Pavle Juranić:: SwissFEL Photonics :: Paul Scherrer Institut

G. Ishkhan, C. Erny, R. Ischebeck, L. Patthey, C. Pradervand, C. Milne, H. Lemke, A. Dax, M. Radović, C. Hauri, S. Owada, T. Togashi, T. Katayama, and Makina Yabashi

Temporal Diagnostics from Photons: The Experience with the PALM

IBIC 11-15.9.2016

PALM2@SACLA

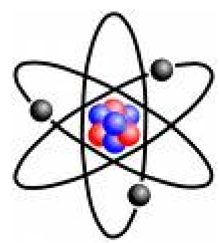
Photon Arrival and Length Monitor (PALM)

The PALM is a THz streak-camera based diagnostics tool that measures the arrival time of the FEL relative to an experimental laser, and measures the rms value of the FEL pulse's temporal profile.

Our previous experiment at SACLA in 2014 has yielded data that showed a pulse length longer than what our Japanese colleagues were expecting. So, we came again in 2016 to do the measurements again and compare it with their own diagnostics. The goal was to get single-shot measurements.

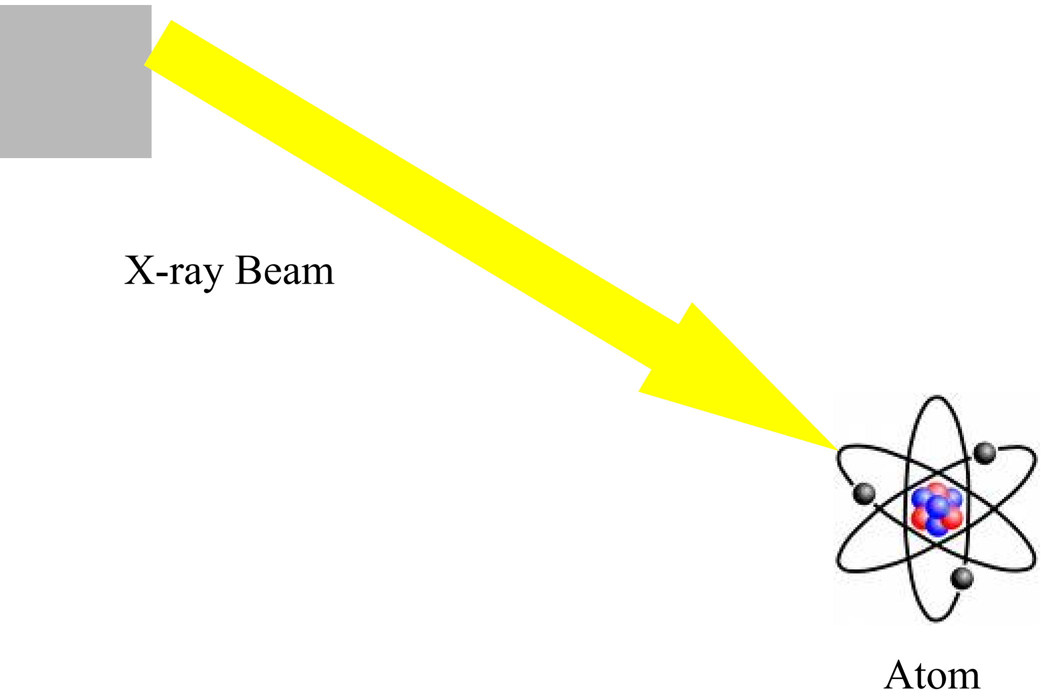
The PALM was already tested at an HHG source at PSI, and measured its pulse length accurately.
(F. Ardana-Lamas et al., PRA **93**, 043838 (2016)).

THz Camera Theory

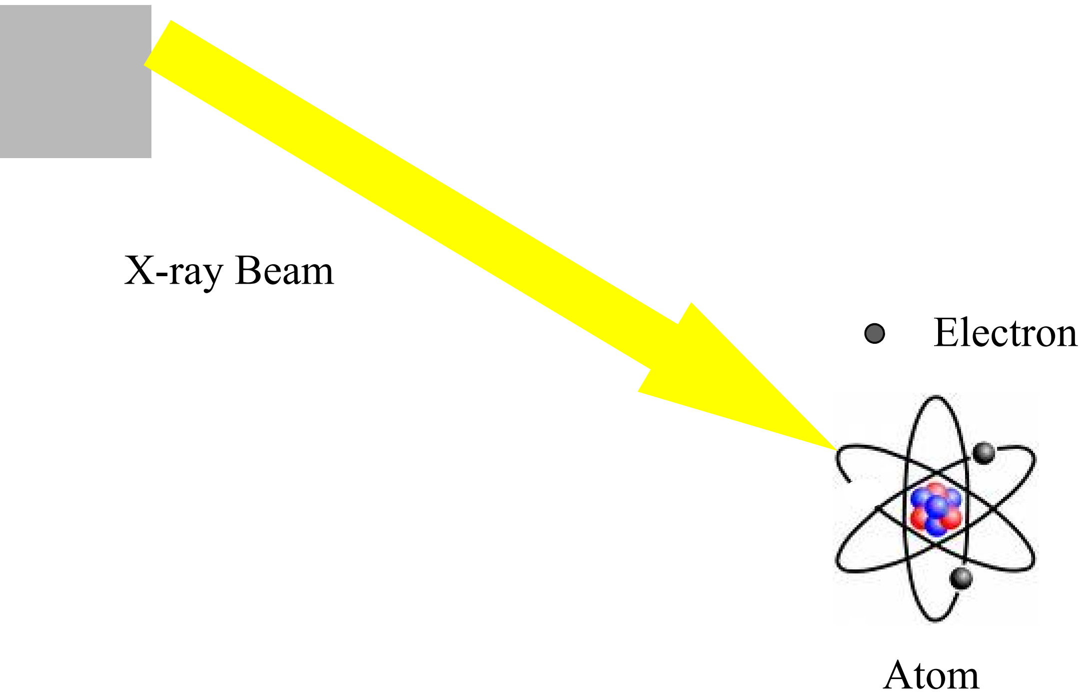


Atom

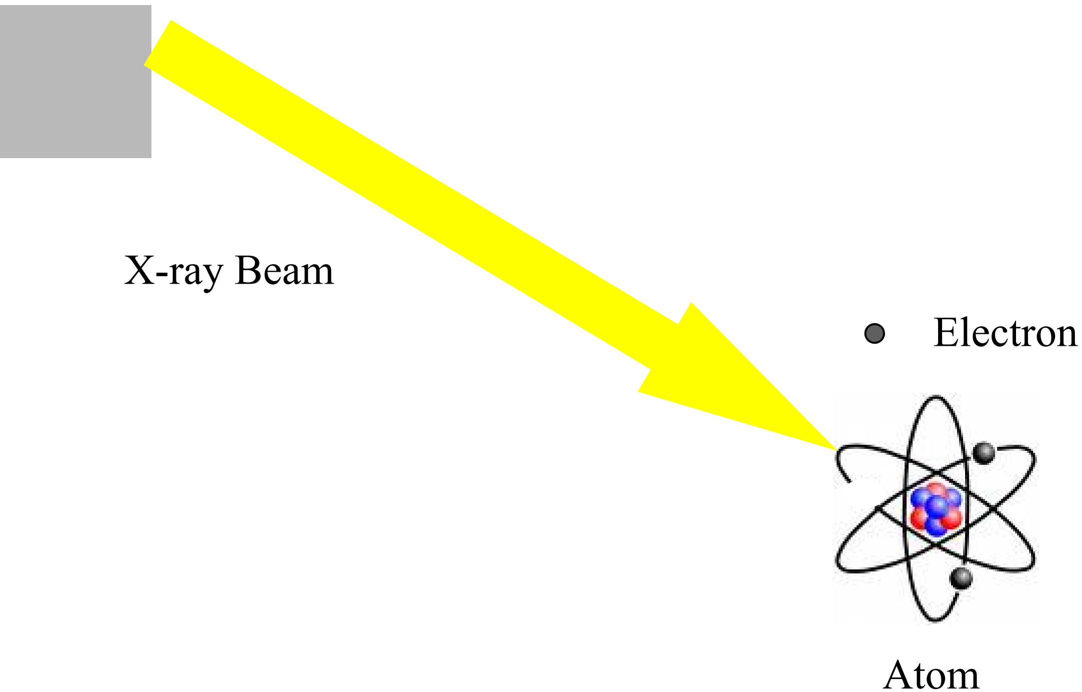
THz Camera Theory



THz Camera Theory

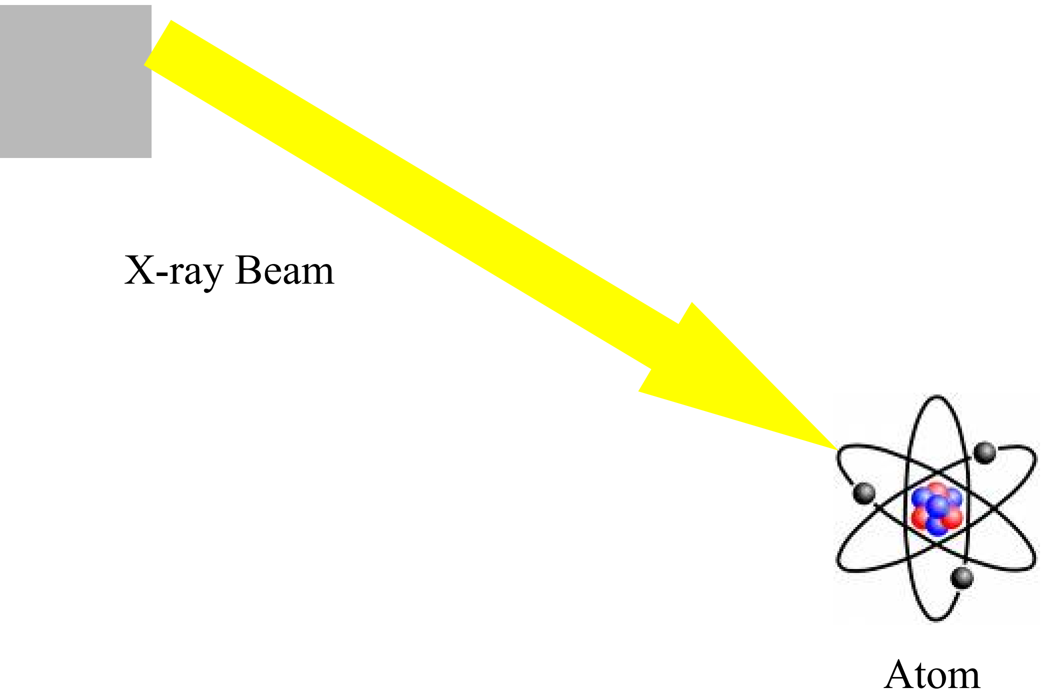


THz Camera Theory



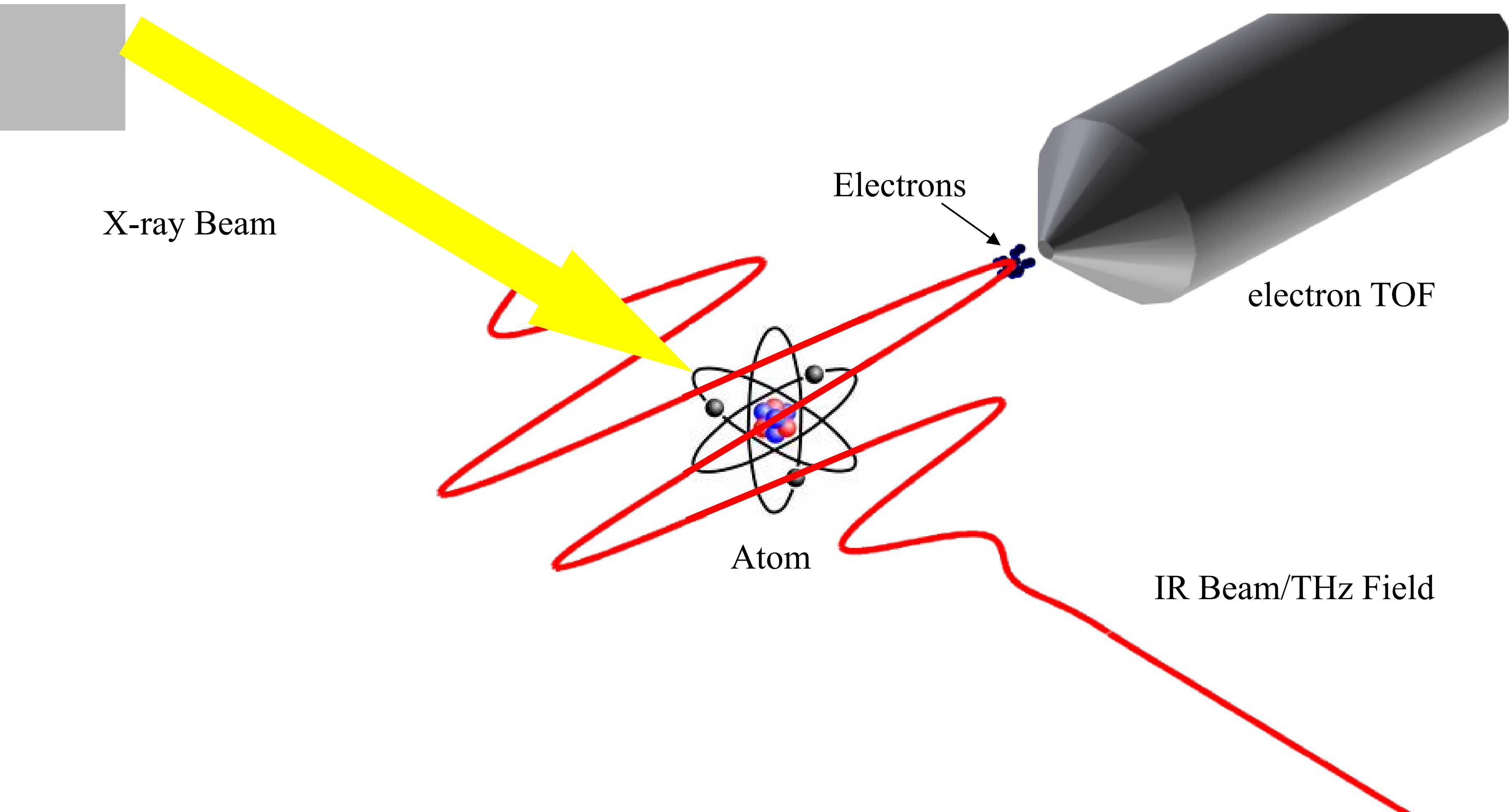
$$KE_{electron} = E_{photon} - \text{Binding Energy}$$

THz Camera Theory



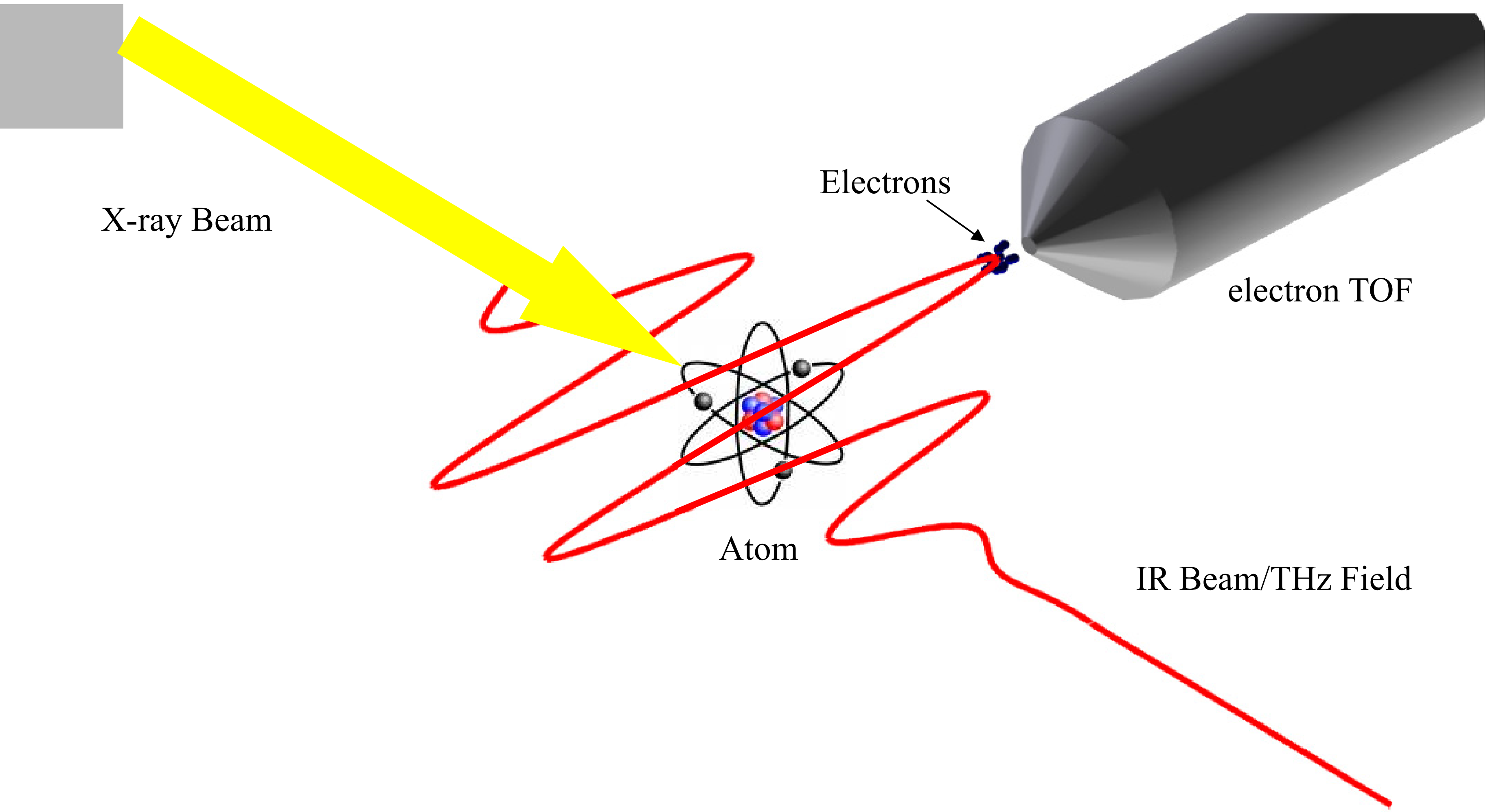
$$KE_{electron} = E_{photon} - \text{Binding Energy}$$

THz Camera Theory



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

THz Camera Theory



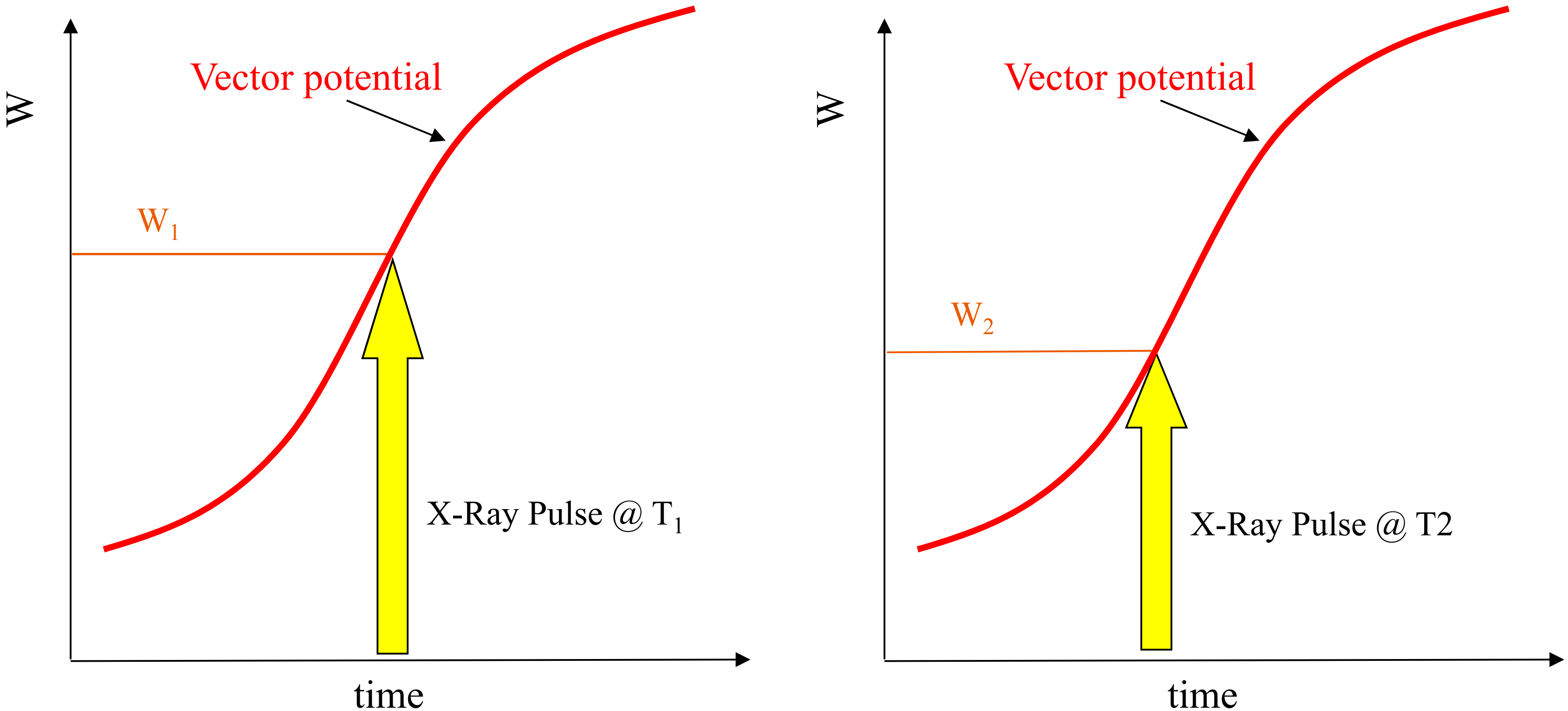
$$KE_{electron} = E_{photon} - \text{Binding Energy} \pm W$$

Quick reminder about THz streaking

$$K_f = K_0 + \sqrt{8K_0U_p}\sin(\omega t_0 + \varphi)$$

W

X-Ray Pulse 1: X-Ray Pulse 2:



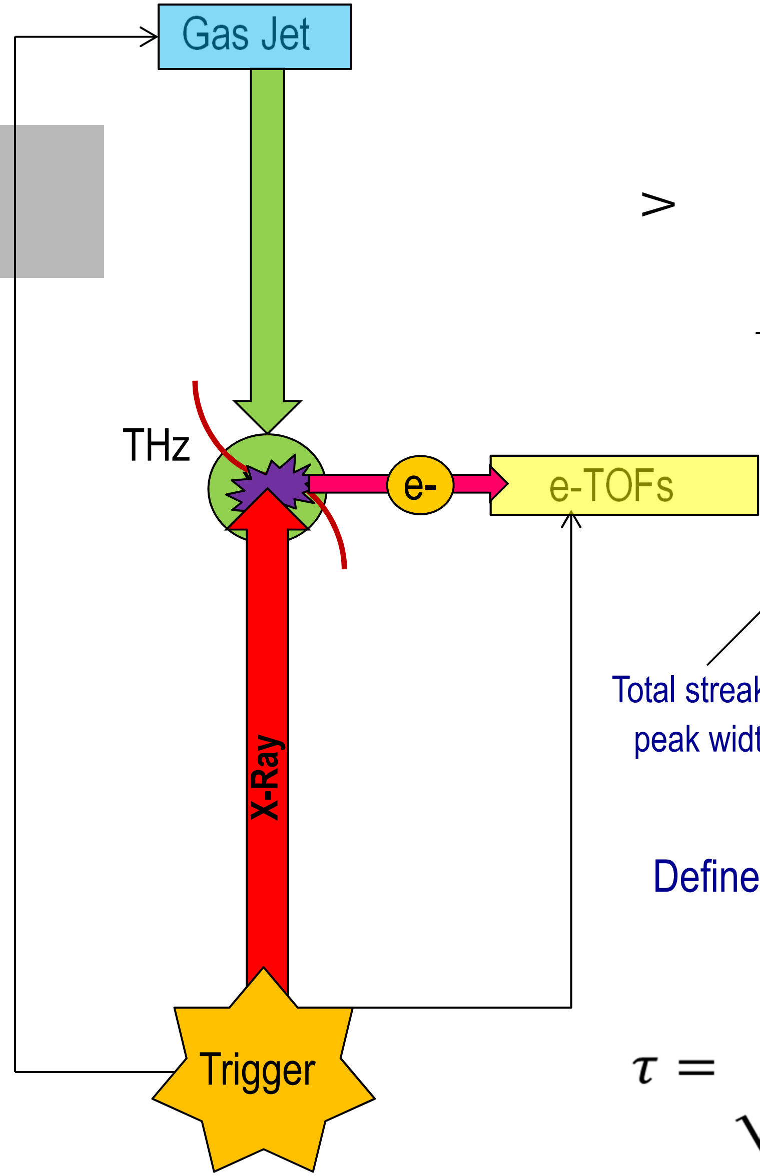
W_2-W_1 → T_2-T_1

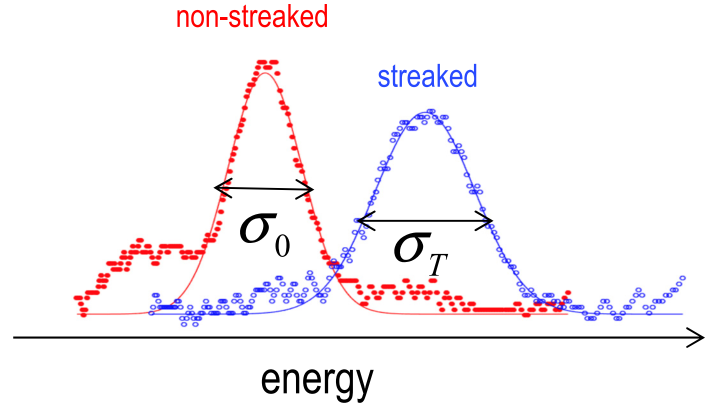
Further reading and references

- U. Fruehling et. al., *Nature Phot.* **3**, 523 (2009).
- I. Grguras et. al., *Nature Phot.* **6**, 276 (2012).
- M. Hentschel et. al., *Nature* **414**, 509 (2001).
- M. Drescher et. al., Science **291**, 1923 (2001).
- I. Gorgisyan et. al., J. Synch. Rad. **23**, 643 (2016).

And many, many more articles. The method is proven to work extremely well with both soft x-ray and HHG sources, and is in use for 15 years already. There is no fundamental difference between these cases and the hard x-ray FEL case except for a smaller cross-section and a stronger streaking effect at higher photon energies.

Reminder about the math





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

Total streaked peak width

"Natural" peak width

Pulse length

Streak strength

Depends on the direction of electrons (i=1,2)

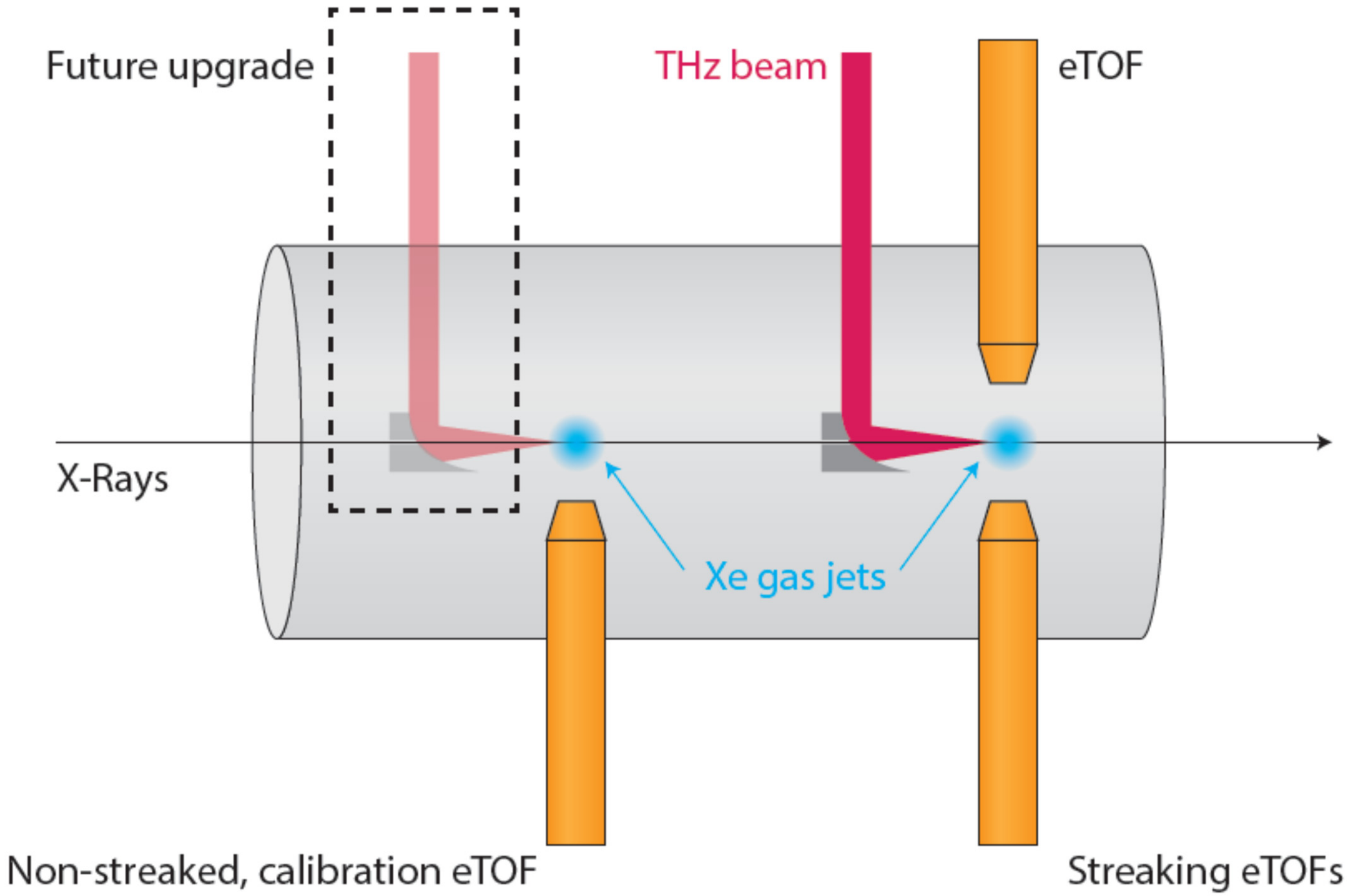
Photon energy chirp

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

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

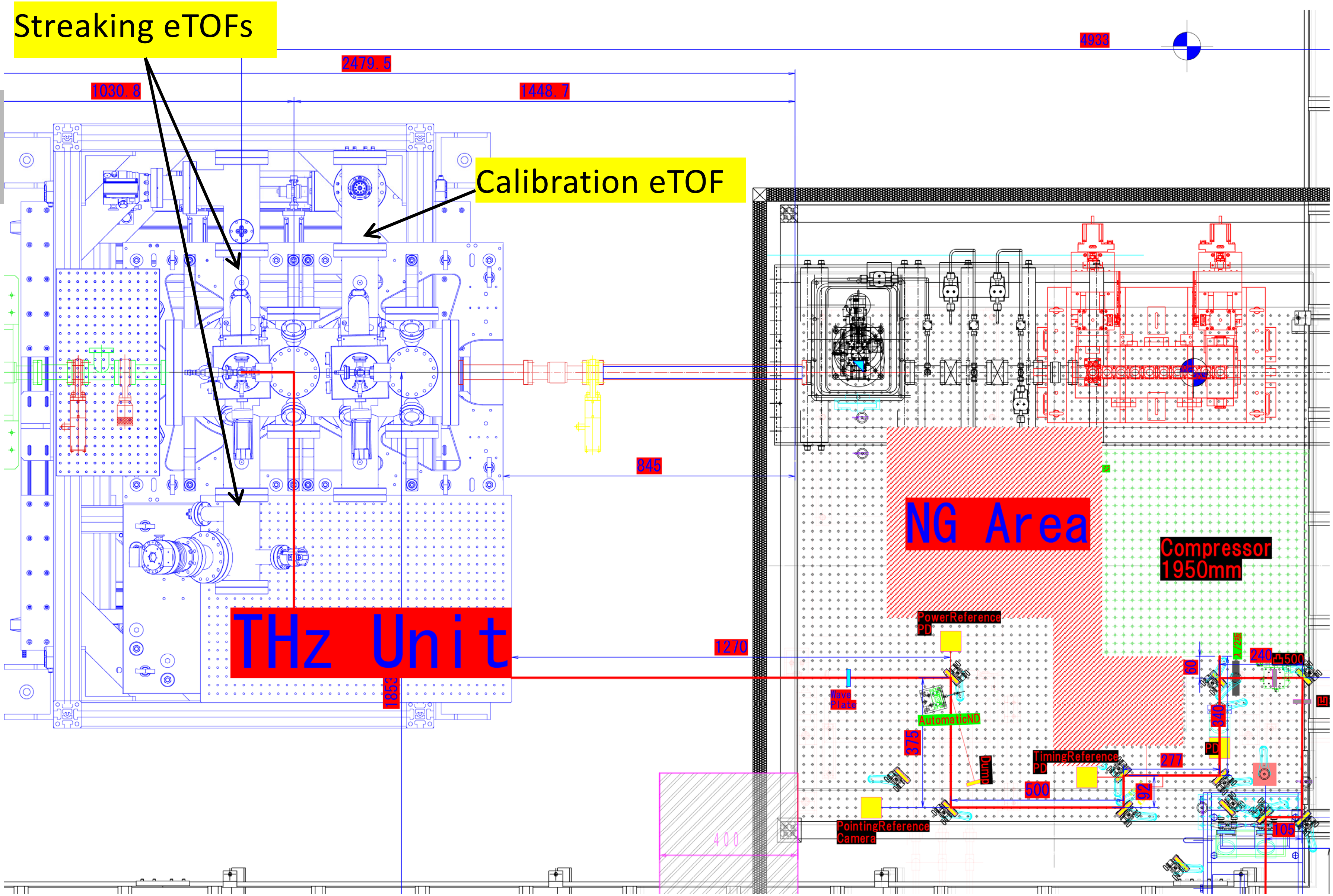
Courtesy of I. Gorgisyan

Schematic PALM layout

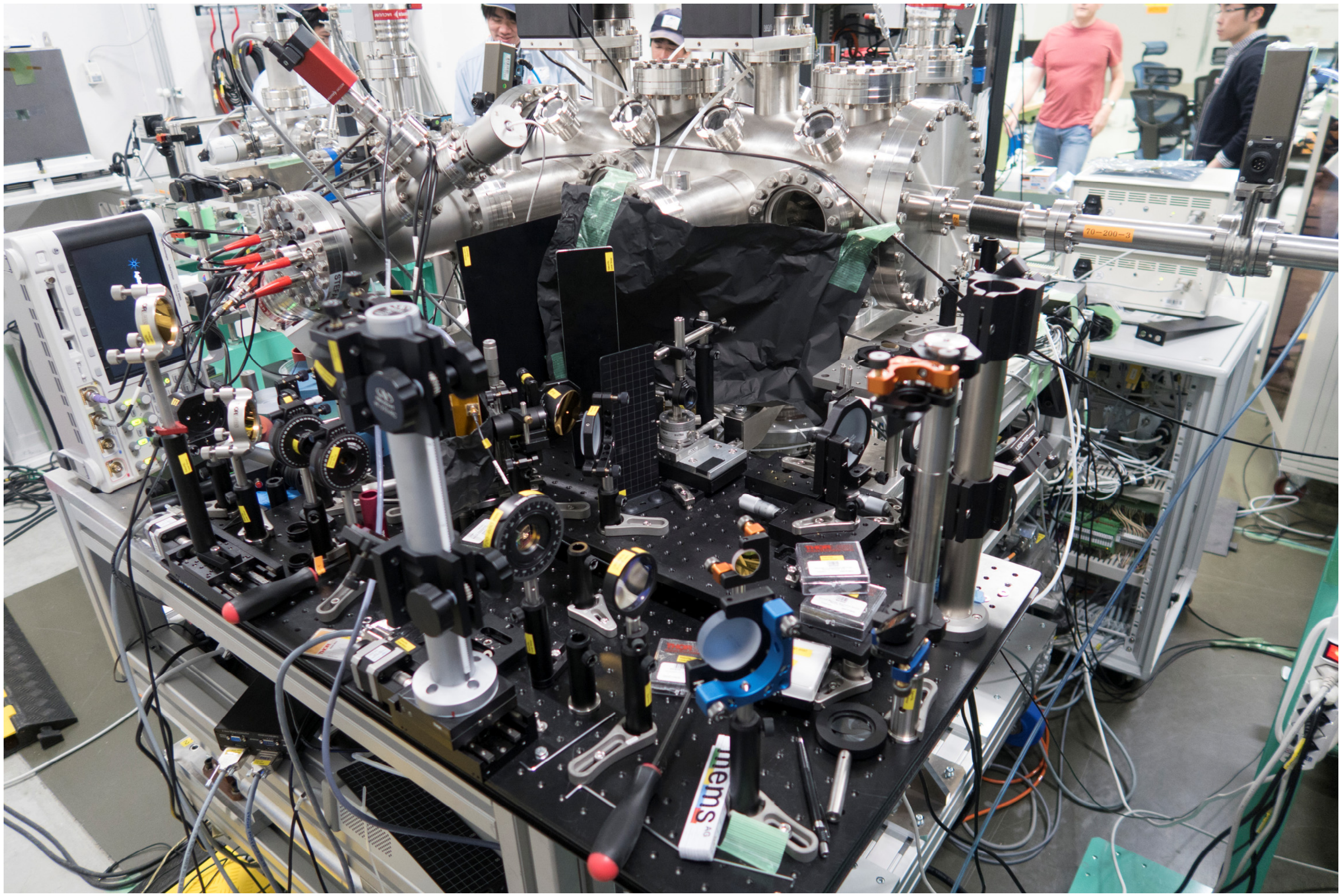


We use the non-streaked eTOF to get the arrival time and non-streaked peak shape to compare with the streaked spectra, getting single-shot measurements.

Experimental Layout

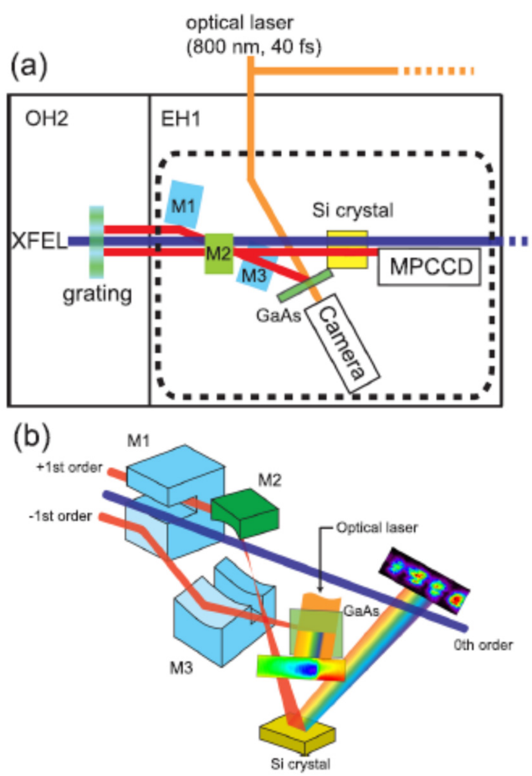


What it looked like



SACLA Timing Tool and Spectrometer

- Measures the arrival time of the FEL X-ray pulse vs. 800 nm laser
- Measures the photon spectrum in hi-resolution or low-resolution mode



Katayama et al., Struct. Dyn. **3**, 034301 (2016)

Experiment participants

PSI:

- P. Juranic
- I. Gorgisyan
- R. Ischebeck
- C. Erny
- A. Dax.
- C. Pradervand
- L. Patthey
- L. Sala
- C. Milne
- H. Lemke
- B. Rippstein

SACLA:

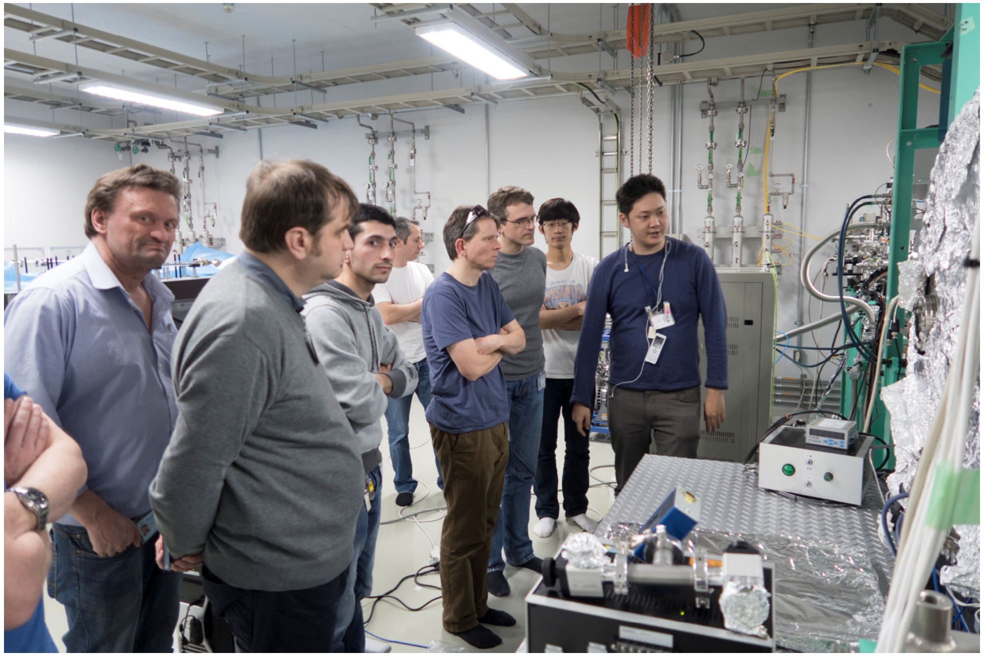
- Makina Yabashi
- Owada Shigeki
- Tetsuo Katayama
- Tadashi Togashi

DESY:

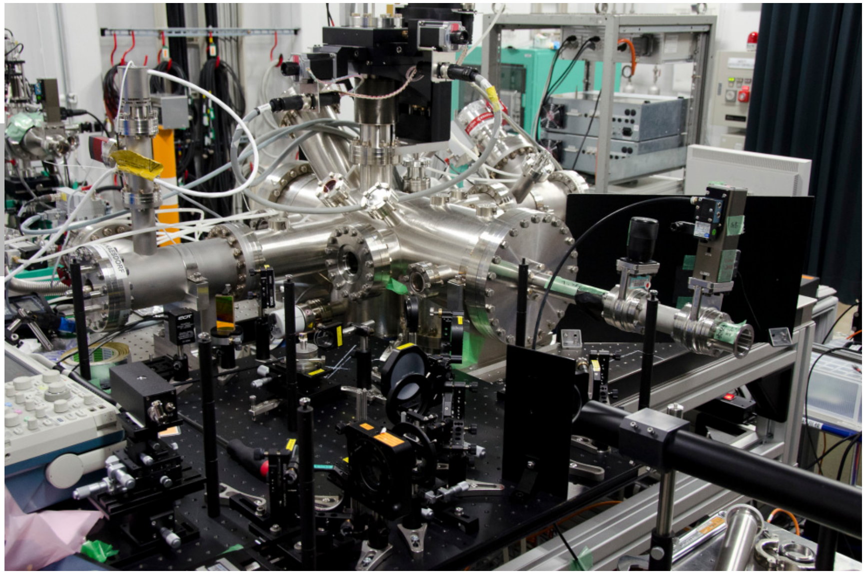
- Rosen Ivanov

XFEL:

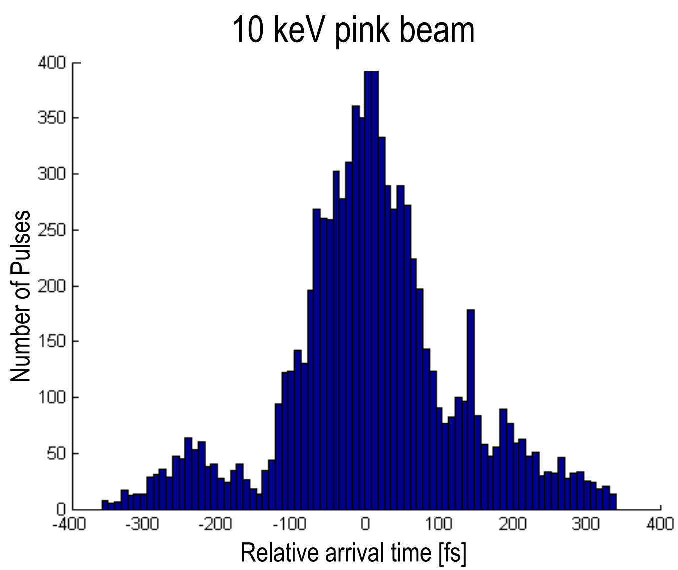
- Jia Liu

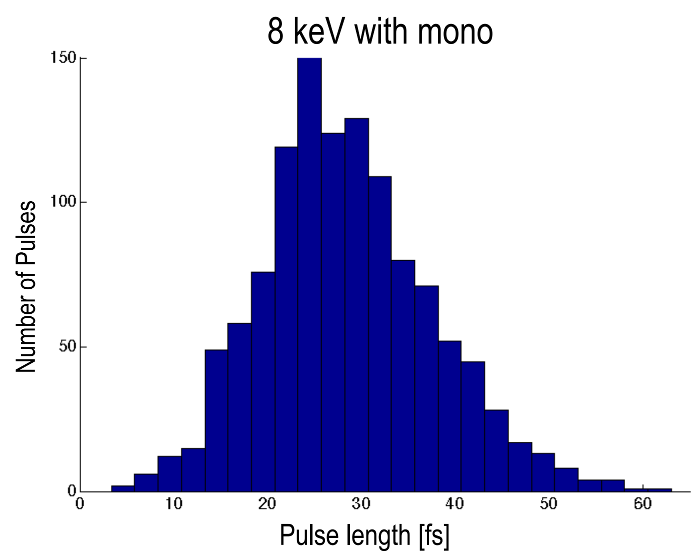


Previously, in 2014



- Arrival time jitter measured to be ~150 fs rms
  - ✓ Good agreement with SACLA specifications
- Estimated accuracy ~ 7 fs rms
- FEL pulse length ~ 38 fs rms
  - ! Disagreement with SACLA specifications
  - ! More measurements needed to clarify the discrepancy



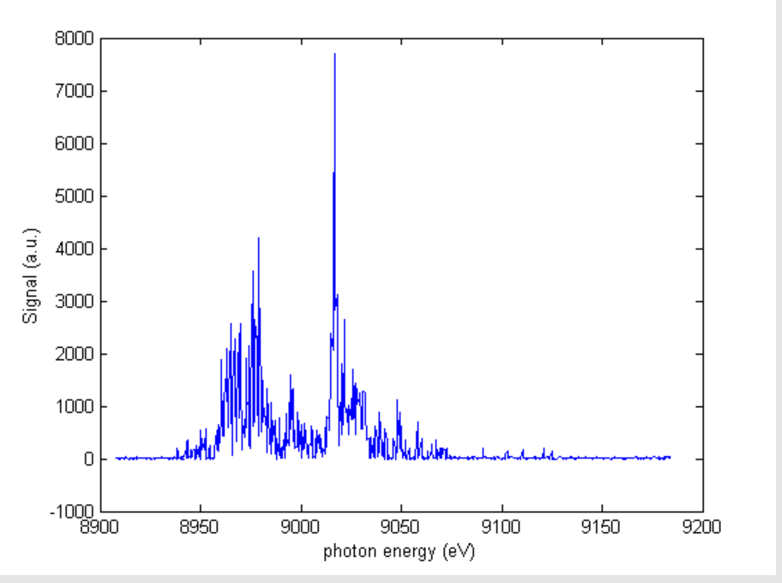


Juranić P. *et al.*, Opt. Express, 22(24):30004–30012, Dec 2014.

FEL conditions

- Photon Energy: 9 keV
- Pulse Energy: 250-400 µJ
- Repetition rate: 30 Hz

Spectra:



FEL conditions

- Photon Energy: 9 keV
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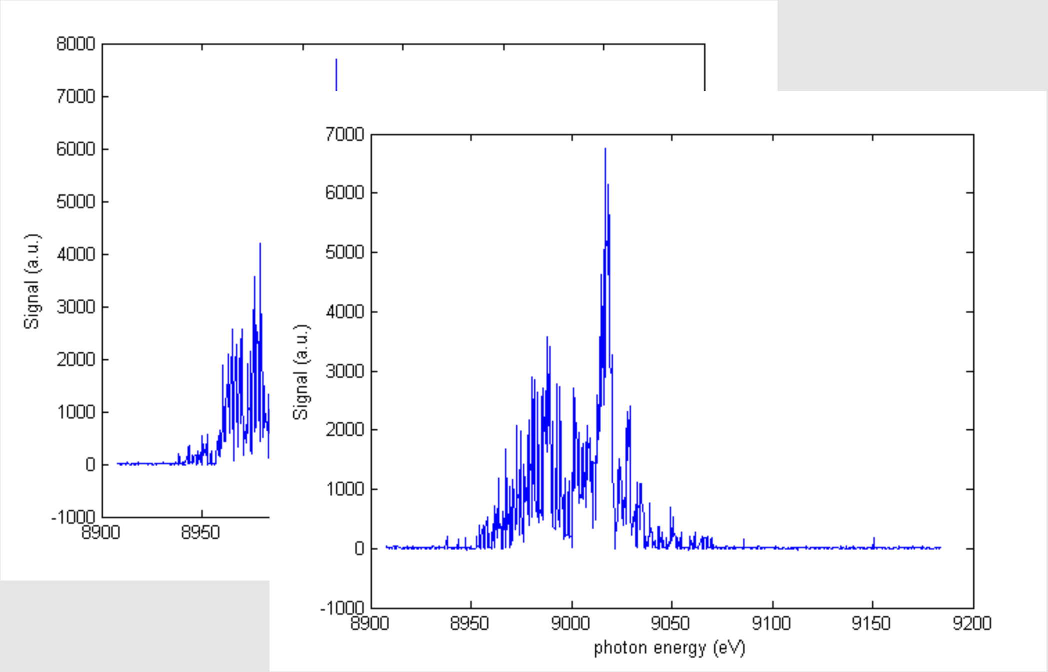
Spectra:



FEL conditions

- Photon Energy: 9 keV
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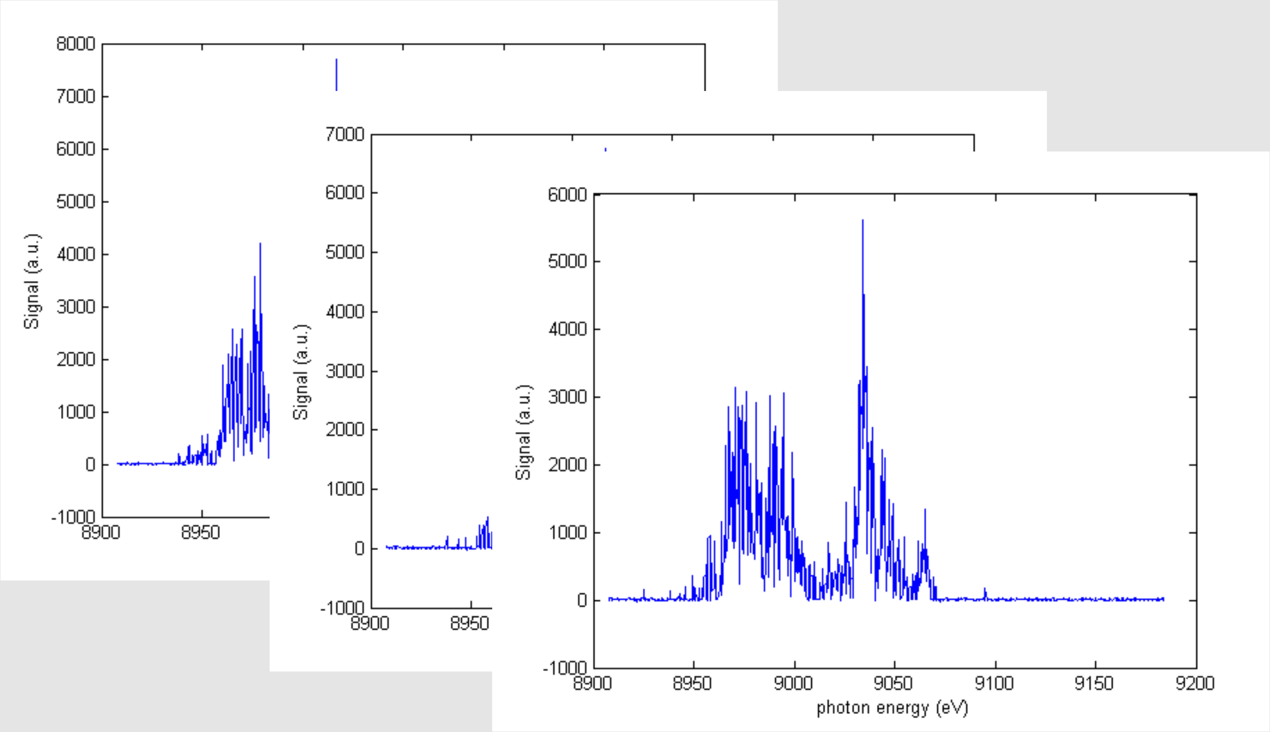
- Repetition rate: 30 Hz

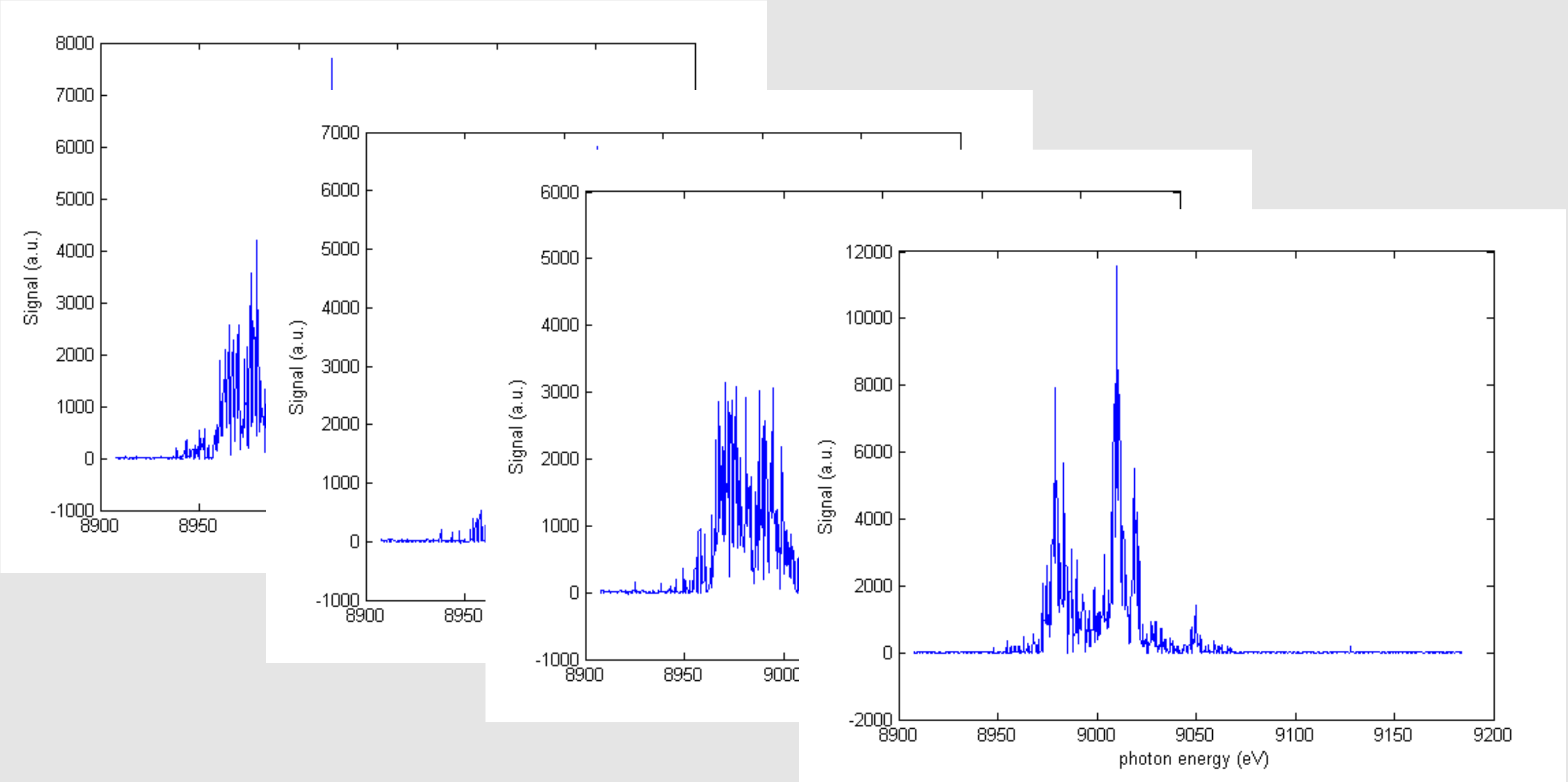
Spectra:



FEL conditions

- Photon Energy: 9 keV
- Pulse Energy: 250-400 μJ
- Repetition rate: 30 Hz

Spectra:



FEL conditions

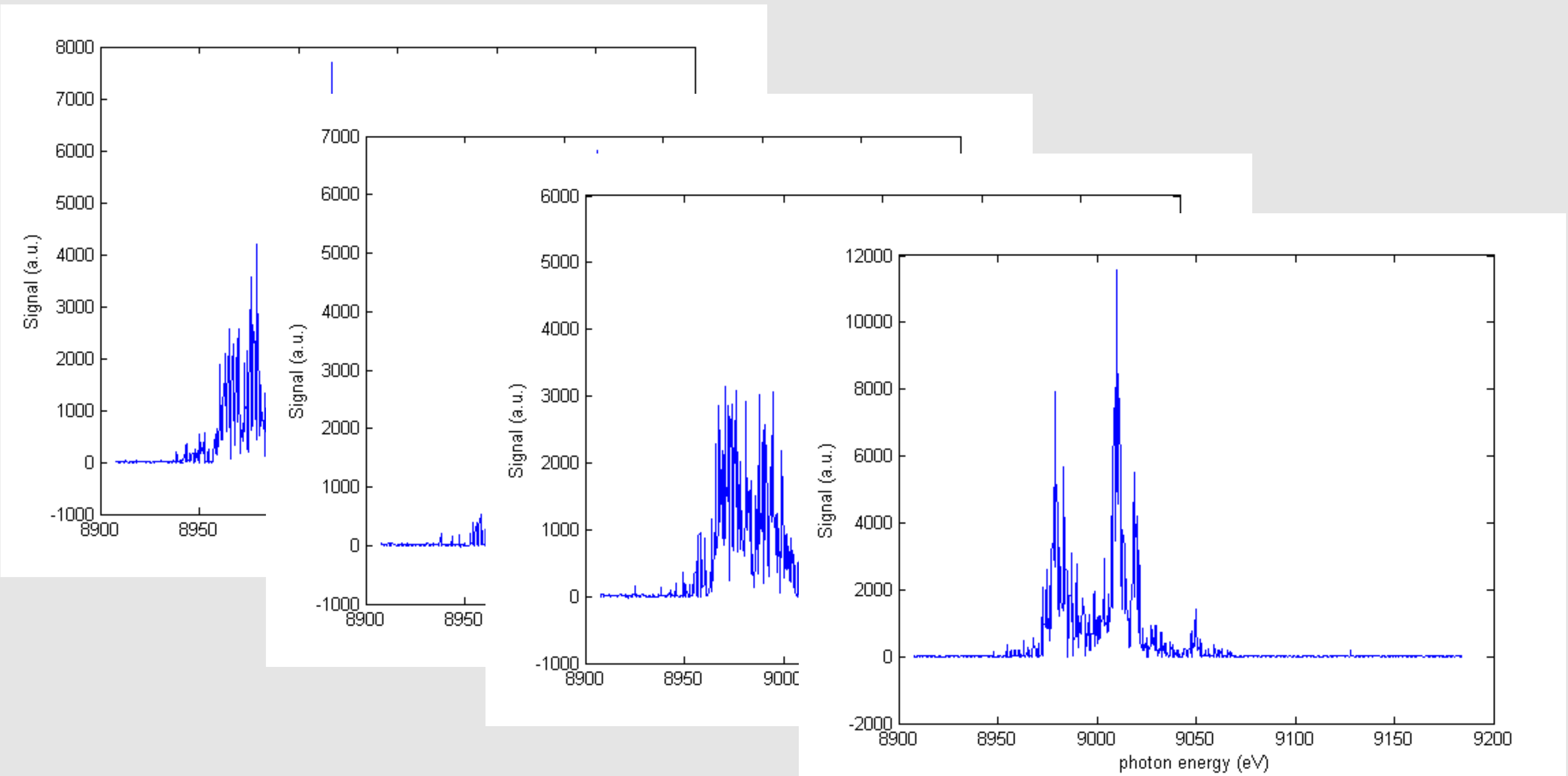
- Photon Energy: 9 keV
- Pulse Energy: 250-400 μJ
- Repetition rate: 30 Hz

Spectra:

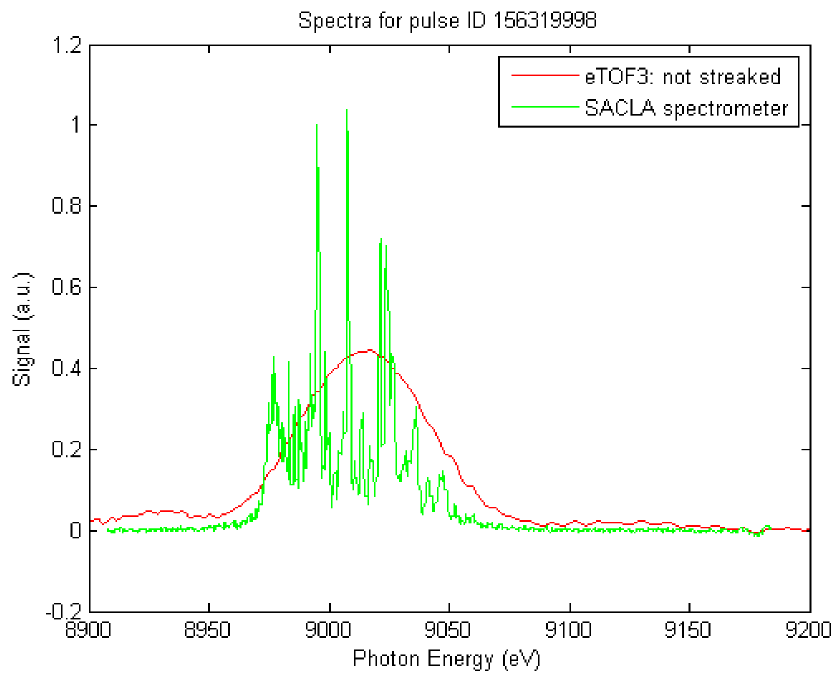
Note:

RMS width in 2014: ≈ 14 eV

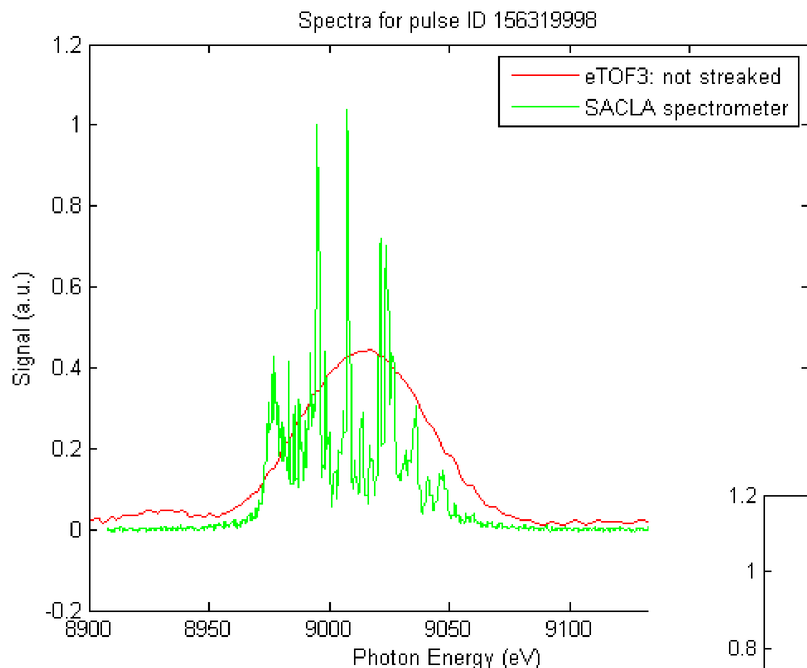
RMS width in 2016: ≈ 25 eV

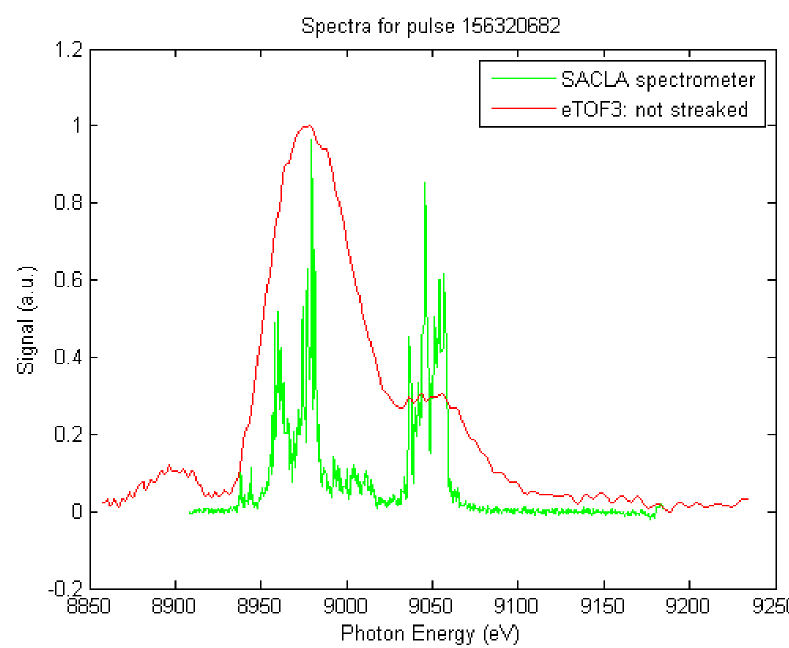


eTOF vs. spectrometer spectra

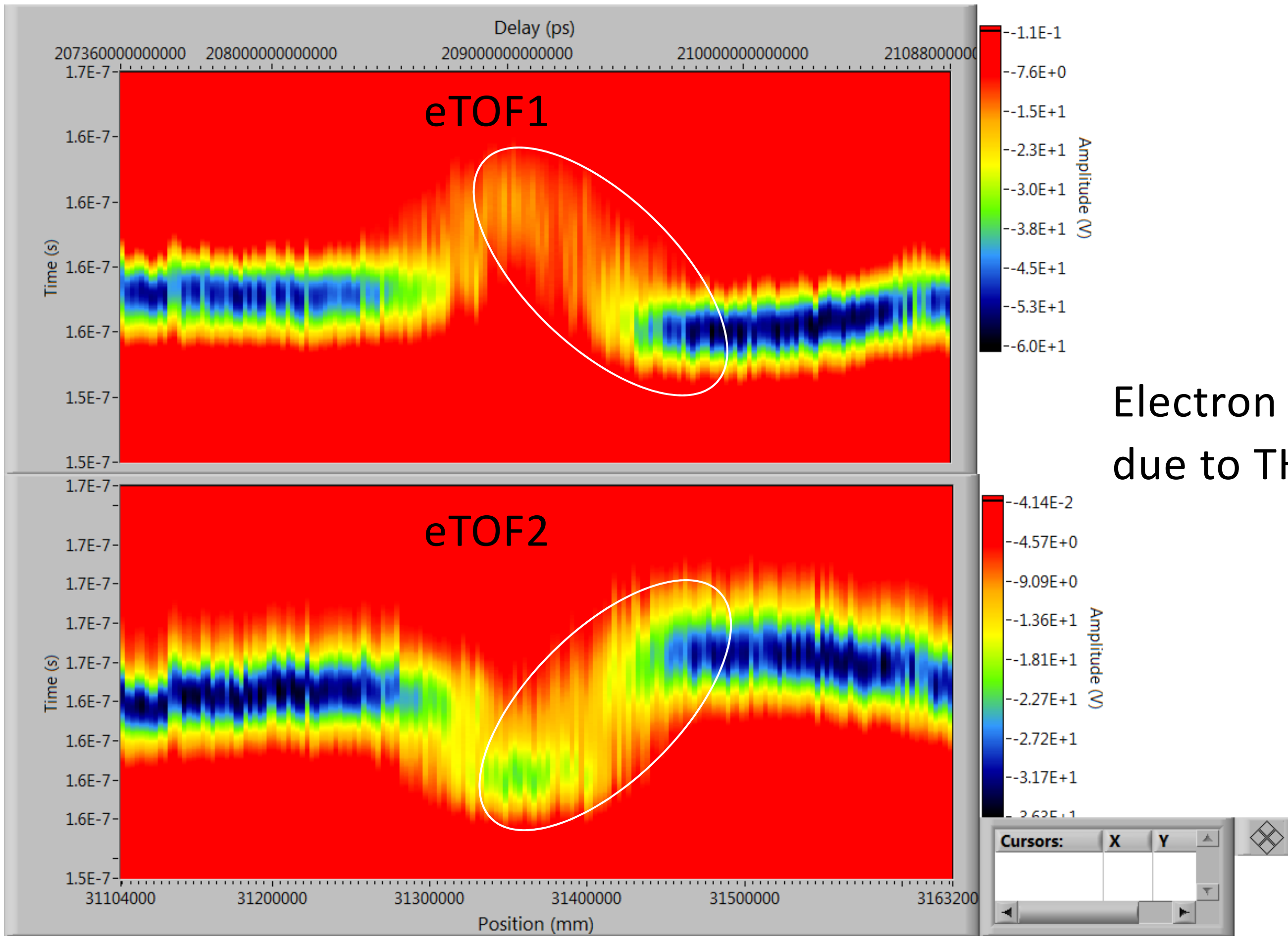


eTOF vs. spectrometer spectra



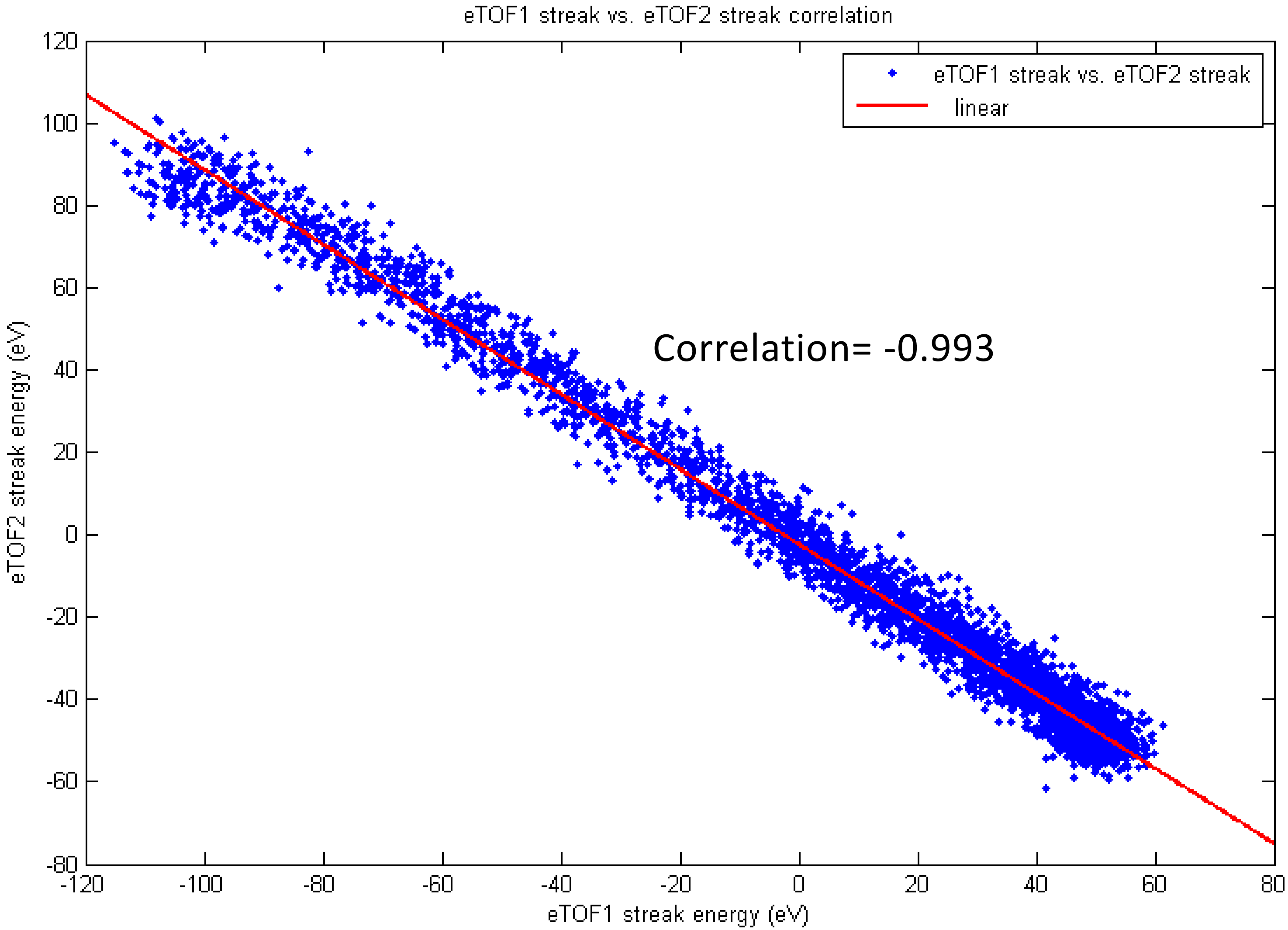


THz scan measurements

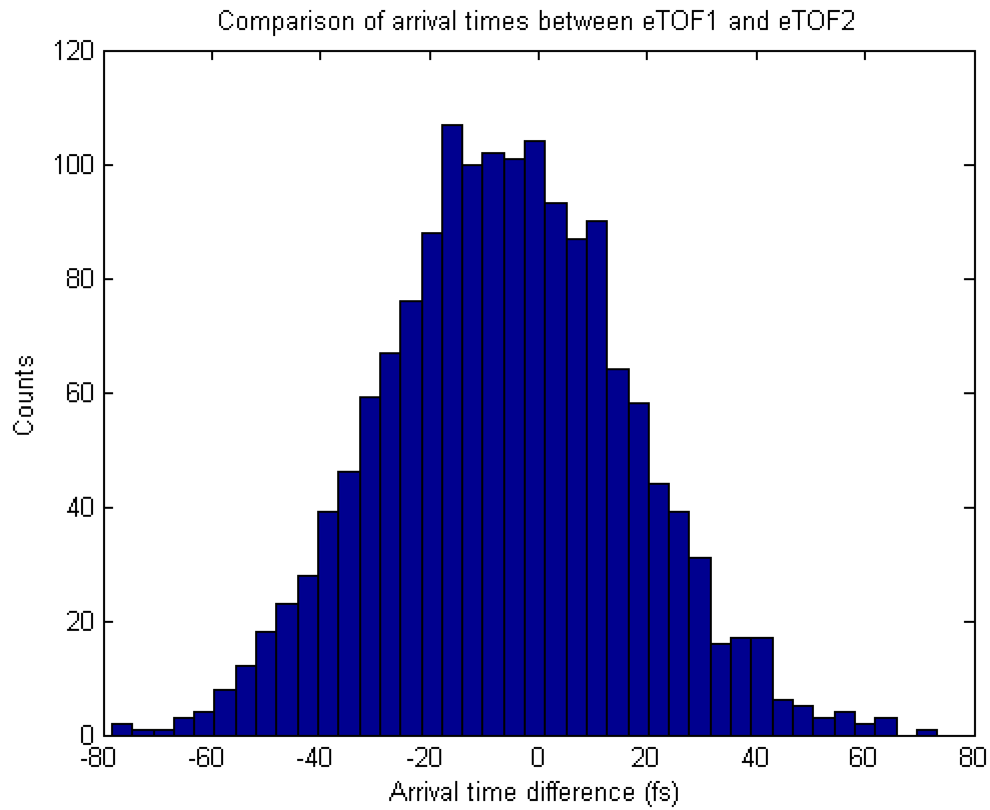


Electron energies shifted due to THz-FEL interactions

Correlation of streaked eTOF spectra

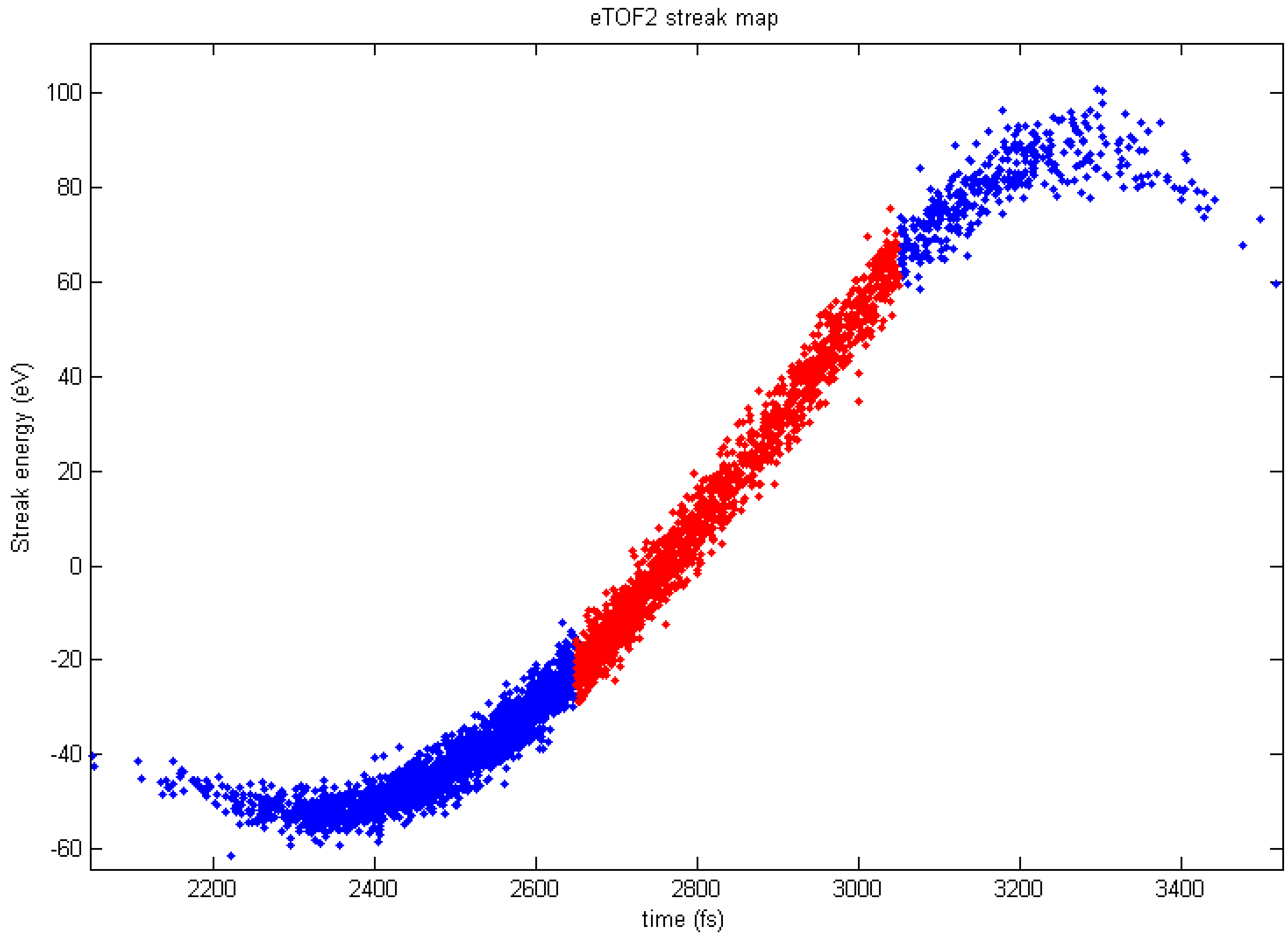


Arrival time comparison between 2 eTOFs

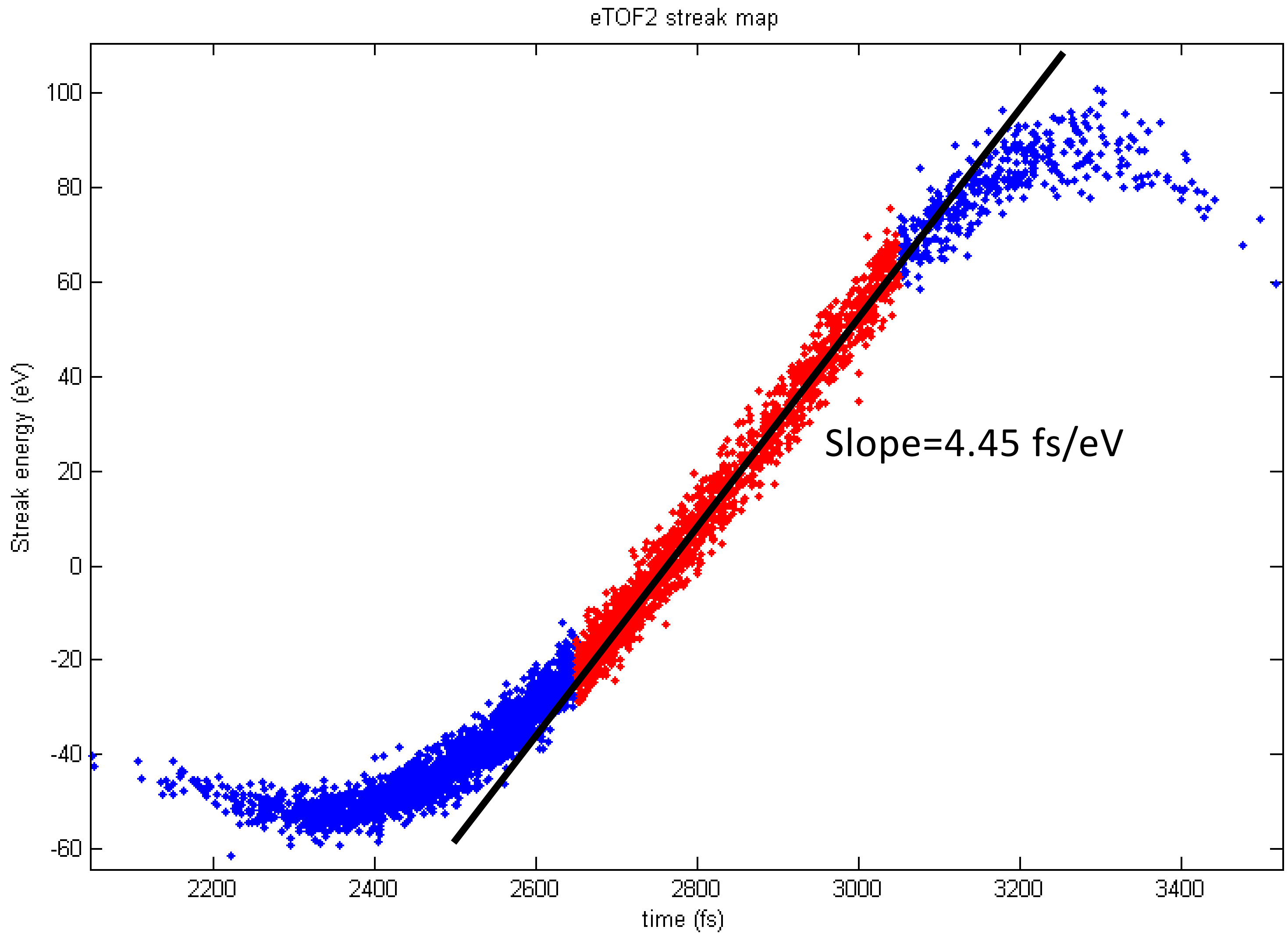


Total of 22 fs rms beween the pair, or about 15 fs rms from a single eTOF.

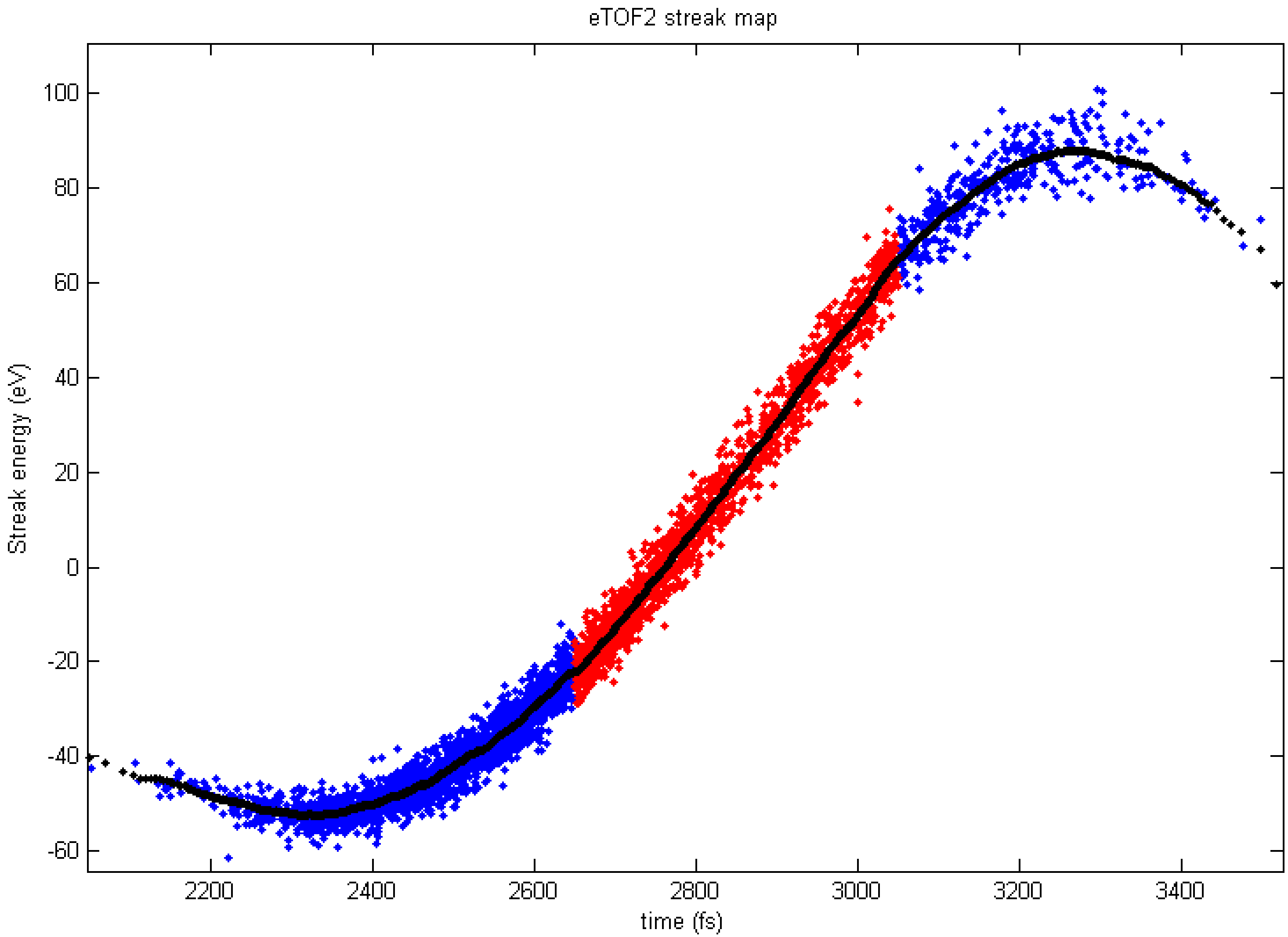
SACLA vs. PALM correlation plot



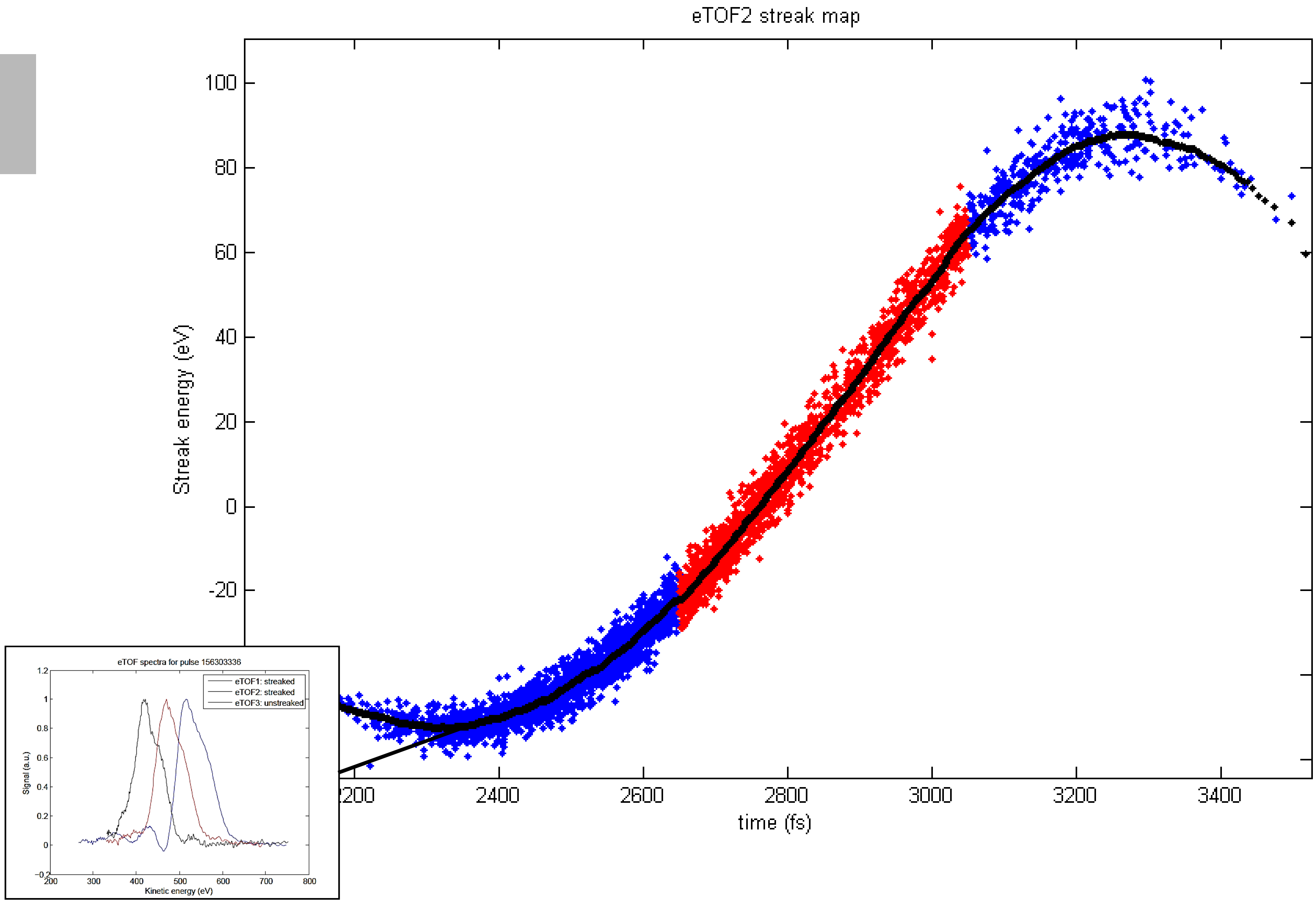
SACLA vs. PALM correlation plot



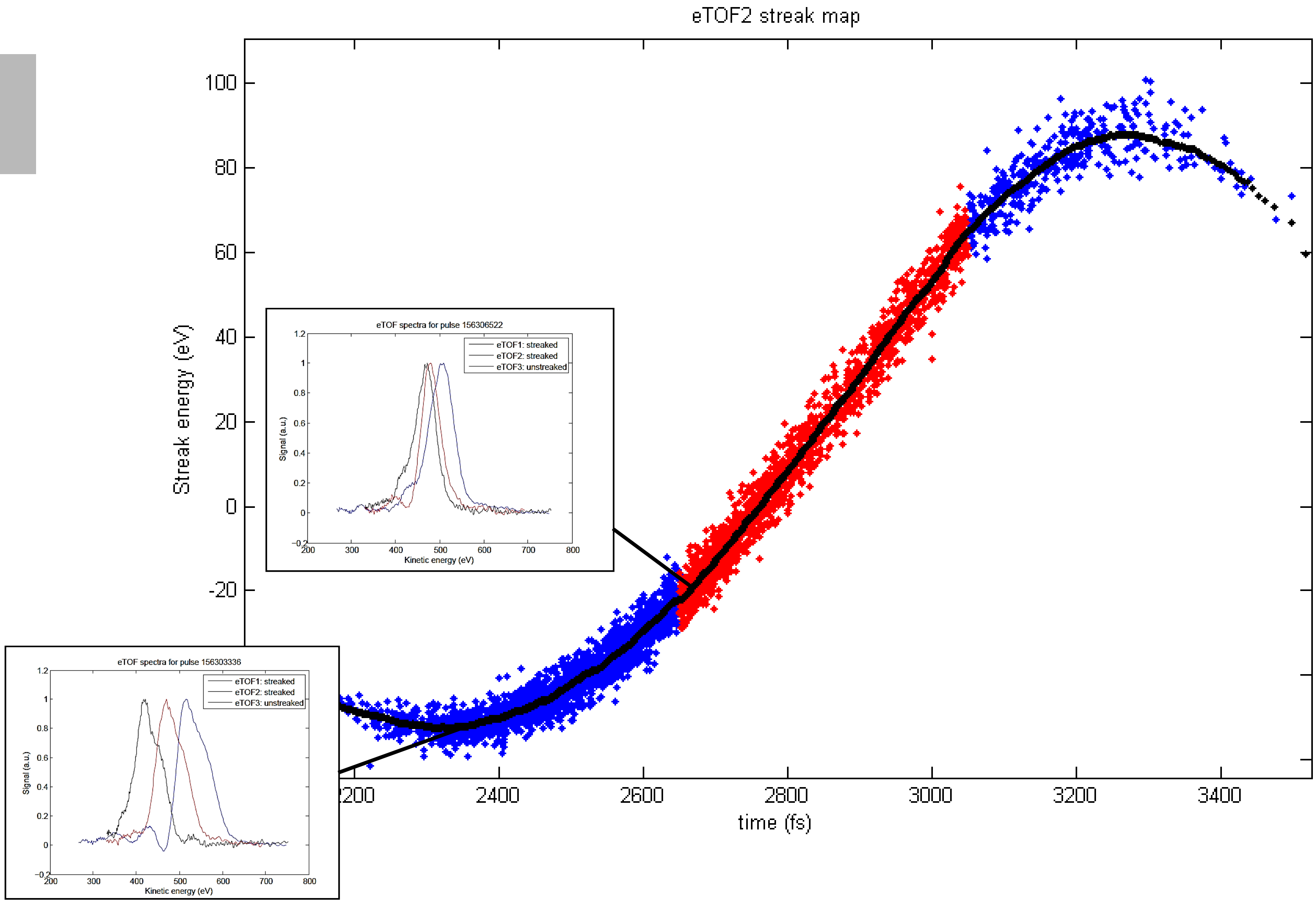
Measure on the middle of the slope



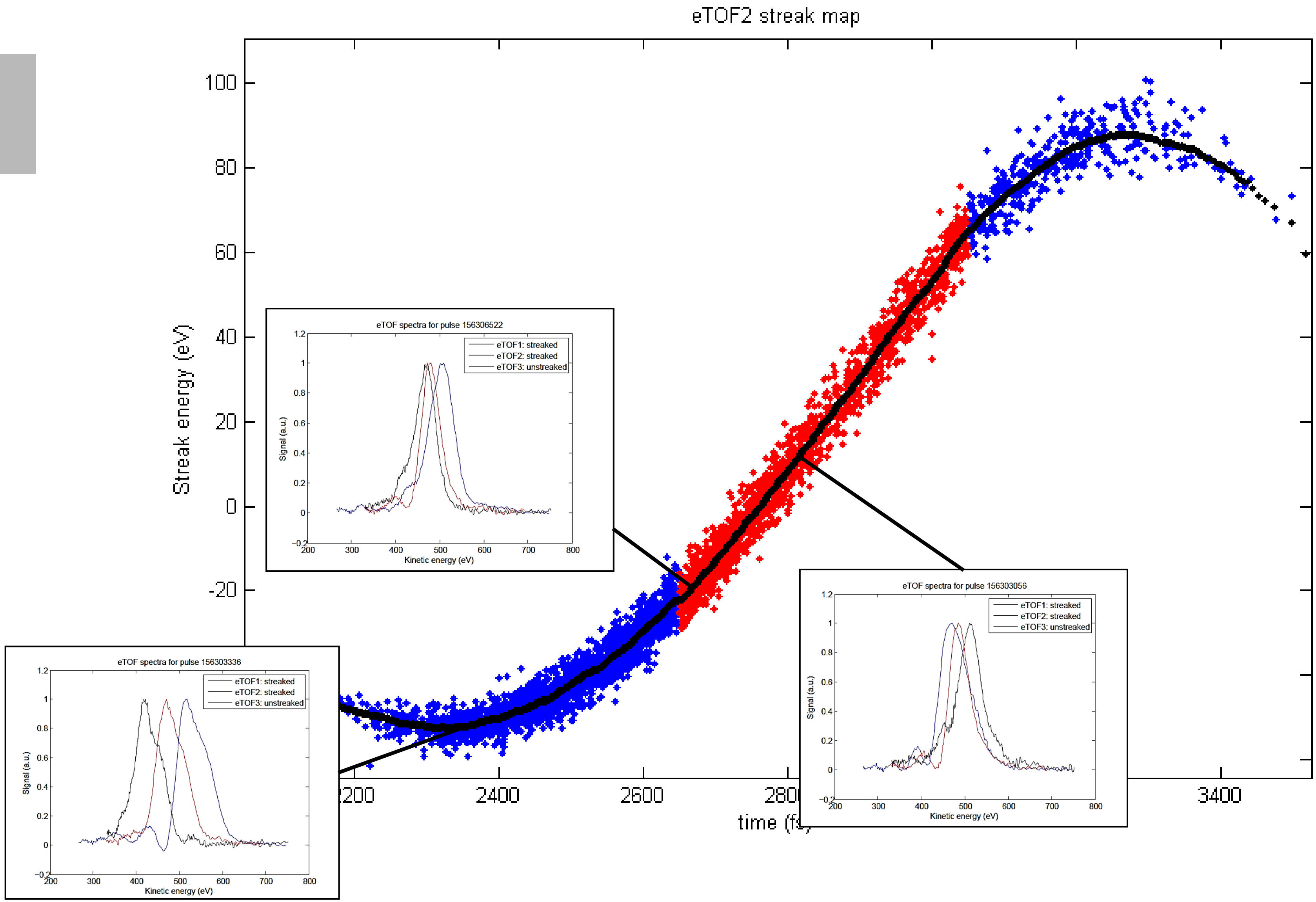
Measure on the middle of the slope



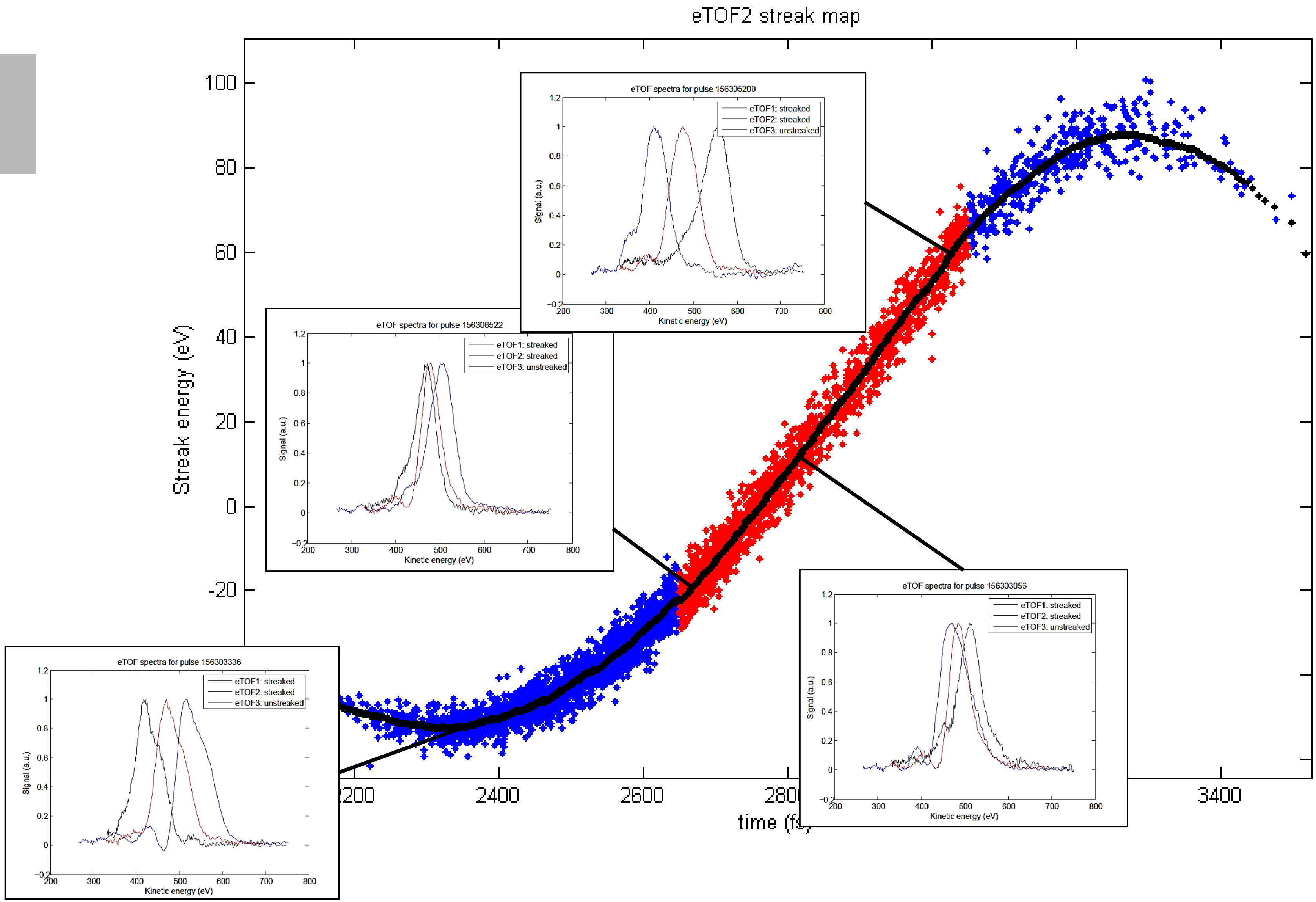
Measure on the middle of the slope



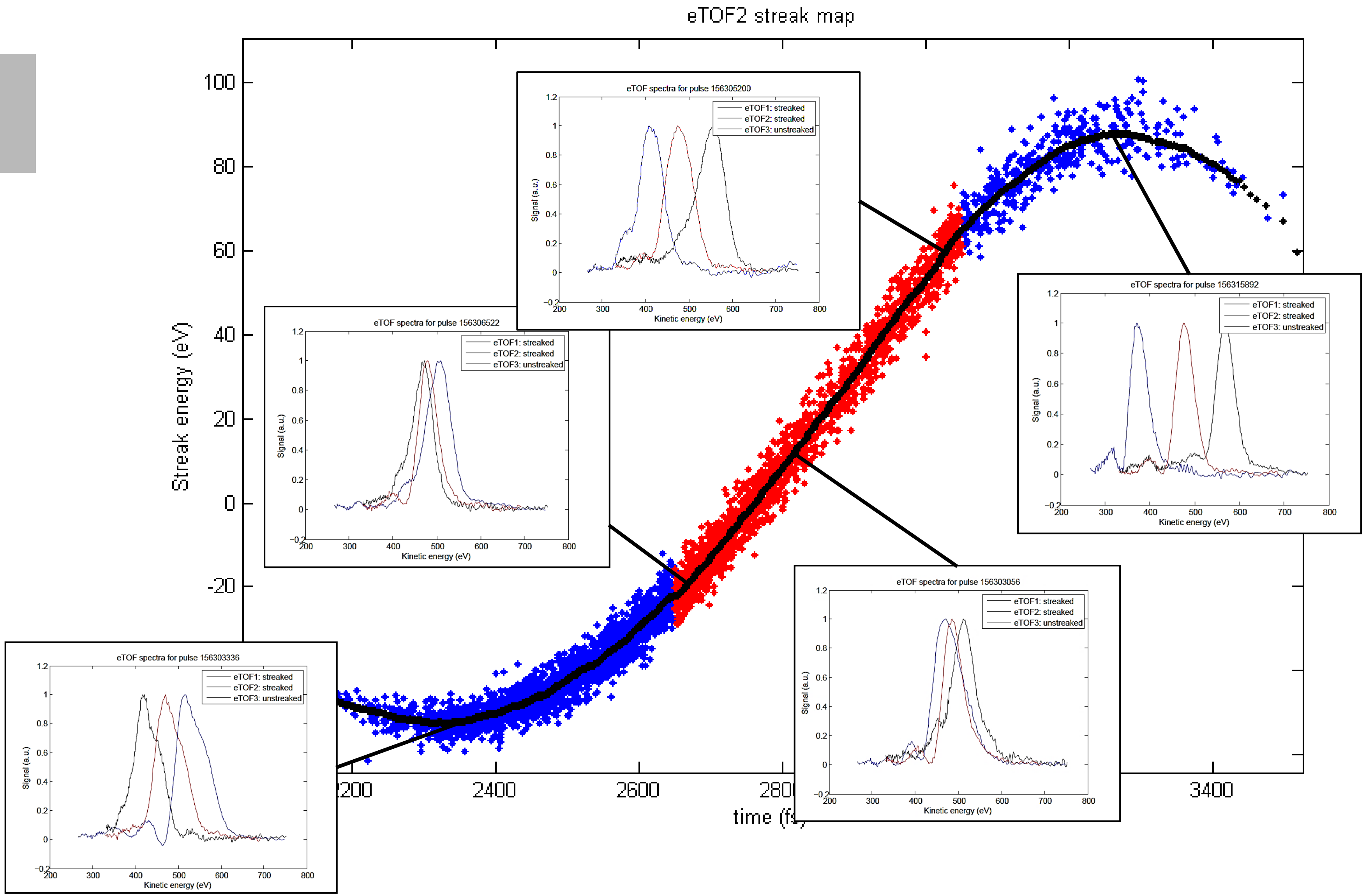
Measure on the middle of the slope



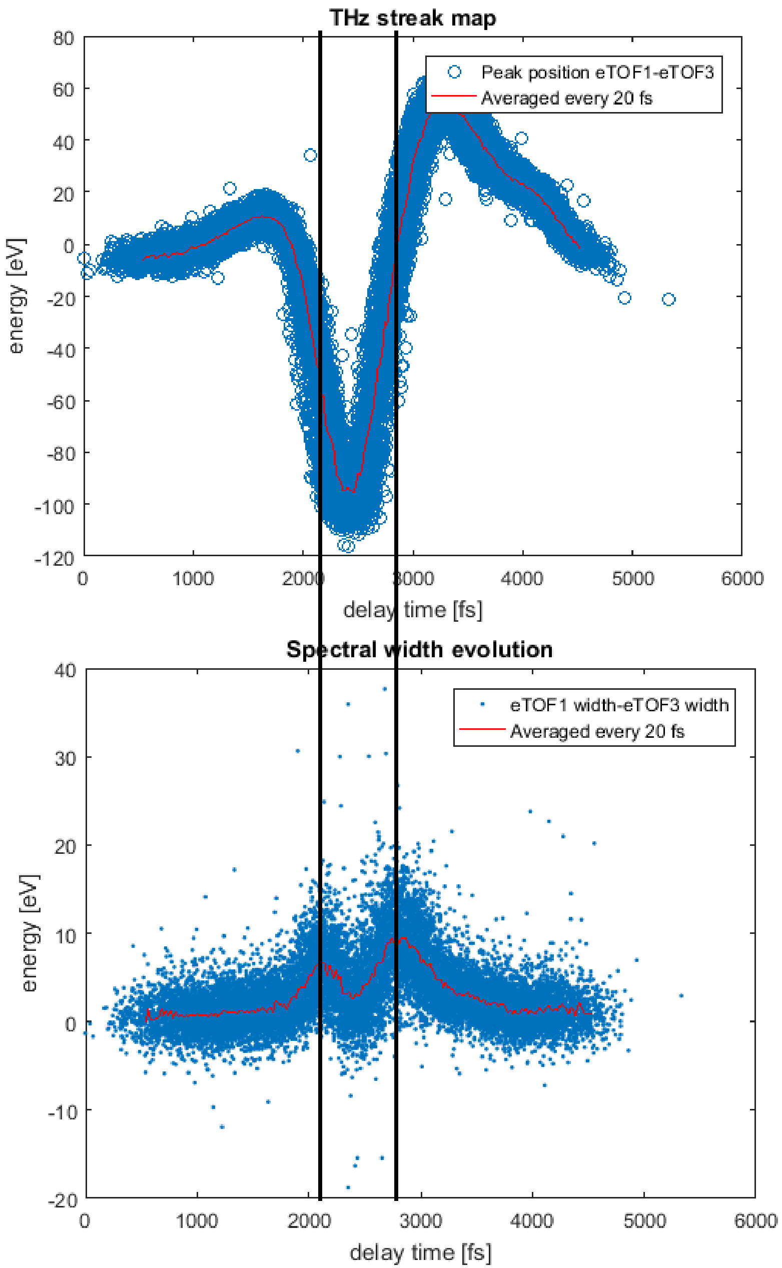
Measure on the middle of the slope



Measure on the middle of the slope



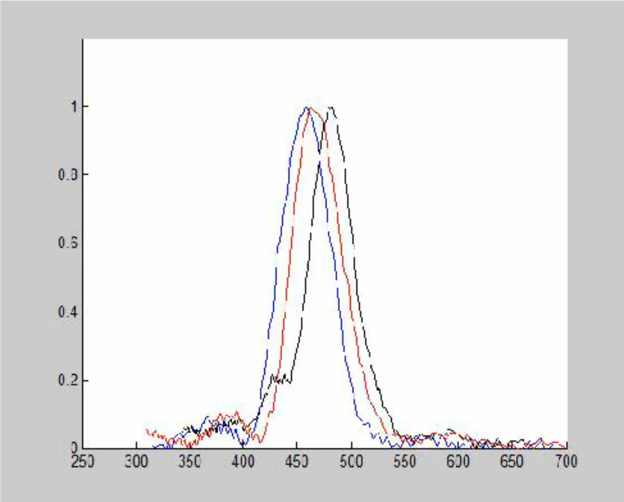
Spectral width difference along potential map



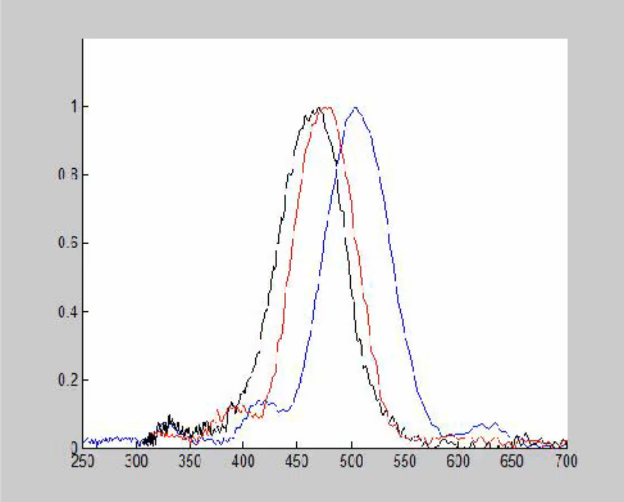
Maximum streak at maximum slope, and minimum streak at minimum slope. The data are as expected.

Shot-to-shot Measurements

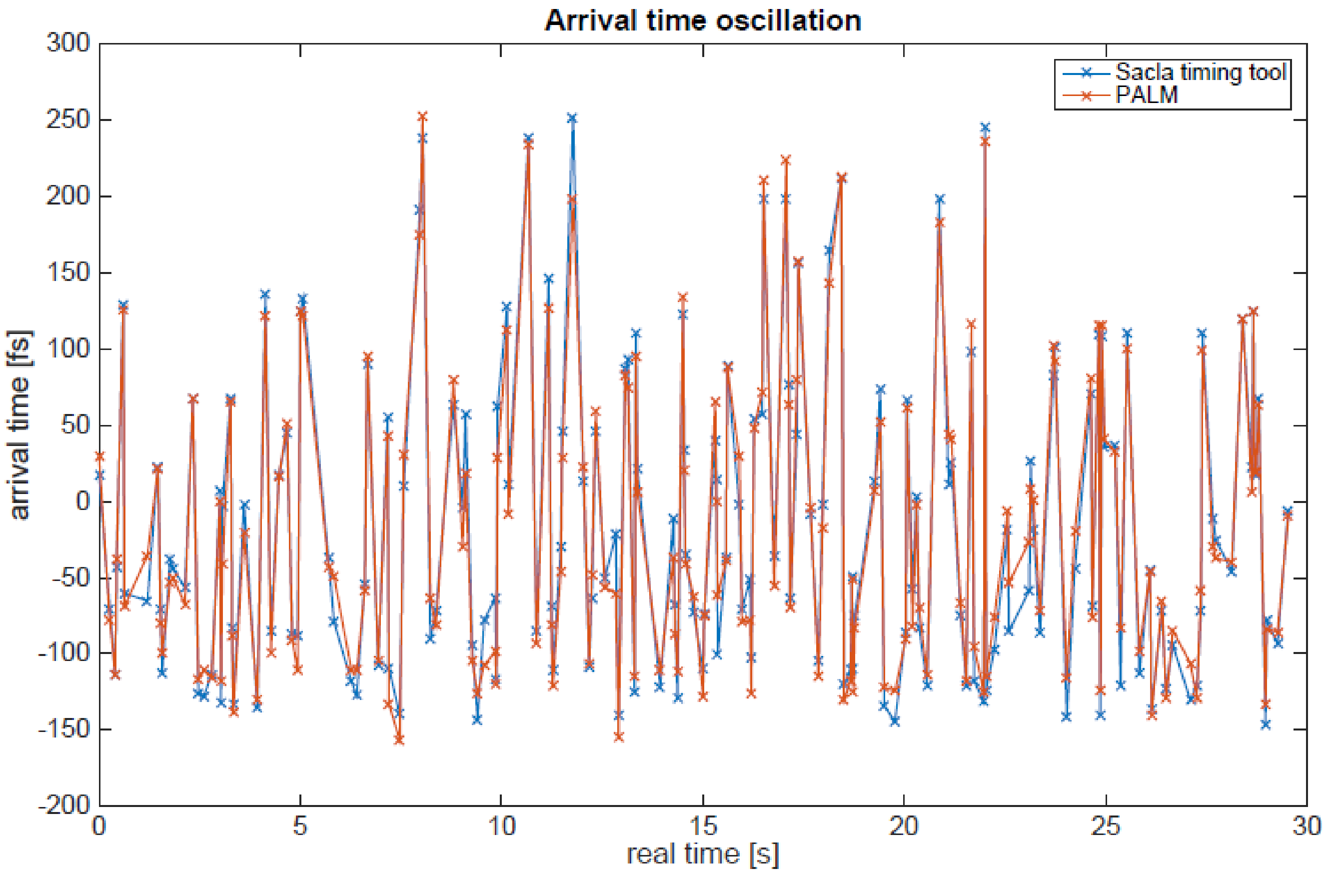
Non-Streaked:



Streaked:

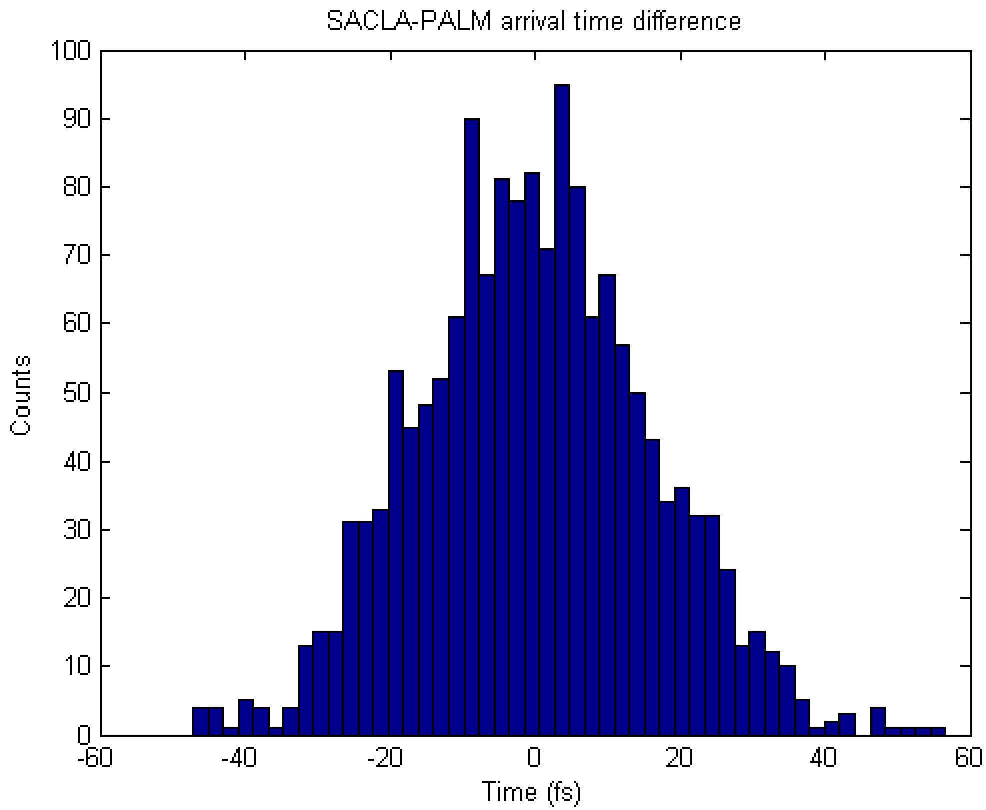


Comparison to SACLA timing tool



Good correlation between the SACLA timing tool and the PALM.

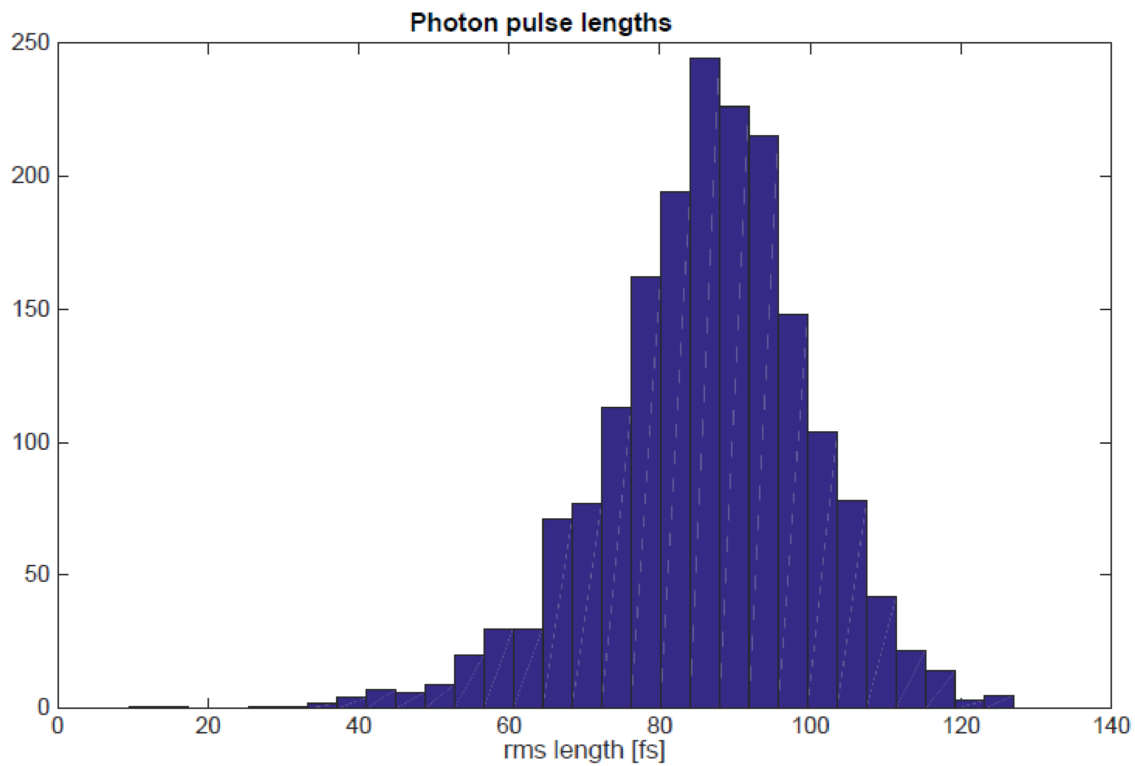
Comparison to SACLA timing tool



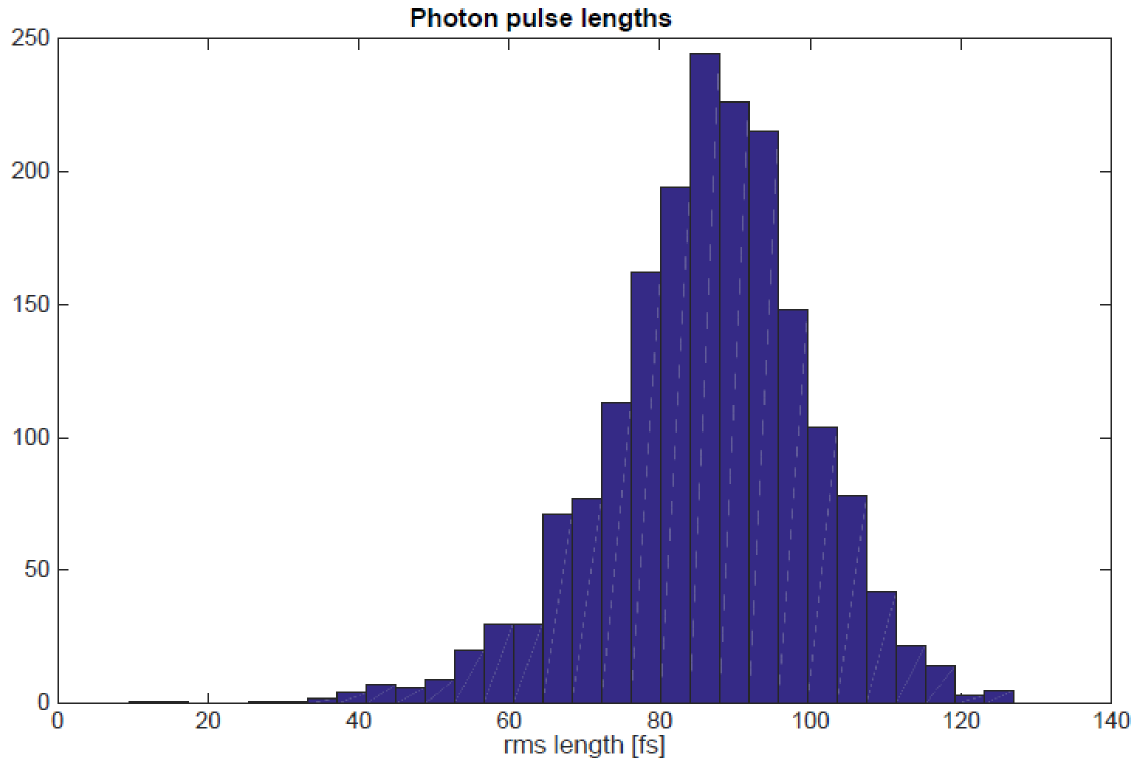
16-19 fs uncertainty between the SACLA timing tool and the PALM:

- 12-15 fs from PALM
- 7 fs from the timing tool
- about 10 fs from the laser jitter between the two.

Pulse length measurement (single color)



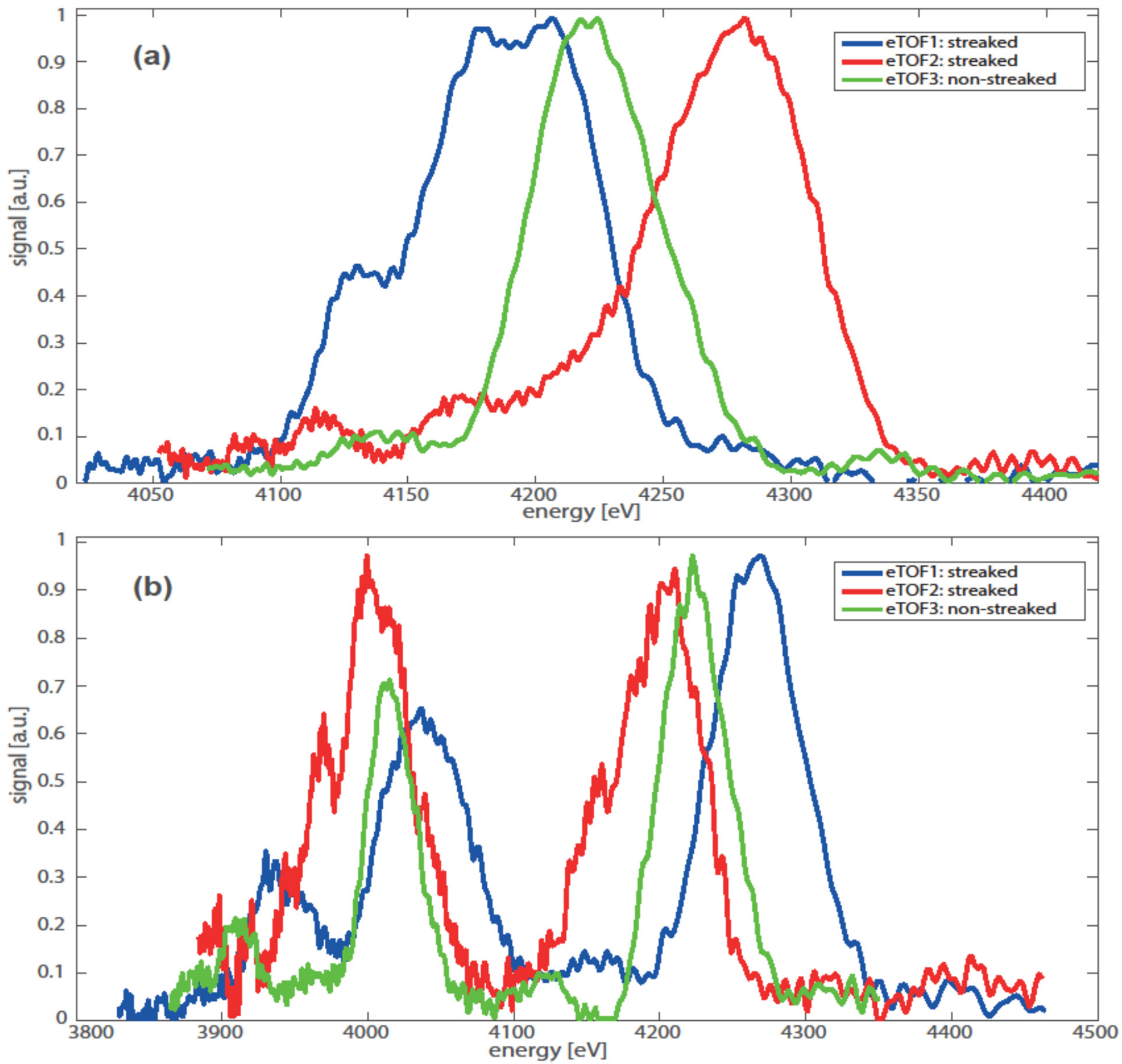
Pulse length measurement (single color)



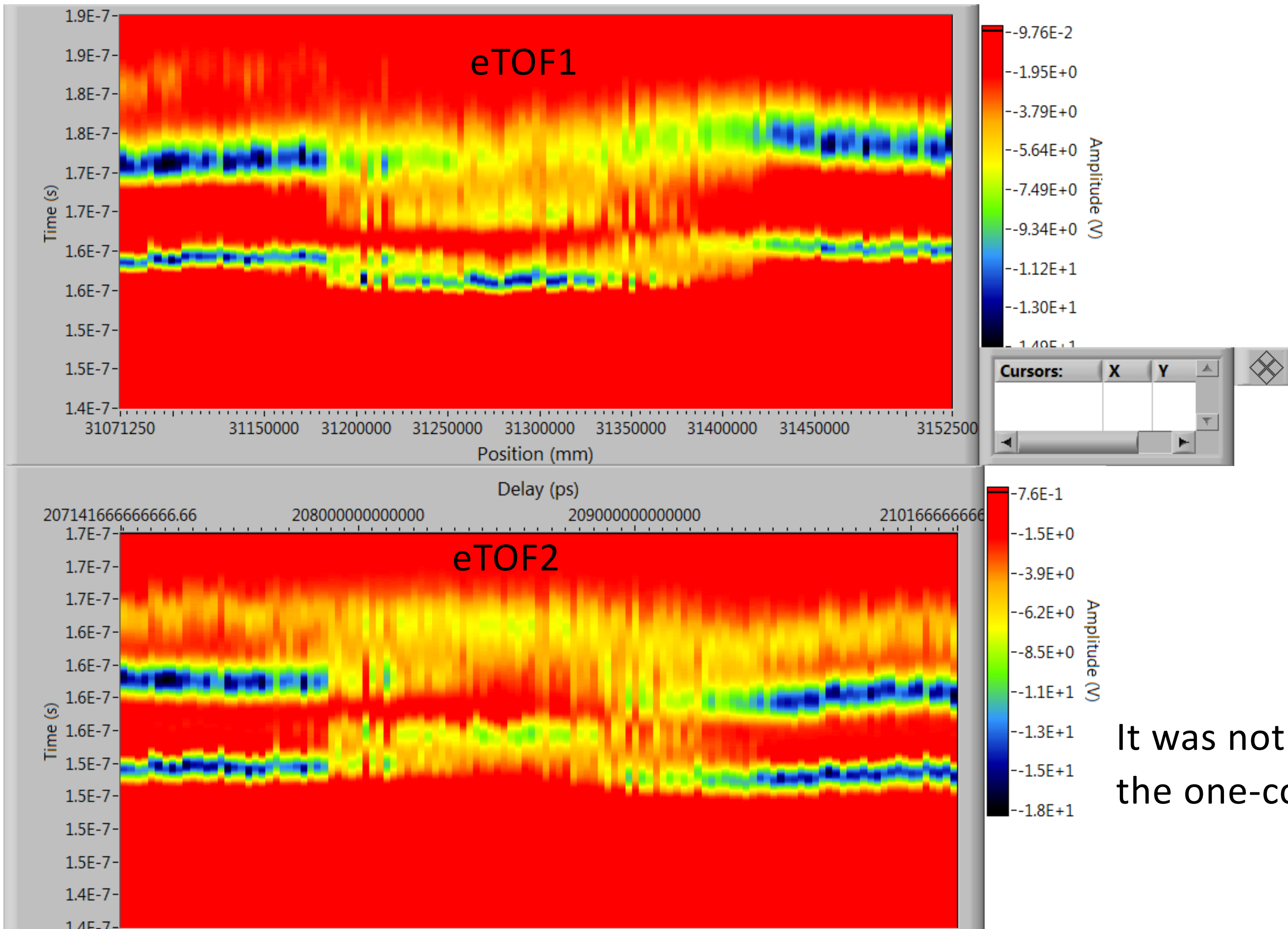
SACLA claims <10 fs FWHM pulse lengths. This is obviously not what we see.

It is a major discrepancy, and a real mystery.

One and two-color mode streaking spectra

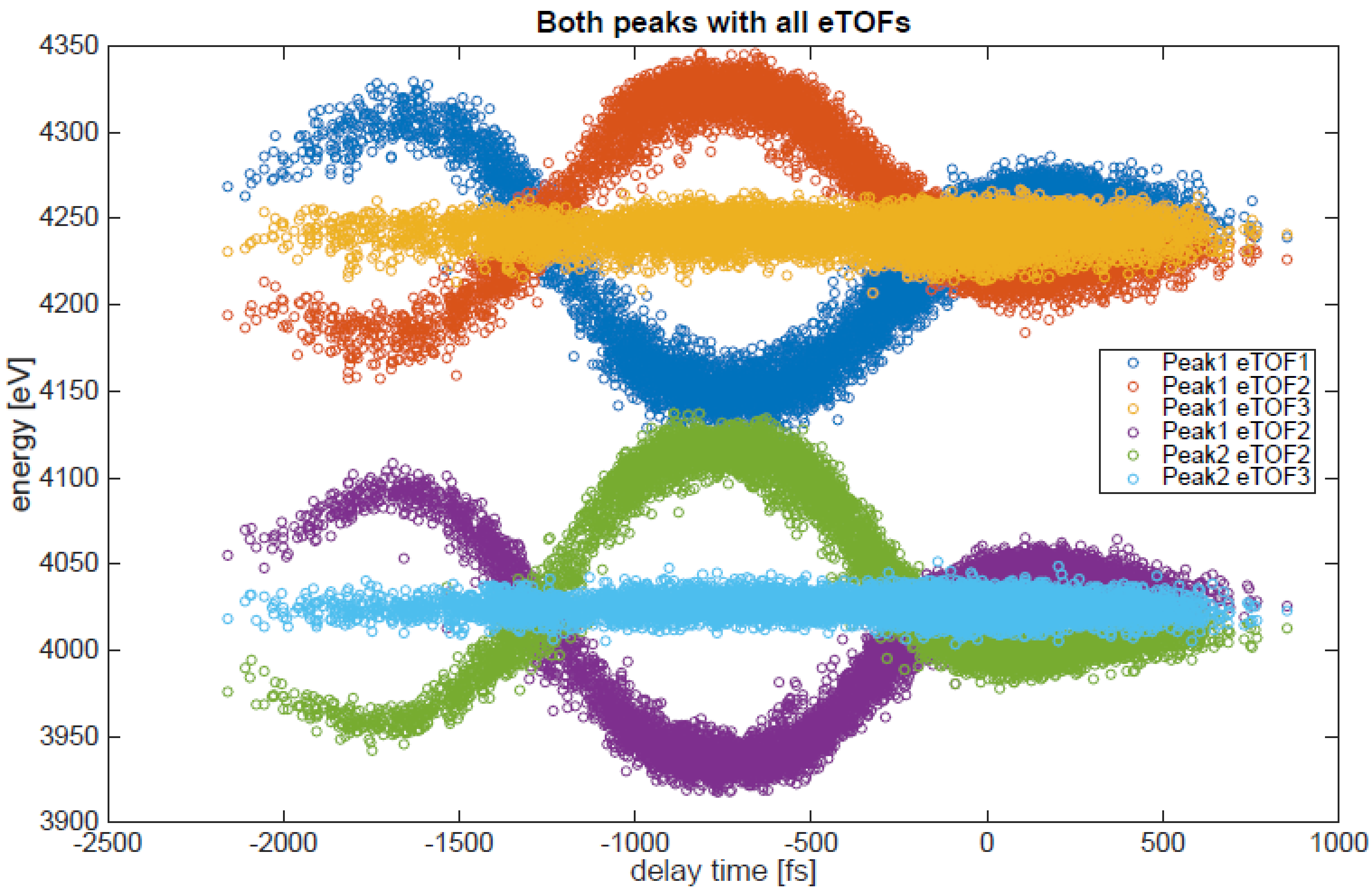


We also did two color mode: 9 and 8.8 keV

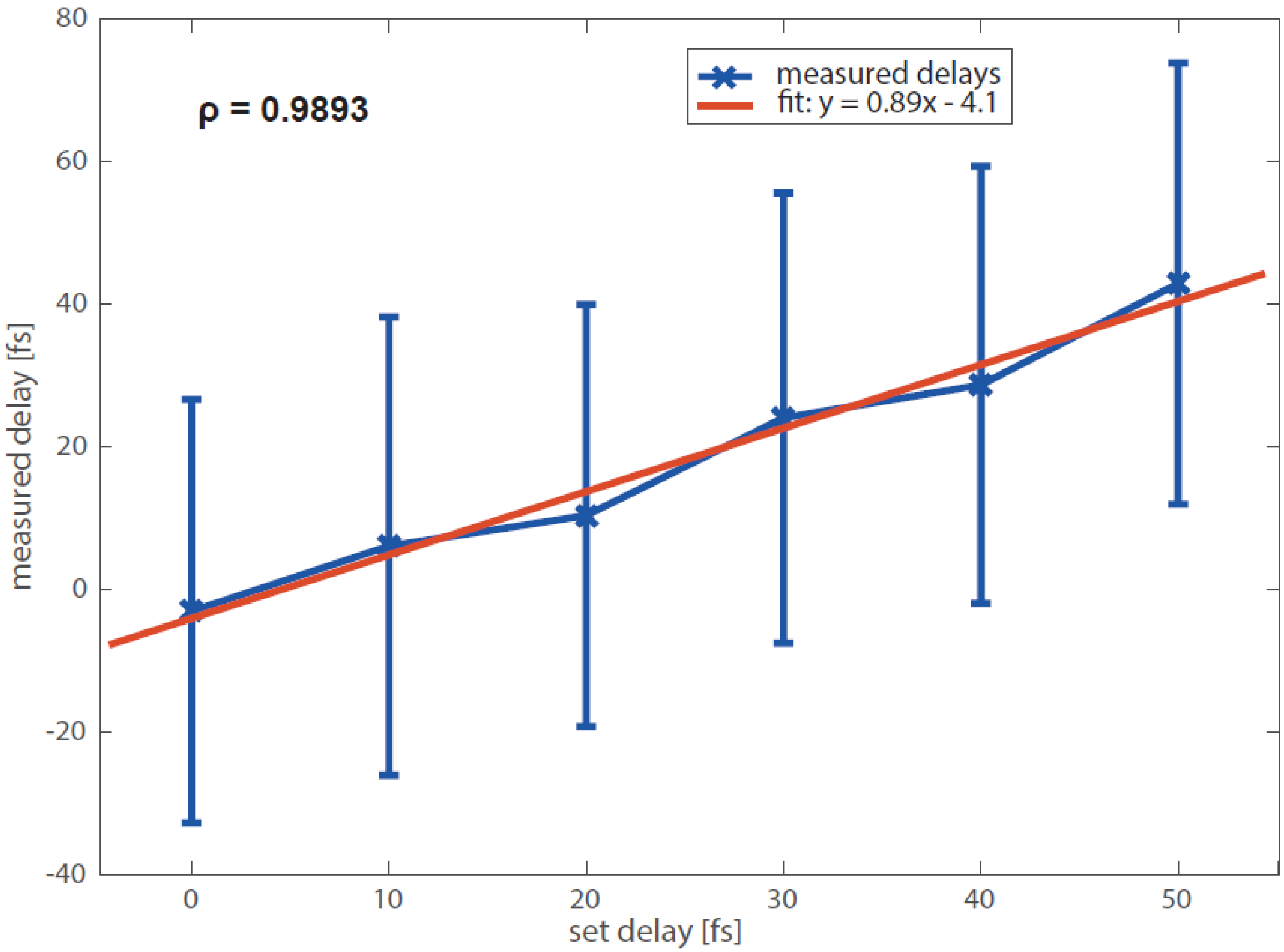


It was not as stable as the one-color mode.

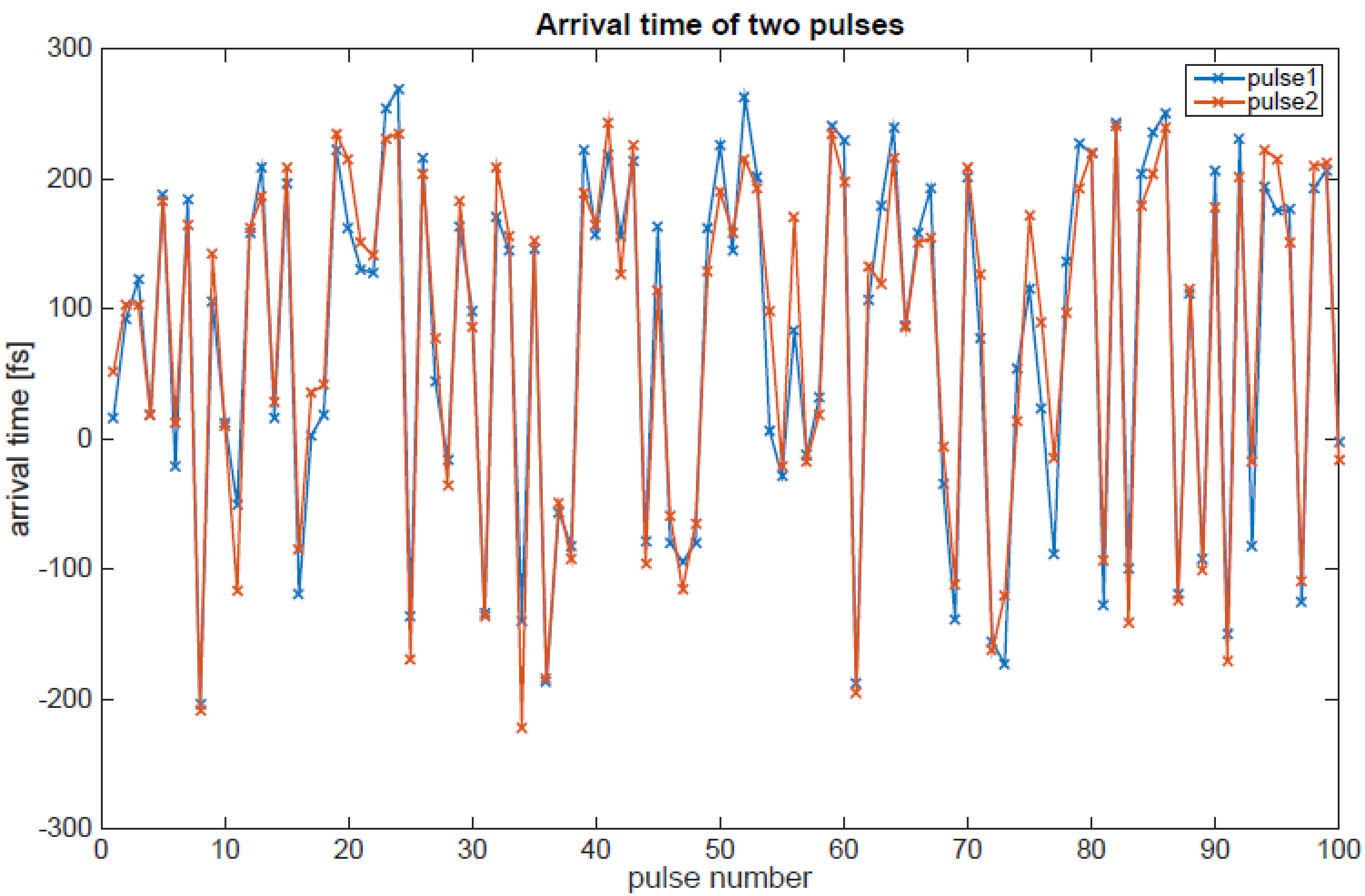
The full streak scan for two-color mode



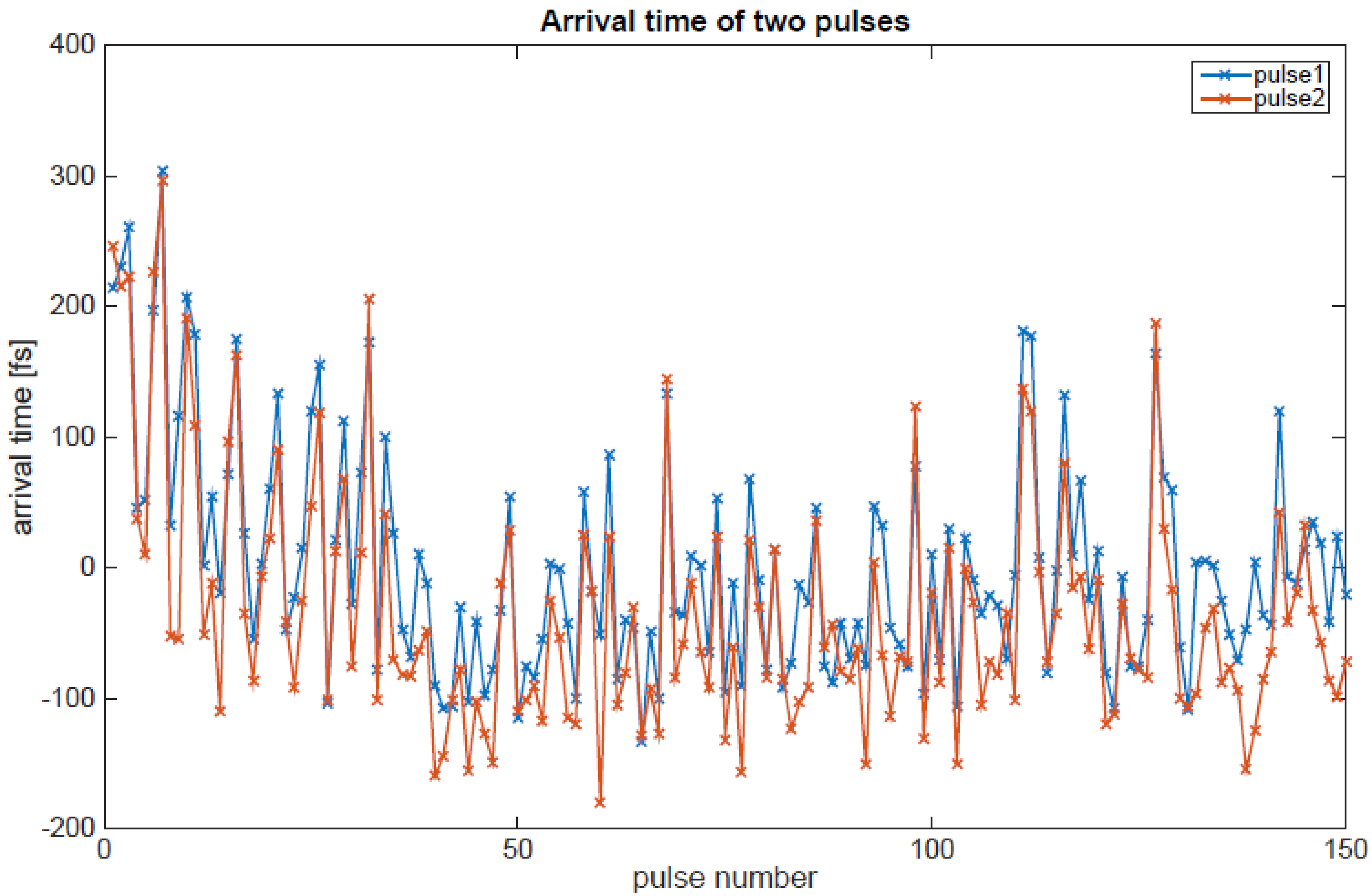
Set delay measurements with the PALM



Two-color arrival time comparison at Δt=0 fs



Two-color arrival time comparison at Δt=50 fs



Back to the Mystery: ask the beam dynamics experts!

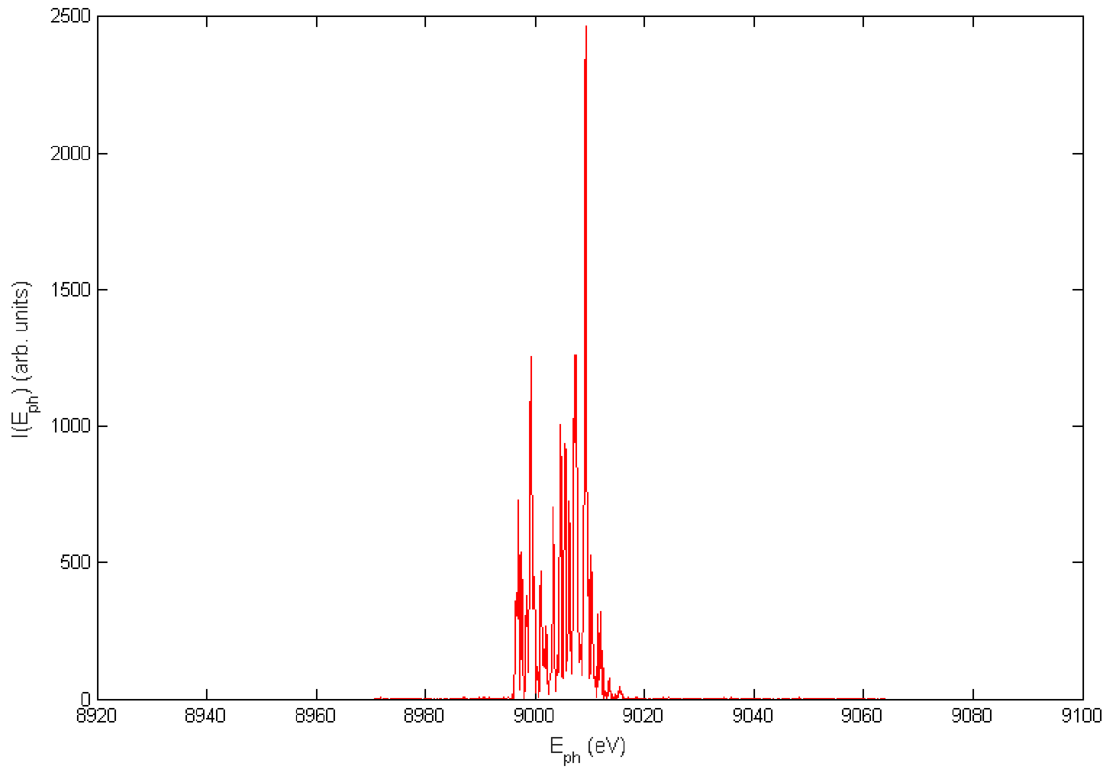
Dr. Sven Reiche (Mr. FEL)

Dr. Eduard Prat

Between the two of them, these guys have been calculating FEL spectra from beam parameters almost as long as I've been alive. Also, they're right across hall from my office and really nice to work with.

Pulse length from spectral measurements

One can also evaluate the pulse length from spectra spike width measurements. For this, SACLA uses a high-resolution Si-444 grating, getting spectra like this:



Note that this is a ‘cut-out’ of the whole spectrum, covering only about 15 eV.

PAUL SCHERRER INSTITUT

Evaluation methods

1. **From spectrum spike widths**

Principle: direct relation between spectrum spikes width and FEL pulse length

$$\sigma_t = \frac{\sqrt{2}h}{2\pi\sigma_\omega}$$

Reference: Y. Inubushi et al. Phys. Rev. Lett. 109, 144801 – Published 1 October 2012

2. **From spectral correlation function**

Principle: spectral second order correlation function is related to pulse shape

Reference: A.A. Lutman et al, Phys. Rev. ST Accel. Beams 15, 030705 – Published 13 March 2012

$$G_2(\delta\omega) = \int_{-\infty}^{+\infty} W(\omega)\left[\frac{\langle S(\omega-\delta\omega/2)S(\omega+\delta\omega/2)\rangle}{\langle S(\omega-\delta\omega/2)\rangle\langle S(\omega+\delta\omega/2)\rangle} - 1\right] d\omega$$

S: single-shot spectrum

For a Gaussian pulse

$$G_2(\delta\omega) = \frac{e^{-\frac{\delta\omega^2\xi_0^2\sigma_t^2}{1+2\sigma^2\sigma_t^2}}}{\sqrt{1+2\sigma^2\sigma_t^2}}$$

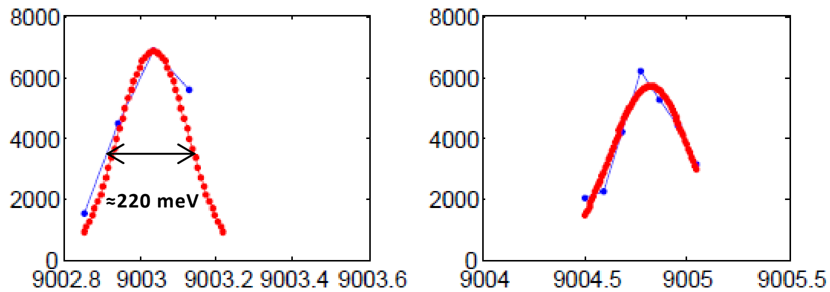
For a flat-top pulse

$$G_2(\delta\omega) = 2\int_0^1 e^{-\zeta^2\sigma^2T^2/2}(1-\zeta)\cos(\delta\omega\xi_0T\zeta)d\zeta$$

Method1: Spike width	Method 2: Correlation function
Need to resolve a single spike (required resolution for SwissFEL at 200pC: 4e-6)	No need to resolve a single spike
Single-shot capability	No single-shot capability
Unable to distinguish between different shapes (Gaussian pulse is assumed)	Some information about the shape can be obtained (e.g. difference between Gauss and flat-top)

Courtesy of E. Prat

Method 1: spectrum spike widths



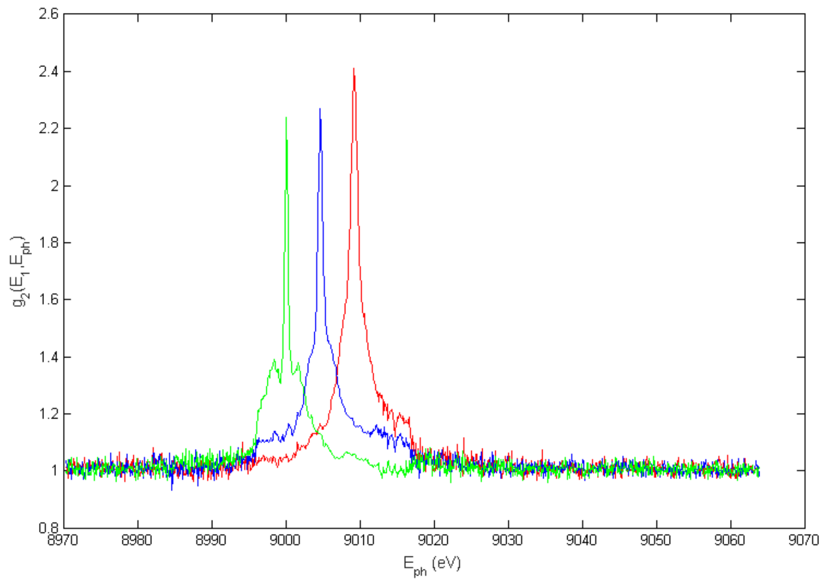
Courtesy of E. Prat

The method yields values of 3-4 fs RMS. However, something is odd: There are way too many spikes. Typically, we would expect 4-6 spikes for a 3-4 fs RMS beam. The spectrum shown in slide 34 has dozens of spikes, with about 200 estimated over the whole spectral bandwidth.

We also double-check with the correlation function method.

Method 2: correlation function

We used 10,000 spectra to get the correlation functions for the individual frequency components of the Si-444 FEL spectrum.



Courtesy of S. Reiche

At the spike, we get 3 fs. There seems no strange effects in the correlation over the bandwidth, so the spikes are behaving properly—there's just a lot of them. This could be an effect of a chirp, which would then make the spectral-based pulse length determinations problematic.

Conclusions

- Arrival time measurements accurate and successful.
- Two color mode measurements were very successful, and show consistency between expected and measured values.
- Length issue needs to be addressed—the measurements go against what is expected by over an order of magnitude.
- SACLA spectrum was a bit strange for this beamtime.
- Further discussions are ongoing.

Wir schaffen Wissen – heute für morgen

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