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Temporal Diagnostics Measurements with the Pulse Arrival and Length Monitor (PALM) at SACLA

Introduction

- Temporal diagnostics overview
- THz streak camera theory
- Description of the setup
- Experimental results
  - Arrival time determination
  - Pulse length and chirp determination
  - Possible sources of uncertainty
- Conclusions and future plans

Poster on Monday, MOP Poster Session

Temporal diagnostics for FEL light: a brief overview

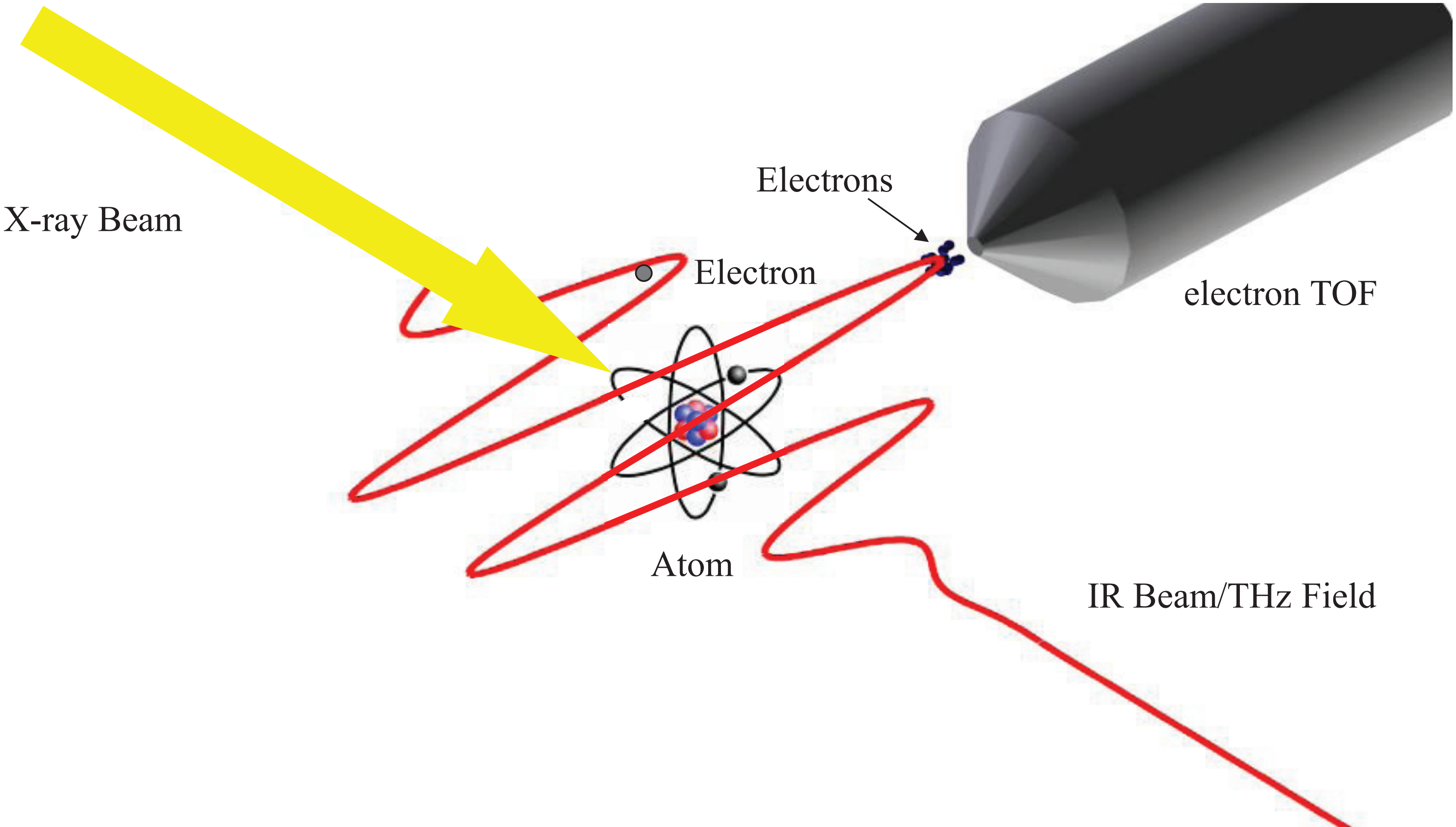
- **Spatial and spectral encoding methods**
  - Has been tried or used at most FEL facilities (FLASH, SACLA, LCLS)
  - Fairly simple setup using a chirped optical beam and crystal that changes transmission properties due to x-ray pulse.
  - Measures arrival time with published accuracy of down to 6fs RMS (M. Harmand et. al., *Nature Phot.* **7**, 215 (2013))
  - Unique schemes have recently gone down to fs-level with soft x-rays (N. Hartmann et. al., *Nature Phot.* **8**, DOI: 10.1038/NPHOTON.2014.164)
  - Loses accuracy with lower light intensities, can act as a strong attenuator at lower photon energies
  - Can not (thus far) measure pulse length

- **Electron deflecting cavities**
  - In use at LCLS as the XTCav (C. Behrens et. al., *Nature Comm.* **5**, 3762 (2014))
  - Looks at energy loss of electron bunch behind the last bending magnet to measure the photon pulse properties.
  - Has a few fs resolution for pulse length and can show which part of the bunch lased
  - Cannot measure arrival time accuracy relative to laser
  - Does not measure the X-ray beam itself, sees no effect from optics, monochromators, etc
  - Completely parasitic, doesn't disturb the beam at all if situated behind the last undulator

- **THz streak camera**
  - Has been tested at FLASH (U. Fruehling et. al., *Nature Phot.* **3**, 523 (2009), I. Grguras et. al., *Nature Phot.* **6**, 276 (2021))
  - Has been used for attosecond measurement of laser pulse lengths (M. Hentschel etl. al., *Nature* **414**, 509 (2001))
  - Can measure both arrival time and pulse length
  - Almost transparent to the FEL beam—hardly any attenuation

THz Streak Camera Theory

- Use a THz streak camera concept to measure the arrival time and length of the photon pulse.



$$KE_{electron} = E_{photon} - \text{Binding Energy} \pm W$$

THz Streak Camera Theory

To derive the expression for W, start off with the final velocity of the just-photoionized electron in the THz electric field:

$$v_f = v_0 + \frac{e}{m_e} A(t)$$

Where $E_{thz} = -\frac{dA}{dt}$ *A* being the vector potential of the electric field.

Knowing that $E_{thz} = E_0 \cos(\omega t + \phi)$

We get for the final kinetic energy of the electron: 0

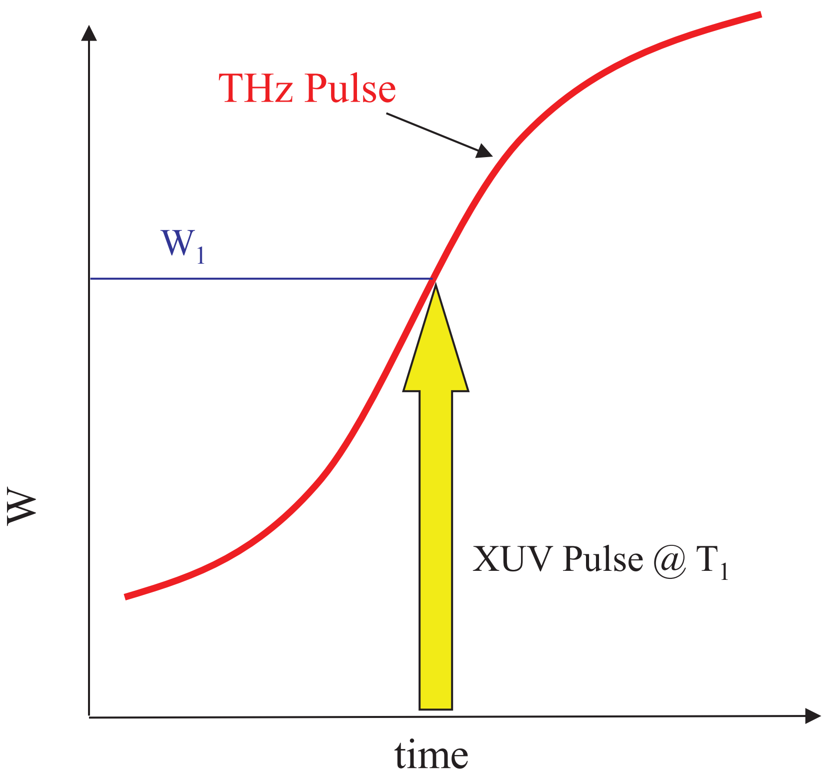
$$K_f = K_0 + 2U_p \sin^2(\omega t + \phi) \pm \sqrt{K_0 U_p} \sin(\omega t + \phi) = W$$

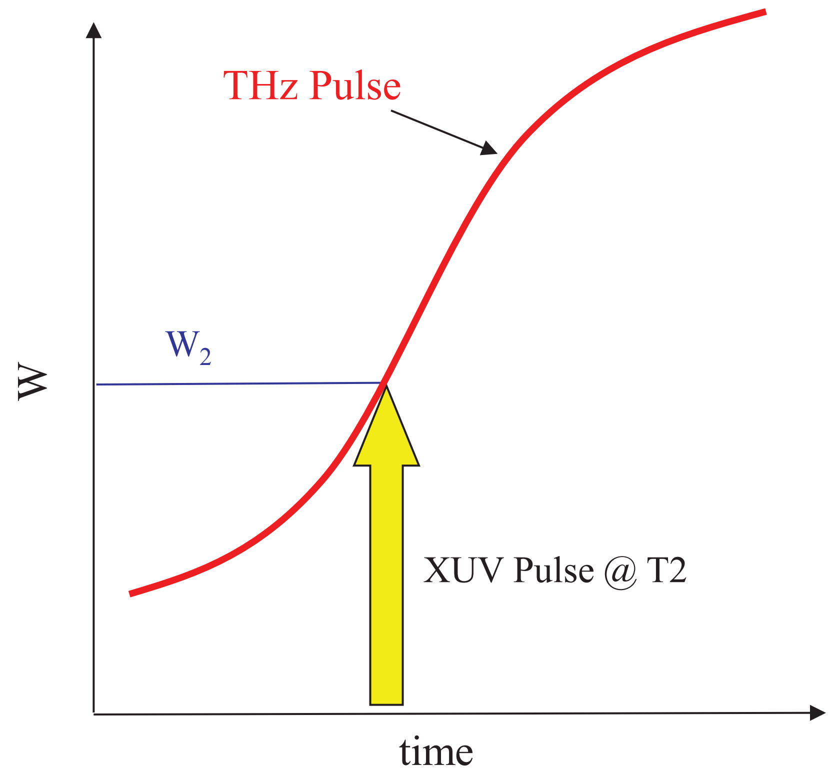
Where $Up = \frac{e^2 E_0^2}{4 m_e \omega^2}$

Arrival Time Determination

XUV Pulse 1:

XUV Pulse 2:





W_2-W_1 → T_2-T_1

Concept works best along a linear slope

Setup: Experimental challenges and solutions

Challenges:

1. Small photoionization cross sections for gases at high photon energies.

2. Photon energy jitter of the FEL beam can be interpreted as a difference in arrival time.

3. Laser intensity jitter can affect the THz pulse, causing misreadings.

4. Finding temporal overlap.

Solutions:

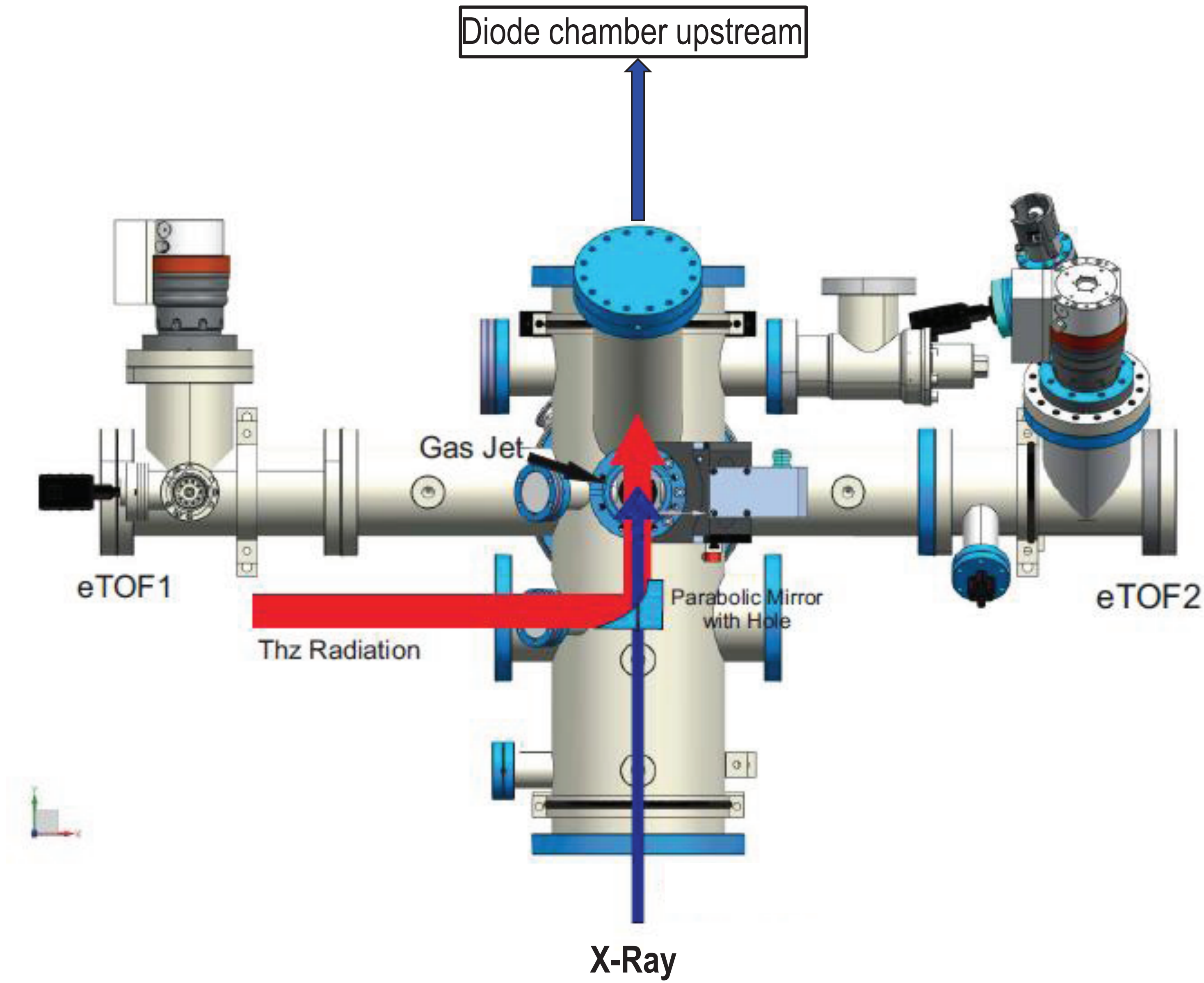
1. Use a pulsed gas jet to create a dense “bullet” of Xe gas for better signal. The Xe gas also clusters, making larger targets for the X-ray pulse to interact with (hundreds-thousand Xe atoms per cluster).

2. Use two e-TOFs to look at the same photoionization process from opposite directions to eliminate the photon energy jitter contribution—look at only the streak as a difference from the mean.

3. Measure laser intensity on a shot-to-shot basis and correct your data accordingly.

4. Use a balanced diode to find ps-level overlap between THz and IR beams, then diode to find ps-level overlap between IR and X-ray. Scan with the stage to find the final overlap with the e-TOFs.

Prototype PALM Setup



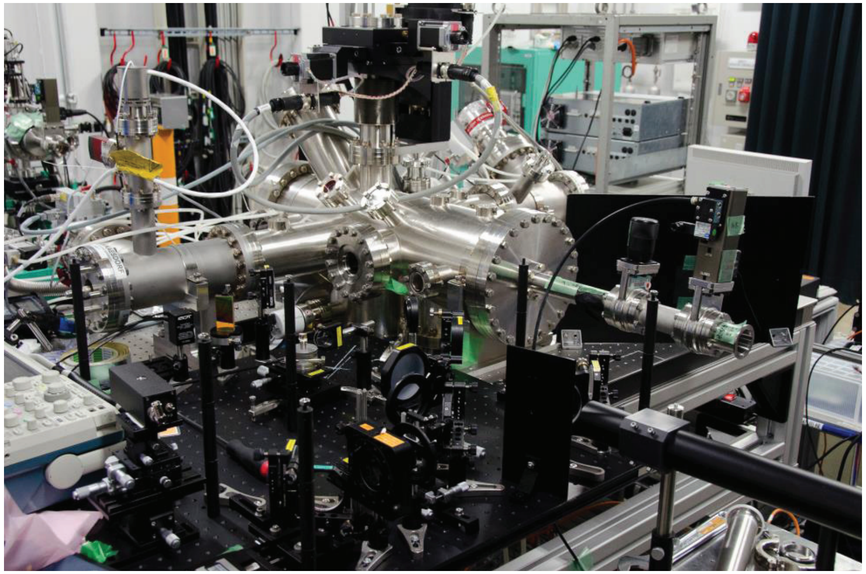
THz setup and FEL beam parameters

THz Setup:

- Laser: 800 nm, ~7 mJ input power, 3-5% intensity jitter
- Online monitoring of laser power shot-to-shot
- $LiNbO_3$ generation for THz pulse
- Pulse frequency about 0.52 THz
- Measured THz field in interaction region of about 50 kV/cm
- No air conditioning in hutch

FEL Parameters:

- Pulse energies between 120-250 μJ
- Used 5 keV, 6 keV, 7 keV, 8 keV, 9, keV, 10 keV, and 12.6 keV photon energies
- Measured with and without the monochromator at most photon energies
- Tested device with a 0.2 mm Si attenuator at 10 keV



It all worked great!

THz Streaking up to 12.6 keV Photon Energy @ SACLA

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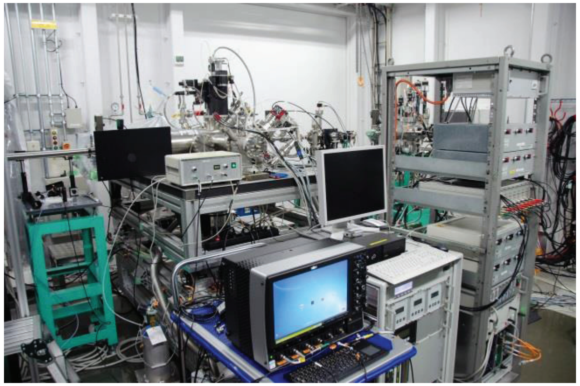
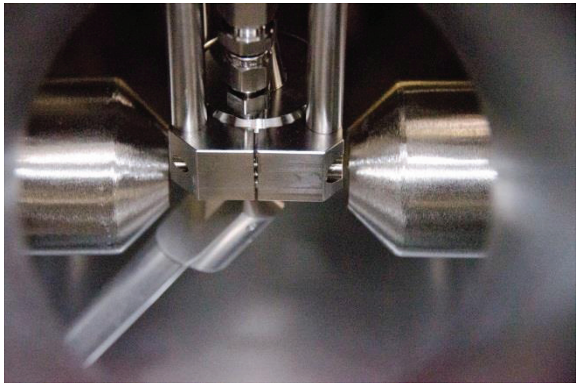
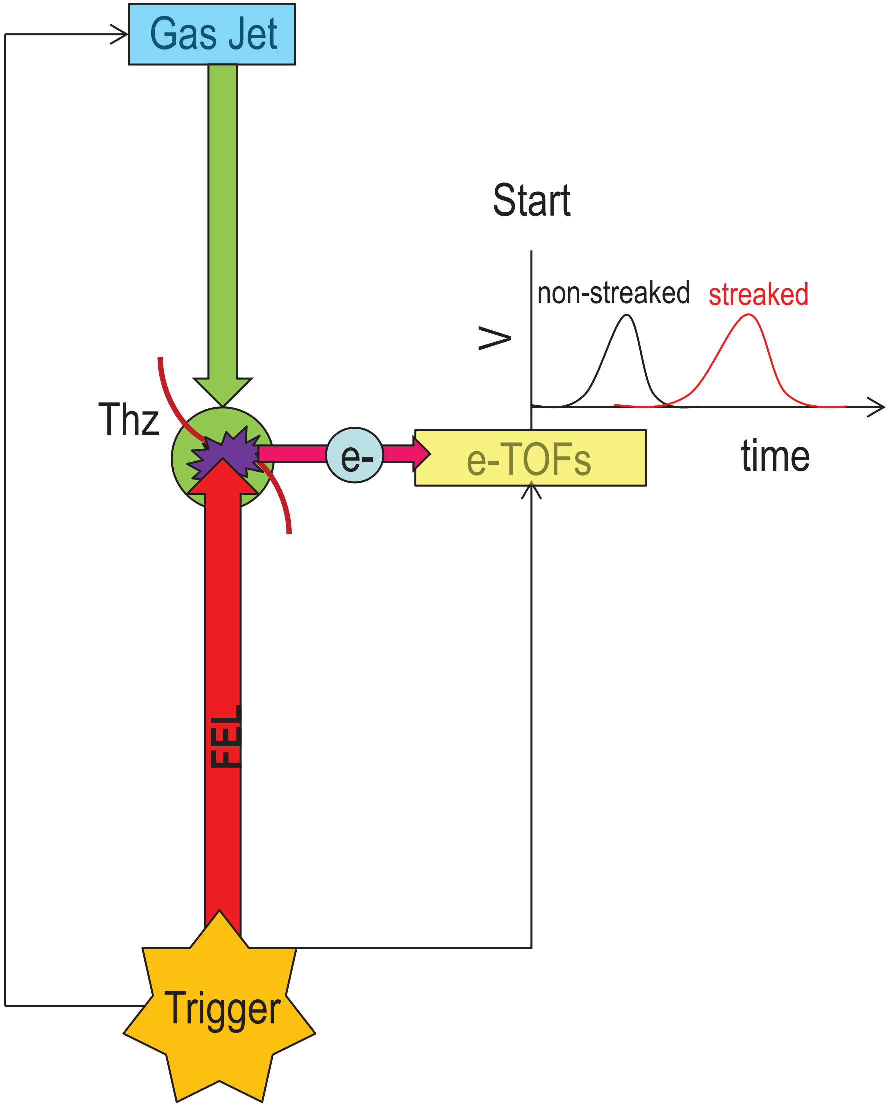
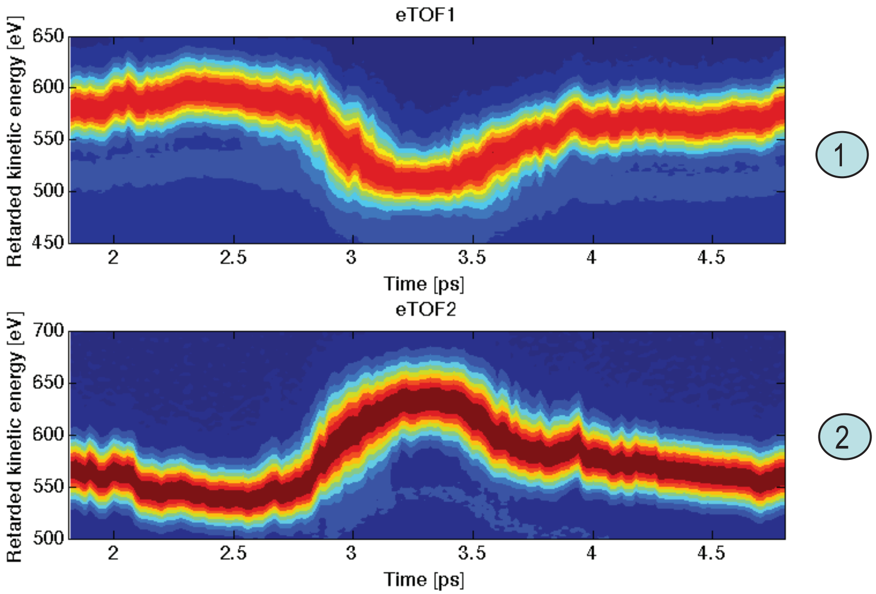




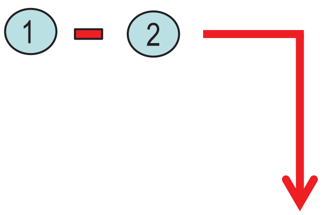


Results: Measurement Features

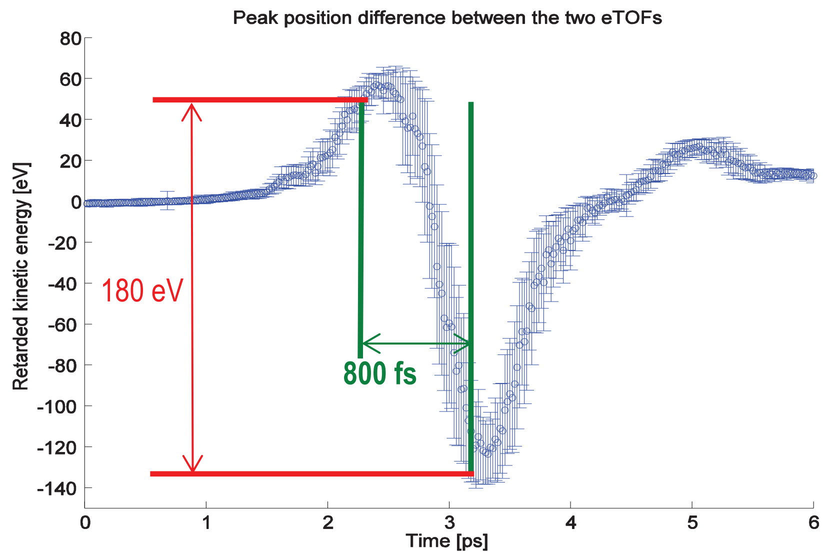
Streak scan for the Xe $2p_{3/2}$ electrons at a photon energy of 10 keV. 100 spectra were taken at each time step.



We get rid of the error due to the photon energy jitter by taking the difference between the two sets of signals. The vertical bars show the RMS distribution of peak positions at each time step.



Photon energy jitter correction



The analysis of the difference of the spectra yield the accuracy of the streak measurement (when convoluted with the eTOF resolution)

E-TOF Mean Peak Energy Accuracy: **0.5-1.2 eV RMS**

Streak Slope: **0.15-0.35 ev/fs ($h\upsilon$ dependent)**

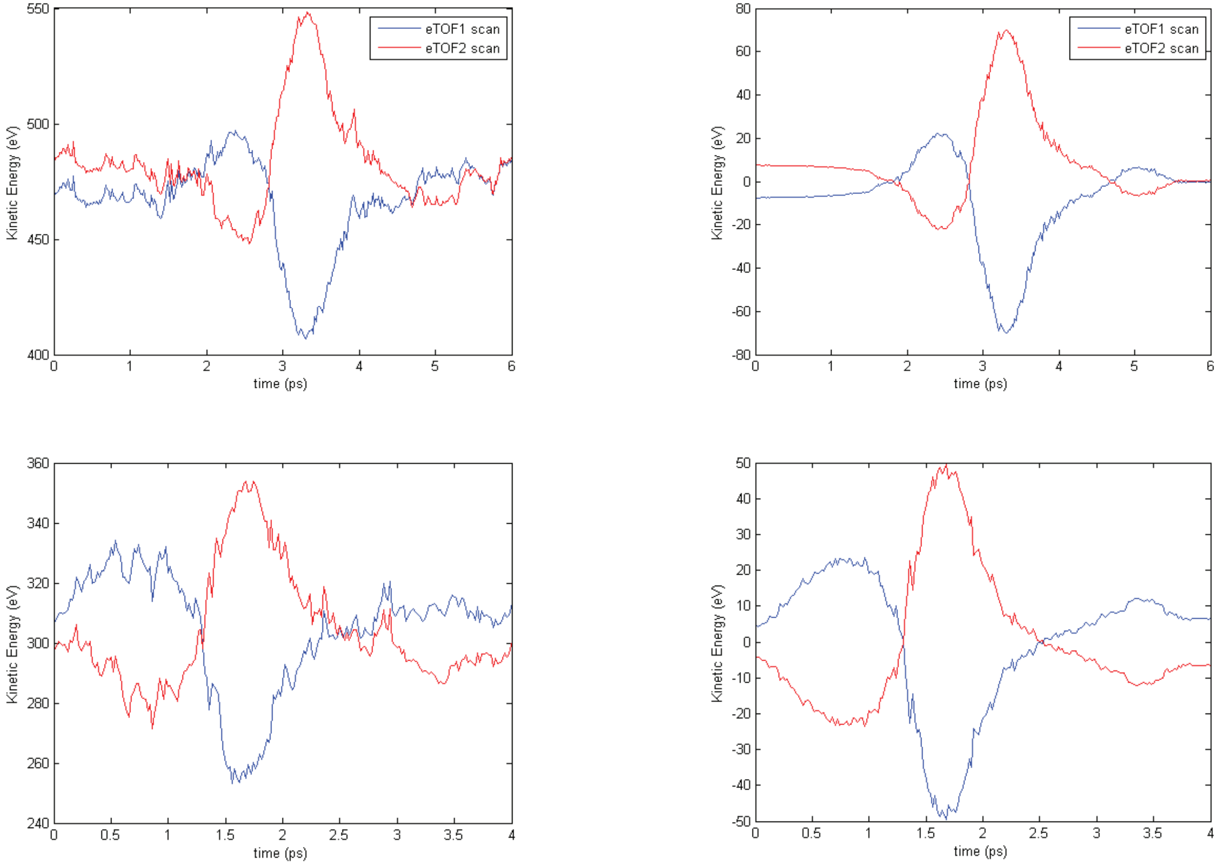
FEL vs Laser Jitter: **100-150 fs RMS**

Photon energy jitter correction for streak scan

Before correction | After correction

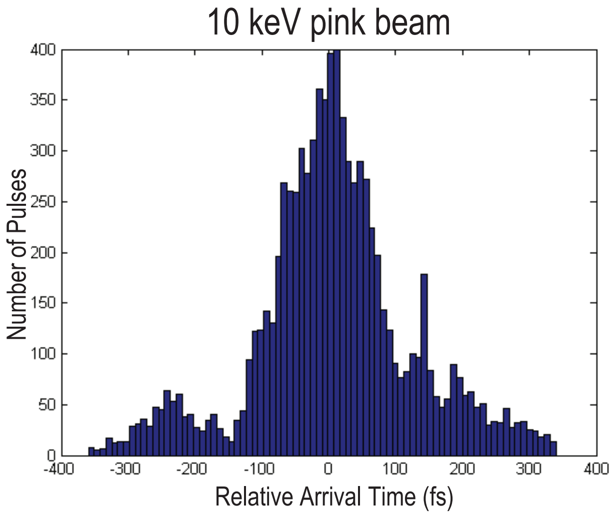
10 keV, pink

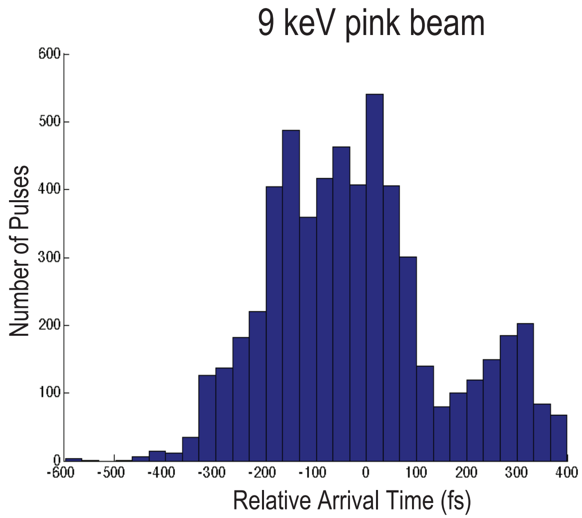
8 keV, pink

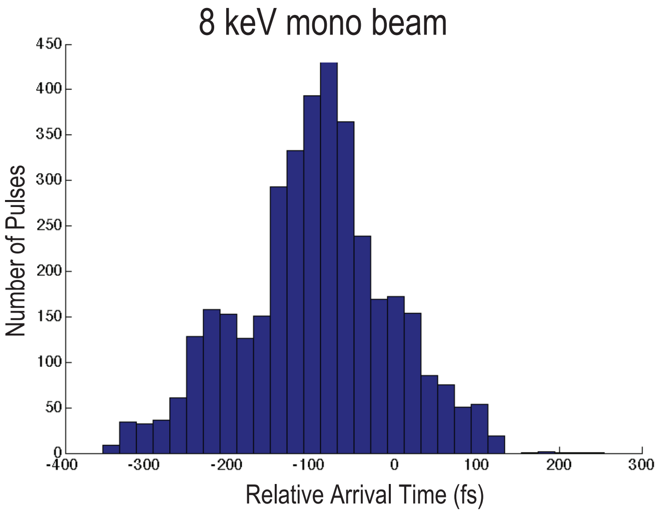


Relative arrival time determination

Find mean peak energy of streaked electrons, match it against the THz delay scan for arrival time!







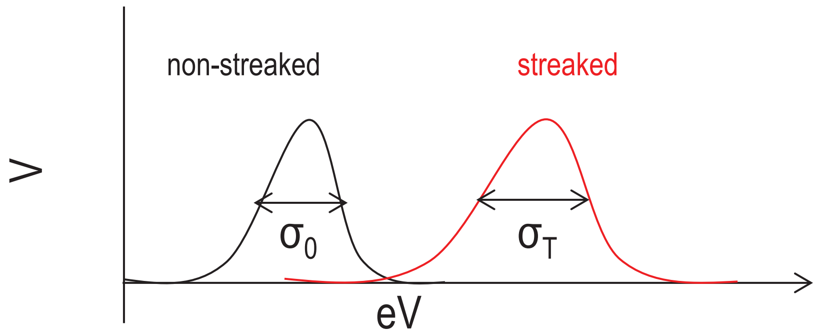
FEL vs. Laser Relative Arrival Time Jitter

- Accuracy is a combination of the e-TOF mean energy measurement jitter and steepness of the THz streaking slope.

- The e-TOFs had to be set differently at every photon energy, which causes some variations in accuracy even for similar slopes. Practice will make it more consistent.

Matches other SACLA measurements quite well!

Pulse Length and Chirp Determination



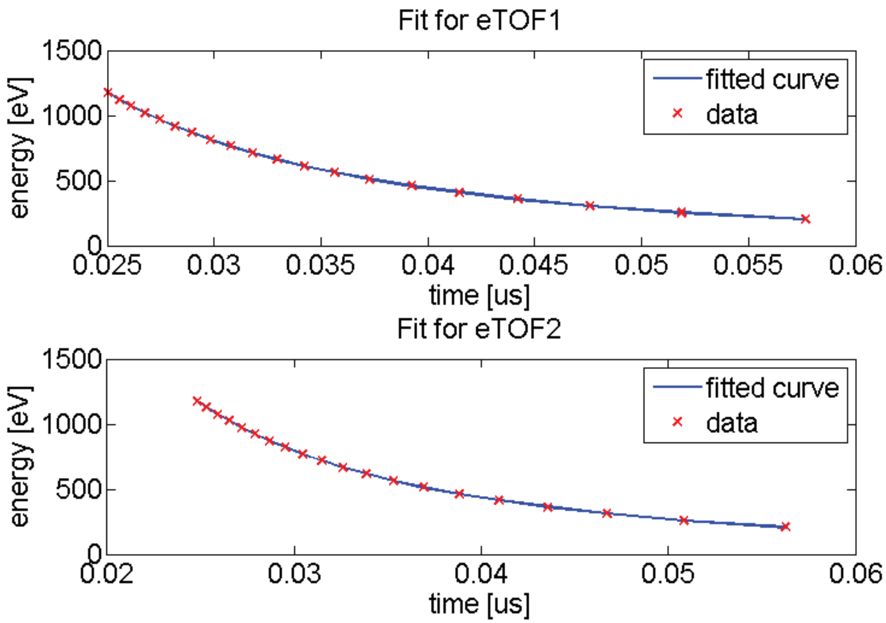
$$\sigma_{Ti}^2 = \sigma_{0i}^2 + \tau^2(s^2 \pm 4cs)$$

- σ_{Ti}^2: Total streaked peak width
- σ_{0i}^2: "Natural" peak width
- τ: Pulse length
- s: Slope
- $\pm$: Depends on orientation of eTOF (i=1,2)
- c: Photon energy chirp

Define: $$\sigma_{di}^2 = \tau^2(s^2 \pm 4cs) = \sigma_{Ti}^2 - \sigma_{0i}^2$$

$$\tau = \sqrt{\frac{\sigma_{d1}^2 + \sigma_{d2}^2}{2s^2}} \qquad c = \frac{\sigma_{d1}^2 - \sigma_{d2}^2}{8\tau^2 s}$$

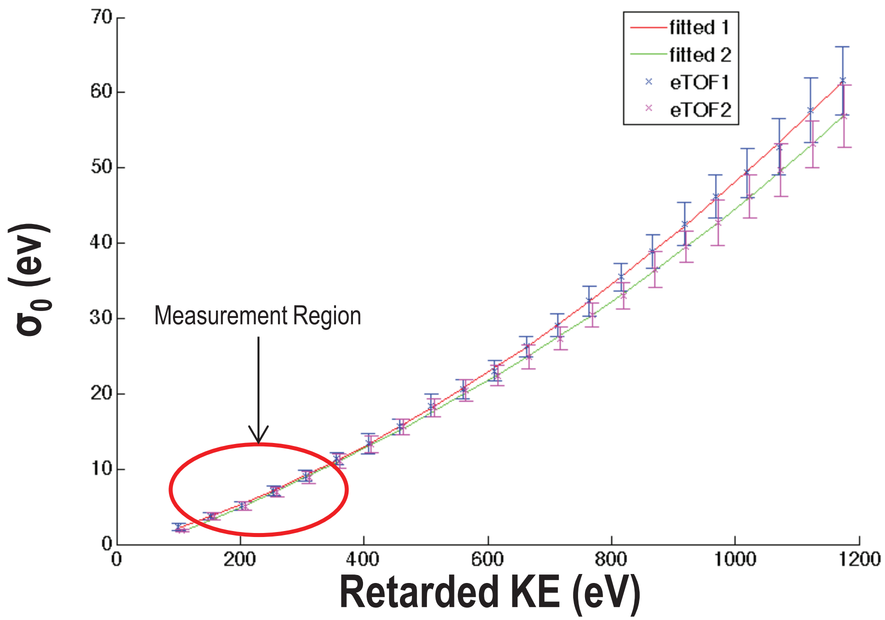
Etof time-to-energy and σ_0 calibration (7 kev with mono)



$$KE=A/(t-B)^2+C$$

Fitted to a third order polynomial to estimate the non-measured points along the curve.

The bars are the measured spectral width jitter for about 200 shots. They are larger for the pink beam.



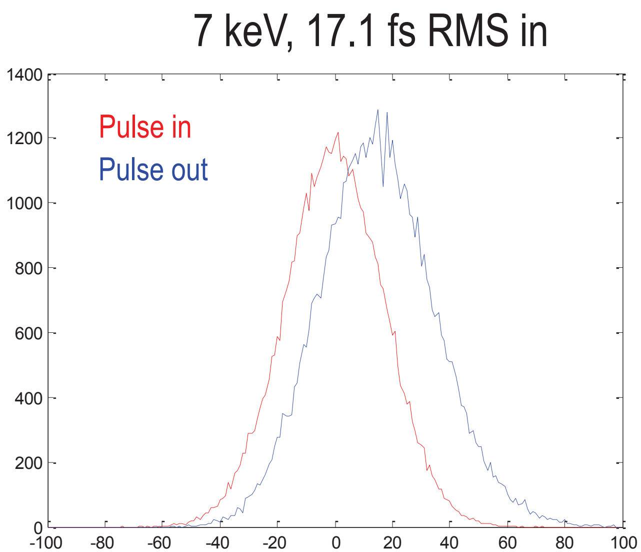
Preliminary pulse length determination

- Pulse length was evaluated only for points at the best slope, to increase our accuracy.
- Typically used 600-1500 points out of 10,000 that were taken for every setup for pulse length evaluation.
- Had to use average $\boldsymbol{\sigma_0}$ from our calibration scans—no eTOF without streaking effect!
- Put all the measured variables into the formula and get a pulse length!

Preliminary pulse length estimates

- Drifts in the FEL spectral width can cause a systematic error, giving pulse lengths that are too long or too short—need a third e-TOF to compensate for those!
- Jitters in the FEL spectral width are the main source of error for the pulse length estimate. A third e-TOF would compensate for these as well.
- The mono measurements are more accurate due to the stability of the spectral width, but the mono may contribute to the pulse length!
- Note that these values differ from those evaluated by the SACLA (< 10 fs FWHM), provided in Dr. Inagaki's talk on Tuesday, 26.8.2014.

Monochromator Effect: Theory



Energy	RMS in	RMS out
7 keV	17.1 fs	19.8 fs
8 keV	17.1 fs	23 fs
9 keV	17.1 fs	24 fs
7 keV	35 fs	35.2 fs

Jakub Szlachetko at PSI modeled the pulse duration change for a Si 111 DCM for various photon energies. The table above shows that there is not a significant increase in pulse length due to the monochromator for pulse lengths that are already long.

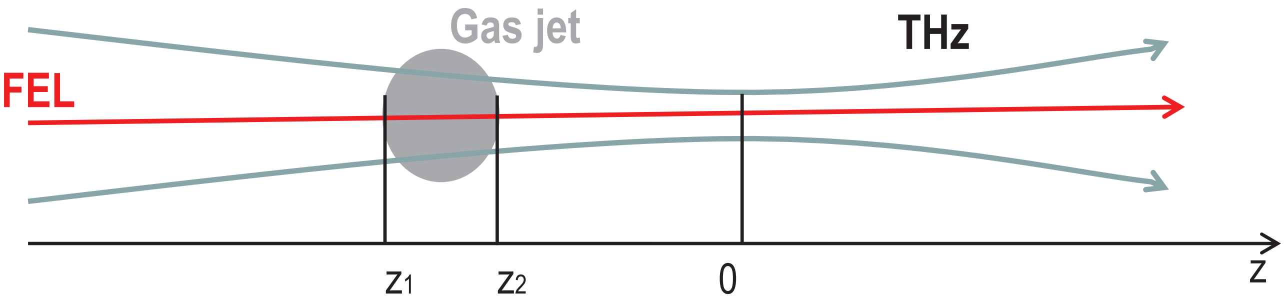
We'll keep on investigating to understand all the effects fully.

Gouy phase shift effect

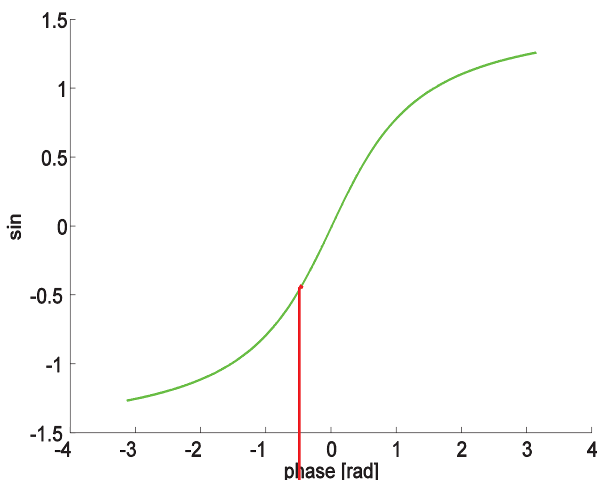
Gouy phase shift

$$\phi_G = -\tan^{-1}\left(\frac{z}{z_R}\right)$$

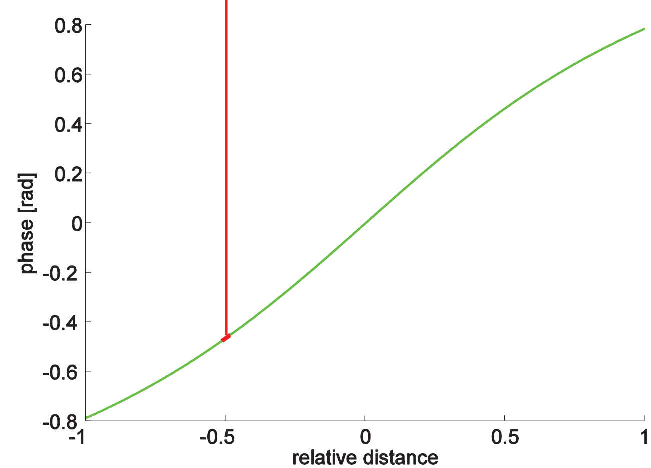
z_R Rayleigh length=40 mm



Gouy phase shift along the interaction region of 1.2 mm: $\phi_G(z_1) - \phi_G(z_2) = 0.024\,rad$



Gouy phase shift in arctan function

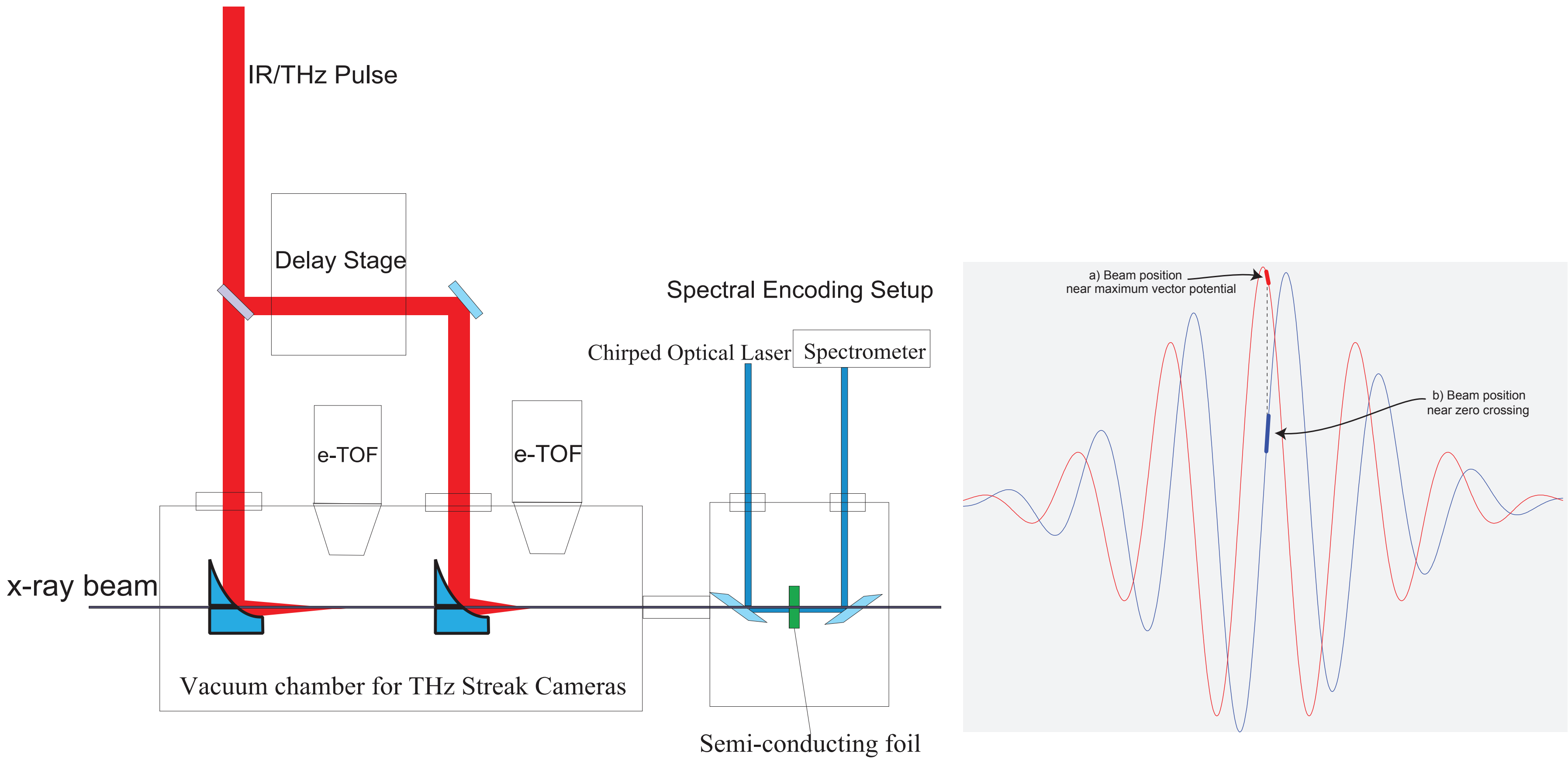


Plots are in actual scale: Insignificant effect both on the arrival time and the slope

Summary and Outlook

- **Successful beamtime:** measured the arrival time quite well, pulse length measurement done as well.
- **Robust system:** no major problems during the 3.5-day beamtime. The device ran non-stop, very reliably.
- **Good arrival time accuracy:** our estimated arrival time accuracy for hard x-rays is as good or better as any reported FEL thus far. Much happiness.
- **Improvement 1:** THz generation and smoothing of the field to get better streaking effect.
- **Improvement 2:** Make the set-up work on-line and single-shot by adding another e-TOF that just looks at the raw beam with no THz field. That will give us a correct σ_0 for every shot.
- **Improvement 3:** Nitrogen/dry air box for the THz generation area to ensure environmental stability.
- **Future Plans:** ideally, a beamtime with a TDC, PALM, and the Spike-width measurement method in tandem. We are already preparing for another SACLA run with an upgraded PALM, with cross-checks from other SACLA diagnostic devices.

Future PALM for ultra-short pulses?



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Acknowledgments: Institutions

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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SPring-8

SACLA

DESY

European XFEL

LCLS

SLAC
NATIONAL ACCELERATOR LABORATORY

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PSI

Many thanks to:

Volker Schlott, Rasmus Ischebeck, Jakub Szlachetko, Nick Schlumpf, Luc Patthey, Patrick Pollet, Elke Zimoch, Dirk Zimoch, Sven Reiche, Peter Peier, Ishkhan Gorgisyan, Beat Rippstein, Peter Wiegand, Peter Heimgartner, Chris Milne, Leonardo Sala, Timo Korhonen, Claude Pradervand, Peter Fischer, Peter Ming, Lothar Schulz, Gaiffi Nazareno, Peter Huber, Rafael Abela, Helge Brands, Christian David, Petri Karvinen, Aldo Mozzanica, Dennis Armstrong, Adrian Cavalieri, Milan Radovic, Franziska Frei, Christoph Hauri, the great nation of Japan, and many, many more.