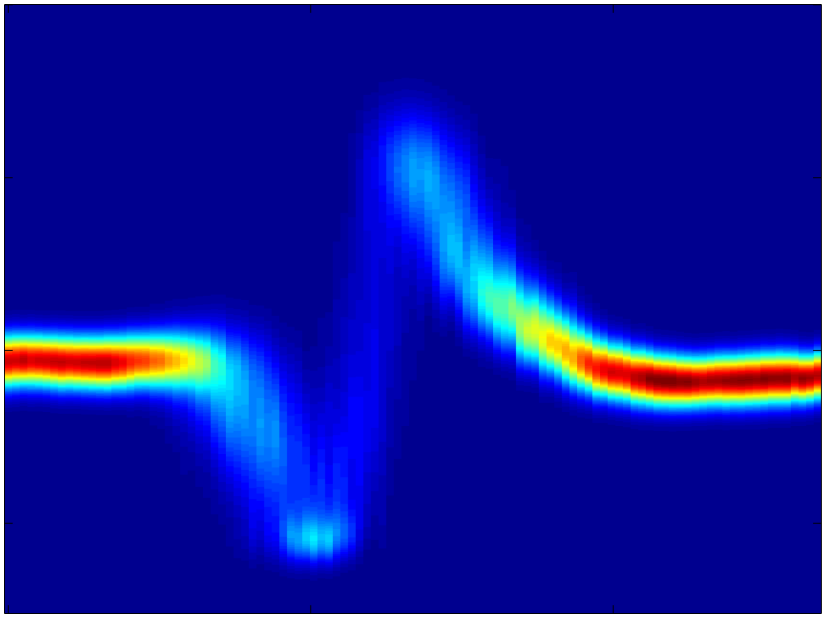
Complete Ultrafast X-ray Pulse Characterization at FELS



34th International Free-electron Laser Conference, Nara Japan

Adrian L Cavalieri

August 28th, 2012

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SASE X-ray Free-electron Lasers

- Emission from soft through hard X-ray regime
- Ultra-intense and ultra short pulse duration

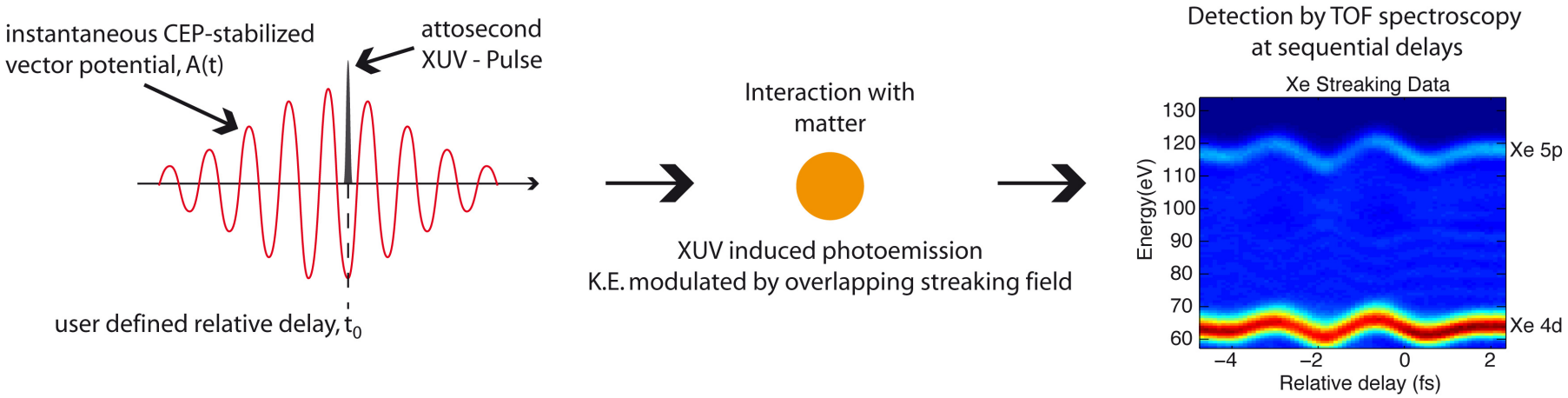
- BUT, X-ray pulses do not have a well-defined temporal profile
  - may be critical for atomic resolution in imaging
- Timing jitter can limits temporal resolution

FLASH

LCLS

SACLA

Streaking for Short Pulse Characterization



- Pulses must be shorter than the streaking field half-cycle (~1 femtosecond for NIR)
- Synchronization and CEO-phase stability for multishot time scan
- Full spectrogram provides access to streaking field parameters
- Analysis of streaked spectra with known streaking field parameters allows characterization of XUV pulse with attosecond resolution

- **GOAL:** Adapt these techniques for use at the FEL
  - -> measure on single-shot basis
  - -> increase streaking wavelength for longer X-ray pulse

Attosecond Streaking Spectroscopy as a General Diagnostic?

- Technique proven for attosecond HHG pulses
- Proven single-shot extension using synchronized long wavelength FIR/THz radiation
  - Reported temporal resolution is very good (Frühling et al. Nature Photonics 2009)
- BUT – Can undulator-based THz radiation be relied upon for low bunch-charge?
- Can this technique be implemented at other facilities?

Holger Schlarb
(DESY)

Can independent THz streaking fields be generated by an optical laser?

Matthias Hoffmann
(MPSD/CFEL)
(now SLAC)

Yes. Maybe.

…and what about timing jitter – standard streaking spectroscopy relies on intrinsic synchronization between sources?

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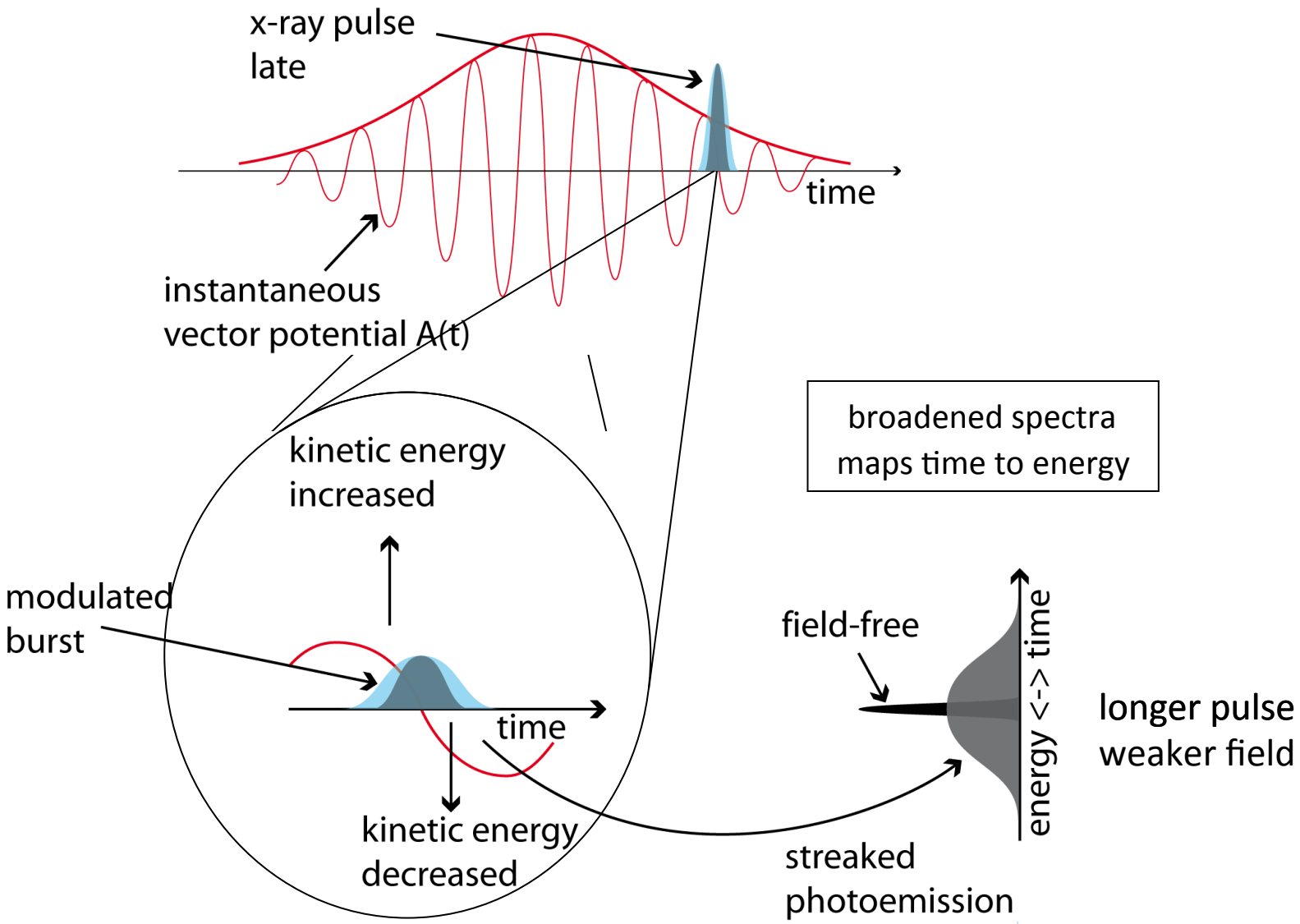
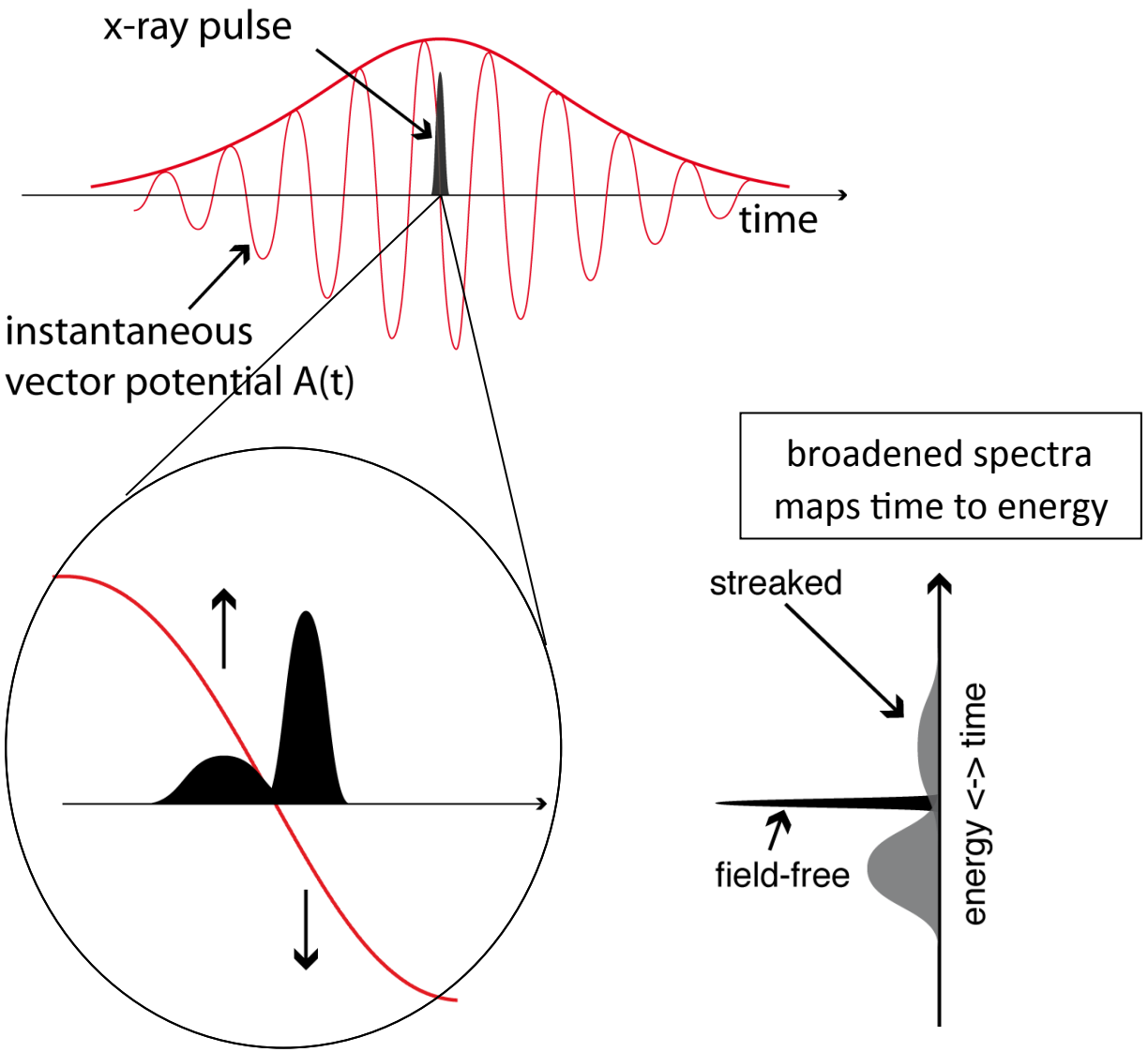
Interpreting Single-Shot Streaked Spectra

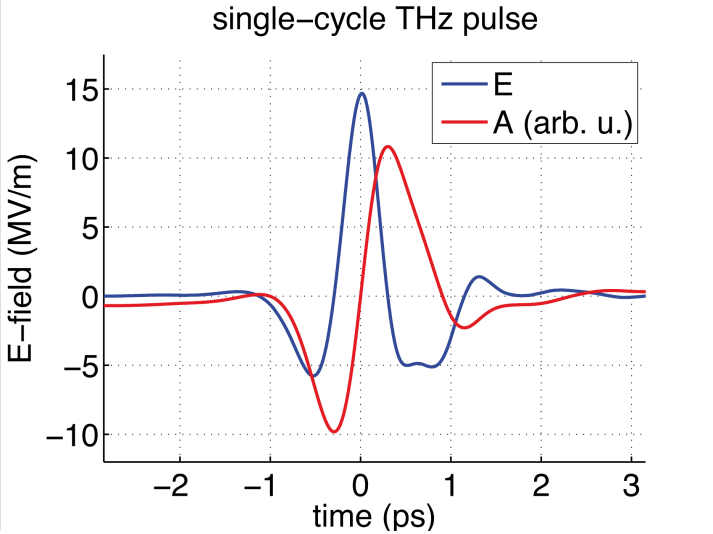


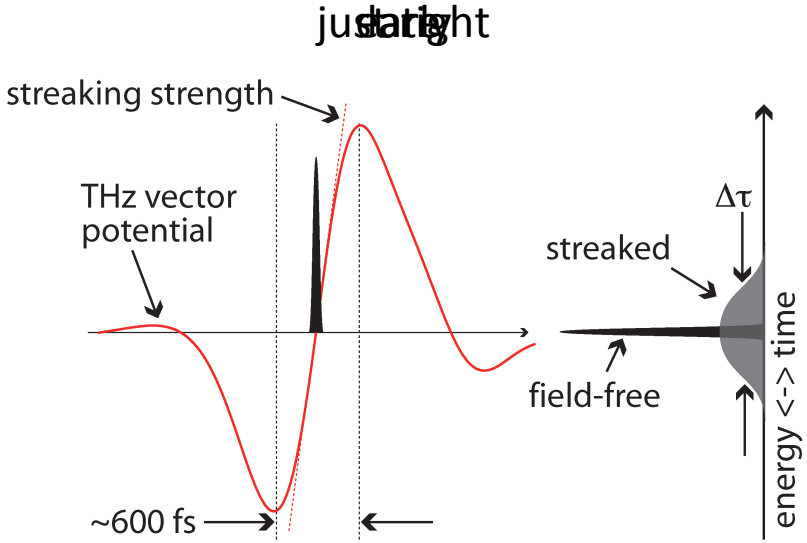
Streaked Spectra with Established Field Parameters



map arbitrary pulse

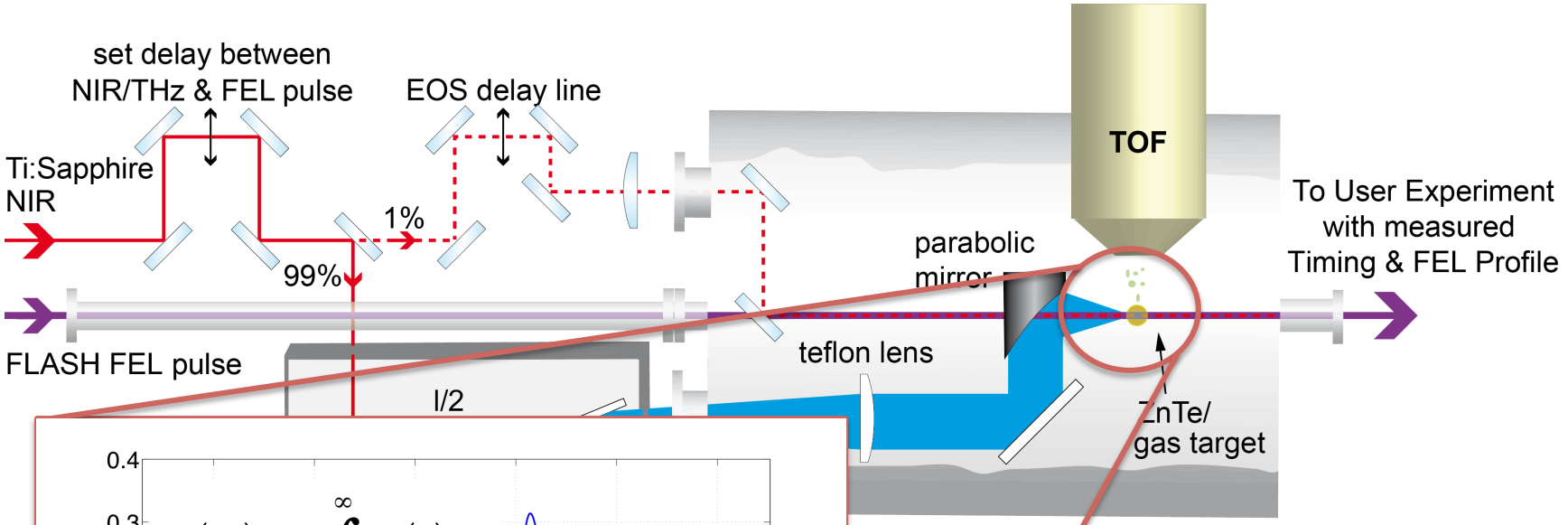
Problem Solved with Single-Cycle Streaking Pulse

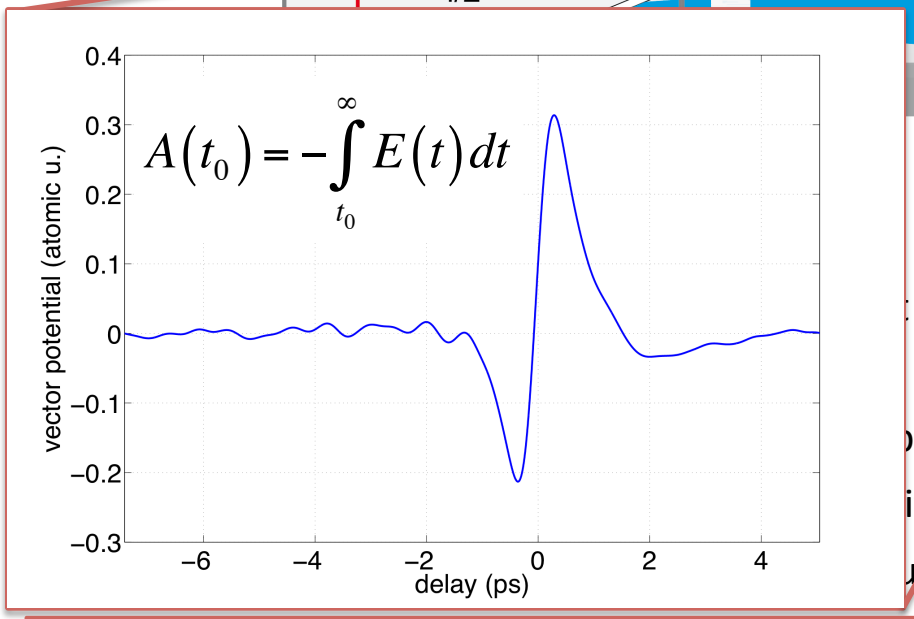




- THz pulse is single-cycle
- Streaking ramp is ~600 femtoseconds in duration – exceeds expected jitter at FELs
- Independent characterization of THz field provides 1-to-1 transformation for KE to time
- Measurement is self-calibrated

THz Streaking at FLASH





method

of THz pulse with NIR probe

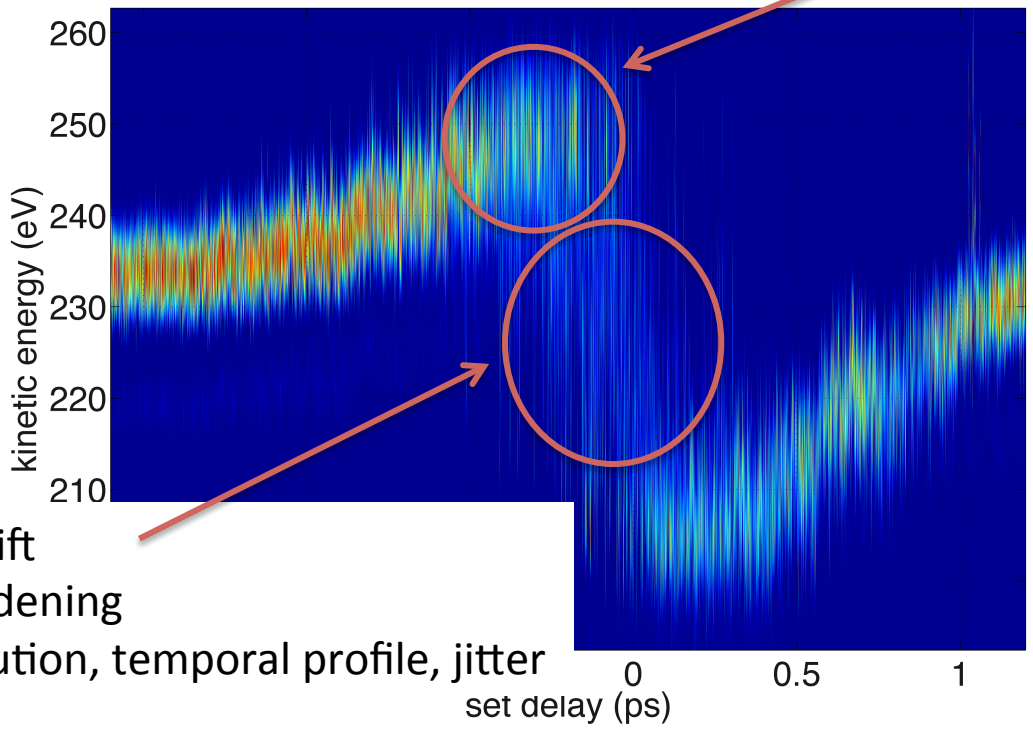
ith XUV

ced photoemission

(streaking effect scales with vector potential)

Streaking Spectrogram at FLASH

Maximum KE shift
Minimum broadening



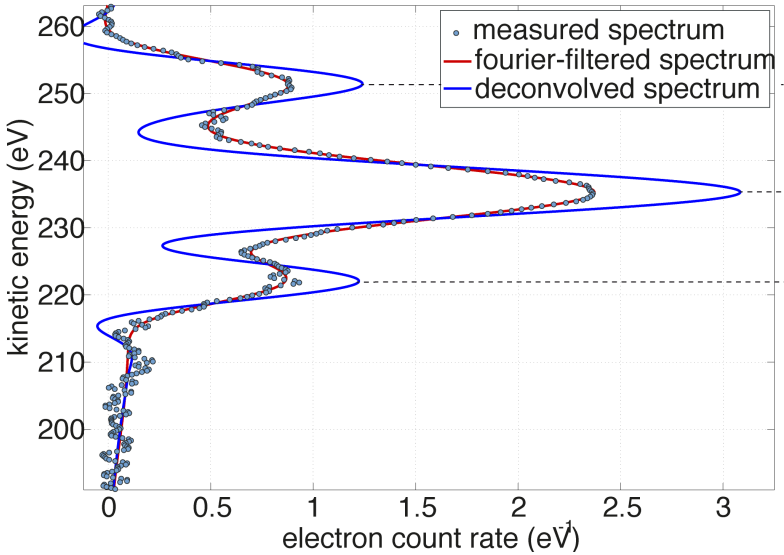
$$\Delta KE = -p_0 A - \frac{A^2}{2}$$

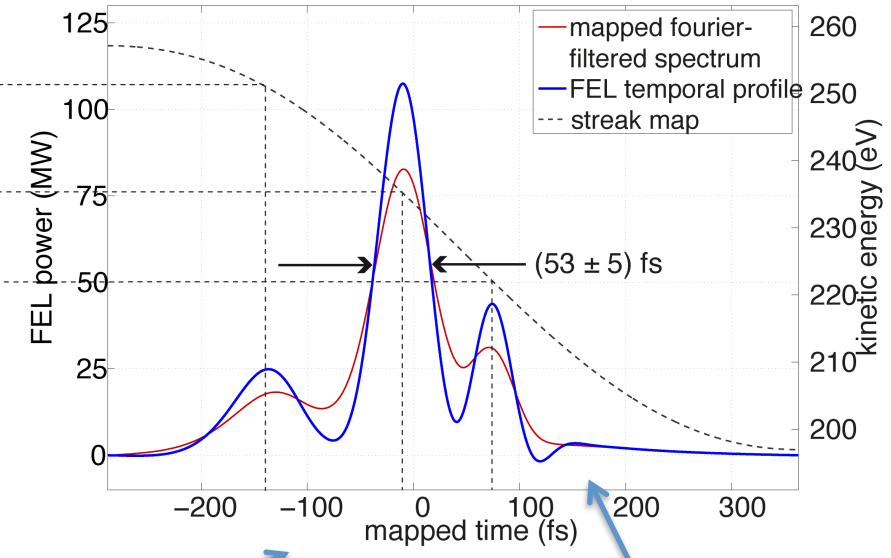
Minimum KE shift
Maximum broadening
High time resolution, temporal profile, jitter

- All single-shots displayed for timescan #56
- Interaction in Helium (isolated line)
- 0.3nC bunches; ~260eV; ~10μJ/pulse

Single-Shot FEL Pulse Characterization at FLASH

200pC bunch charge; ~ 258 eV photon energy; ~10µJ XUV pulse energy



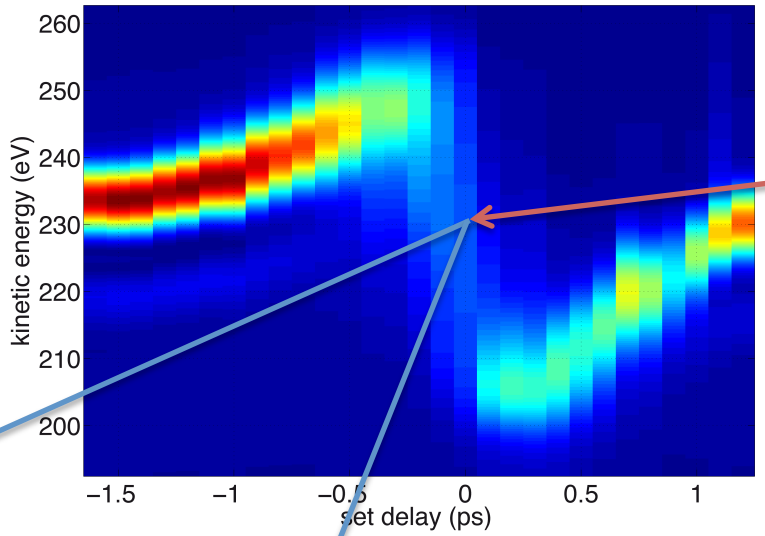


- time axis w.r.t. FLASH pump-probe laser to 6 fs rms
- critical when dynamics occur within the X-ray pulse exposure
- relative timing currently limited by FEL photon energy fluctuation

leading edge of FEL pulse

Quantify Timing Jitter at FLASH

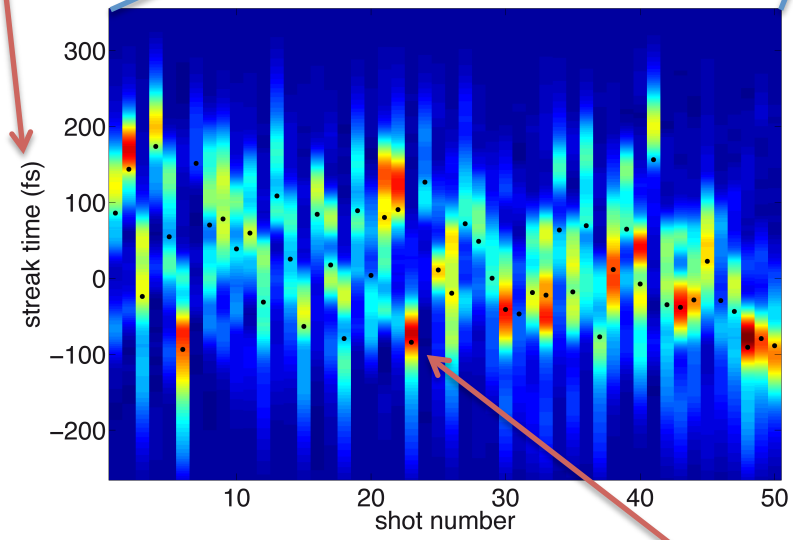
averaged spectrogram



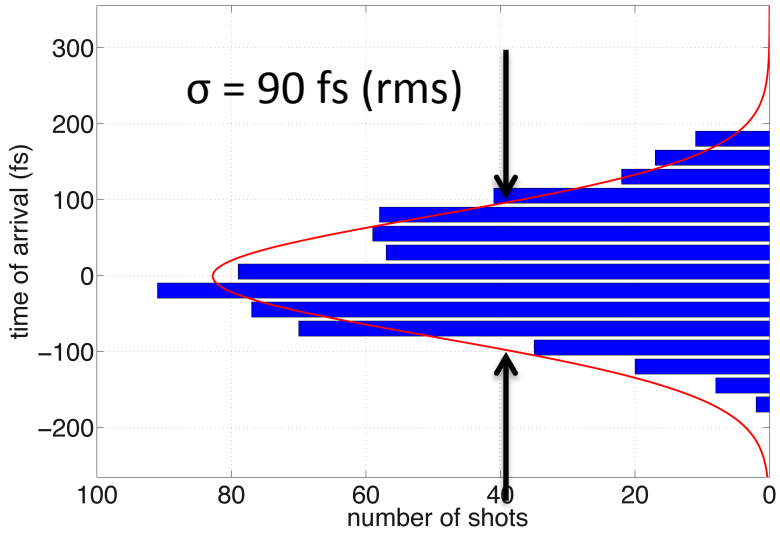
time-zero shots

transformation calculated from streak-map/EOS

fixed set delay



arrival-time distribution



collapse full timing information to COM

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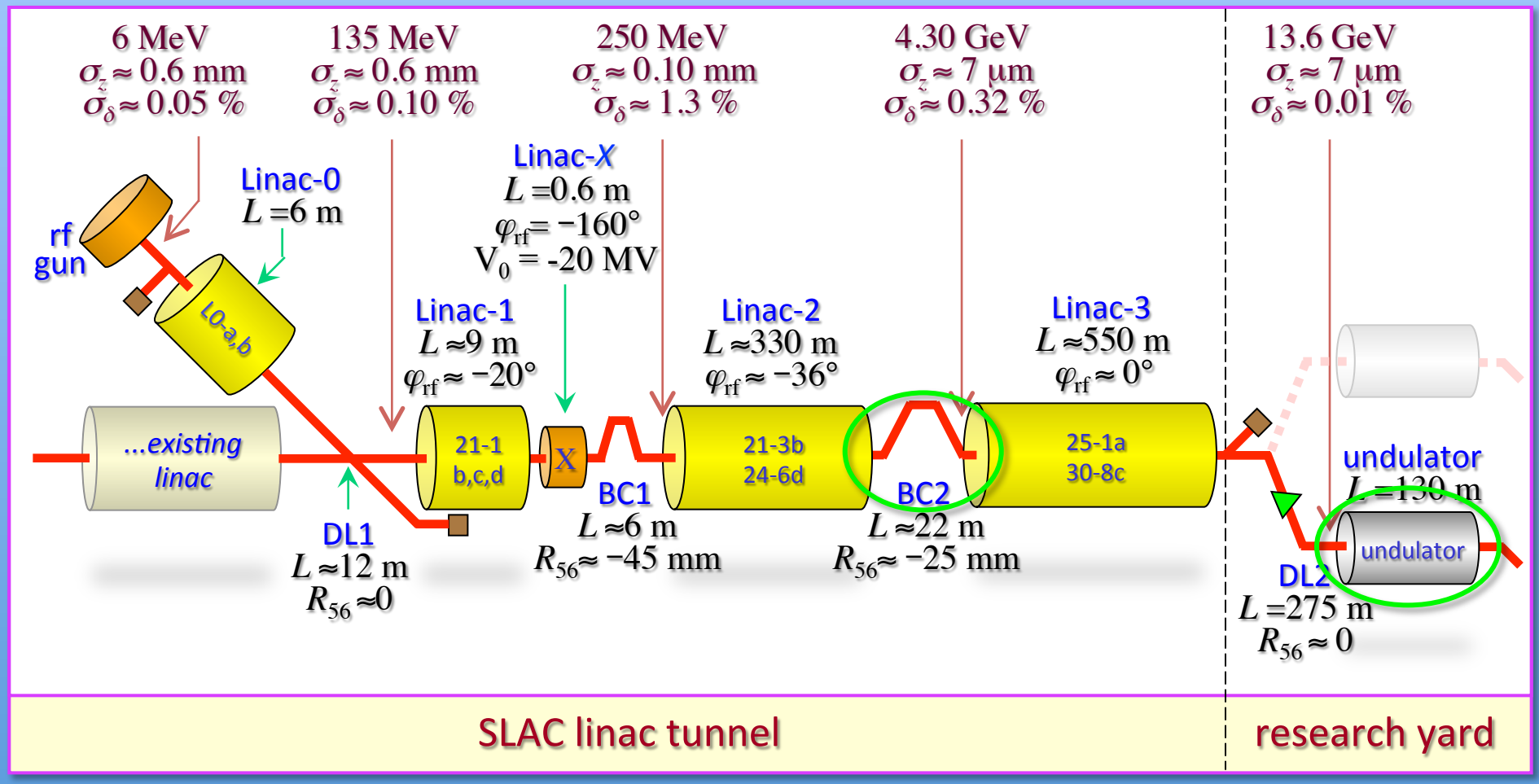
LCLS Accelerator Required for SASE X-Ray FEL

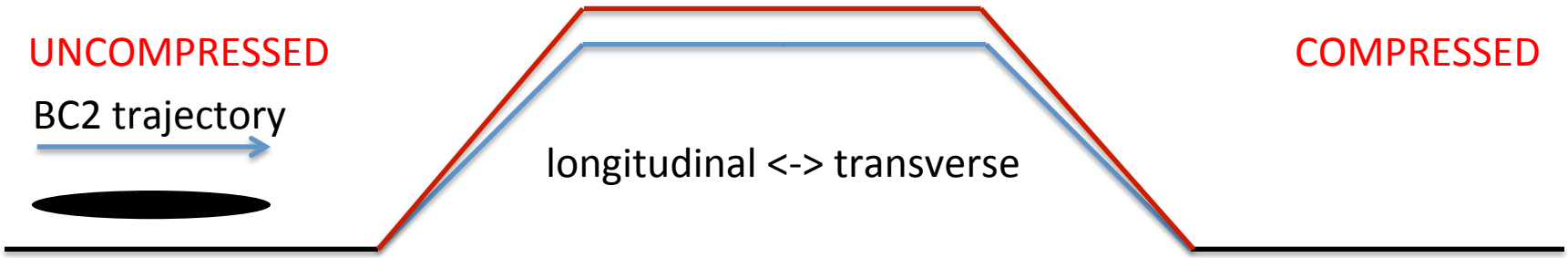
Entire machine is >2000 m long

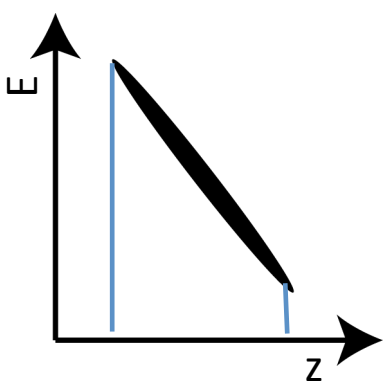


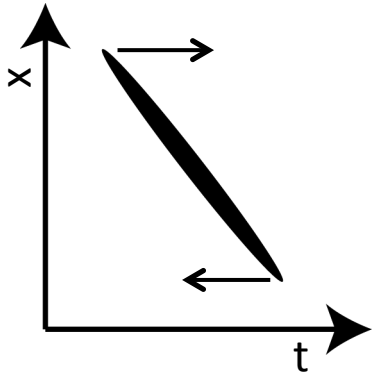
Most of accelerator existed (1960's), but new electron source, new bunch compressors, and new undulator were added

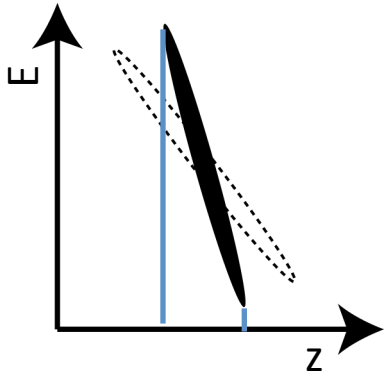
Paul Emma (SLAC/LBNL)

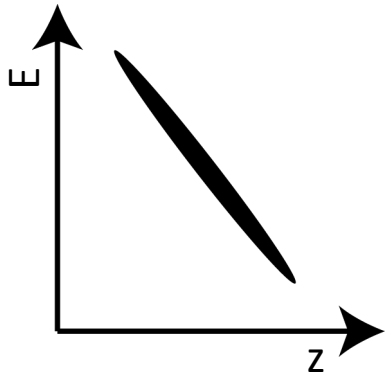
Phase-Space Bunch Compressor 2 (BC2)

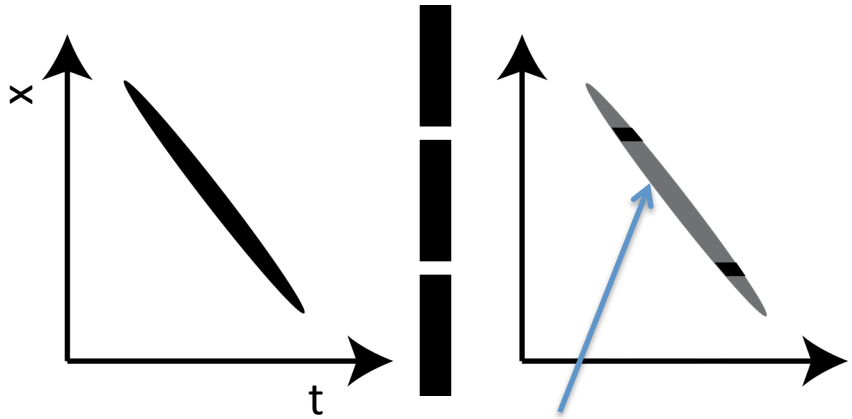


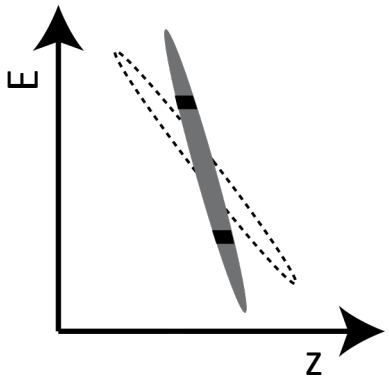








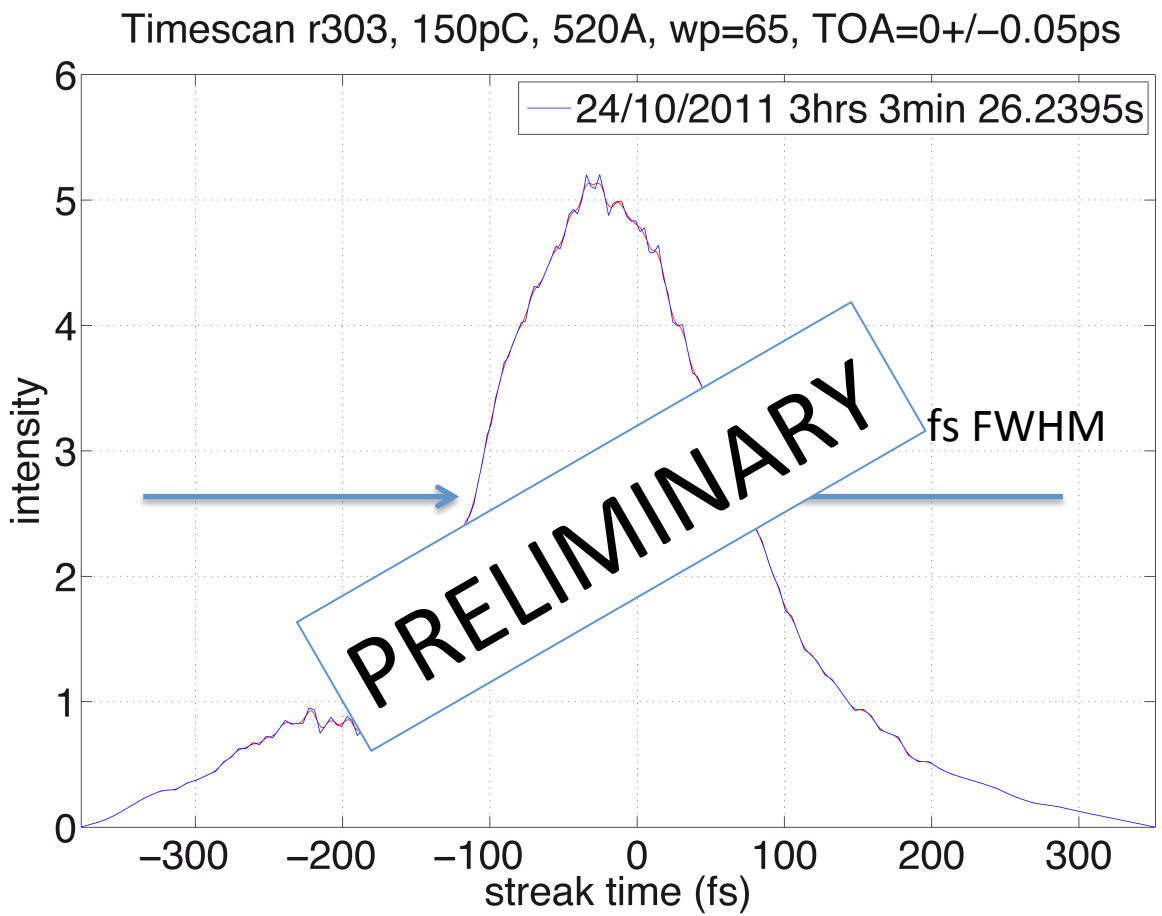




spoiled emmitance

Slotted Spoiler Accelerator Split & Delay

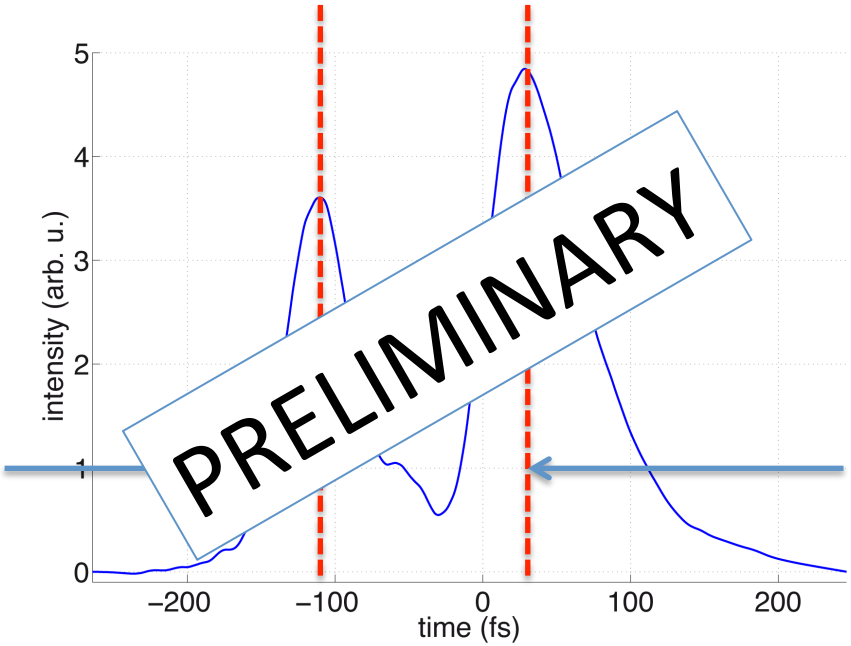
Spoiler-Free Pulse



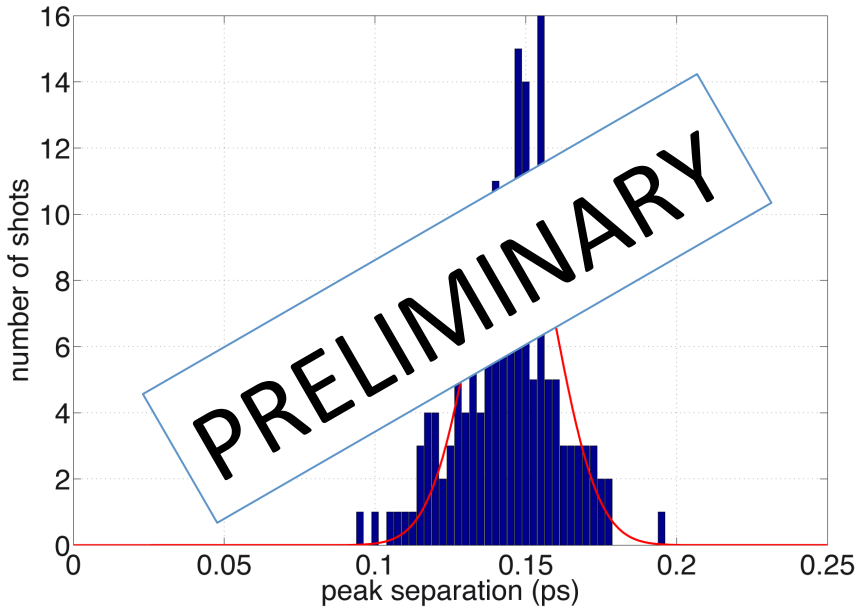
(preliminary analysis)

THz ~3mJ Pump, ~150pC, 1keV, V-spoiler -26,500µm

single-shot measurement



distribution of peak separations

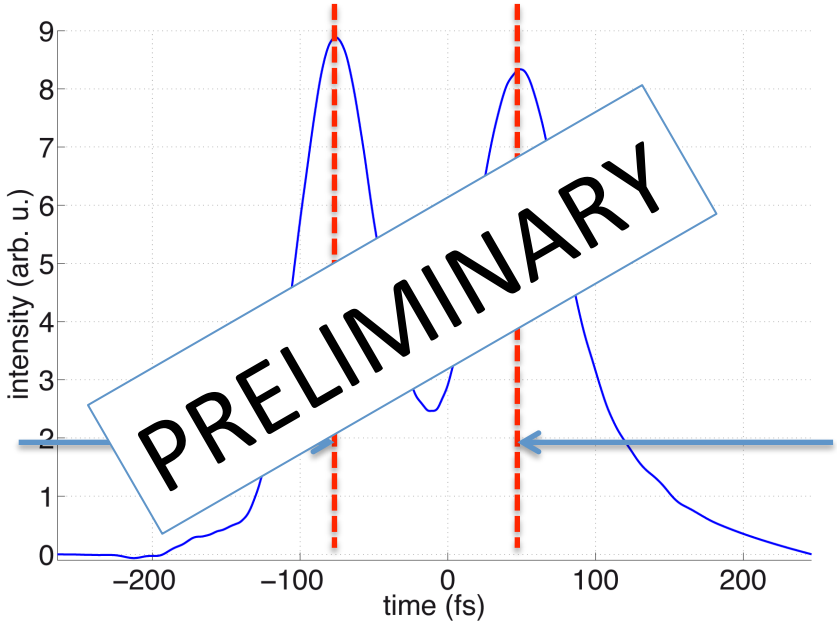


Peak Separation : 150± 15 fs

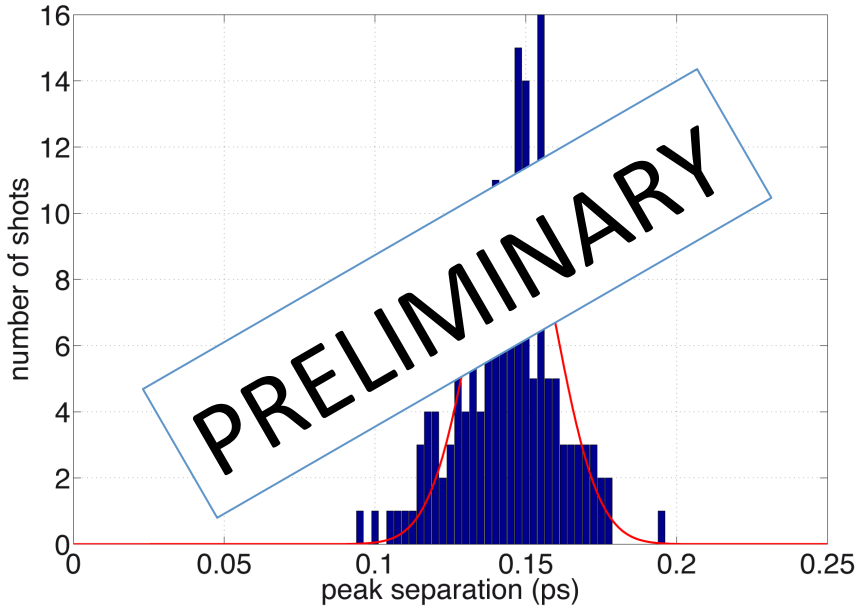
(preliminary analysis)

THz ~3mJ Pump, ~150pC, 1keV, V-spoiler -24,500µm

single-shot measurement



distribution of peak separations

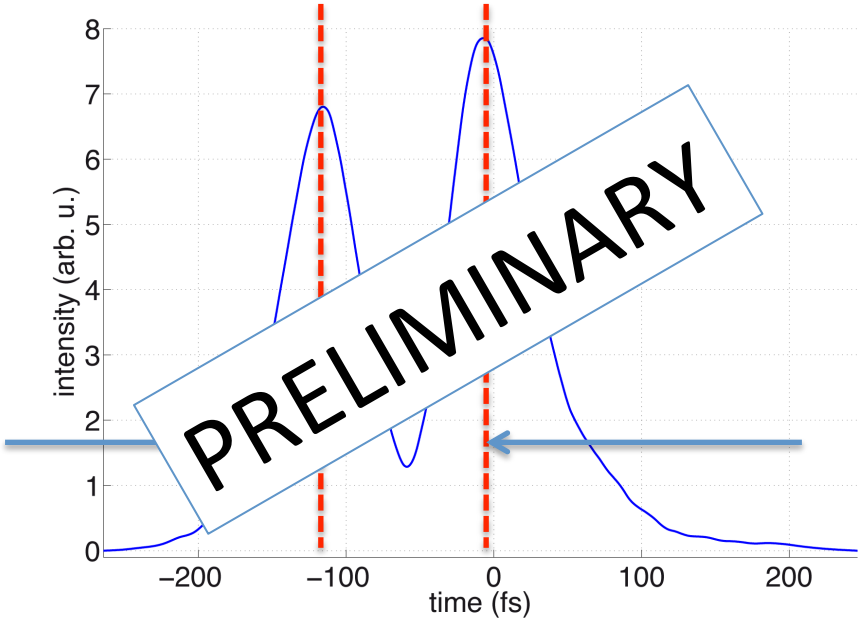


Peak Separation : 125 ± 10 fs

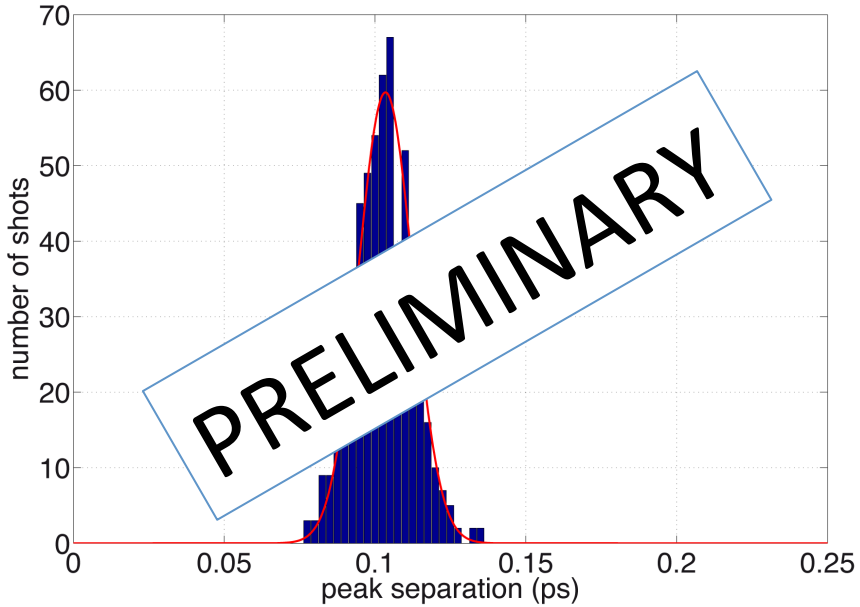
(preliminary analysis)

THz ~3mJ Pump, ~150pC, 1keV, V-spoiler -22,500µm

single-shot measurement



distribution of peak separations

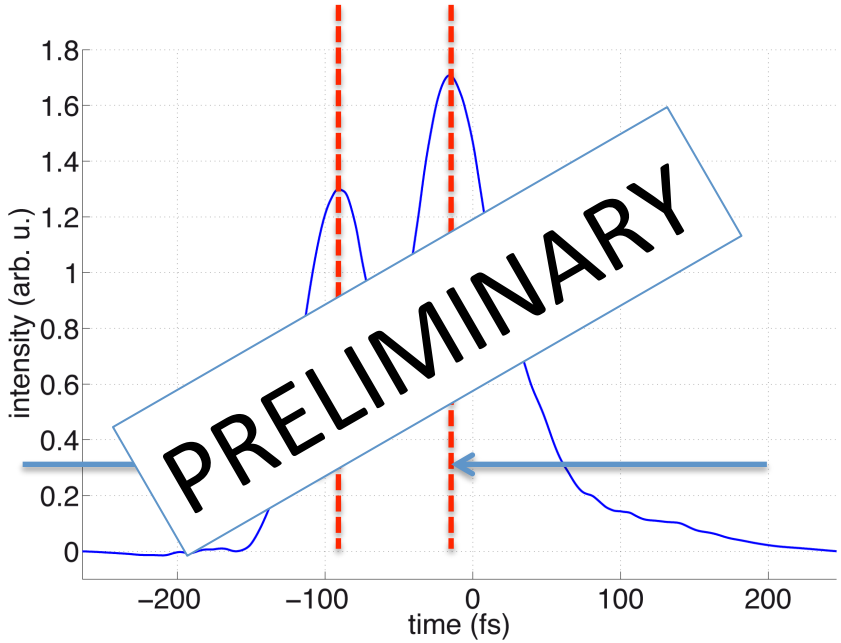


Peak Separation : 105 ± 9 fs

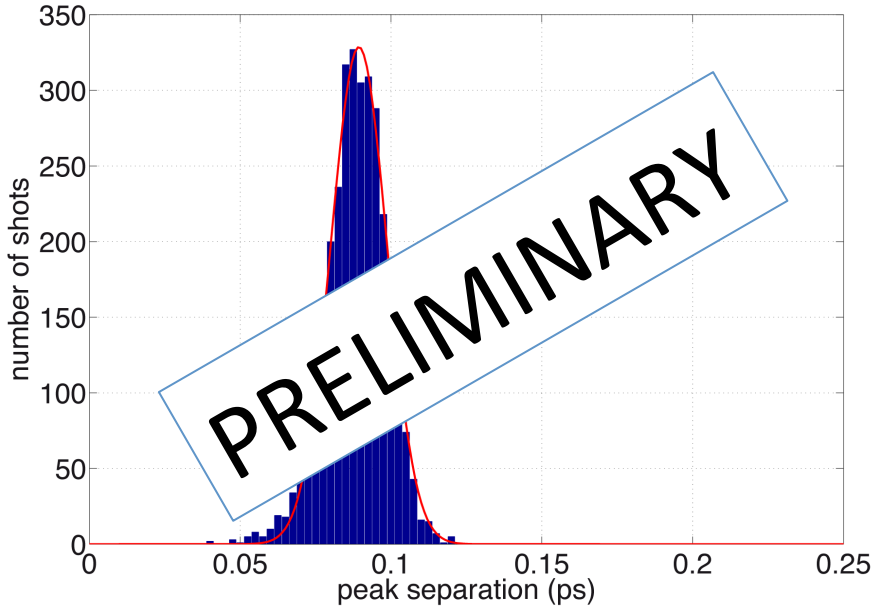
(preliminary analysis)

THz ~3mJ Pump, ~150pC, 1keV, V-spoiler -20,500µm

single-shot measurement



distribution of peak separations

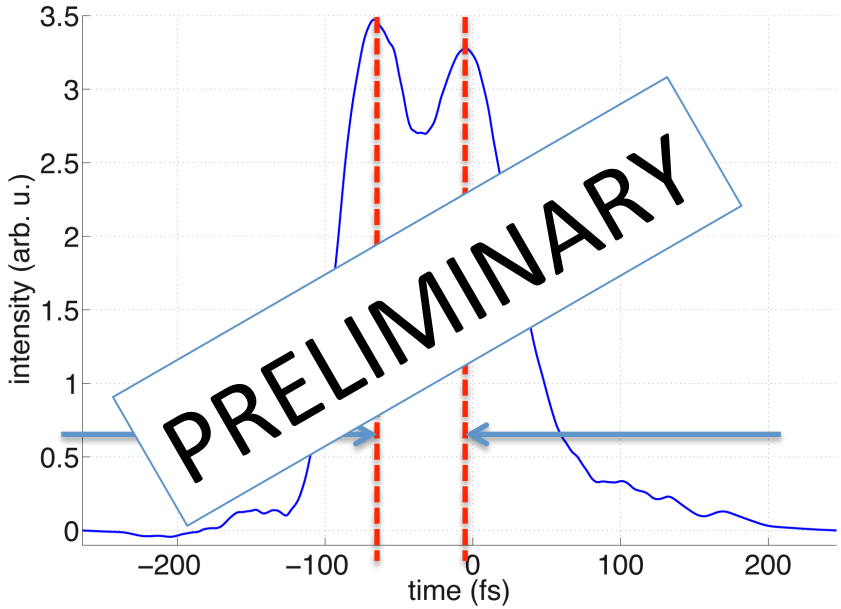


Peak Separation : 90 ± 8 fs

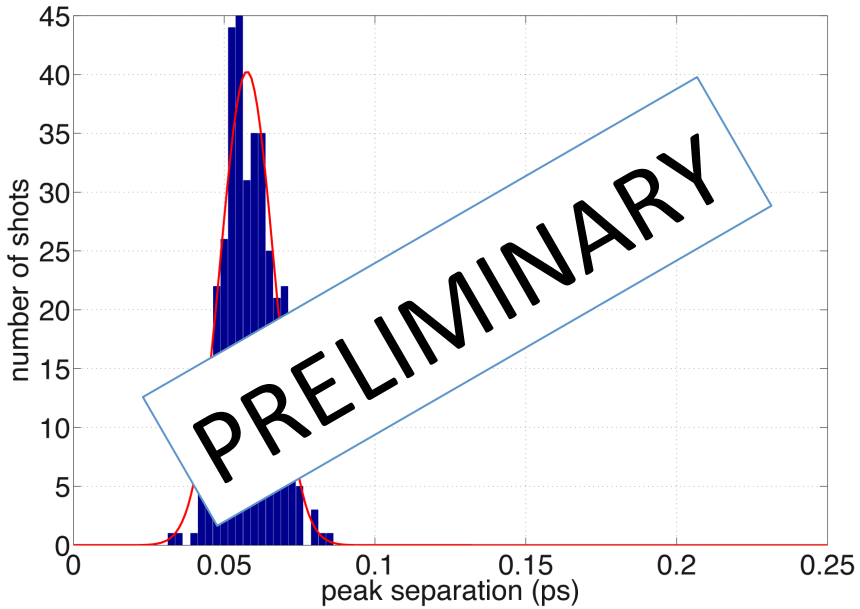
(preliminary analysis)

THz ~3mJ Pump, ~150pC, 1keV, V-spoiler -18,500µm

single-shot measurement



distribution of peak separations

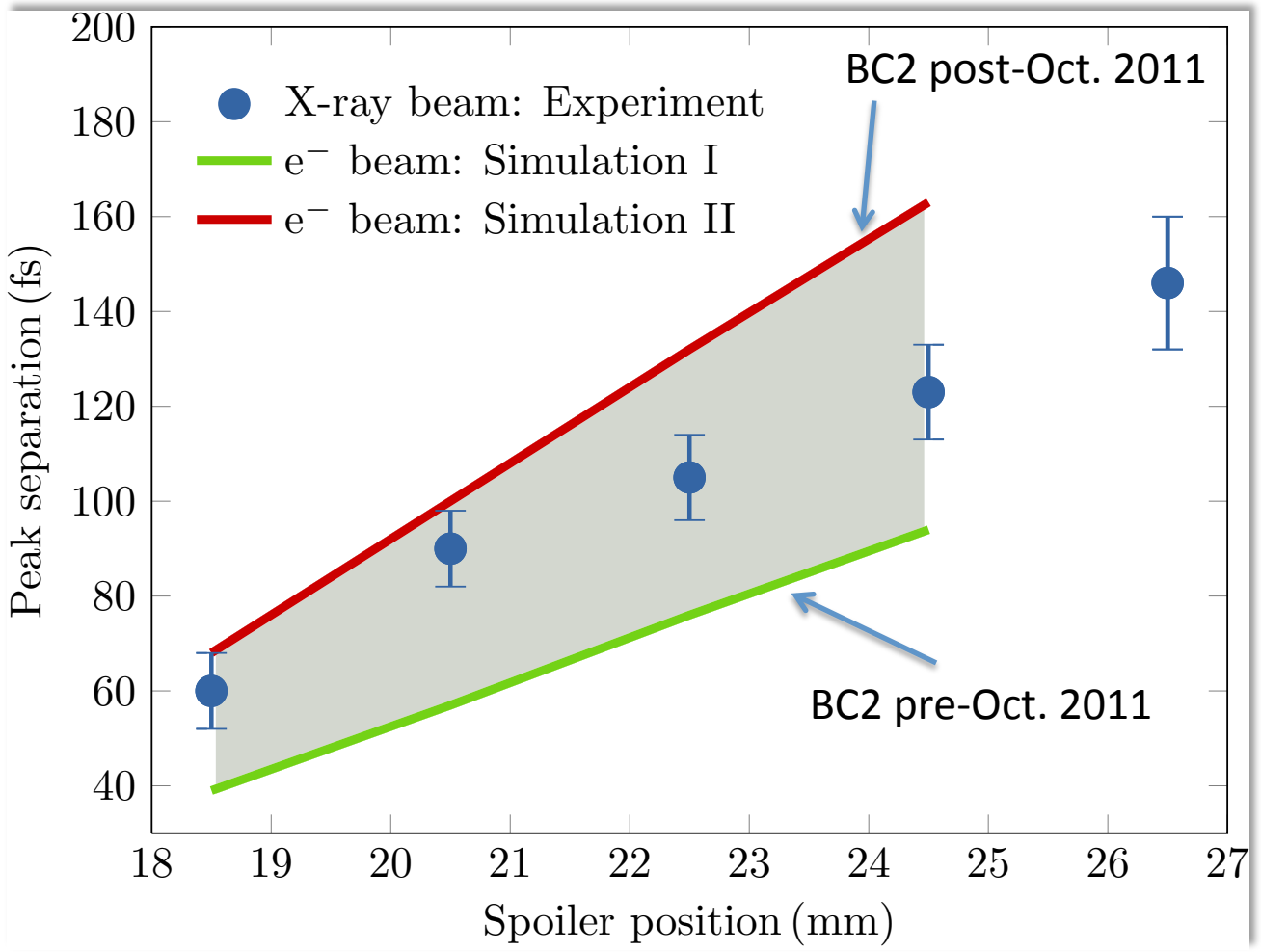


Peak Separation : 60 ± 8 fs

- Provides upper bound on measurement resolution of ~ 60 fs FWHM
- Opens possibility for tailored X-ray emission using pulse profile for feedback

(preliminary analysis)

THz ~3mJ Pump, X-ray Double Pulse Resolved



(Y. Ding)

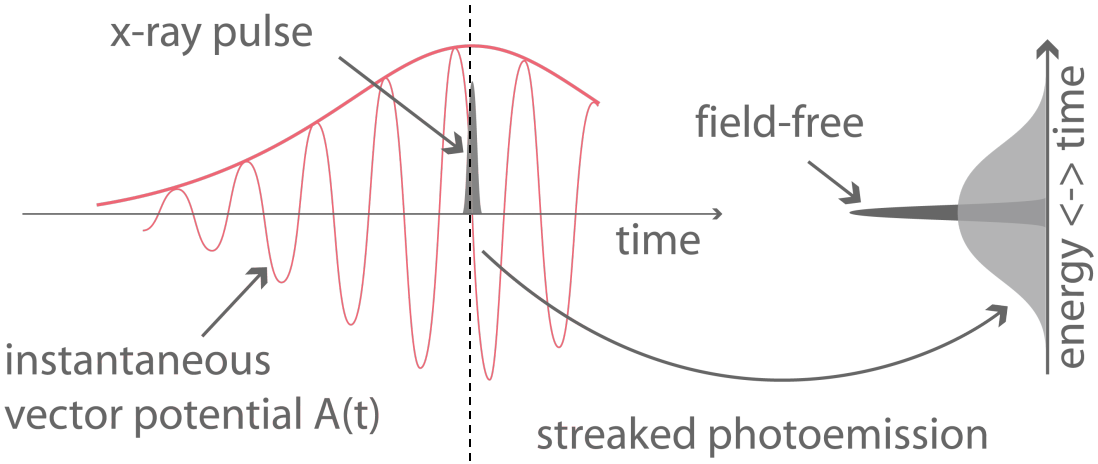
(preliminary analysis)

Outlook

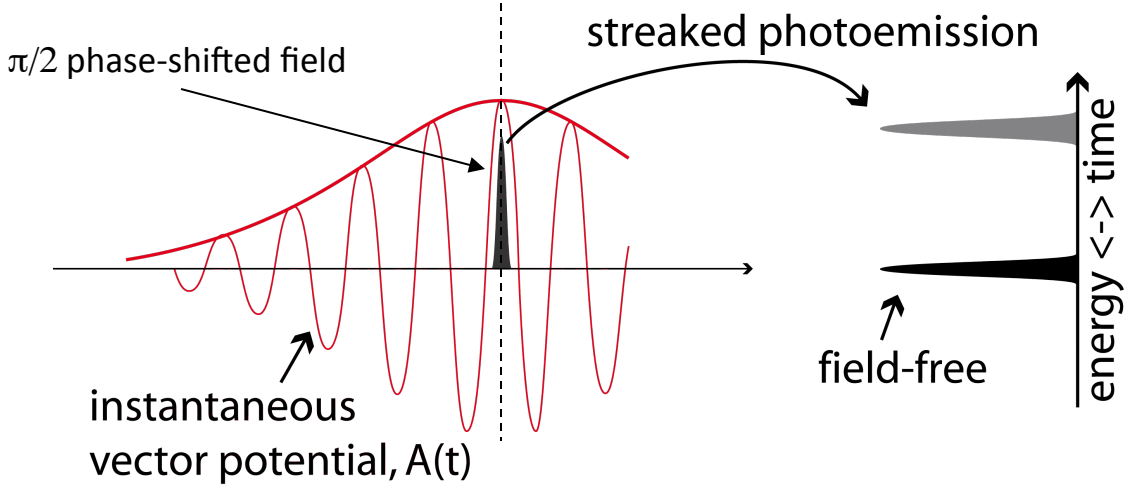
Optical Wavelength Streaking Fields - > for Attosecond Resolution

- Ultimately, time resolution is limited by gradient of streaking field
- Need optical wavelengths to achieve gradients for attosecond resolution
- Not possible to produce single-cycle pulses in this range – timing jitter must be readdressed
- Make two independent measurements per X-ray pulse
  - One measurement for calibration (point of temporal overlap and phase)
  - One measurement provides pulse profile

Phase-shifted Measurement for Self-Calibration

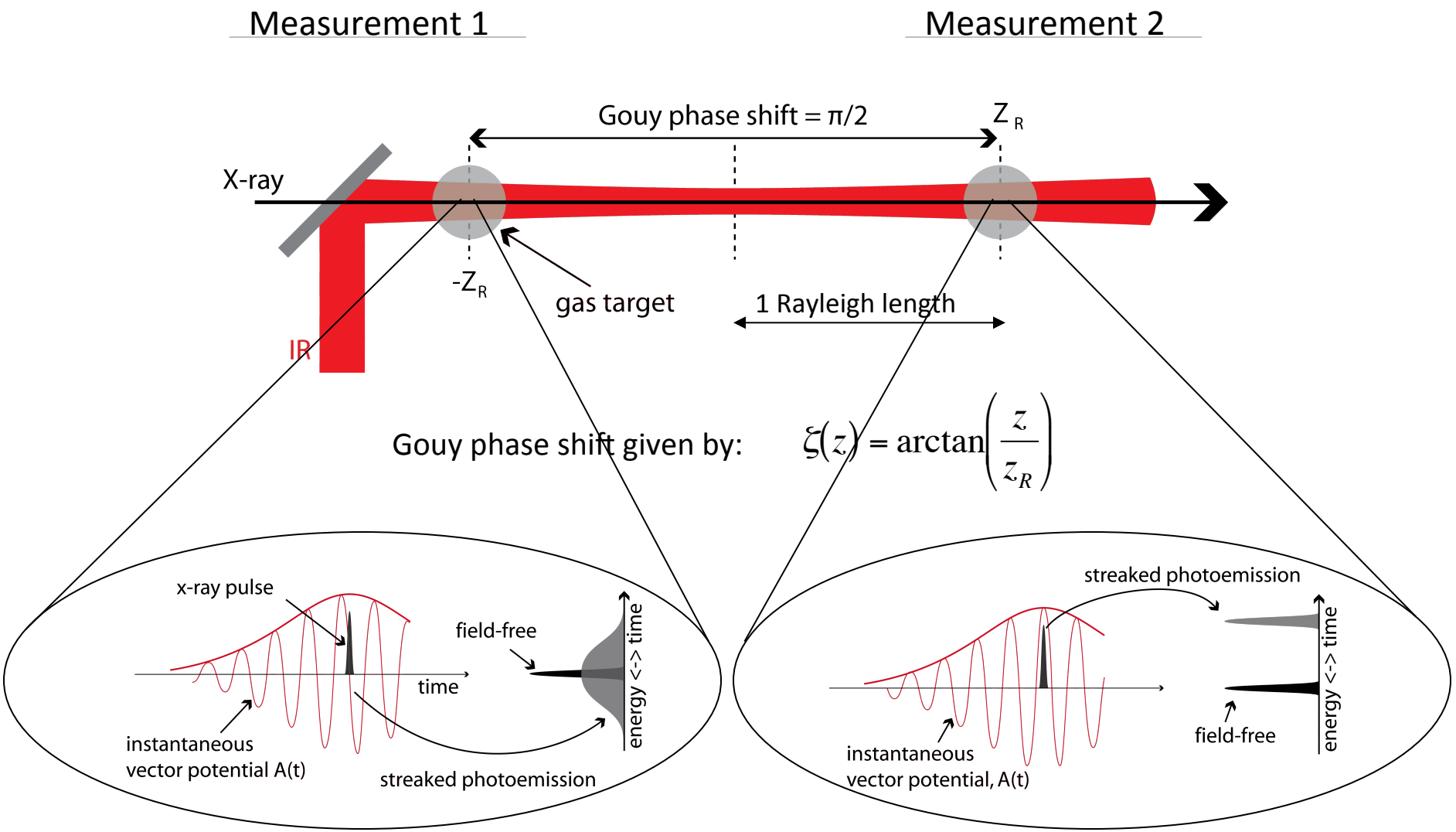


Measurement 1:
broadened spectra
maps time to energy



Measurement 2:
shifted spectra
provides calibration

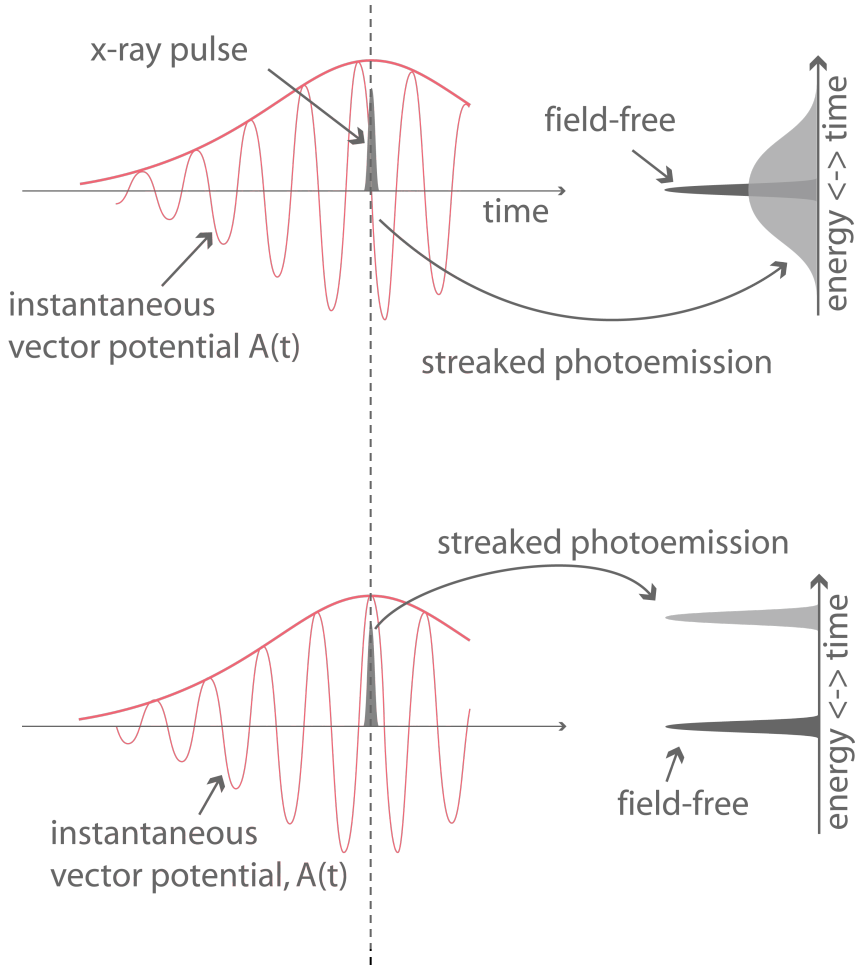
Tandem Geometry Utilizes Gouy Phase Shift

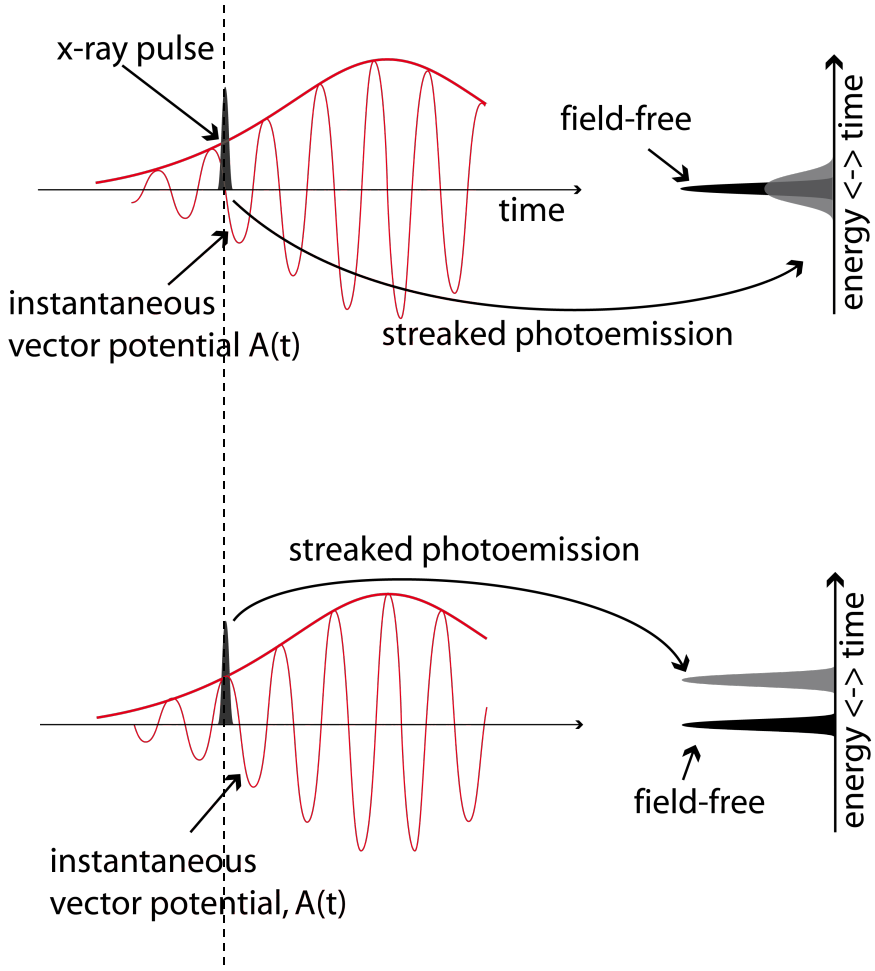


Tandem Streaking also Delivers Relative Timing

near time-zero arrival

early arrival





single-shot streaking strength gives the relative timing information

Collaboration

- **DESY**
  - Holger Schlarb
  - Stefan Düsterer
  - Christopher Behrens
- **MPQ**
  - Reinhard Kienberger
  - Andreas Maier (Florian Grüner)
  - Wolfram Helml
  - Wolfgang Schwienberger
- **XFEL**
  - Michael Meyer
  - Tommaso Mazza
  - Thomas Tschentscher
  - Nikolay Kabachnik
- **SLAC**
  - Matthias Hoffmann
  - Jerry Hastings
  - Christoph Bostedt
  - Sebastian Schorb
  - John Bozek
  - Yuanto Ding
  - Ryan Coffee
- **MPSD/CFEL/UHH**
  - Ivanka Grguras
  - Sebastian Huber
  - Hubertus Bromberger
  - Haiyun Liu
- **Argonne National Lab**
  - Gilles Doumy
- **Dublin City University**
  - John Costello
  - Thomas Kelly
- **Ohio State University**
  - Louis DiMauro
- **UPV-EHU**
  - Andrey Kazansky

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Thank you for your attention.