Single-Shot Electro-Optic Detection of Bunch Shapes and THz Pulses: Fundamental Temporal Resolution Limitations and Cures Using the DEOS Strategy

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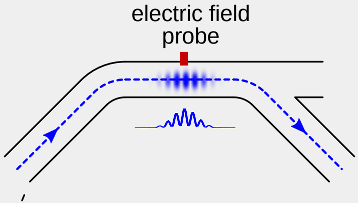
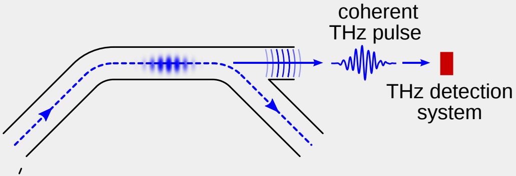
Topics: non-destructive and single-shot electric field measurements

Bunch shape measurements



THz pulse measurements (CSR, CTR, FEL...)

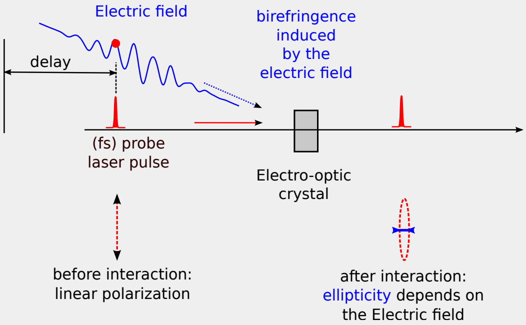


Motivations

- Single-shot measurements of longitudinal bunch shapes in LINACs and FELs: here European XFEL.
- Microbunching instability in storage rings (long electron bunches with short-scale microstructures): SOLEIL (France) and KARA@KIT (Germany).
- THz science applications: single-shot THz spectroscopy at light source beamlines (THz FELs and table-top sources). TERAFERMI and TELBE.

Electro-Optic Sampling of electric fields: principle

- The electric field modifies the birefringence of a crystal (Pockels effect).
- The field-induced birefringence is probed using a laser pulse.
- → **Multi-THz bandwidth obtained: limited by crystal speed and laser pulse duration.**



Popular since the 80s:

- Near-fiel measurements Valdmanis, Mourou, Gabel, APL 41, 211, (1982)
- Free-propagating THz pulses (time-domain spectroscopy) [Wu and Zhang, APL 67 3523 (1995)]

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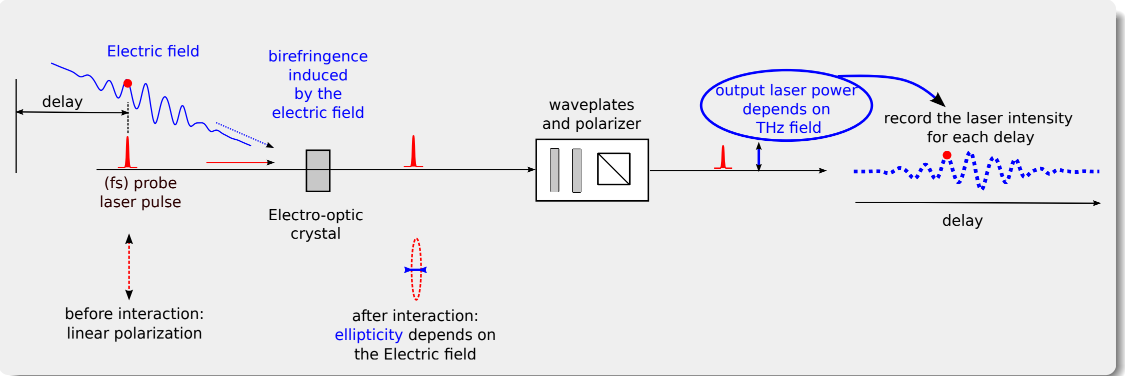

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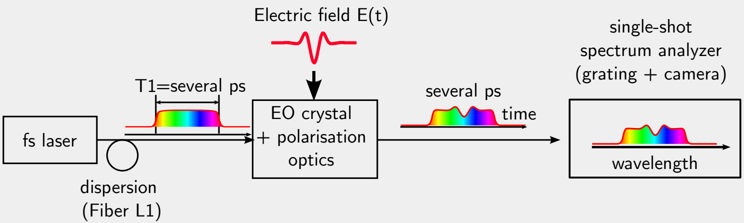
Single-shot operation? → use chirped pulses

Principle: Time-to-wavelength conversion (aka *spectral decoding*)



First demonstration for THz pulses (table-top exp.): Jiang and Zhang, Appl. Phys. Lett. 72, 1945 (1998)
First demonstration in the accelerator context: bunch shapes at FELIX [Wilke et al. , PRL 88, 124801 (2002)]
Novel design for speed (<200 fs) and sensitivity (fibered system): [Bernd Steffen et al., Proc. DIPAC09 TUPB42 (2009), RSI 91, 045123 (2020)]

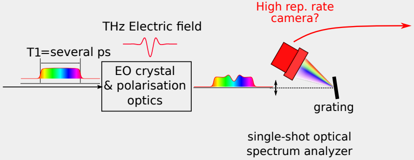
Challenges & and key questions:

1. **High repetition rate?** Need to record **>1e6 bunch shapes/second** at SOLEIL, KARA, European-XFEL.
2. **Achievable temporal resolution?**
3. Sensitivity and SNR

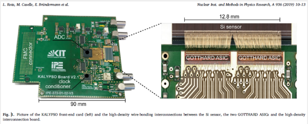
High repetition rate single-shot Optical Spectrum Analyzer

Option 1: Develop high-speed cameras

Speed world record: KALYPSO (KIT Karlsruhe)



KALYPSO photodiode array detector

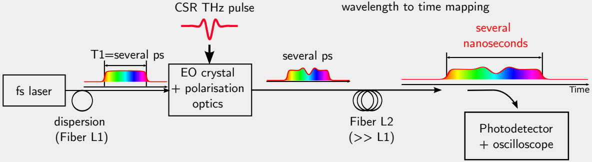


Michele Caselle et al, NIMA 936 (2019) 10, https://doi.org/10.1016/j.nima.2018.10.093

- Performances of the current release: ≈4 M Frames/s (for the 512 pixel version).
- KALYPSO+EO-sampling used at Eu-XFEL, KARA, FLASH.
  KARA: [PRAB 22, 022801 (2019)], DESY [RSI 91, 045123 (2020)]

Option 2: Photonic time-stretch electro-optic sampling

Photonic time-stretch: [B. Jalali team, Electron. Lett. 34, 1081 (1998)]

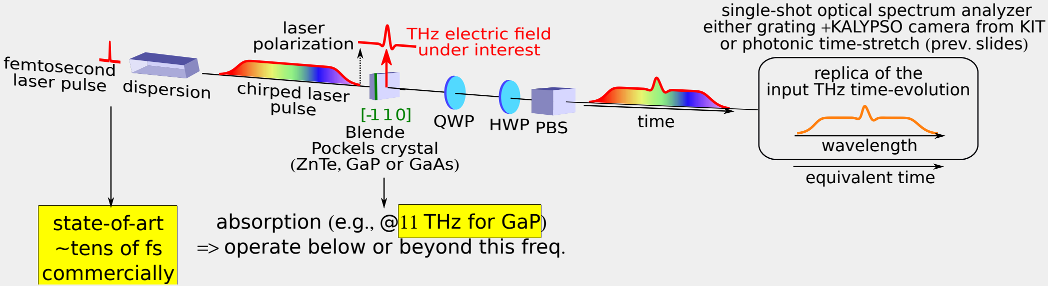


- On the oscilloscope: replica of the THz pulse that is "temporally stretched" by a factor $M = 1 + L_2/L_1$.
- If $L_1 = 10$ m and $L_2 = 2$ km $\Rightarrow M \approx 200$.
  $\Rightarrow$ 5 GHz on the oscilloscope corresponds to 1 THz at the input
  Phlam-SOLEIL [Sc. Rep. 5, 10330 (2015); RSI 10, 10311 (2016); PRL 118, 054801 (2017); Nat. Phys. 15, 635 (2019)], PhLAM-KARA [Sc. Rep. 9, 10391 (2019)]

Time resolution limitations

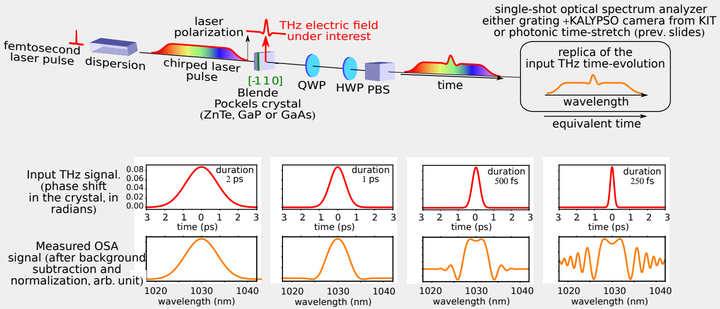
State-of-art of "obvious" limitations (from hardware)

- Femtosecond lasers → few **tens of fs** (commercial Yb fiber lasers).
- Electro-optic crystal usable bandwidth from ≈DC to below the "transverse phonon absorption" **(11 THz for GaP)**.
- *Note: possibility to perform measurements above the absorption line.*

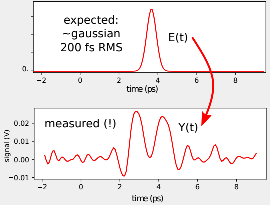


The "time resolution bottleneck" [Sun, Jiang & Zhang Appl. Phys. Lett. 73, 2233 (1998)]

Main time-resolution limitation is NOT due to a hardware limit



Electro-optic sampling measurement at Eu-XFEL (DESY)

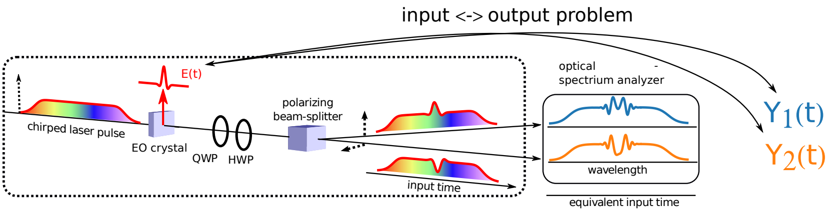


Measurement after 2nd BC (700 MeV).

20 year-old bottleneck: The technique is not directly usable technique unless the bunch is long and/or the analysis window is short: $t_{duration} \gg t_{issue} = \sqrt{t_{window} \times t_{laser}}$.

Example: $t_{window} = 10$ ps and $t_{laser} = 100$ fs $\Longrightarrow$ $t_{resolution} \approx 1$ ps $\gg t_{laser}$

Is it possible to **invert** the problem? i.e. retrieve the input field $E(t)$ from measurements $Y_{1,2}(t)$



Strategy – step 1: attempt to derive Fourier-domain transfer functions

Input field $E(t) \rightleftarrows \tilde{E}(\Omega)$

Measurements $Y_{1,2}(t) \rightleftarrows \tilde{Y}_{1,2}(\Omega)$

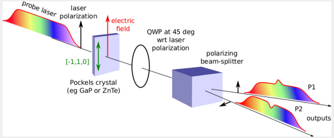
$$H_{1,2}(\Omega) = \frac{\text{measurement}}{\text{input field}} = \frac{\tilde{Y}_{1,2}(\Omega)}{\tilde{E}(\Omega)} \quad \text{with} \quad \begin{aligned} H_1(\Omega) &= h_1 \cos\left(B\Omega^2 + \phi_1\right) \\ H_2(\Omega) &= h_2 \cos\left(B\Omega^2 + \phi_2\right), \end{aligned}$$

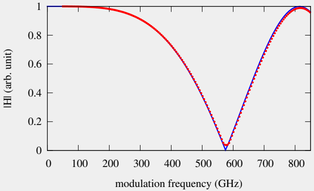
h_1, h_2, ϕ_1, ϕ_2 depend on the crystal and waveplate orientations. $B = \frac{1}{2C}$ and $C = \frac{\partial\omega}{\partial t}$: laser chirp.
See calculation details in the supplementary information of LSA 11, 14 (2022)

Step 2: Examine the frequency-domain transfer functions

$$H_{1,2} = \frac{\text{measurement}}{\text{input field}} = \frac{Y_{1,2}(\Omega)}{\tilde{E}(\Omega)}$$

Transfer functions H_1 and H_2 for the "classical" crystal & waveplates orientations





$$H_1(\Omega) = h_0 \cos B\Omega^2$$
$$H_2(\Omega) = -h_0 \cos B\Omega^2,$$

with $B = \frac{1}{2C}$

$C = \frac{\partial \omega}{\partial t}$: laser chirp

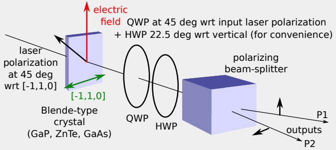
Observations:

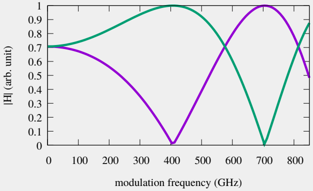
1. The transfer functions present **ZEROS** at specific frequencies.
   $\Longrightarrow$ impossible to make a "deconvolution" using a single channel: $\tilde{E}(\Omega) = \tilde{Y}_1(\Omega)/H_1(\Omega)$ is ill-posed.
2. For this "classic" optics adjustement, the zeros of H_1 and H_2 are at the same frequencies
   $\Longrightarrow$ can we change this?...

Step 3: Our solution, Diversity Electro-optic Sampling (DEOS)

Key point #1: interleave the transfer function zeroes

In practice: use crystal and waveplate orientations that are different from the "classical" ones.





$$H_1(\Omega) = h_0 \cos\left(B\Omega^2 - \frac{\pi}{4}\right)$$

$$H_2(\Omega) = -h_0 \cos\left(B\Omega^2 + \frac{\pi}{4}\right)$$

Key point #2: For the reconstruction: use a combination of the two measured EO signals Y_1 and Y_2 with "optimal" weights

Maximum Ratio Combining (MRC) algorithm
Retrieve the input electric field $\tilde{E}_R(\Omega)$ using:

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

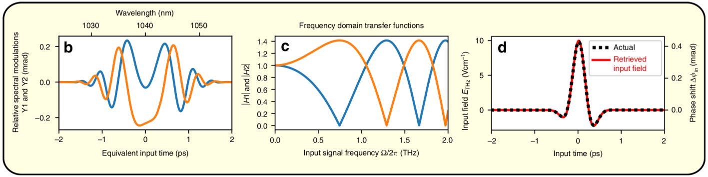
Note: frequency space: $\tilde{Y}_1 = Y_1(\Omega)$, etc. $\tilde{Y}_1(\Omega)$ and $\tilde{Y}_2(\Omega)$: measured EO signals

Reconstruction algorithm: numerical tests

Step 1: OSA data preprocessing (background subtraction and normalisation)

Step 2: Use frequency domain transfer functions between input signal and OSA data for inverting the problem in Fourier space

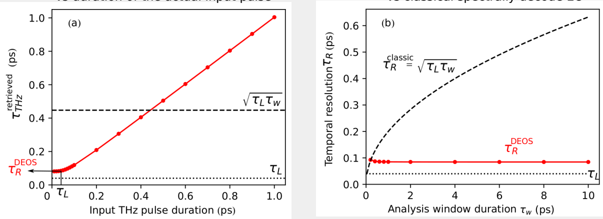
Step3: Deduce the input THz signal



Achievable temporal resolution

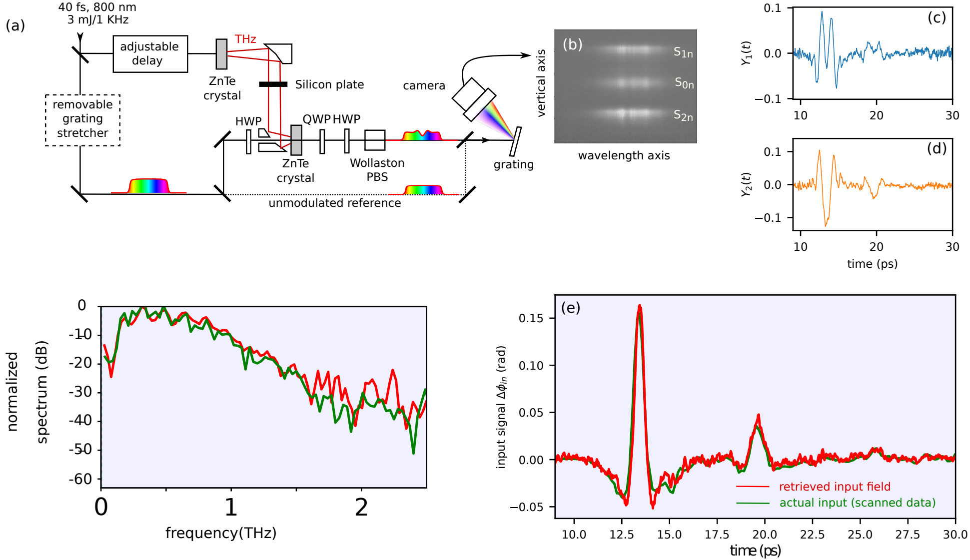
Duration of the retrieved input pulse vs duration of the actual input pulse

Temporal resolution DEOS vs classical spectrally decode EO



Input field=Gaussian pulse, laser duration 39 fs FWHM (40nm BW), infinitely fast crystal

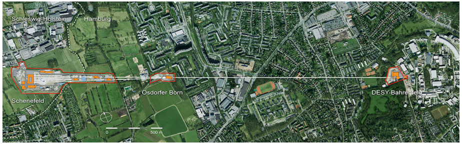
Experimental results using phase diversity Electro-Optic Sampling

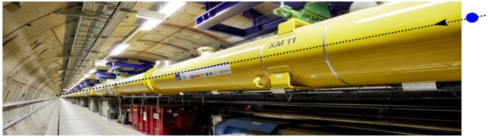


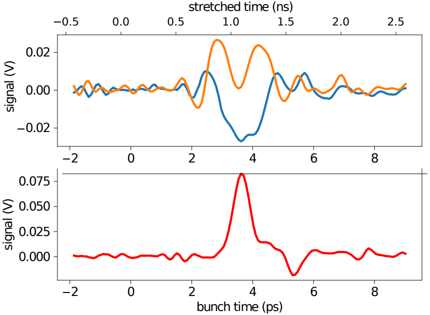
Roussel et al. Light: Science & Applications **11**, 14 (2022)

Studies of electron bunch shapes at the European X-ray Free-Electron Laser using DEOS

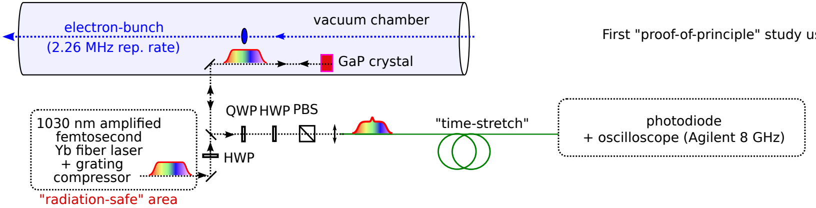
Proof-of-principle of DEOS using time-stretch





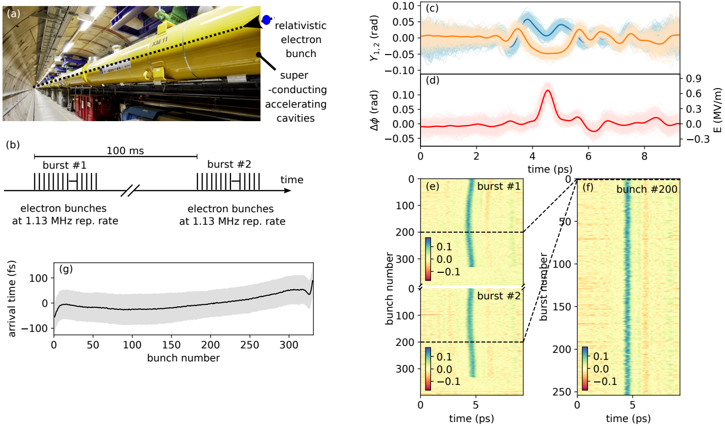


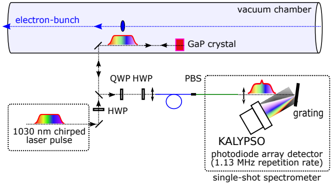
First "proof-of-principle" study using time-stretch



Studies of electron bunch shapes at the European X-ray Free-Electron Laser using DEOS

Proof-of-principle of DEOS using spectral decoding, and the KALYPSO ultrafast camera (single-shot measurements).





Conclusion

Diversity Electro-Optic Sampling (DEOS)

- High resolution (limited by laser and crystal) for arbitrarily long recording windows
- Preliminary tests at Eu-XFEL (DESY). Table-top tests.
- Upgrade from existing EO diagnostics to DEOS is relatively simple.

Related projects in machine physics in progress

- PhLAM-DESY project: investigate DEOS and photonic time-stretch
- PhLAM-TERAFERMI THz beamline (MOMENTUM project by ER)
- PhLAM-KARA-SOLEIL (ULTRASYNC ANR project)
- PhLAM-TELBE

Other foreseen applications for single-shot measurements: Users of THz radiation

- Single-shot Time-Domain Spectroscopy of rapidly-varying phenomena
- Single-shot Time-Domain Spectroscopy using very low rep. rate THz sources: TERAFERMI, also table-top THz sources

For details, see: Roussel et al, Light Sci Appl 11, 14 (2022) https://doi.org/10.1038/s41377-021-00696-2

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