

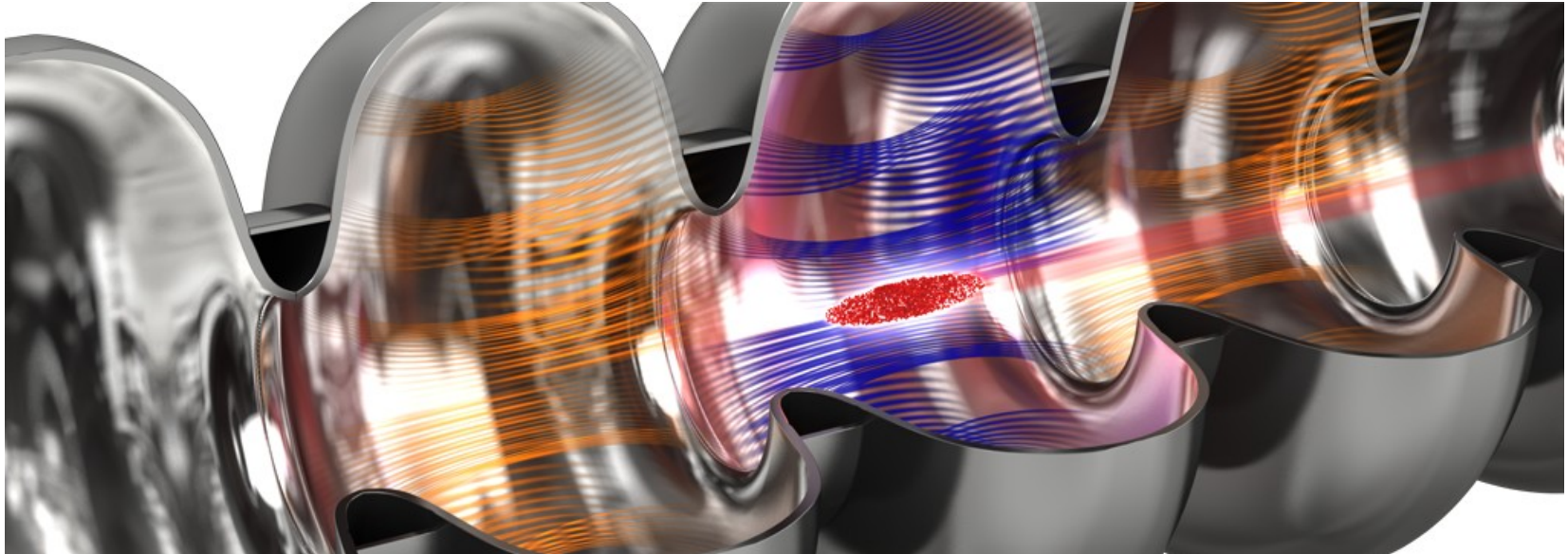
# *Single shot diagnostic of electron bunch shapes at MHz+ repetition rates using diversity electro-optic scheme at EuXFEL, FLASH and FELBE*

Quentin Demazeux, Christophe Sz waj, Eléonore Roussel, Serge Bielawski (PhLAM, France)

Bernd Steffen, Marie Kristin Czw alinna (DESY, Germany)

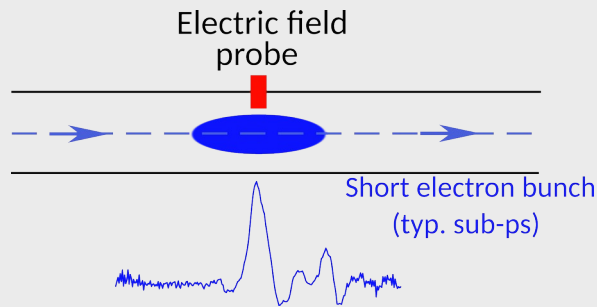
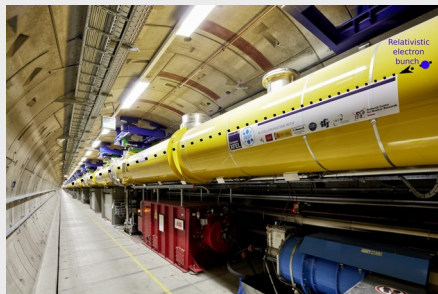
Michael Klop f (HZDR, Germany)

**FELs Europe, Grado, 2025**



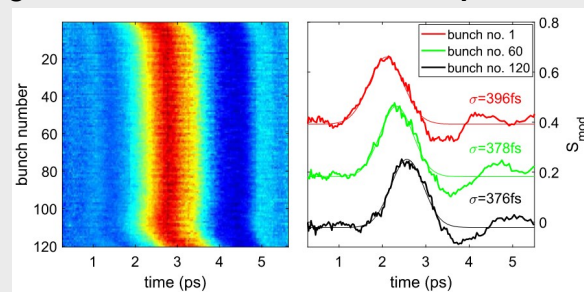
# Why single-shot measurement for THz electric field in Accelerator facilities 1/20

Recording electron bunch shape in accelerators (including Free Electron Laser and synchrotron radiation facilities)



Information we can get : Bunch shapes, Arrival time, Jitter and drift

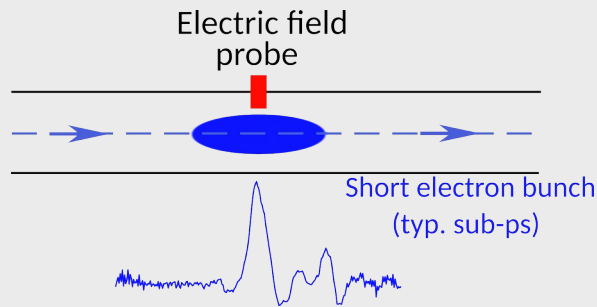
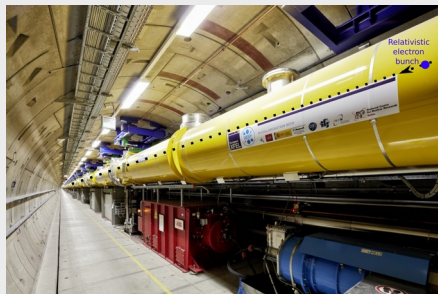
Single shot measurement at MHz+ rep.rate at EuXFEL



B.steffen et al. Rev. Sci. Instrum. 91, 045123 (2020)

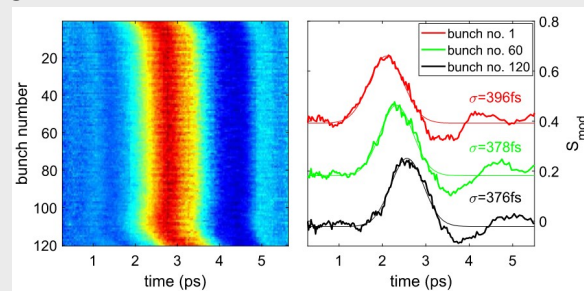
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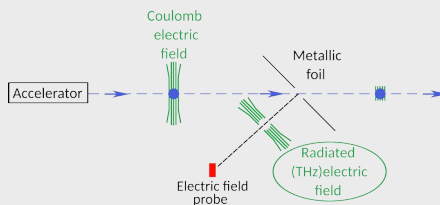
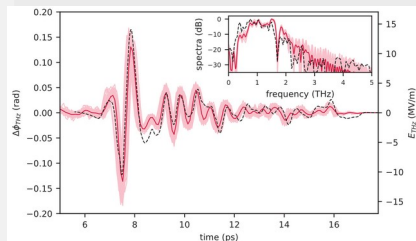
## THz sources (CSR, CTR, FEL)

UCLA FEL : M. Lenz et al. Opt. Expr 30, 33804 (2022)

FELBE FEL : I. Ilyakov et al. Opt. Expr 30, 42141 (2022)

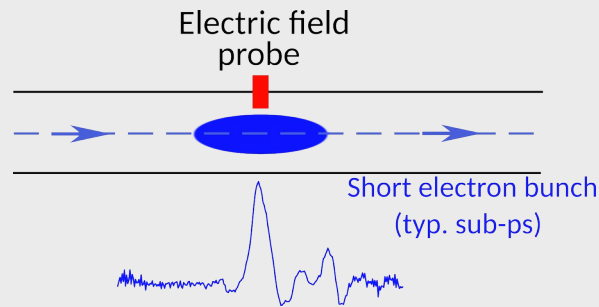
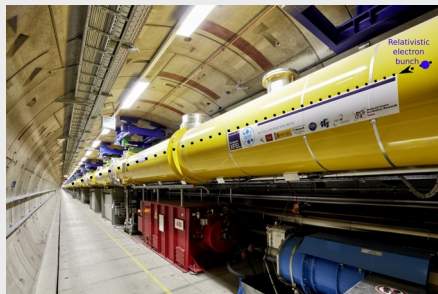
TERAFERMI CTR source: E.Roussel, et al. [Opt. Expr 31, 31072 (2023)]

### Single shot measurement of CTR at TeraFERMI



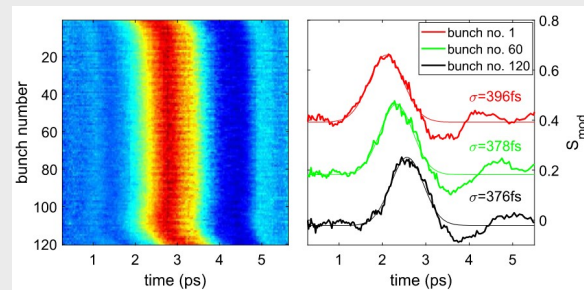
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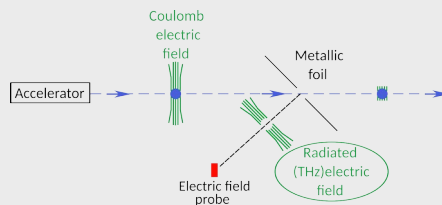
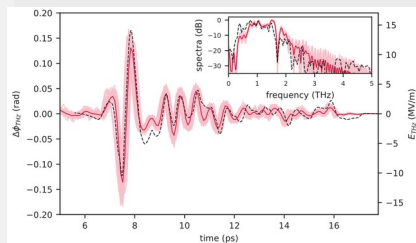
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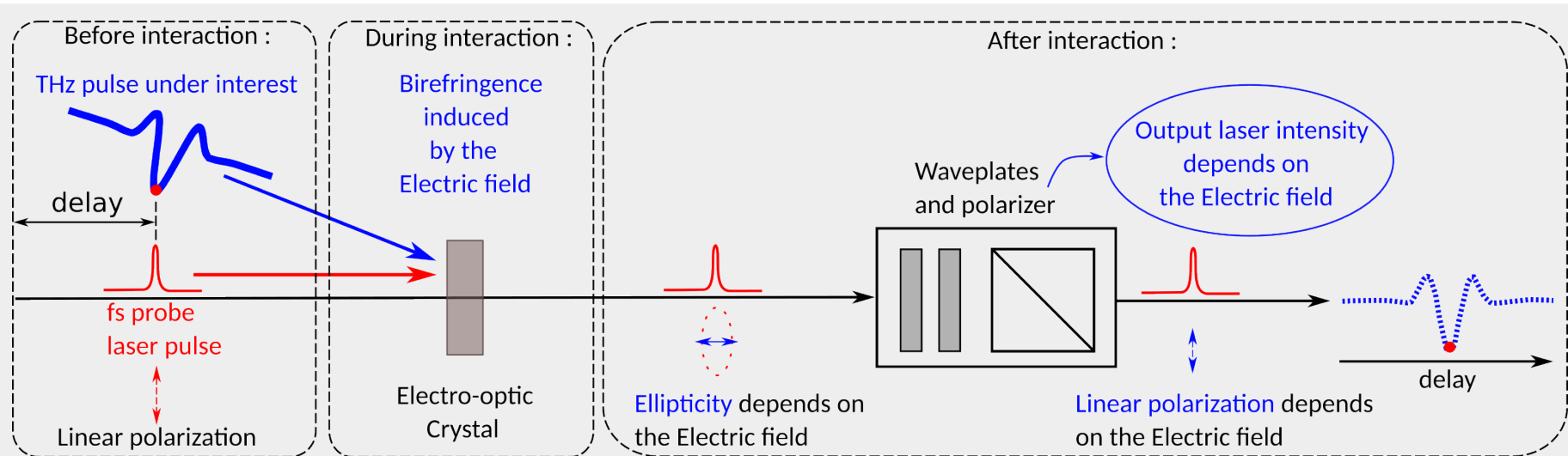
## Objective and requirements

The purpose is to **develop systems** that are able to record in **single shot** the longitudinal profile of femtoseconds relativistic electron bunches in a **non destructive** manner **at the actual state of art and beyond...**

### Challenges :

- Duration : Sub ps to few hundreds of **femtoseconds**
- Frequency : **MHz** repetition rates
- Fidelity : Minimize **distortions** or information **losses**

- The **electric field** modifies the **birefringence of the crystal** ( Pockels effect ).
- A **laser pulse** is used to **probe the birefringence** induced by the electric field under interest.
- The **bandwidth** is limited by the **laser pulse duration and the crystal speed**.

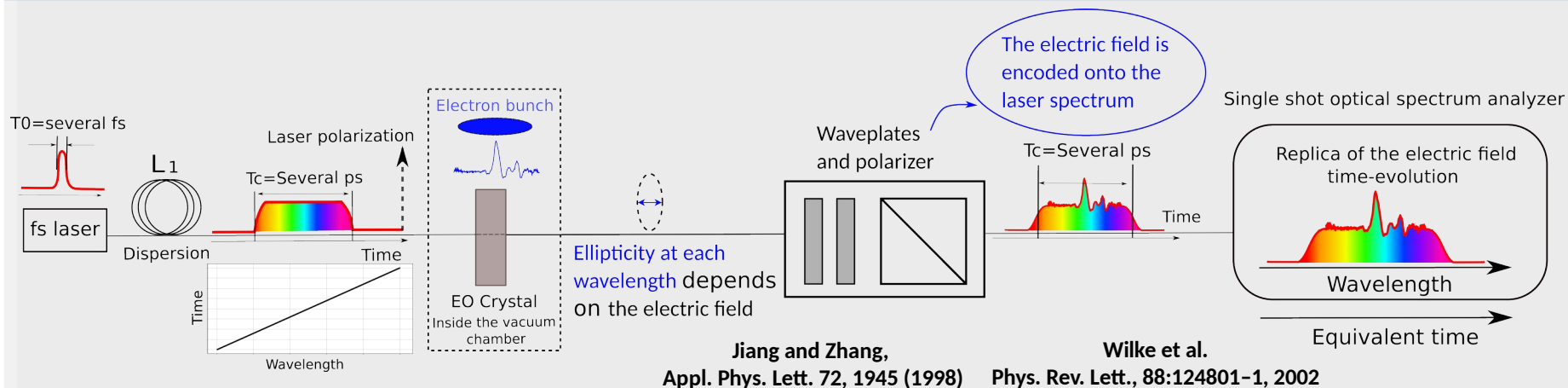


**This is NOT a single shot technique !**

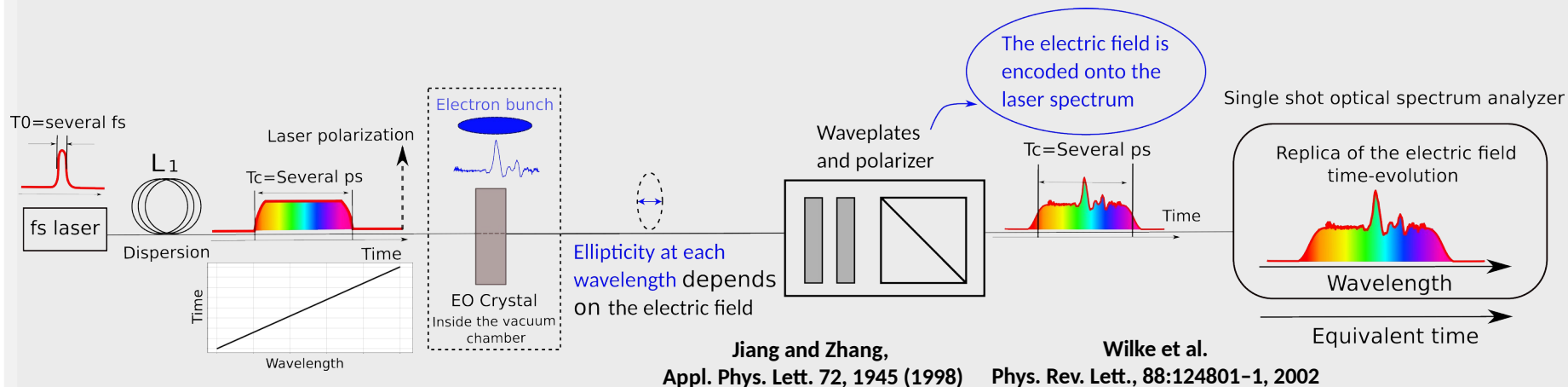
**Popular since the 80s :**

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

## Principle: time to wavelength conversion (spectral decoding)

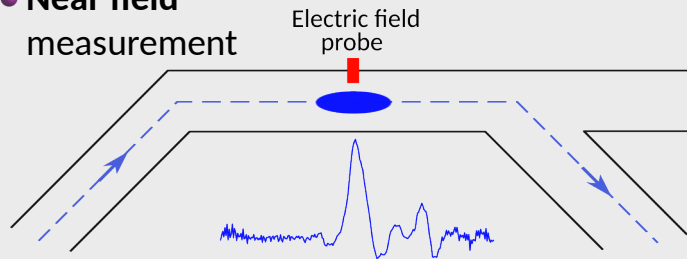


## Principle: time to wavelength conversion (spectral decoding)



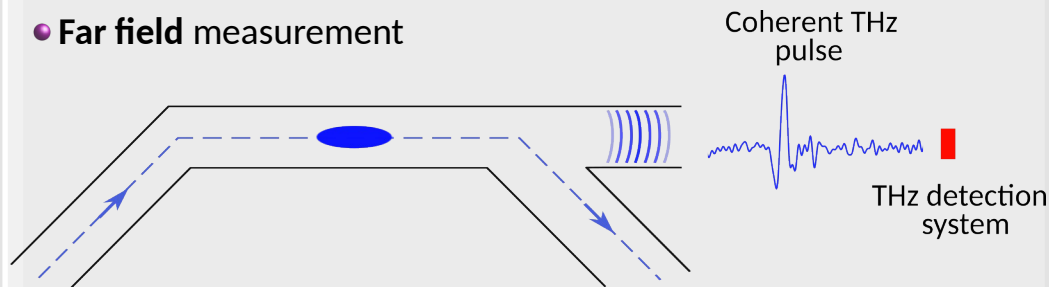
## Non destructive bunch shape measurements

### • Near field measurement



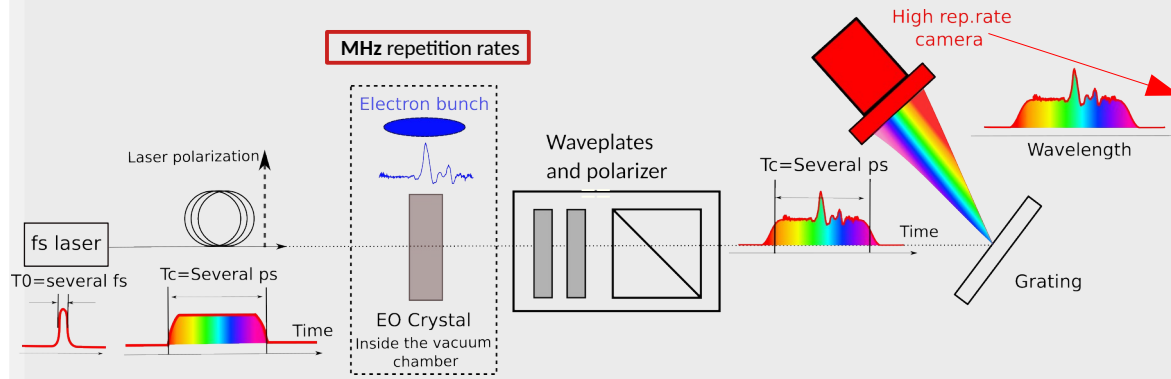
## THz pulse measurements

### • Far field measurement



# Electro-optic detection : High repetition rate single shot

## Optical spectrum analyzer : Grating + high-speed camera



### KALYPSO photodiode array detector (4M Frames/s)

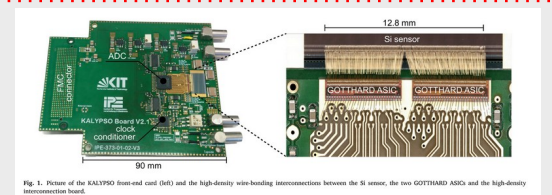
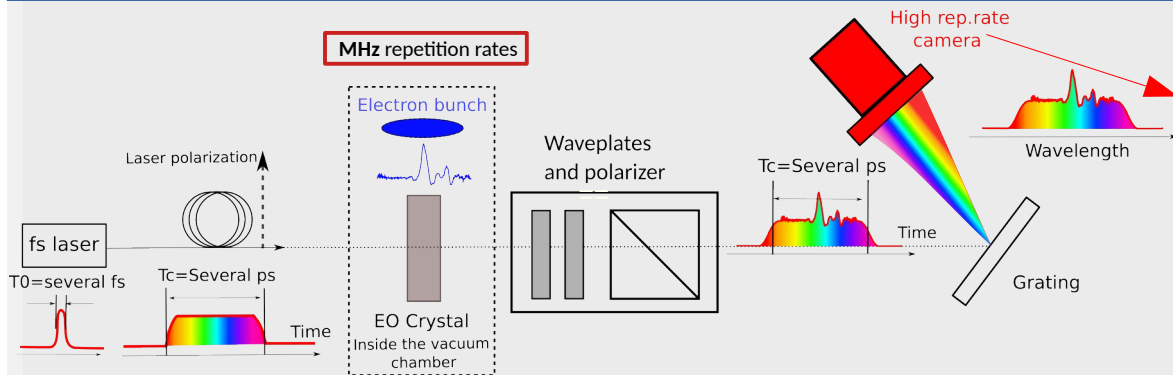


Fig. 1. Picture of the KALYPSO front-end card (left) and the high-density wire-bonding interconnections between the Si sensor, the two GOTTHARD ASICs and the high-density interconnection board.

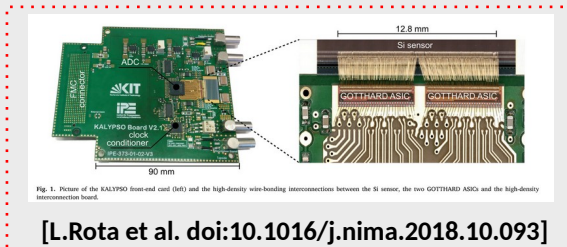
[L.Rota et al. doi:10.1016/j.nima.2018.10.093]

# Electro-optic detection : High repetition rate single shot

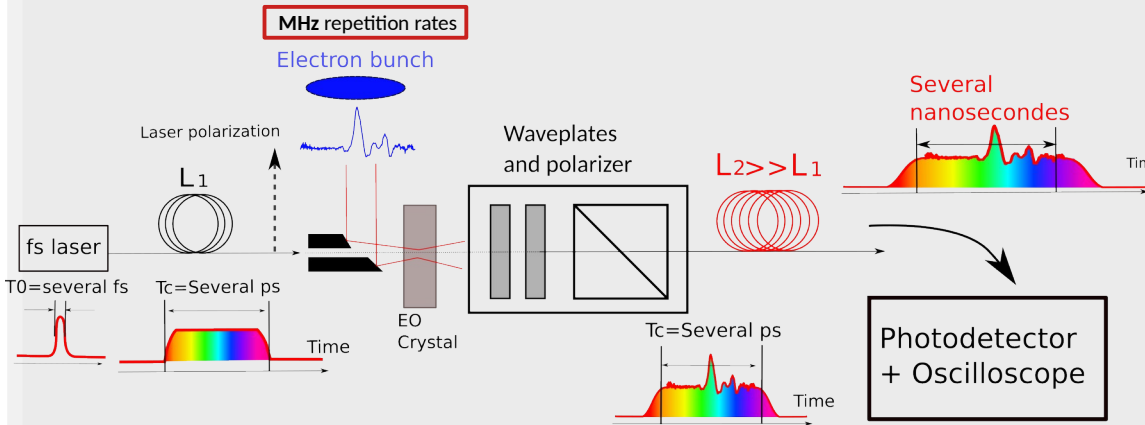
## Optical spectrum analyzer : Grating + high-speed camera



### KALYPSO photodiode array detector (4M Frames/s)



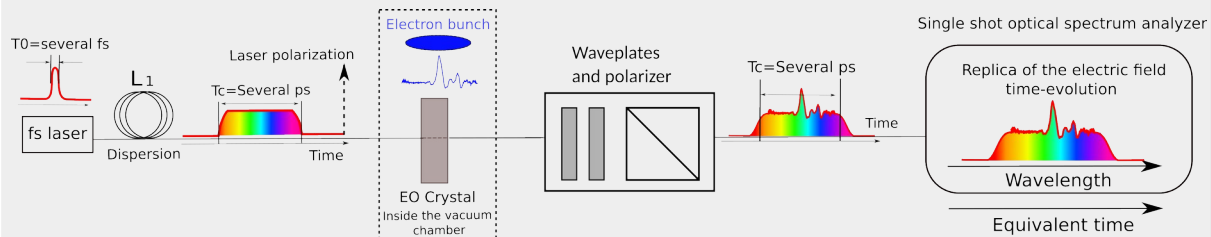
## Photonic time-stretch + photodetector and oscilloscope



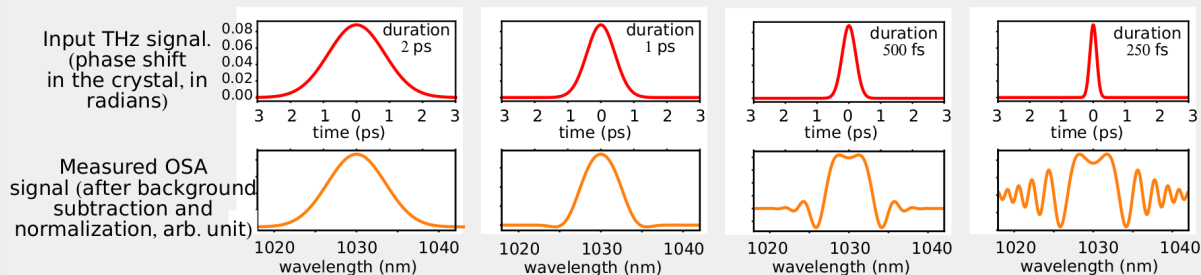
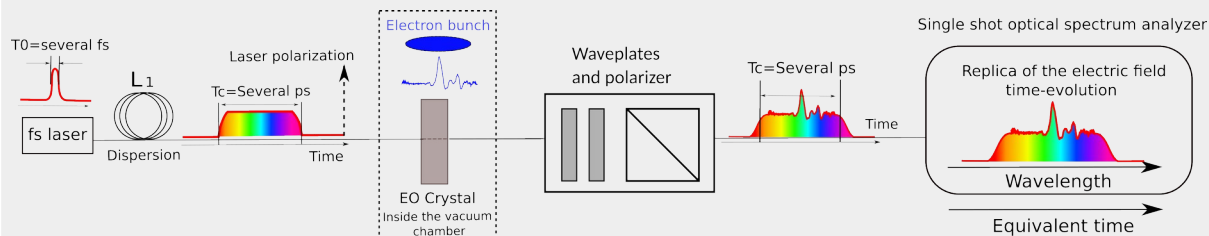
Photonic time stretch :  
[B. Jalali team, Electron. Lett. 34, 1081 (1998)]

On the oscilloscope: replica of the THz pulse that is "temporally stretched" by a factor  $M = 1 + L2/L1$ .

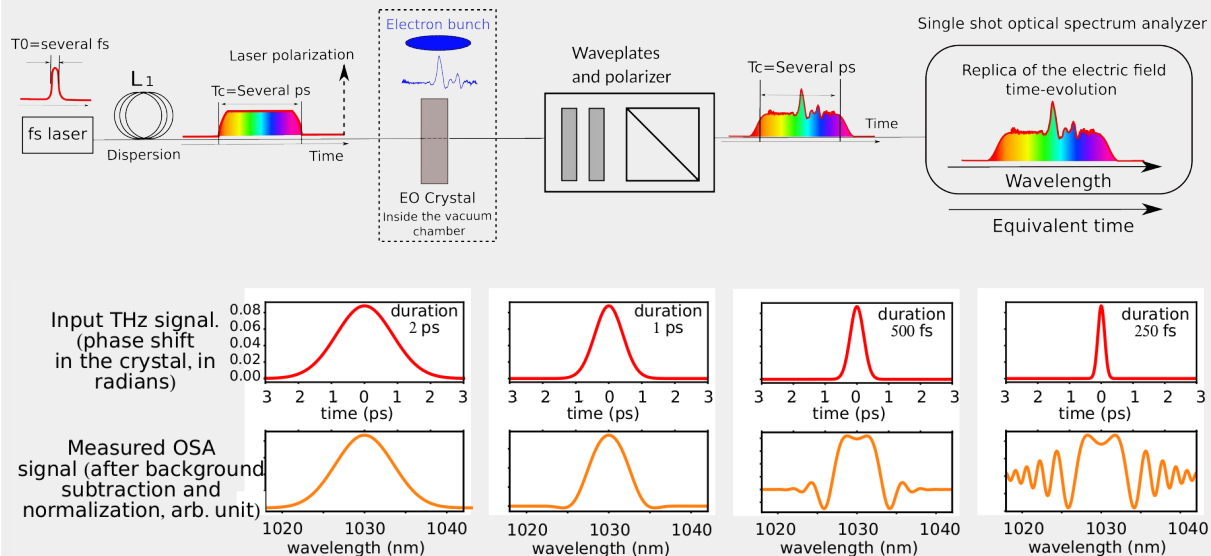
## Time resolution bottleneck : NOT due to hardware limitation



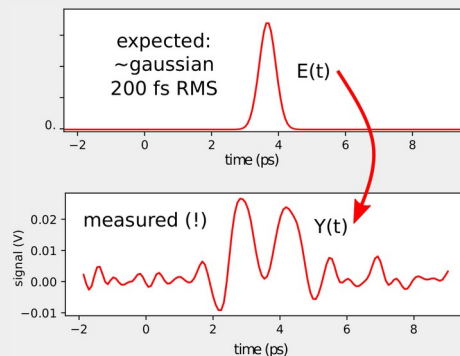
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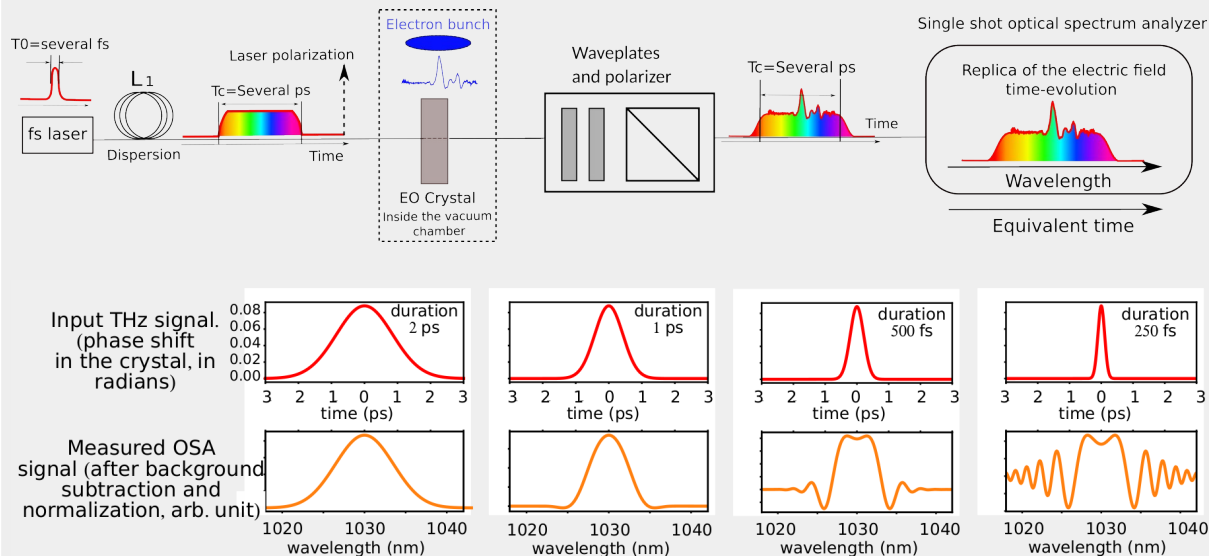
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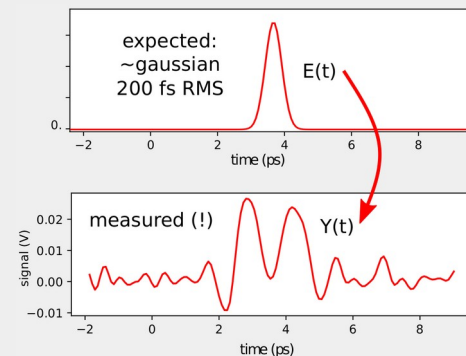
## Experimental time-resolution limitation



## Time resolution bottleneck : NOT due to hardware limitation



## Experimental time-resolution limitation



## 20 year-old bottleneck [Sun, Jiang & Zhang Appl. Phys. Lett. 73, 2233 (1998)]

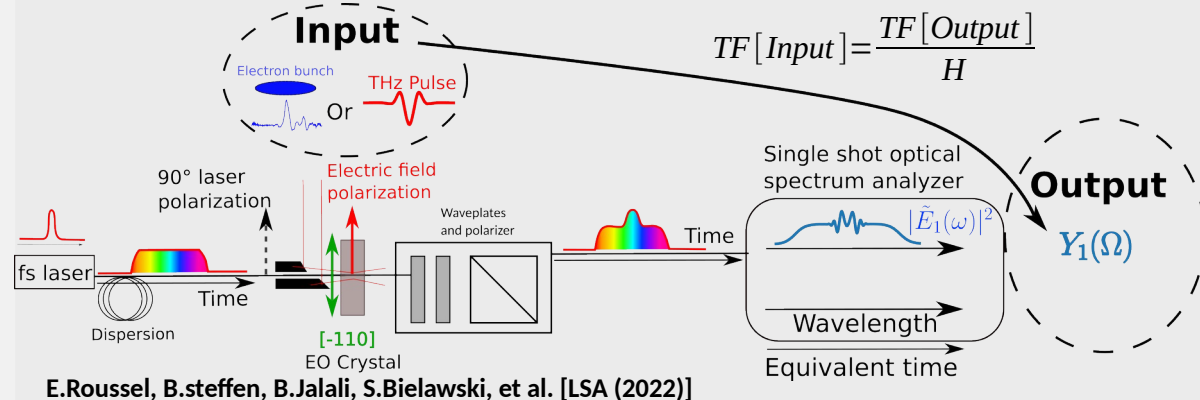
The method is not readily applicable unless there is a long bunch and/or a short analysis window.

$$t_{\text{resolution}} = \sqrt{t_{\text{window}} \times t_{\text{laser}}}$$

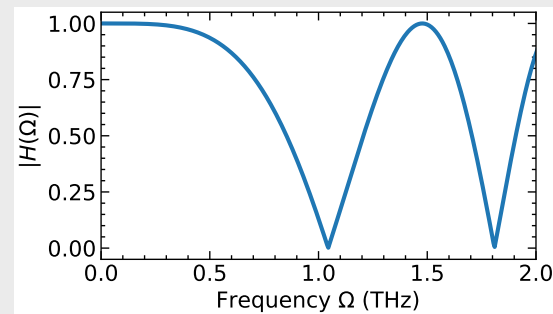
Example :  $t_{\text{window}} = 10 \text{ ps}$  and  $t_{\text{laser}} = 100 \text{ fs} \Rightarrow t_{\text{resolution}} \approx 1 \text{ ps}$

## Standard EO (Hardware)

- Standard EO using only one output



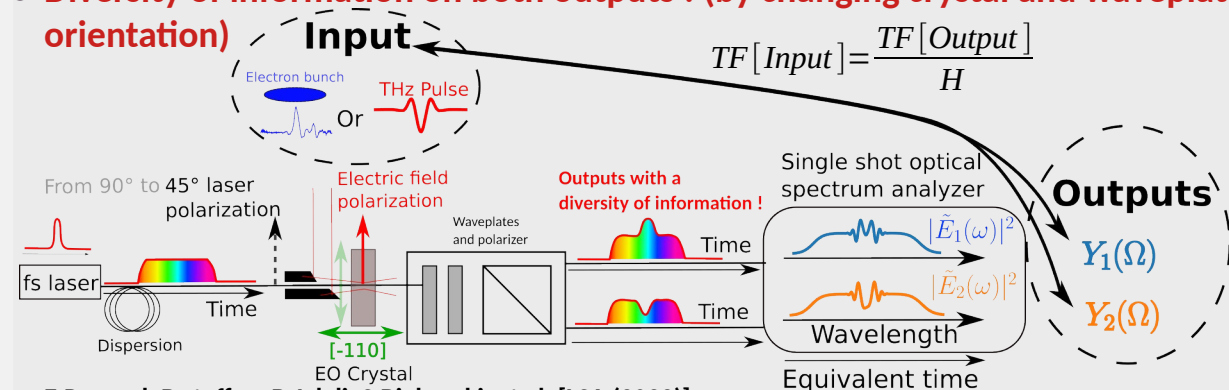
**H = Transfer functions**  
(i.e. : Fourier transform of the outputs)



**Some frequency are missing !**

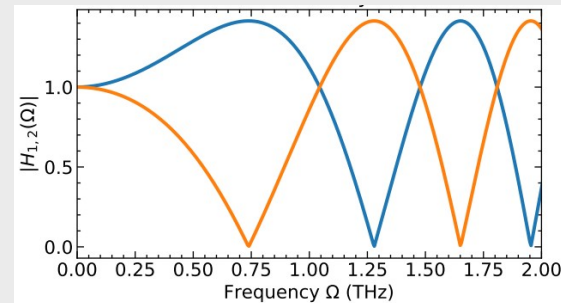
## Phase diversity (Hardware)

- Diversity of information on both outputs ! (by changing crystal and waveplates orientation)



E.Roussel, B.steffen, B.Jalali, S.Bielawski, et al. [LSA (2022)]

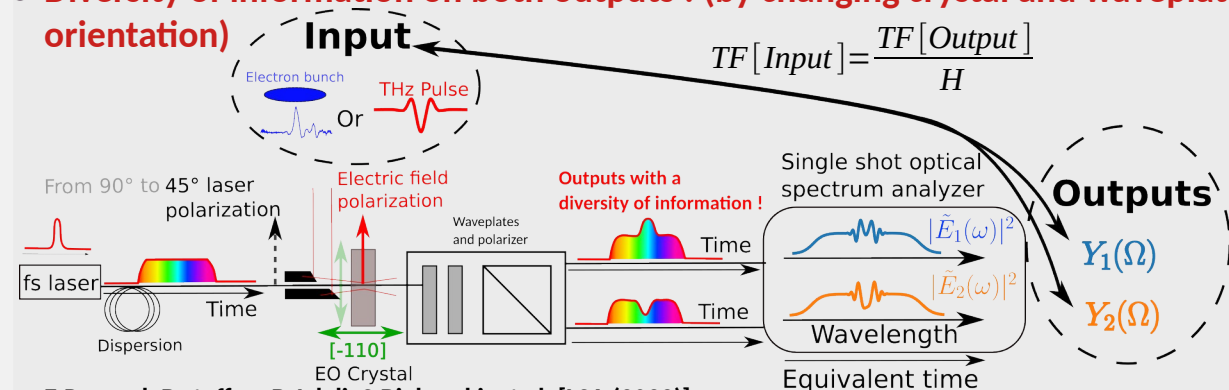
**H = Transfer functions**  
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Interleaved zeros

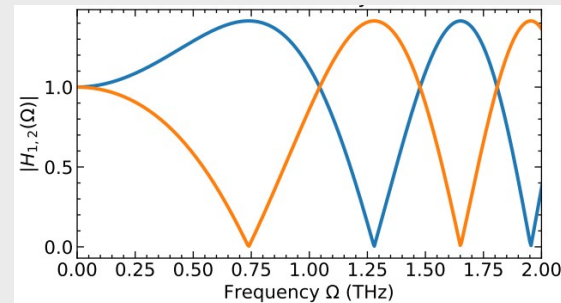
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(i.e. : Fourier transform of the outputs)



## MRC algorithm (Software)

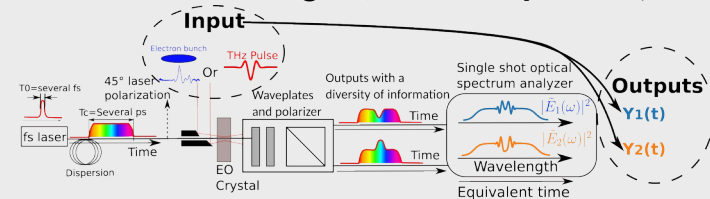
- Need of a **software method** to retrieved the input (i.e. the electron bunch shape) :

Maximum Ratio Combining (MRC) algorithm :

$$\tilde{E}_R(\Omega) = \frac{H_1(\Omega)\tilde{Y}_1(\Omega) + H_2(\Omega)\tilde{Y}_2(\Omega)}{|H_1(\Omega)|^2 + |H_2(\Omega)|^2} \quad \tilde{E}_R(\Omega) : \text{Input electric field retrieved}$$

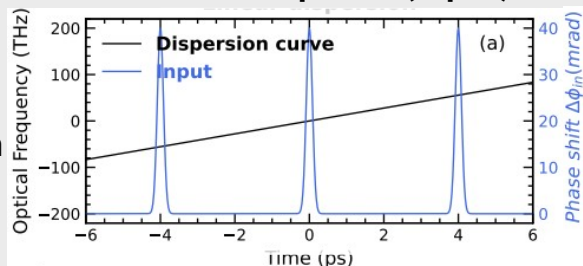
**This is the usual software method to reconstruct the input but there are some limitations ...**

- System described by transfer function need to be **invariant by translation in time** !
- Since we encode our signal onto a **chirped probe laser**, time is strongly linked with **wavelength** (due to dispersion)

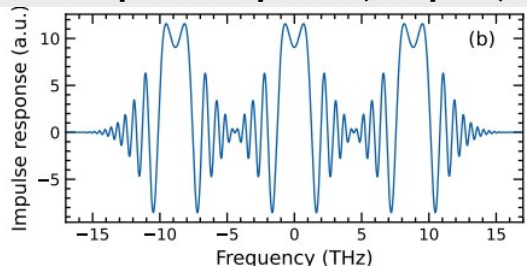


## Time invariance breaking : Illustration

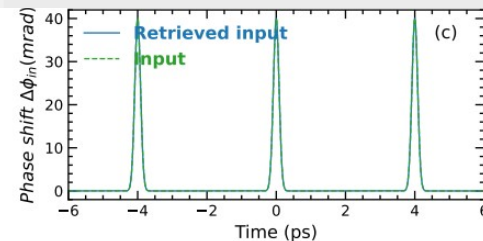
Three short pulses (Input)



Impulse response (Outputs)

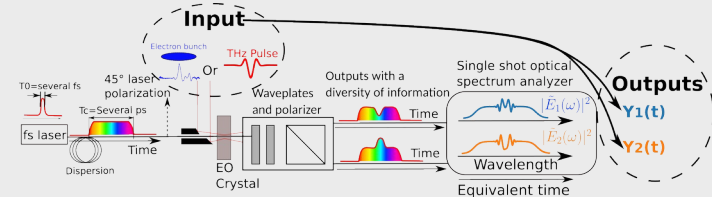


## MRC Reconstruction



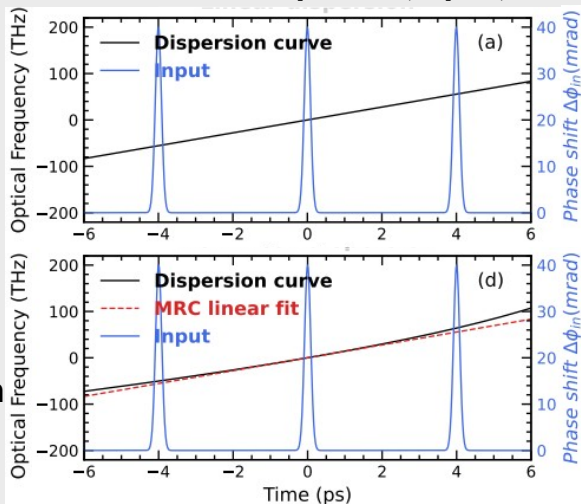
Linear  
dispersion

- System described by transfer function need to be **invariant by translation in time** !
- Since we encode our signal onto a **chirped probe laser**, time is strongly linked with **wavelength** (due to dispersion)
- The **time invariance** of our system is **broken by higher order dispersion**
- The **system** cannot be interpreted as **transfer functions anymore** !

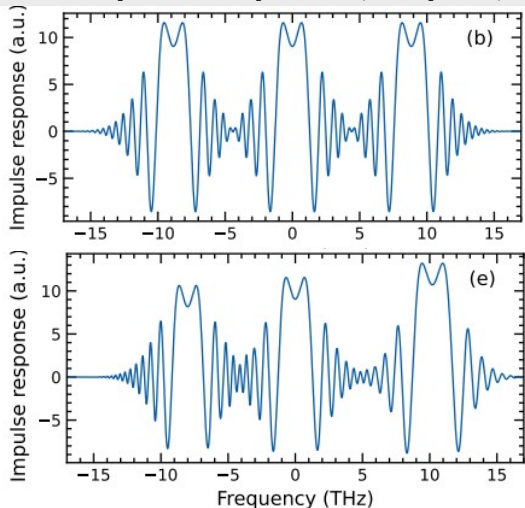


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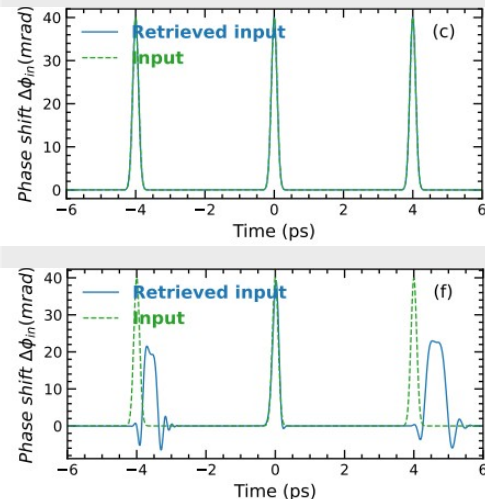
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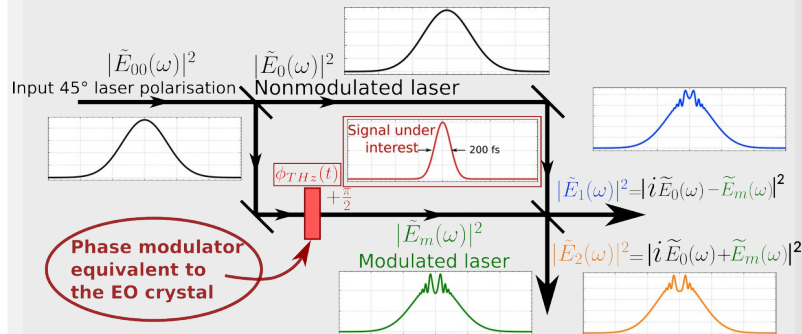
Impulse response (Outputs)



## MRC Reconstruction

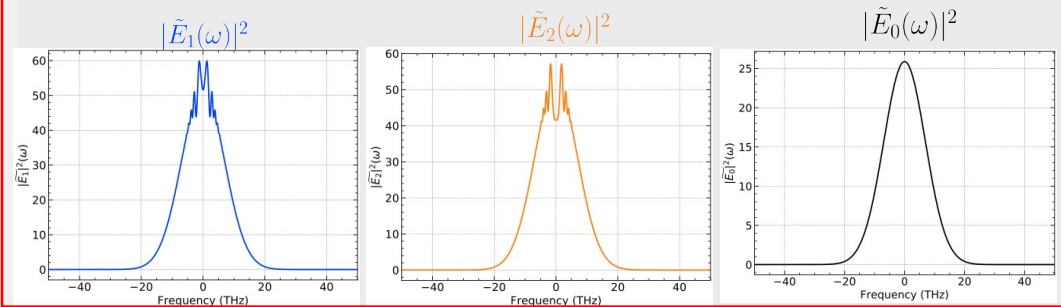


DEOS setup  $\equiv$  Mach-Zehnder interferometer

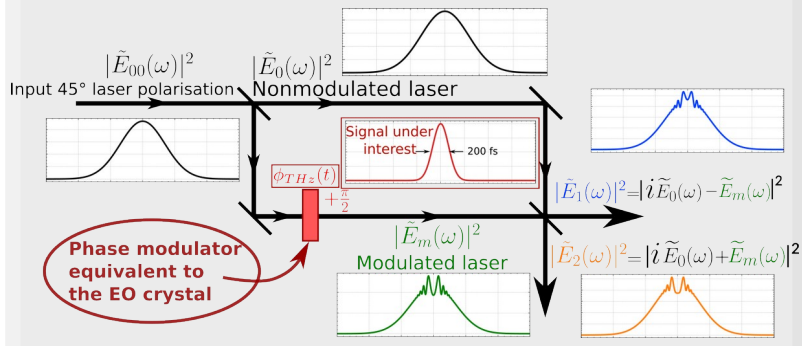


Signals to be recorded

Recorded signals

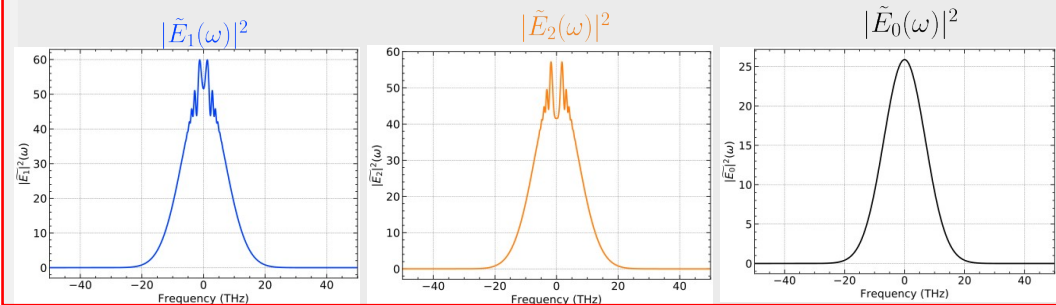


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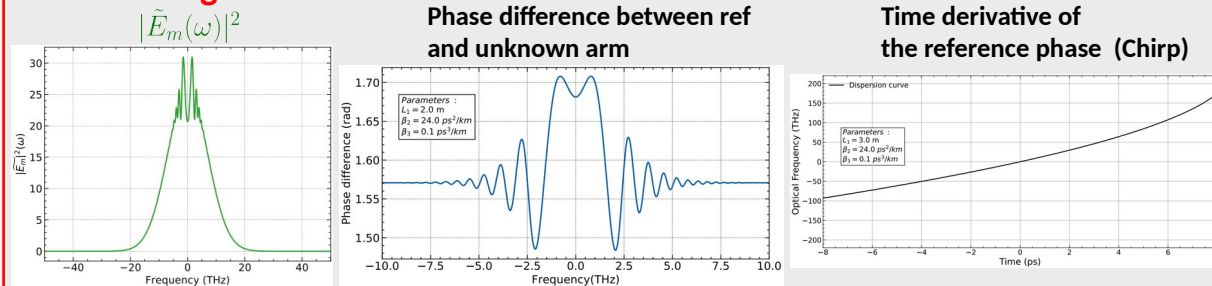
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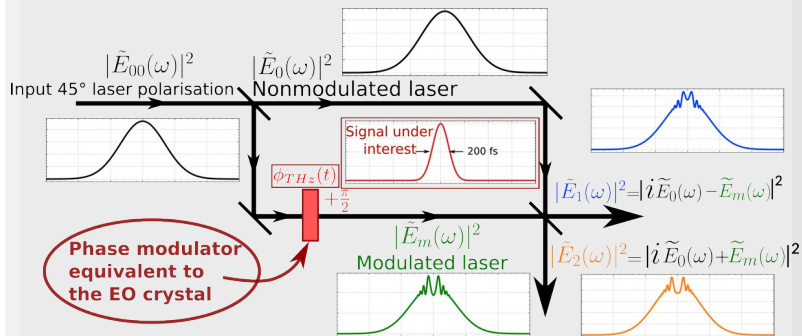
## Reconstruction based on Spectral Interferometry for Direct Electric field Reconstruction (SPIDER)

### Retrieved signals



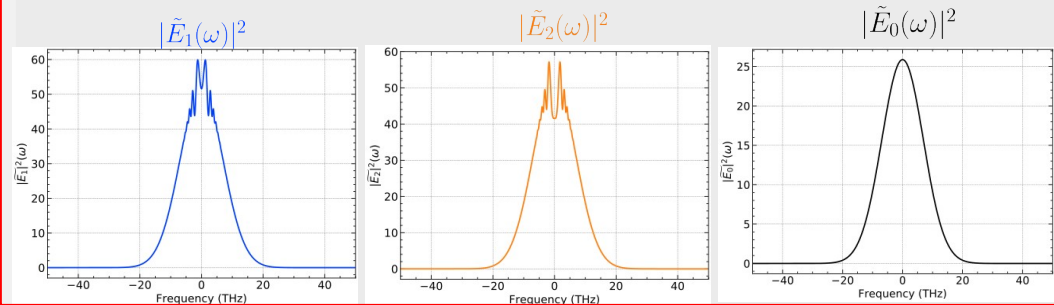
Using this information, we are able to reconstruct the complex electric field of the reference and unknown arm

## DEOS setup $\equiv$ Mach-Zehnder interferometer



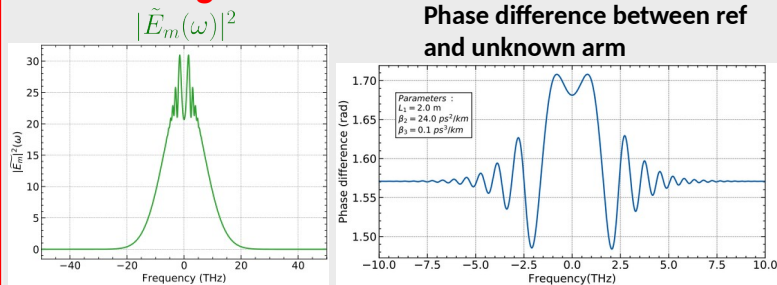
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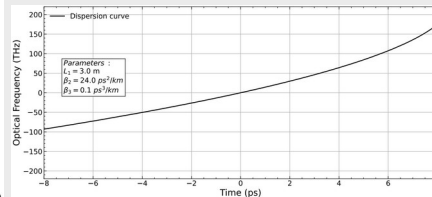


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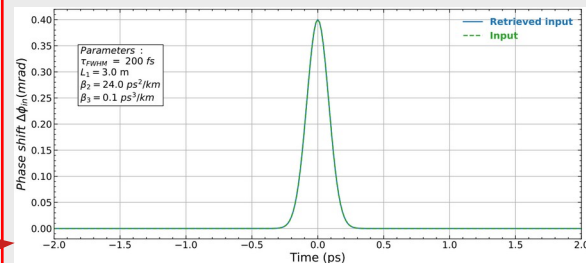
### Retrieved signals



### Time derivative of the reference phase (Chirp)



### Reconstruct signal

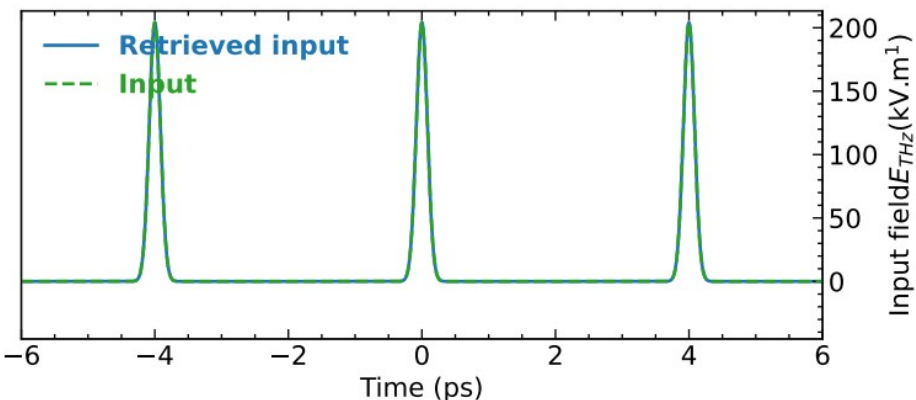
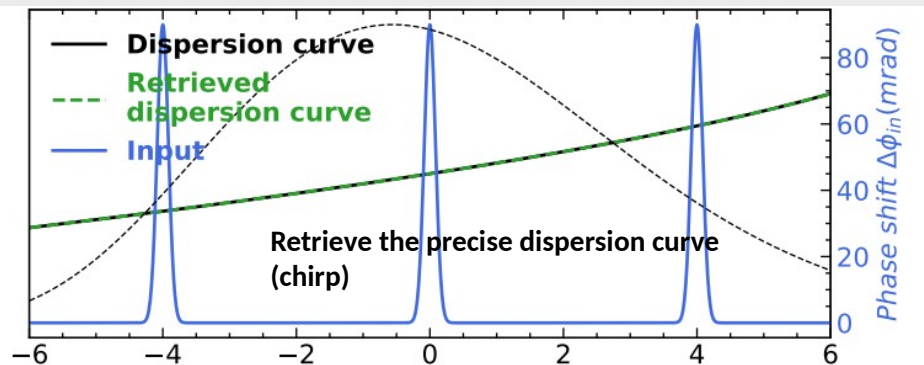
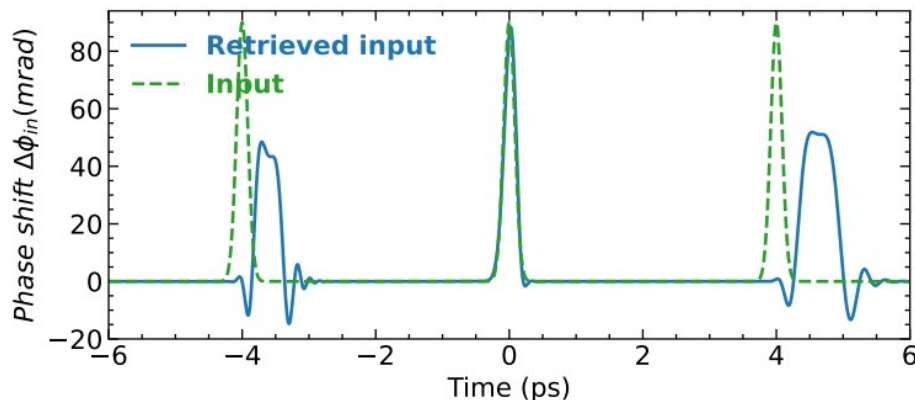
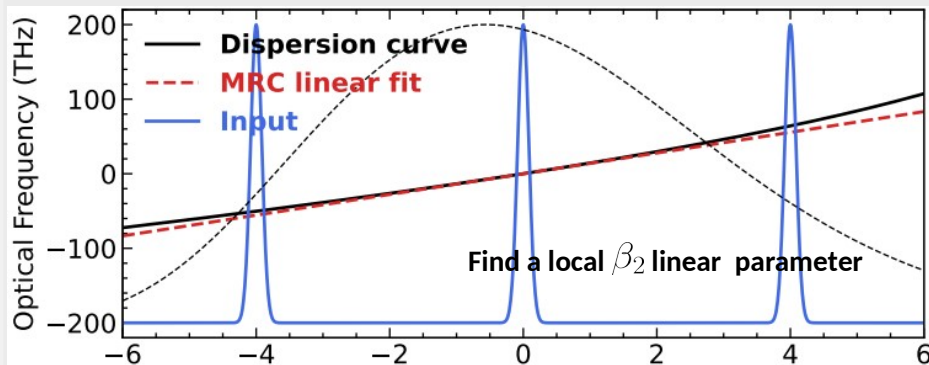


Using this information, we are able to reconstruct the complex electric field of the reference and unknown arm

## Comparison between MRC and the new reconstruction algorithm

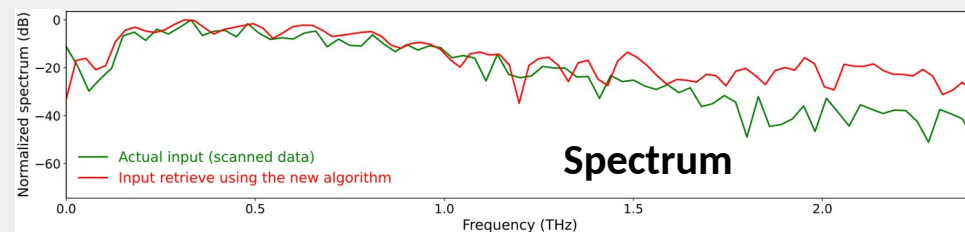
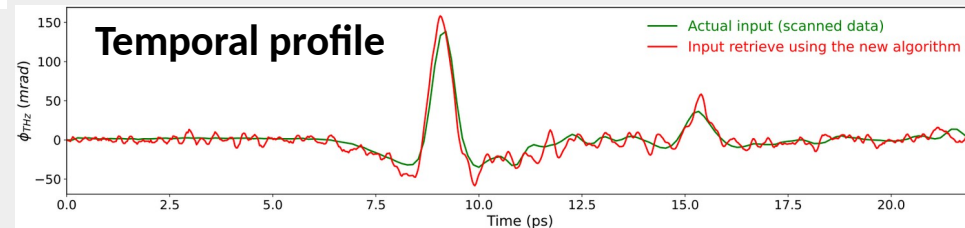
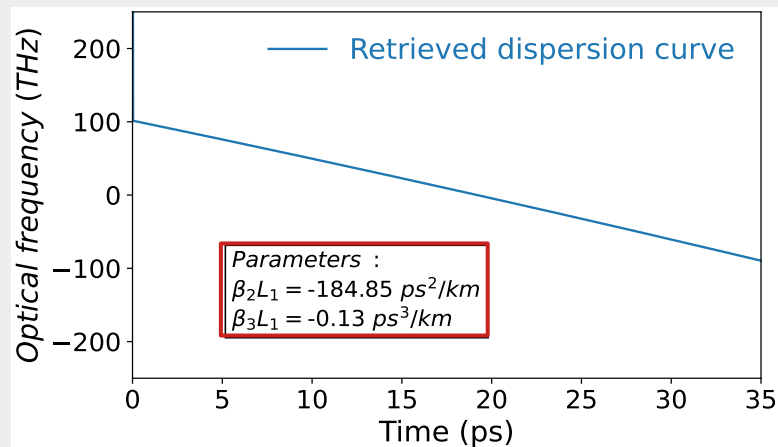
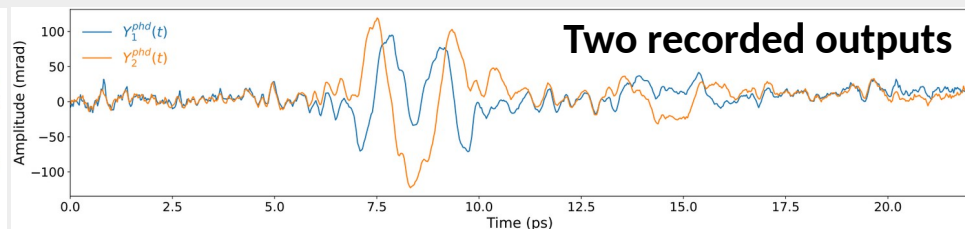
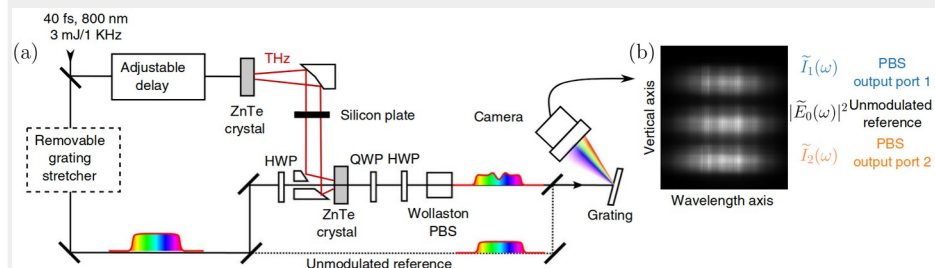
### MRC algorithm

### New algorithm



## Table top experiment at PhLAM recorded with a grating+camera

### Table top experiment at PhLAM (Lille, France) Laser based THz source



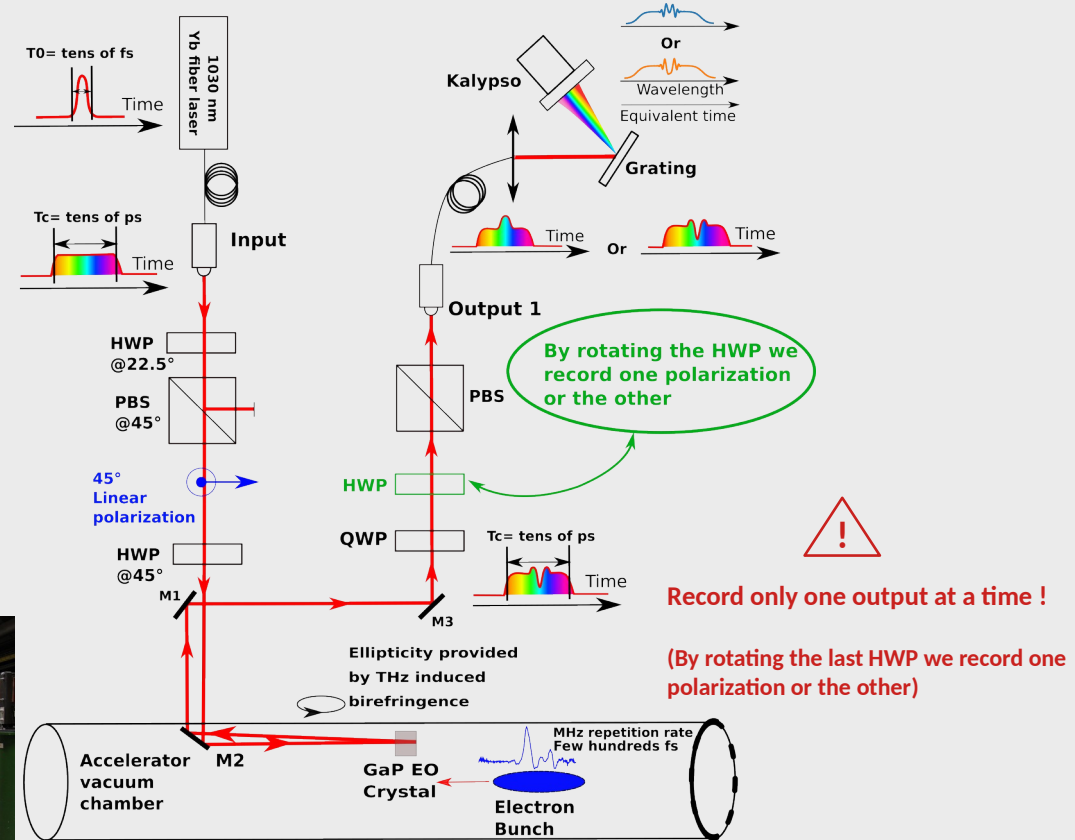
***Single-shot electron bunch shapes***  
***Diagnostic at DESY (EuXFEL and FLASH)***

## Optical setup using grating and fast camera

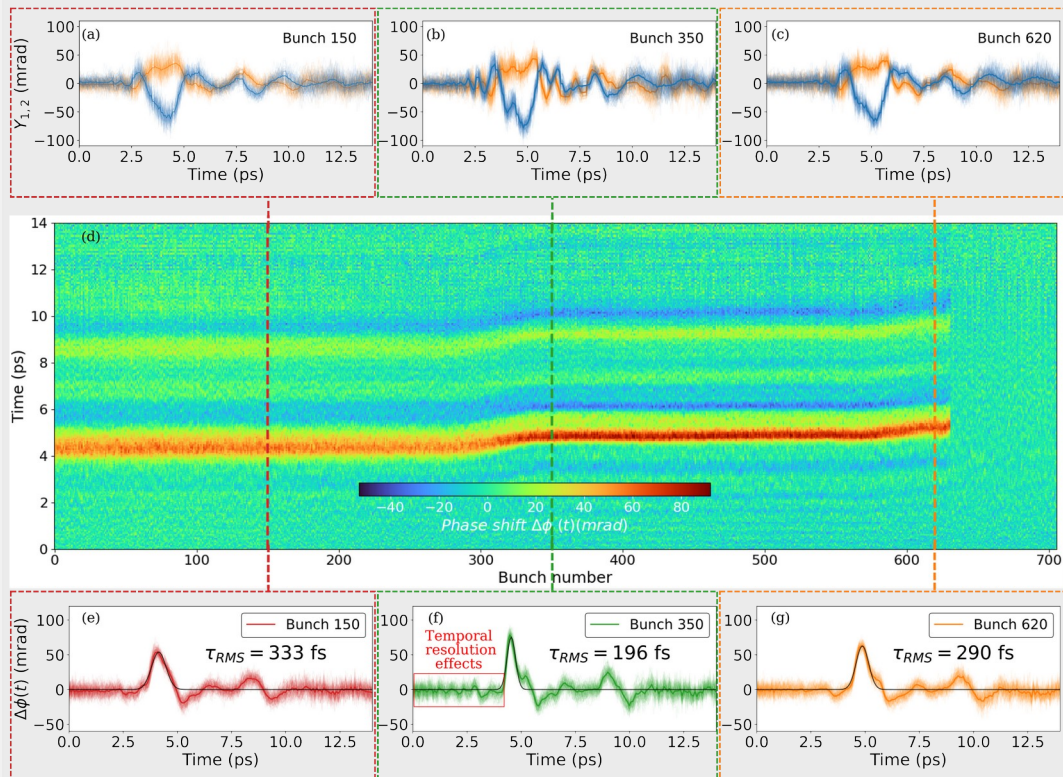
### Optical setup of EuXFEL



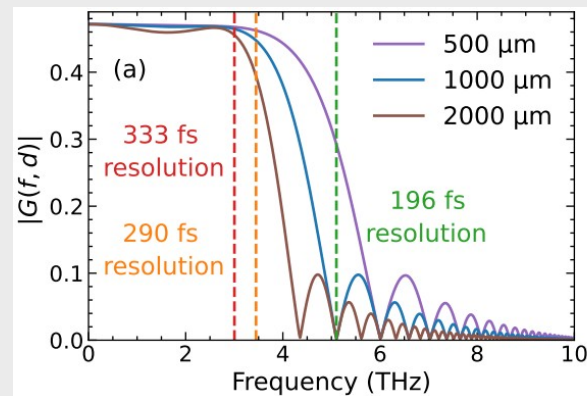
EuXFEL tunnel



## Reconstructed electron bunch train with different electron bunch compression at MHz+ rep rate



### EO response of the EO crystal



- Measurement during special configuration of the electron bunch train.
- Three different electron bunch compression in a single train !  
(For the three different user beamlines)

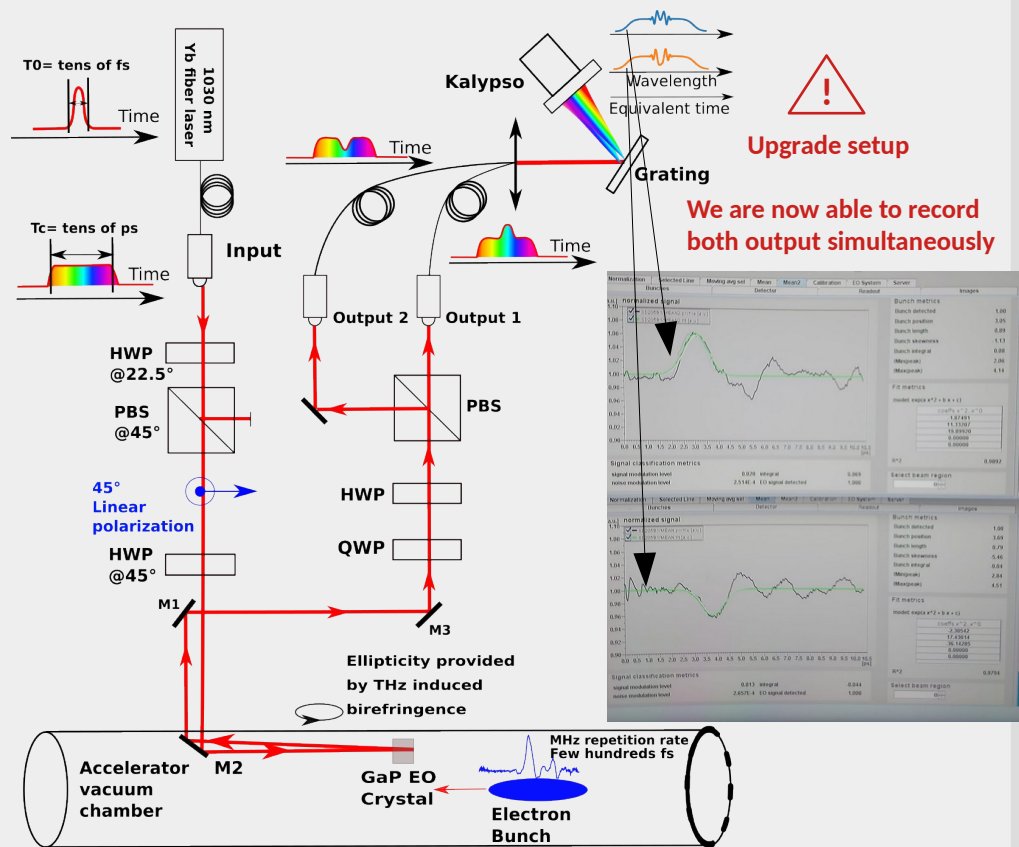
## Optical setup at FLASH



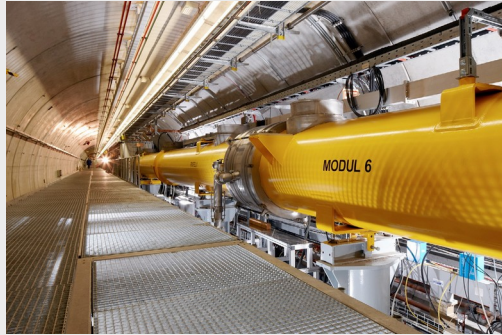
**FLASH.**  
Free-Electron Laser FLASH

FLASH tunnel

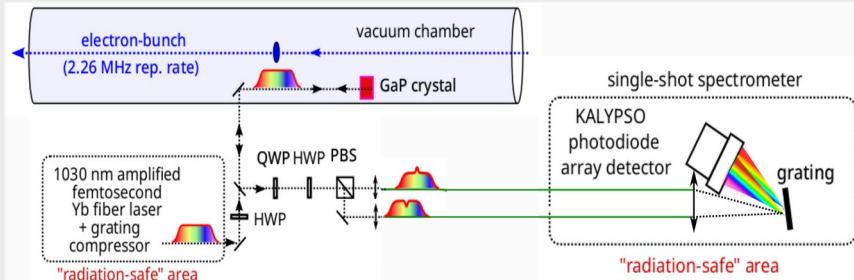
**Easier access than EuXFEL  
to upgrade the setup**



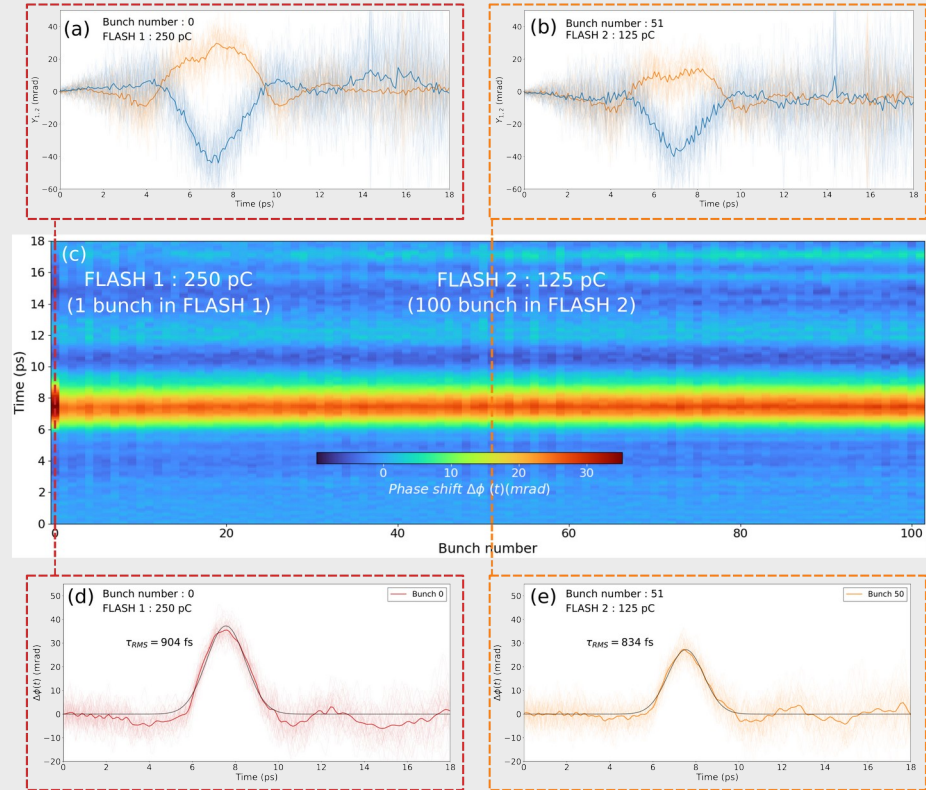
## Reconstructed electron bunch train with different bunch charge at FLASH at MHz+



**FLASH.**  
Free-Electron Laser FLASH



- Two different electron bunch compression in a single train !
- One electron bunch for FLASH 1 and one hundred for FLASH 2



***Carrier Envelope phase (CEP)***  
***Diagnostic at FELBE***

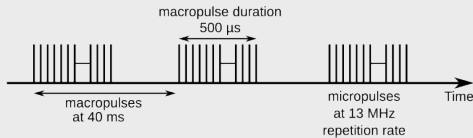
## FELBE parameters

- **FELBE: Multi-cycles THz pulses at frequencies ranging from 1.2 THz up to 60 THz**

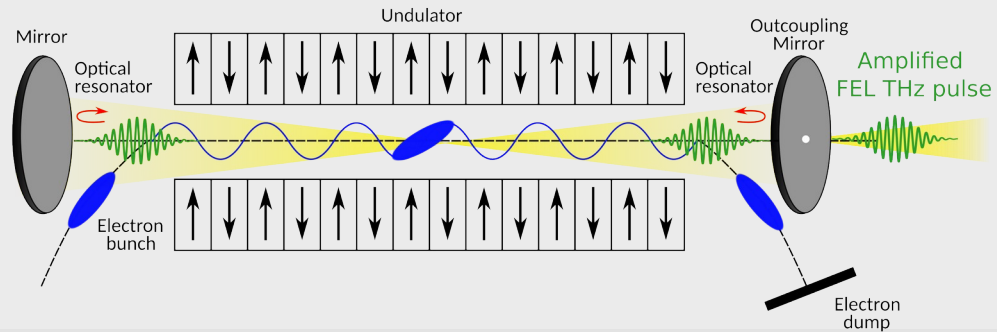
- **38 number of periods**

Example:  $N=38$ ,  $\nu_{\text{THz}} = 4 \text{ THz} \rightarrow T = 9.5 \text{ ps}$

- **Repetition rates at 13 MHz**



## FEL oscillator : Principle



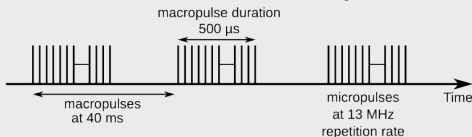
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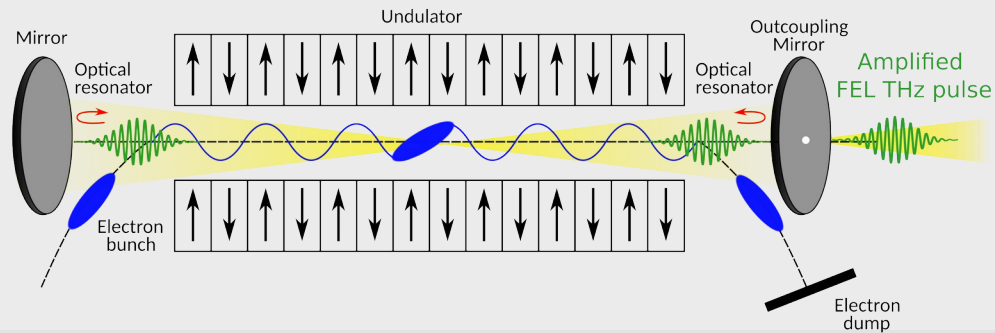
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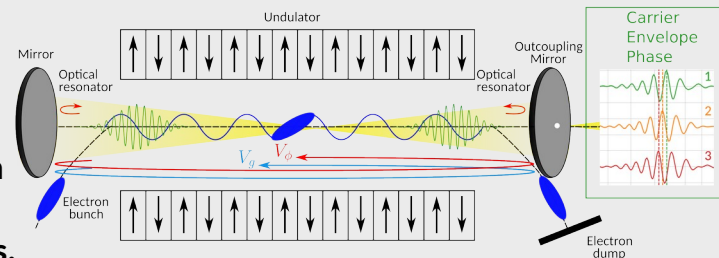


## Motivations : Carrier envelope phase (CEP)

- **Velocity mismatch between phase and group velocity when they interact in the amplifying medium (i.e. the electron bunch)**

**Solution :**

**Adjust a mirror position and provide feedback using EO measurements.**



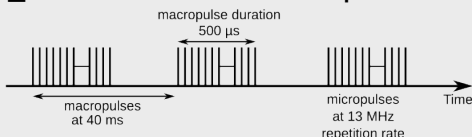
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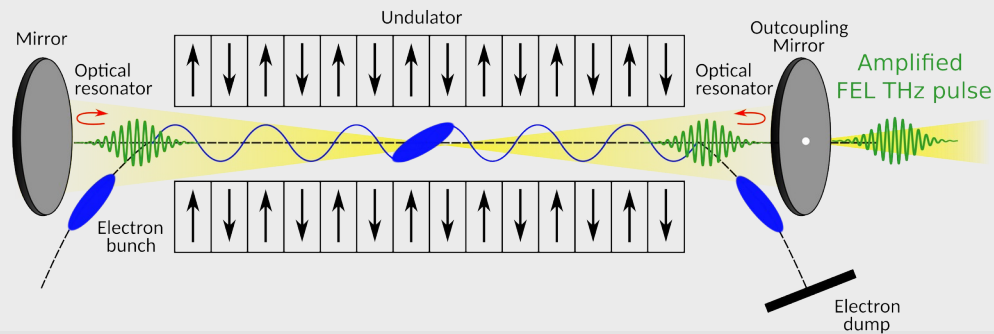
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- **Repetition rates at 13 MHz**



## FEL oscillator : Principle



## Other FEL already interested in monochromatic THz pulses CEP diagnostic

- Pitz (Berlin)
- Stern (DESY)

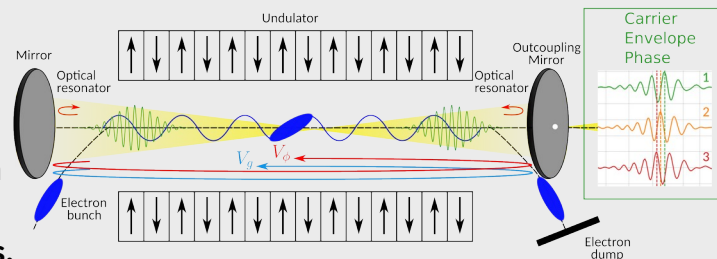


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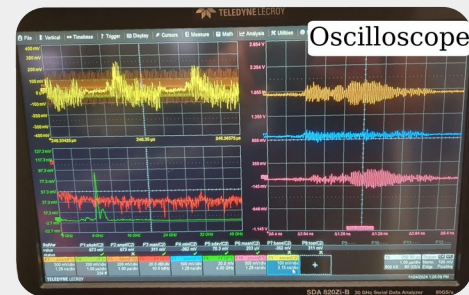
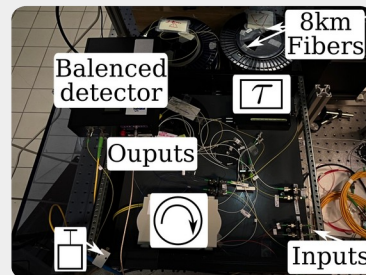
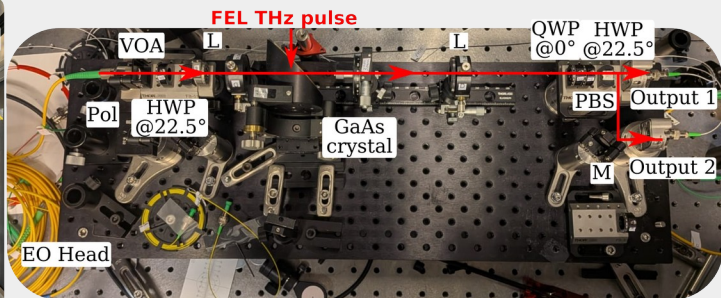
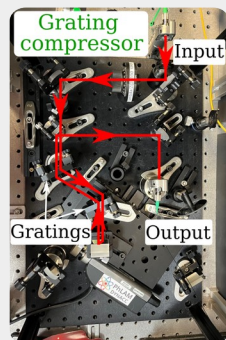
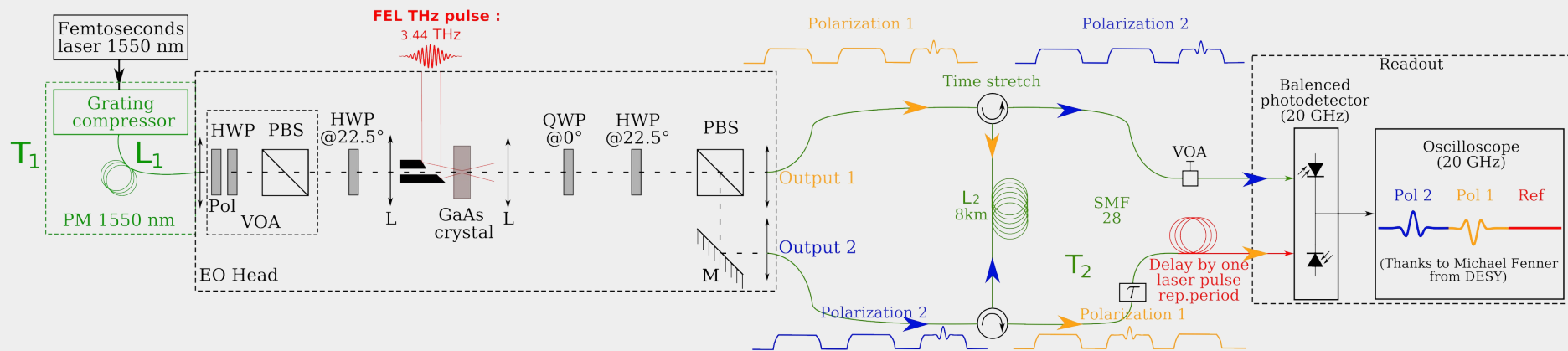
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# Detection schemes for CEP diagnostic at FELBE

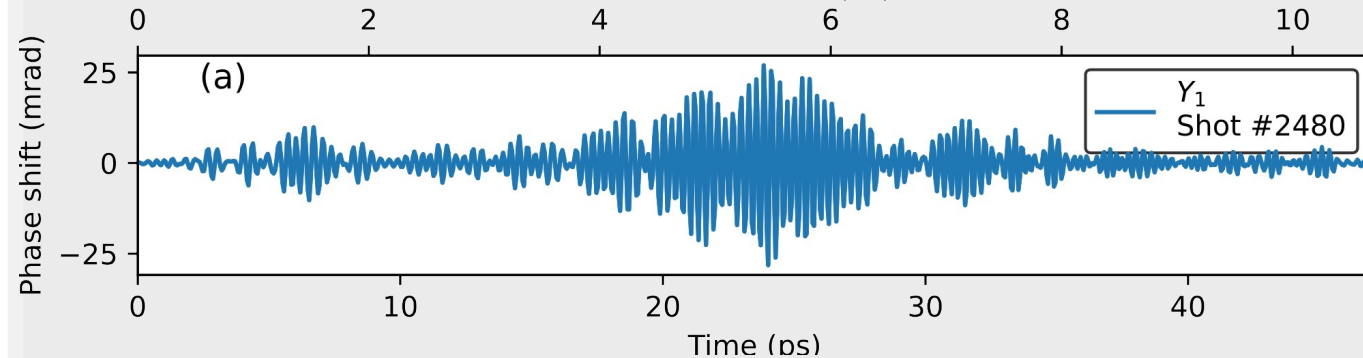
## Overview of the experimental DEOS setup combined with photonic time stretch at 1550 nm



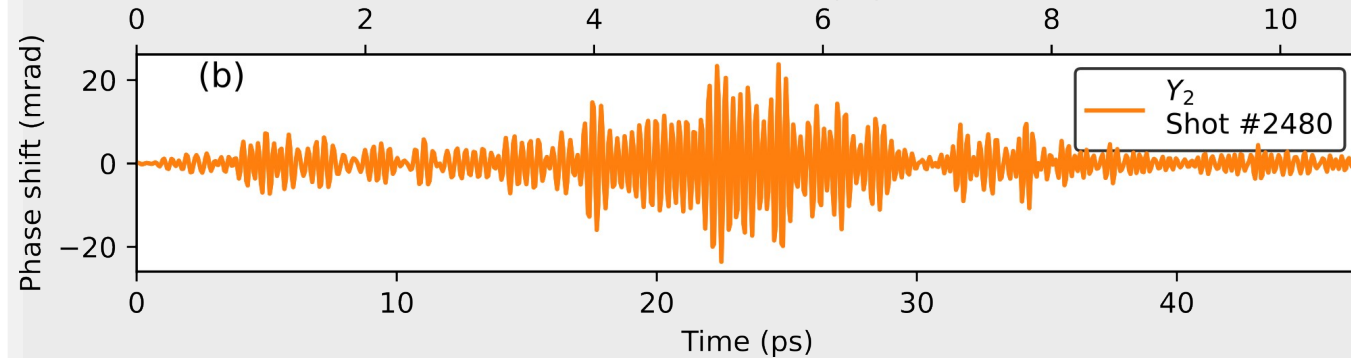
## Dual single-shot recorded outputs from the DEOS setup

### Temporal profile

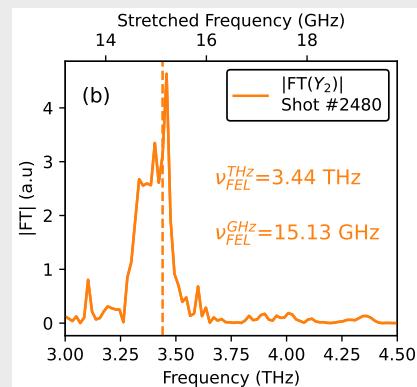
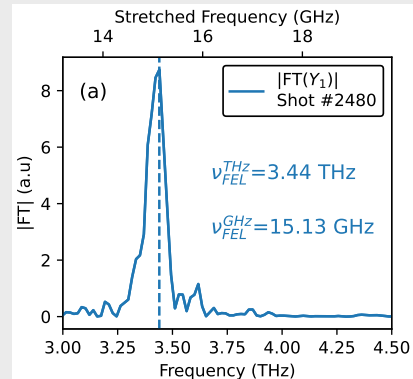
Stretched time (ns)



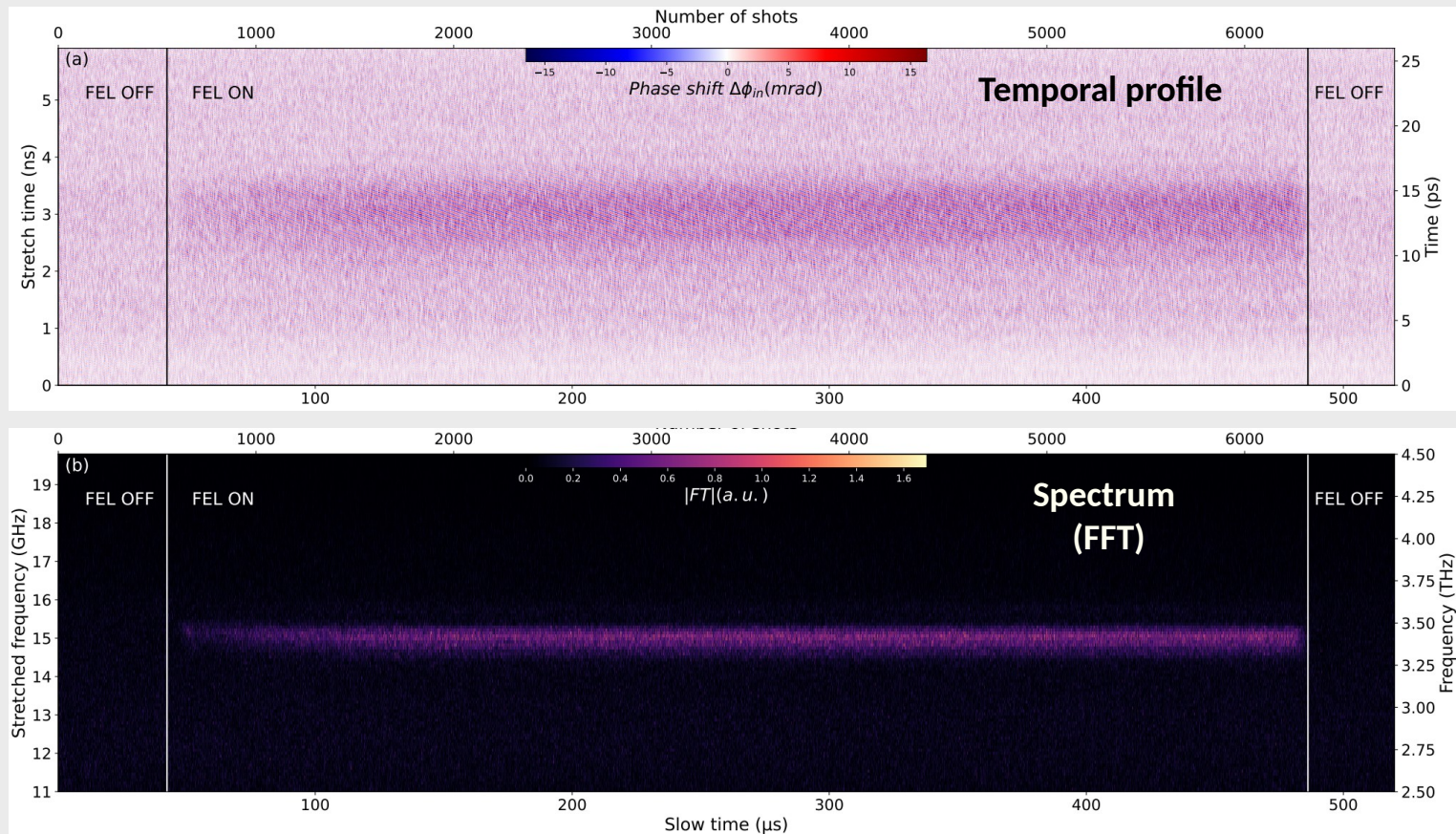
Stretched time (ns)



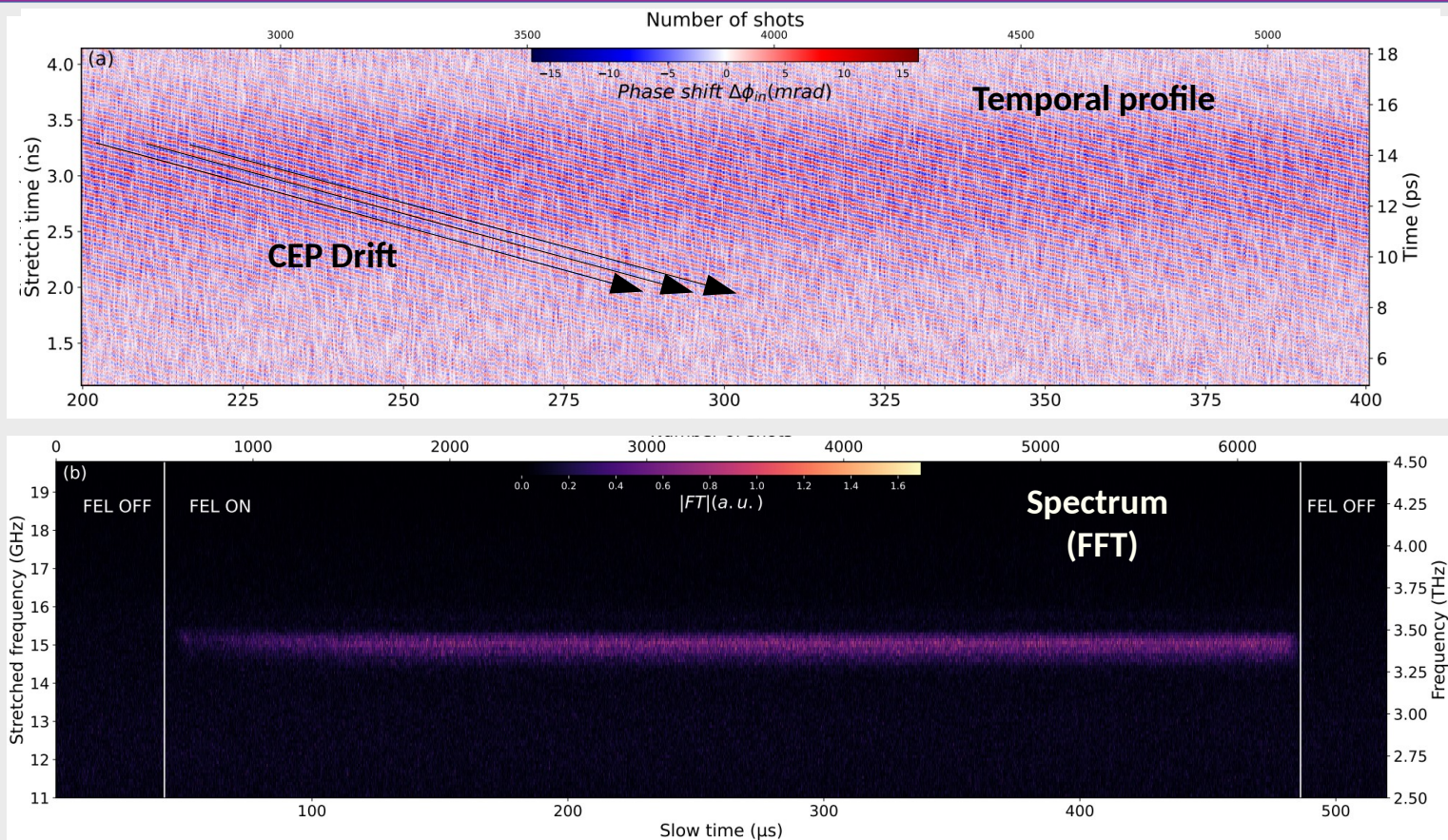
### Spectrum (FFT)



## Entire single-shot FEL macropulse of FELBE

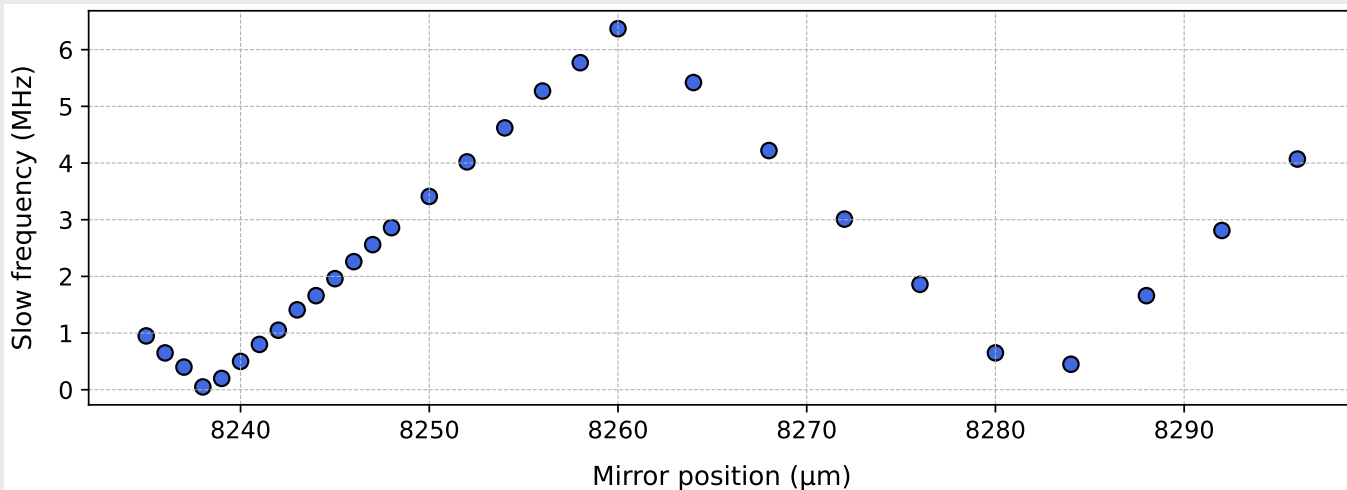
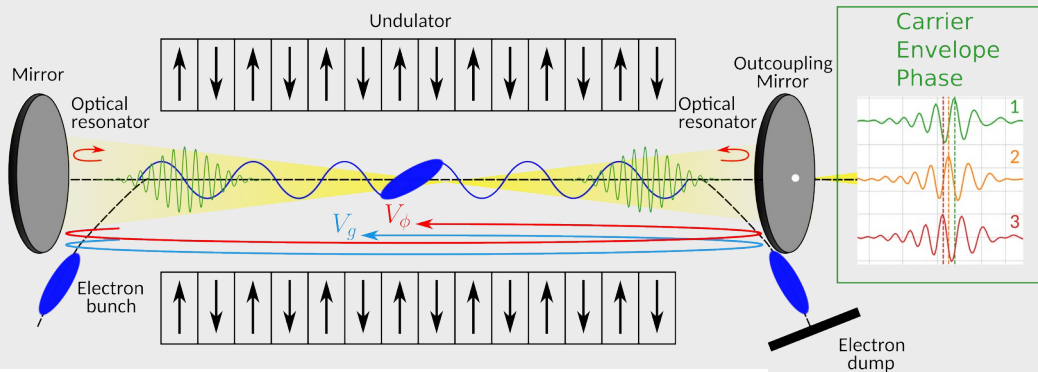


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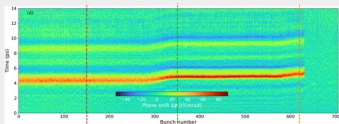
## Study of the CEP vs detuning of the cavity

- The **CEP** is tuned by changing the **mirror position**
- The **CEP** varies periodically with a period of  $\frac{\lambda}{2}$



## DESY

- DEOS technique  
→ measurement of **hundreds femtoseconds electron bunch shapes** at XFEL, at MHz+ rep. Rate
- Expected resolution limitations  
→ **laser and crystal bandwidths**
- **New reconstruction algorithm** able to cope with any (reasonable) laser chirp (linear or not)

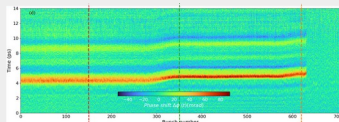


## Perspectives

- **Increasing temporal resolution** using a thinner EO crystal.
- **Implementation** of a **real-time** reconstruction algorithm with a **user-friendly interface** for non-specialists.

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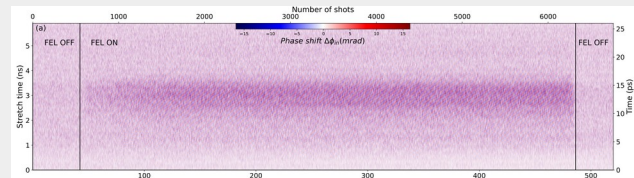


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- **First recording of an entire FEL macropulse** in **single-shot** (from turn-on to turn-off)

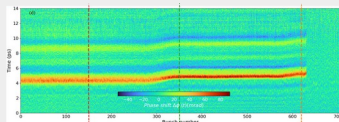


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- Measurements were performed at 3.44 THz **BUT** FELBE can generate multi-cycle THz pulses **up to 60 THz**.  
**How to record them ?**
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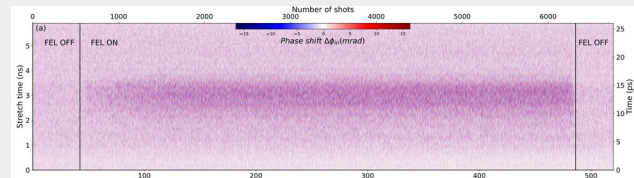


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## Main take home message about DEOS

- This **single shot DEOS system** can be applied to any THz electric field at **low** and **high** repetition rates (**Tabletop or Accelerator based sources**)

# Thank you for your attention !

## Photos taken during our winter shift measurement at HZDR Dresden

