A New Electro-Optic Detection Scheme for Recording Electron Bunch Shapes With High Resolution and Record Recording Length

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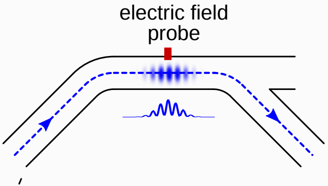
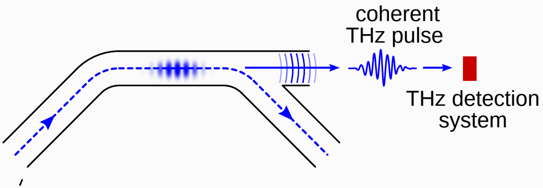
How to record the electron bunch temporal profile and/or THz radiation ?

→ probe its electric field...

... in the near-field (NF)



... or in the far-field (FF)



- ☺/☹ crystal near the e- bunch
  - ☺ "very direct" measurement, access to the whole e-field
  - ☺ intense electric field

- ☺ detection far from the e- bunch
- ☺/☹ "high-pass" filter, only access to fast-evolving component
- ☹ less intense field (V-kV/cm)

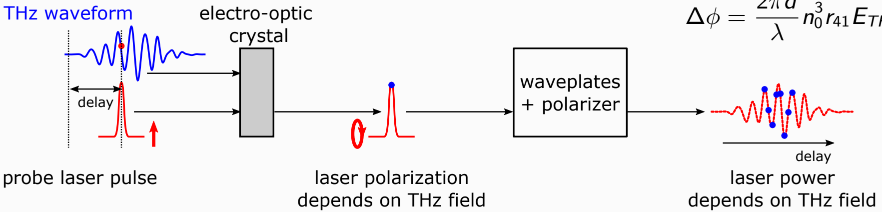
In both cases, need for:

(1) 100's fs resolution; (2) single-shot; (3) MHz+ acquisition rate

Electro-optic sampling of electric field: principle

Simple cross-correlation of the THz and optical pulses based on the **Pockels effect**:

- An external electric field modifies the refractive indexes of a birefringent crystal (EO crystal).
- The THz-induced birefringence is probed using a laser pulse.
- ▷ Multi-THz bandwidth obtained: limited by crystal speed and laser pulse duration.



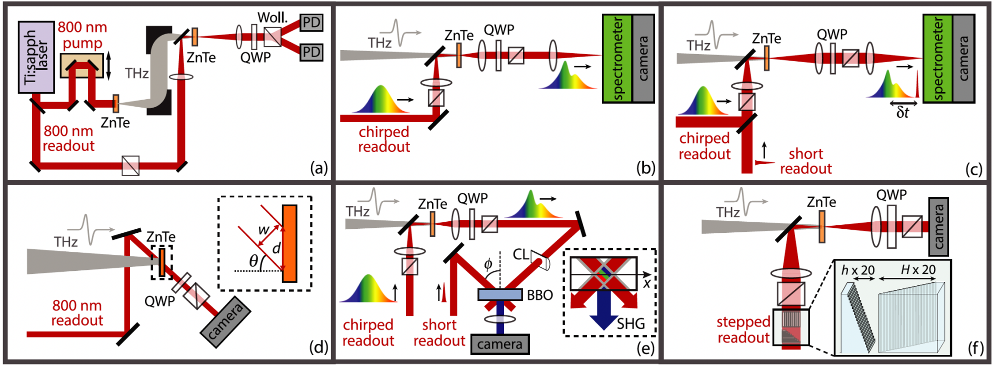
$$\Delta\phi = \frac{2\pi d}{\lambda} n_0^3 r_{41} E_{THz}$$

Free-propagating THz pulses (Time-domain spectroscopy, TDS): [Q. Wu & X.-C. Zhang, Appl. Phys. Lett. **67** (24), (1995)]
Scanned EO in accelerators: [Wilke et al., Phys. Rev. Lett. 88, 124801 (2002)], [Katayama et al., App. Phys. Lett. 100, 111112 (2012)]

Single-shot recording ?

Various strategies:

- time-to-space conversion,
- time-to-angle conversion,
- time-to-wavelength conversion.



[S. M. Teo, B. K. Ofori-Okai, C. A. Werley, K. A. Nelson, Rev. Sci. Instrum. **86**, 051301 (2015)]

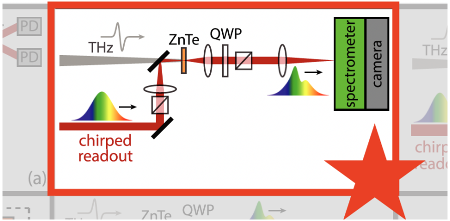
Single-shot recording ? → using chirped laser pulses

Various strategies:

- ~~time-to-space conversion,~~
- ~~time-to-angle conversion,~~
- **time-to-wavelength conversion.**

Potential applications:

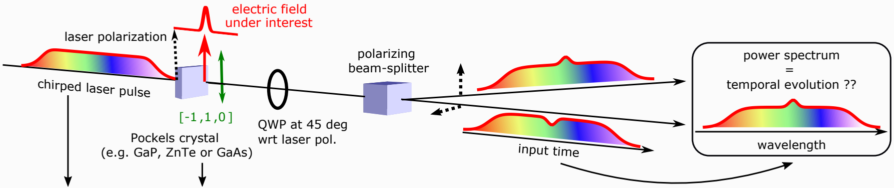
- **Monitoring non-repetitive phenomena**, e.g. in accelerators
- **Time Domain Spectroscopy** in situations where scanning is unpractical (low-rep. rate source, fast irreversible processes)



First demonstration using OSA readout: [Z. Jiang & X.-C. Zhang, Appl. Phys. Lett., **72**, 1945 (1998)]
Applications in accelerators: [Müller et al., Phys. Rev. ST Accel. Beams 15, 070701 (2012)], [Hiller et al., IPAC'13, p. 500 (2013)]
MHz+ acquisition rate with photonic time-stretch readout: [Roussel, et al., Sci Rep **5**, 10330 (2015)], [Bielawski, et al., Sci Rep **9**, 10391 (2019)]

(20-year-old) Temporal resolution issue: the “time × bandwidth” limit (1)

Time-resolution limitation (20-year-old problem) [Sun, Jiang & Zhang, Appl. Phys. Lett. **73**, 2233 (1998)]



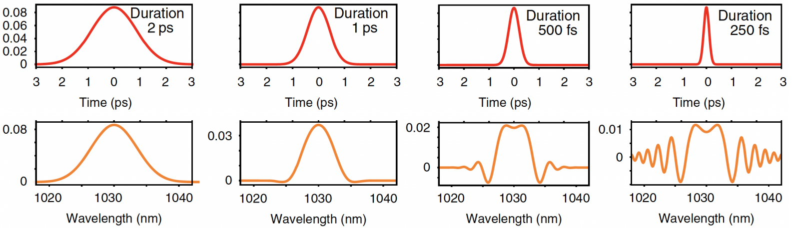
Laser contribution to resolution: ~few tens of fs

Crystal bandwidth: many THz

naive picture.... --> major limitation to temporal resolution !

Input THz signal. (phase shift in the crystal, in radians)

Measured OSA signal (after background subtraction and normalization, arb. unit)

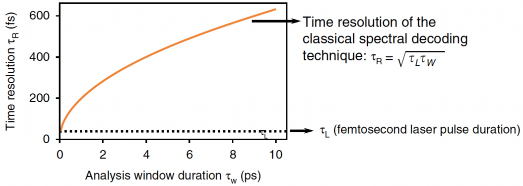


Temporal resolution issue: the "time × bandwidth" limit (2)

Time-resolution (assuming an infinitely fast crystal) [Sun, Jiang & Zhang, Appl. Phys. Lett. **73**, 2233 (1998)]

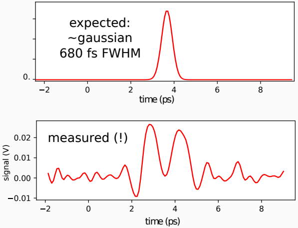
$$\tau = \sqrt{t_{laser} \times t_{window}}$$

Example: $t_{laser} = 100\ fs$, $t_{window} = 10\ ps$ $\rightarrow \tau = 1\ ps \gg t_{laser}$ ☹

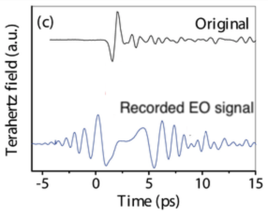


Examples of temporal resolution issue

- **at short timescales** e.g. e-bunch near field at EuXFEL

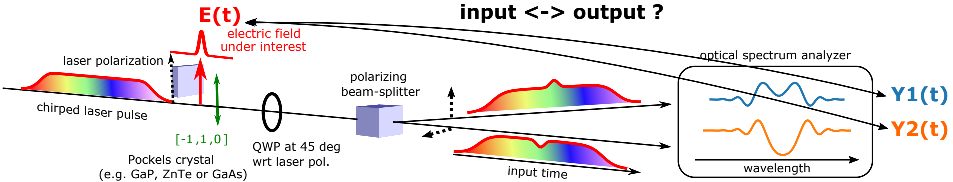


- **for long observation windows** e.g. TDS



[Murakami, doi: 10.5772/67195 (2017)]

A new point of view: calculation of Fourier-domain transfer functions



Derivation of the transfer functions

$$\text{Input field} \quad E(t) \quad \leftrightarrows \quad \tilde{E}(\Omega)$$

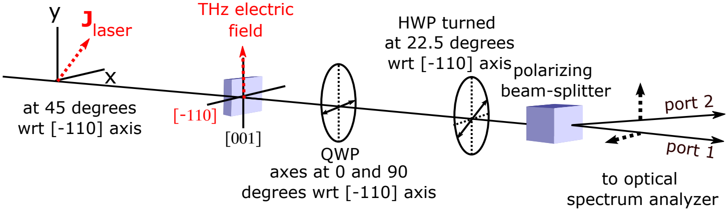
$$\text{Measurements} \quad Y_{1,2}(t) \quad \leftrightarrows \quad \tilde{Y_{1,2}}(\Omega) \approx H_{1,2}(\Omega) \times \tilde{E}(\Omega)$$

with $H_{1,2}(\Omega) = h_{1,2} \cos\left(B\Omega^2 + \phi_{1,2}\right)$, the transfer functions !

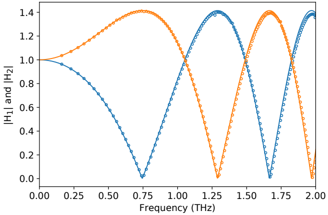
$h_{1,2}$, $\phi_{1,2}$ depend on the crystal and waveplates orientation, $B = 1/2C$ with $C = \partial\omega/\partial t$ the laser chirp.

calculation details in [Roussel et al., Light Sci Appl **11**, 14 (2022)]

Our strategy: Diversity Electro-Optic Sampling (DEOS)



transfer functions



Goal: interleave the zeros of transfer functions

$$H_1(\Omega) = \sqrt{2}\cos\left(B\Omega^2 + \frac{\pi}{4}\right)$$

$$H_2(\Omega) = -\sqrt{2}\cos\left(B\Omega^2 - \frac{\pi}{4}\right)$$

- in practice: crystal and waveplates orientation $\neq$ “classical” EO
- problem well-posed $\rightarrow$ “deconvolution” possible using the two channels

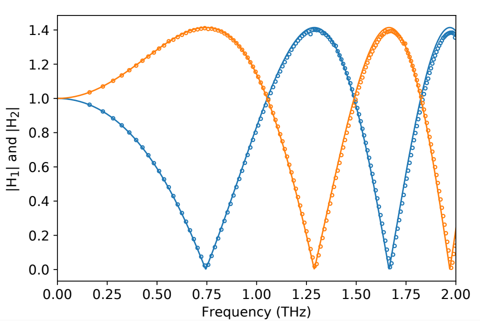
Algorithm for input field reconstruction: Maximum Ratio Combining (MRC)

Simple approach: retrieve the input field $\tilde{E}$ from the measured EO signals $\tilde{Y}_{1,2}$ using either

$$\tilde{E}_R(\Omega) = \frac{\tilde{Y}_1(\Omega)}{H_1(\Omega)} \quad \text{or} \quad \tilde{E}_R(\Omega) = \frac{\tilde{Y}_2(\Omega)}{H_2(\Omega)} \quad \text{depending on frequency } \Omega$$

Refined algorithm

Use a combination of the two EO signals $\tilde{Y}_{1,2}$ with **optimal** weights

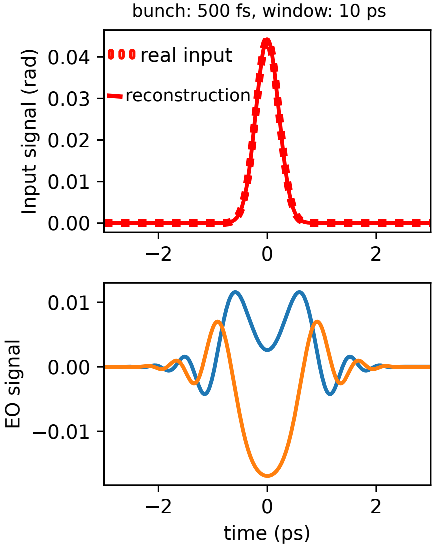


Maximum Ratio Combining (MRC) method:

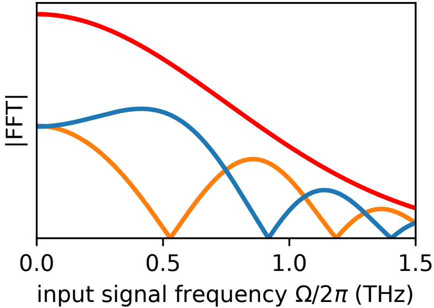
$$\tilde{E}_R = \frac{H_1\tilde{Y}_1 + H_2\tilde{Y}_2}{|H_1|^2 + |H_2|^2}$$

Inspired by: [Han, Boyraz & **Jalali**, Microwave Theory and Techniques, IEEE Transactions on **53**, 1404-1408 (2005)]

Reconstruction algorithm: numerical test

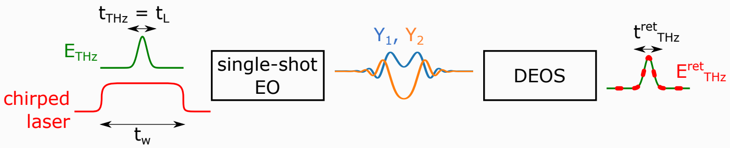


- ~~Old limitation $\tau = \sqrt{t_{laser} \times t_{window}}$~~
- New resolution limit $\tau \sim t_{laser}$?
- Time window t_{window}: no limit (theoretically)

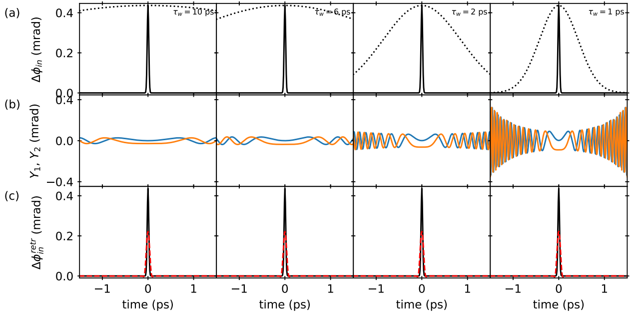


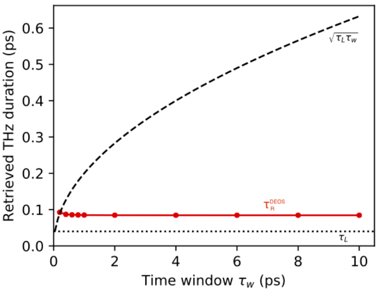
"Time resolution" of DEOS

Time resolution of DEOS: $\tau_R^{DEOS} \equiv \tau_{THz}^{retrieved}$ when $\tau_{THz} = \tau_L$



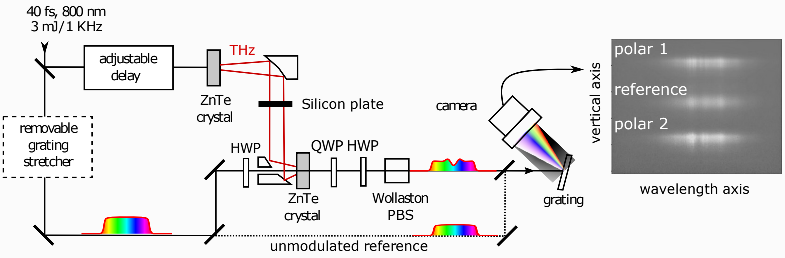
DEOS reconstruction versus time window τ_w:



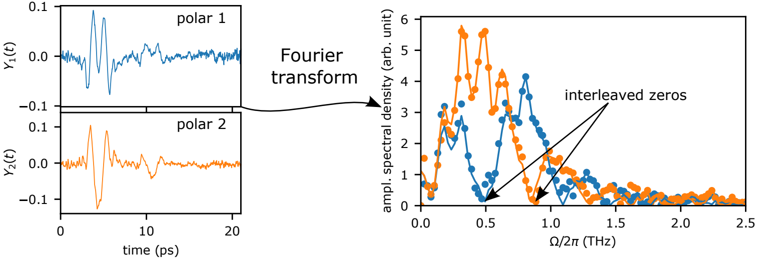


Experimental investigations using a table-top experiment

Terahertz signal generated by optical rectification of laser pulses

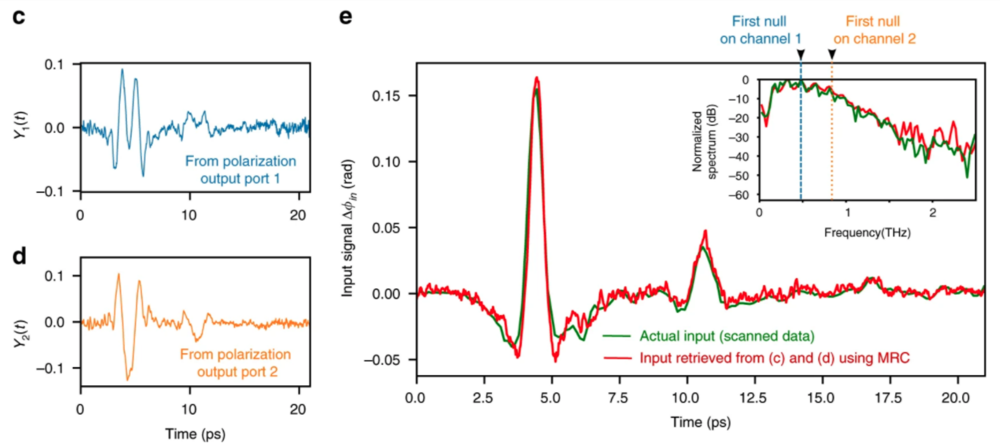


Computed EO signals:



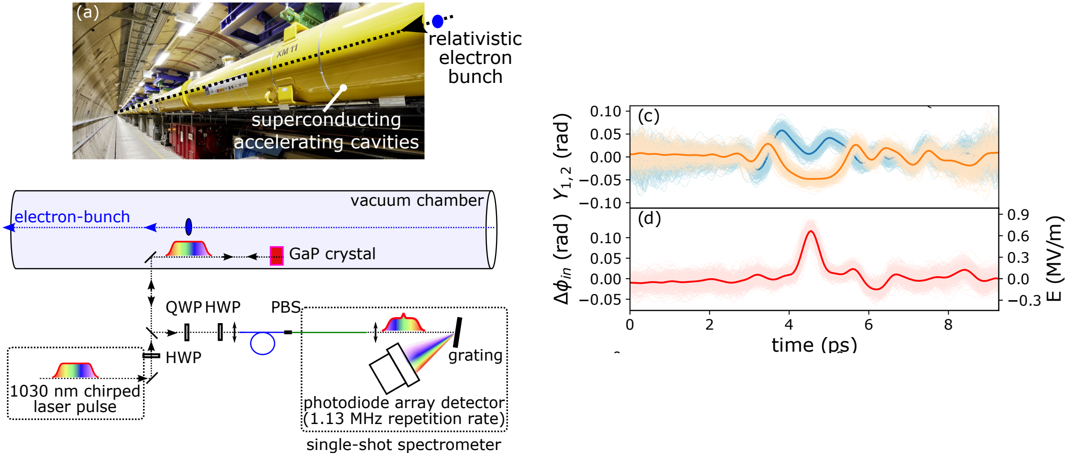
Comparison between DEOS and scanned EOS

Reconstructed single-shot THz signal vs reference signal (obtained with scanned EOS)

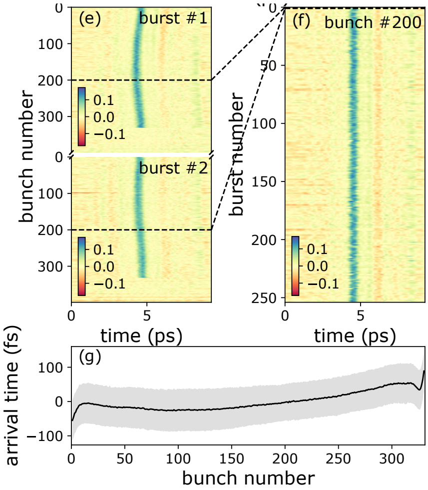


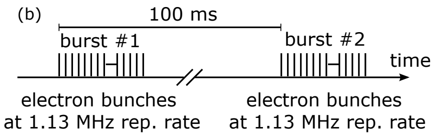
[Roussel et al., Light Sci Appl **11**, 14 (2022)]

Studies of e-bunch shapes at the European XFEL



Preliminary results at the European XFEL





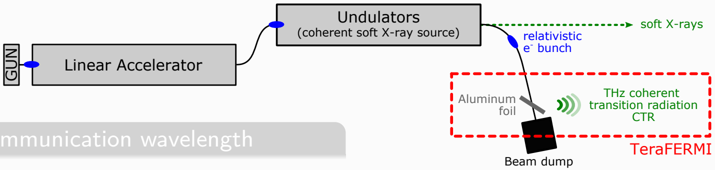
Train of 300 e-bunches over 250 bursts.

- bunch duration: $\sim$ 218 fs RMS
- arrival time jitter: $\sim$ 58 fs

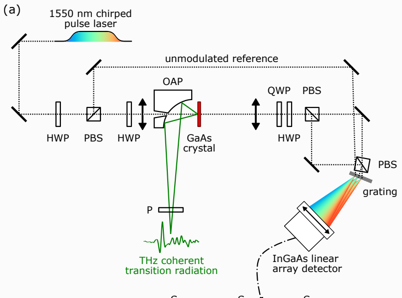
TeraFERMI: a "parasitic" THz source

TeraFERMI (Italy)

Single-cycle THz pulses from the coherent transition radiation (CTR) emitted by a short relativistic e-beam passing through a 1 μm thick Al foil. [A. Perucchi et al., Rev. Sci. Instrum. **84**, 022702 (2013)]



THz TDS at telecommunication wavelength



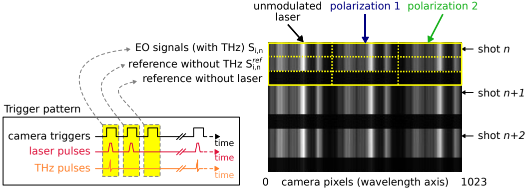
Energy per pulse	$\geq 10\ \mu$J ☺
Pulse duration	$\lesssim 1$ ps
Frequency range	$1 - 10$ THz
THz e-field strength	~ 50 MV/m ☺
Repetition rate	50 Hz ☹

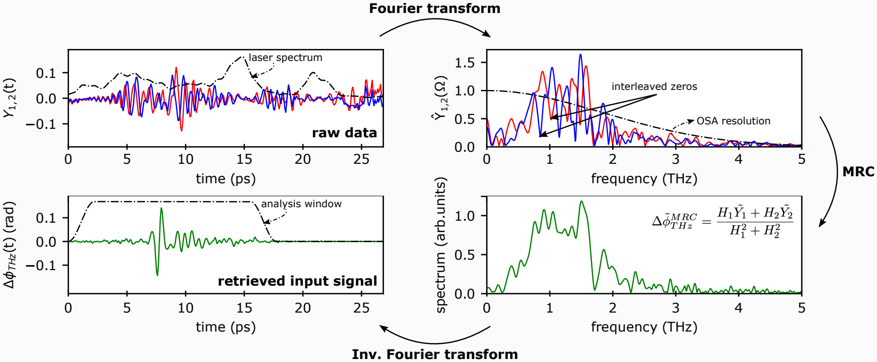
High peak power THz CTR recording

At each FERMI clock (@50 Hz):

- 1 laser pulse modulated by THz signal
- 1 reference laser pulse, i.e. unmodulated
- 1 camera background

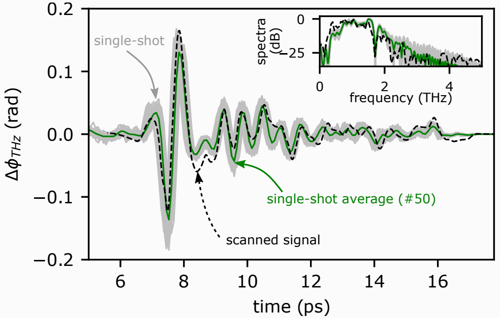
[Roussel et al., Opt. Express **31**, 31072 (2023)]





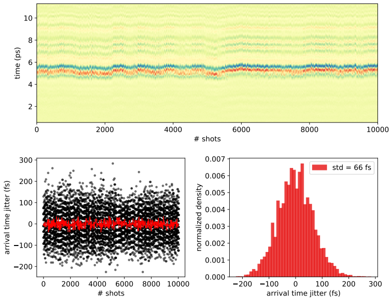
Comparison with scanning technique

Scanned signal obtained by passing the optical stretcher (laser pulse duration ∼ 110 fs).



The scanning technique is sensitive to the time jitter between the THz signal and the laser pulse.

- e-bunch arrival time jitter: ∼ 40 fs
- + jitter of laser synchronization loop



→ Measured time jitter of ∼ 66 fs.

Potential applications for fs-XUV light pulses characterization ?

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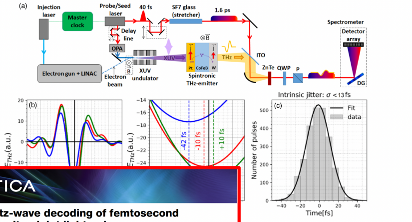

OPTICA

Terahertz-wave decoding of femtosecond extreme-ultraviolet light pulses

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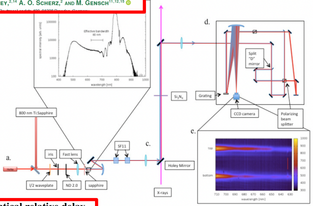

Spectral encoding of x-ray/optical relative delay

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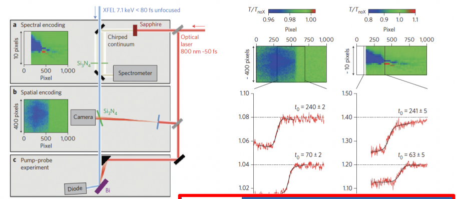
LETTERS NATURE PHOTONICS DOI: 10.1038/NPHOTON.2013.11

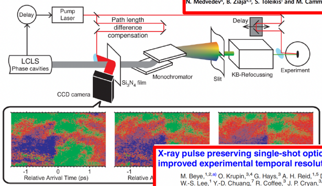


nature photonics LETTERS
PUBLISHED ONLINE: 17 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2013.11

Achieving few-femtosecond time-sorting at hard X-ray free-electron lasers

M. Harmand[1†]*, R. Coffee[2], M. R. Bionta[2,3], M. Chollet[2], D. French[2], D. Zhu[2], D. M. Fritz[2], H. T. Lemke[2], N. Medvedev[4], B. Ziaja[4,5], S. Toleikis[1] and M. Cammarata[6]*

121108-2 Beye et al.



X-ray pulse preserving single-shot optical cross-correlation method for improved experimental temporal resolution

M. Beye,[1,2,a)] O. Krupin,[3,4] G. Hays,[3] A. H. Reid,[1,5] D. Rupp,[3,6] S. de Jong,[3] S. Lee,[3] W.-S. Lee,[1] Y.-D. Chuang,[7] R. Coffee,[3] J. P. Cryan,[3,8] J. M. Glownia,[3,8] A. Föhlisch,[2] M. R. Holmes,[3] A. R. Fry,[3] W. E. White,[3] C. Bostedt,[3] A. O. Scherz,[1] H. A. Durr,[1,8] and W. F. Schlotter[3,a)]

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Conclusion

Diversity Electro-Optic Sampling (DEOS)

- High temporal resolution (limited by laser and crystal) for arbitrary long windows.
- Table-top proof-of-principle tests + experiments in accelerator environments.

Related projects in machine physics

- PhLAM/DESY project: investigate DEOS + photonic time-stretch readout
- PhLAM/FERMI: TeraFERMI THz beamline (high power, low rep. rate source)
- PhLAM/KARA/SOLEIL (French-German ANR-DFG ULTRASYNC project).
- Feasibility studies at TELBE and FELBE.
- Advanced diagnostics for the European TWAC project (THz Waveguide Accelerating Cavity).

Other milestones

- High acquisition rate with photonic time-stretch readout. [Roussel, et al., Sci Rep **5**, 10330 (2015)]
- High sensitivity EOS. [Szwaj et al., Rev. Sci. Instrum. **87**, 103111 (2016)]
- Cost reduction, using 1550 nm wavelength. [Roussel et al., Opt. Express **31**, 31072 (2023)]

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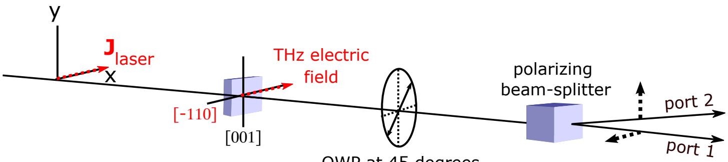
EuXFEL: B. Steffen, C. Gerth ,
FERMI: P. Di Pietro, N. Adhlakha, P. Cinquegrana, M. Veronese, S. Di Mitri, A. Perucchi

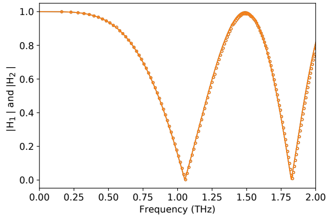
Fundings

CPER Photonics4Society, CEMPI, CNRS Momentum (METEOR), ANR/DFG (ULTRASYNC), EIC Pathfinder (TWAC).

"Classical" EO configuration



transfer functions

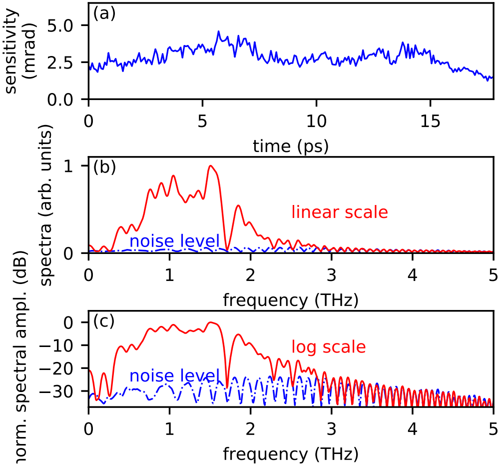


Transfer functions $H_{1,2}$ for the "classical" crystal & waveplates orientations

$$H_1(\Omega) = \cos\left(B\Omega^2\right)$$
$$H_2(\Omega) = -\cos\left(B\Omega^2\right)$$

- clear existence of **zeros** at particular frequencies
  problem ill-posed → "deconvolution" impossible using one channel
- "classical" EO configuration: zeros of H_1 and H_2 at the same frequencies

→ find an other configuration to separate the zeros ?



- RMS noise fluctuation (estimated from data without THz signal): **2.5 mrad over 5 THz bandwidth**
- Noise-equivalent input e-field: **2.1 kV/cm** (crystal thickness $d = 100\ \mu$m !)

$$\Delta\phi = \frac{\pi d}{\lambda} n_0^3 r_{41} E_{THz}$$

- Dynamic range: $\sim$ **30 dB**