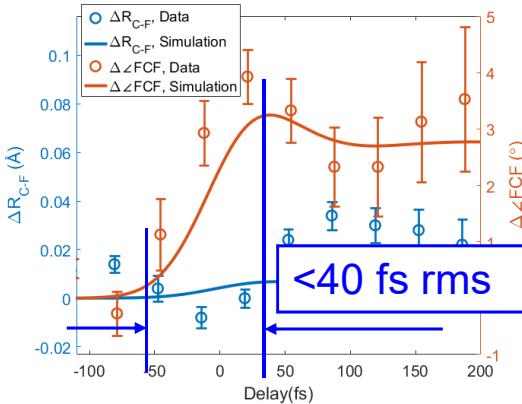
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Ultrafast electron diffraction

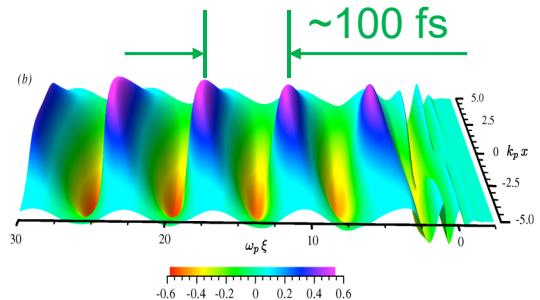
optical pump
+
electron probe



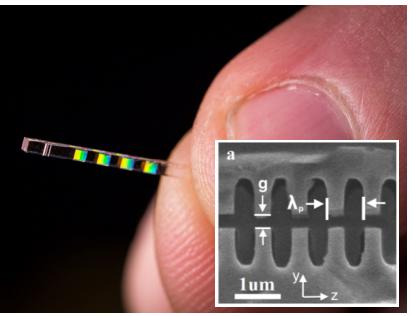
Science 361, 64 (2018)



External injection into laser-driven accelerators



Courtesy of E. Esarey

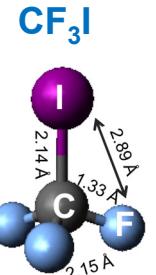
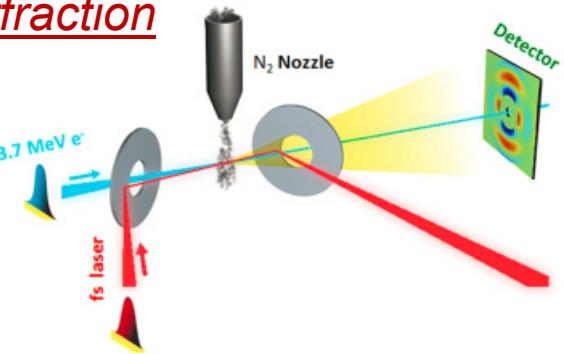


ACHIP, also AXSIS projects

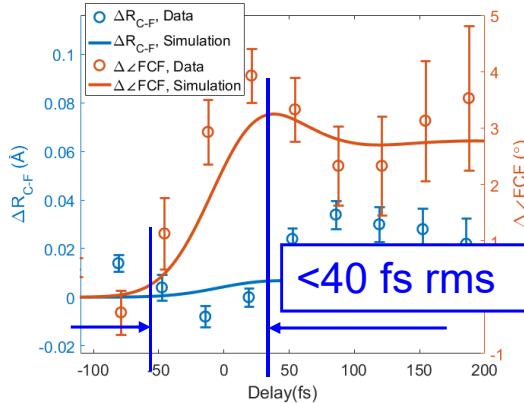
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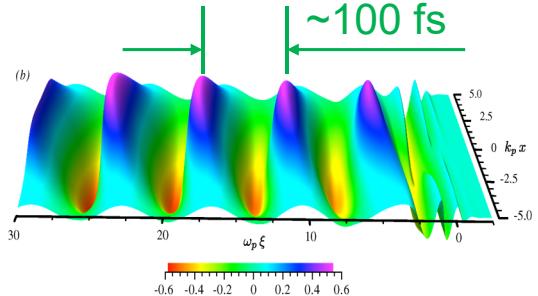
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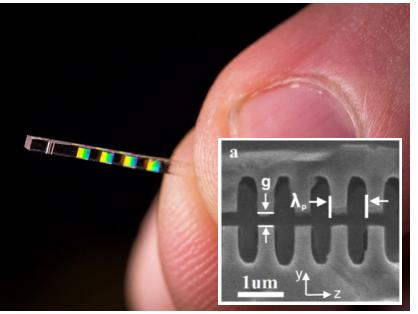
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External injection into laser-driven accelerators



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ACHIP, also AXSIS projects

Requirement

femtosecond e-beam
bunch length +
femtosecond e-beam to
laser **timing jitter**



Challenge with the timing jitter

$$\tau^2 = \tau_{\text{ph}}^2 + \tau_e^2 + \tau_{\text{vm}}^2 + \tau_{\text{toa}}^2$$

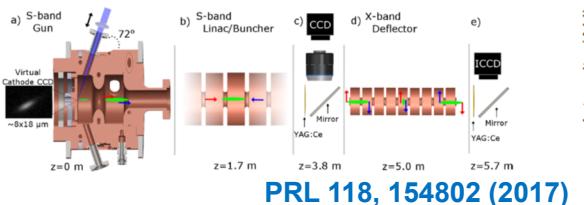
Overall temporal resolution laser e-beam velocity mismatch
time-of-arrival jitter between pump and probe
(negligible w/ MeV e-)

Challenge with the timing jitter

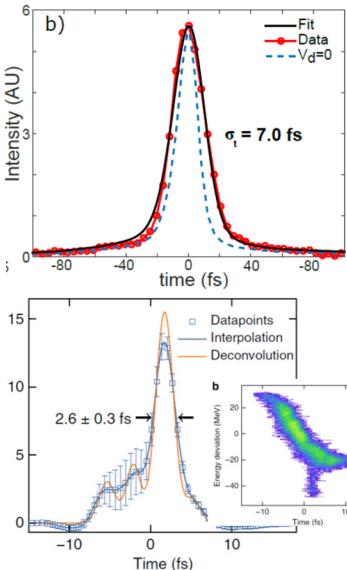
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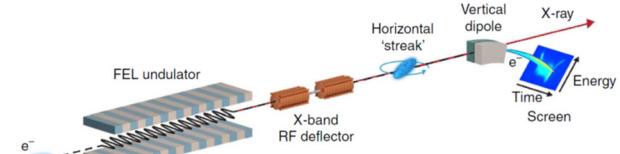
MeV beams for UED



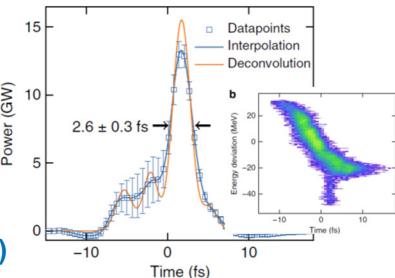
PRL 118, 154802 (2017)



GeV beams for XFEL



Nat. Commun. 5, 3762 (2014)



- characterization using rf deflecting cavity to a-few-fs resolution already demonstrated
- Direct $\tau_e e e e$ characterization using rf deflecting cavity to a-few-fs resolution already demonstrated
- 10s of fs jitter between high power rf and pump laser
- TOA measurement down to fs level²³

Challenge with the timing jitter

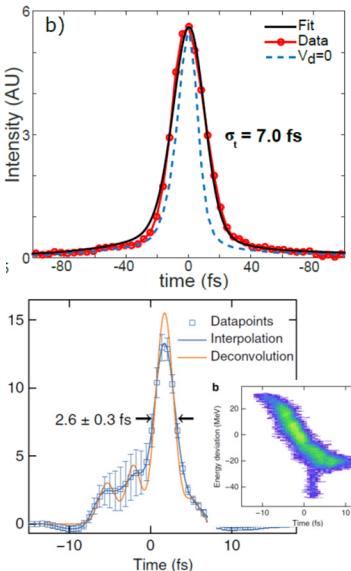
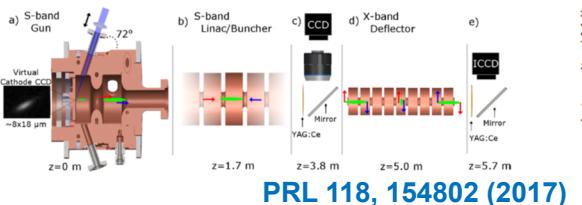
$$\tau^2 = \tau_{\text{ph}}^2 + \tau_e^2 + \tau_{\text{vm}}^2 + \tau_{\text{toa}}^2$$

Overall temporal resolution

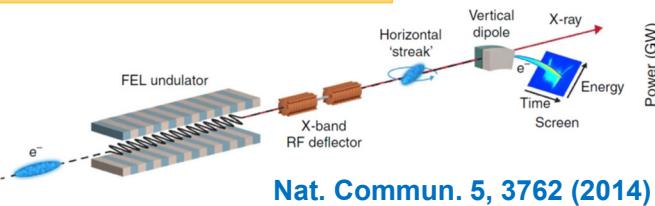
laser e-beam velocity mismatch (negligible w/ MeV e-)

time-of-arrival jitter between pump and probe

MeV beams for UED



GeV beams for XFEL



- characterization using rf deflecting cavity to a-few-fs resolution already demonstrated
- 10s of fs jitter between high power rf and pump laser
- TOA measurement down to fs level still challenging, especially for fC beam charge
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rf v.s. laser-generated THz manipulation of e-beams

Introduced correlation in phase space:
 y' - t , E - t , etc.

$$\text{slope} \propto \frac{E \times L}{\lambda}$$

field strength interaction length
wavelength

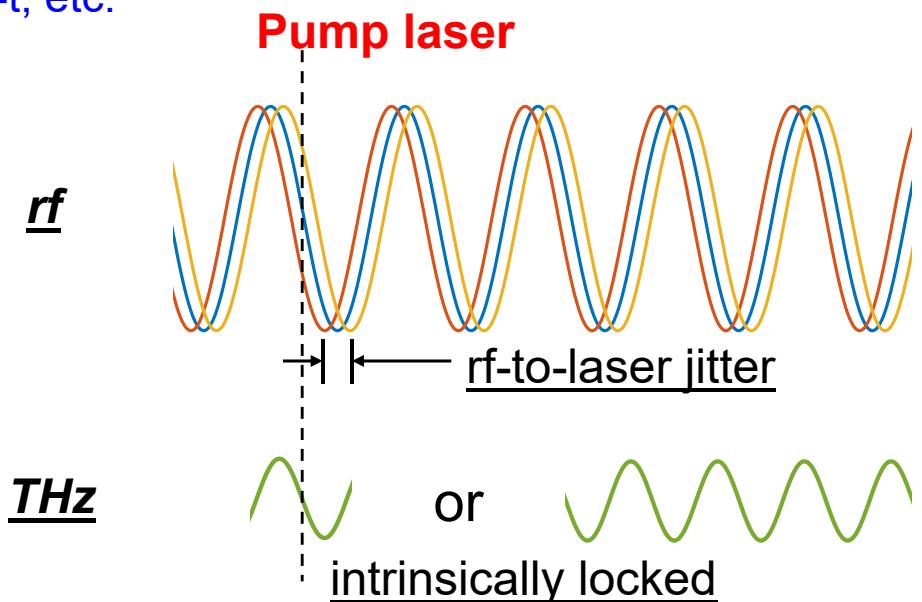
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Introduced correlation in phase space:
 $y'-t$, $E-t$, etc.

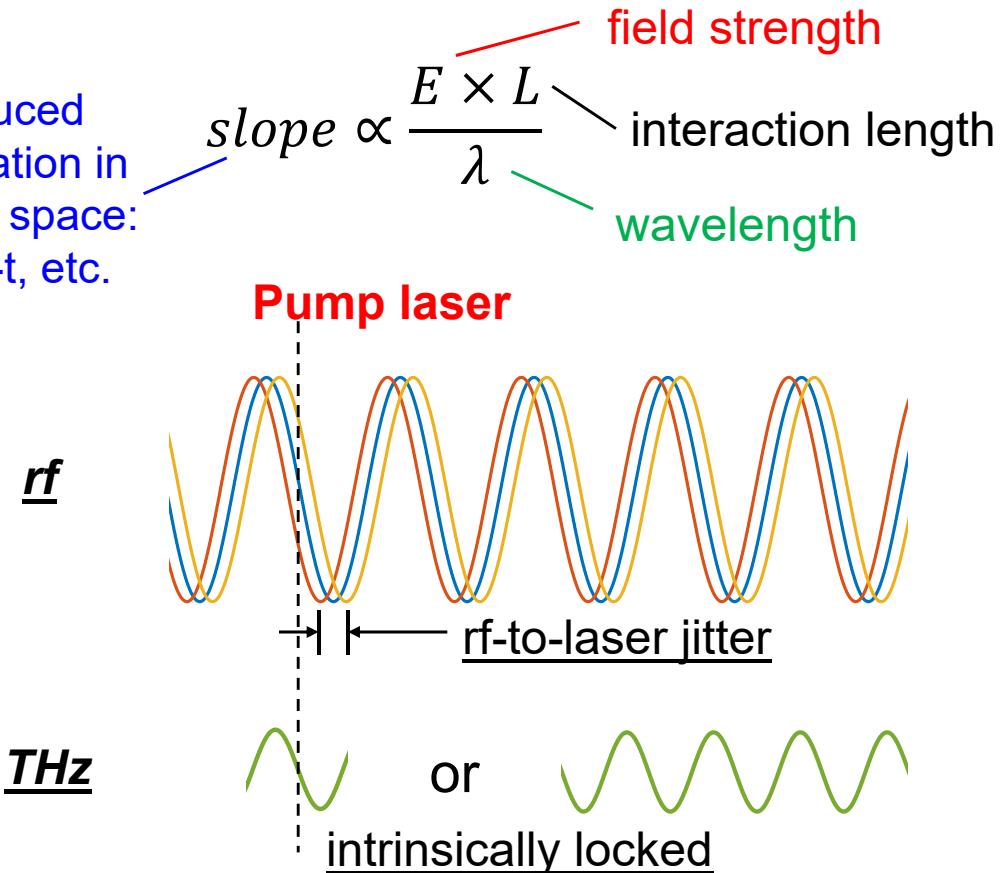
$$slope \propto \frac{E \times L}{\lambda}$$

field strength
interaction length
wavelength



rf v.s. laser-generated THz manipulation of e-beams

Introduced correlation in phase space:
y'-t, E-t, etc.

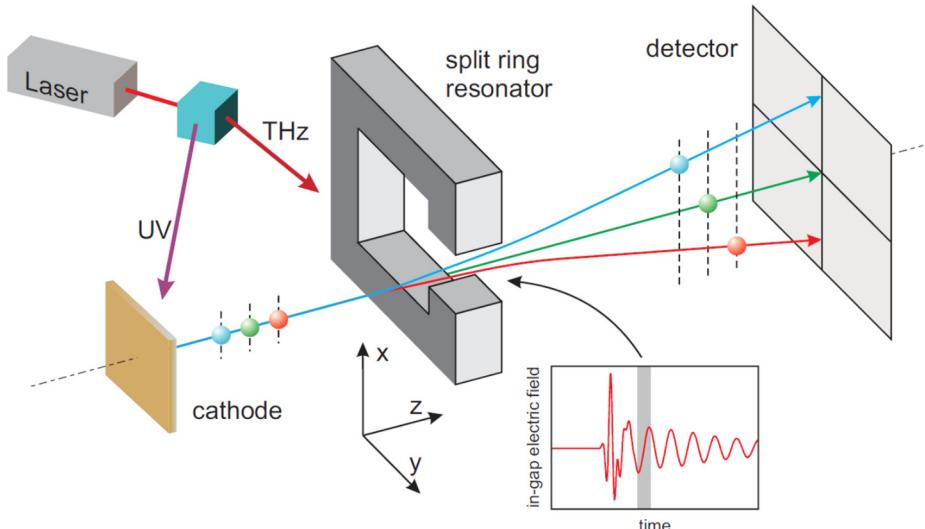


- Laser-generated THz essentially eliminates the timing jitter
- Short wavelengths of THz favorable for streaking/compression

	rf v.s. THz
E	up to ~ 100 s MV/m v.s. up to 1 GV/m
L	~ 1000 times cm to m v.s. mm
λ	~ 1000 times

Streaking MeV e-beams w/ laser-generated THz

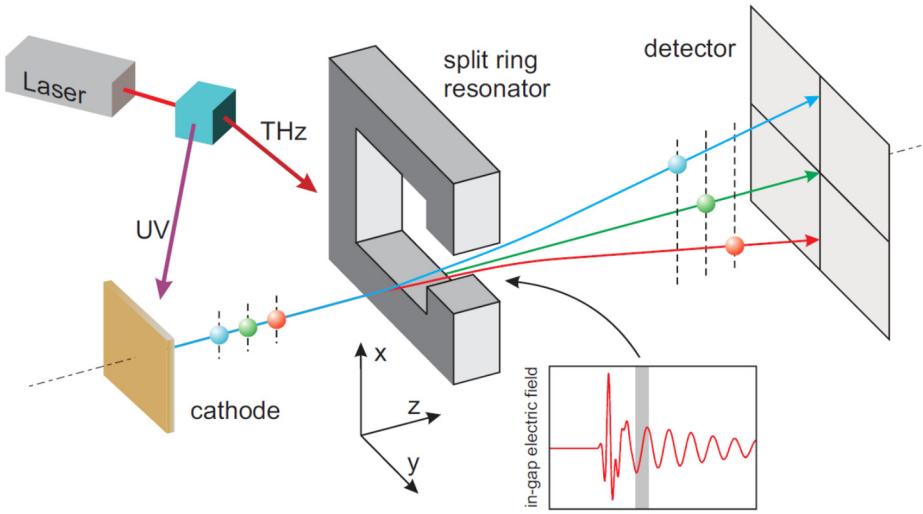
Collaboration between PSI (Villigen, Switzerland),
KIT (Karlsruhe, Germany) and University of Bern
(Bern, Switzerland)



J. Fabiańska, G. Kassier, and T. Feurer, Sci. Rep. 4, 5645 (2014).

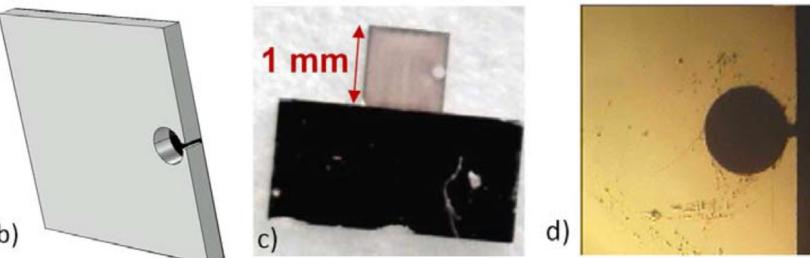
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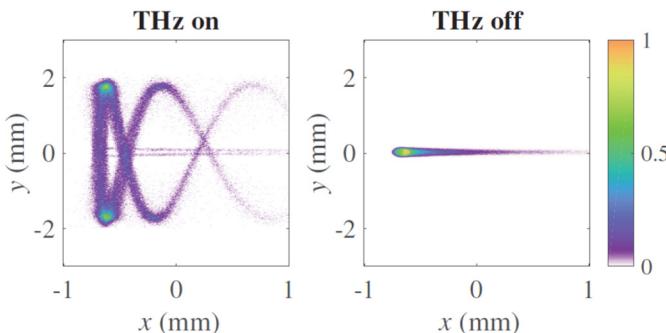


J. Fabiańska, G. Kassier, and T. Feurer, Sci. Rep. 4, 5645 (2014).

Split ring resonator (SRR) structured fabricated



Simulated beam profile w/ THz and spectrometer



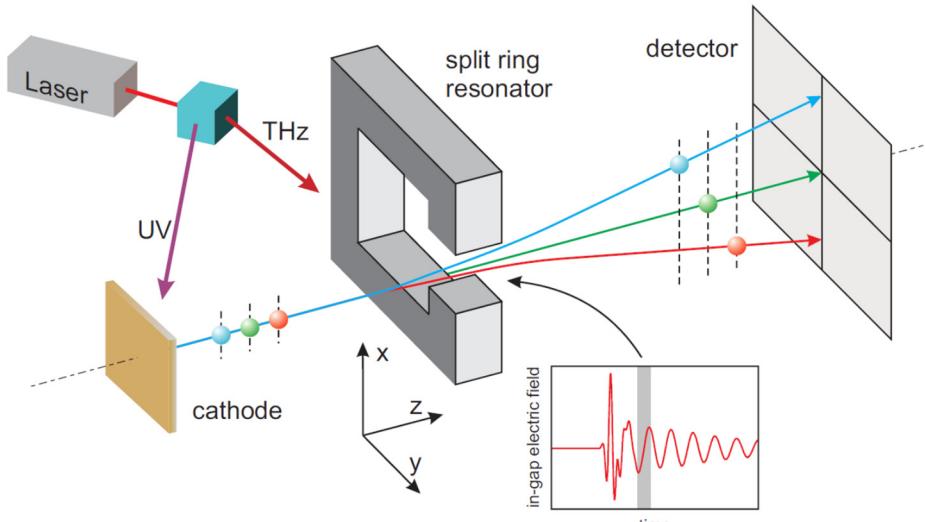
M. Yan et al., IBIC 2016, TUPG56

V. Schlott et al., IBIC 2017, TUPCC16

S.P. Jamison et al., IBIC 2016, WEPG48

Streaking MeV e-beams w/ laser-generated THz

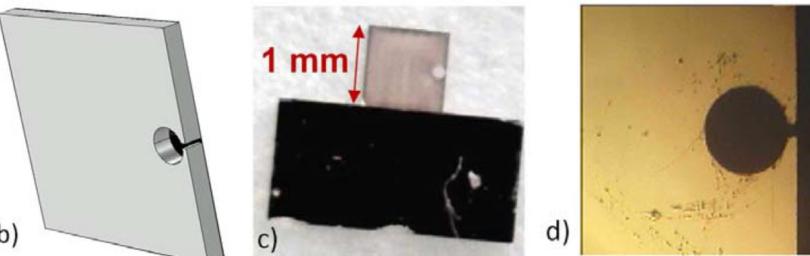
Collaboration between PSI (Villigen, Switzerland), KIT (Karlsruhe, Germany) and University of Bern (Bern, Switzerland)



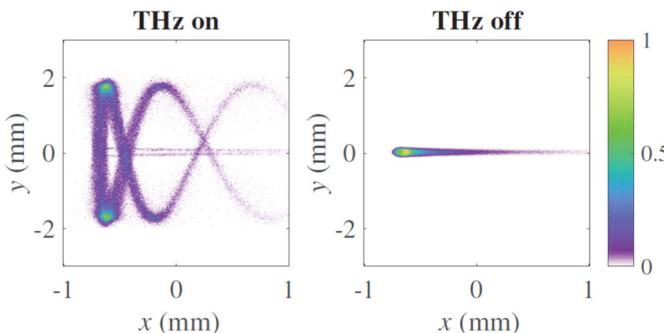
J. Fabiańska, G. Kassier, and T. Feurer, Sci. Rep. 4, 5645 (2014).

L. Zhao et al., PRX 8, 021061 (2018)
 Jang et al., J. Korean Phy. Soc. 73, 466 (2018)

Split ring resonator (SRR) structured fabricated



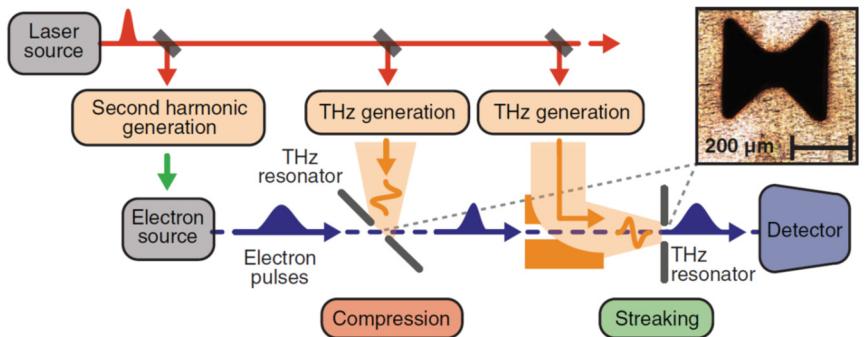
Simulated beam profile w/ THz and spectrometer



M. Yan et al., IBIC 2016, TUPG56
 V. Schlott et al., IBIC 2017, TUPCC16
 S.P. Jamison et al., IBIC 2016, WEPG48

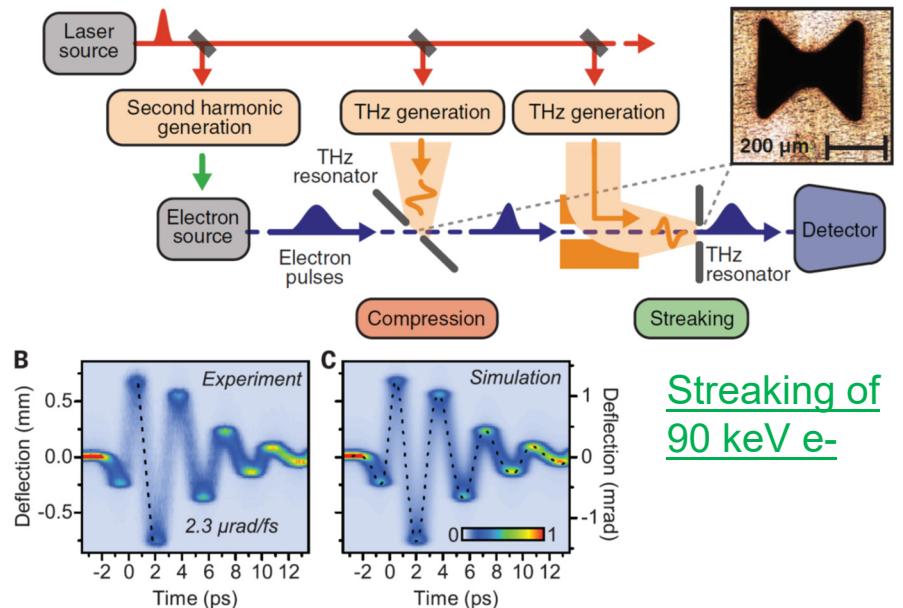
THz manipulation of keV e-beams

C. Kealhofer et. al., Science 352, 429 (2016).



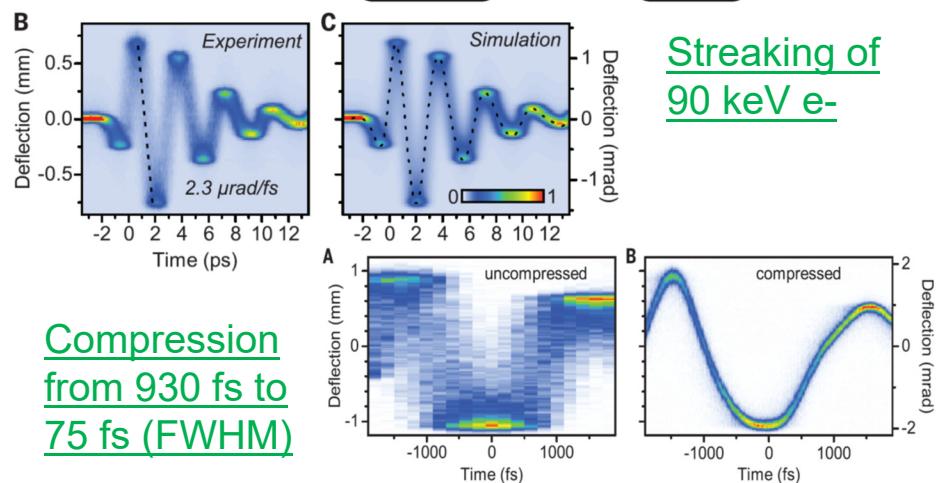
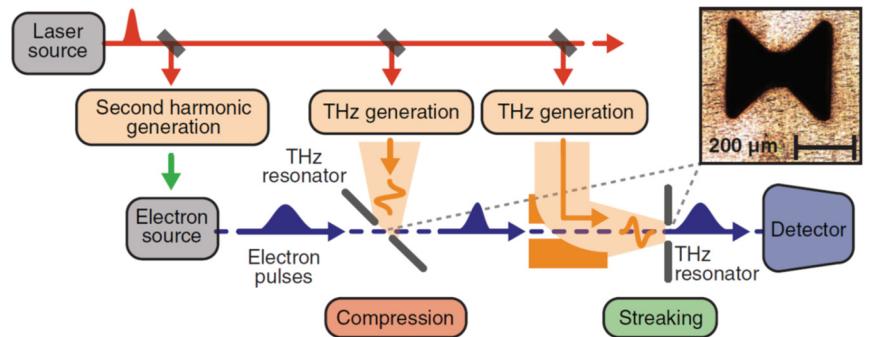
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THz manipulation of keV e-beams

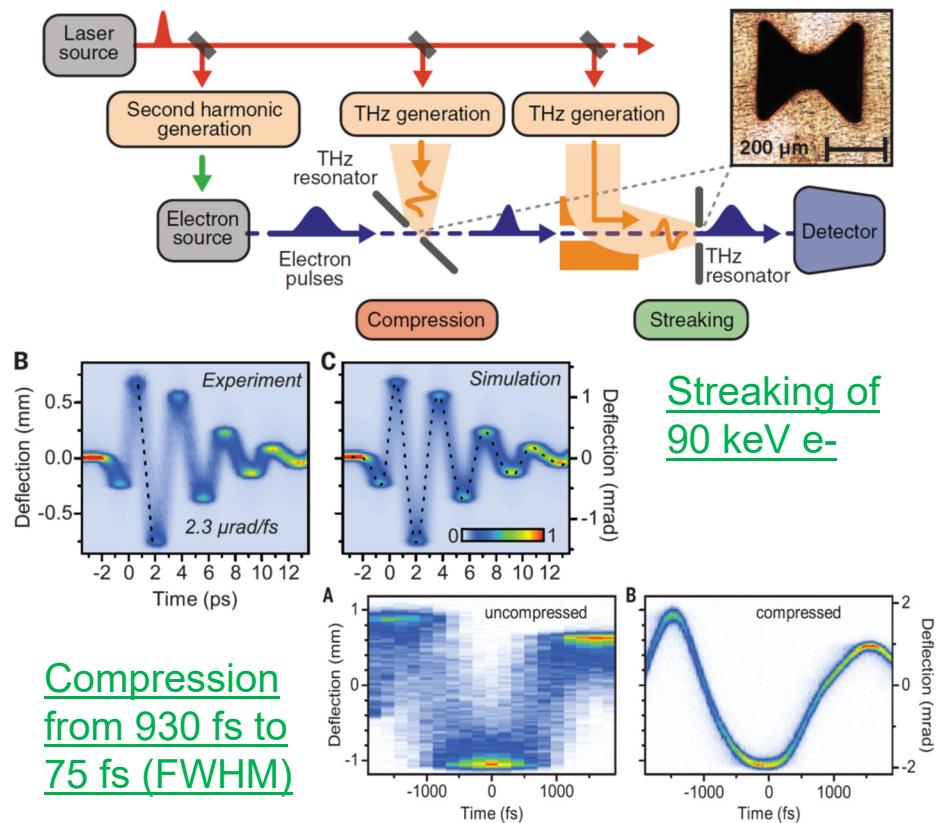
C. Kealhofer et. al., Science 352, 429 (2016).



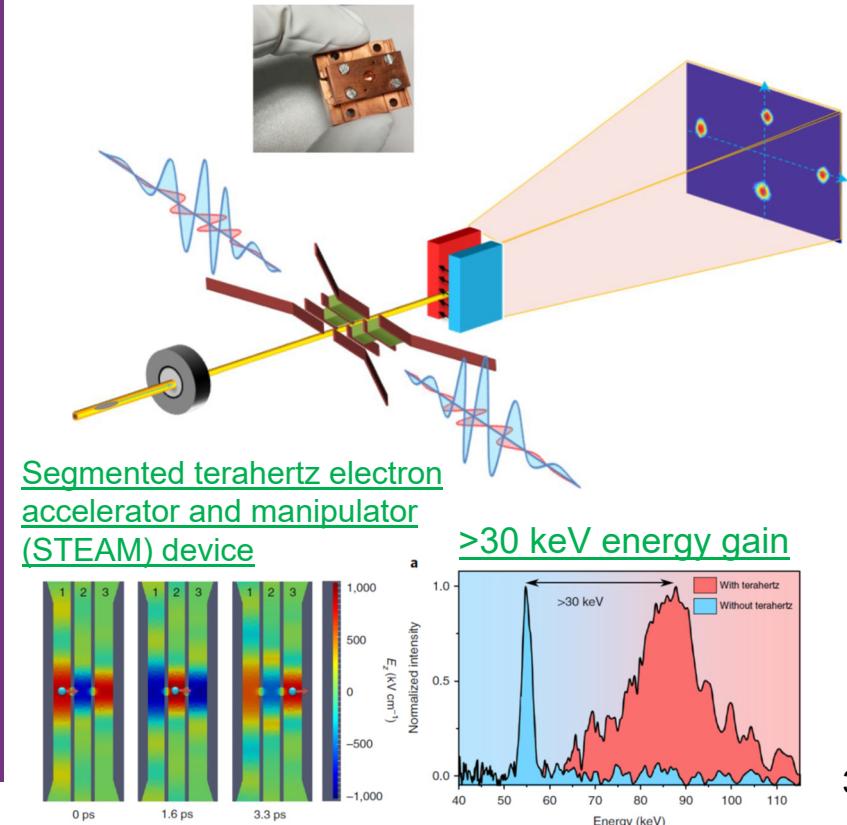
Compression from 930 fs to 75 fs (FWHM)

THz manipulation of keV e-beams

C. Kealhofer et. al., Science 352, 429 (2016).

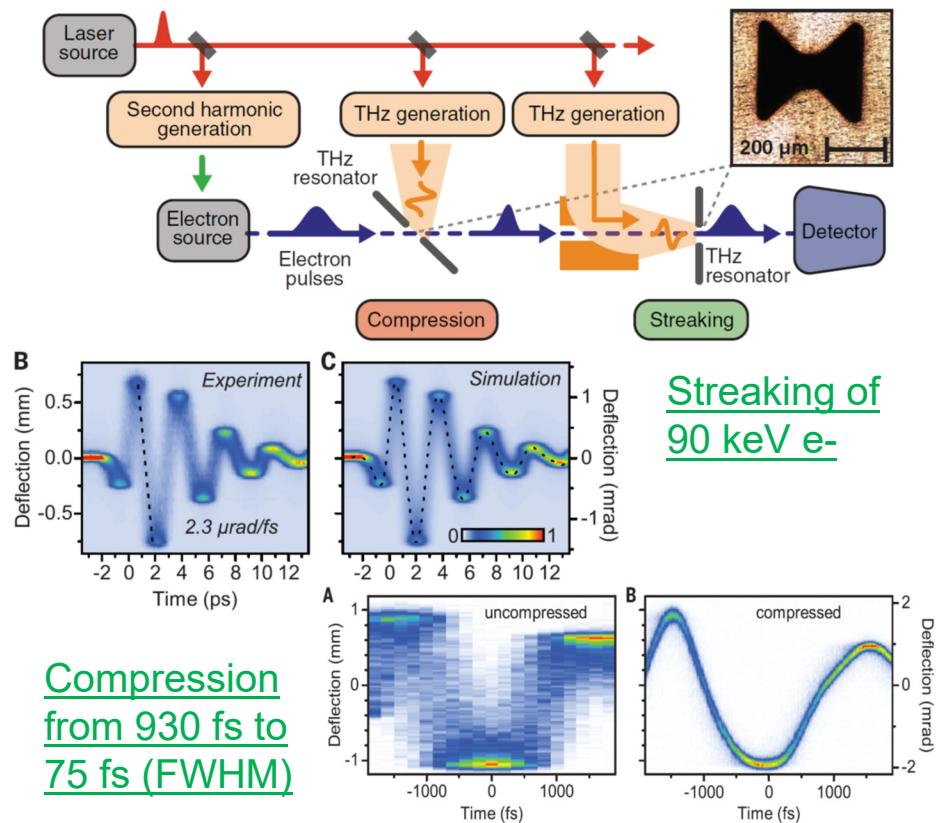


D. Zhang et. al., Nat. Photonics 12, 336 (2018).

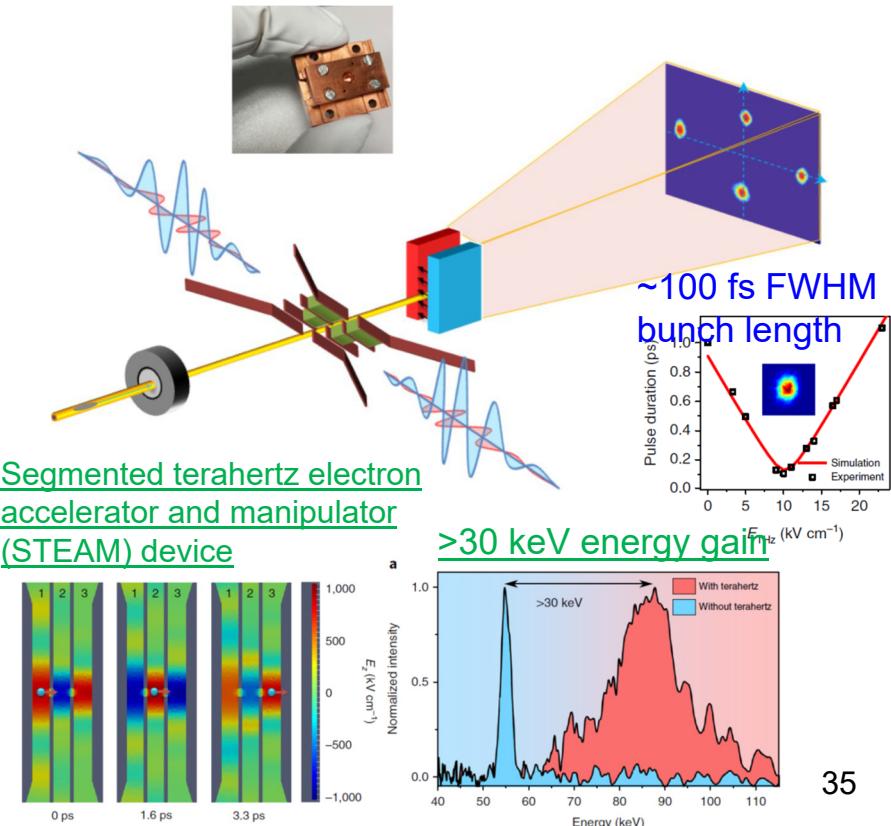


THz manipulation of keV e-beams

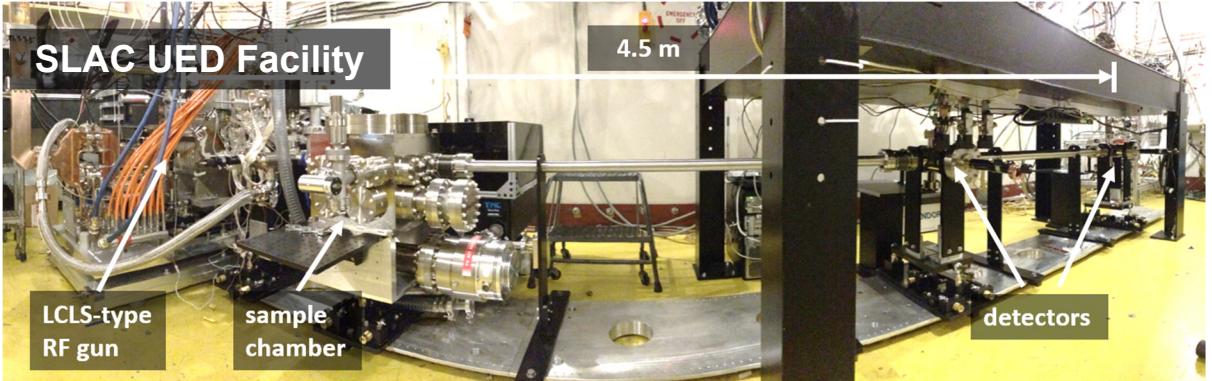
C. Kealhofer et. al., Science 352, 429 (2016).



D. Zhang et. al., Nat. Photonics 12, 336 (2018).



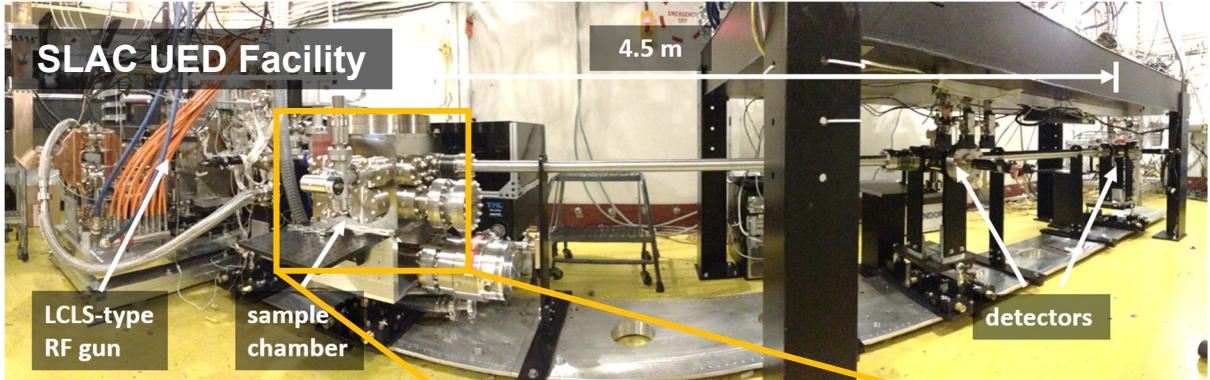
THz streaking experiment at SLAC



RSI **86**, 073702 (2015)

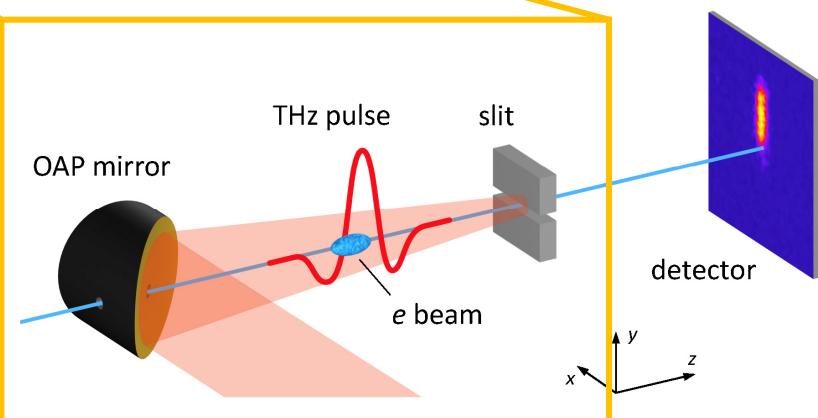
Parameters	Values
rep. rate	SS - 180 Hz
beam energy	2 - 4 MeV
bunch charge	10^4 - 10^6
emittance	2 - 20 nm
bunch length	<50 fs rms

THz streaking experiment at SLAC

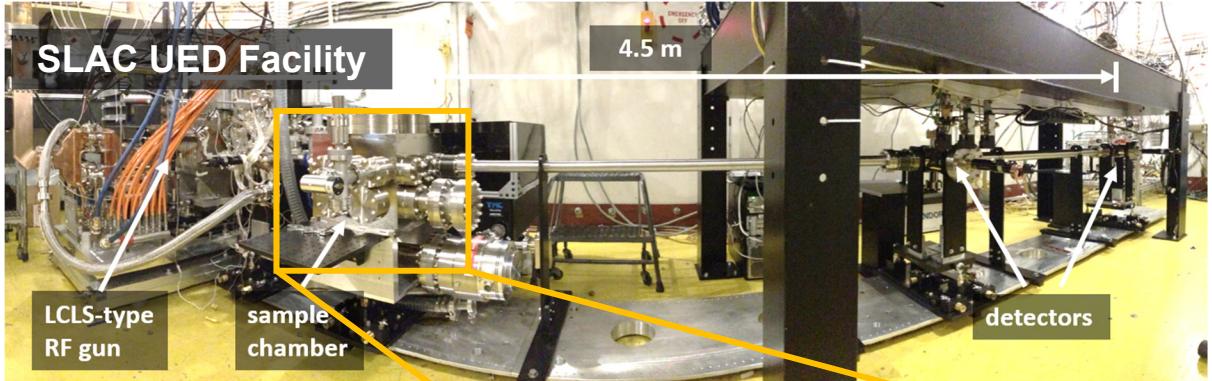


RSI 86, 073702 (2015)

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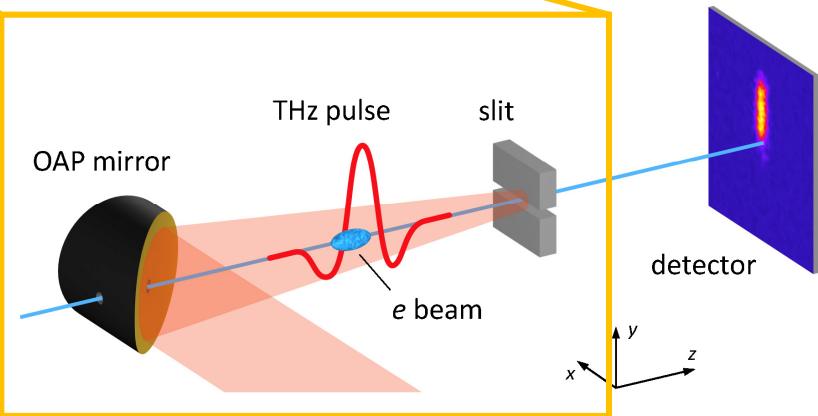
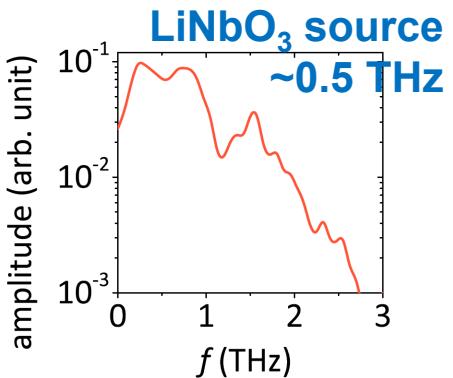


THz streaking experiment at SLAC

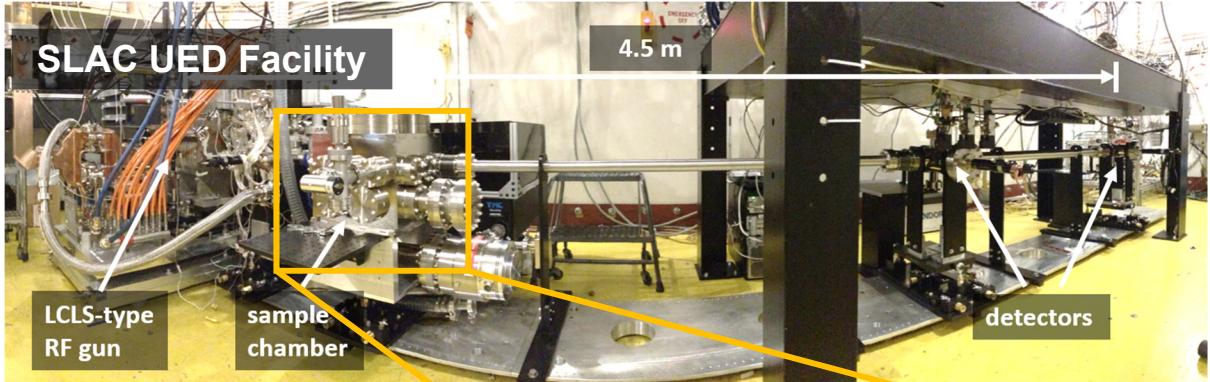


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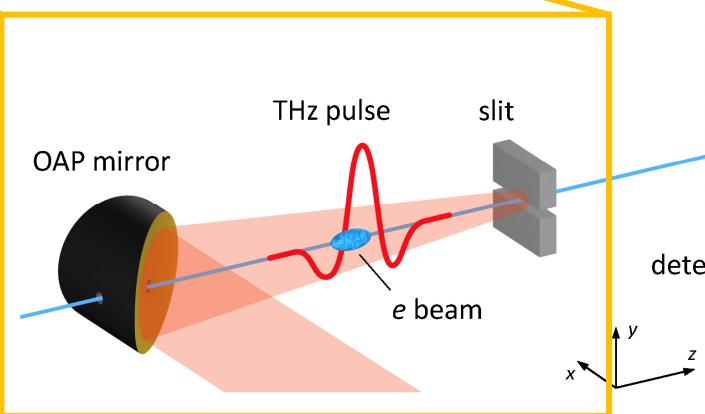
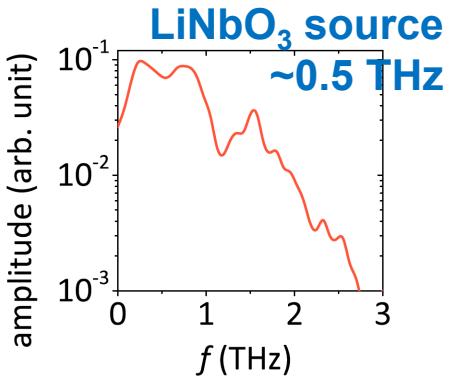


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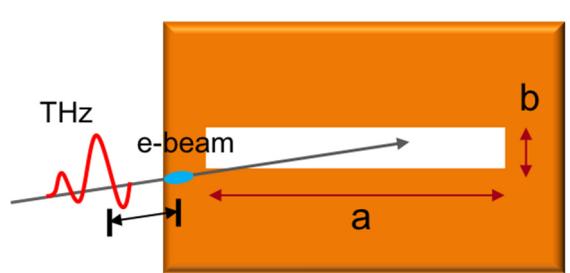
Sensitive single-shot detector



R. K. Li et al., JAP 110, 074512 (2011)

Design of the THz structure (slit)

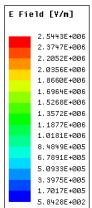
- Parallel plate geometry for uniform illumination
- Wide bandwidth to preserve the temporal shape
- In future improve coupling with 1D taper



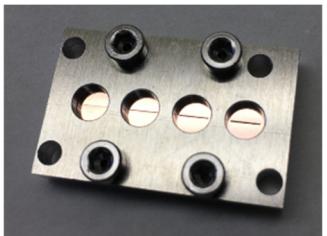
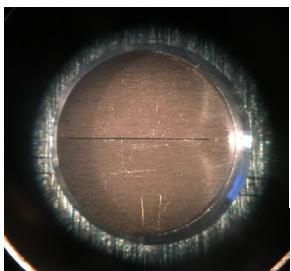
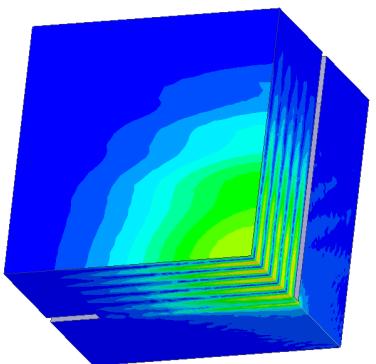
$a=4$ mm (larger than beam)

$b=50\text{-}250$ μm

Foil thickness = 25-100 μm

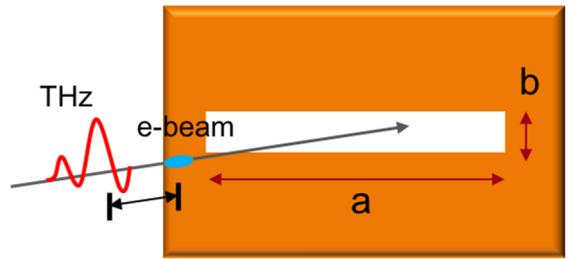


HFSS model
by E. Nanni



Design of the THz structure (slit)

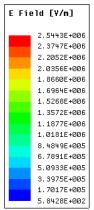
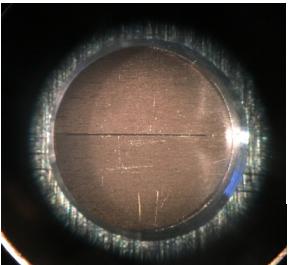
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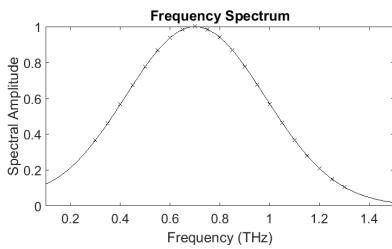
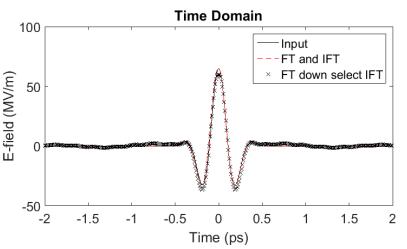
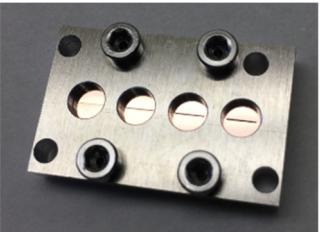
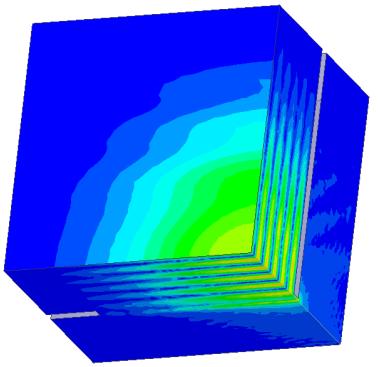
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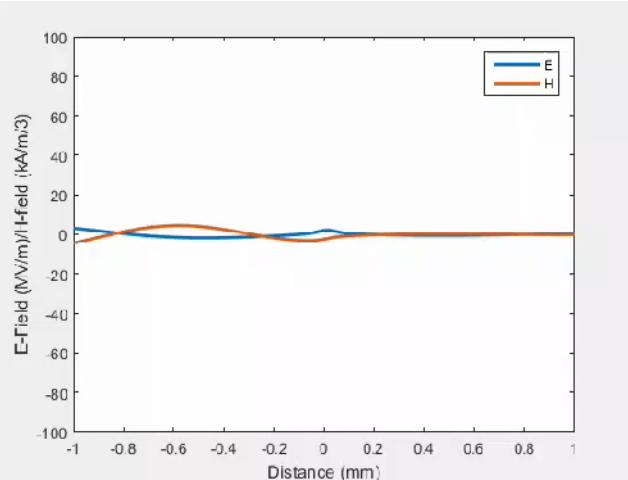
Foil thickness = 25-100 μm



HFSS model
by E. Nanni

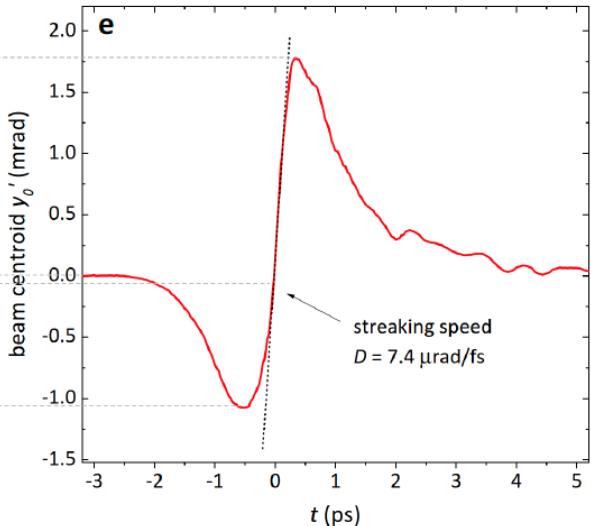
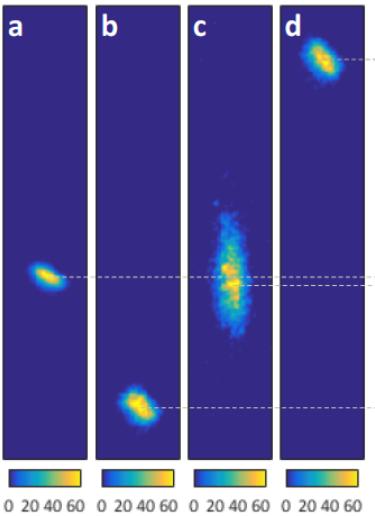
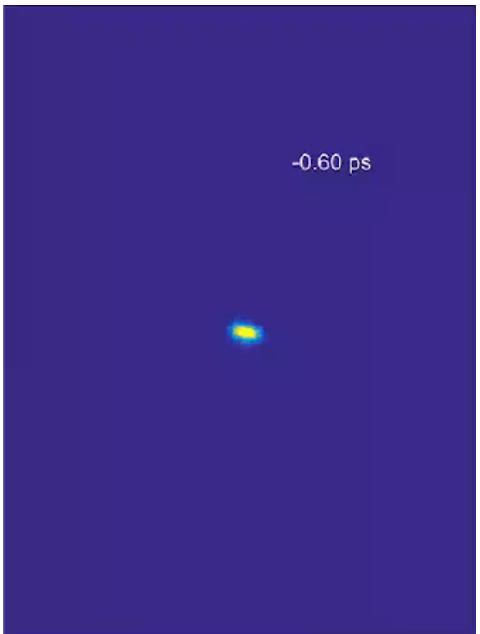


Time domain response



Experimental results: timing determination

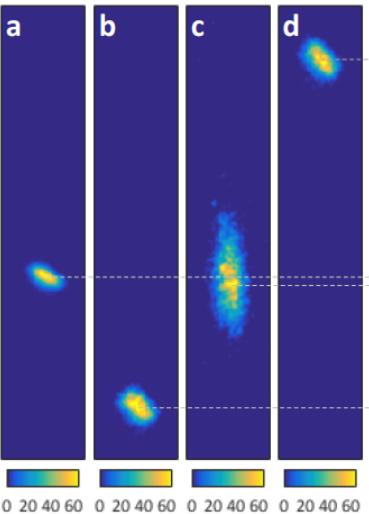
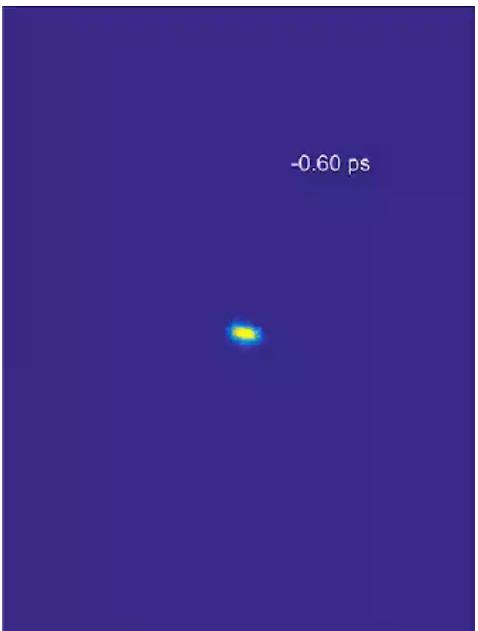
3.1 MeV electrons, 50 μm
gap, 100 μm thick slit



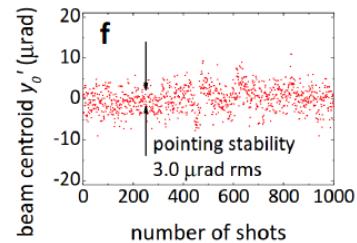
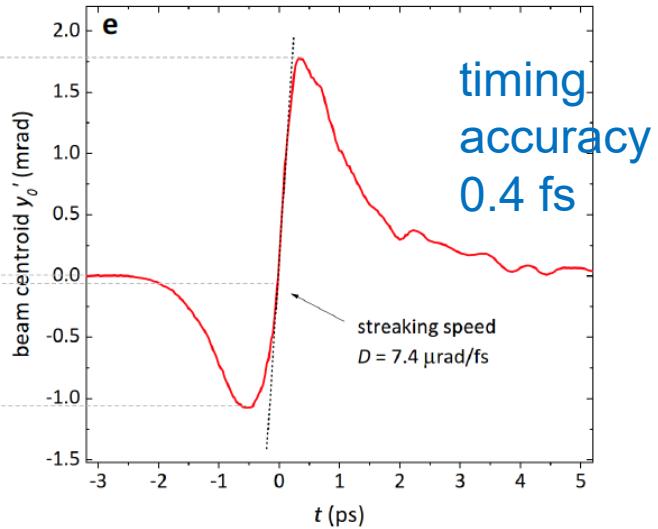
R. K. Li, M. C. Hoffmann, E. A. Nanni et al.,
PRAB 22, 012803 (2019).

Experimental results: timing determination

3.1 MeV electrons, 50 um gap, 100 um thick slit



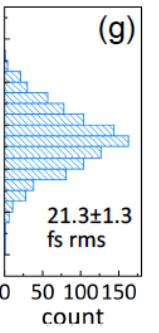
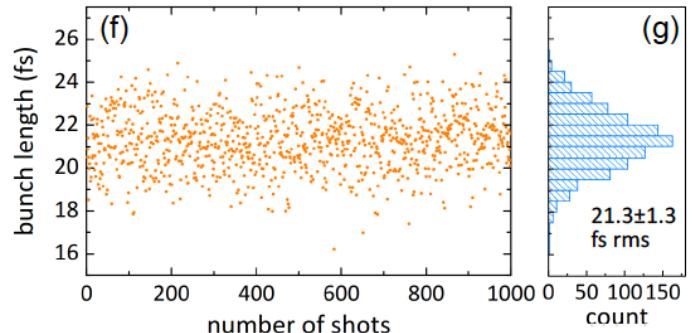
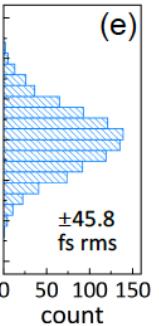
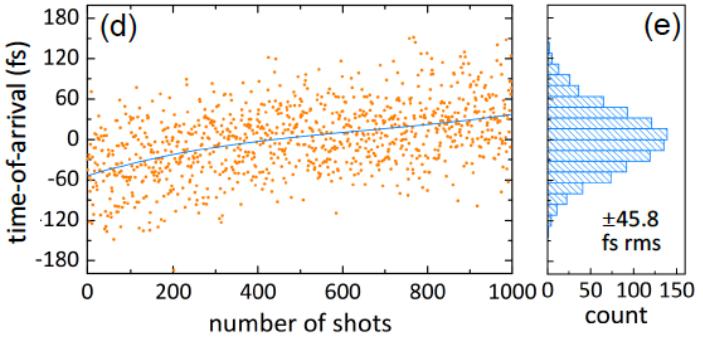
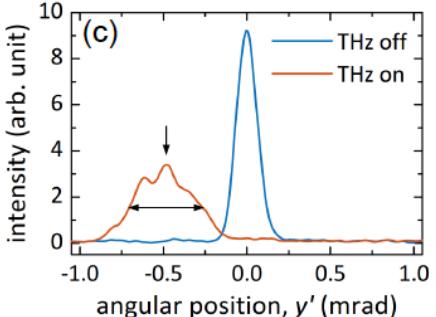
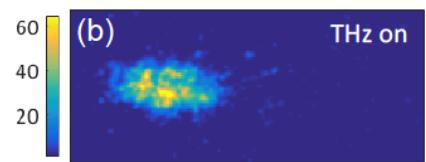
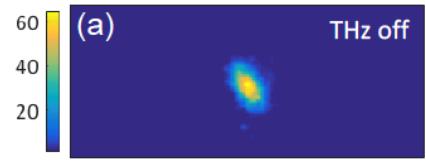
$$\text{timing accuracy} = \frac{\text{pointing stability}}{\text{streaking speed}}$$



R. K. Li, M. C. Hoffmann, E. A. Nanni et al.,
PRAB 22, 012803 (2019).

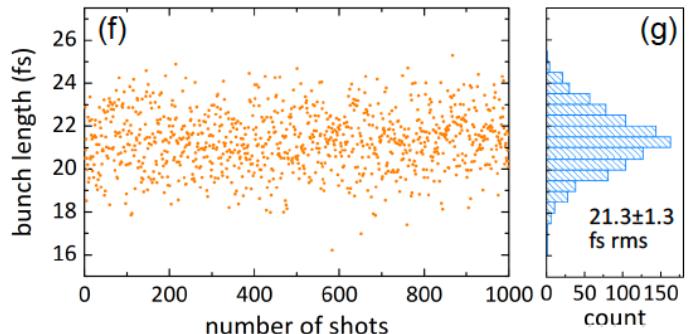
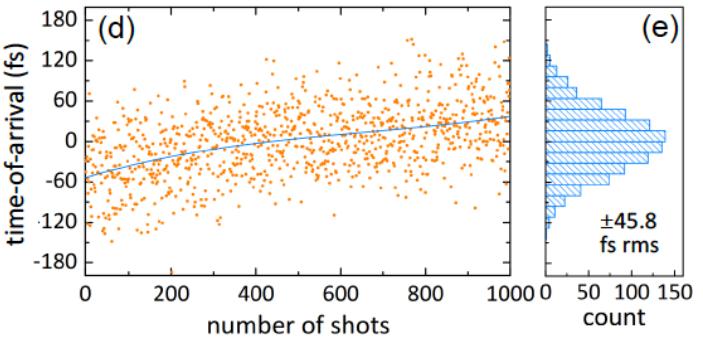
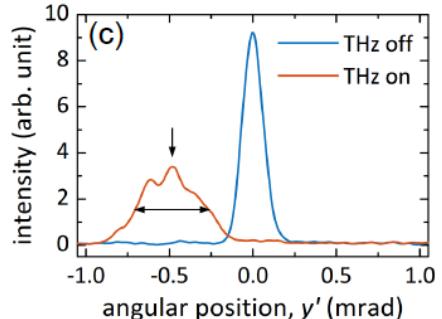
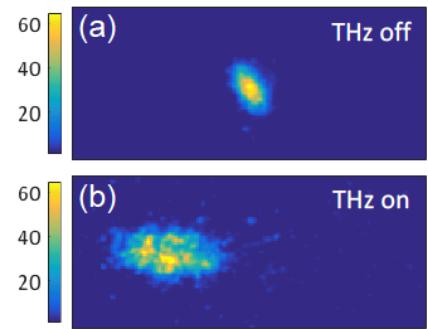
Single-shot determination of both timing and bunch length

Determine **timing** and **bunch length** from **each and every single-shot images** (0.4 fs timing accuracy and 2.4 fs resolution for bunch length @ 3.1 MeV beams)

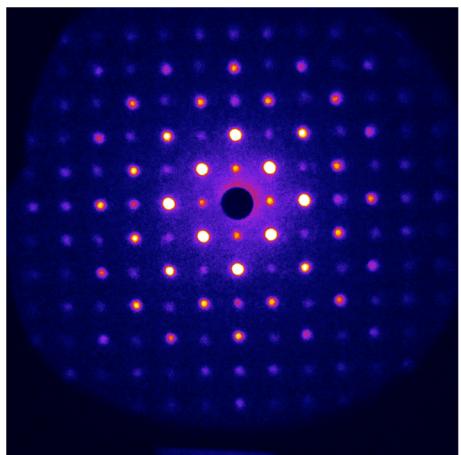
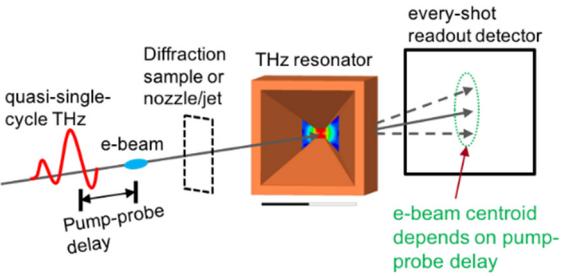


Single-shot determination of both timing and bunch length

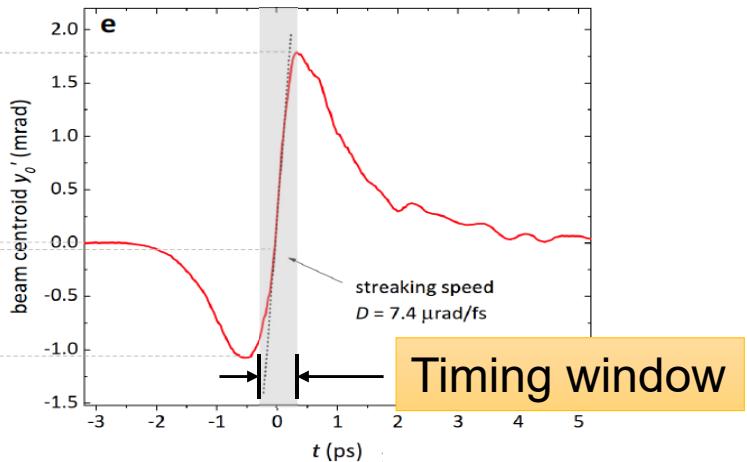
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Timing-tool for UED

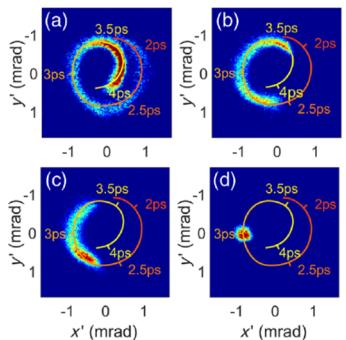
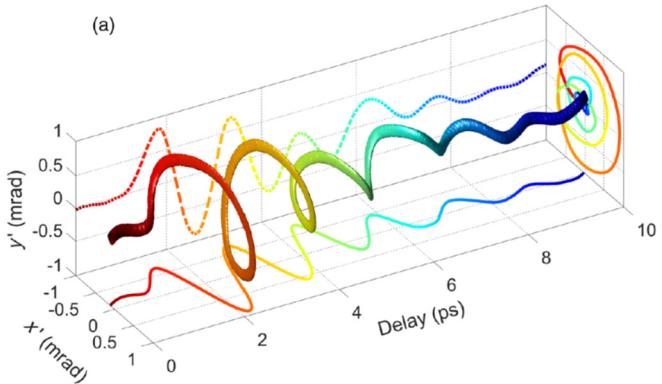
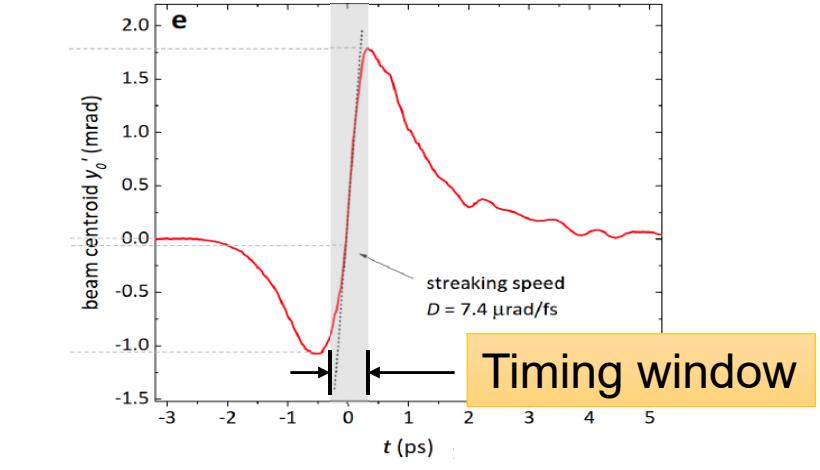


'Time window' of THz streaking



- e- beams (bunch length and jitter included) need to be injected within a 'time window' w/ one-to-one position-time correlation
- Width of the 'time window' set by the THz spectrum and the THz structure
- With quasi-single cycle THz the efficiency/slope/resolution is the largest

'Time window' of THz streaking



- e- beams (bunch length and jitter included) need to be injected within a 'time window' w/ one-to-one position-time correlation
- Width of the 'time window' set by the THz spectrum and the THz structure
- With quasi-single cycle THz the efficiency/slope/resolution is the largest

- Using multi-cycle and two-dimensional (to avoid overlapping) THz streaking to significantly increase the width of the 'time-window'

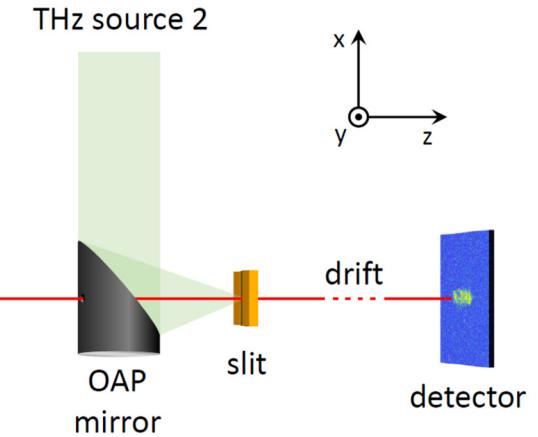
L. Zhao et al., PRL 122, 144801 (2019)

Outline



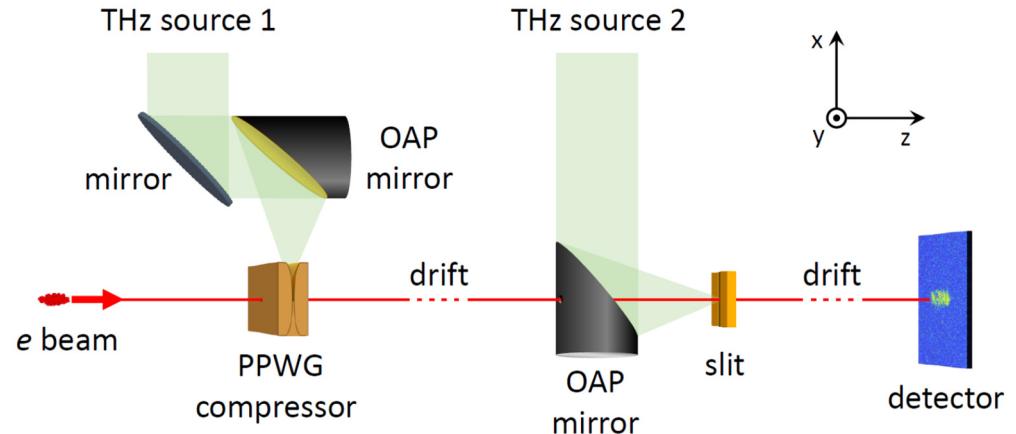
- Background and Motivation
 - UED, low charge beams, THz manipulation and metrology
- THz streaking of MeV beams
 - direct measurement e-beam-to-optical timing jitter
- THz compression
 - bunch length reduction and intrinsic timing jitter stabilization
- Summary and outlook

THz compression



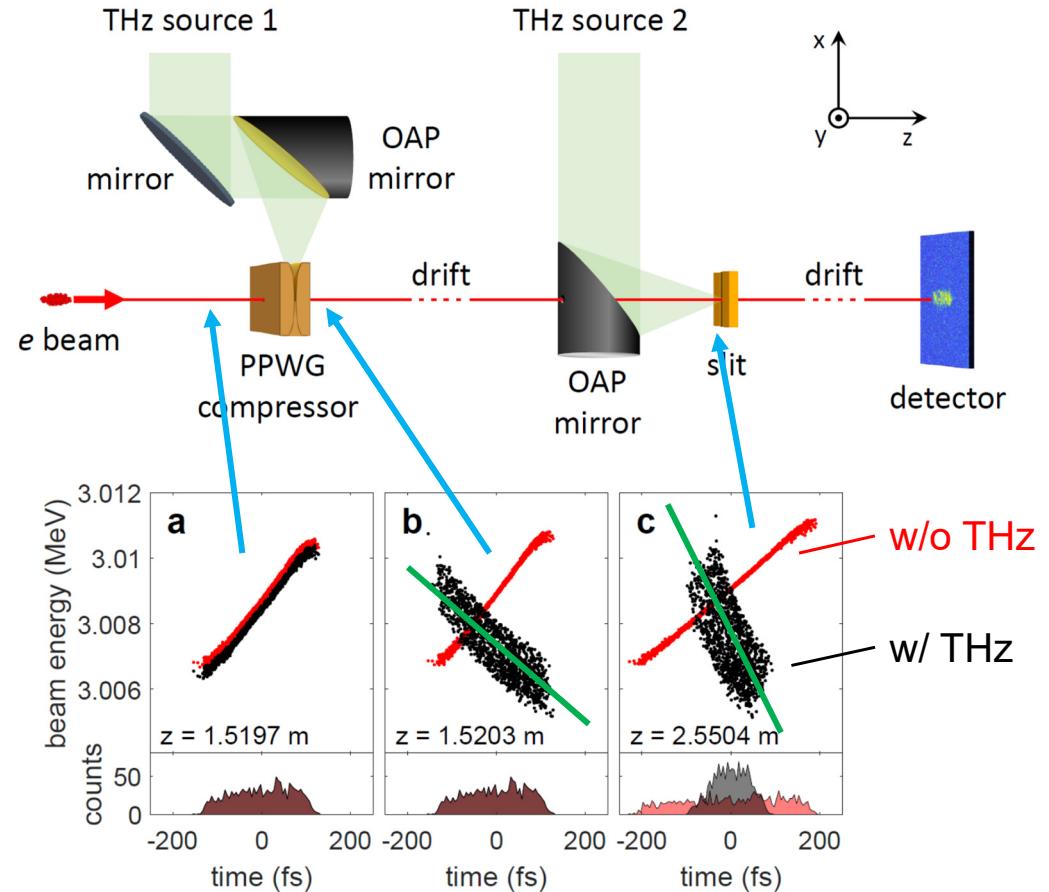
E. Snively et al., arXiv: 1906.03358

THz compression

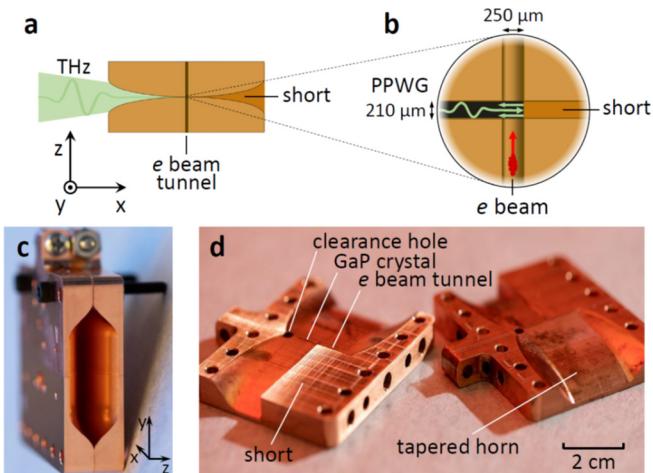


E. Snively et al., arXiv: 1906.03358

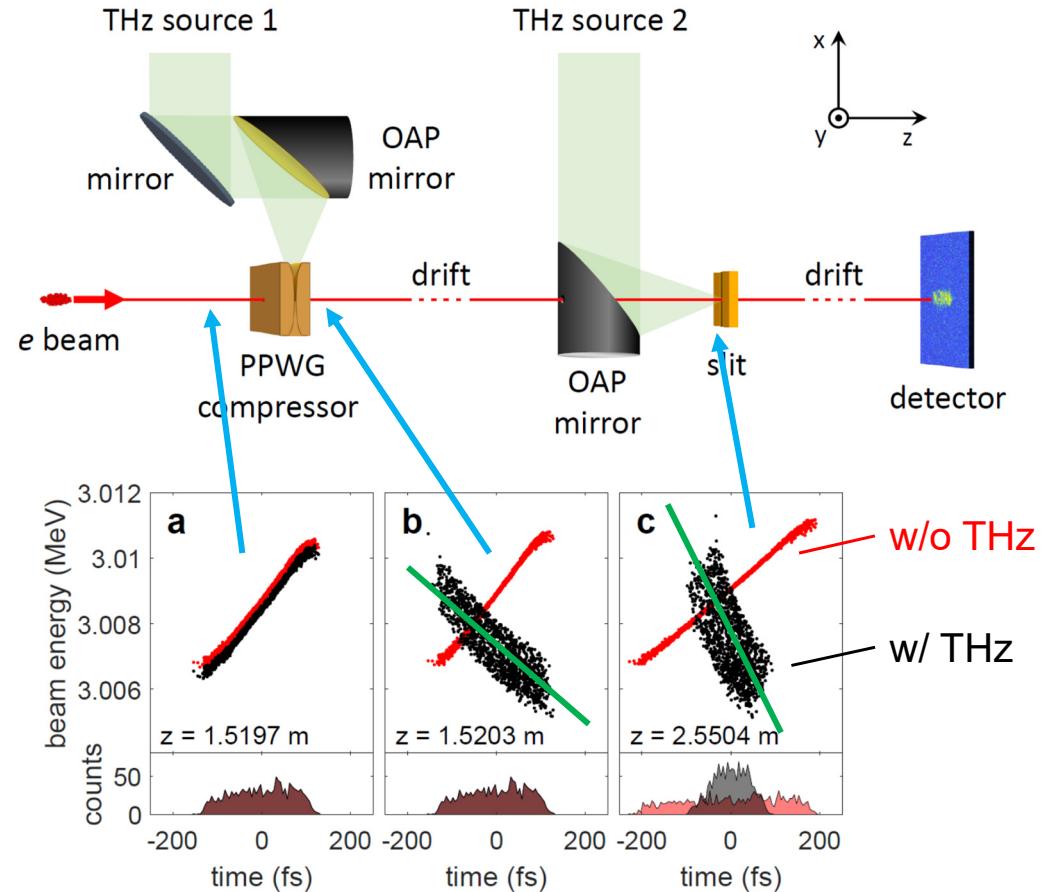
THz compression



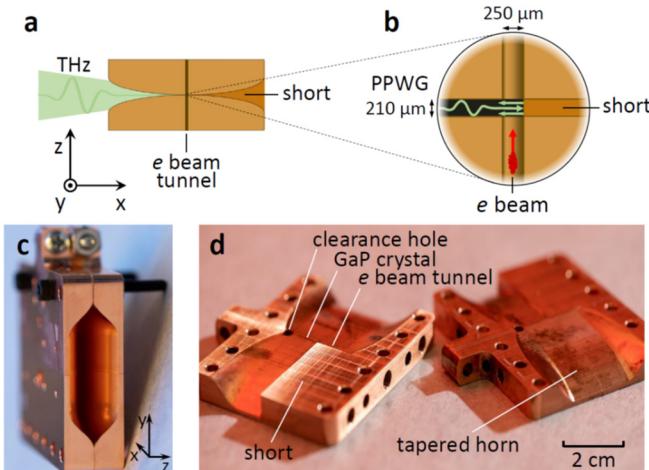
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THz compression

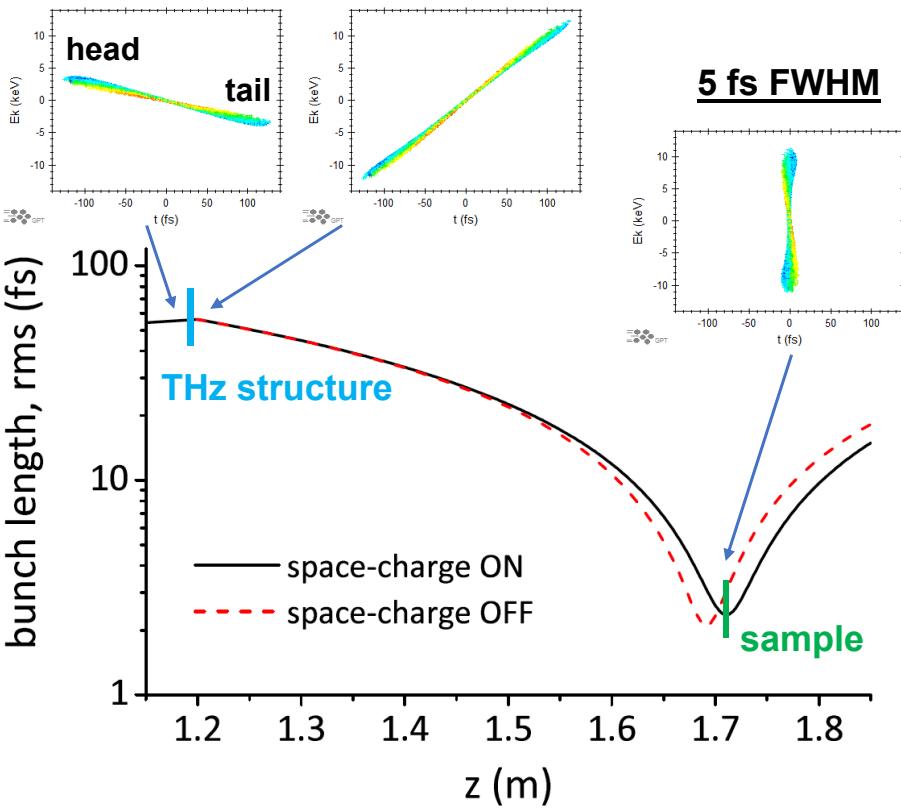


E. Snively et al., arXiv: 1906.03358



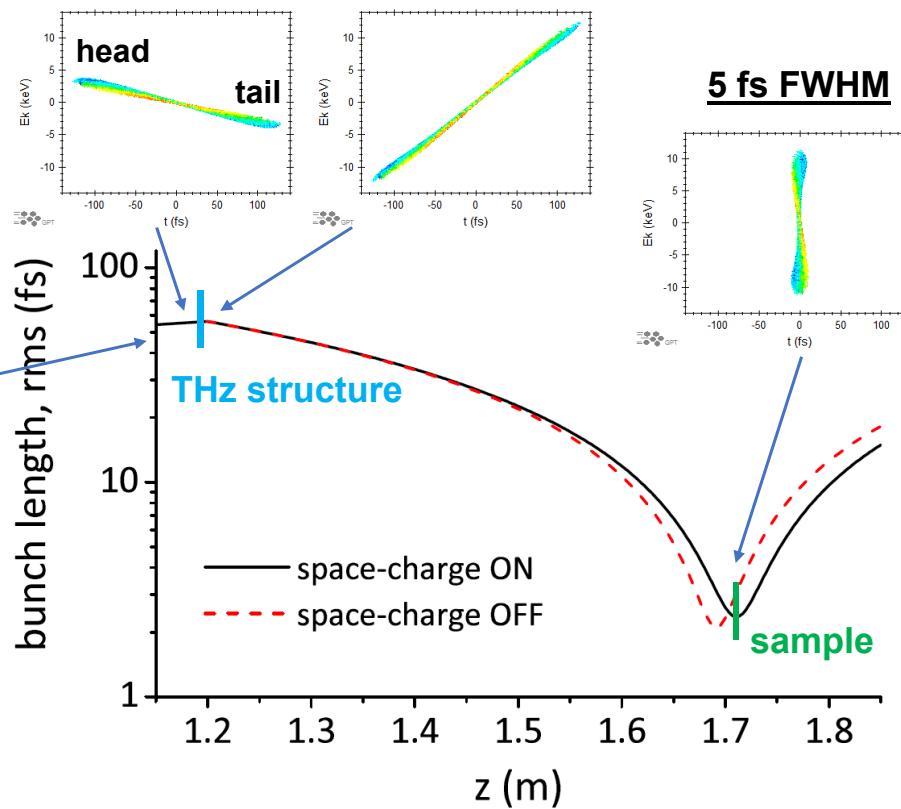
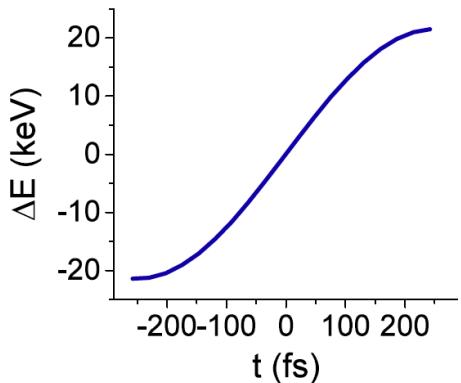
- Laser generated THz can compress the bunch length
- And, stabilize the timing jitter at the same time, relative to the pump laser

Time-of-arrival stabilization



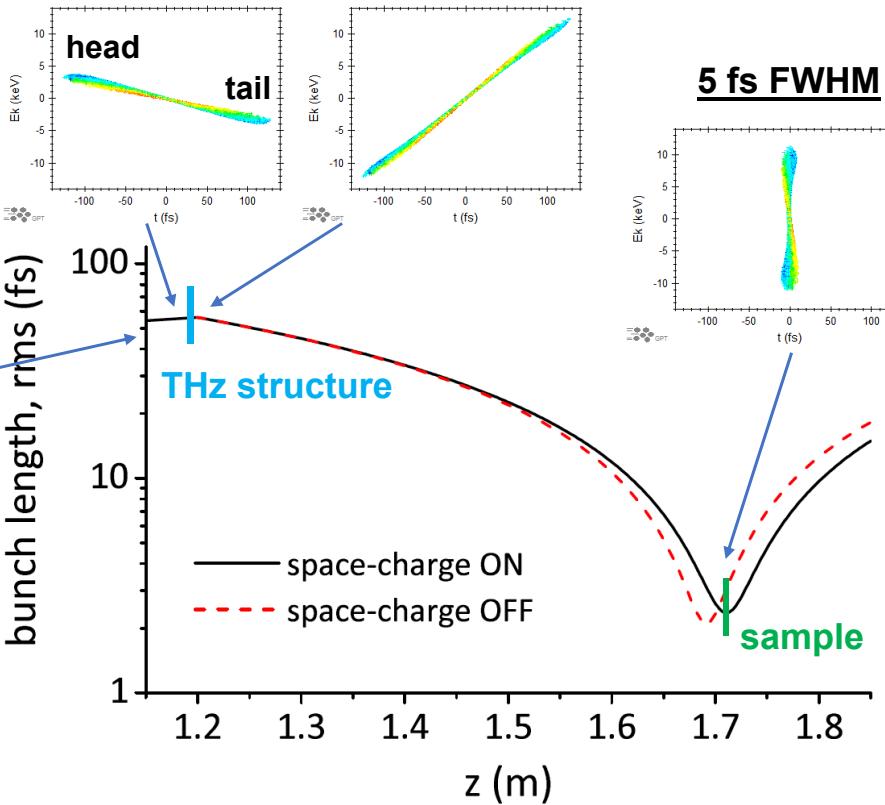
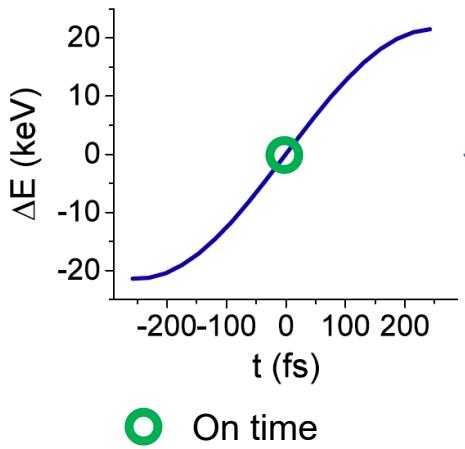
Time-of-arrival stabilization

- THz-induced chirp compress the bunch length
- The chirp/slope also stabilizes the **time-of-arrival**



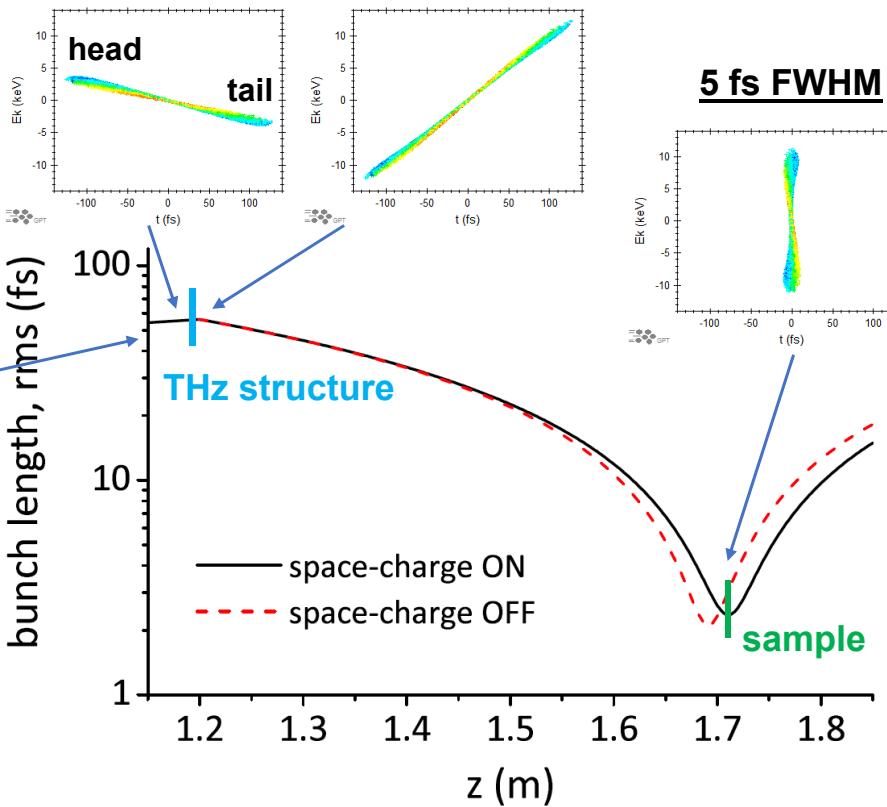
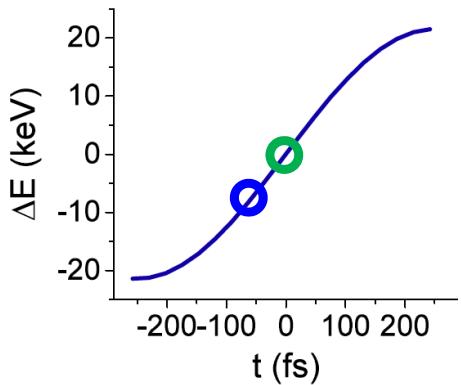
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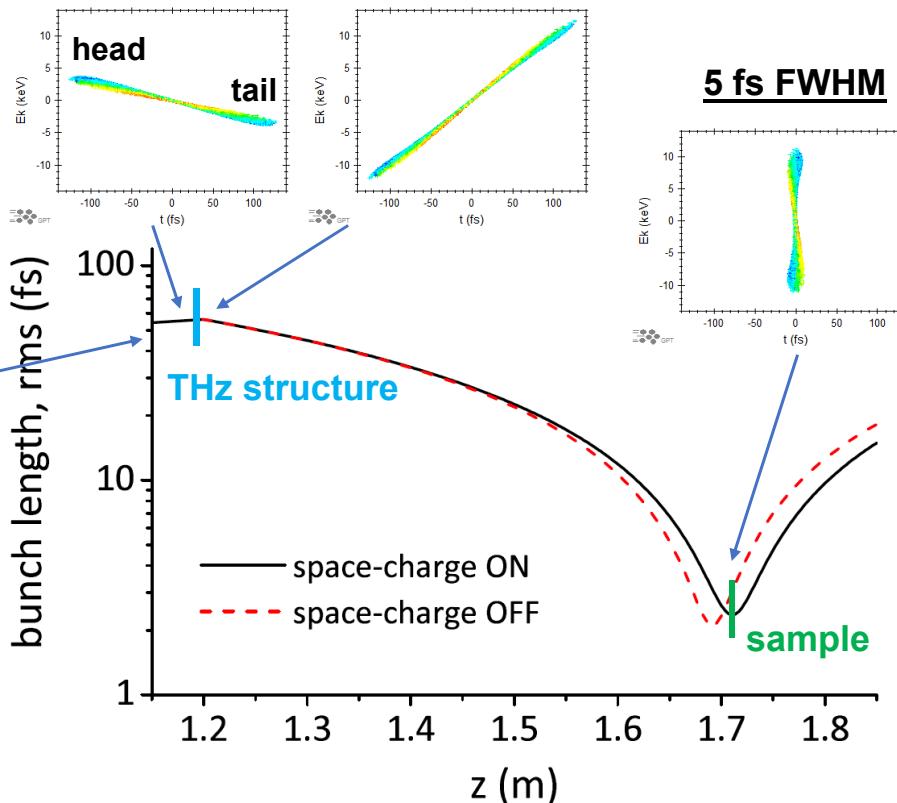
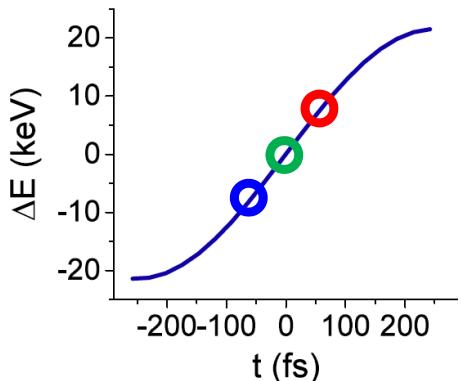
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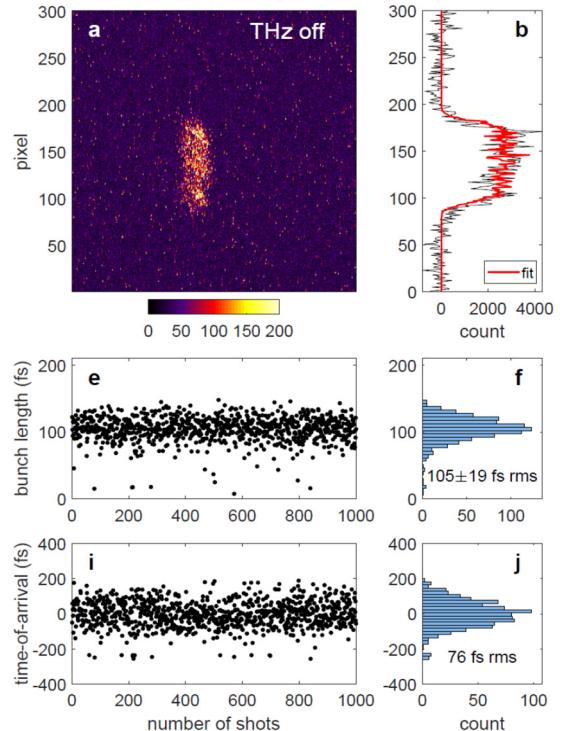


Time-of-arrival stabilization

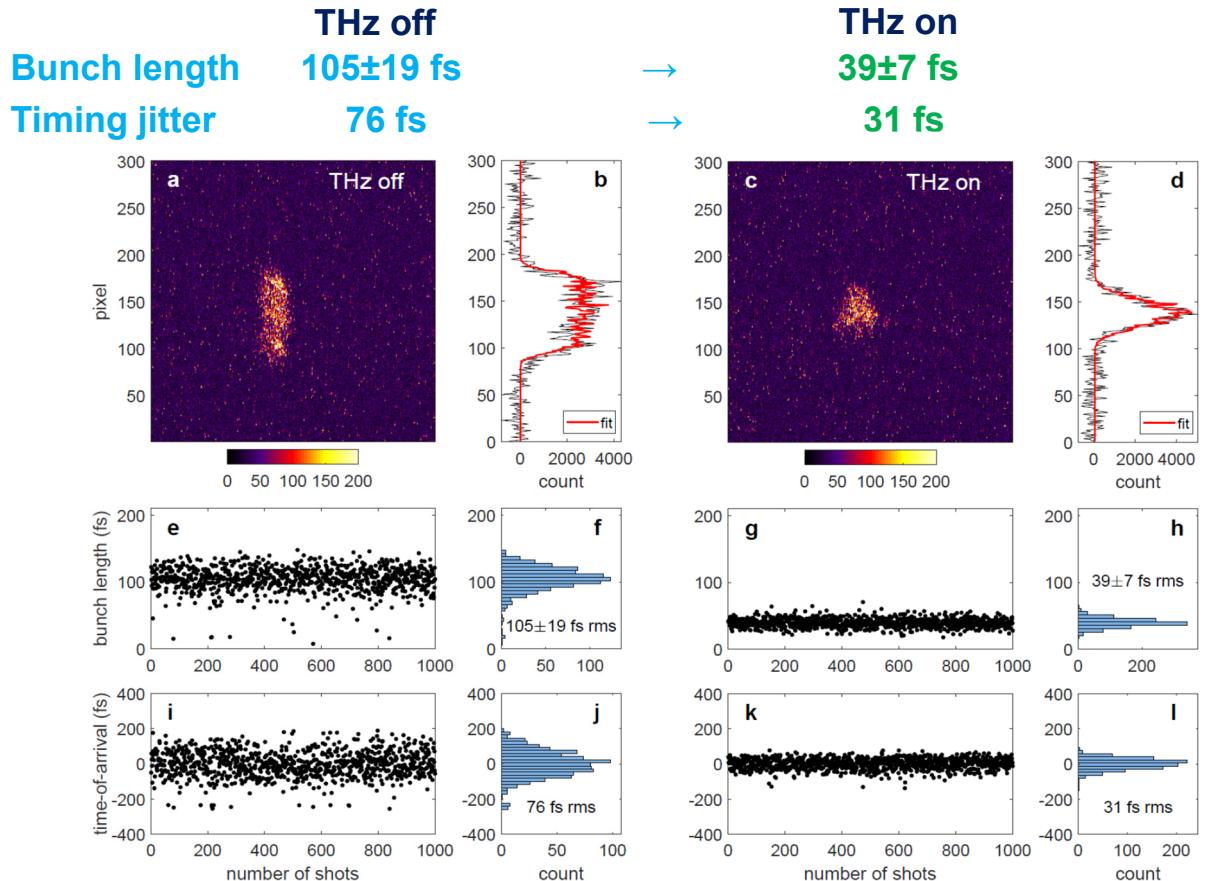
THz off

Bunch length 105 ± 19 fs

Timing jitter 76 fs

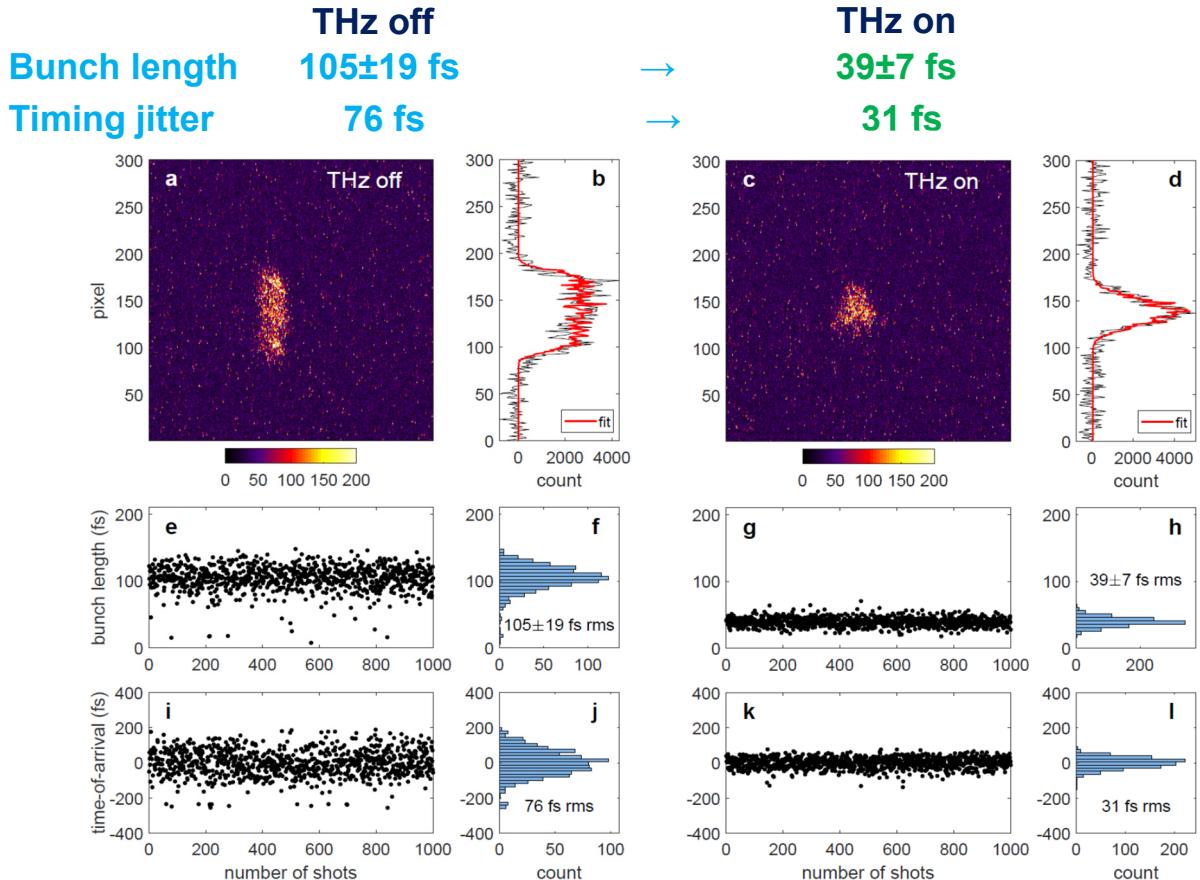


Time-of-arrival stabilization



E. Snively et al., arXiv: 1906.03358

Time-of-arrival stabilization



- Measured **2-3 times** improvement in bunch length and timing jitter
- More dramatic improvement expected, with further optimized **THz radiation and structures**
- Further study and optimization of THz-induced **transverse effects** on the e-beams



Summary and outlook

- High brightness, femtosecond (bunch length and timing), low charge, MeV e-beams **directly** generate exciting, high-impact science results
- Demand shorter bunch and better timing – **toward and beyond fs!**
- **Laser-generated THz**, which is intrinsically synced with pump laser, is effective and efficient in measuring and controlling MeV e-beams
- **Next step:** stronger THz source, optimized THz structures, higher energy e-beams, staged scheme (THz manipulation + injection into laser plasma/dielectric accelerators), etc.



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Thank you for your attention!

Comparison with simulation

- Good agreement between measurement and simulations, especially in the ‘fast part’
- measured time-dependent kick is the integration over the entire interaction region (close to the slit)
- E and B forces almost cancel in vacuum

