Enregistrement de signaux terahertz en “monocoup” à l’aide de lasers femtoseconde

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MOIoTOP, Mars 2021

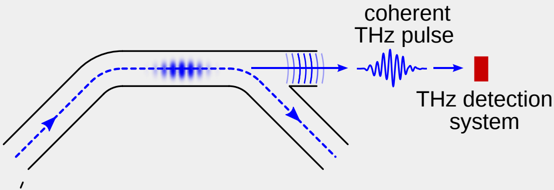
PhLAM Université Lille1 Sciences et Technologies cnrs CEMPI CENTRE EUROPÉEN POUR LES MATHÉMATIQUES, LA PHYSIQUE ET LEURS INTERACTIONS AGENCE NATIONALE DE LA RECHERCHE ANR

Why trying to record a (possibly complex) THz pulse **in single-shot**?

Initial motivations: study of the THz pulses emitted in synchrotron radiation facilities

Accelerator studies: Coherent synchrotron radiation electron bunch shapes, Free-Electron Lasers...

At SOLEIL (below), and also at European XFEL, KARA (Karlsruhe...)



Other applications using "normal" laser-based THz sources?

→ Applications to **very low repetition rate** experiments? (e.g., spectroscopy using mJ laser-based THz sources)

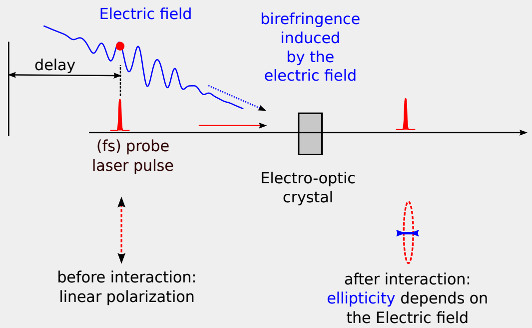
→ Applications to **very high repetition rate** experiments? (e.g., spectroscopy of fast irreversible processes)

→ ...

Observation challenges: (i) bandwidth (ps/sub-ps resolution), (ii) single-shot operation, (iii) optionally >MHz rep.

Electro-Optic Sampling of electric fields: principle

- Apply the electric field to be measured on an electro-optic crystal
- Pockels effect occurs → a birefringence is created (or modified) by the field
- Analyze the crystal birefringence using a short laser pulse



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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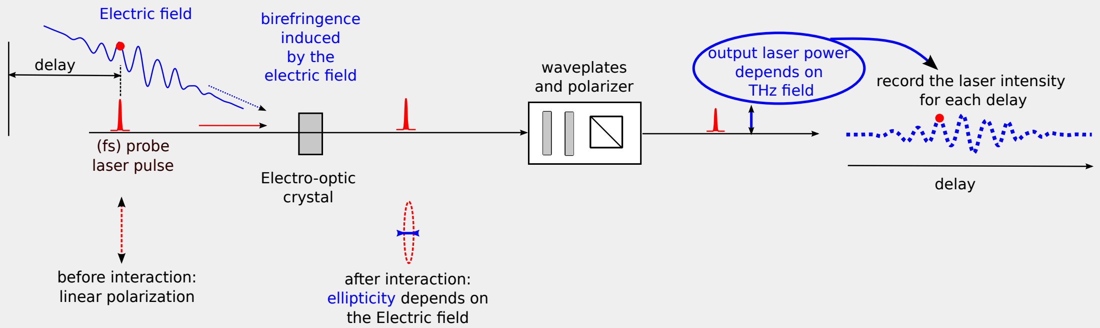

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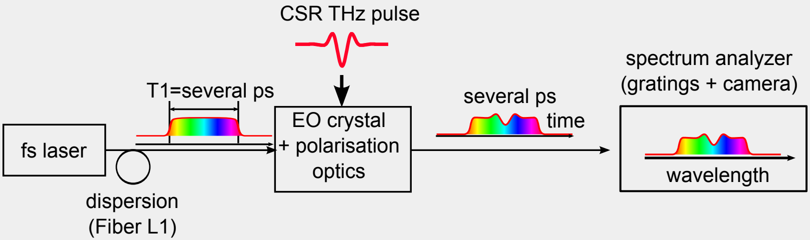
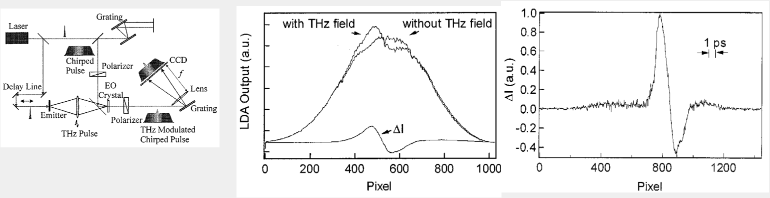
Single-shot operation? → use chirped pulses

First possibility: Time-to-wavelength conversion



First demonstration using OSA readout: Jiang and Zhang, Appl. Phys. Lett. 72, 1945 (1998)



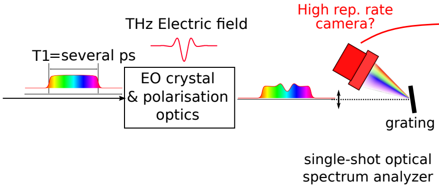
Outline of the talk

3 parts, corresponding to "3 challenges":

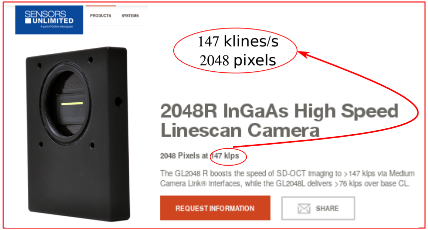
1. How to achieve **higher repetition-rate** EO sampling (when needed)?
2. How to achieve **"high" sensitivity**?
3. How to reach the same **temporal resolution**/THz bandwidth as scanned EO sampling?

1.0 Time-to-wavelength conversion: number of traces/second?

Commercial state-of-art ≈ 150 k lines/s (@2048 pix).



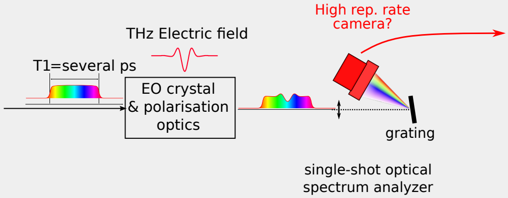
Commercial camera (e.g., Goodrich/sensors inc)



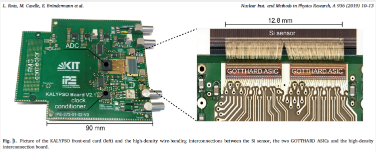
- OK for KHz-range THz sources (e.g., based on mJ Ti-Sapphire lasers)
- However: Some applications required higher repetition rates: for instance 1-10-100 MHz... for SOLEIL, Eu-XFEL, or the THz Free-Electron Lasers (e.g., T-ELBE)... 10 GHz for pulsed QCLs...

1.1 High repetition rate – "Option 1": work on the electronics, i.e., develop a new generation of cameras

Speed world record: KALYPSO (KArlsruhe Linear arraY detector for MHz rePetition-rate SpectrOscopy)



KALYPSO photodiode array detector



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

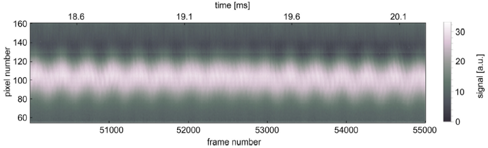
- **Current version (v2) Line rate: 4 Mfps for 512 pixels** (2 Mfps for 1024 pixels). Silicon or InGaAs sensor for the moment. On-board FPGA for real-time processing. SNR=60 dB. Next version (v3): 10 Mfps, 80 dB SNR.
- Developed at Karlsruhe Institute of Technology (KIT) by the M. Caselle team.

EO sampling using KALYPSO cameras: see in particular

PSI: Muller, Peier, Schlott, Steffen, Proc. FEL conference, https://accelconf.web.cern.ch/FEL2010/papers/wepa09.pdf

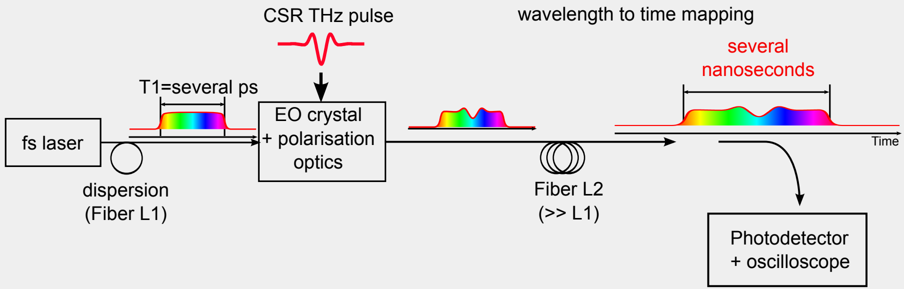
KARA (Karlsruhe) Phys. Rev. Accel. Beams 22, 022801 →

DESY: Steffen et al., Rev. Sci. Instrum. 91, 045123 (2020)



1.2 High repetition rate – Option 2: Work on the optics → "photonic time-stretch"

Main idea: Associate EO sampling with photonic time-stretch, [B. Jalali team, Electronics Letters 34, 1081 (1998)]

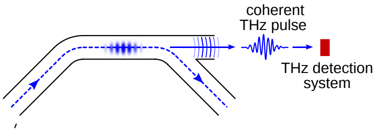


On the oscilloscope: replica of the THz pulse that is "temporally stretched" by a factor $M = 1 + L_2/L_1$.
Following slides: $L_1 = 10$ m and $L_2 = 2$ km $\Rightarrow M \approx 200$.
$\Rightarrow$ 5 GHz on the oscilloscope corresponds to 1 THz at the input.

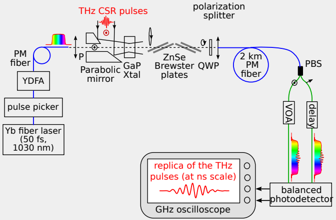
First demonstration of THz time-stretch EO: [(PhLAM-SOLEIL coll.) Roussel et al. Sci. Rep. 5, 10330, 2015]

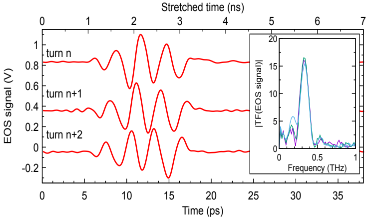
Challenge #2: **High sensitivity** and high repetition-rate time-stretch EO sampling

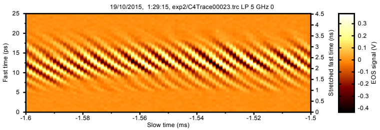
Let us start by the result!...

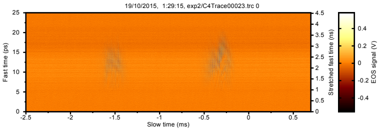


Detection system $\approx 1 - 88 \times 10^6$ shapes/second









Demonstration: [Roussel et al. Scientific Reports 5, 10330, 2015]

High-sensitivity design (this slide) [C.Szwaj et al., Rev. Sci. Instr. 10, 10311 (2016), C. Evain et al., PRL 118, 054801 (2017)]

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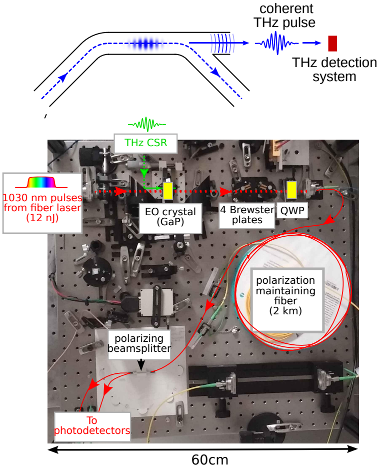

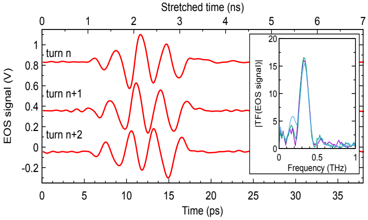

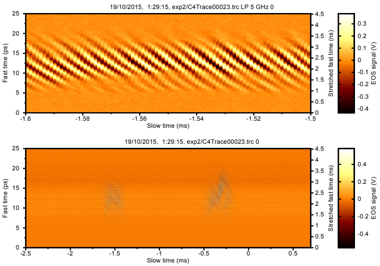

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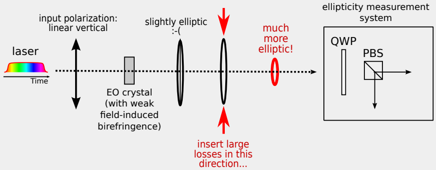
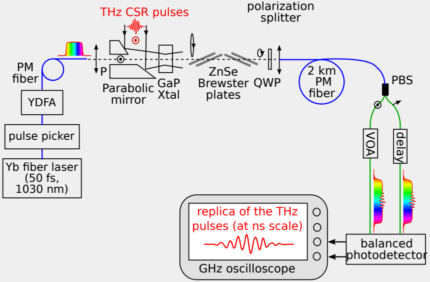
Focus on a technique aiming at increasing SNR

Original idea from [Ahmed *et al.*, Rev. Sci. Instr. 85, 013114 (2015)]

An efficient point of view: our weak signal IS the ellipticity

We can increase this ellipticity by introducing **losses** in one polarization direction.





Hence the Brewster plates!
here ≈ x400 attenuation $\Longrightarrow$ a x20 increased in SNR :-)
Measured: ≈ 1.25 V/cm over the first 0-300 GHz band.

Summary:

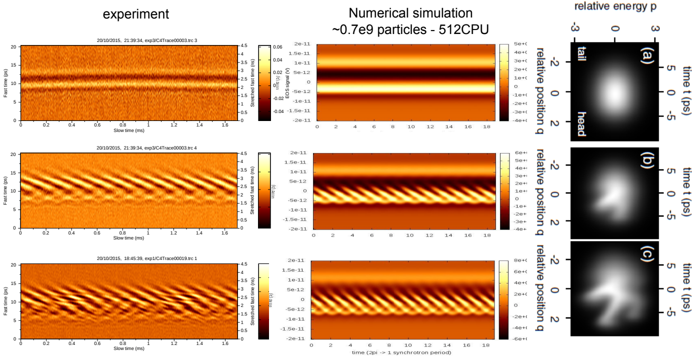
- Balanced detection for noise cancellation (laser and ASE)
- Introduction of Brewster plates (with transmission T) increases sensitivity by a factor $1/\sqrt{T}$.

[C.Szwaj et al., Rev. Sci. Instr. 10, 10311 (2016), C. Evain et al., PRL 118, 054801 (2017)]

This sensitivity enhancement was necessary for investigating the "burst-free" operation mode at SOLEIL

Known as "low-alpha CSR" – the prefered mode for users of coherent THz

Measurement sensitivity: ≈ 1.25 V/cm over the first 0-300 GHz band.



Bunch charge ≈ 0.1 nC.
Bunch length: 3 ps RMS

C. Evain, E. Roussel, M. Le Parquier, C. Szwaj, M.-A. Tordeux, J.-B. Brubach, L. Manceron, P. Roy, and S. Bielawski,
PRL 118, 054801 (2017)

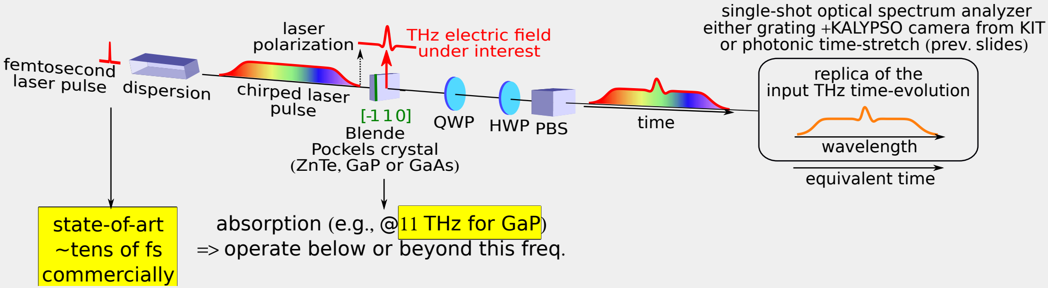
$$\frac{\partial f(q,p,\theta)}{\partial \theta} - p\frac{\partial f}{\partial q} + \frac{\partial f}{\partial p}\left[q - I_c E_{wf}\right] = 2\varepsilon \frac{\partial}{\partial p}\left(pf + \frac{\partial f}{\partial p}\right)$$

q: position, p: momentum, E_{wf}: field created by the bunch.
Parameters: ϵ small, I_c= beam current (main control parameter).

Part 3: The "time resolution bottleneck"

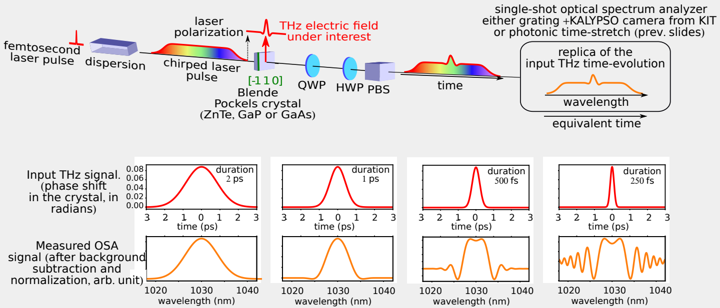
State-of-art of "obvious" limitations (from hardware)

- 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.*

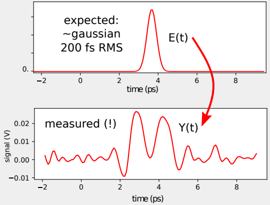


3. The "time resolution bottleneck" [Sun, Jiang & Zhang Appl. Phys. Lett. 73, 2233 (1998)]

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



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

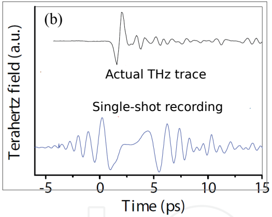


Measurement after 2nd BC (700 MeV).

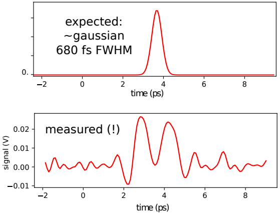
20 year-old bottleneck: The technique is not directly usable technique unless the bunch is long and/or the analysis window is short: $t_{duration} \gg t_{issue} = \sqrt{t_{window} \times t_{laser}}$.

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

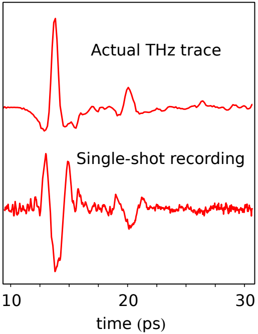
Resolution/deformation issue: gallery of failures...



H. Murakami, [...] Towards Time-resolved Terahertz **Spectroscopy of Protein in Water**
Interchopen,
http://dx.doi.org/10.5772/67195

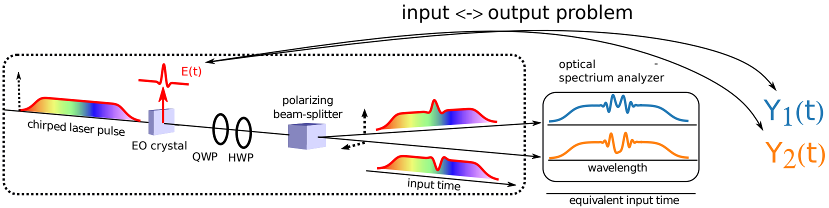


Near field of the relativistic electron bunch at **European XFEL**



We, at PhLAM: Generation of a THz using optical rectification of 800 nm pulses in ZnTe. Scanned TDS trace vs single-shot measurement.

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**

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

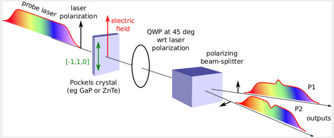
$$H_{1,2}(\Omega) = \frac{\text{measurement}}{\text{input field}} = \frac{Y_{1,2}(\Omega)}{\tilde{E}(\Omega)} \quad \text{with} \quad \begin{aligned} H_1(\Omega) &= h_1 \cos\left(B\Omega^2 + \phi_1\right) \\ H_2(\Omega) &= h_2 \cos\left(B\Omega^2 + \phi_2\right), \end{aligned}$$

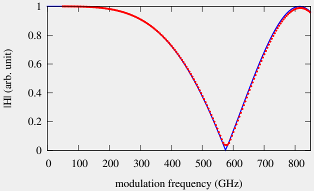
h_1, h_2, ϕ_1, ϕ_2 depend on the crystal and waveplate orientations. $B = \frac{1}{2C}$ and $C = \frac{\partial \omega}{\partial t}$: laser chirp.
See calculation details in **https://arxiv.org/pdf/2002.03782**

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:

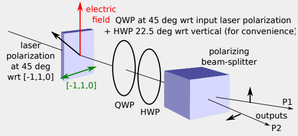
1. The transfer functions present **ZEROS** at spécific frequencies.
   $\Longrightarrow$ impossible to make a "deconvolution" using a single channel: $\tilde{E}(\Omega) = \tilde{Y}_1(\Omega)/H_1(\Omega)$ is ill-posed.
2. For this "classic" optics adjustement, the zeros of H_1 and H_2 are at the same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

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

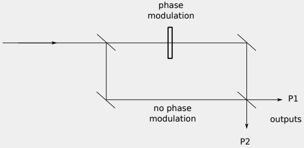
Key point #1: interleave the transfer function zeroes

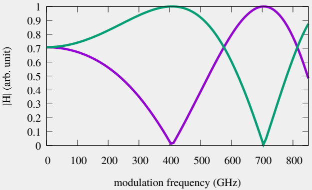
In practice: use crystal and waveplate orientations that are different from the "classical" ones.

(a)



(b)





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

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

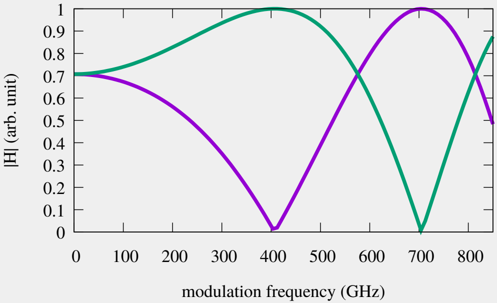
Intuitive picture: we can now retrieve the input field $\tilde{E}$ from the measurements $Y_{1,2}$ using

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

... but we can even refine this algorithm...

Algorithm for input signal retrieval: Maximum Ratio Combining (MRC)

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



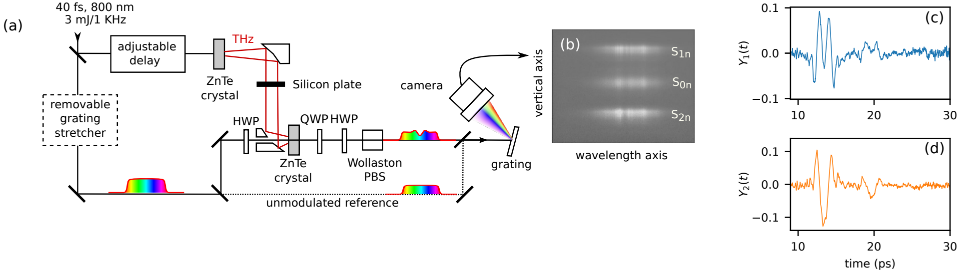
Retrieve the input electric field $\tilde{E}_R(\Omega)$ using:

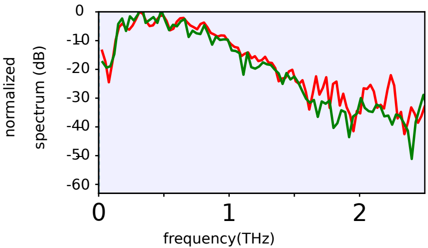
$$\tilde{E}_R = \frac{H_1\tilde{Y}_1 + H_2\tilde{Y}_2}{|H_1|^2 + |H_2|^2} \quad (1)$$

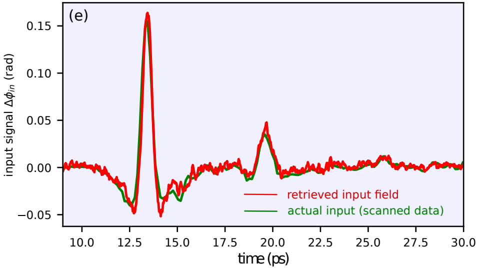
Note: frequency space: $\tilde{Y}_1 = Y_1(\Omega)$, etc.
$\tilde{Y}_1(\Omega)$ and $\tilde{Y}_2(\Omega)$: measured EO signals

A bit of history:
Initially introduced for wireless communications using multiple antennas [Kahn Proc. IRE 42, 1704 (1954) + wikipedia page]
Photonic context: [Han, Boyraz & Jalali, IEEE Trans. Microwave Theory and Tech. 53, 1404 (2005)]

Experimental results using phase diversity Electro-Optic Sampling



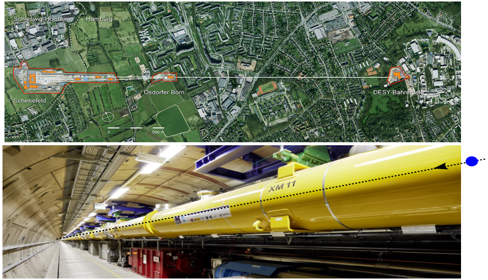


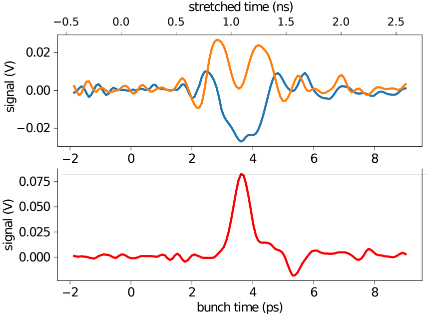


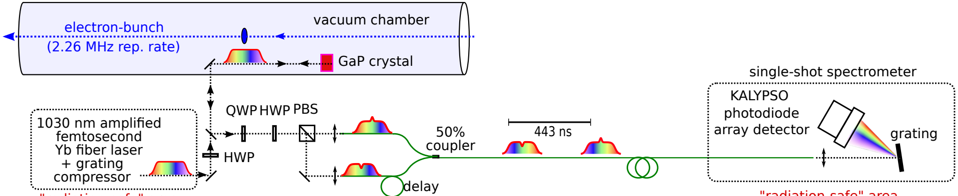
Roussel et al. https://arxiv.org/abs/2002.03782,

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

In progress: Diversity Electro-Optic Sampling (DEOS) using photonic time-stretch as well as OSA strategies.







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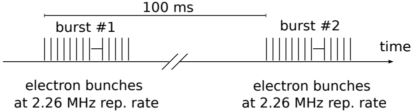

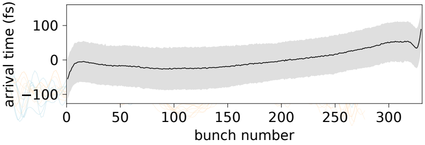

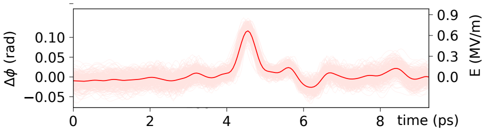

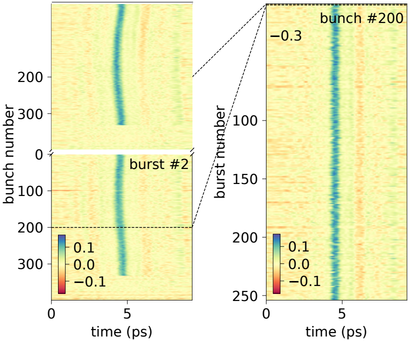

Conclusion

Single-shot electro-optic sampling

- Solution 1 for "MHz+" repetition rate EO sampling: chirped EO sampling + KALYPSO camera readout
- Solution 2: EO sampling + photonic time-stretch readout.
- Attention!! Without data processing, time-resolution is terrible when a long recording length is required
- A special "two-output design"+reconstruction algorithm (Diversity EO Sampling) → same time-resolution as scanned EO sampling.

→ details in https://arxiv.org/pdf/2002.03782

Future directions – questions

- Associate knowledges in photonics and electronics → for progressing in sensitivity, cost reduction, effective number of points, real-time operation... Some ideas: work at telecom wavelength (1550 nm), design new ADC/FPGA readout systems for time-stretch, new EO optical front-ends for KALYPSO-type cameras...
- Use for studying accelerator-based sources: SOLEIL and KARA/KIT (in the framework of the ULTRASYNC ANR project). Collaborations with Eu-XFEL and FERMI in progress. Feasibility study at T-ELBE.
- Open question: Applications outside the accelerator domain?

→ Spectroscopy requiring high power THz pulses? (i.e., low rep. rate), Monitoring single or non-periodic events? THz laser dynamics? (FELs, Quantum cascade lasers...). Spectroscopy of irreversible processes?...

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- **KIT/KALYPSO project** Michele Caselle team.
- **DESY (Germany)** Bernd Steffen and Christopher Gerth
- **UCLA (USA)** Bahram Jalali

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High temporal resolution: Roussel et al. Arxiv: https://arxiv.org/pdf/2002.03782
Time-stretch, first tests: Roussel et al., Sci Rep 5, 10330 (2015). https://doi.org/10.1038/srep10330
High sensitivity: Evain et al. PRL 118, 054801 (2017). https://doi.org/10.1103/PhysRevLett.118.054801
and: Szwaj et al., Rev. of Sci. Instrum. 87, 103111 (2016). https://doi.org/10.1063/1.4964702
Near field + time-stretch: SB et al., Sci. Rep. 9, 10391 (2019). https://doi.org/10.1038/s41598-019-45024-2

Deconvolution using phase diversity (table-top THz experiment)

Deconvolution

$$Y_{1,2}(\Omega) = H_{1,2}X \quad (2)$$

$$H_{1,2}(\Omega) = h_0 \cos\left(B\Omega^2 + \phi\right)$$

$$H_{1,2}(\Omega) = h_0 \cos\left(B\Omega^2 - \phi\right)$$

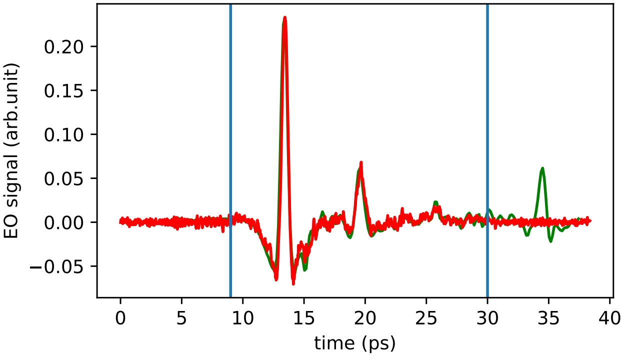
Deconvolution using Maximum Ratio Combining (MRC):

$$X_R = \frac{H_1 Y_1 + H_2 Y_2}{|H_1|^2 + |H_2|^2} \quad (3)$$

[Han, Boyraz & Jalali, IEEE Trans. Microwave Theory and Tech. 53, 1404 (2005)]

Question: How can we find B and ϕ?
Minimize the reconstruction error:
$\epsilon^2 = |Y_1 - H_1 X_R|^2 - |Y_2 - H_2 X_R|^2$

Reconstructed single-shot THz signal vs scanned reference

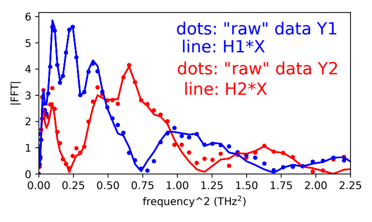


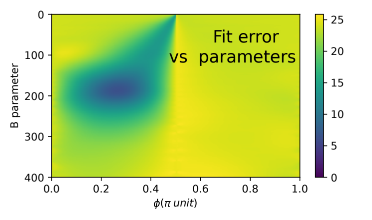
Red: Result (deconvolution)
Green: scanned reference (i.e., the "real signal")

Deconvolution using phase diversity (table-top THz experiment)

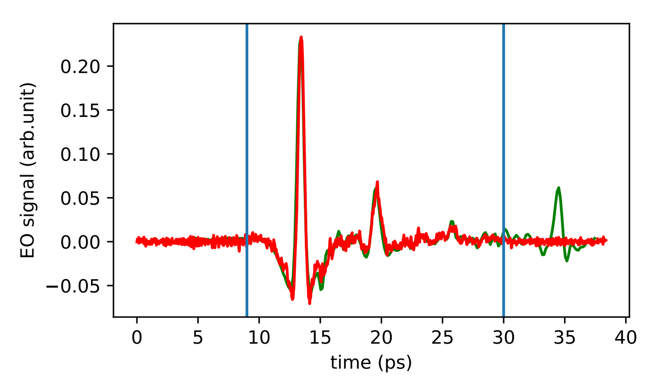
Automatic search for B and ϕ parameters (fit)

$$H_{1,2}(\Omega) = h_0 \cos\left(B\Omega^2 \pm \phi\right)$$



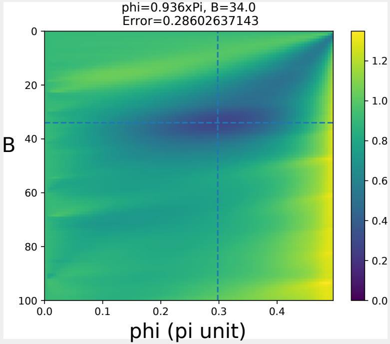


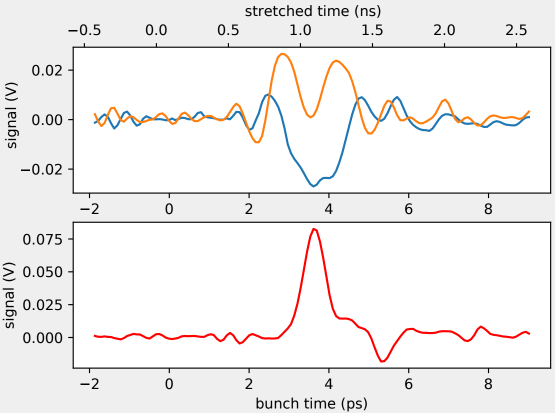
Reconstructed single-shot THz signal vs scanned reference

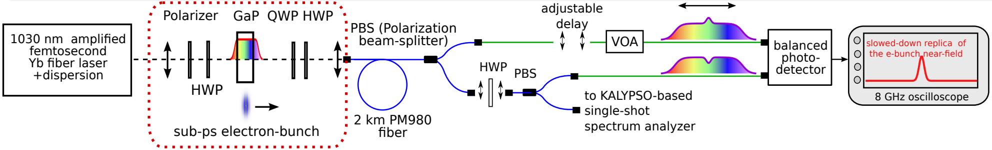


Red: Result (deconvolution)
Green: scanned reference (i.e., the "real signal")

Preliminary tests at the European X-ray Free-Electron Laser



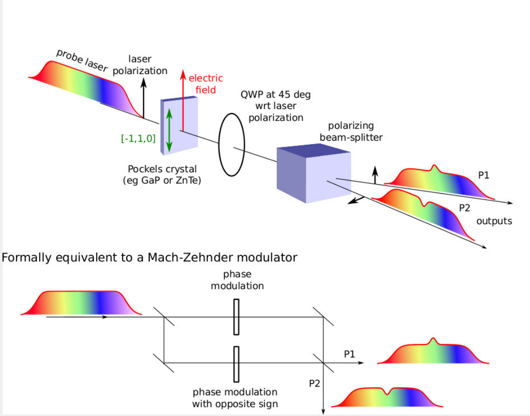




Let us change our point of view: calculate the transfer functions

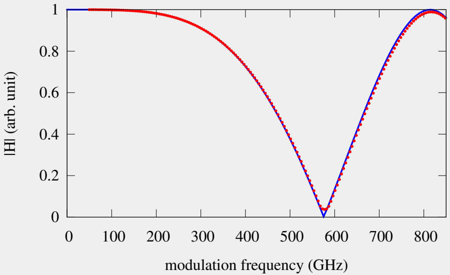
Classic crystal orientation (optimized for maximal response)

Fourier tranform of the Input electric field $\tilde{E}(\Omega) \xrightarrow{time-to-spectrum\ conversion} H_{1,2}(\Omega) \times \tilde{E}(\Omega)$



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

with $B = \frac{1}{2C}$ and $C = \frac{\partial\omega}{\partial t}$: laser chirp



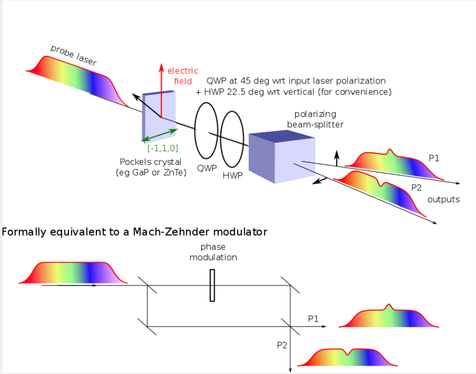
Transfer functions already known for time-stretch with a Mach-Z. Modulator! [Coppinger, Bushan & Jalali IEEE Trans. Microw. Th. and Tech. 47, 1309 (1999)]

Conclusion: impossible to make a deconvolution
Existence of zeroes $\implies$ the problem is ill-posed :-(

Transfer functions suitable for deconvolution? → Search for phase diversity

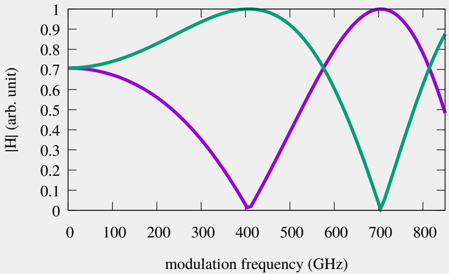
[Han, Boyraz & Jalali, IEEE Trans. Microwave Theory and Tech. 53, 1404 (2005)]

Objective: interleave the transfer function zeroes



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

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



→ Well-posed deconvolution problem !