Demonstration of time-stretch Electro-optical sampling, with phase-diversity at the Radiation Source ELBE

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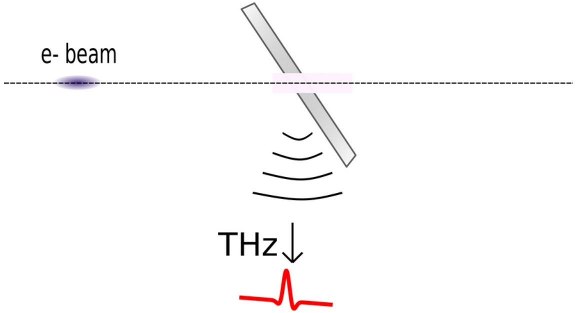
Single-shot THz pulse measurements: motivation and challenges

General motivations:
- Obtain information on bunch shapes
- Potentially: user applications (e.g., spectroscopy)

Requirements:

- Single-shot
- Sufficient temporal resolution/BW (ps/sub-ps range)
- High acquisition rate (MHz+) for a range of machines, e.g., Eu-XFEL, SOLEIL, KARA, and ELBE

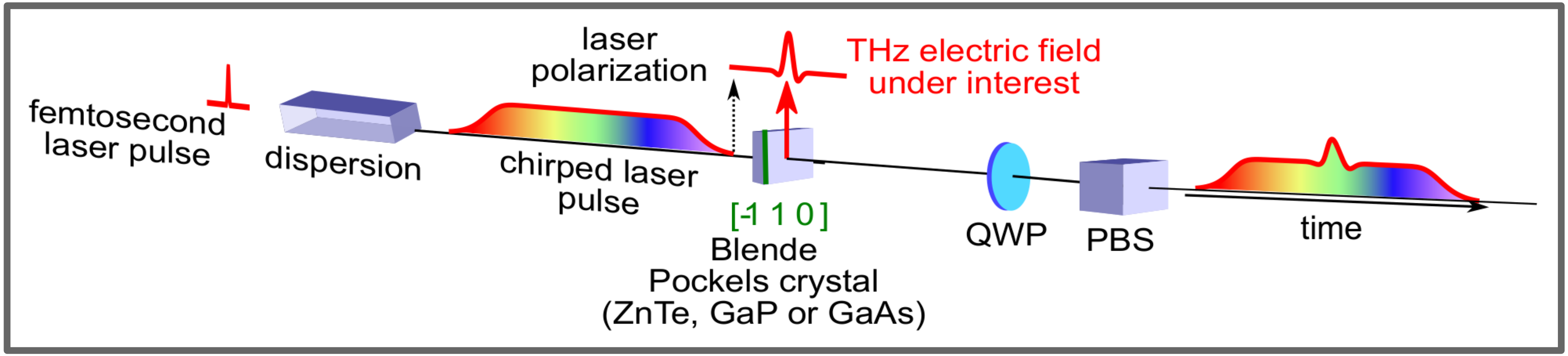
In this talk: measurement of CDR THz pulses at ELBE



Content

- Single shot electro-optic sampling
- Spectrally decoded EO sampling
- Time stretch EO sampling
- Experiment at ELBE
- Time resolution limitation
- Phase diversity technique
- Time stretch electro-optic sampling with phase diversity
  Experiment at ELBE with phase diversity
  Results
- Conclusion and perspectives

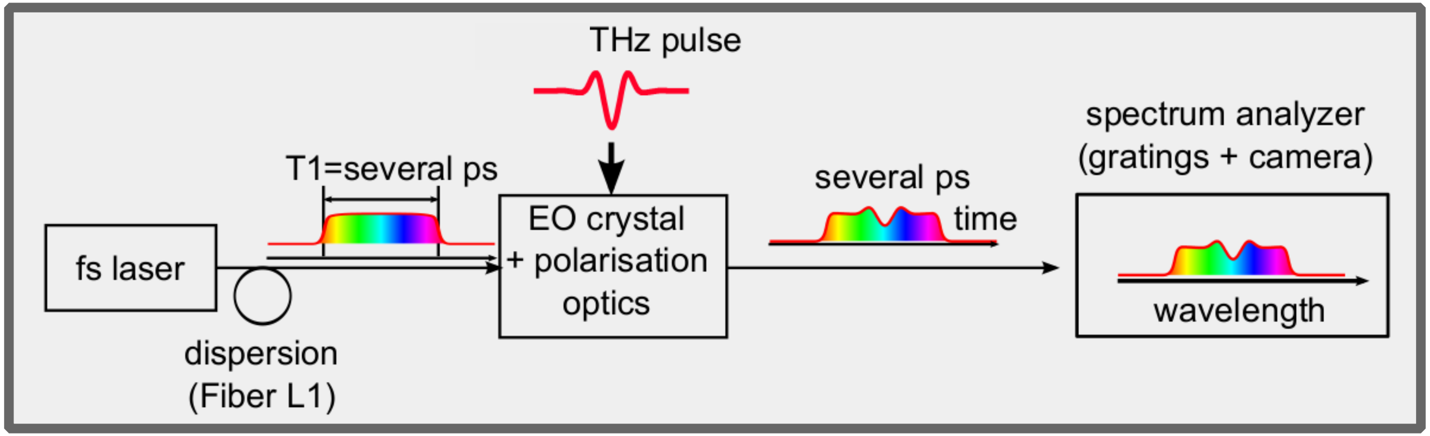
Principle of single-shot electro-optic (EO) sampling using chirped laser pulses



- ➢ The electric field modifies the birefringence of a crystal.
- ➢ The field-induced birefringence is probed using a laser pulse

Popular since the 80s: Near-field measurements Valdmanis, Mourou, Gabel, APL 41, 211, (1982)

Spectrally decoded EO sampling, and the acquisition rate challenge



Commercial cameras: up to ≈ 150 k lines/s

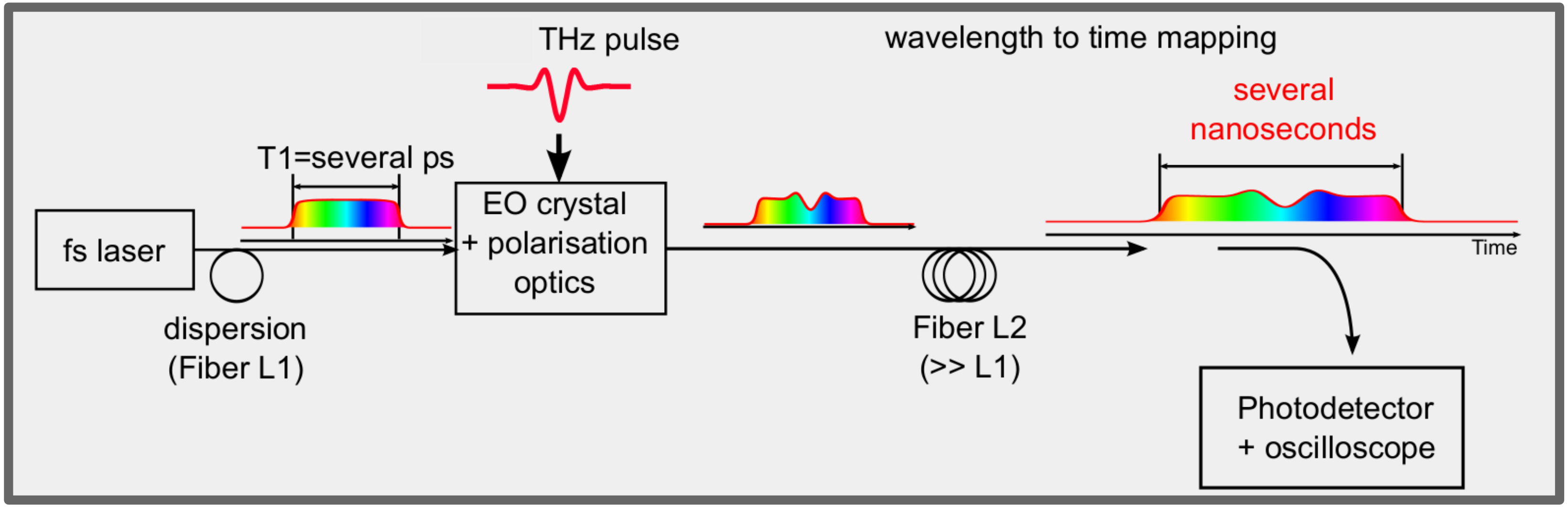
Option 1: KALYPSO project at KIT. Currently 4 Mf/s over 512 pixels.

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)]

Option 2 (this work): Time stretch EO sampling

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

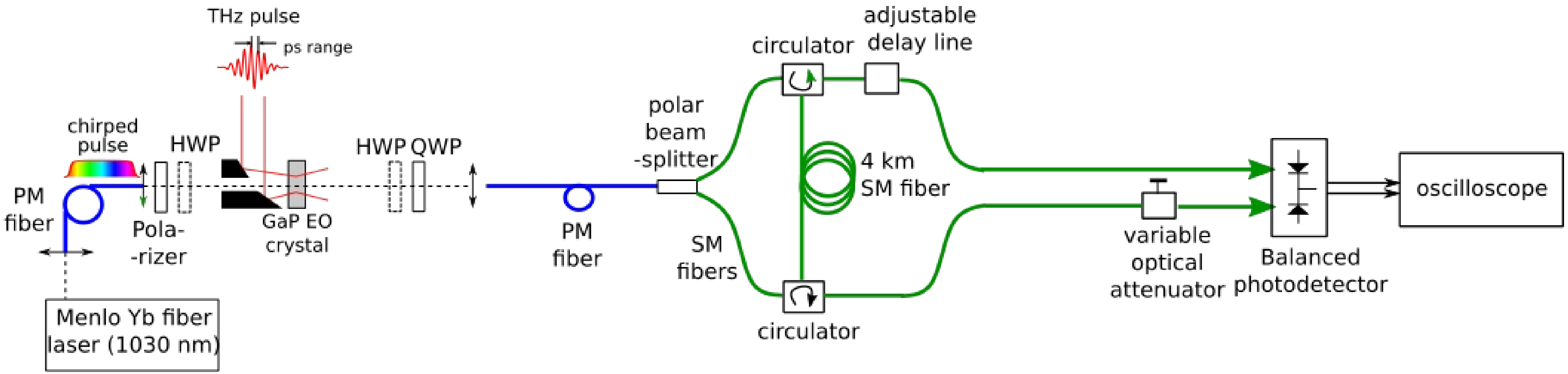
First demonstration of THz time-stretch EO: [(PhLAM-SOLEIL coll.) Roussel et al. Sci. Rep. 5, 10330, 2015]
KARA@KIT: Bielawski, S., Blomley, E., Brosi, M. et al. Scientific Reports 9, 10391 (2019). https://doi.org/10.1038/s41598-019-45024-2
(ongoing ANR-DFG collaboration projet between PhLAM, SOLEIL and KIT)



On the oscilloscope: replica of the THz pulse that is “temporally stretched” by a factor $M = 1 + \frac{L_2}{L_1}$
Following slides: L1 = 16 m and L2 = 4 km M ≈ 242.
➔4.13 GHz on the oscilloscope corresponds to 1 THz at the input.

Experimental setup at ELBE:Time stretch EO sampling

Acquisition rate = 26.10⁶ traces/s



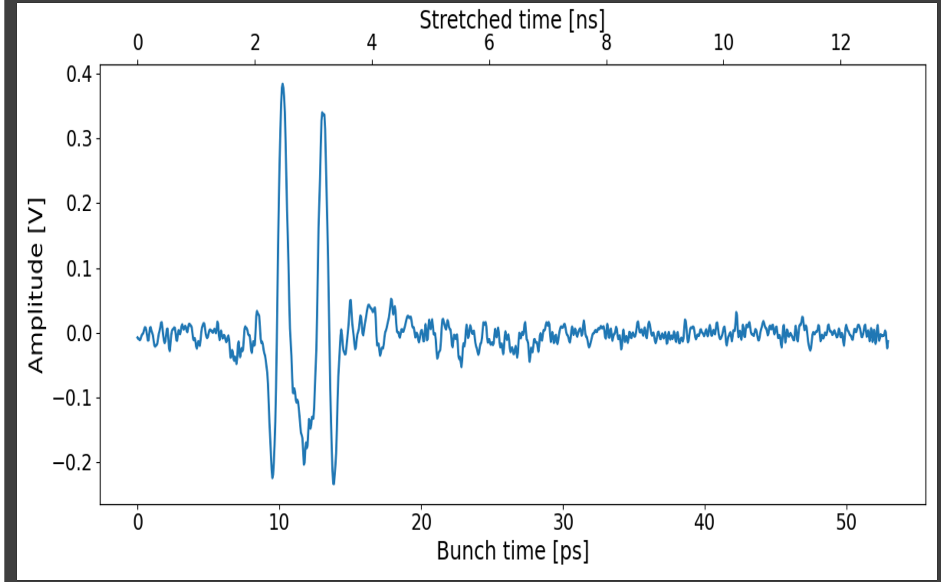
Stretch factor M=242.

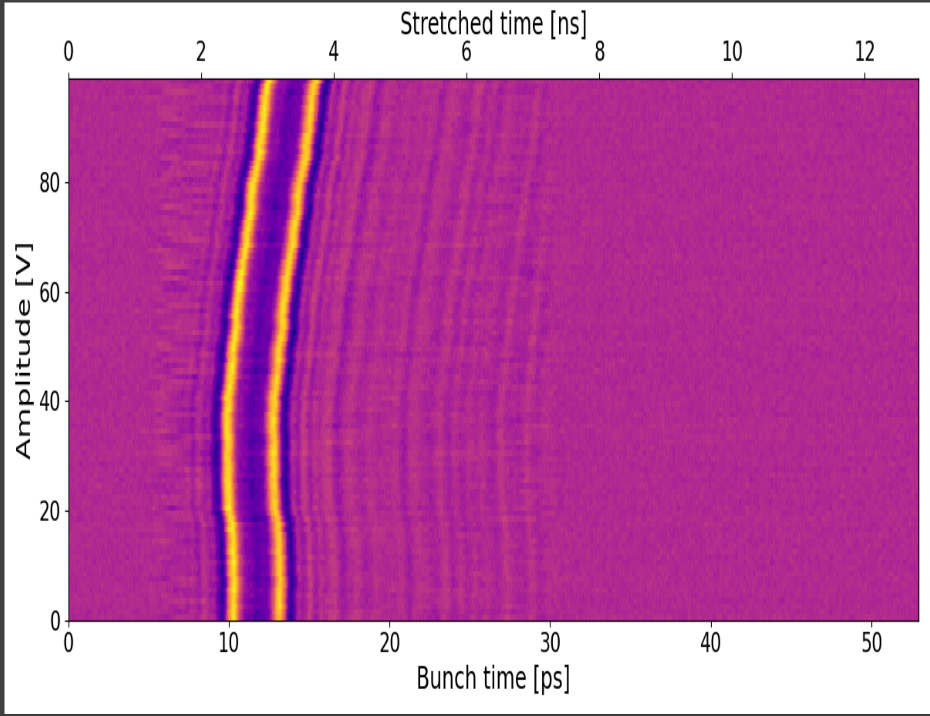
Tests using two oscilloscopes.

- 20 GHz bandwidth (Teledyne) → 4.8 THz BW limitation
- 8 GHz bandwidth (Agilent) → 1.9 THz BW limitation

ELBE: Results

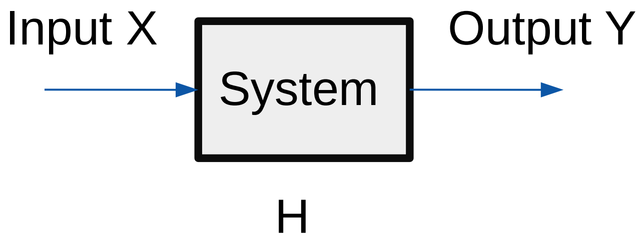
Recorded signal



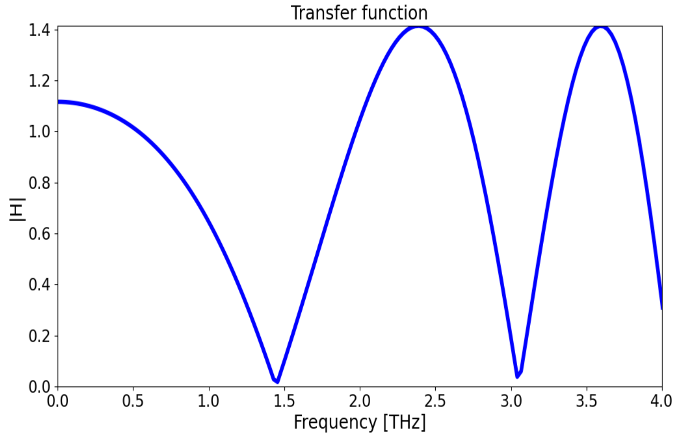


Time resolution & Bandwidth limitation

The bandwidth of the system is limited by the so-called dispersion penalty.



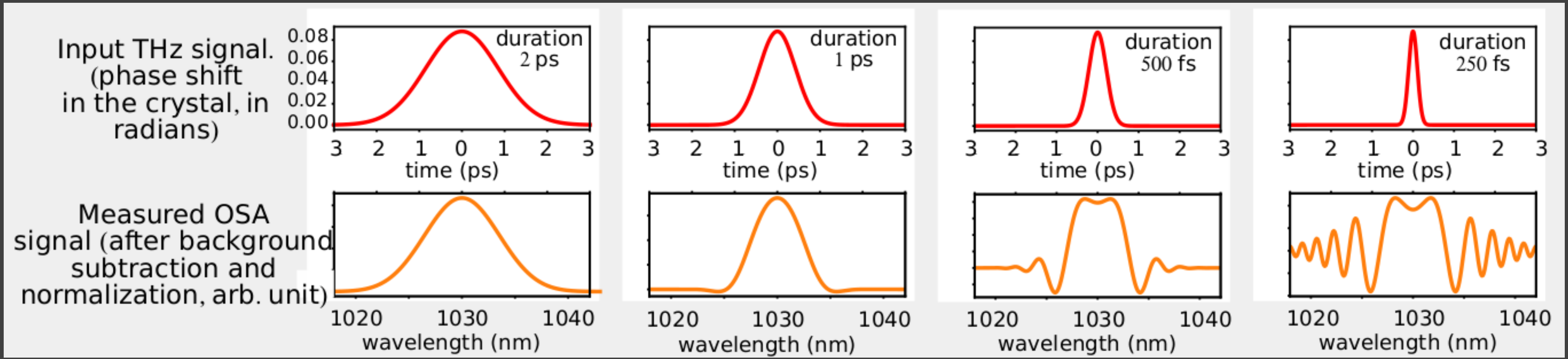
Y= H X



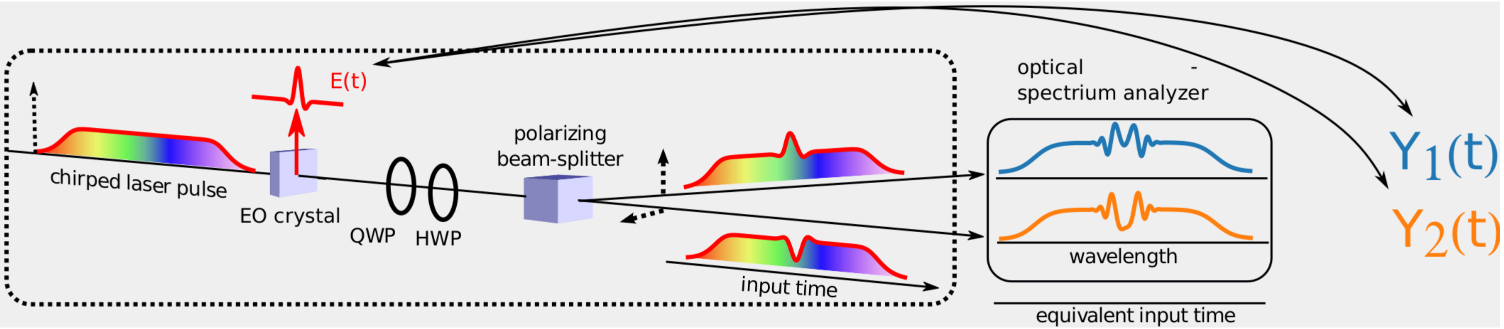
Position of the first zero of the transfer function:

$$f_0 = \sqrt{\frac{1}{4\pi\beta_2 L_1}} = \sqrt{\frac{c\Delta\lambda}{2\lambda^2 T_1}}$$

Simulation: Typical deformations observed for short THz pulses (40 fs-long laser pulse and ideal Pockels crystal)



Deconvolution using phase diversity



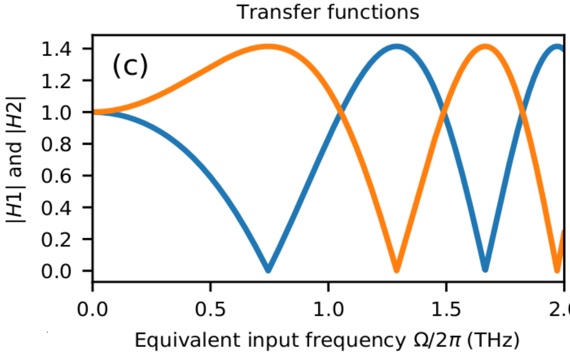
$$Y_{1,2}(\Omega) = H_{1,2}X \quad (1)$$

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

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

Deconvolution using Maximum Ratio Combining (MRC):

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



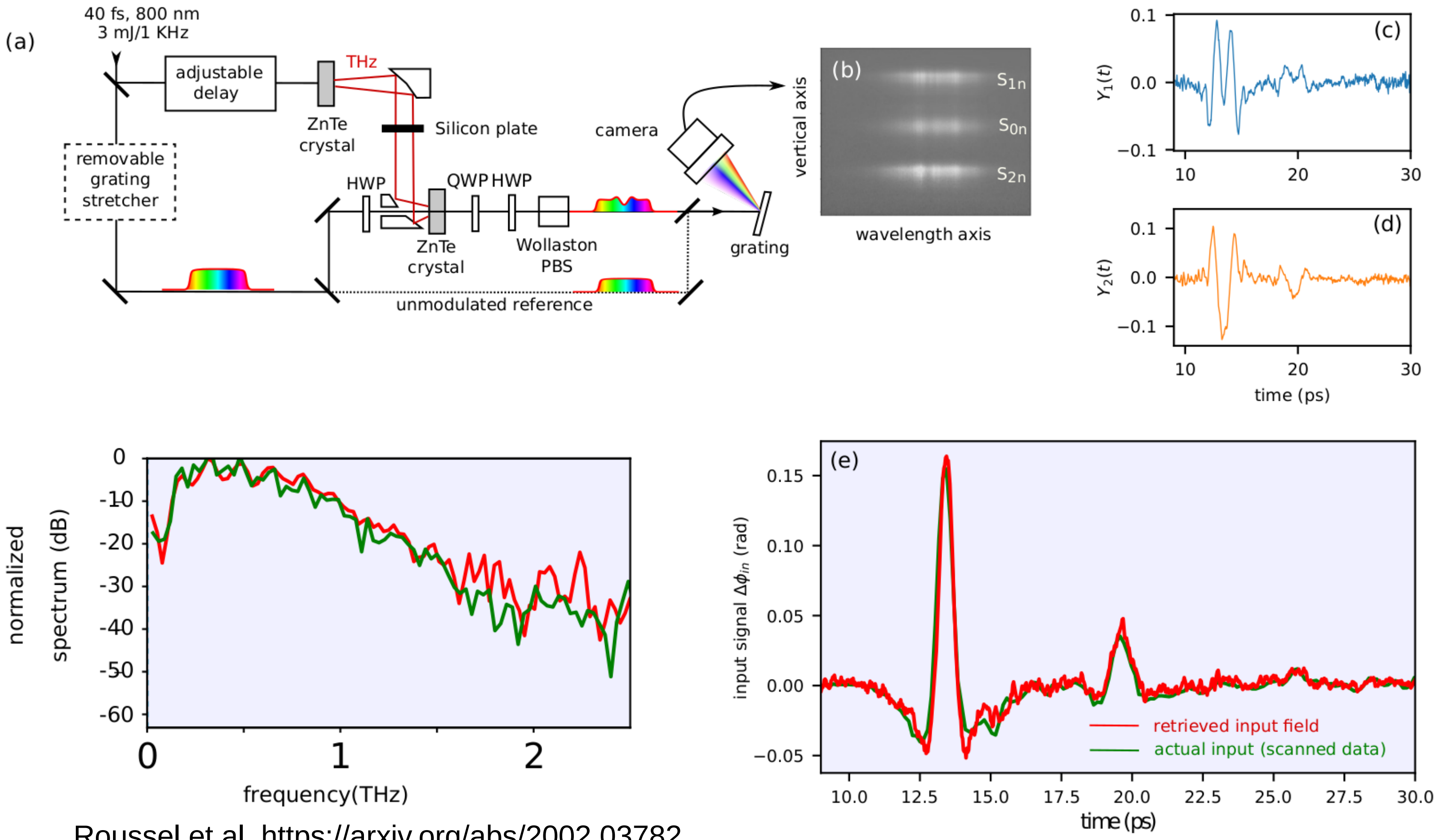
B and ϕ (unknown) are found by minimizing the reconstruction error:

$$\varepsilon^2 = \int_{-\infty}^{+\infty} d\Omega \left(\left| Y_1 - H_1 X_R \right|^2 + \left| Y_2 - H_2 X_R \right|^2 \right)$$

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

https://arxiv.org/pdf/2002.03782

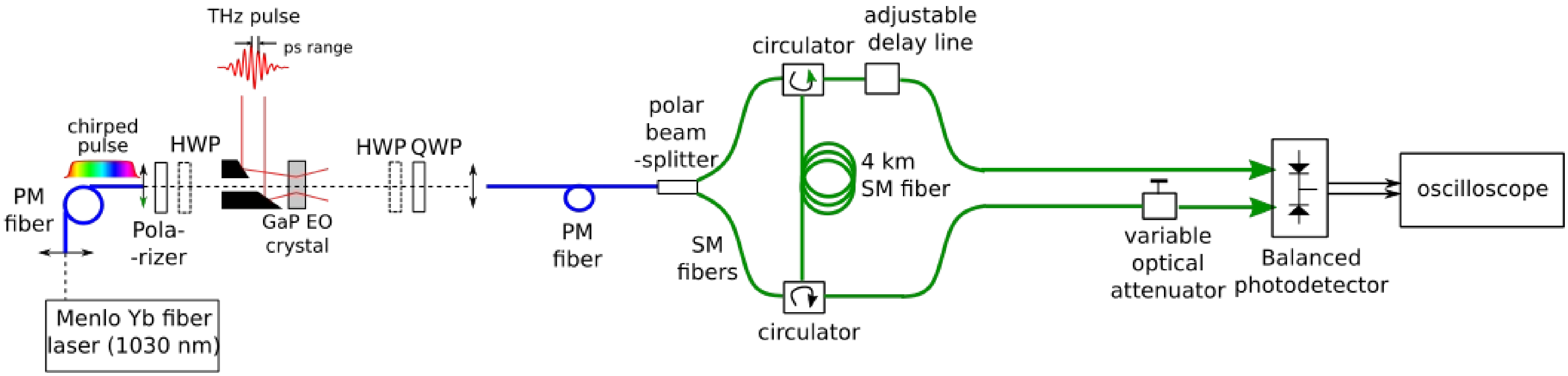
Tests at PhLAM (Roussel et al. https://arxiv.org/abs/2002.03782)

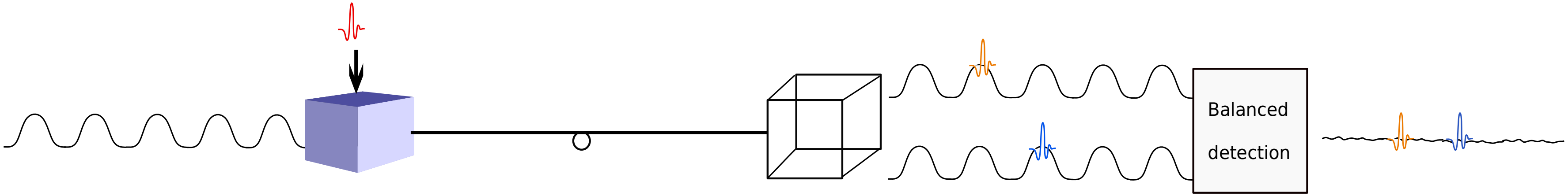


Roussel et al. https://arxiv.org/abs/2002.03782

Experimental setup at ELBE:Time stretch EO sampling with phase diversity

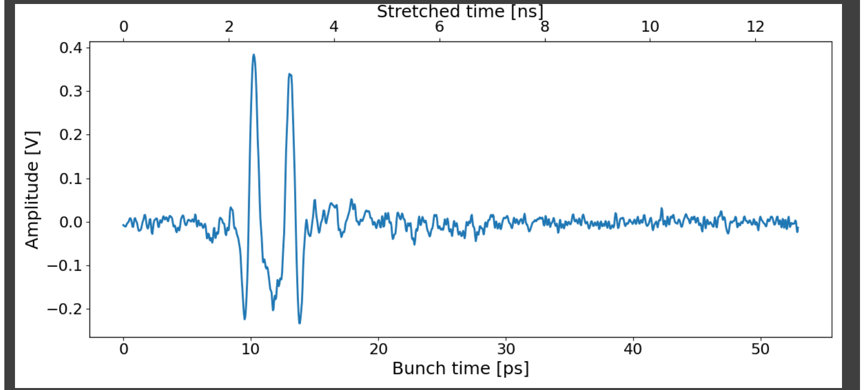
Acquisition rate = 26.10^{6} traces/s



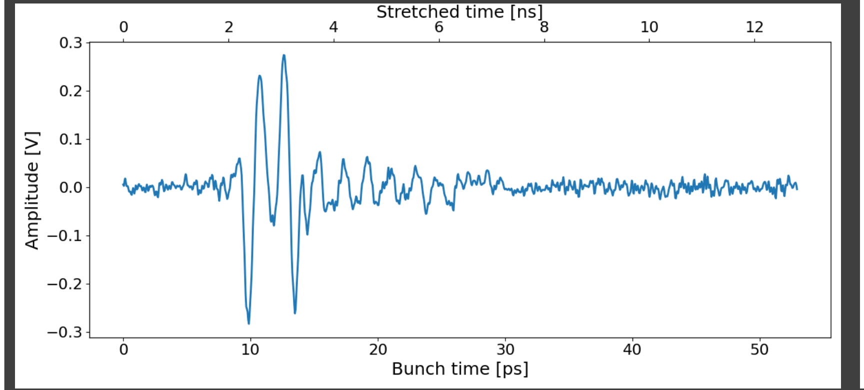


ELBE: Results

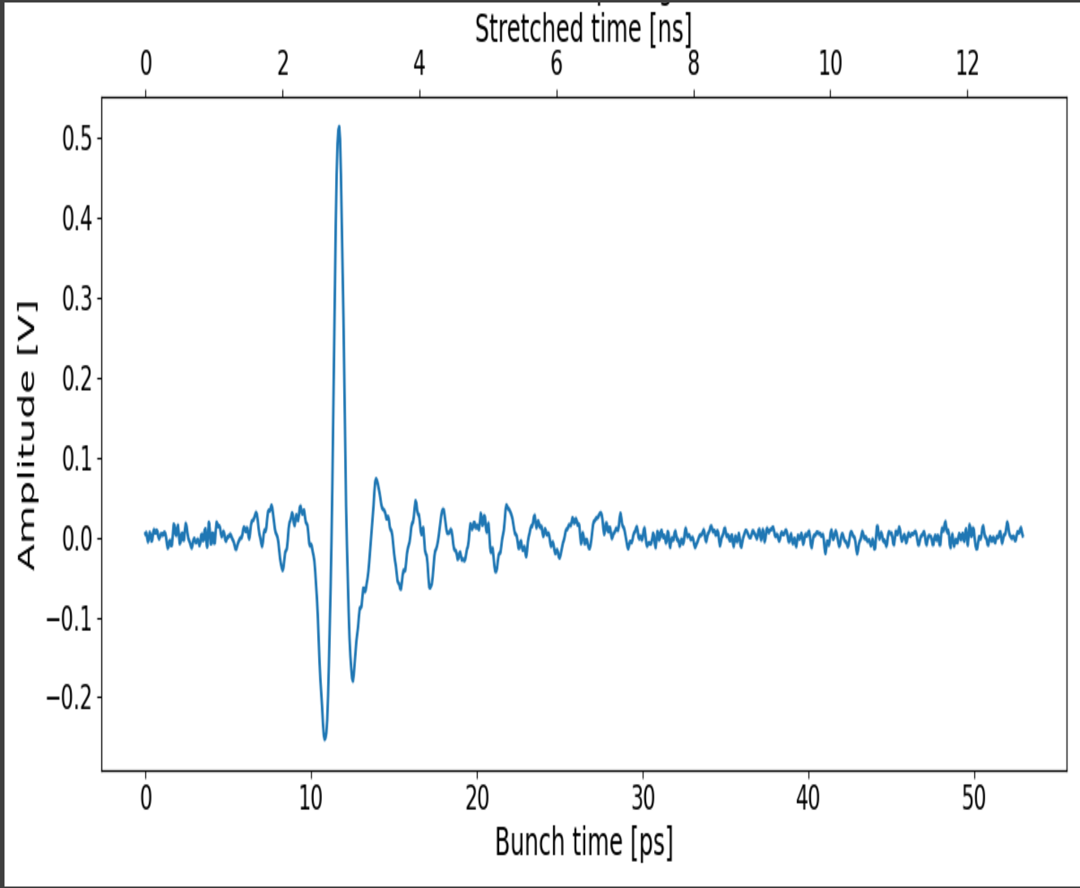
Polarisation 1



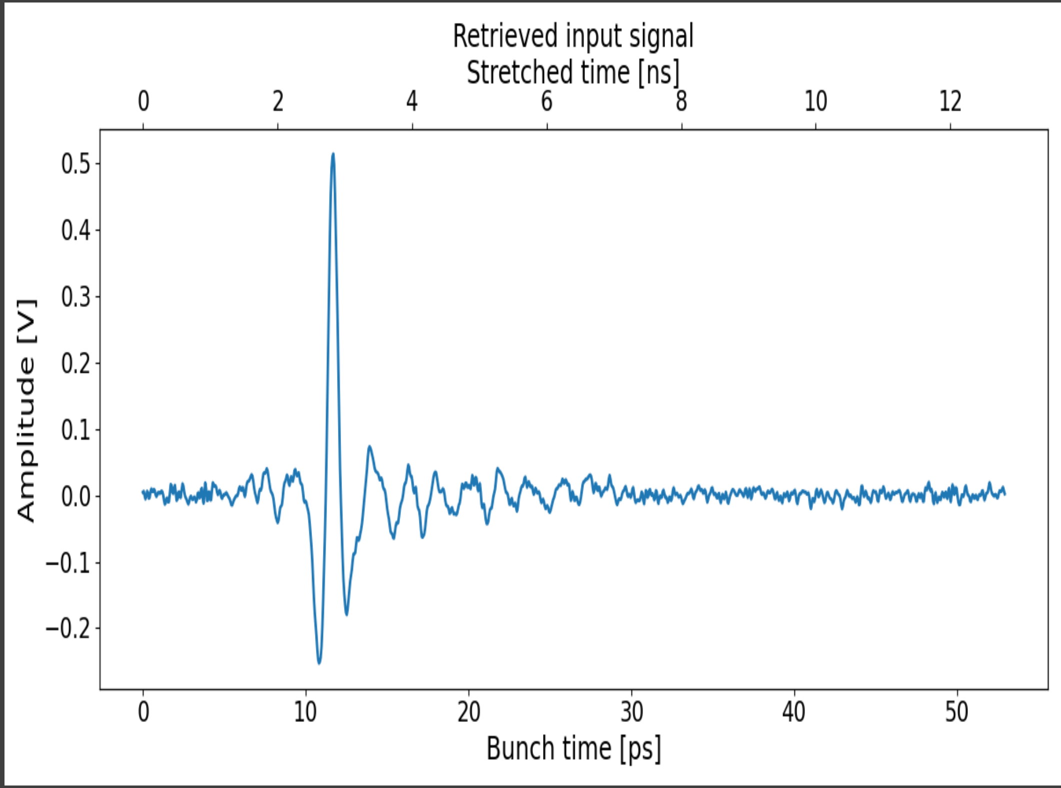
Polarisation 2

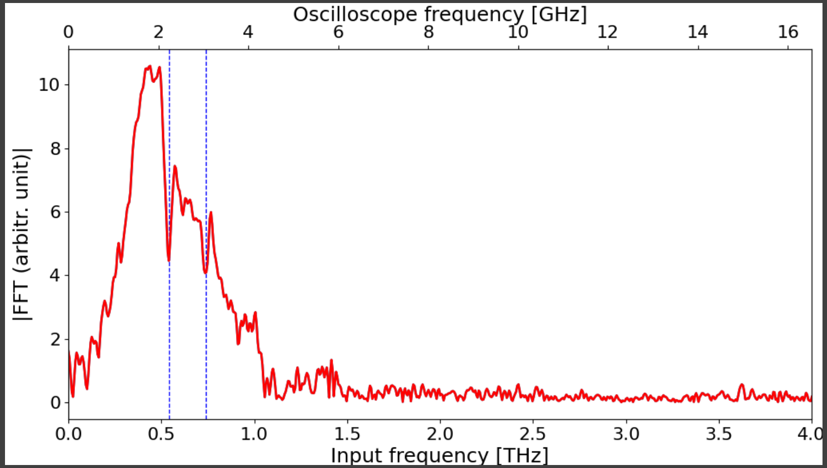


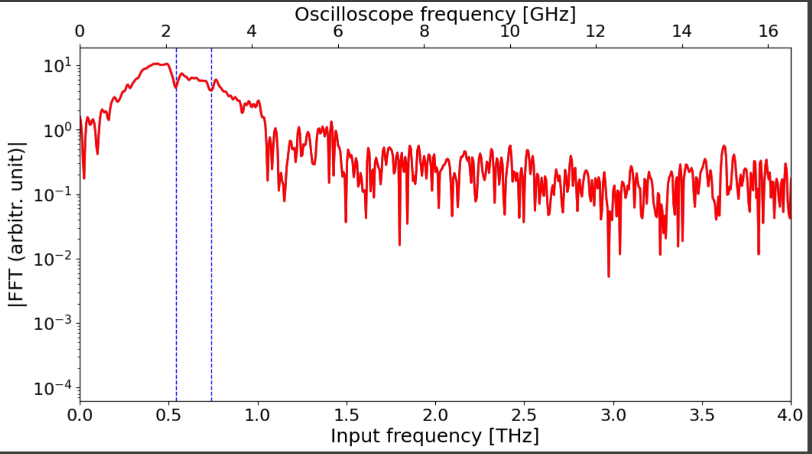
Retrieved input signal

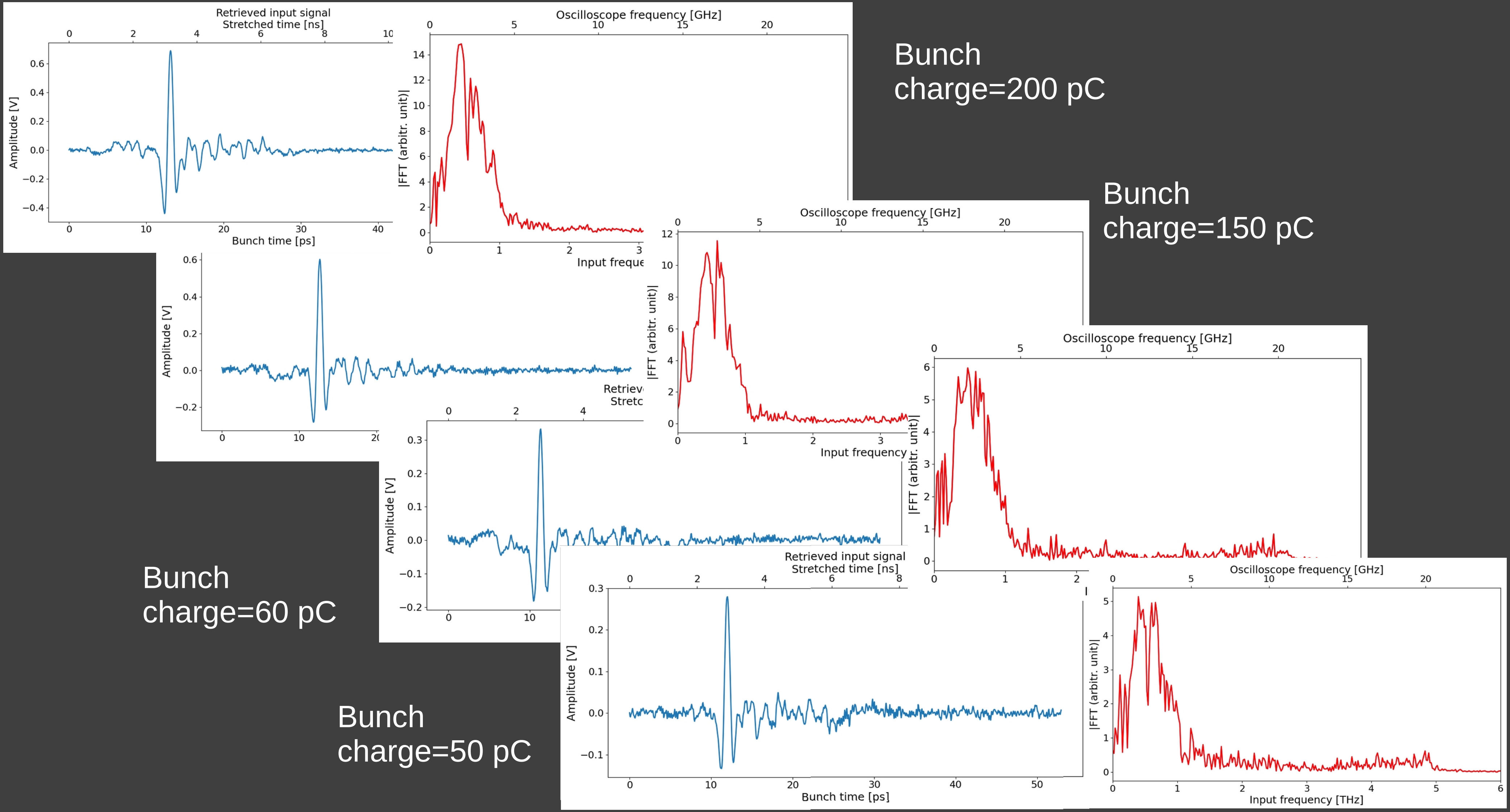


ELBE: Results

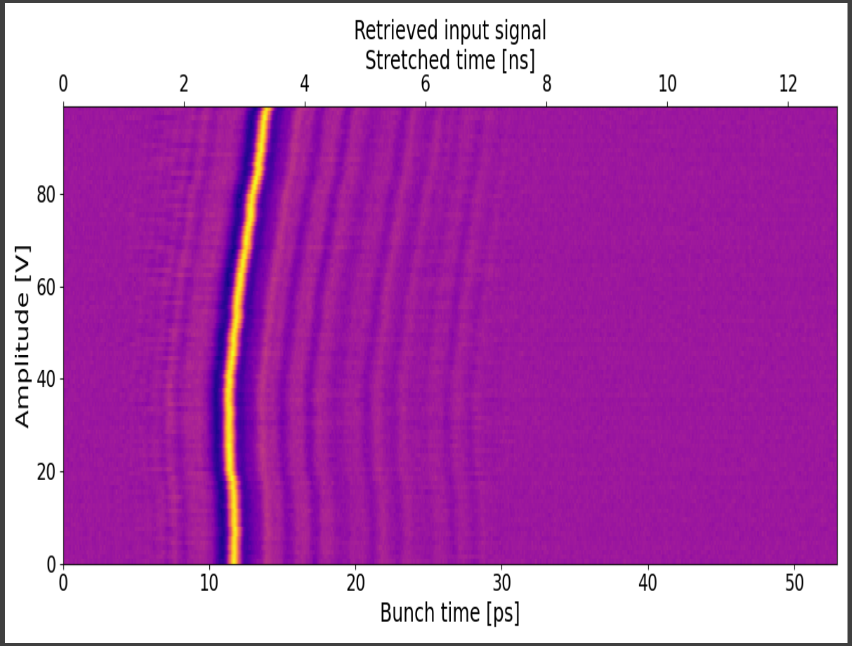




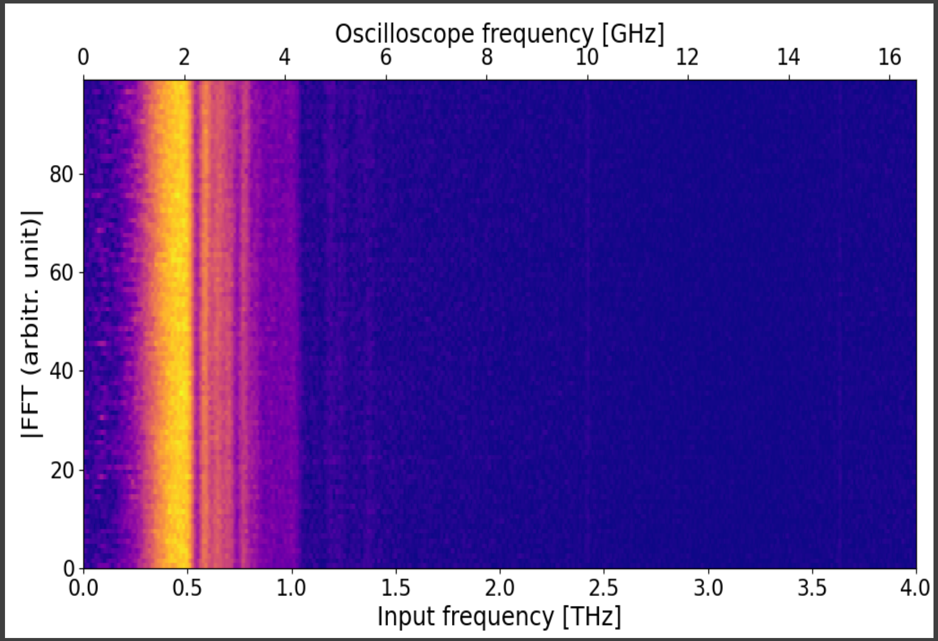



Bunch charge=200 pC
Bunch charge=150 pC
Bunch charge=60 pC
Bunch charge=50 pC
Retrieved input signal
Stretched time [ns]
Amplitude [V]
Bunch time [ps]
Oscilloscope frequency [GHz]
|FFT (arbitr. unit)|
Input frequency [THz]

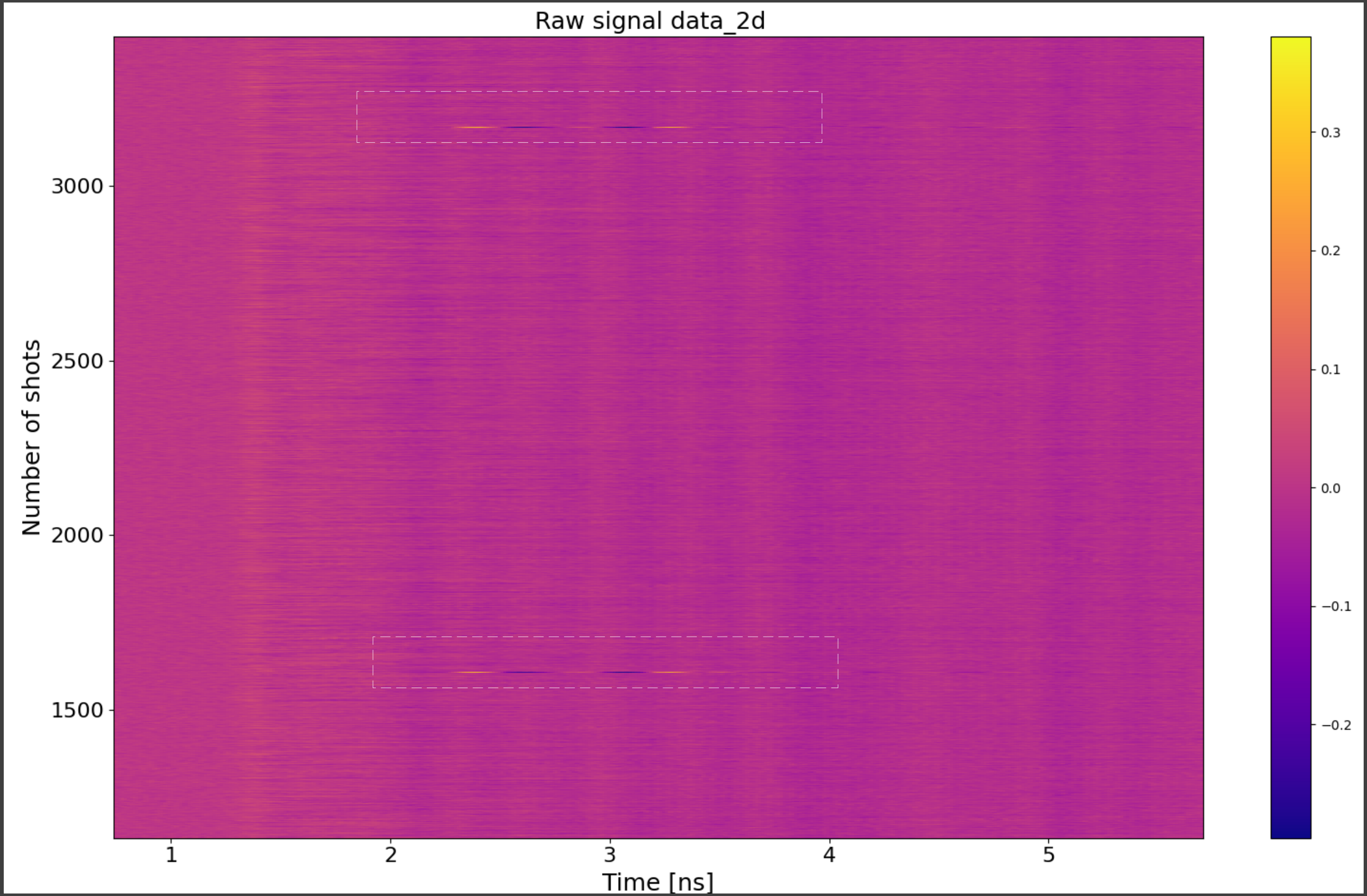
ELBE: Results



Retrieved input THz signal at ELBE



Spectrum of the electron beam at ELBE



Laser @ 78 MHz

CDR pulses @50 Khz at ELBE

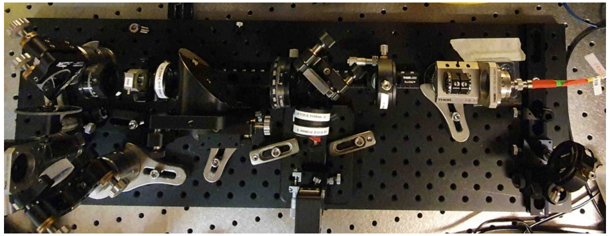
Acquisition rate up to 26 MHz

Conclusion and future perspectives

First test of time-stretch EO at ELBE:

- ✓ Tested on the CDR THz source (50 KHz rep. rate)
- ✓ Sufficient BW/temporal resolution using the Phase diversity technique
- ✓ Note: acquisition rate capability (26 MHz) much higher than the CDR source repetition rate

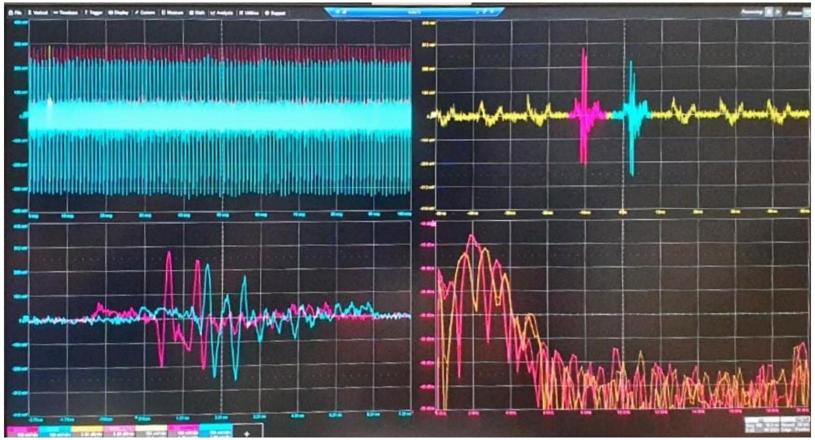
Robust and relatively compact setup (19’’ rack)



...and a 60 cmx20 cm breadboard

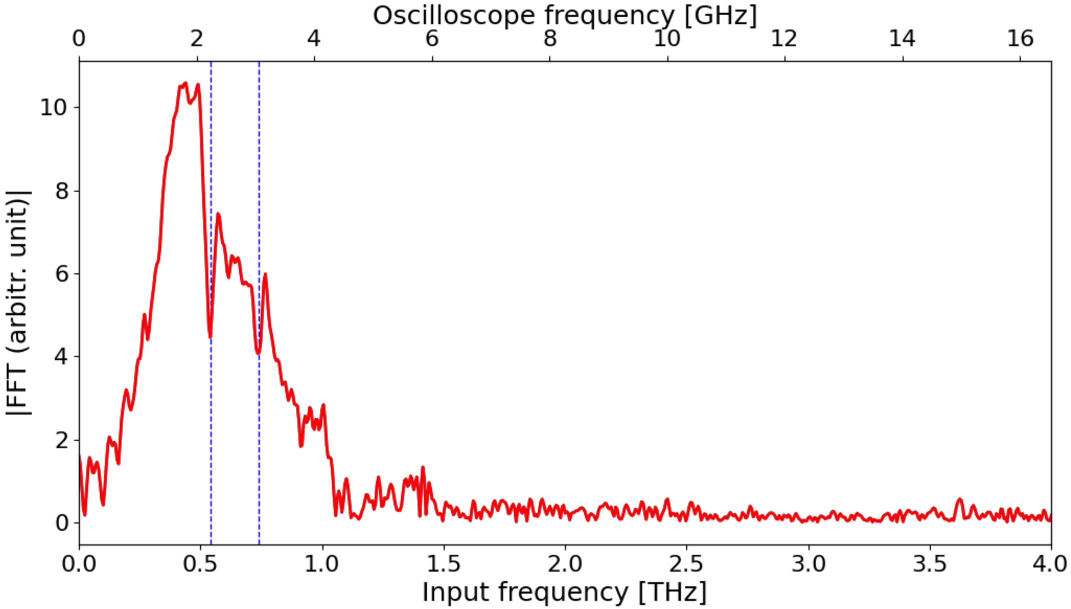
Conclusion and future perspectives

Machine diagnostics



ELBE control room

Other applications to, e.g., spectroscopy…?



Fundings: CEMPI Labex, CNRS MOMEMTUM/METEOR, ULTRASYNC ANR-DFG

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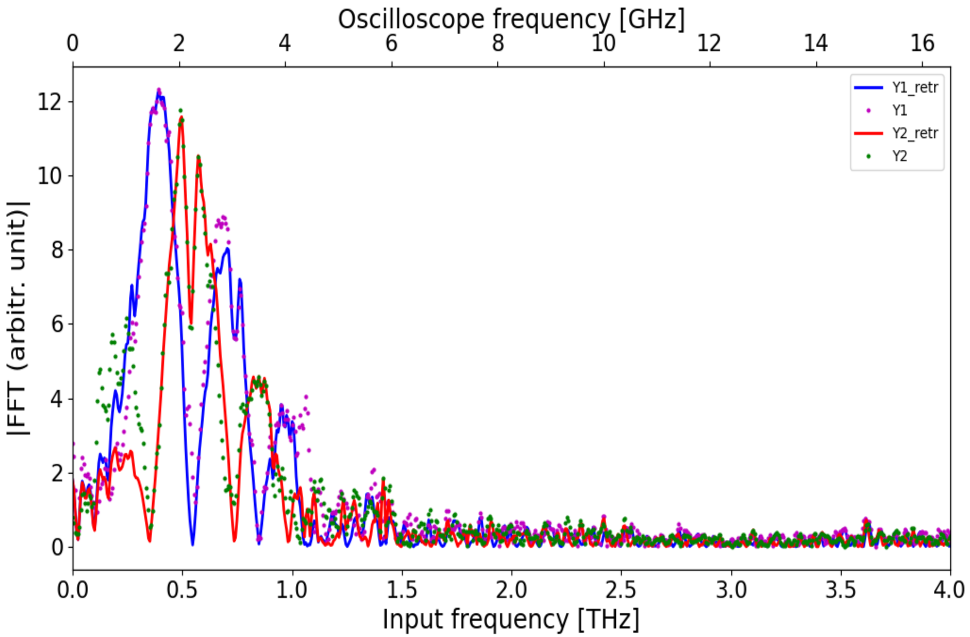
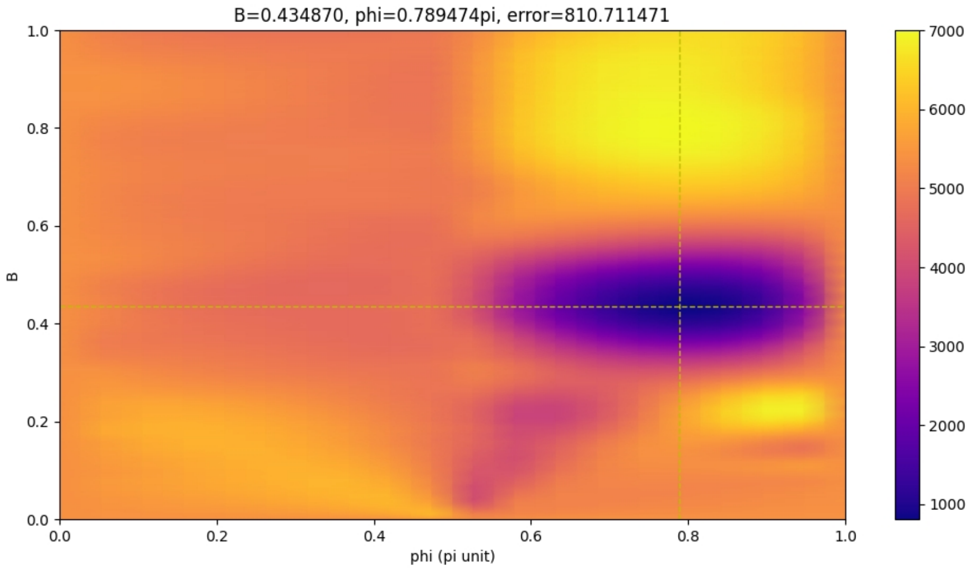
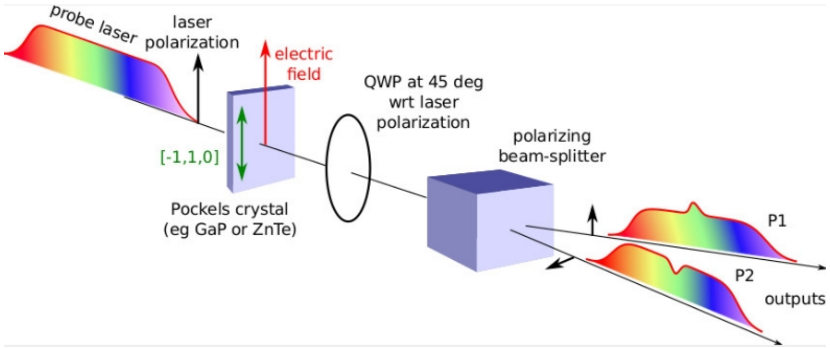
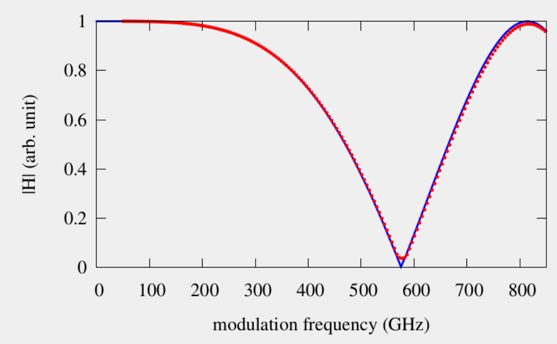
Additional steps for reconstructing the input signal





Transfer functions for the phase diversity technique



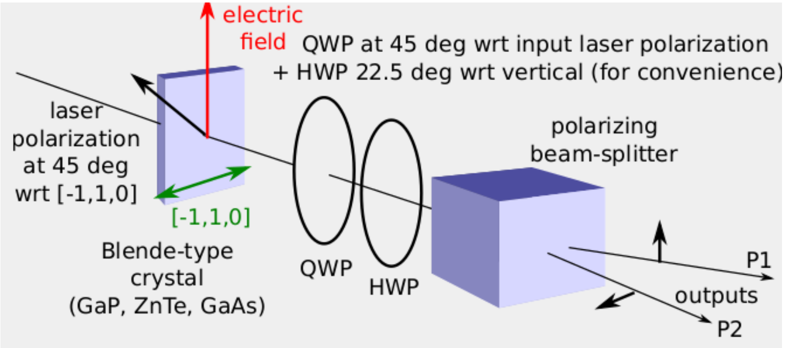


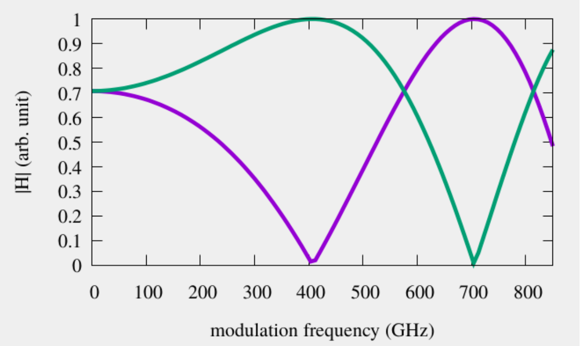
$$H_1(\Omega) = h_0 \cos B\Omega^2$$
$$H_2(\Omega) = -h_0 \cos B\Omega^2,$$

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

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

Key point: Interleave the transfer functions zeros
Practically by using different crystal and waveplates orientations than the “classical” one.





$$H_1(\Omega) = h_0 \cos\left(B\Omega^2 - \frac{\pi}{4}\right)$$
$$H_2(\Omega) = -h_0 \cos\left(B\Omega^2 + \frac{\pi}{4}\right)$$