Electro-Optic Longitudinal Bunch Profile Measurements at FLASH

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Free-Electron Laser
in Hamburg

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Overview

- Motivation
- Basics
  - Electro-optic effect
  - EO measurement principle
  - Detection schemes
- Measurement schemes and results
  - Electro-optic sampling using a variable delay
  - Spectrally resolved detection
  - Temporally resolved detection
- Applications
- Conclusion

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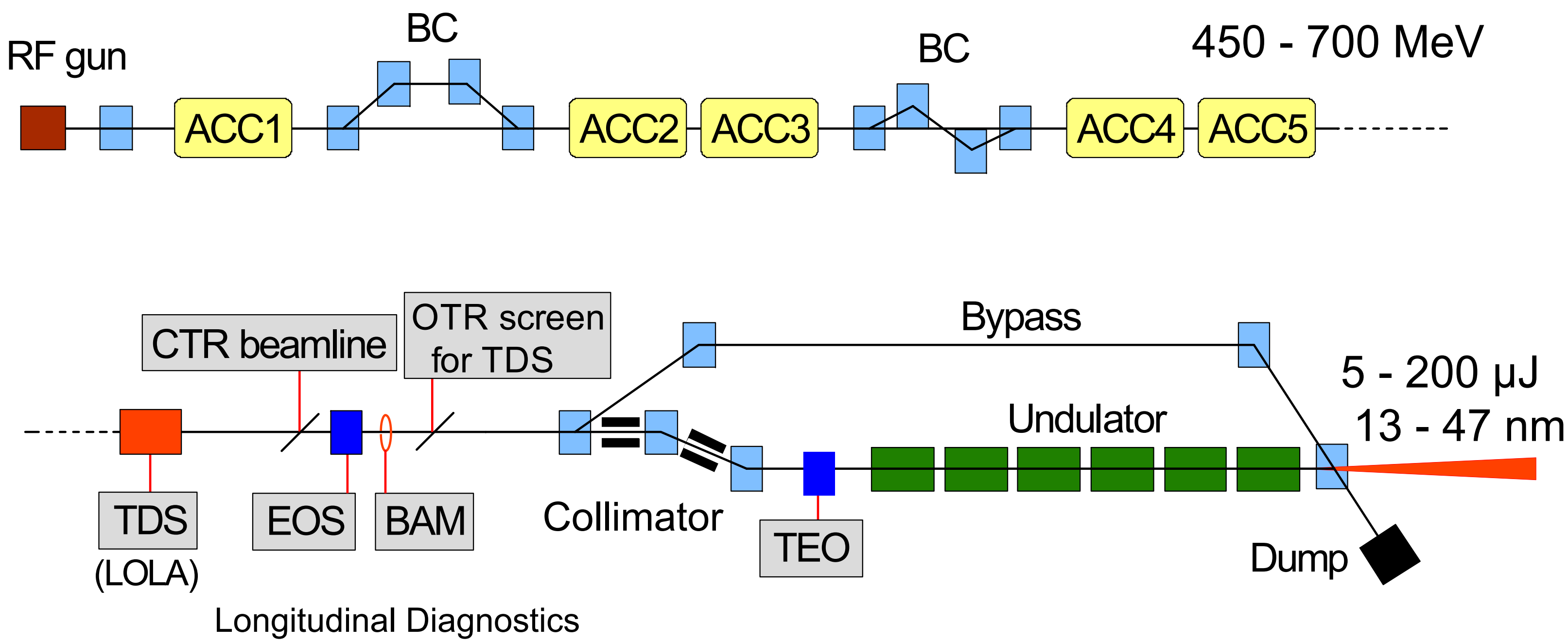

Electron bunches: ≈ 30 fs duration
≈ 700 MeV electron energy
≈ 0.5 nC charge
≈ 1 kA peak current

All pulse length:
σ of a fitted Gaussian

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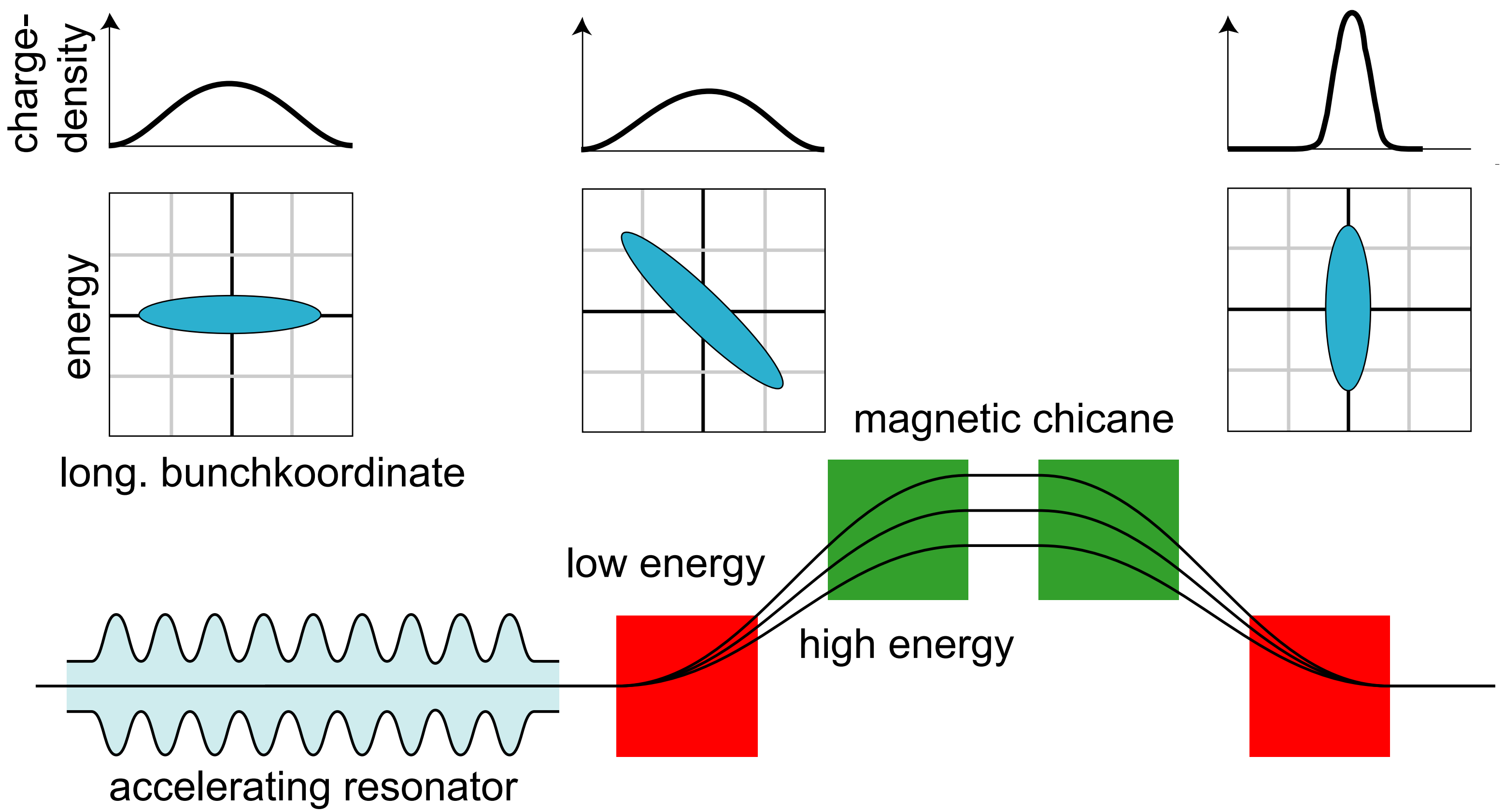
Bunch compression



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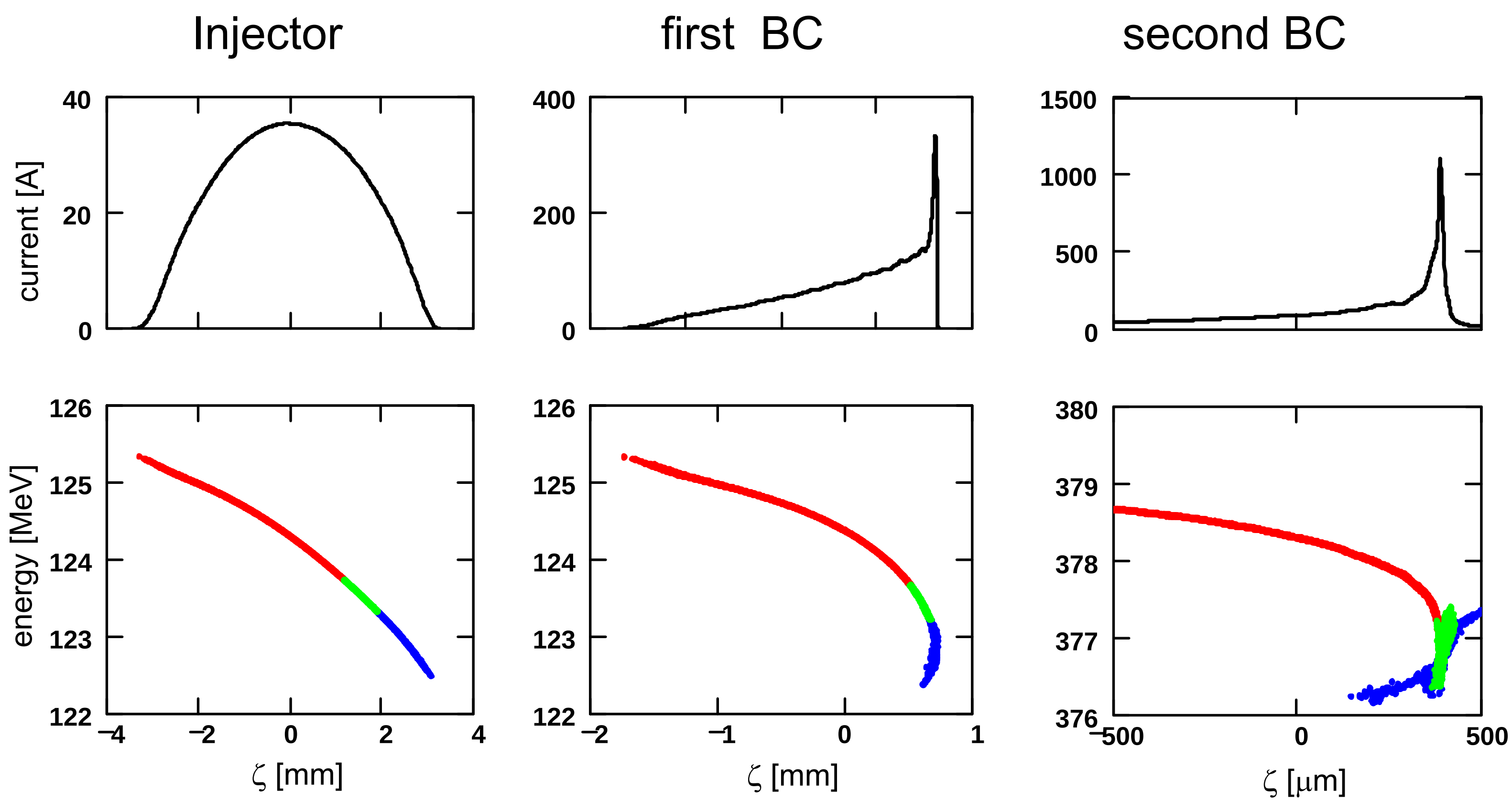
Bunch compression



Courtesy of Martin Dohlus

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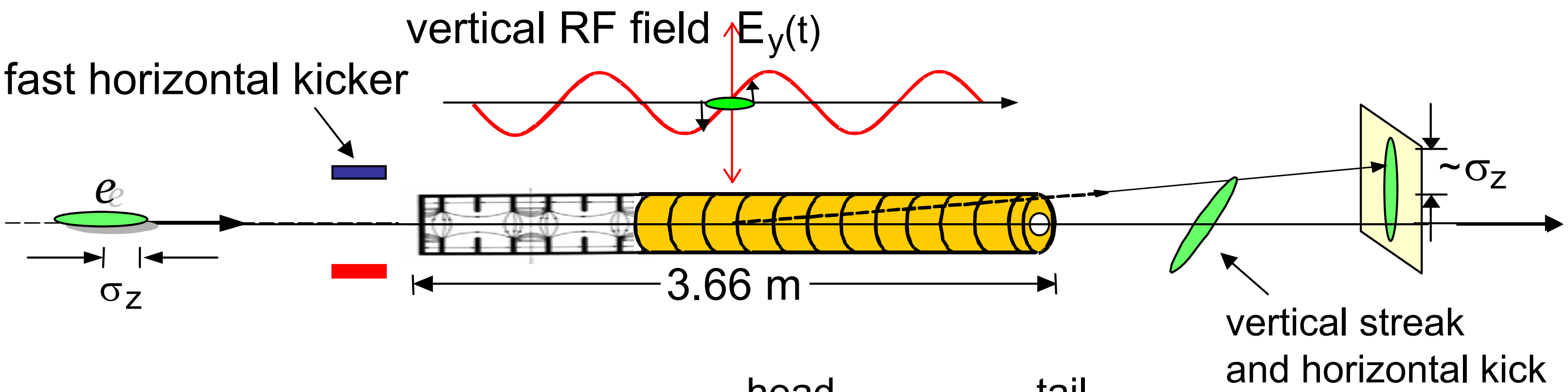
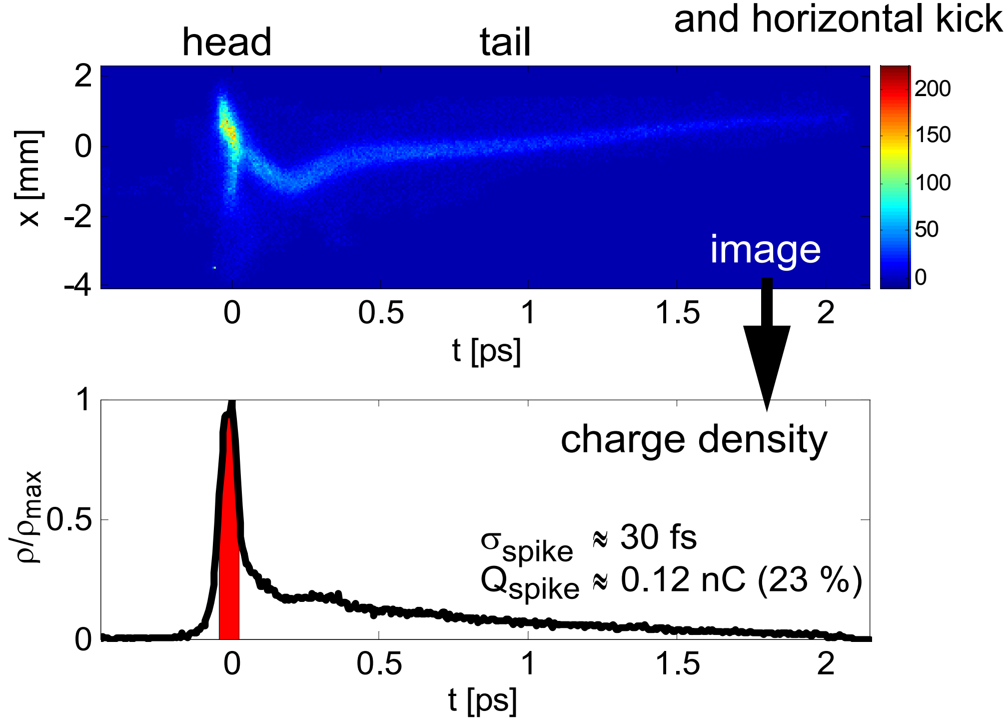
Bunch length measurements using the transverse deflecting structure (TDS)





Resolution:
approx. 20 fs
at a time window of 2 ps

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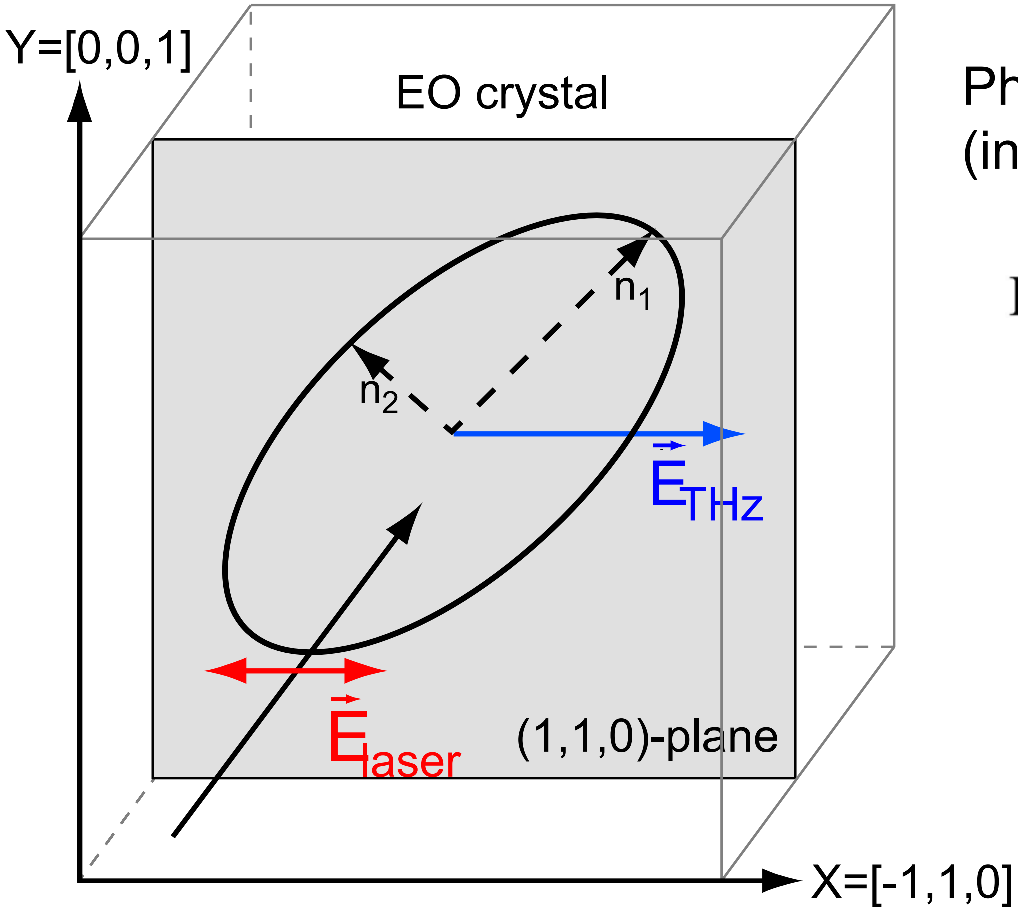
The Electro-Optic Effect: THz-field induced Birefringence



Phase retardation
(in the small signal limit):

$$\Gamma = \frac{\omega d}{c}(n_1 - n_2) = \frac{\omega d}{c} n_0^3 r_{41} E_{\mathrm{THz}}$$

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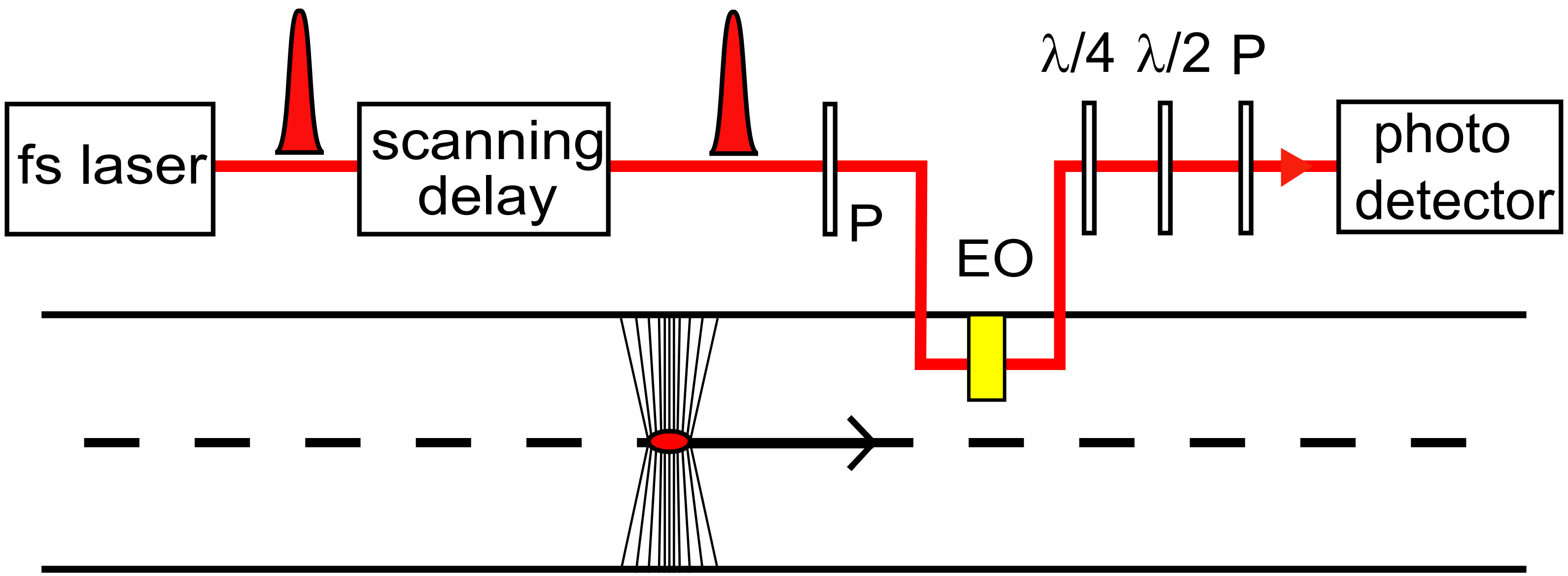
Electro-Optic Sampling



- Coulomb field of electron bunch induces birefringence in EO-crystal.
- birefringence is sampled by Ti:Sa laser pulse.

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Effect of the wave plates

$$E_{\text{det}}(\theta, \phi, \Gamma) = \begin{pmatrix} 0 & 1 \end{pmatrix} \cdot \boldsymbol{H}(\theta) \cdot \boldsymbol{Q}(\phi) \cdot \boldsymbol{EO} \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} \cdot E_{\text{laser}}$$

$$\boldsymbol{EO} = \boldsymbol{R}(-\pi/4) \cdot \begin{pmatrix} \exp(-i\Gamma/2) & 0 \\ 0 & \exp(+i\Gamma/2) \end{pmatrix} \cdot \boldsymbol{R}(\pi/4)$$

$\boldsymbol{Q}(\phi)$: Quarter wave plate, rotated by ϕ

$\boldsymbol{H}(\theta)$: Half wave plate, rotated by θ

$$I_{\text{det}}(\theta, 0, \Gamma) = \frac{I_{\text{laser}}}{2} [1 - \cos(\Gamma + 4\theta)]$$

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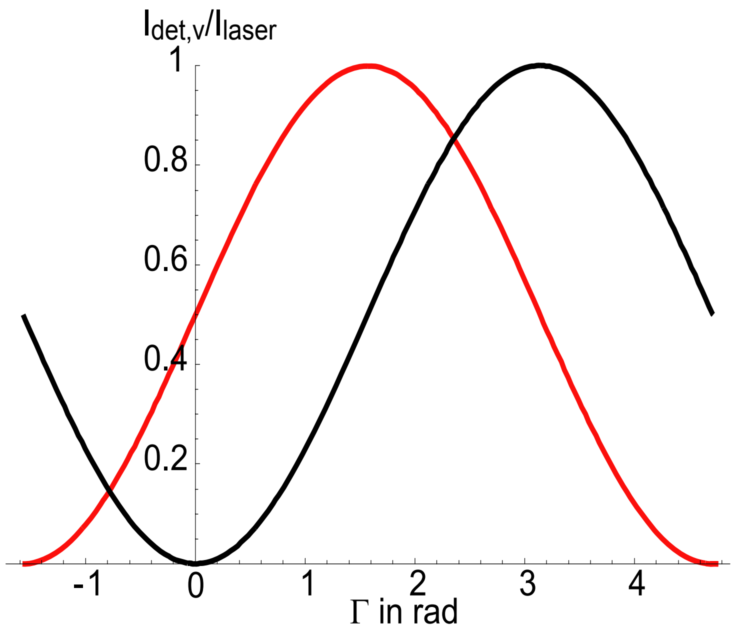
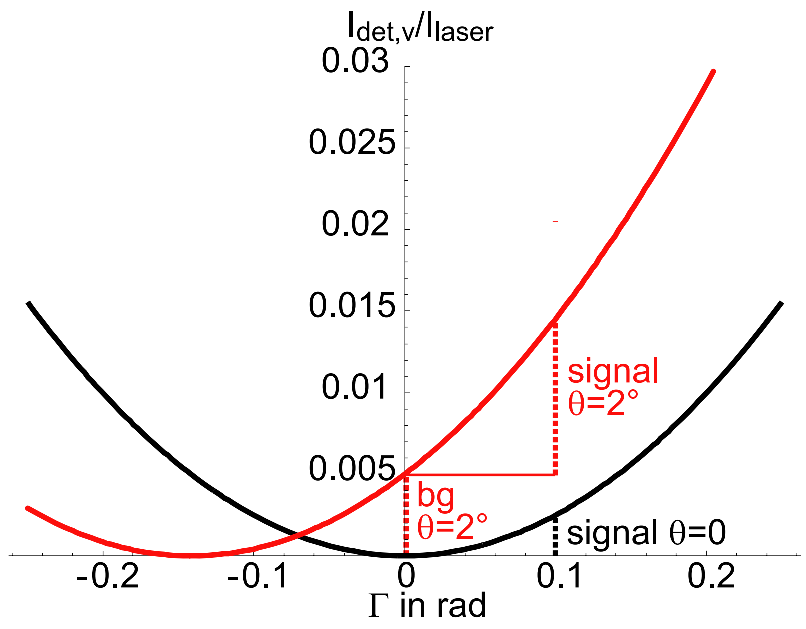
Effect of half wave plate





θ=0 4θ=π/2

θ=0° θ=2°

$$I_{det}(\theta, 0, \Gamma) = \frac{I_{laser}}{2}\left[1 - \cos(\Gamma + 4\theta)\right]$$

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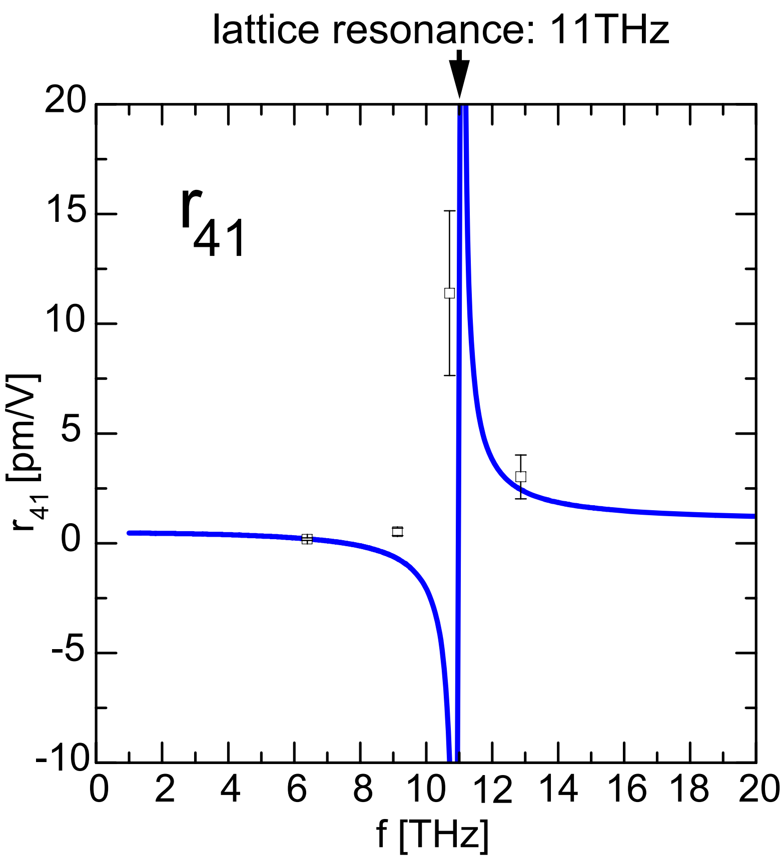
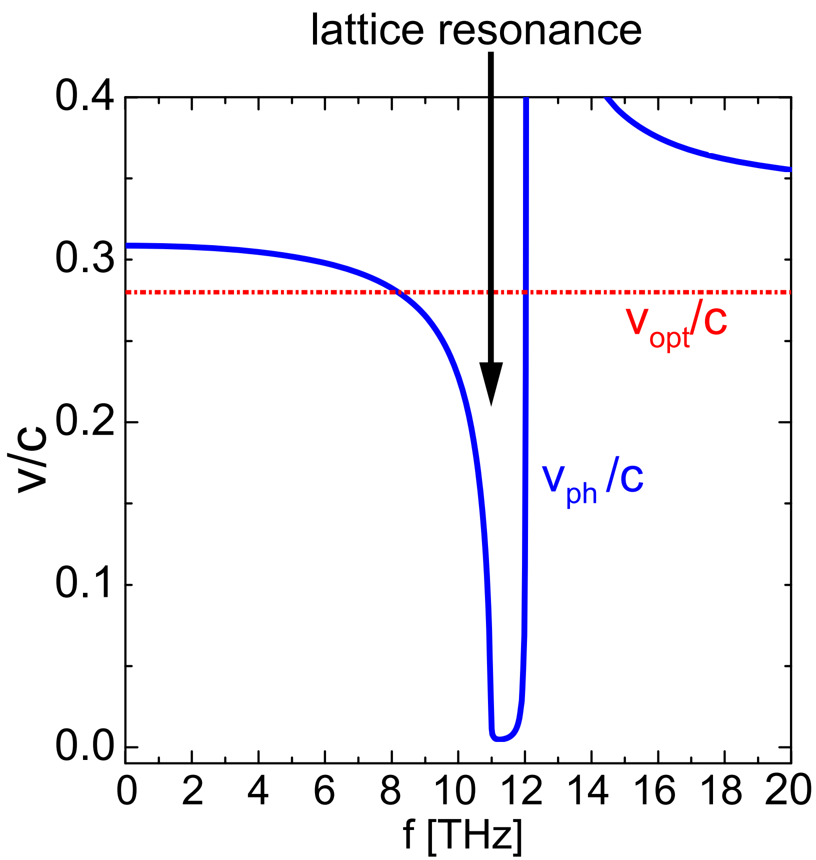
EO coefficient $r_{41}(f)$ and THz phase velocity in GaP





Faust, Henry. PRL 1966
Nelson, Turner. J. Appl. P. 1968

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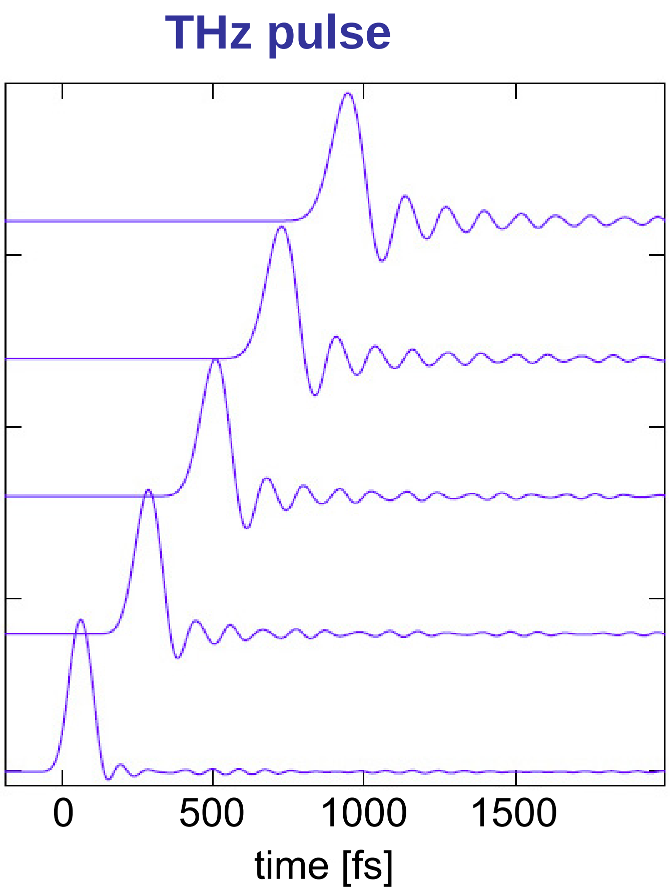
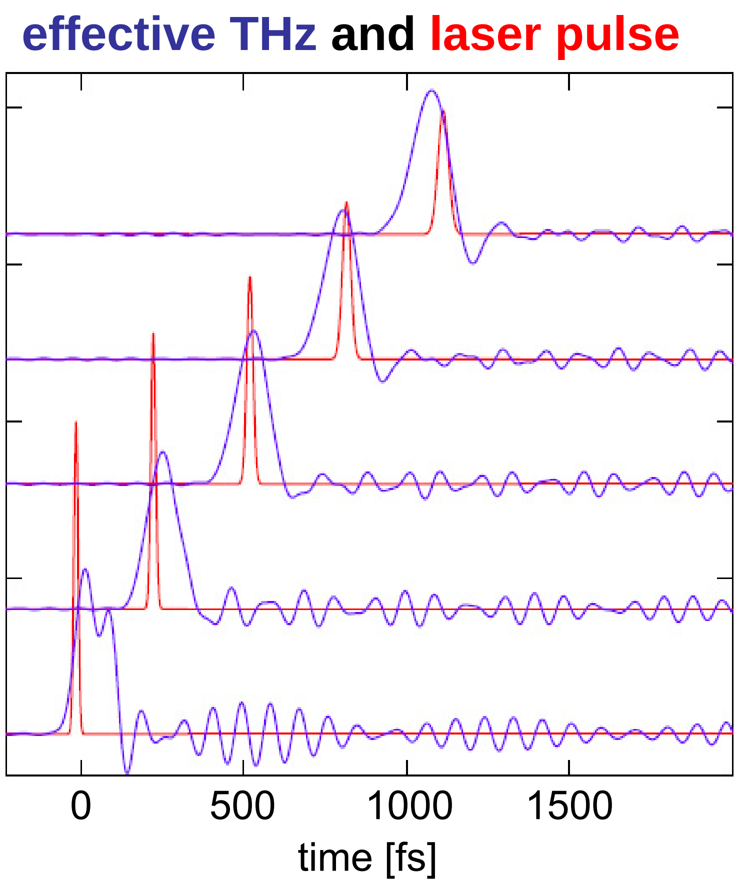
Propagation of the pulses in 100 µm GaP: EO-Sampling





EO-Signal: Product of the effective THz-field and laser integrated over the thickness of the crystal

The simulation program

- Effective THz pulse calculated from electron bunch and EO response function
- Phase retardation Γ from effective THz pulse
- Complex electric field of the modulated chirped laser pulse calculated according to:

$$
\begin{aligned}
E_{\mathrm{det}}(\theta,\phi,\Gamma) &= \begin{pmatrix} 0 & 1 \end{pmatrix} \cdot \boldsymbol{H}(\theta) \cdot \boldsymbol{Q}(\phi) \cdot \boldsymbol{EO} \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} \cdot \; E_{\mathrm{laser}} \\
&= \frac{E_{\mathrm{laser}}}{\sqrt{2}} \left[\cos(2\theta)\sin(\Gamma/2) - \sin(2\phi - 2\theta)\cos(\Gamma/2)\right. \\
&\quad \left. -i\left(\sin(2\theta)\cos(\Gamma/2) + \cos(2\phi - 2\theta)\sin(\Gamma/2)\right)\right]
\end{aligned}
$$

- Temporal and spectral intensity in both polarisations can be calculated.

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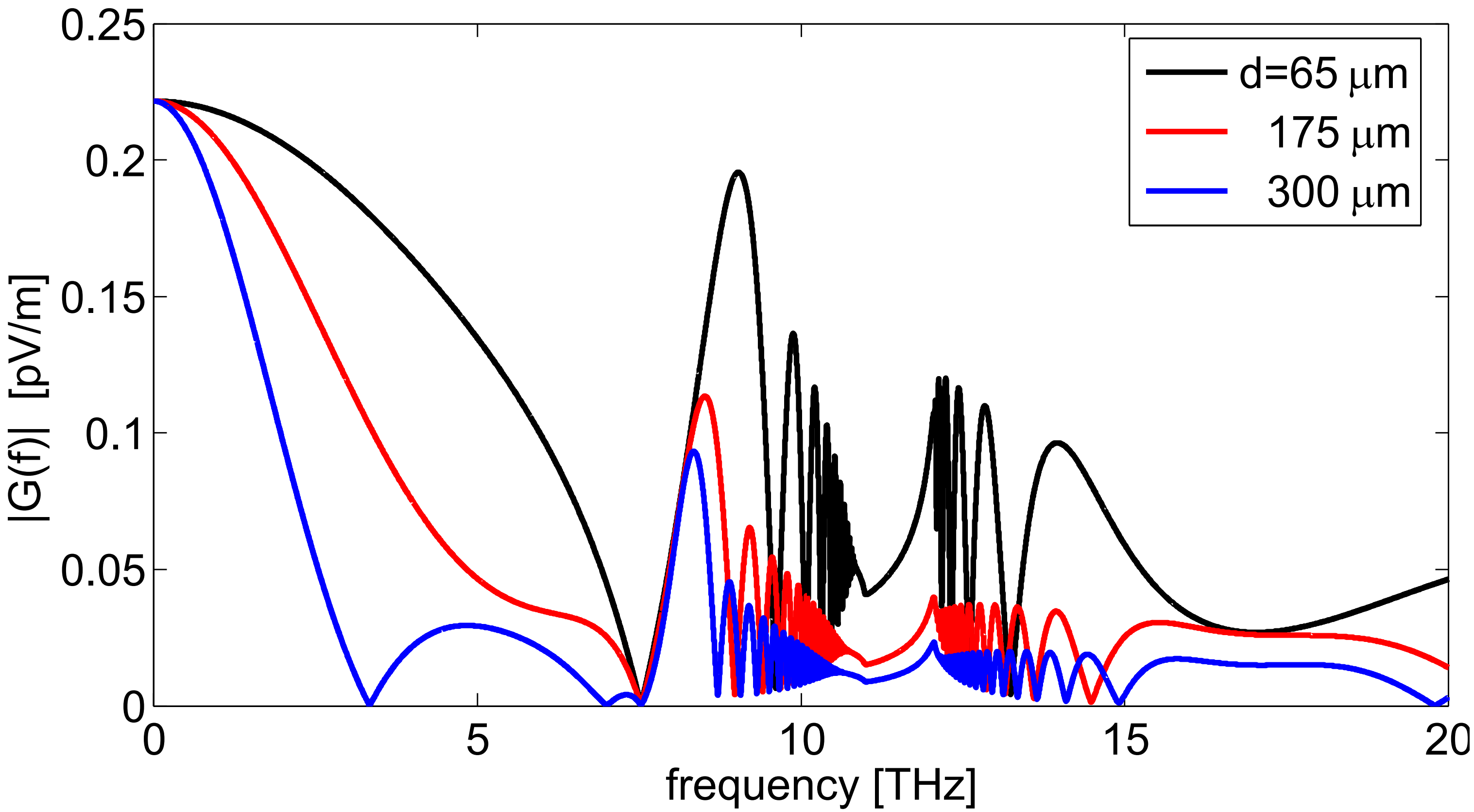
Response function of the EO crystal



$$G(f,d) = r_{41}(f)\frac{2}{1+n(f)+i\kappa(f)}\,\frac{1}{d}\int_0^d \exp\left[i\,2\pi f\,z\left(\frac{1}{v_{\mathrm{ph}}(f)}-\frac{1}{v_{\mathrm{g}}}\right)\right]\mathrm{d}z$$

EO coeff., transmission, velocity matching

Signal distortion esp. for thick crystals !

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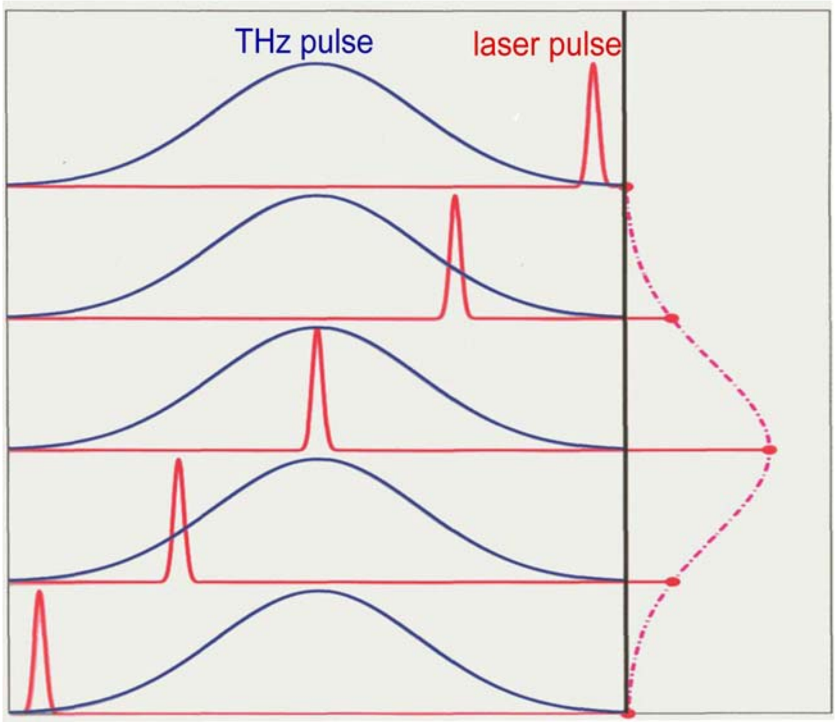
Electro-Optic Sampling using a variable Delay



EOS:
Electro-Optic Sampling

- frequently used for THz-spectroscopy
- technically simple, high resolution

Problem:
- averages over many bunches
- sensitive to time jitter

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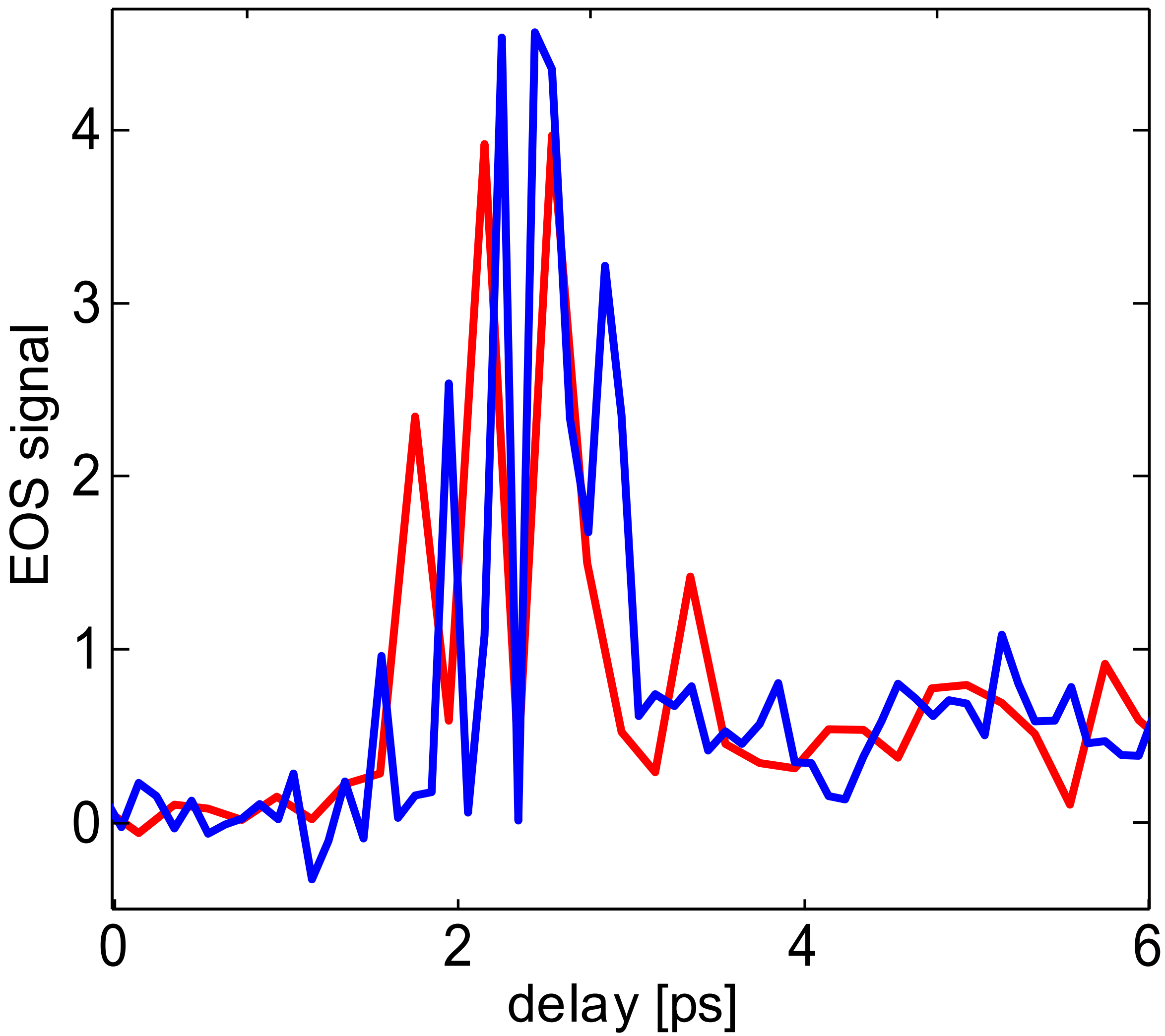
Electro-Optic Sampling using a variable delay

Time jitter: approx. 200 fs, larger than bunch length

Single shot measurements necessary!



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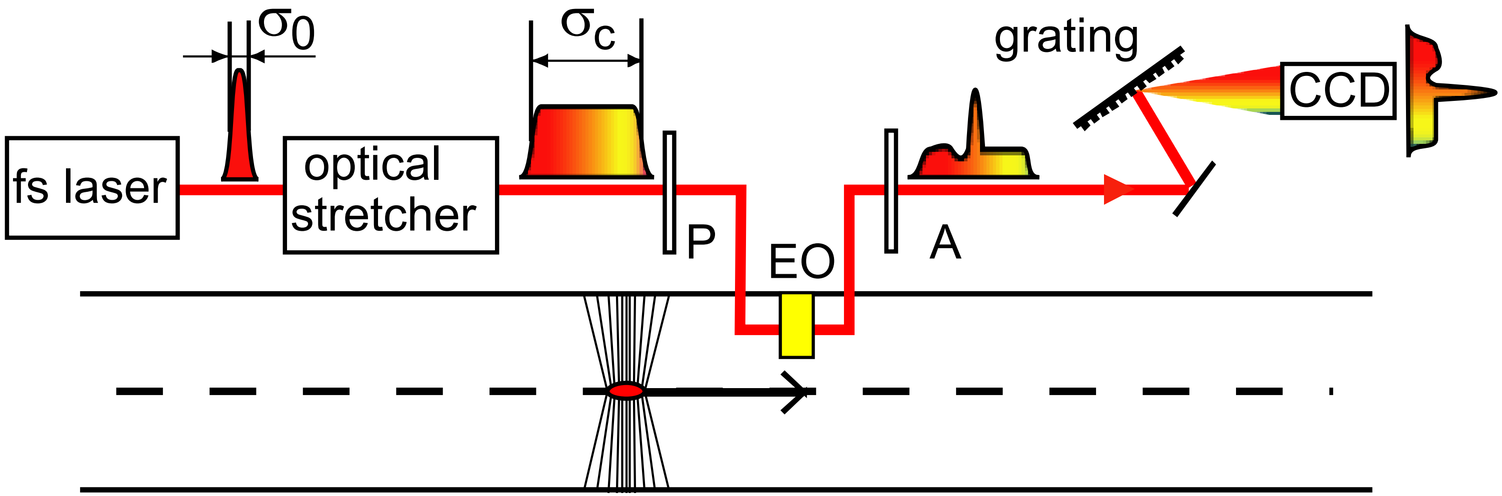
EO Spectral Detection

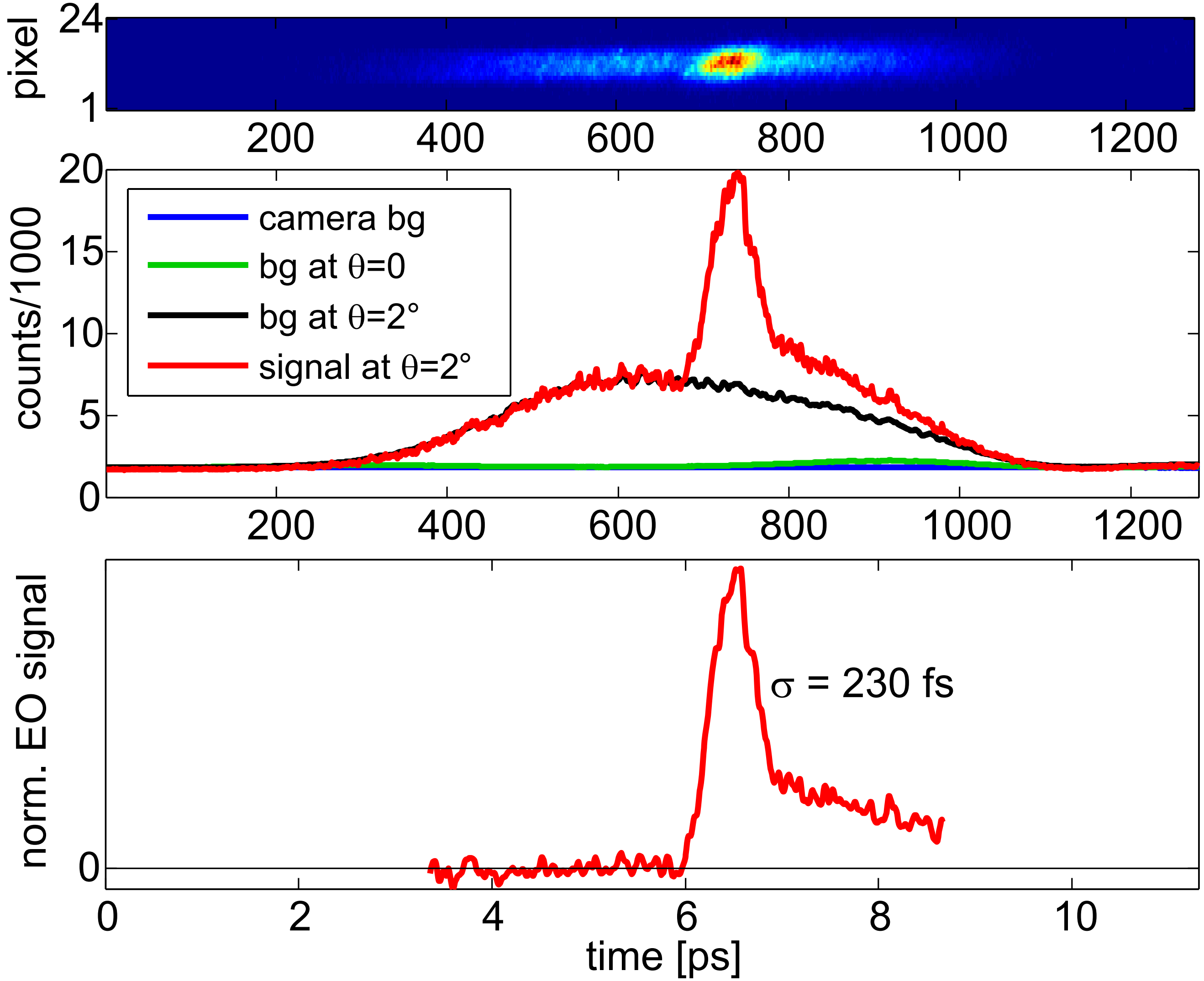


- Linear relationship between wavelength and long. position in laser pulse (“linear chirp“)
- Bunch profile is transferred to spectral profile of the laser pulse
  - Problem: Frequency mixing with THz pulse creates new frequency components:

    ⇒ Distortions at large chirp $\alpha \approx 1/\sqrt{\sigma_0\,\sigma_c}$

$$\sigma_{\min} \approx 2.6\sqrt{\sigma_0\,\sigma_c} \approx 200\ \text{fs}$$ (for Gaussian pulses!)

EO Spectral Detection



GaP 175 μm, σ_0=7 fs, σ_c=1.5 ps

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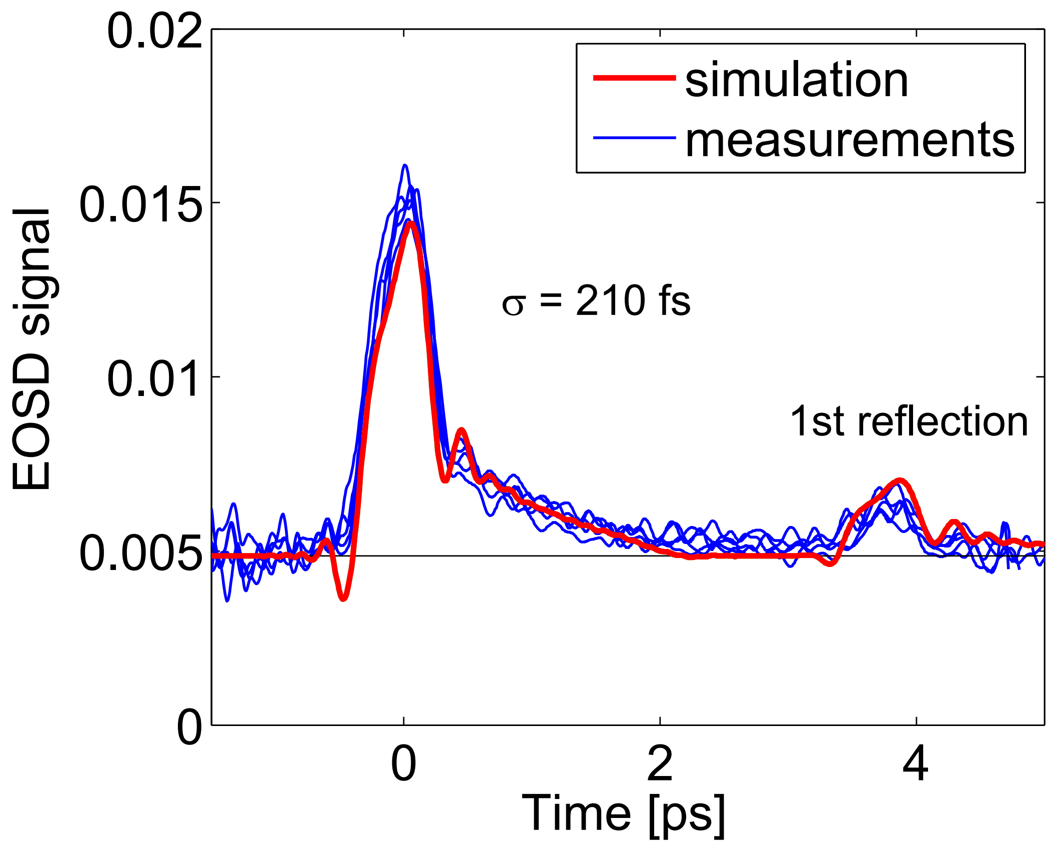
Spectrally resolved detection: Comparison of measured to simulated signals

5 consecutive bunches, corrected for different arrival times

Simulation:
EOSD signal of a bunch measured with TDS

GaP 175 µm
θ=2°
σ_0=7 fs
σ_c=1.5ps



Excellent agreement with simulation in shape and amplitude, but much wider than electron bunch due to response function and frequency mixing

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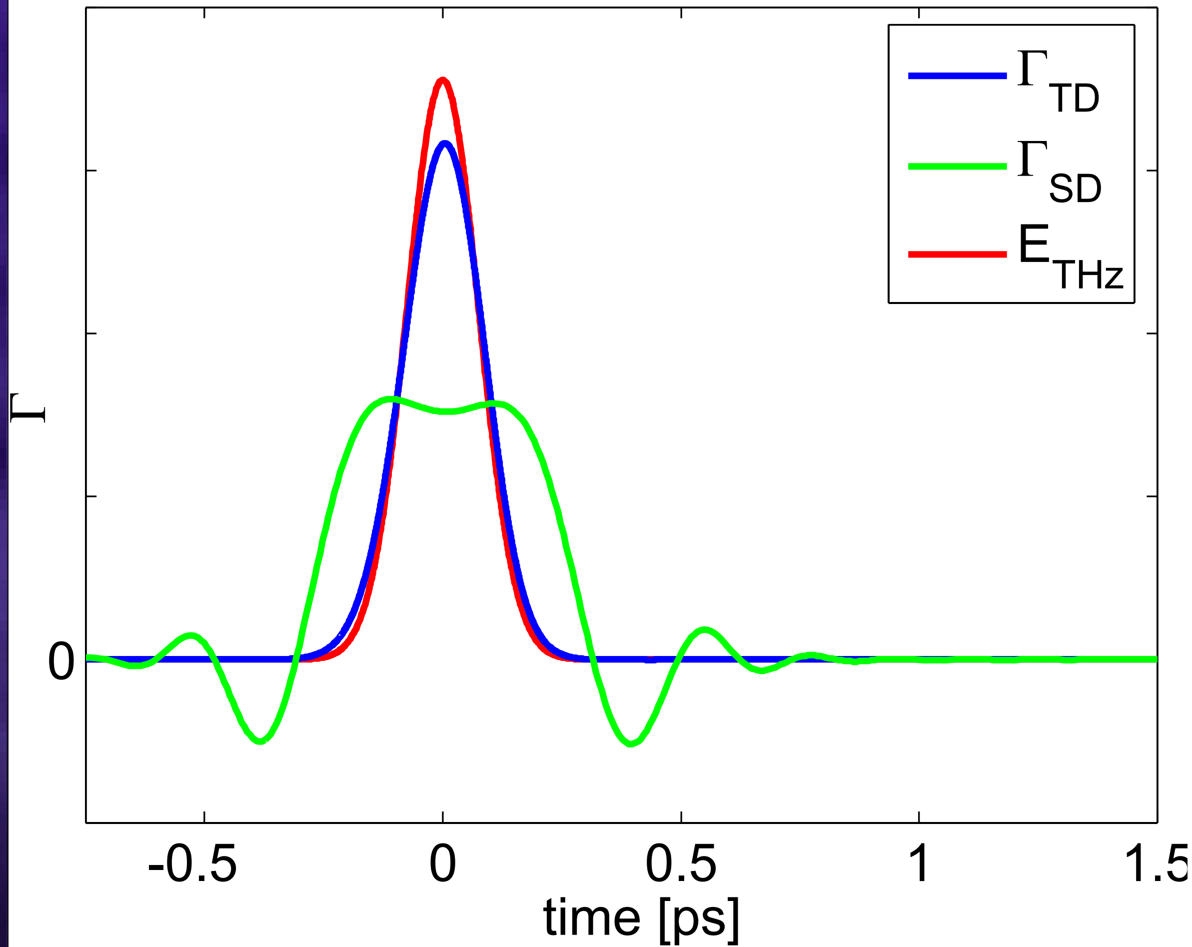
EOSD: Distortions due to frequency mixing for thin crystal and large chirp



GaP 100μm thick

σ_{THz}= 75 fs

Laser σ_0=6 fs
chirped to: σ_c=1.5 ps

θ=45°

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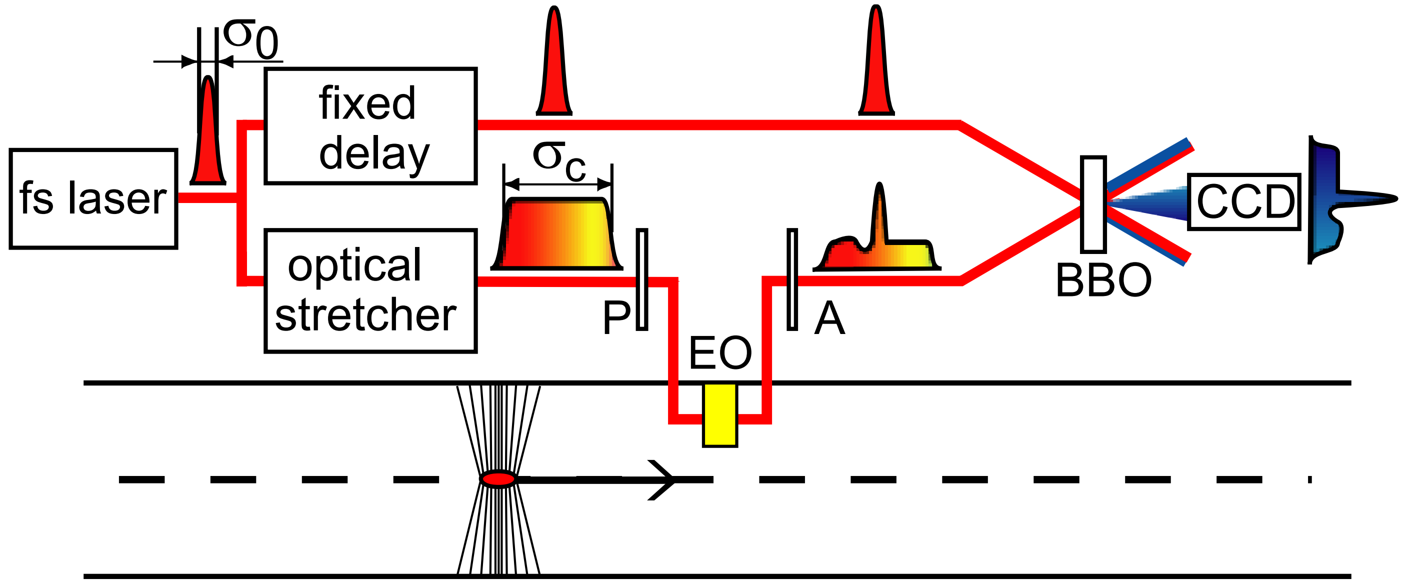
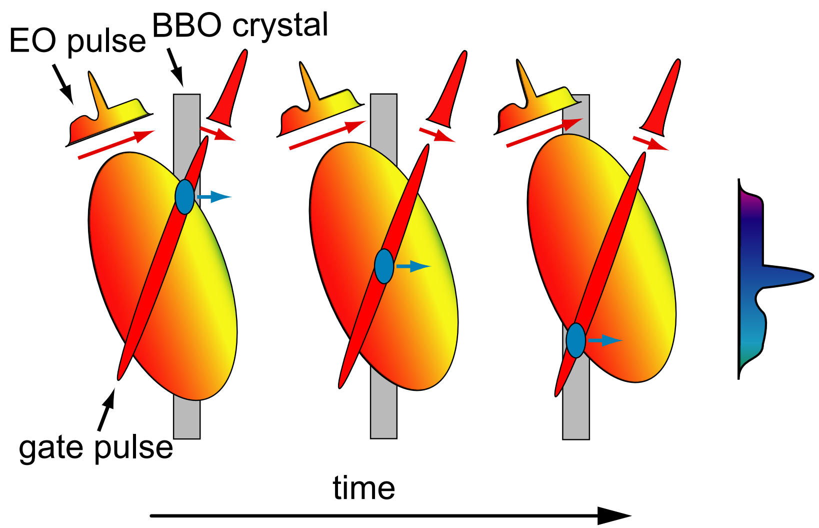
EO Temporal Detection



- Cross-correlation with fs pulse in a frequency doubling crystal (BBO)

- approx. 100 µJ pulse energy necessary for 10 ps time window



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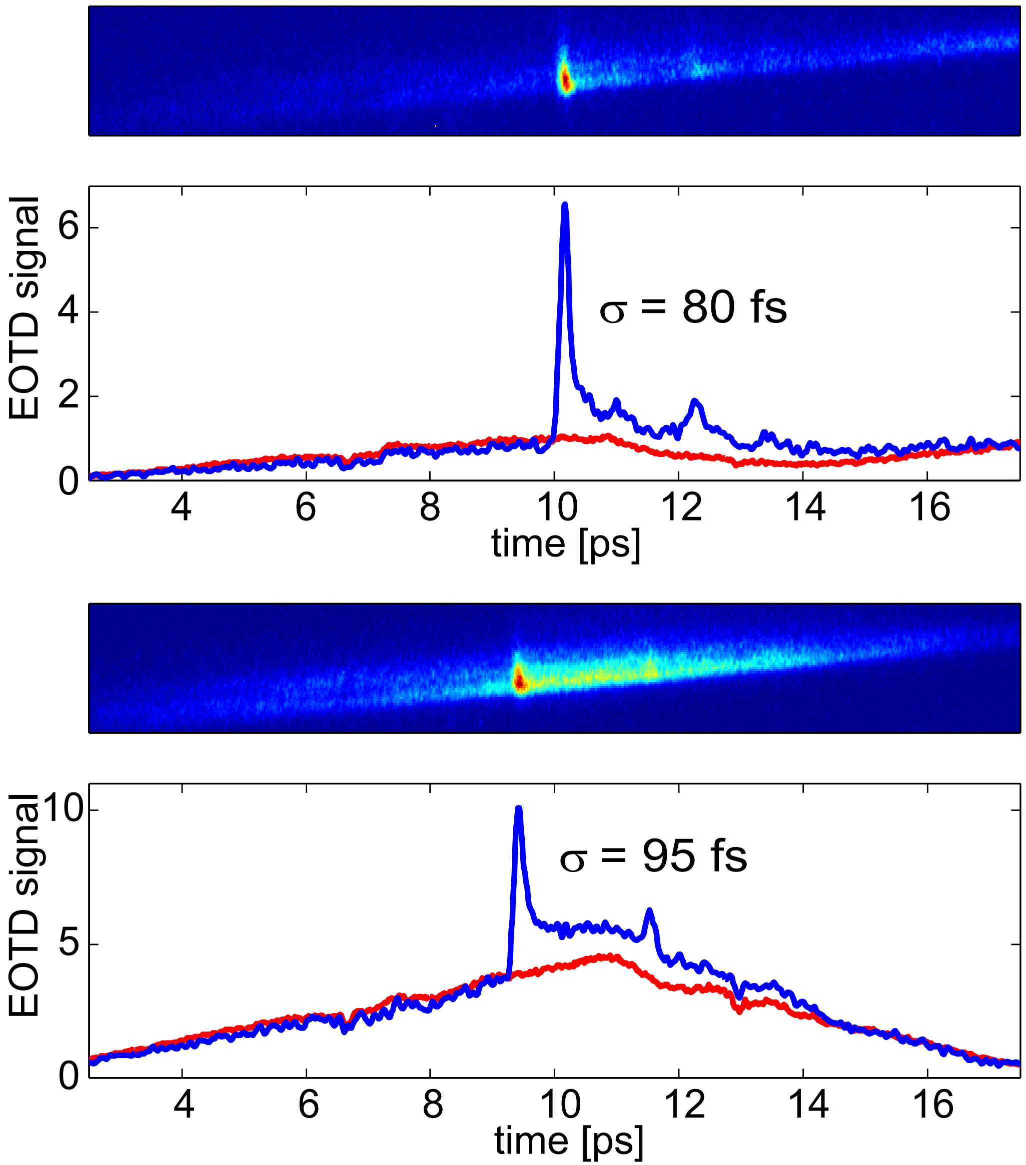
EO Temporal Detection



$\theta = 0$

EO signal □ E_{THz}^2

$\theta = 1°$

EO signal □ E_{THz}

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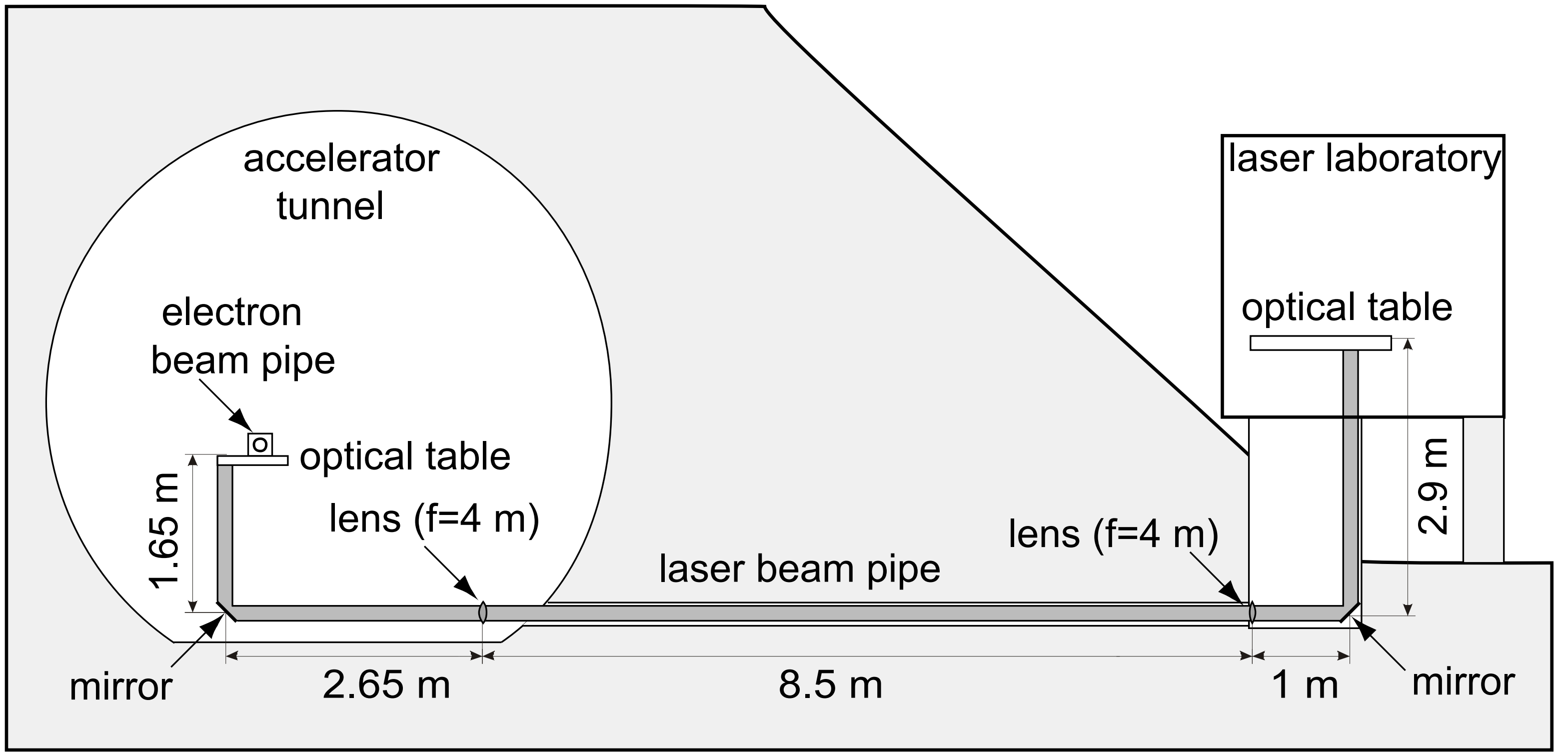
EO setup at FLASH



- Laser systems in lab outside the accelerator:
    - 4 nJ, 7 fs Ti:Sa Oscillator
    - 1 mJ, 15 fs Ti:Sa amplifier
- 20 m evacuated transfer pipe to the tunnel

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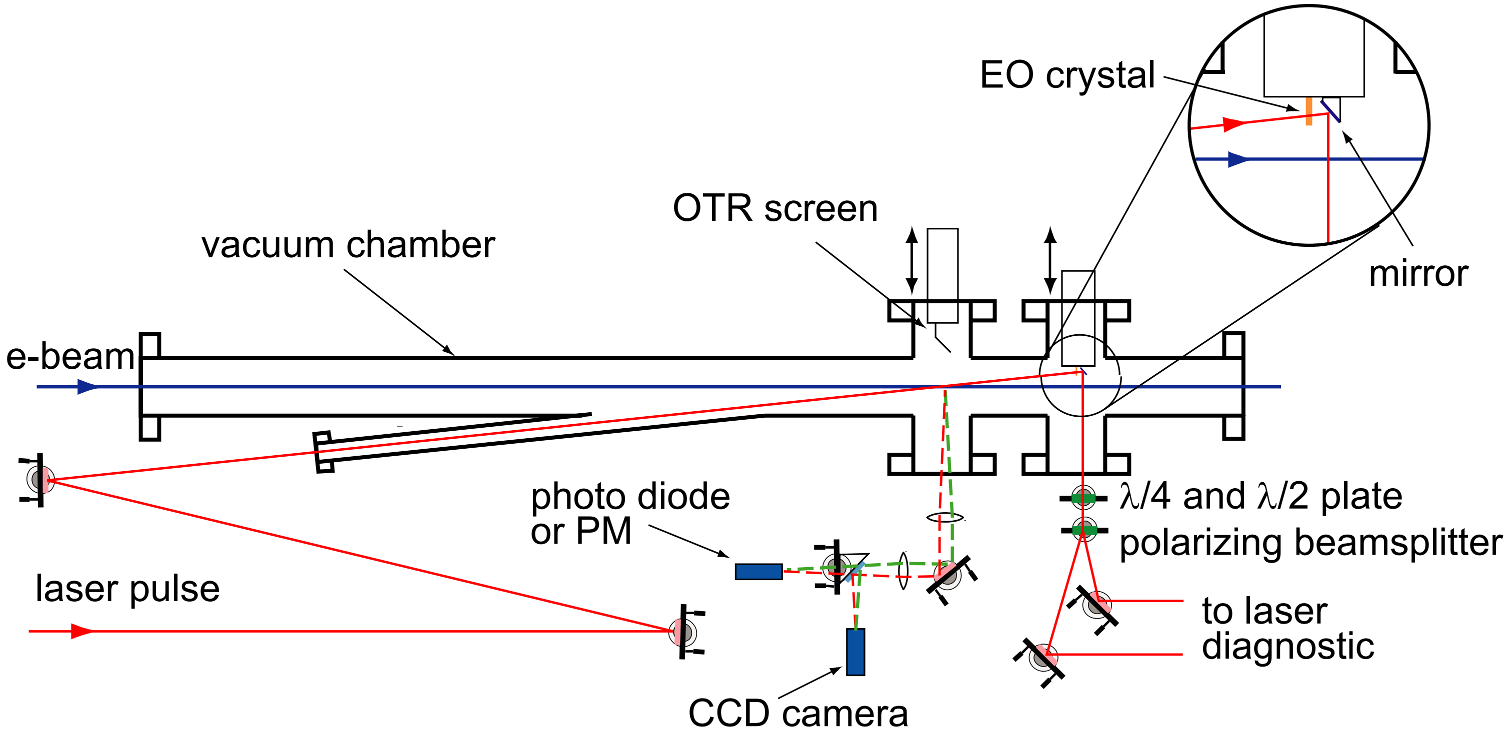
EO vacuum chamber in the beam pipe



- plane (175 μm) and wedged (30-200 μm) GaP crystal in the beam pipe

- allows spectrally and temporally decoded measurements

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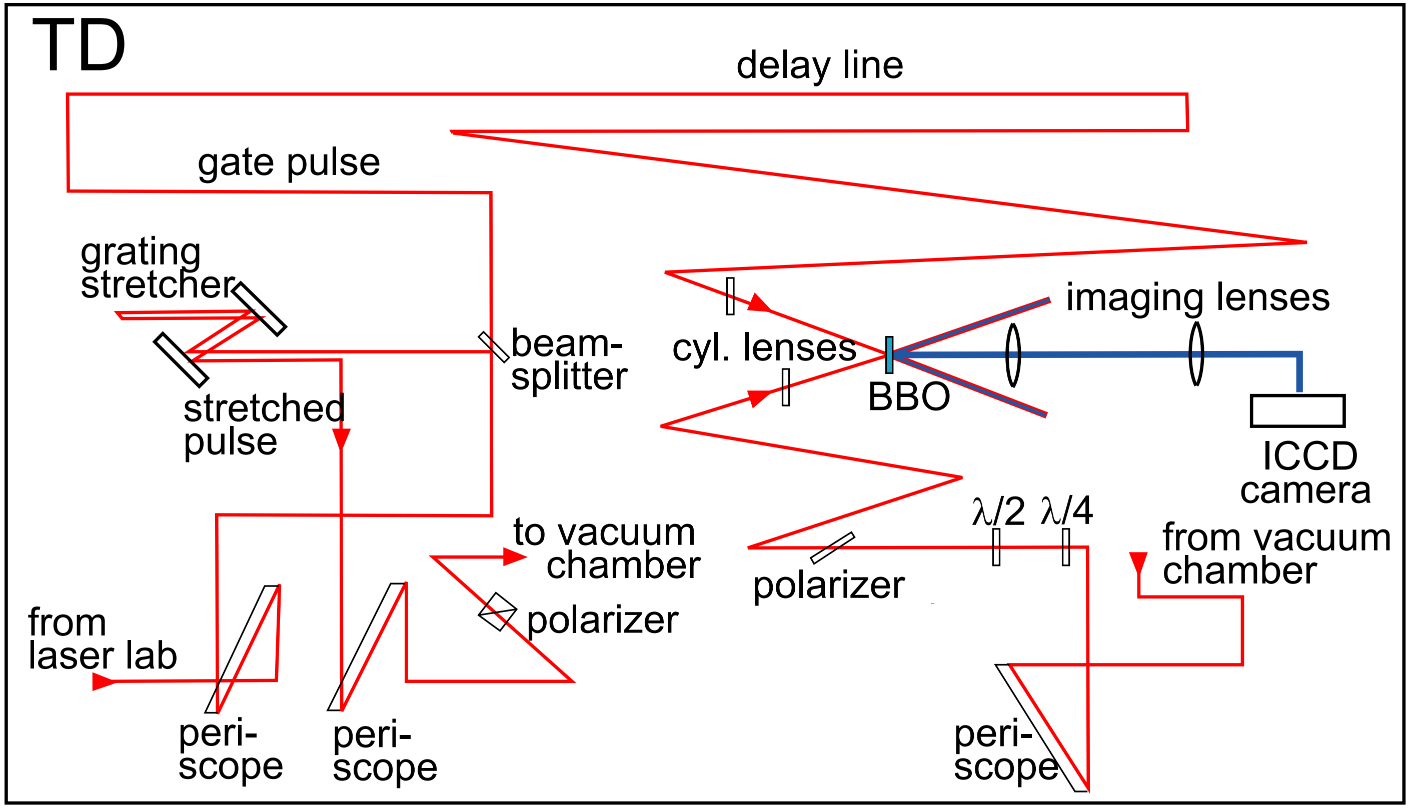
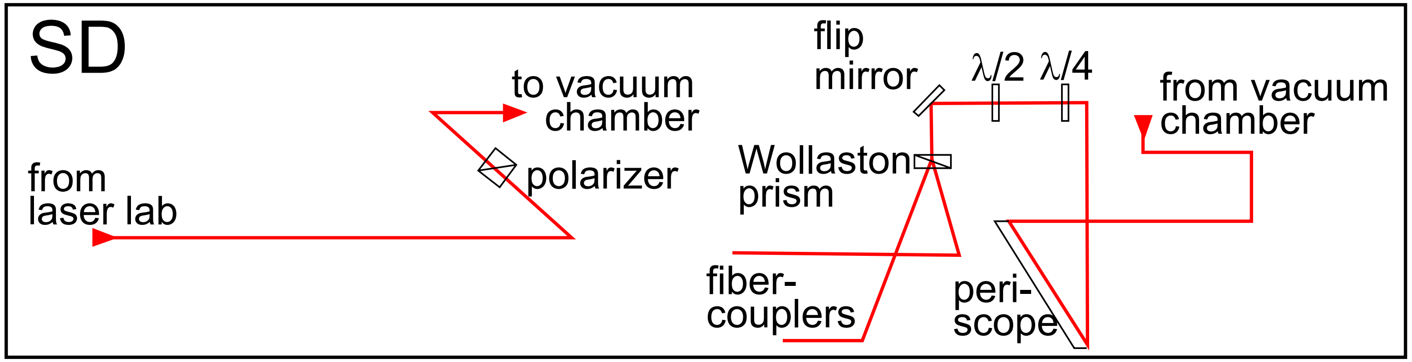
EO setup in the accelerator tunnel





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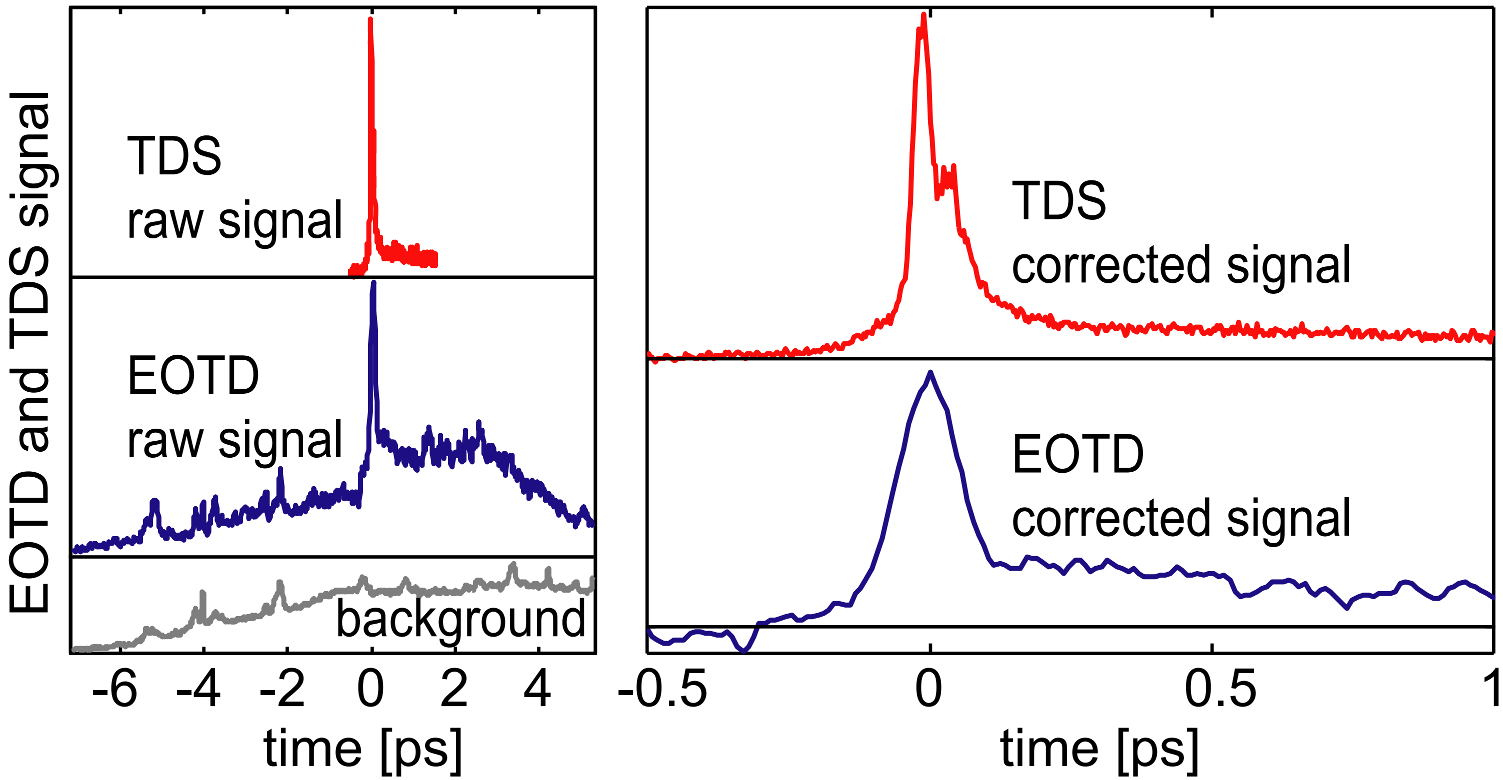
Comparison of EOTD vs. TDS measurements



- 10th bunch in bunch train: electro-optic detection
- 11th bunch: TDS

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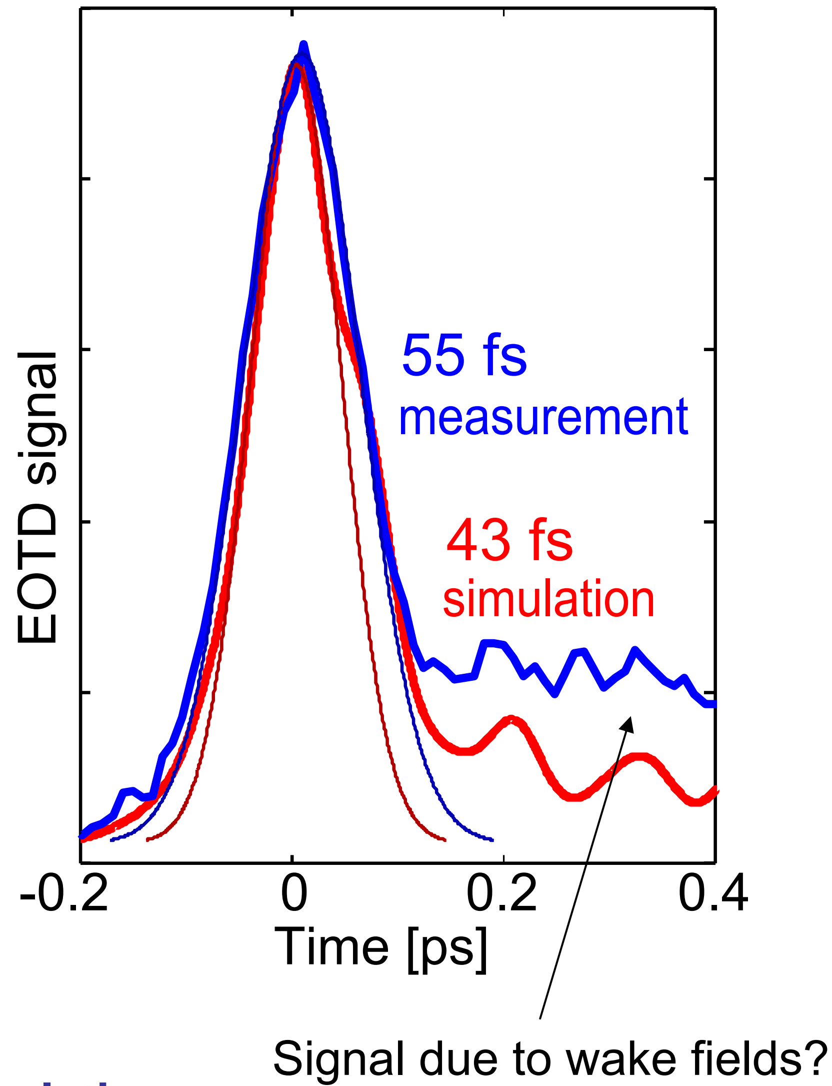
Comparison of EOTD vs. TDS measurements



- Good agreement between measurement and simulation

- close to the resolution limit of GaP

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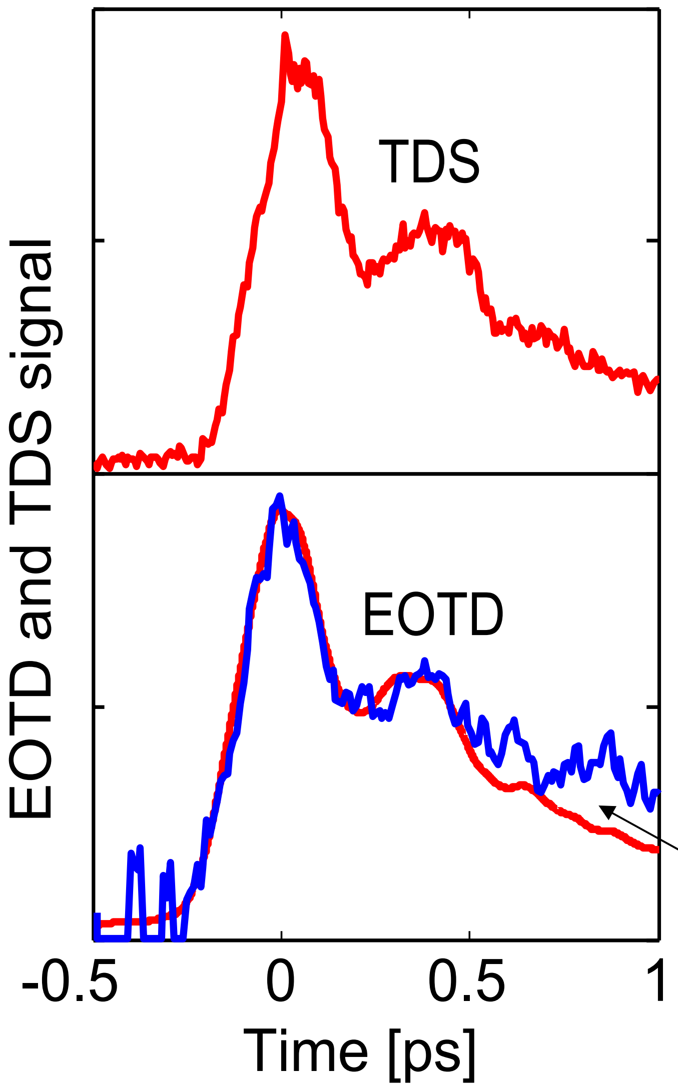
TDS and EOTD measurement of overcompressed bunches



In good agreement with the electron bunch shape

Signal due to wake fields?

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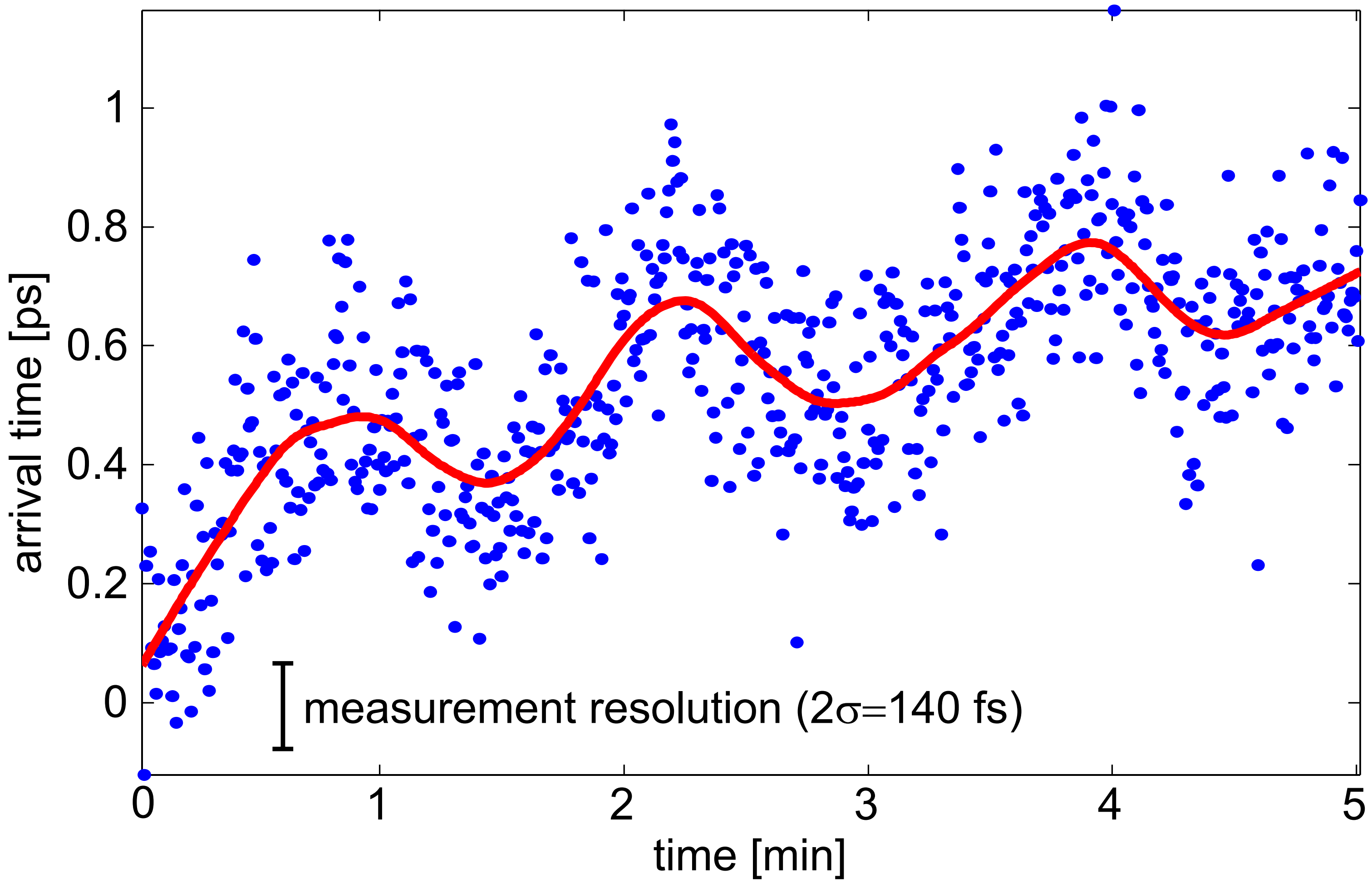
Time jitter, measured with EOSD



- Time jitter: 200 fs (rms) incl. slow drift
- Slow drift removed: **130 fs (rms)**

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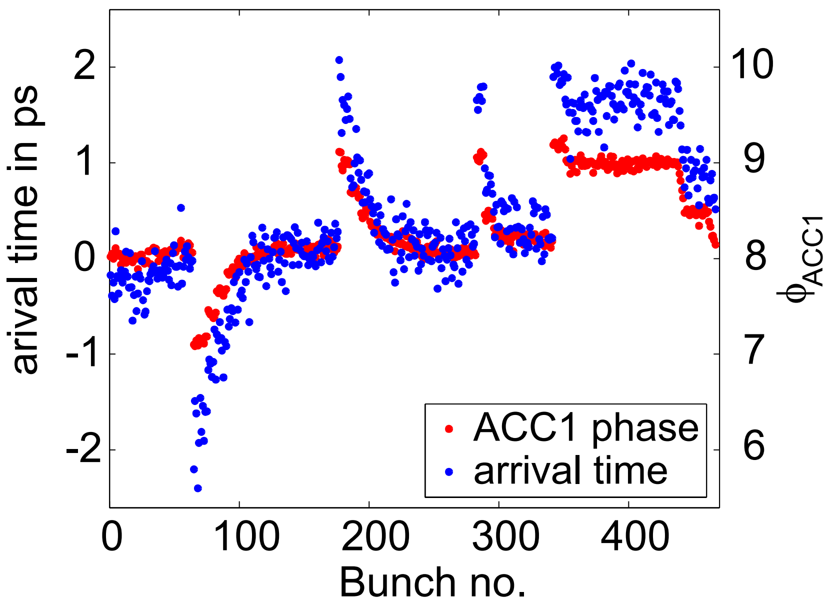
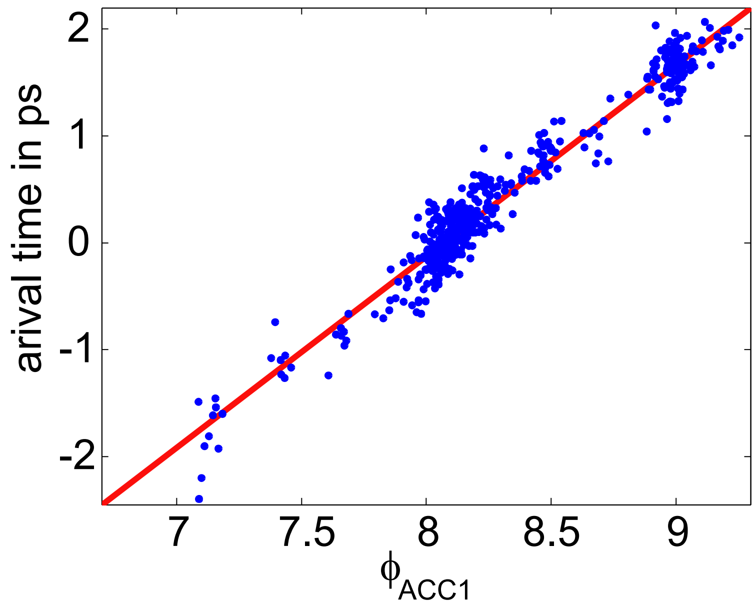
Bunch arrival time dependence on the ACC1 phase





Arrival time change: 1.79 ps/Grad

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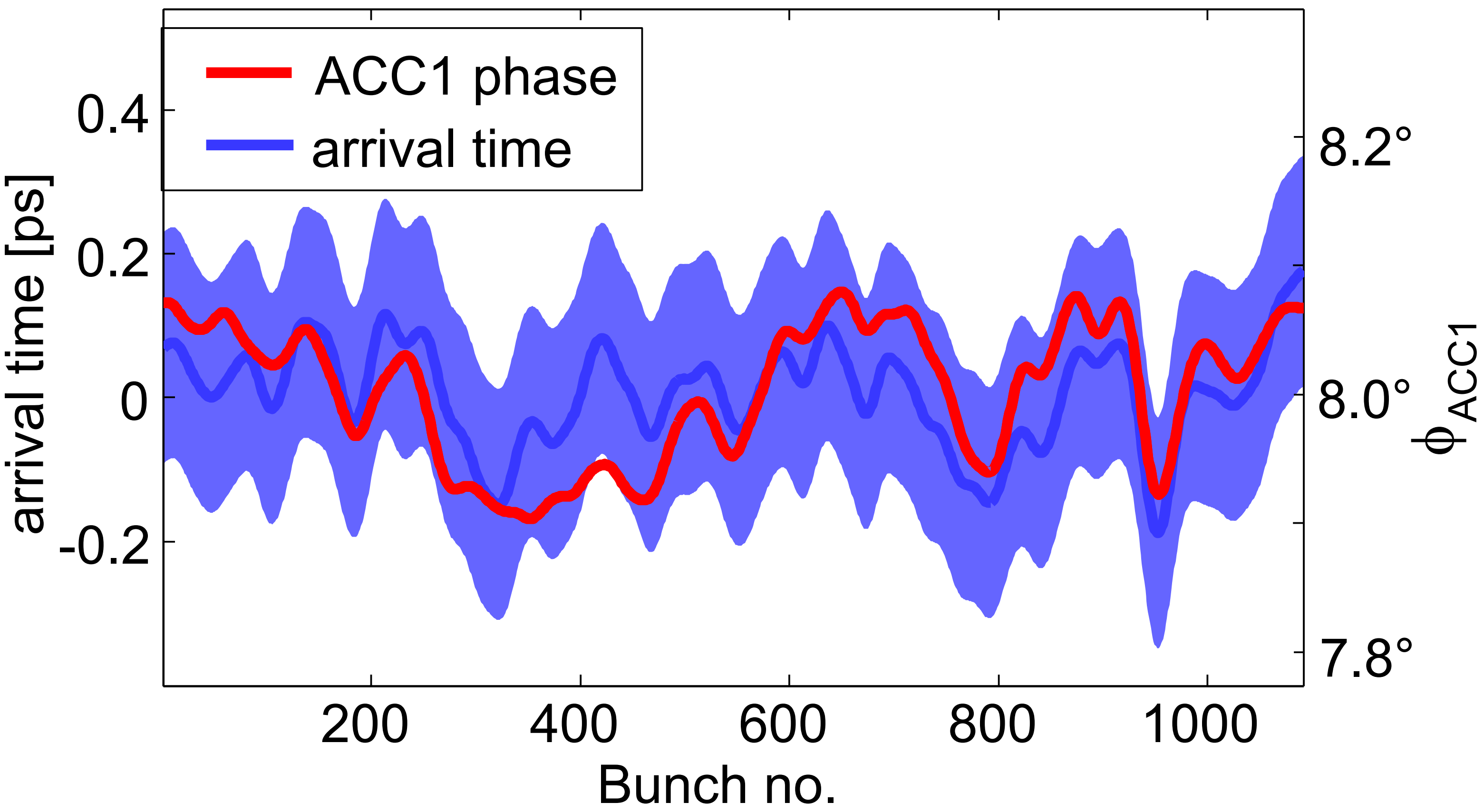
Correlation between arrival time and ACC1 phase



⇒ correlated time jitter due to phase jitter: 103 fs
⇒ uncorrelated time jitter due to other sources: 135 fs
⇒ uncertainty in the phase measurement: 0.04° or 73 fs

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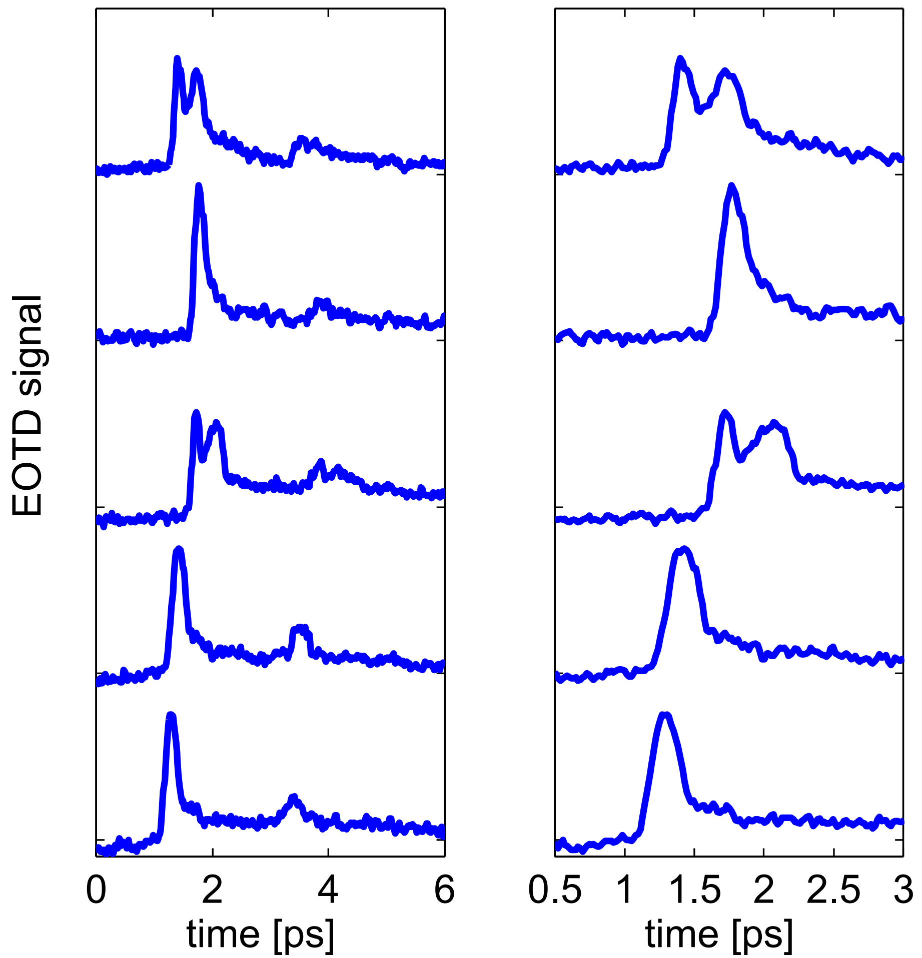
Bunch shape without at maximum compression (without feedback)



occasionally double pulses

Down to a separation of approx. 130 fs double pulses can be separated

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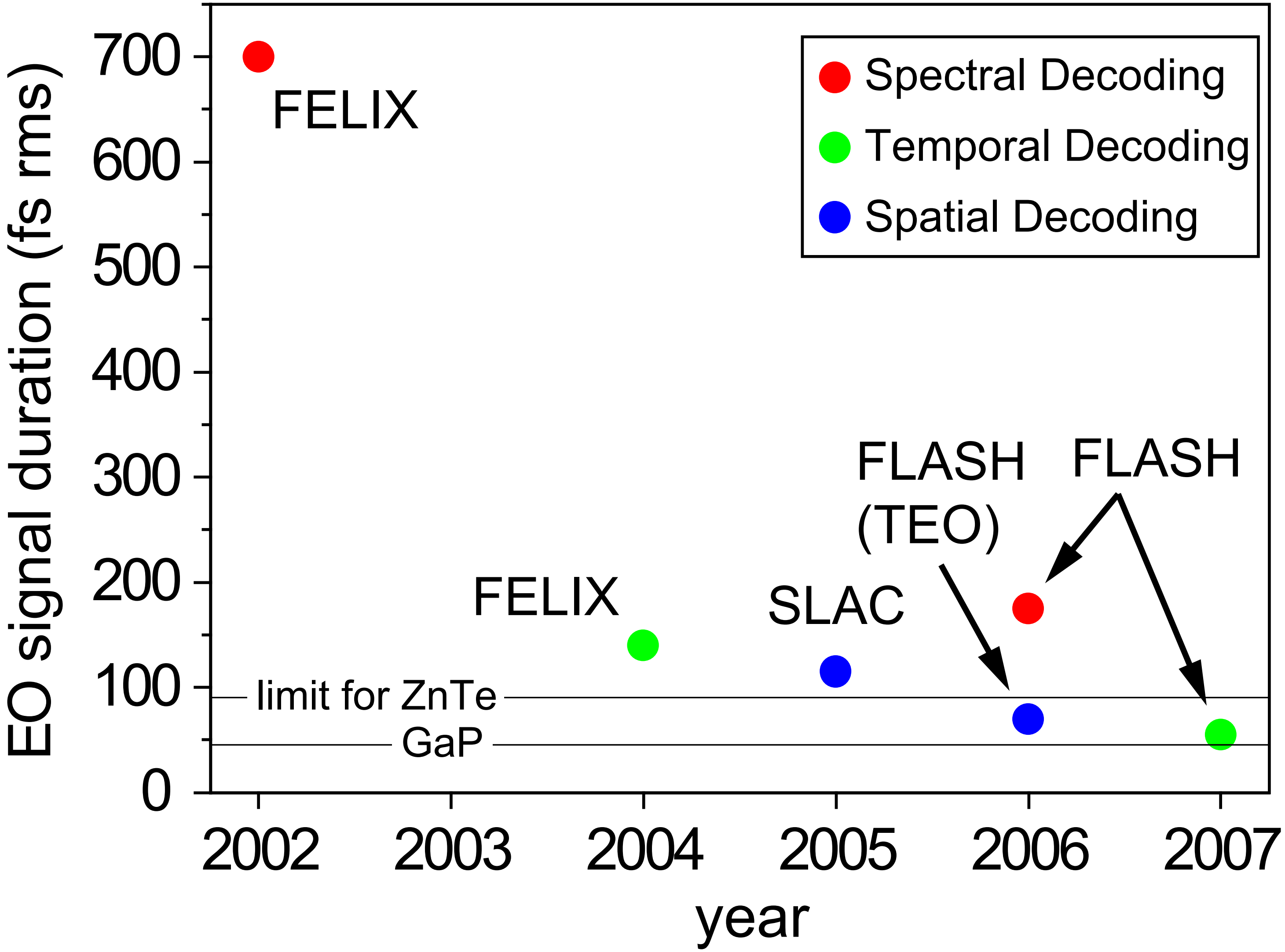
Comparison to other EO experiments



Conclusions

- Benchmarked EO detection against TDS
- Simulations based on published material data consistent in shape and amplitude with measured signals for GaP
- EO signals measured with of 55 fs (rms) length (linear in field and without deconvolution!) are close to the resolution limit of GaP

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