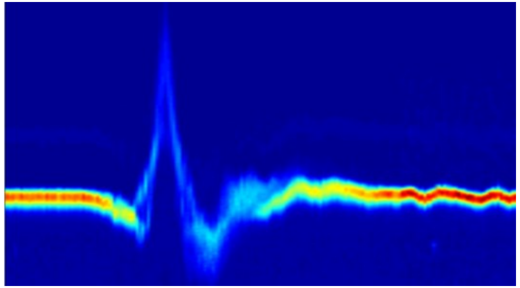
THz streaking of the seeded FLASH pulse

Armin Azima on behalf of the seeding team

FLASH Seminar 25.04.2017

- ***Introduction***
- ***Latest results***
- ***Outlook***



Supported by BMBF under contract 05K13GU4 and 05K13PE3
DFG GrK 1355
Joachim Herz Stiftung
Helmholz Accelerator R&D

Bundesministerium für Bildung und Forschung

Universität Hamburg — Der Forschung | Der Lehre | Der Bildung

DFG Deutsche Forschungsgemeinschaft

Joachim Herz Stiftung

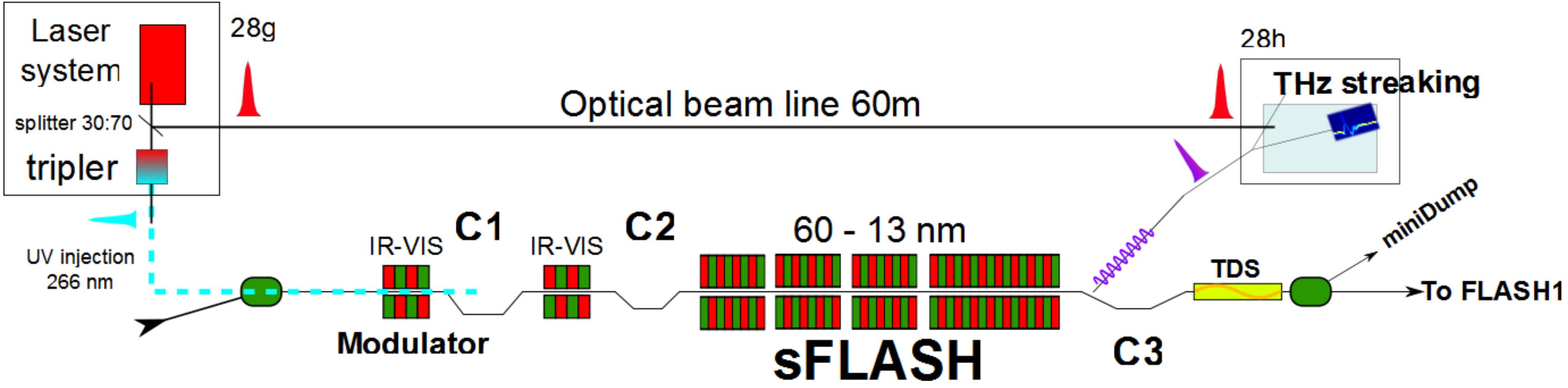
technische universität dortmund

HELMHOLTZ | ASSOCIATION

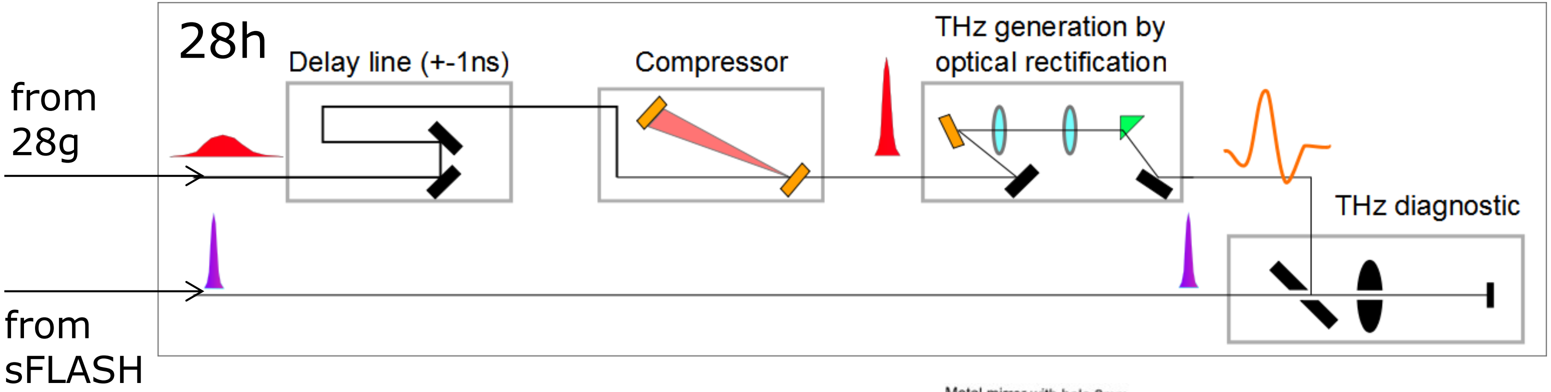
Accelerator Research and Development (ARD) — Helmholtz Gemeinschaft

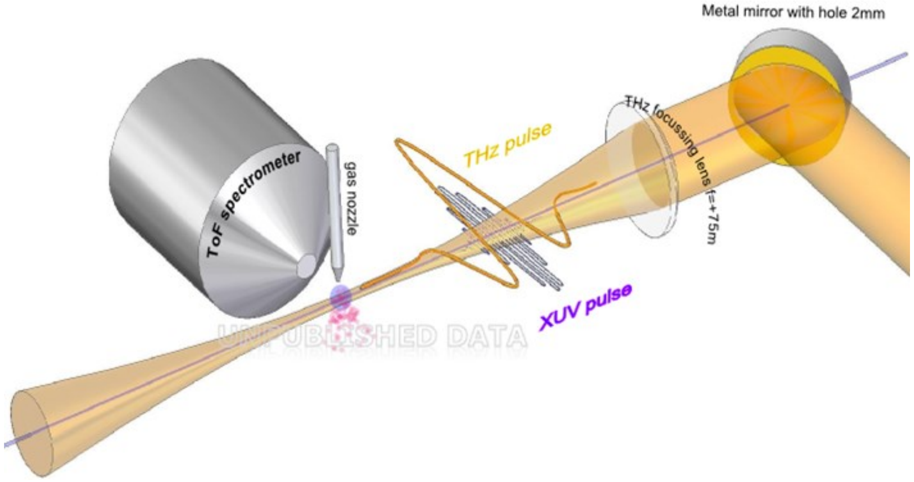
DESY

sFLASH layout

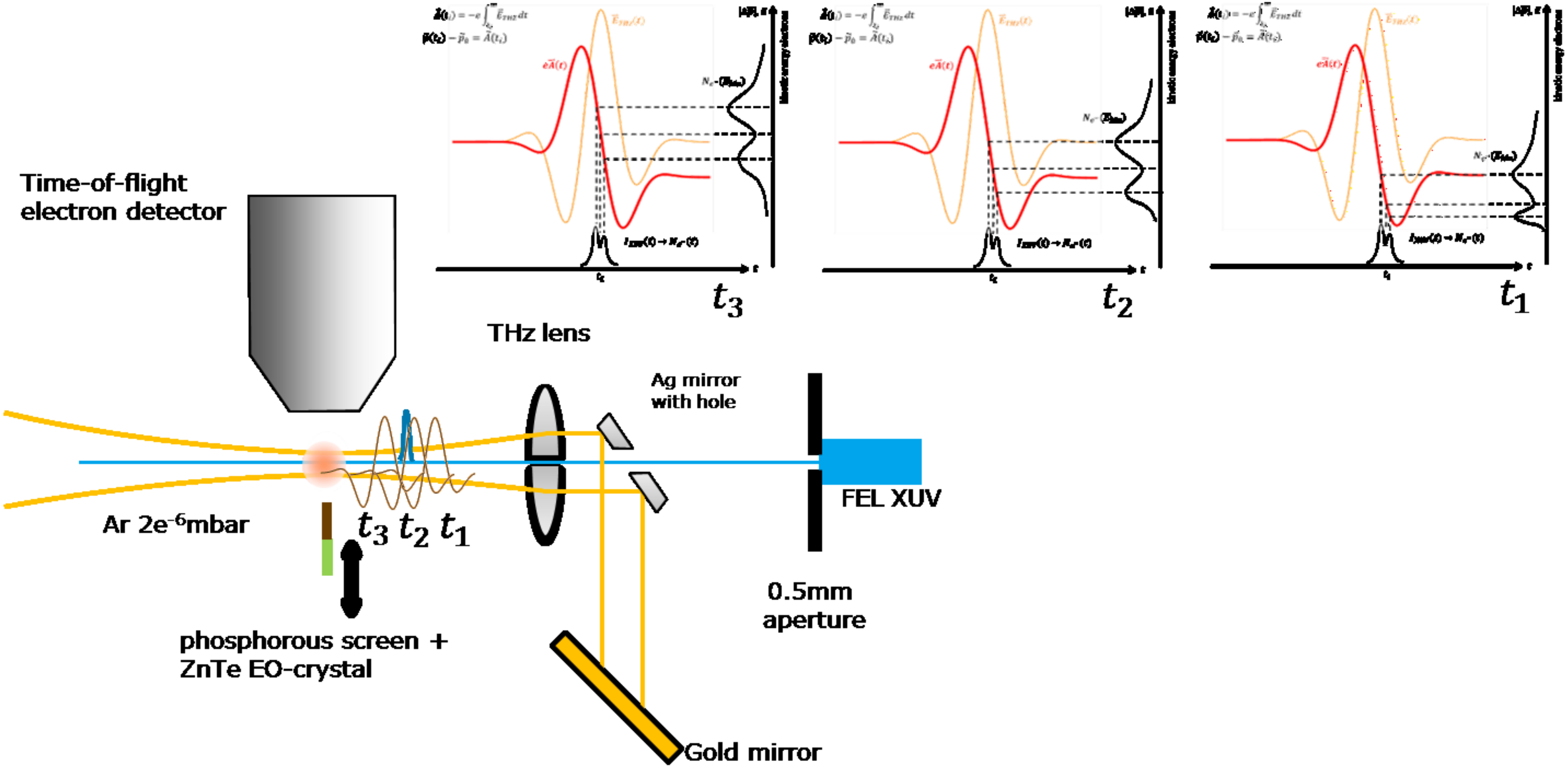


THz streaking – setup in 28h

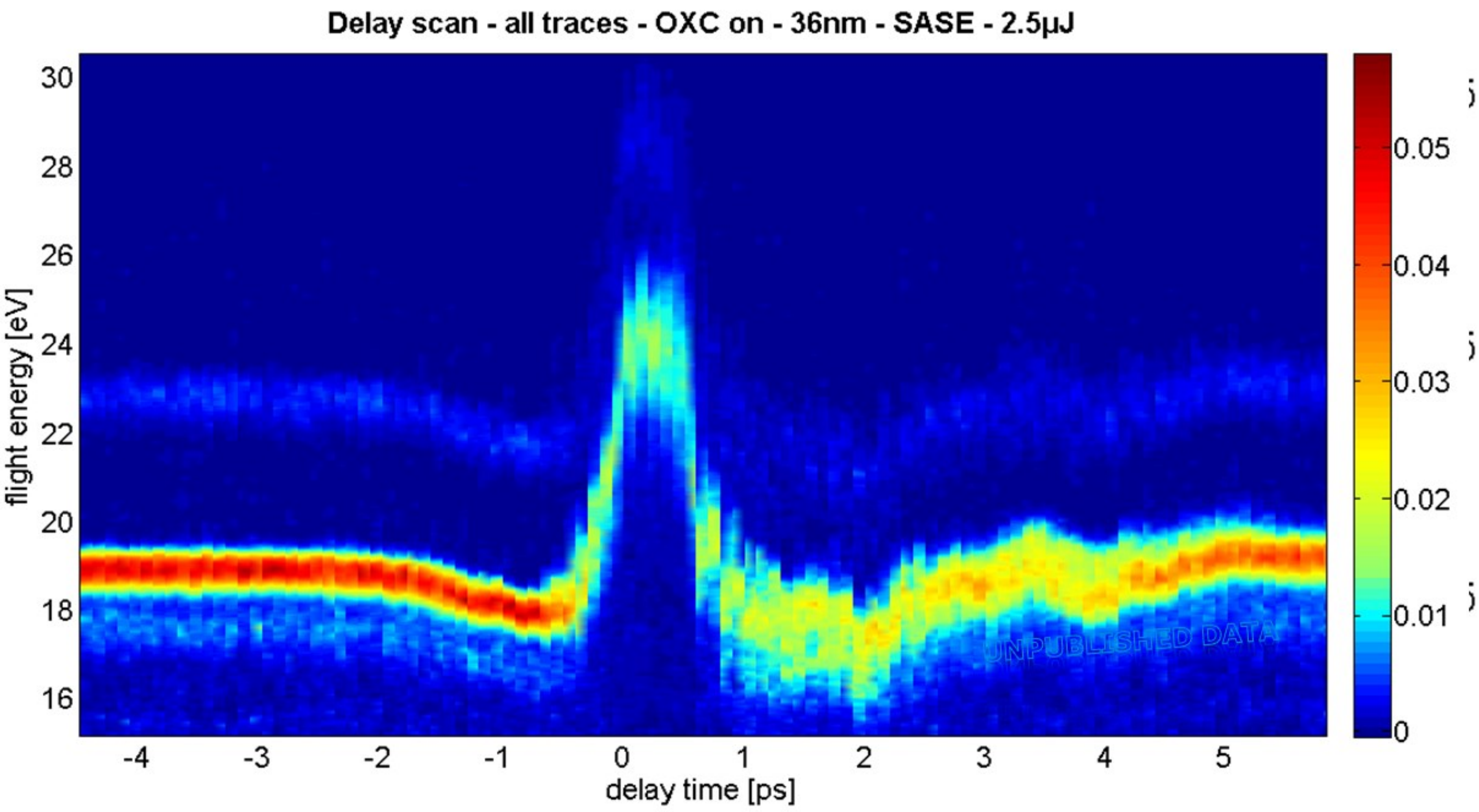




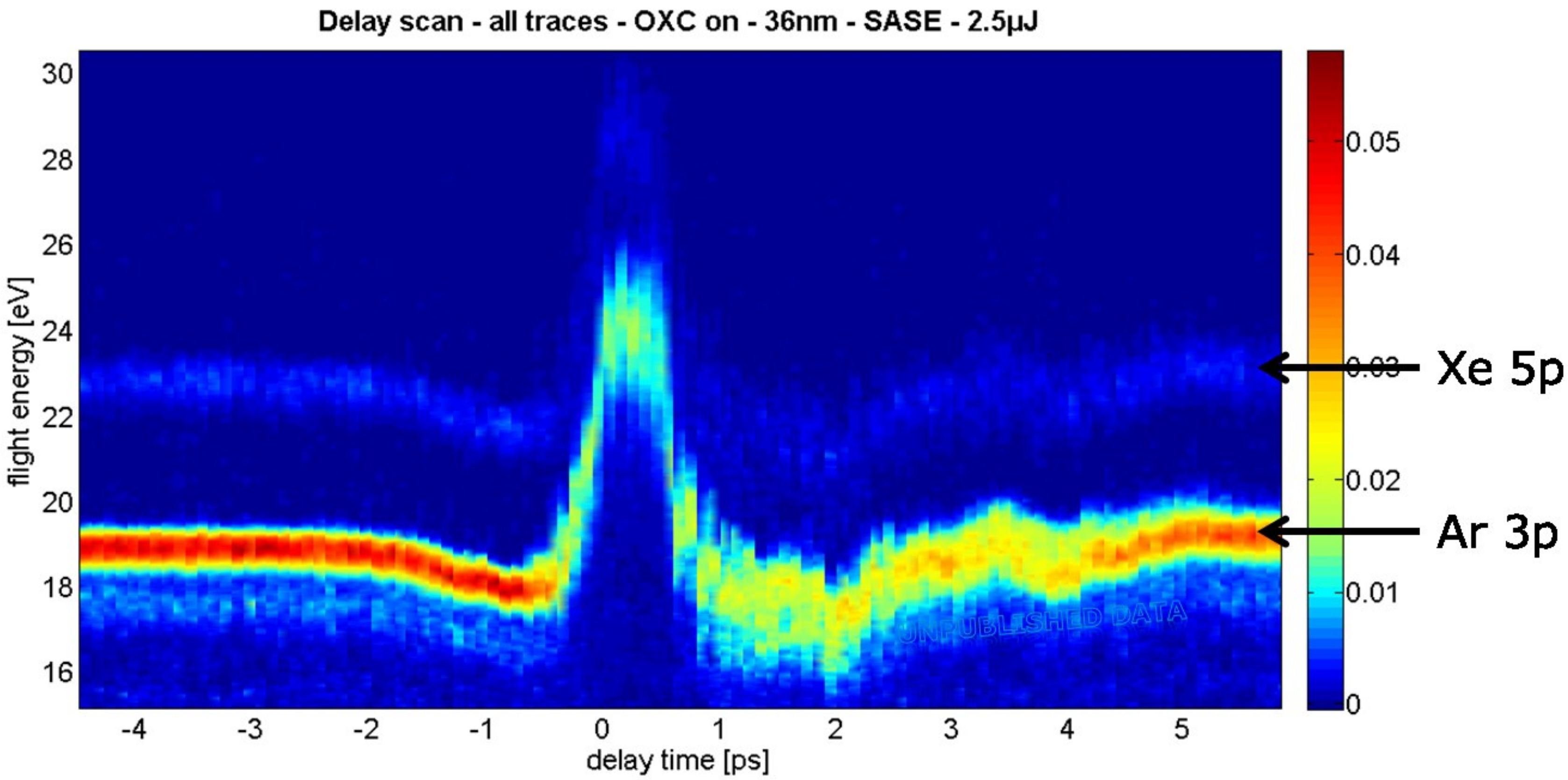
THz streaking – principle



THz streaking with SASE pulses (21.01.2017)



THz streaking with SASE pulses

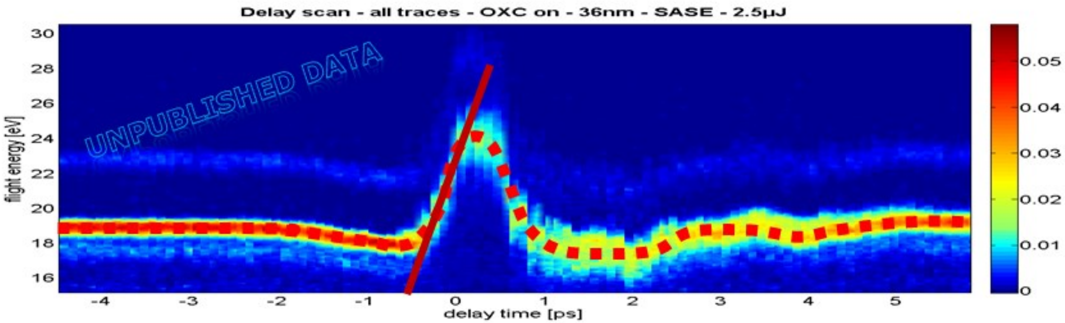


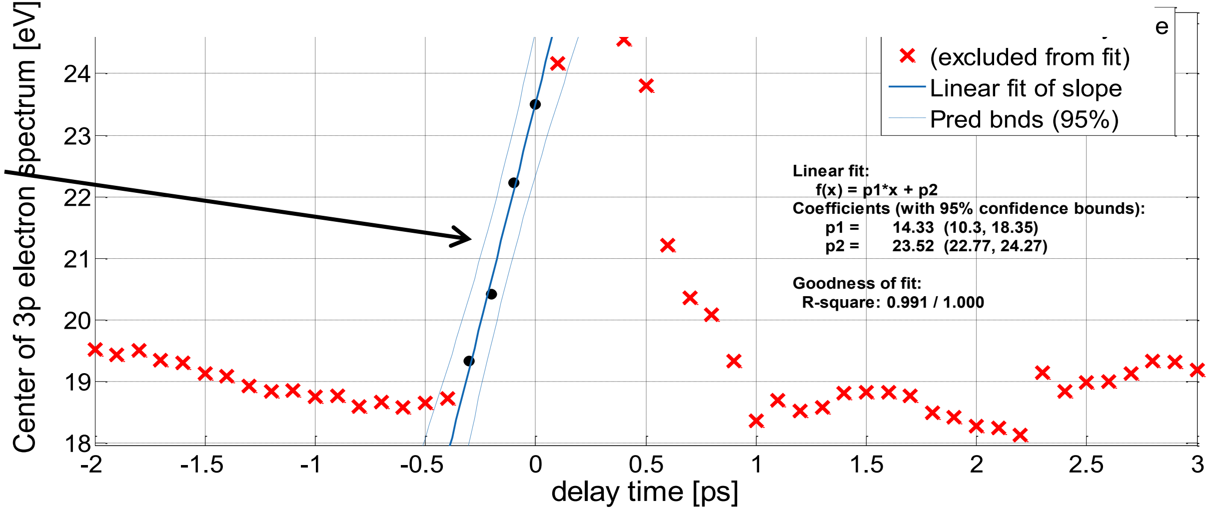
Averaged spectra: 15#/(50fs time bin)

THz streaking with SASE pulses

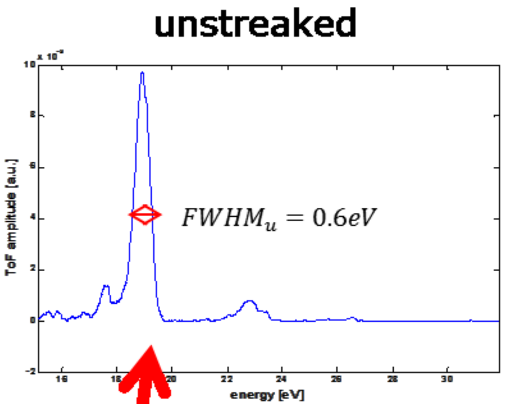
Slope of the streaking trace defines streaking speed.

max.streaking speed
s= 14.3 meV/fs



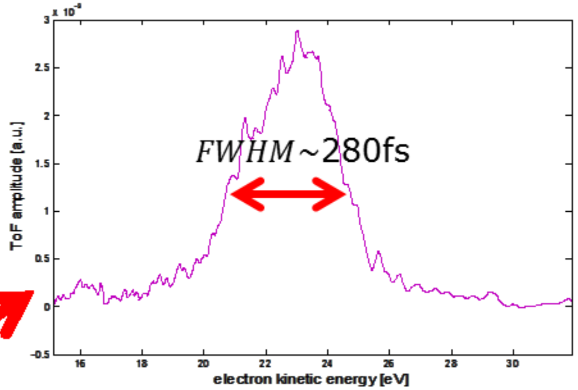


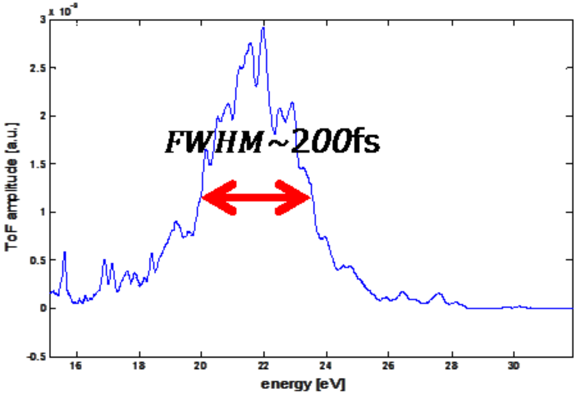
THz streaking with SASE pulses

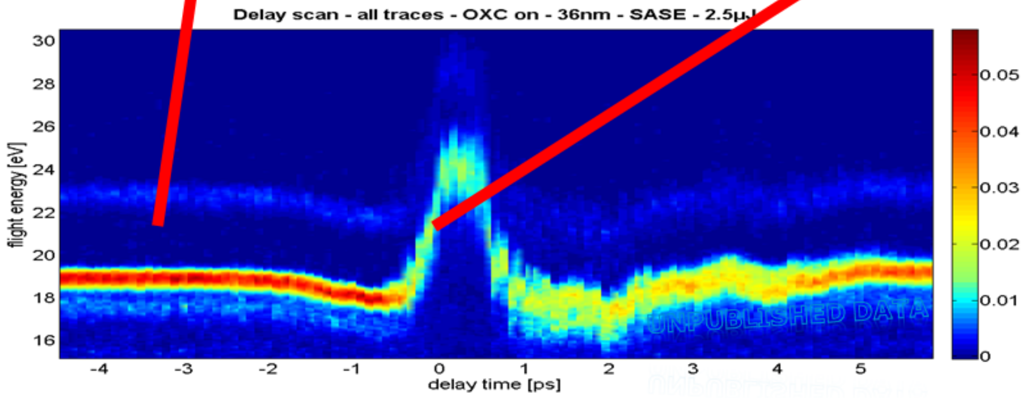


streaking speed
s= 14.3 meV/fs

$$\Delta t_{XUV} = \frac{\sqrt{\sigma_s{}^2 - \sigma_u{}^2}}{s}$$

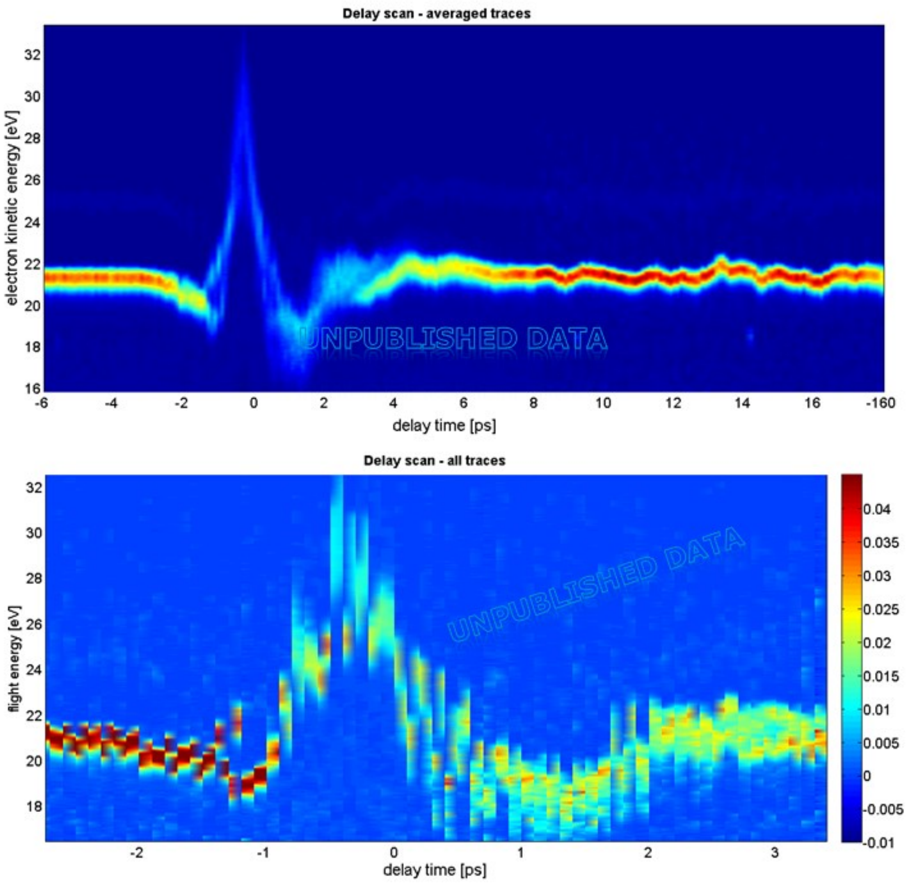






co...
I. Grguras et al, Nature Photonics 6, 852–857 (2012)

First THz streaking with seeded pulses (28.01.2017



Averaged delay scan

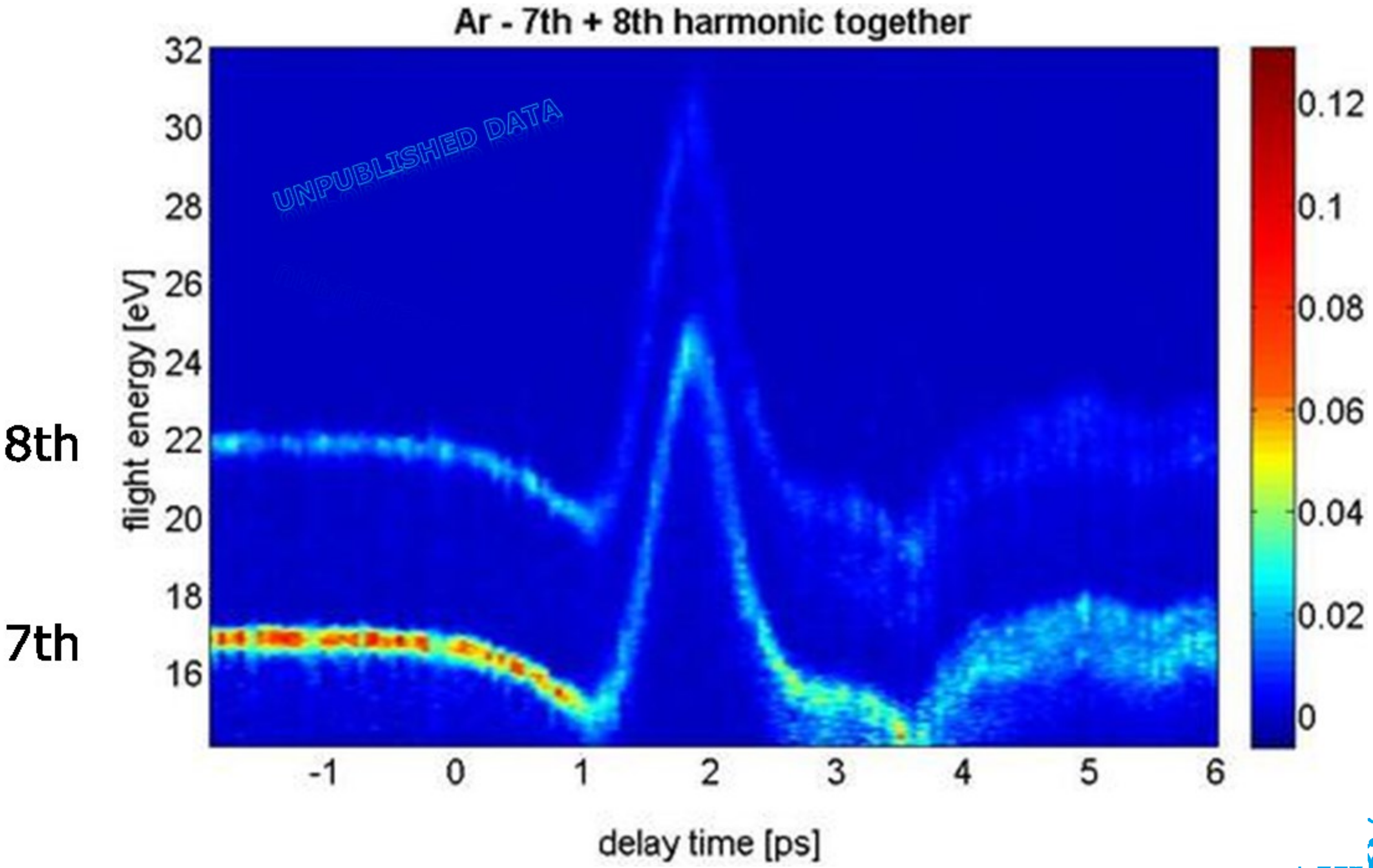
Single shot

Problems with climate system in 28g:
a motor induced vibrations, which affected the THz generation

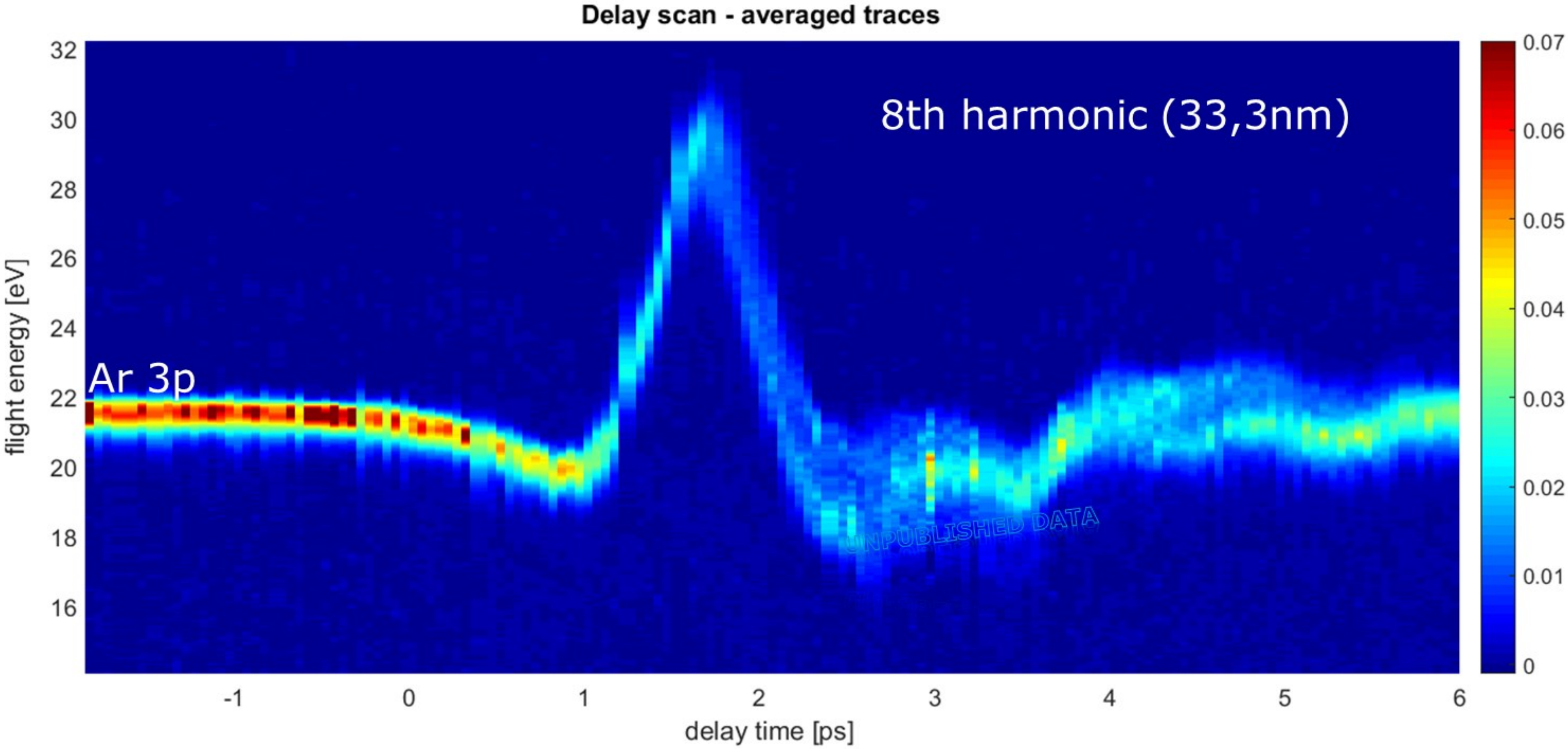
First THz streaking with seeded pulses with two colors

First 3 radiator to 7th and 4th radiator to 8th harmonic

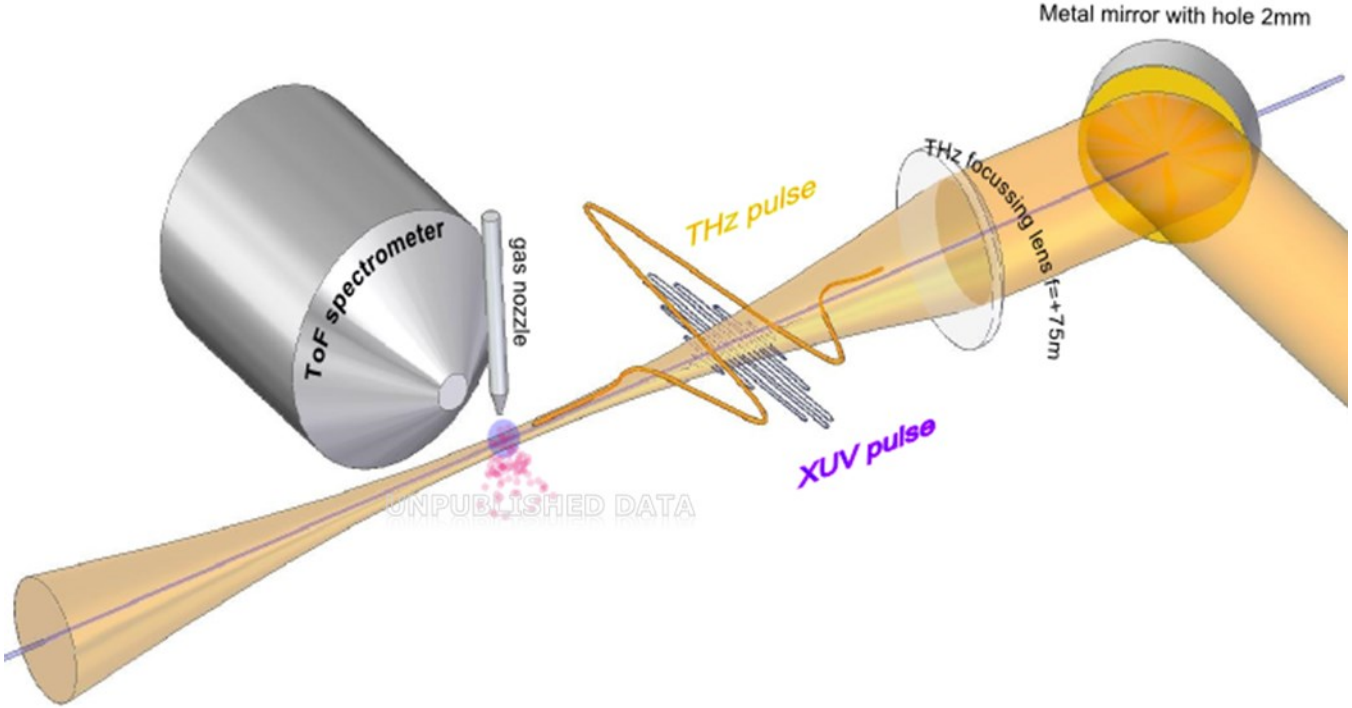
➔ 5µJ + 5µJ



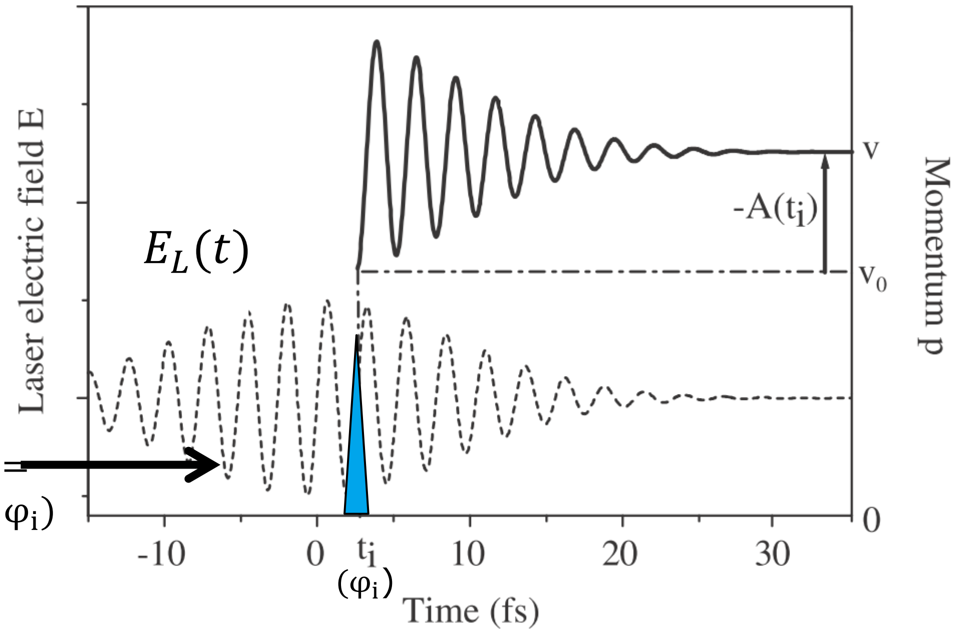
THz streaking with seeded pulses – 8th hamonic only (05.02.2017)



Streaking theory – semiclassical model



Streaking theory – semiclassical model



Extra momentum by the laser field.

$$\vec{p} = \vec{p}_0 + e\vec{A}(t_i)$$

$$\Delta\vec{p} = e\vec{A}(t_i) = e\int_{t_i}^{\infty} \vec{E}_L(t_i, t')dt'$$

$$\vec{E}_L(t) = \frac{\partial \vec{A}(t)}{\partial t}$$

(Slowly-varying envelope appr.)

$$E_L(t) = E_{THz}(t) = E_0(t)\cos(\omega_{THz}t + \varphi_i)$$

$$\varphi_i = \omega_{THz}t_i$$

Measurable quantity is the final electron kinetic energy W (and not the final momentum)

$$W(t_i) = \frac{\vec{p}^2}{2m} = \frac{\left(\vec{p}_0 + e\int_{t_i}^{\infty}\vec{E}_L\right)^2}{2m}$$

QUÉRÉ, MAIRESSE and ITATANI, Journal of modern optics, vol 52., 339-360, 2005

Streaking theory – semiclassical model

W is the energy modulation from the quiver field, which can be calculated analytically:

$$W = \frac{\vec{p}^2}{2m} = \frac{\left(\vec{p}_0 + e\int_{t_i}^{\infty} \vec{E}_L\right)^2}{2m} \text{ with } E_L(t) = E_{THz}(t) = E_{0,THz}(t)\cos(\omega_{THz}t + \varphi)$$

$$\Rightarrow \; W(t_i) = W_0 \pm \sqrt{8W_0 U_p(t_i)}\sin(\varphi_i)$$

Ponderomotive energy $\hbar\omega_{THz} \ll U_p(t) = \frac{e^2 E_{0,\mathrm{THz}}^2(t)}{4m_e\omega_{THz}^2} \ll W_0$ (!)

Unstreaked kinetic energy $W_0 = \frac{\overrightarrow{p_0}^2}{2m} = \hbar\omega_{XUV} - I_{pot} \gg 0$ (!!)

(Polarization of $\vec{E}_L$ parallel to $\vec{v}$ electrons)

ITATANI et. al., Physical Review Letters, vol 88, Nr. 17, 2002

Streaking theory – semiclassical model

Inserting $U_p(t) = \frac{e^2 E_{0,\mathrm{THz}}^2(t)}{4 m_e \omega_{THz}^2}$ into $W(t) = W_0 \pm \sqrt{8 W_0 U_p(t)} \sin(\omega_{THz} t)$

leads to $W(t) \approx W_0 \pm e\sqrt{\frac{2W_0}{m_e}} \frac{E_{0,\mathrm{THz}}(t)}{\omega_{THz}} \sin(\omega_{THz} t) = W_0 \pm e\sqrt{\frac{2W_0}{m_e}} A(t)$ *

➔ $$E_{THz}(t) = \frac{1}{e}\sqrt{\frac{m_e}{2W_0}}\, s(t)$$

, with streaking speed $s(t) = \frac{\partial W(t)}{\partial t}$

* Gulliemakis, et. al., SCIENCE , vol 305, 08/2004

Streaking theory – Gaussian pulse with linear chirp

- a quantum mechanical model assuming a linearly chirped XUV pulse

$$E_{XUV}(t) = E^0_{XUV} e^{-a(t-t_0)^2} e^{i(\omega_0(t-t_0)+c(t-t_0)^2)}$$

with the two unknown parameters chirp parameter c and pulse duration $\tau_{XUV} = \frac{1}{2\sqrt{a}}$ leads to the relation

$$\sigma_\pm = \sqrt{\sigma_0^2 + \tau_{XUV}^2 s_{eff}^2}$$

with effective streaking speed

$$s_{\mathrm{eff}} = \sqrt{s^2 \pm 4cs}$$

with the widths of the spectra $\sigma_\pm$ at each inflexion point of the streaking trace W(t).

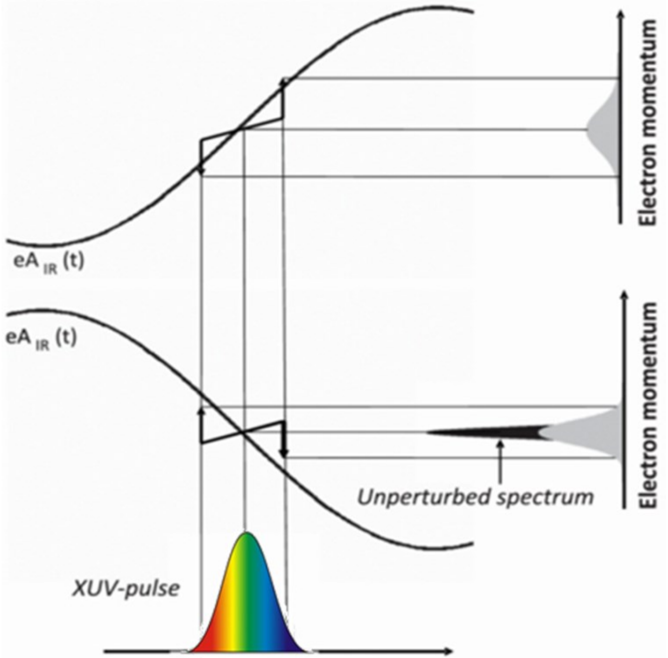
ITATANI et. al., Physical Review Letters, vol 88, Nr. 17, 2002

Streaking theory – Gaussian pulse with linear chirp

From the two formula $\sigma_{\pm} = \sqrt{\sigma_0^2 + \tau_{XUV}^2(s^2 \pm 4cs)}$ one obtains two equations to determine τ_{XUV} and chirp paramter c

$$\tau_{XUV} = \sqrt{\frac{\sigma_{+,decon}^2 + \sigma_{-,decon}^2}{2s^2}}$$

$$c = \frac{(\sigma_{+,decon}^2) - (\sigma_{-,decon}^2)}{8s\tau_{XUV}^2}$$



with the de-convoluted widths

$$\sigma_{\pm,decon} = \sqrt{\sigma_{\pm}^2 - \sigma_0^2}$$

Frühling, J. Phys. B: At. Mol. Opt. Phys.44 (2011)

Streaking theory – Temporal resolution

For the simple case of equal spectral widths $\sigma_+ = \sigma_-$ one obtains the intuitive formula

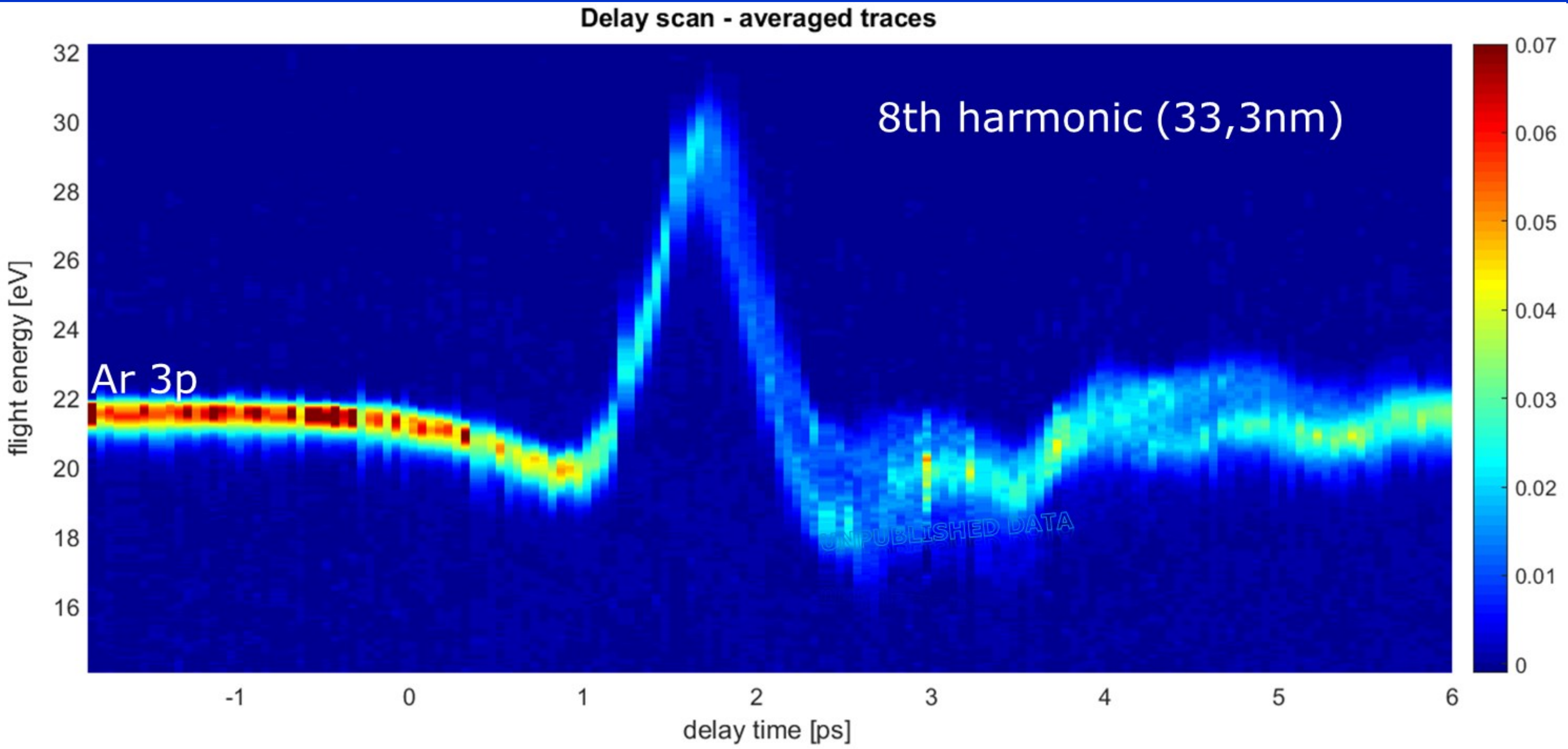
$$\tau_{XUV} = \sqrt{\frac{\sigma_{+,decon}^2 + \sigma_{-,decon}^2}{2s^2}} = \frac{\sigma_{decon}}{s}$$

, from which one obtains for the **temporal resolution** τ_{res} of the THz transient field streak camera with the unstreaked width σ_0 (as for every streak camera)

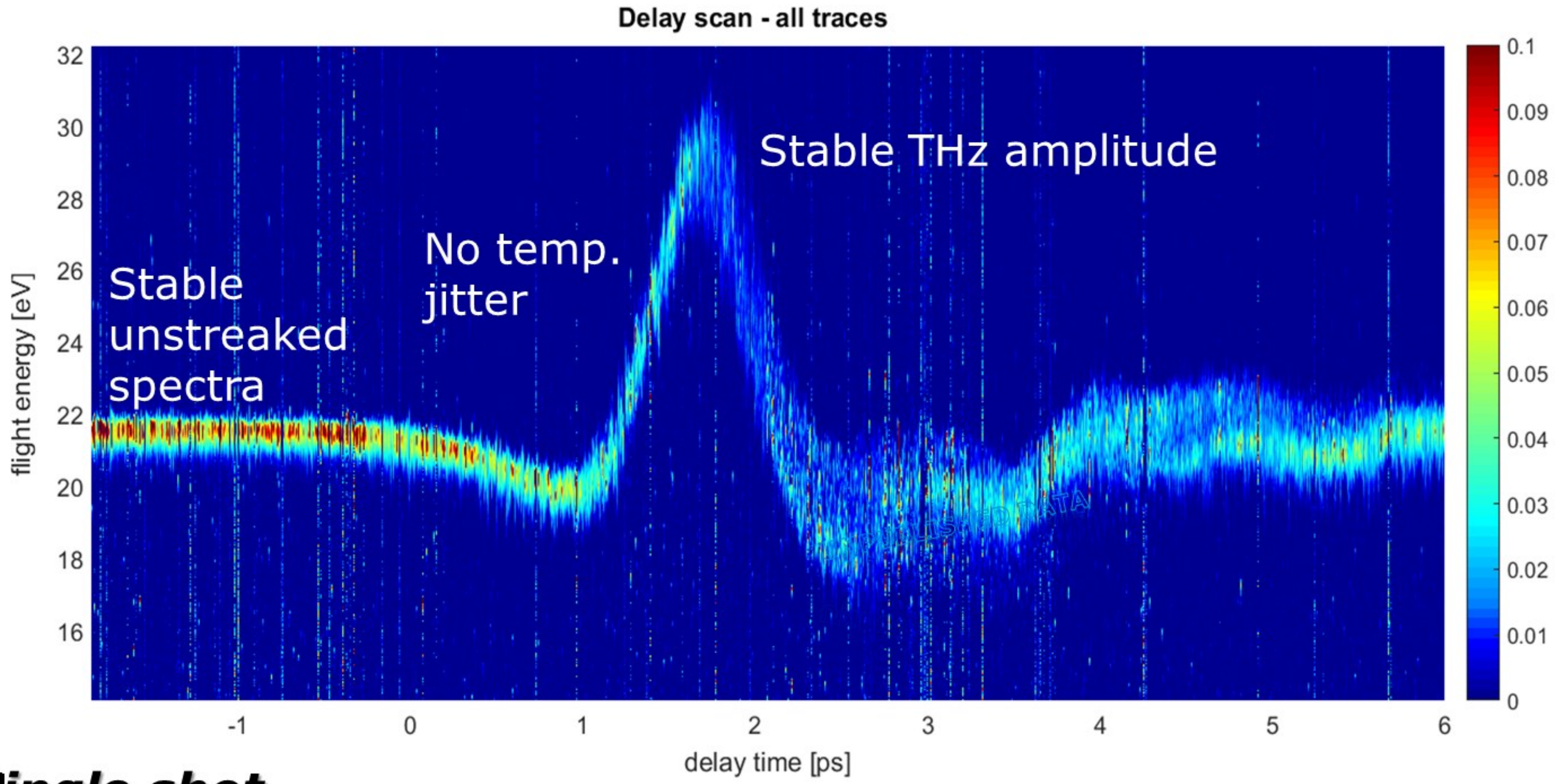
$$\boxed{\tau_{res} = \frac{\sigma_0}{s}}$$

Frühling, J. Phys. B: At. Mol. Opt. Phys.44 (2011)

Second try - THz streaking with seeded pulses – averaged data

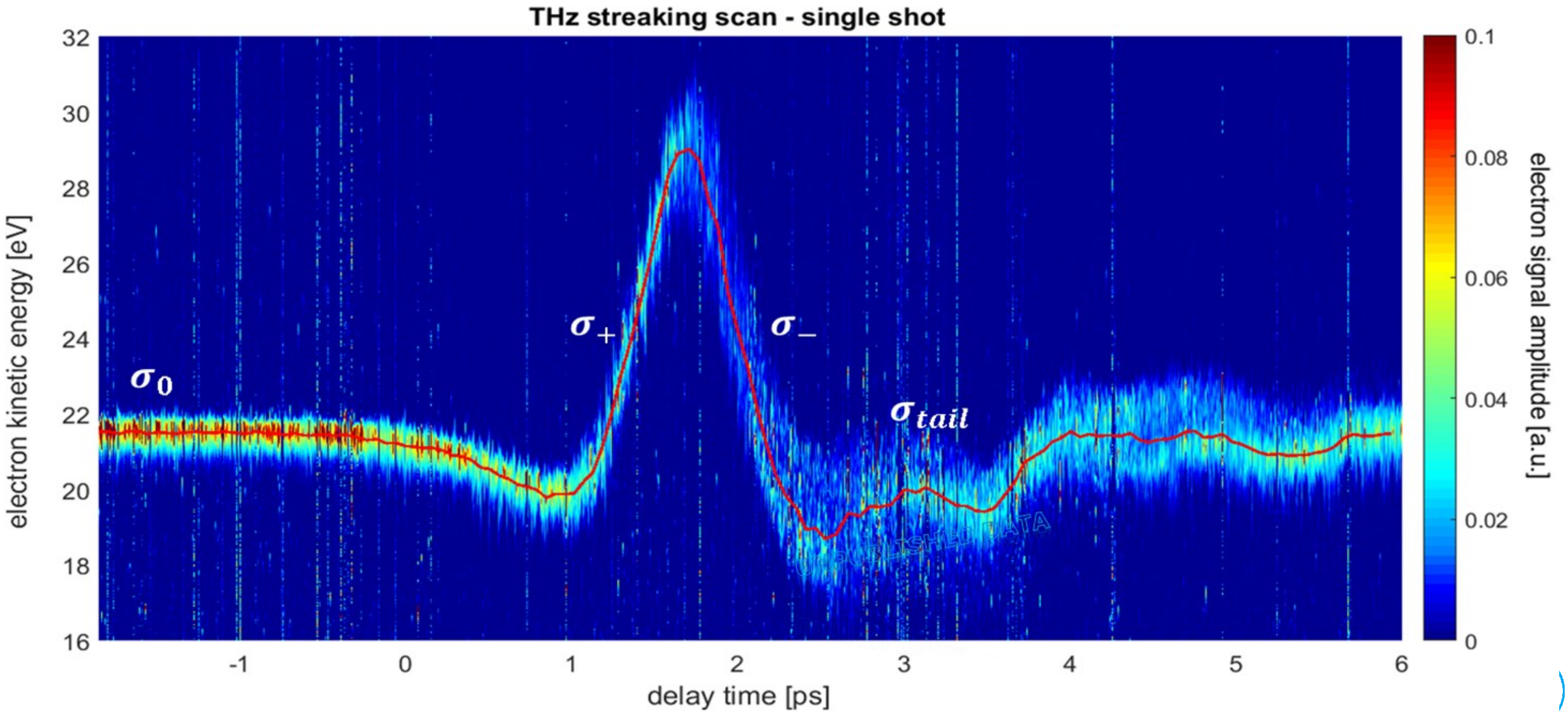


Second try - THz streaking with seeded pulses – single shot data

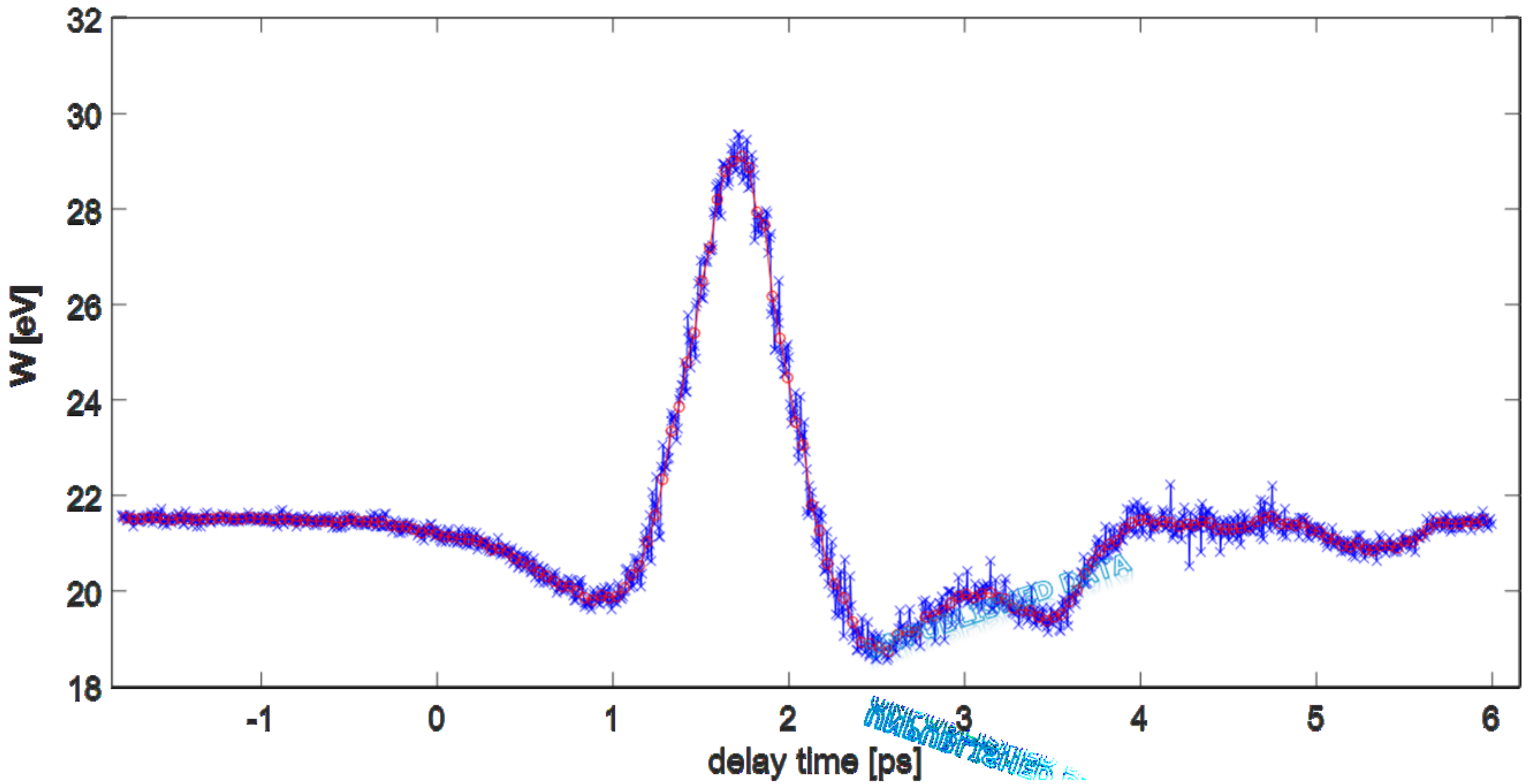


Single shot

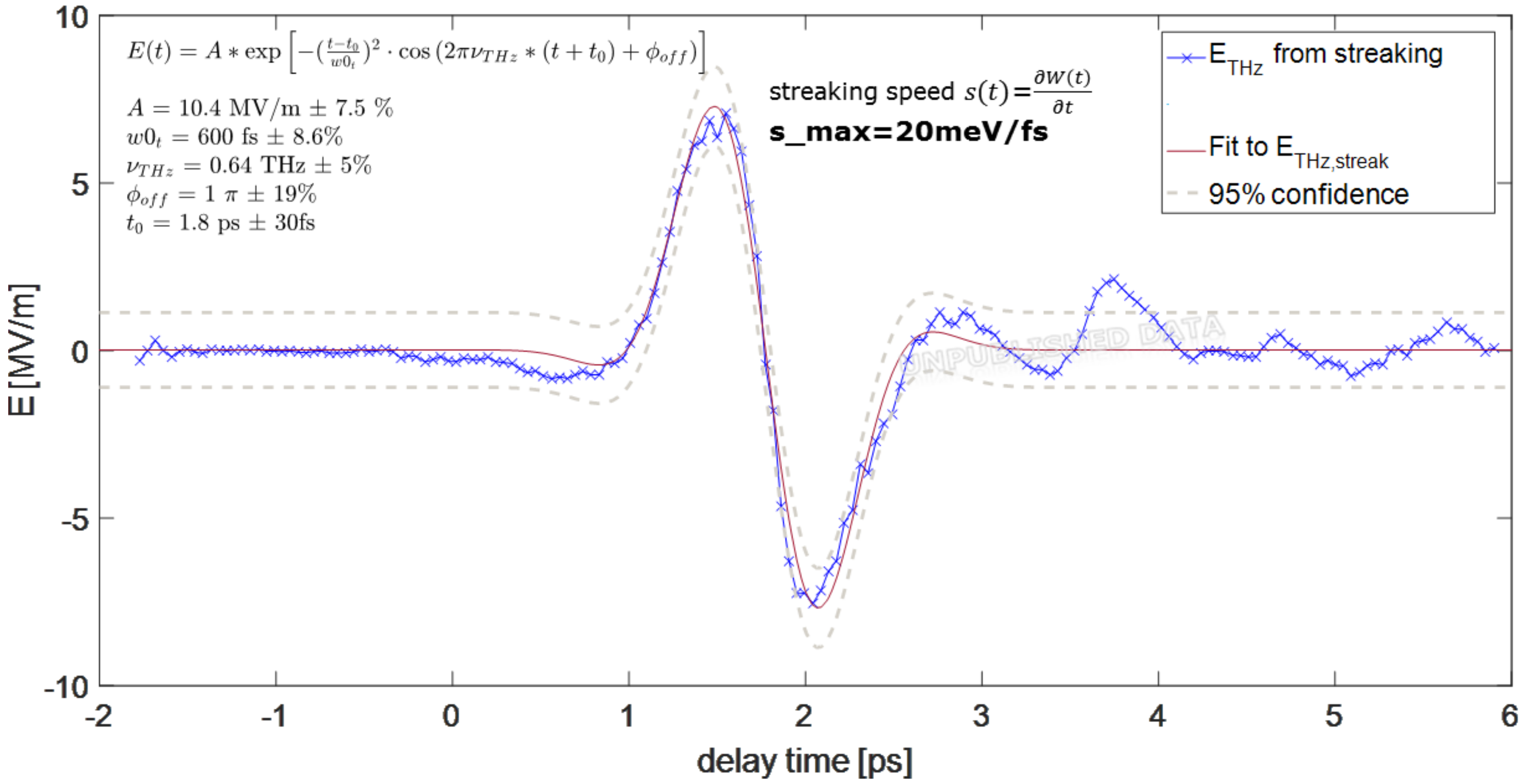
Second try - THz streaking with seeded pulses - definitions



The retrieved kinetic energy modulation W

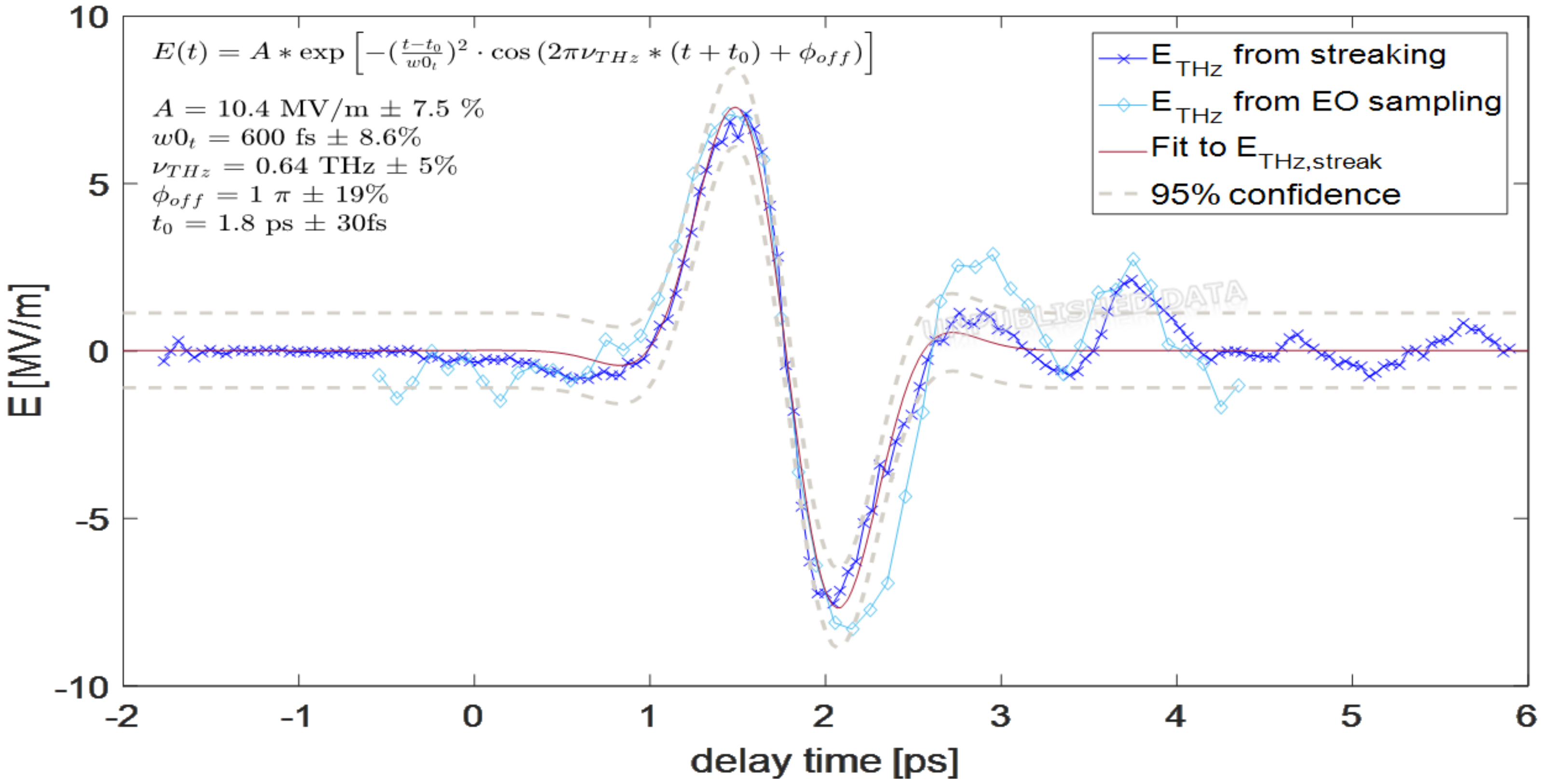


Derived electrical field of the THz pulse

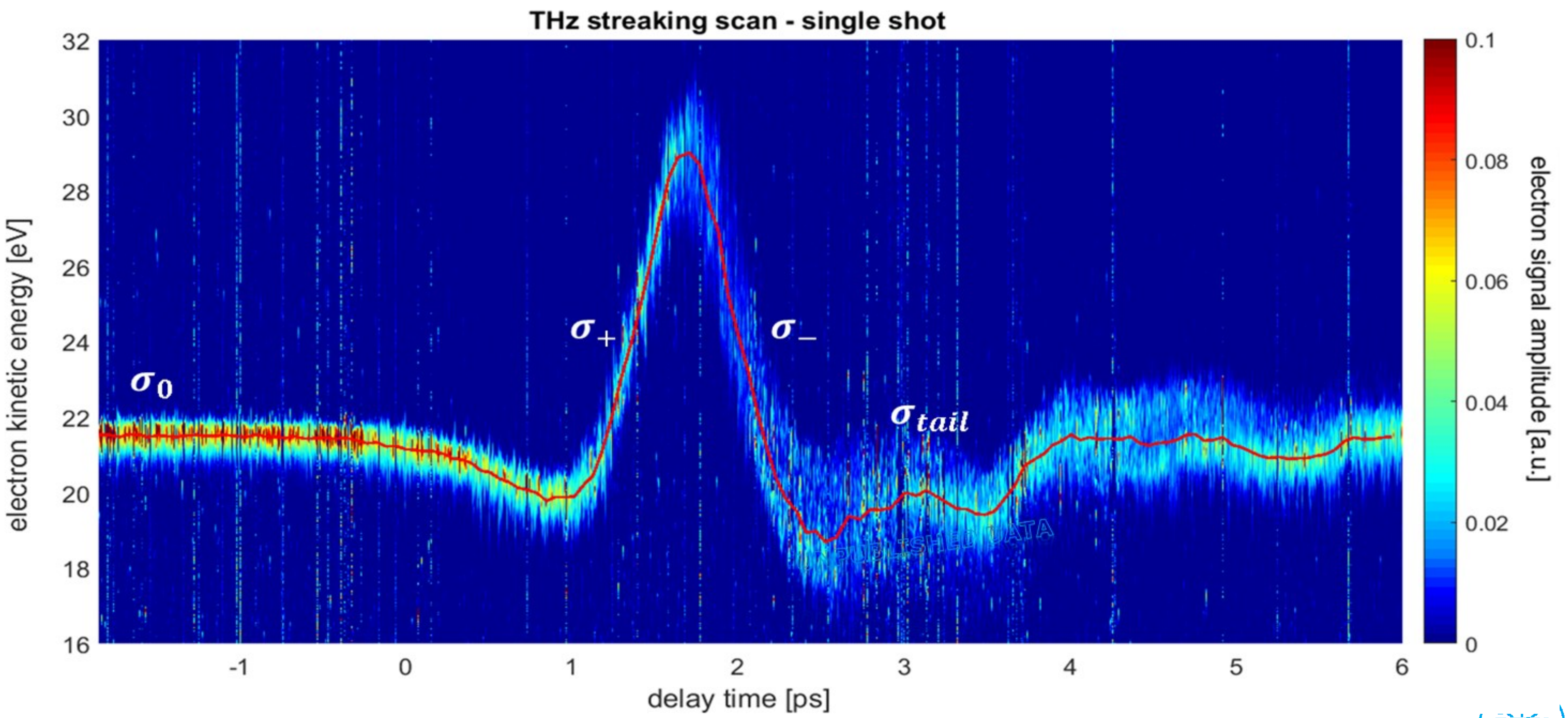


$$E_{THz}(t) = \frac{1}{e}\sqrt{\frac{m_e}{2W_0}}\frac{\partial W(t)}{\partial t}$$

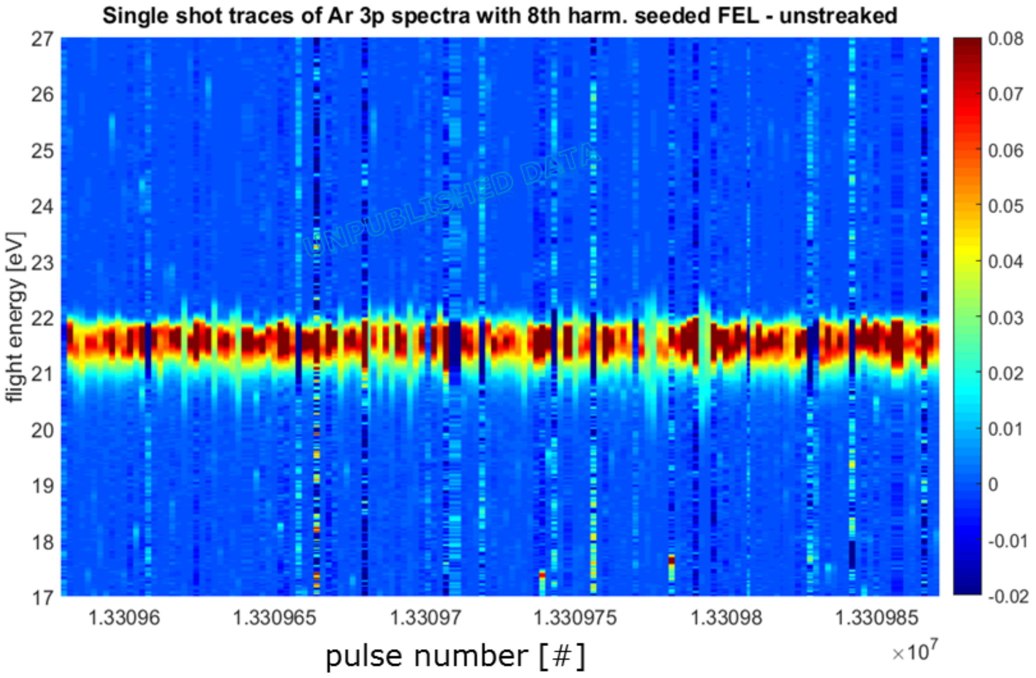
… with electro optical sampling

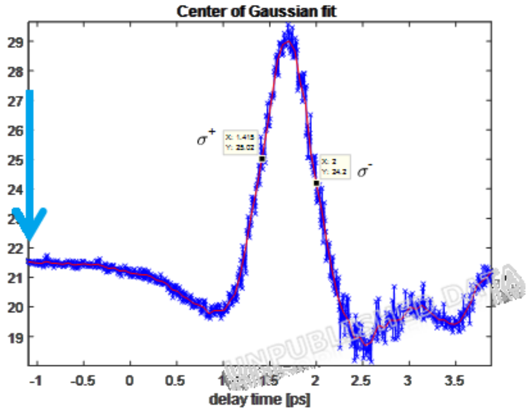


Second try - THz streaking with seeded pulses - definitions



Single shot analysis - σ_0





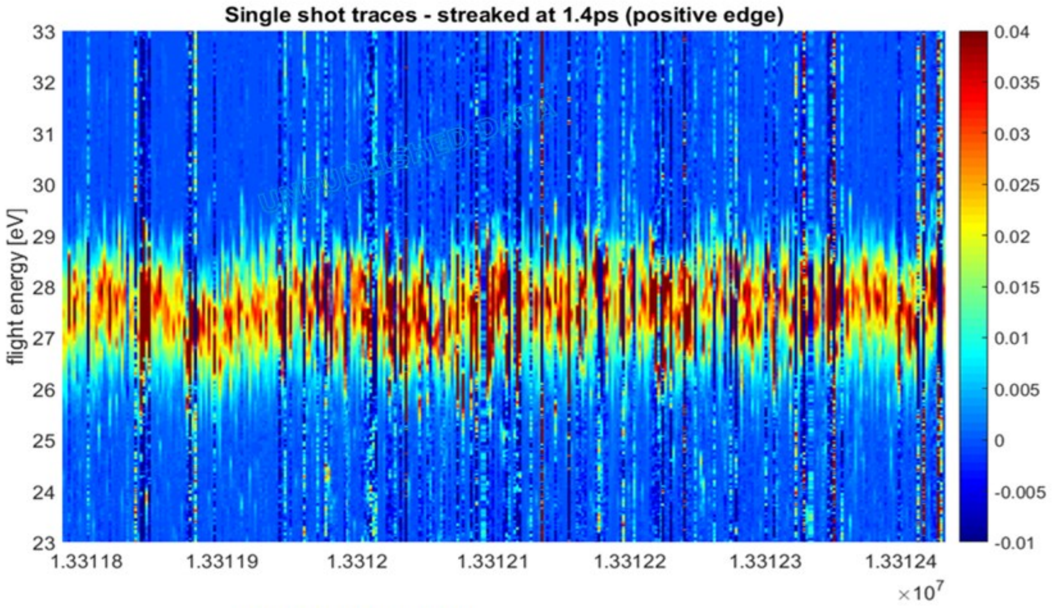
$$\tau_{res} = \frac{\sigma_0}{s}$$

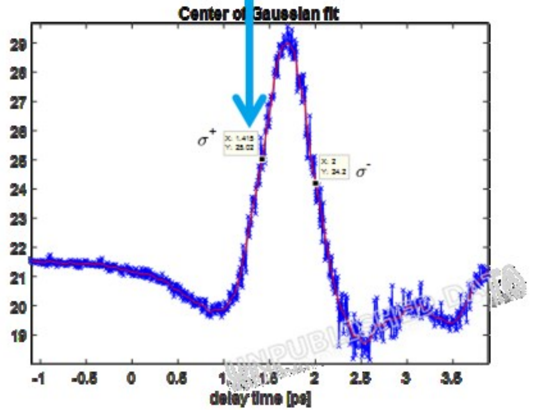
(s_max=20meV/fs)

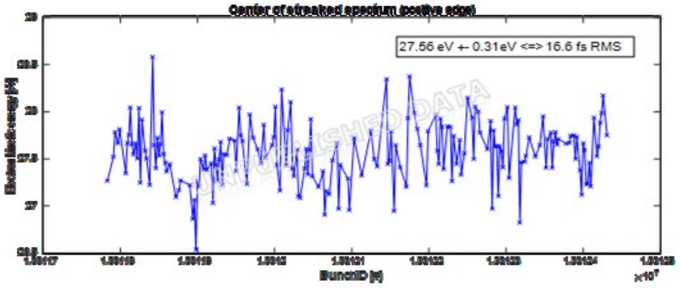
$\overline{\sigma_0}$=0.37eV ⇔ τ_{res}=19fs

$\bar{E}_{XUV}=(\overline{21.56}+15.75)$eV ± 0.12eV = 37.3eV ± 0.3%

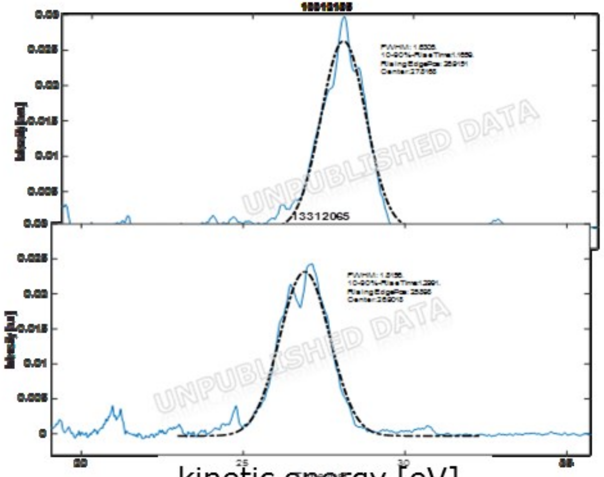
Single shot analysis - σ+



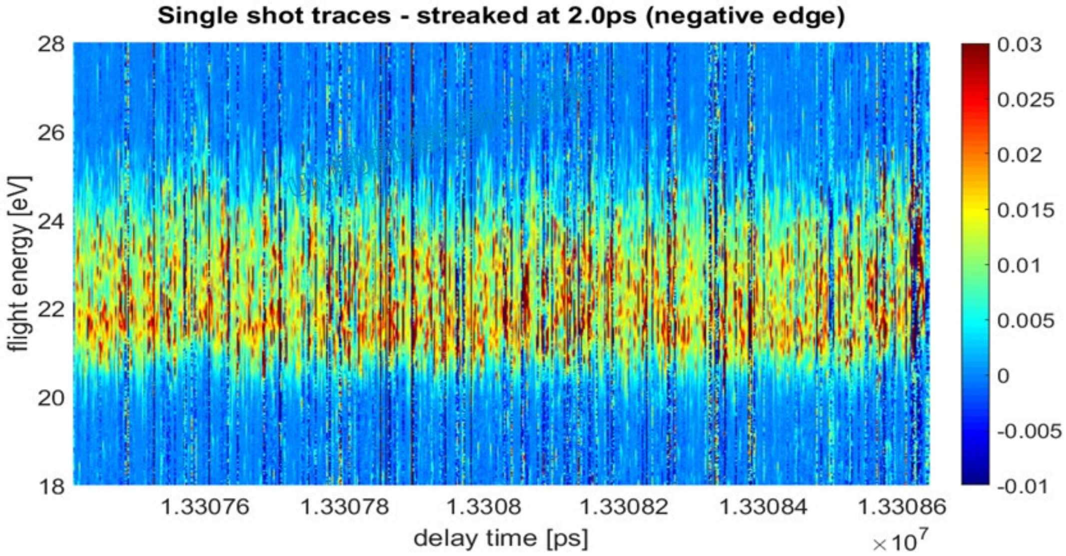


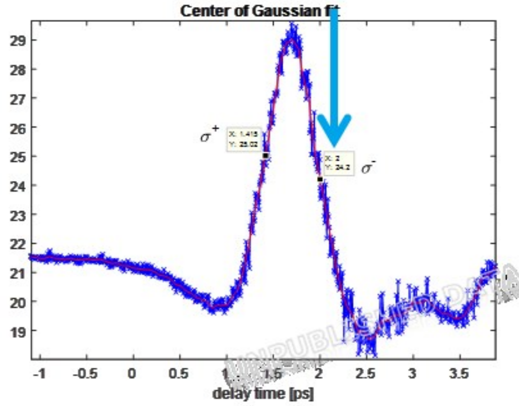


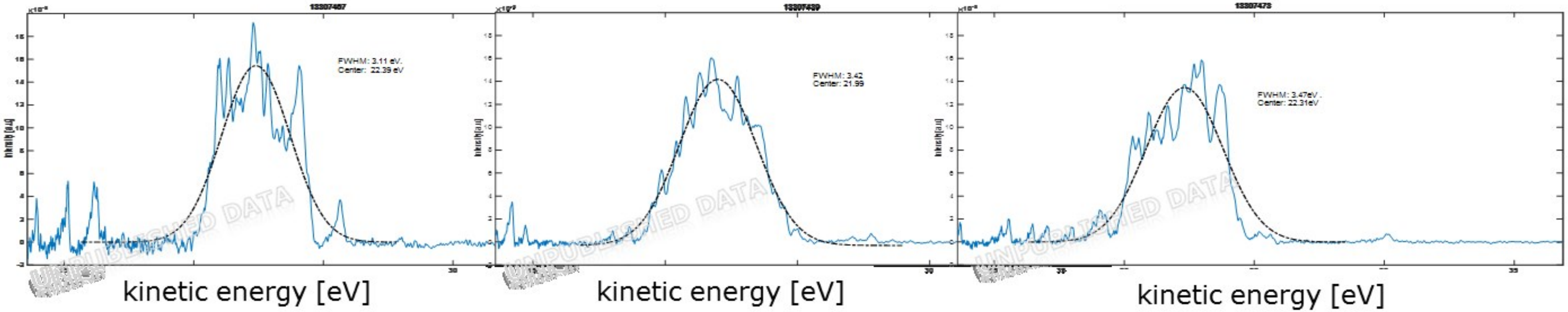
Temporal jitter: ~16fs RMS



Single shot analysis - σ_-

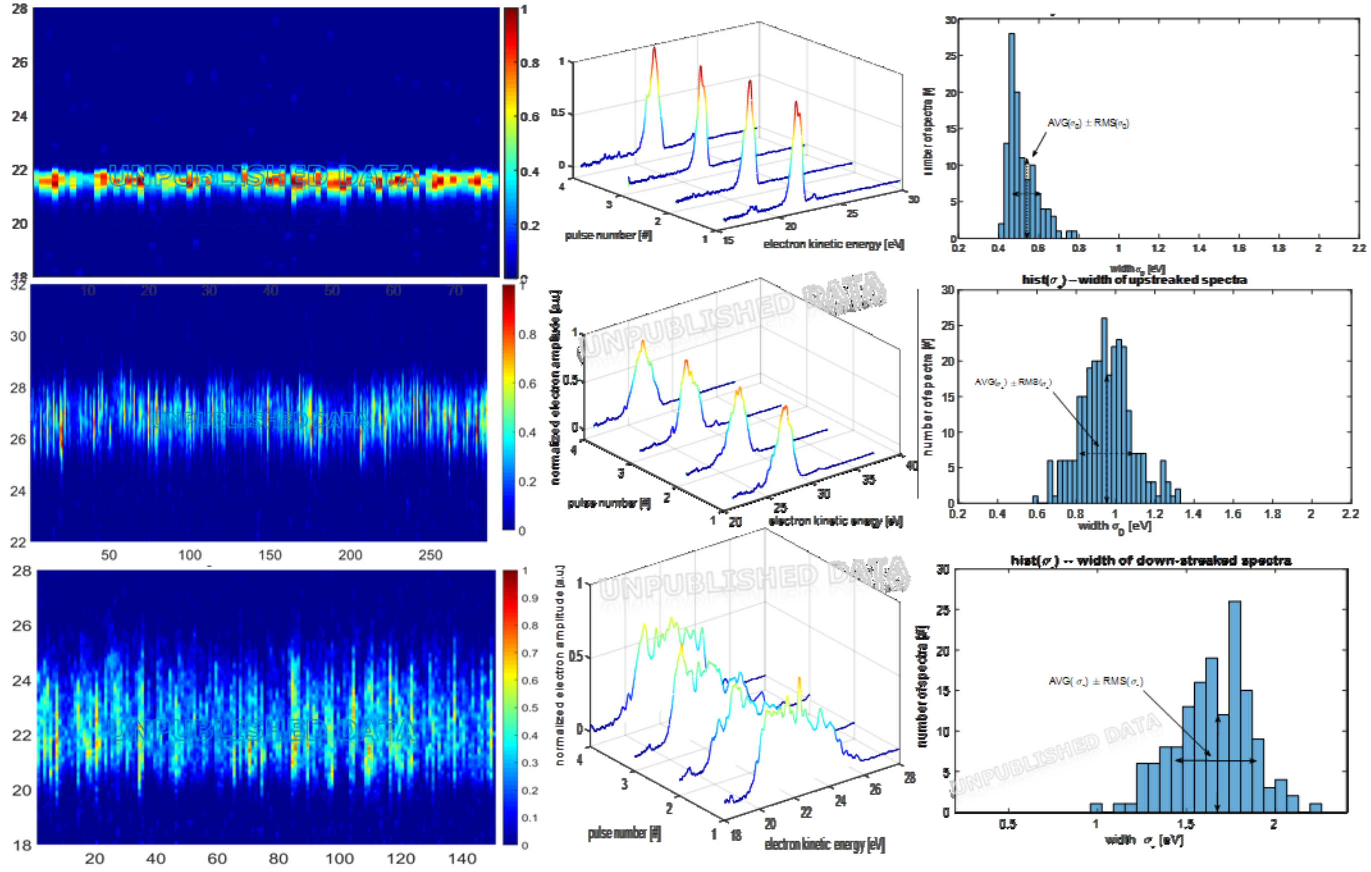






Single shot analysis – overview

All spectra of a series | **Single spectra** | **Histograms of the σ-widths**



$\sigma_0 = 0.37eV \pm 12\%$

$\sigma_+ = 0.95eV \pm 14\%$

$\sigma_- = 1.65eV \pm 13\%$

XUV pulse parameters from THz streak camera

$$\sigma_0 = 0.37eV \pm 12\%$$
$$\sigma_+ = 0.95eV \pm 14\%$$
$$\sigma_- = 1.65eV \pm 13\%$$

$$\sigma_{+,decon} = 0.87eV \pm 17\%$$
$$\sigma_{-,decon} = 1.61eV \pm 13.5\%$$

$$\boldsymbol{\tau_{XUV,RMS} = 64.6fs \pm 11\%}$$

$$\boldsymbol{c_{XUV} = -2.7\frac{meV}{fs} \pm 46\%}$$
$$\boldsymbol{= -2.3\frac{nm}{ps}}$$

$$\tau_{XUV} = \sqrt{\frac{\sigma^2_{+,decon} + \sigma^2_{-,decon}}{2s^2}}$$

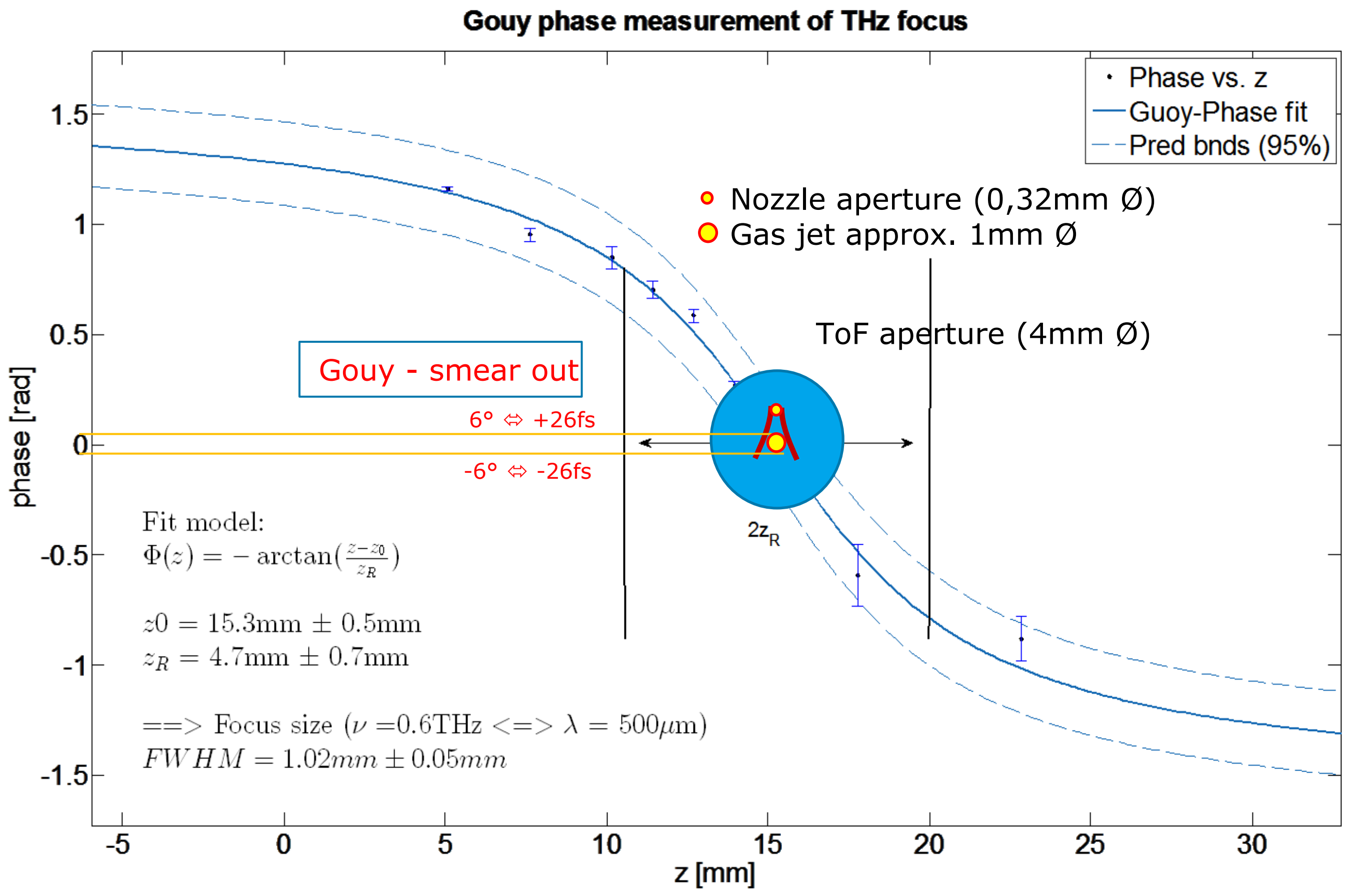
$$c = \frac{(\sigma^2_{+,decon}) - (\sigma^2_{-,decon})}{8s\tau^2_{XUV}}$$

Conclusions

1. Even with only one time-of-flight detector it is possible to determine the pulse duration of a single pulse with ~10% uncertainty !

2. The chirp is negative ⇔ anomalous dispersion or logic error ?

Influence of the Guoy phase shift



$$E(t) = A * \exp\left[-(\frac{t-t_0}{w0_t})^2 \cdot \cos(2\pi\nu_{THz} * (t+t_0) + \phi_{off})\right]$$

$A = 10.4$ MV/m $\pm$ 7.5 %
$w0_t = 600$ fs $\pm$ 8.6%
$\nu_{THz} = 0.64$ THz $\pm$ 5%
$\phi_{off} = 1\ \pi \pm 19\%$
$t_0 = 1.8$ ps $\pm$ 30fs

Compensate the spectral Guoy broadening

$$\sigma_{\pm,real} = \sqrt{\sigma^2_{\pm,meas} - s^2 * \tau^2_{Guoy}}$$

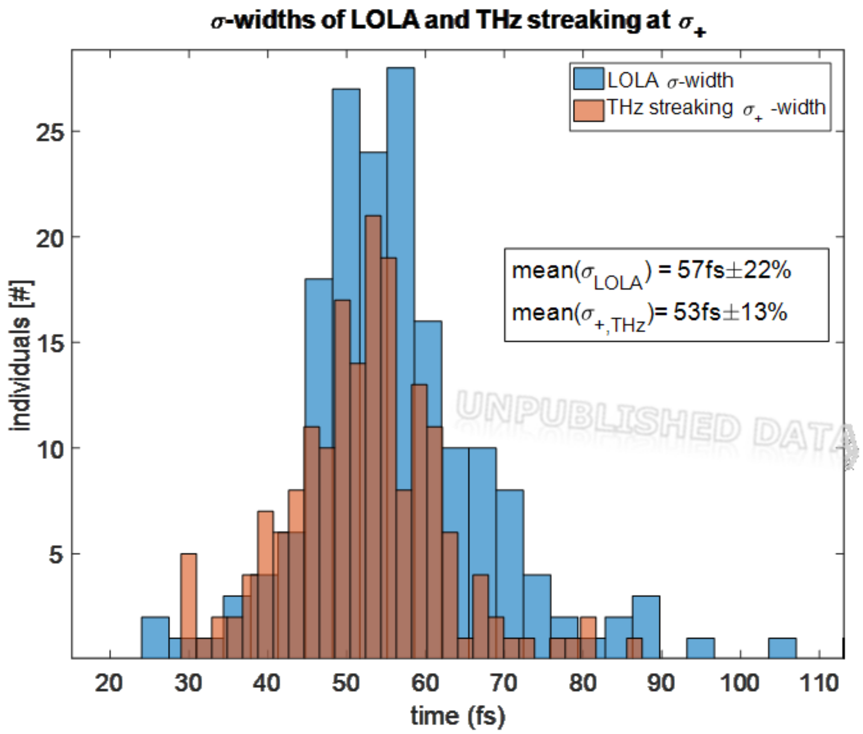
➔

$$\boldsymbol{\tau_{XUV,RMS} = 59fs \pm 11\%}$$
$$\boldsymbol{\tau_{XUV,FWHM} = 138fs}$$

$$\boldsymbol{c_{XUV} = -3.2\frac{meV}{fs} \pm 46\%}$$

Comparison with TDS measurement on electron bunch

- Last seminar we presented a method how to estimate the XUV light pulse duration from a TDS electron bunch energy streak trace.



TDS: $\tau_{XUV,RMS} = 57fs \pm 22\%$

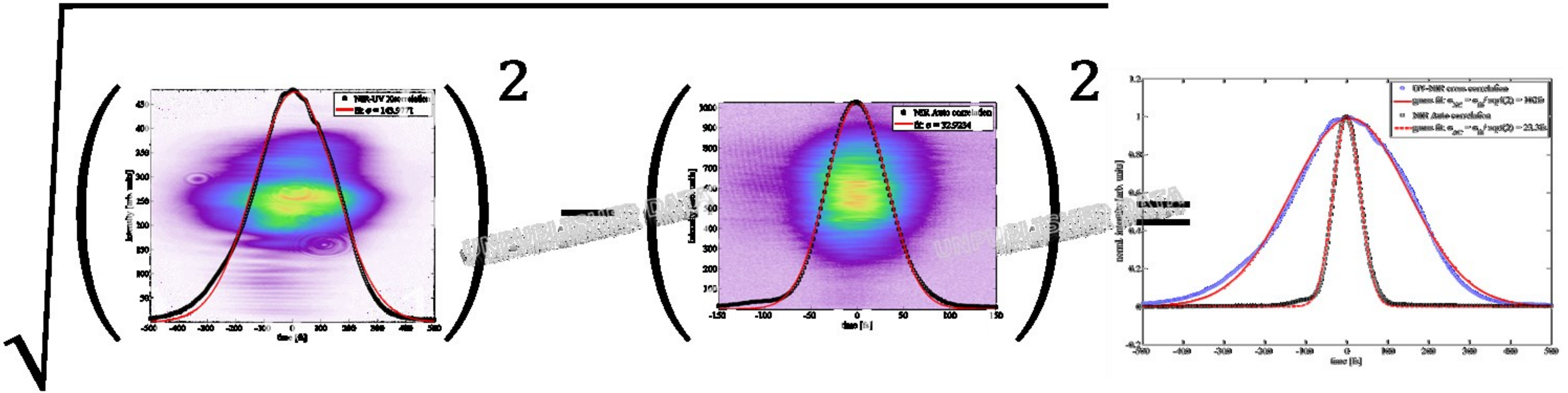
THz: $\tau_{XUV,RMS} = 59fs \pm 12\%$

A direct comparison of the widths histograms shows comparability of both measurement methods.

(But a single shot correlation didn‵t succeed)

The optical seed pulse

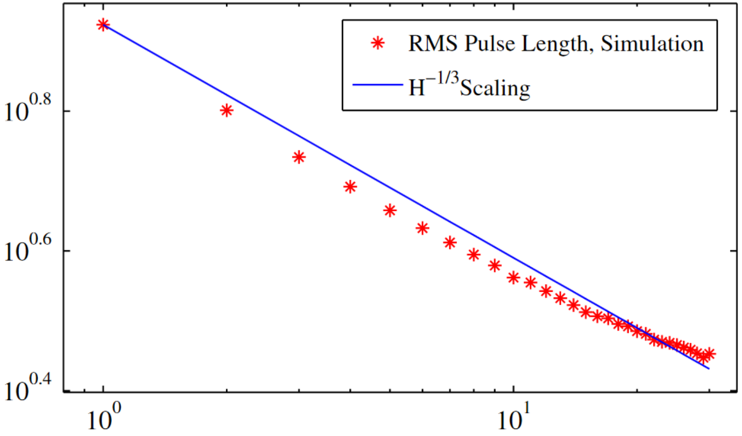
- We have established a pulse duration measurement (Mehdi Kazemi) to measure the temporal duration of the 266nm seed pulse using a single-shot line DFG cross-correlation setup.

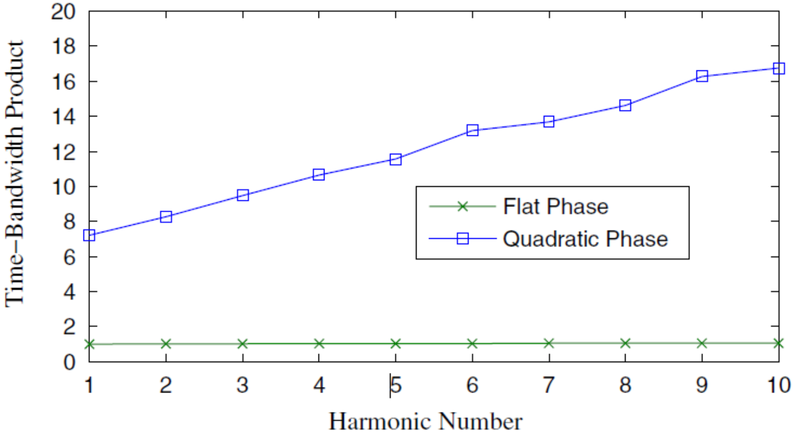


$$\sqrt{\left(\frac{142fs}{\sqrt{2}}\right)^2 - \left(\frac{32fs}{\sqrt{2}}\right)^2} = 99fs\ RMS \pm 10\% \ \equiv 234fs\ FWHM > 140fs\ FWHM\ (TDS\ and\ THz)$$

$(Fourier\ limit\!:\ 60fs\ FWHM)$ ➔ strong chirp !

Test of theory on pulse properties of HGHG seeded pulses





Ratner, Stupakov, et.al., PhysRevSTAB, 15, 030702 (2012)

For 8th Harmonic

$$\tau_{XUV,FEL} = 0.93 * (8)^{-\frac{1}{3}} * \tau_{optical}$$
$$= 0.47 * \tau_{266nm}$$
$$= 0.47 * 234\text{fs FWHM}$$
$$= 110\text{fs FWHM}$$
$$< 135\text{fs FWHM}$$ ***(TDS,THz)***

Does this plot means, that HGHG works as a chirp enhancer ?

Test theory by inducing chirp in a controlled way in the optical seeder and measure chirp c of FEL !

Outlook

- Upgrade THz streak camera with 2 more ToF‘s to measure each $\sigma_{\pm,0}$ on single shot basis and try to test single shot correlation with TDS again
  (although the pulse-to-pulse fluctuation of the seeded FEL pulse duration are already small)
- Test the chirp measurement by implementing chirp (finite glass plates) in the optical seeder and measure the chirp rate c via THz streaking and compare the result with HGHG theory by Rattner/Stupakov.

➔ opens the path way to phase controlled XUV FEL pulses !

Summary

- A THz streak camera has been implemented and comissioned for a seeded FEL pulse **(first time in the world !).**
- The THz diagnostic has measured the pulse properties of
  - SASE XUV pulses
  - seeded XUV pulses
  - measured with simultaneous two color emission of sFLASH
- Evidence for a linear chirp of a seeded FEL has been found **(first time in the world)!**
- The simultaneous average pulse duration of sFLASH measured with THz streaking and the TDS-energy-drop showed similar values.

Thank you for your attention !