Electro-Optic Longitudinal Bunch Profile Measurements at FLASH: Experiment, Simulation, and Validation

Bernd Steffen, DESY

FEL 2007

Novosibirsk, August 29th 2007

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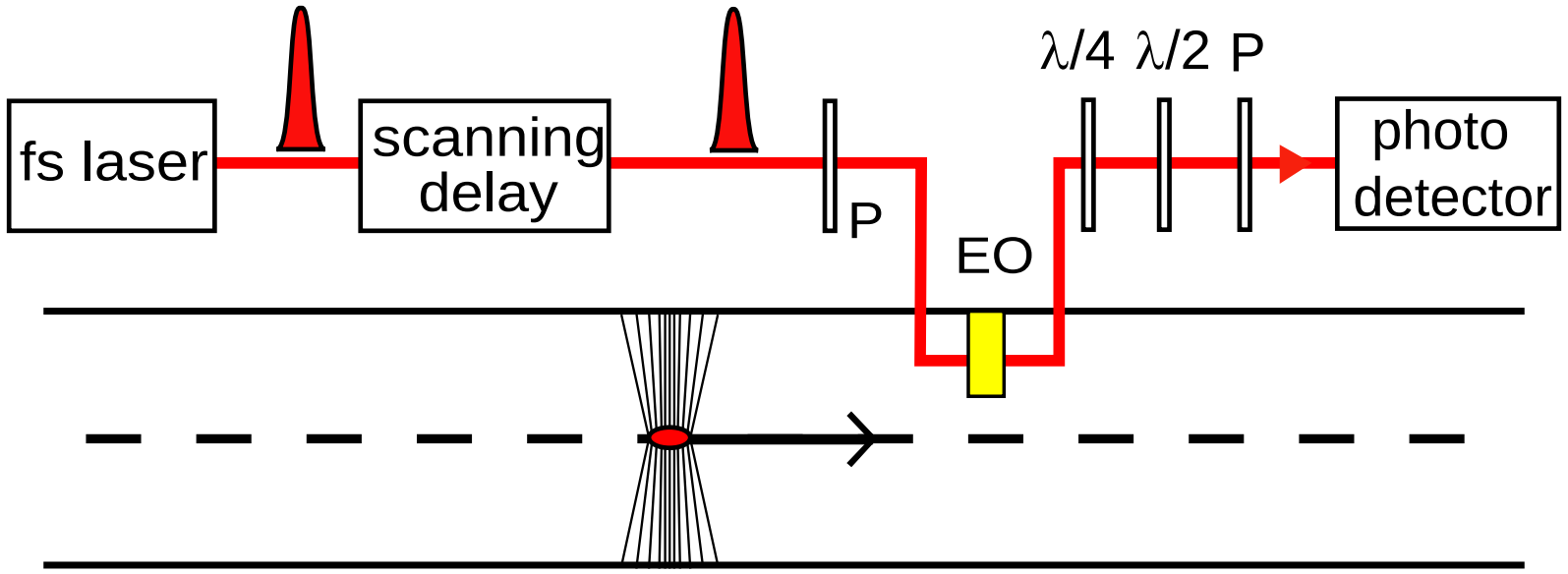
Electro-Optic Bunch Length Detection



- Coulomb field of electron bunch induces birefringence in EO crystal.

- birefringence is sampled by Ti:Sa laser pulse.

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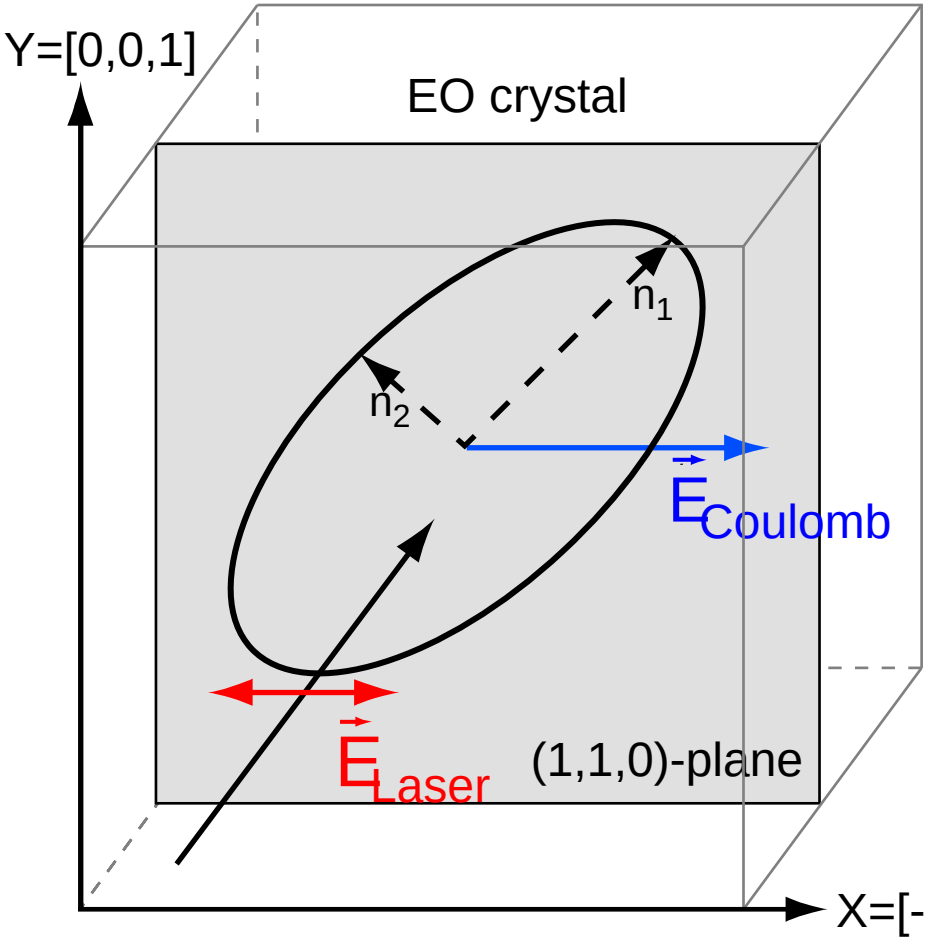
The Electro-Optic Effect: Coulomb Field induced Birefringence



Phase retardation
(in the small signal limit):

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

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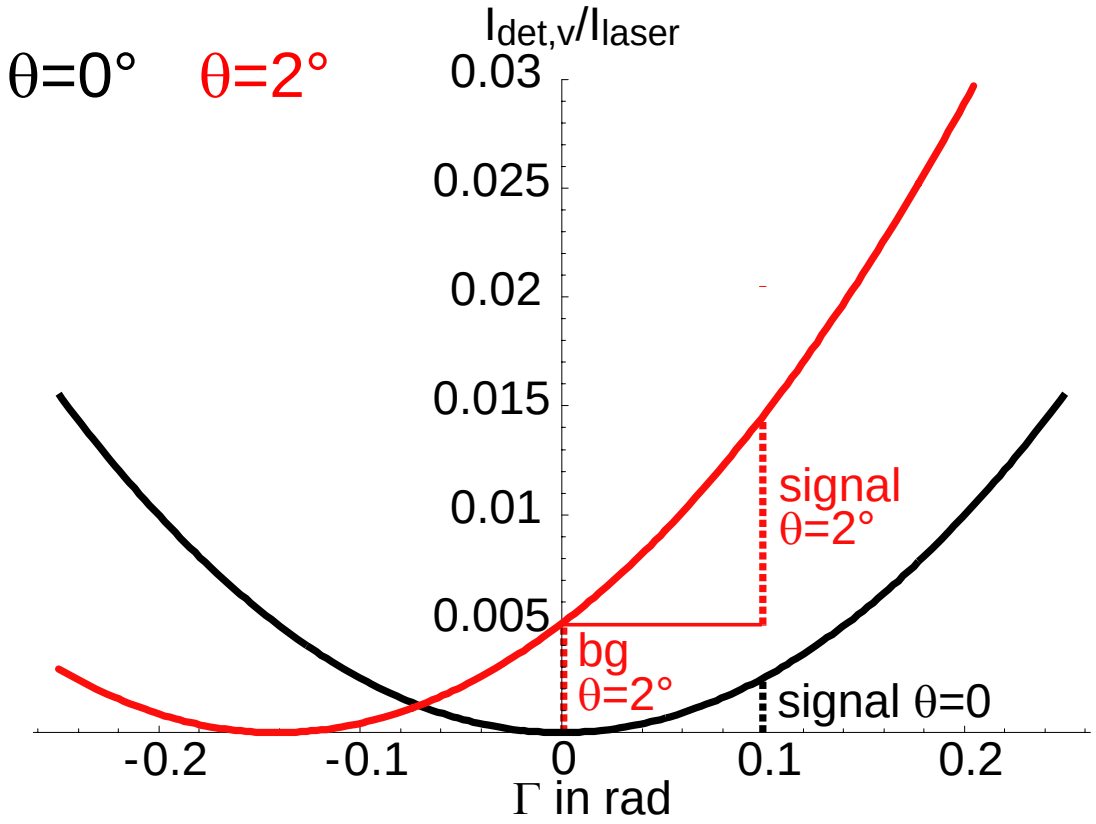
Effect of the half wave plate



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

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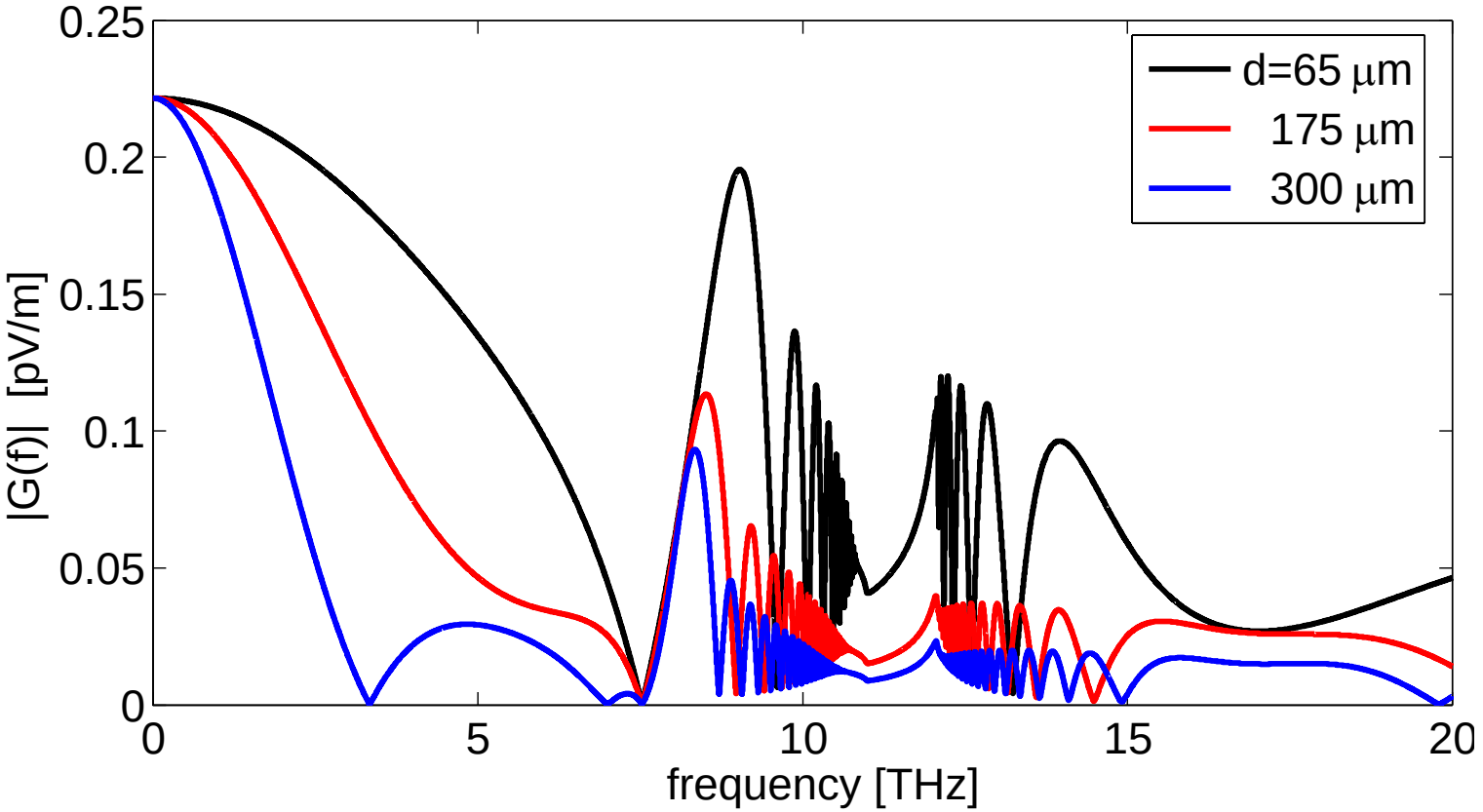
Response function of the GaP crystal



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

EO coeff., transmission, velocity matching

Signal distortion esp. for thick crystals !

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The simulation program

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

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

$$= \frac{E_{\mathrm{laser}}}{\sqrt{2}} [\cos(2\theta)\sin(\Gamma/2) - \sin(2\phi - 2\theta)\cos(\Gamma/2)$$

$$-i\,(\sin(2\theta)\cos(\Gamma/2) + \cos(2\phi - 2\theta)\sin(\Gamma/2))]$$

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

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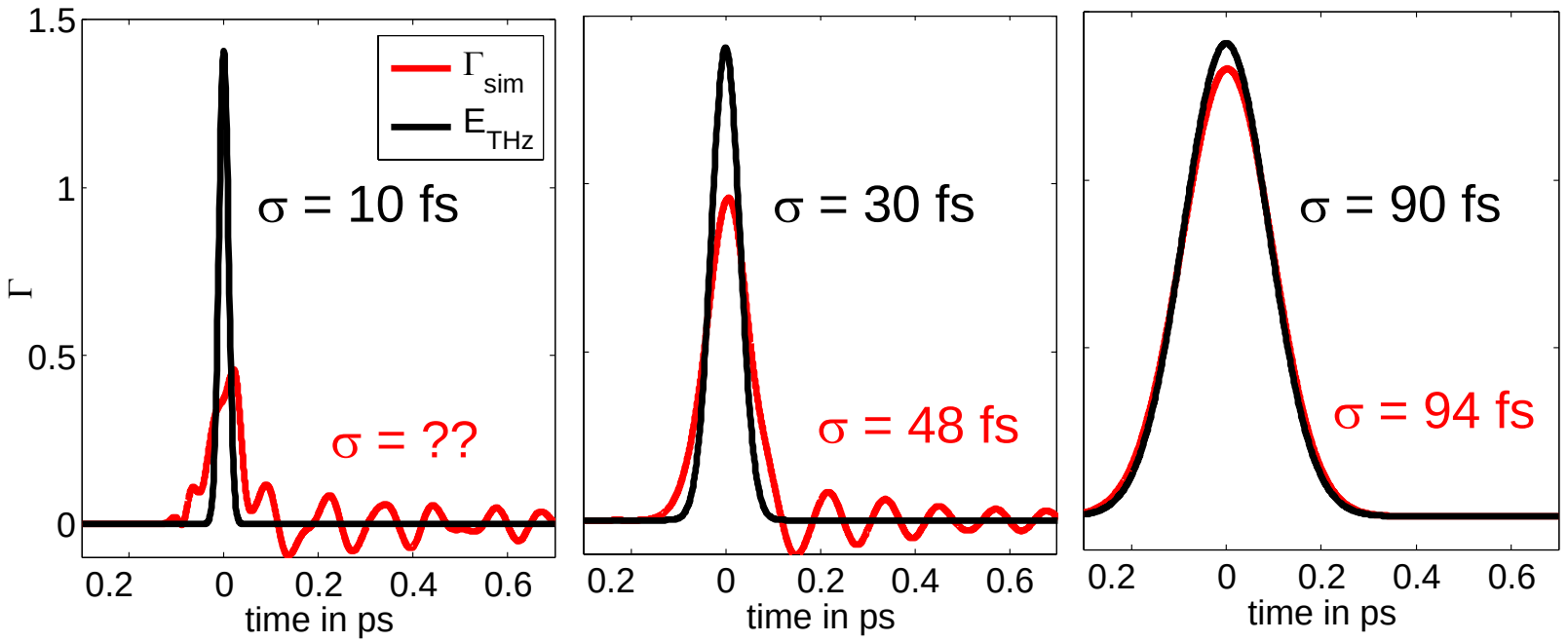
Simulated EOTD signals of Gaussian THz pulses in 65 µm GaP



All pulse length:
σ of a fitted Gaussian

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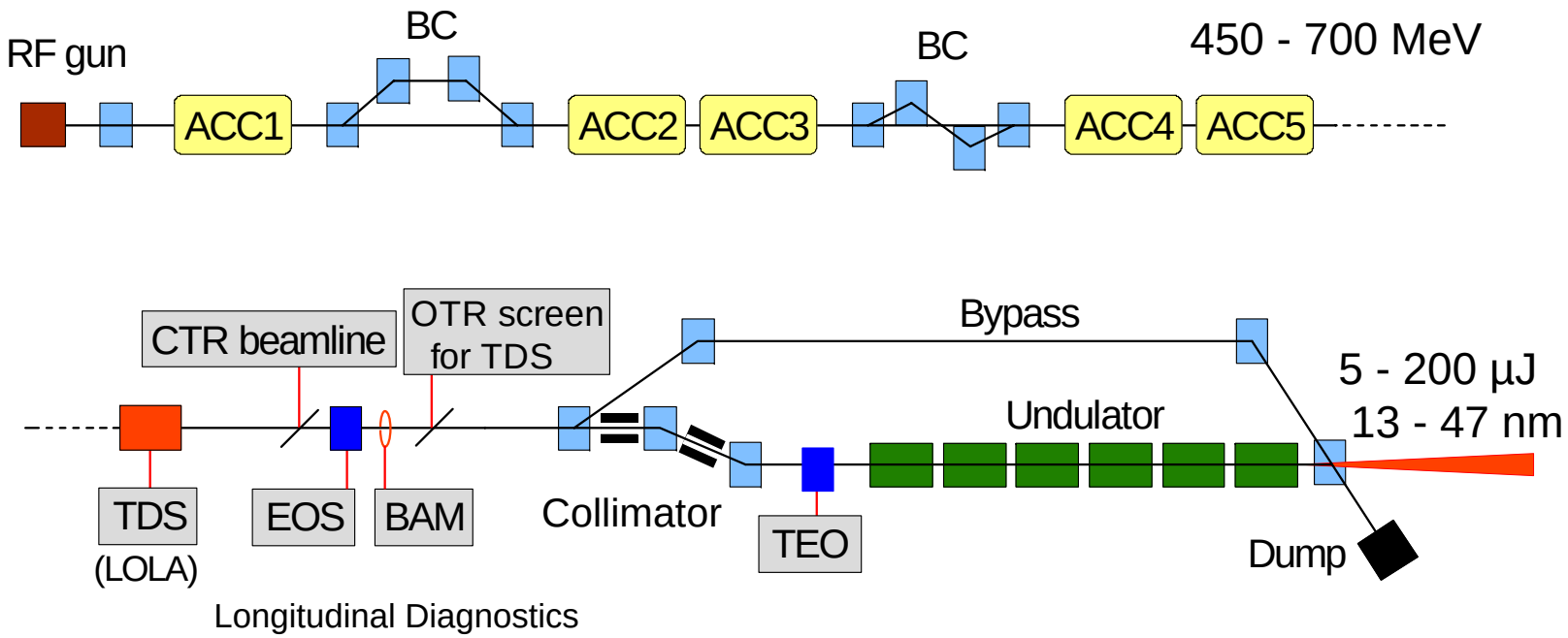

Electron bunches:
- ≈ 30 fs duration
- ≈ 700 MeV electron energy
- ≈ 0.5 - 1 nC charge
- ≈ 1 kA peak current

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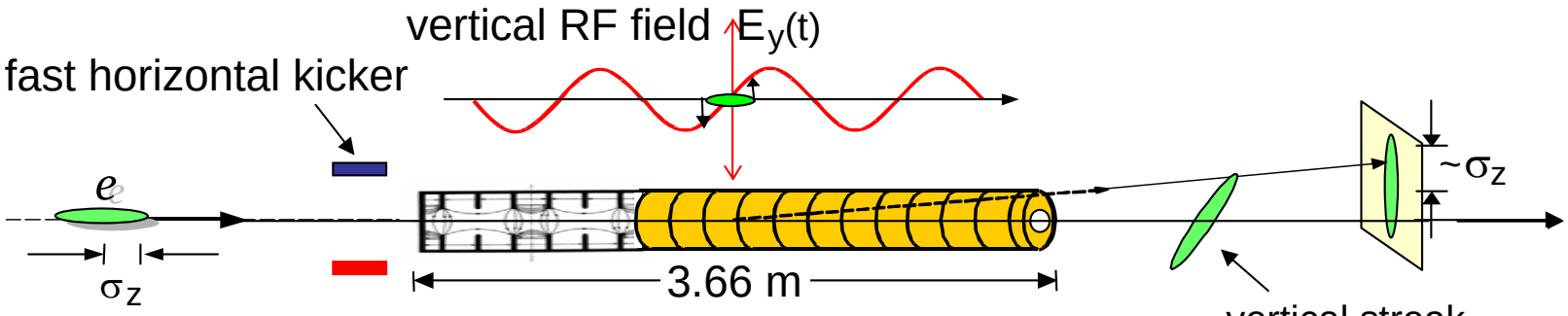
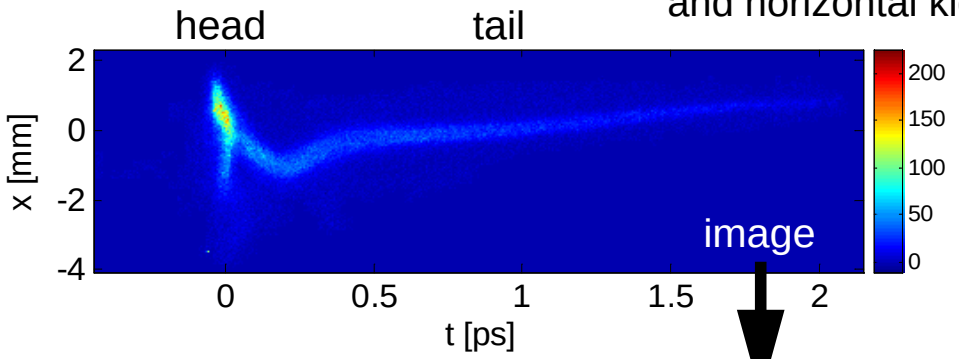
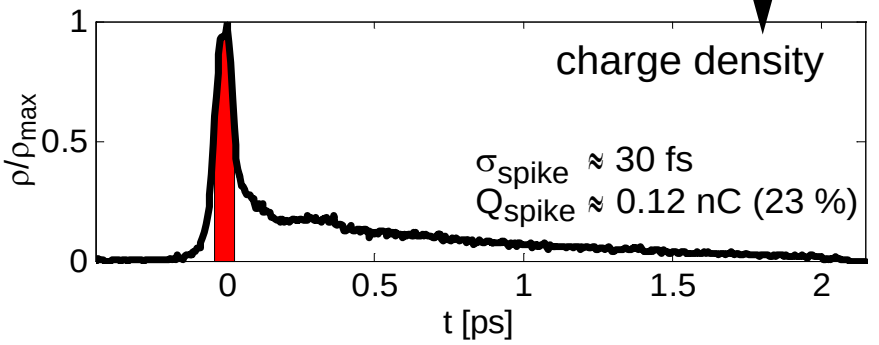
Bunch length measurements using the transverse deflecting structure (TDS)







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

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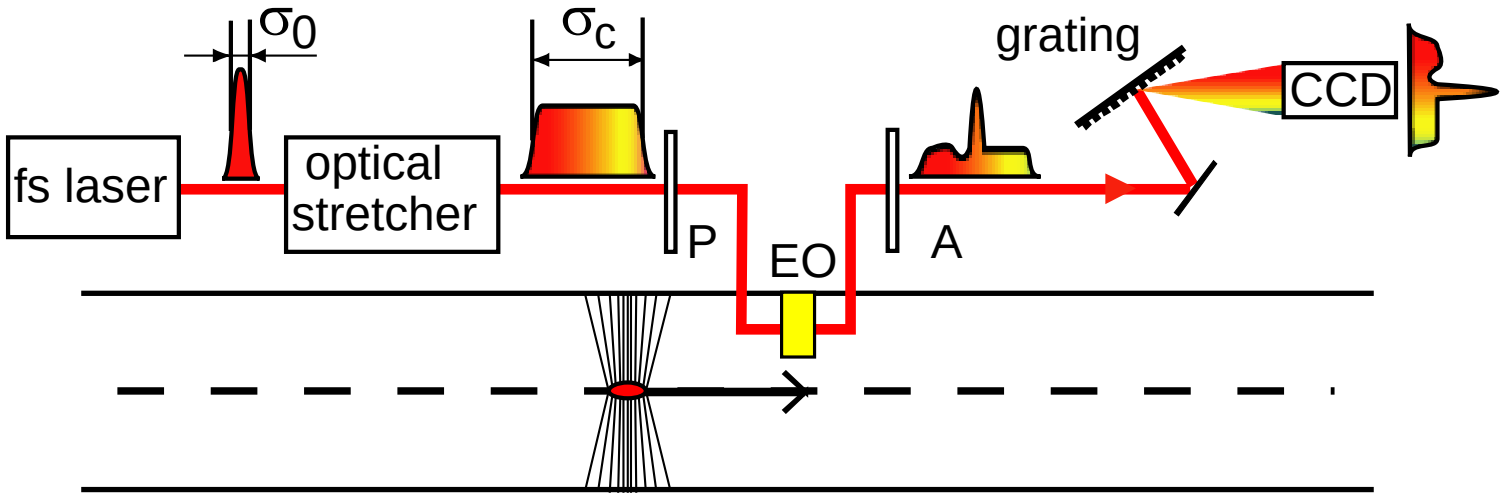
EO Spectral Detection



- 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 Coulomb field creates new frequency components:

    $\Rightarrow$ 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!)

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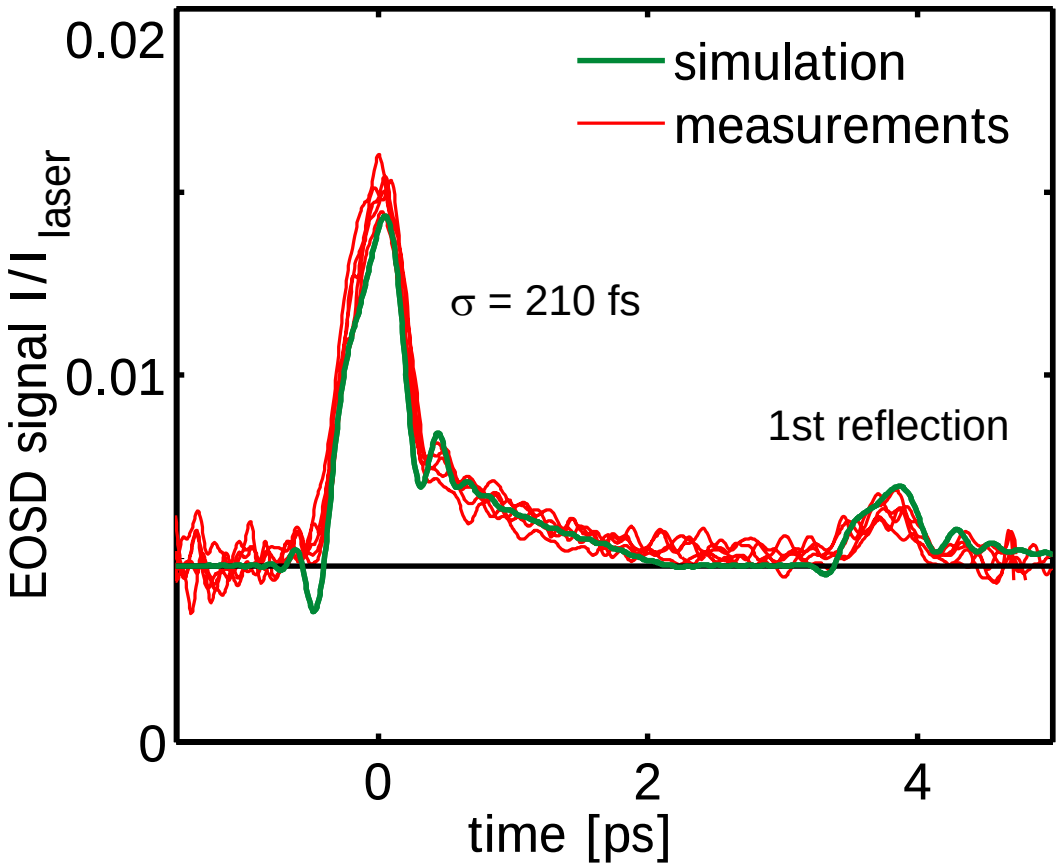
Spectrally resolved detection: Comparison of measured to simulated Signals

5 consecutive bunches, corrected for different arrival times

Simulation:
EOSD signal of a bunch measured with TDS

GaP 175 µm
θ=2°
σ_0=6 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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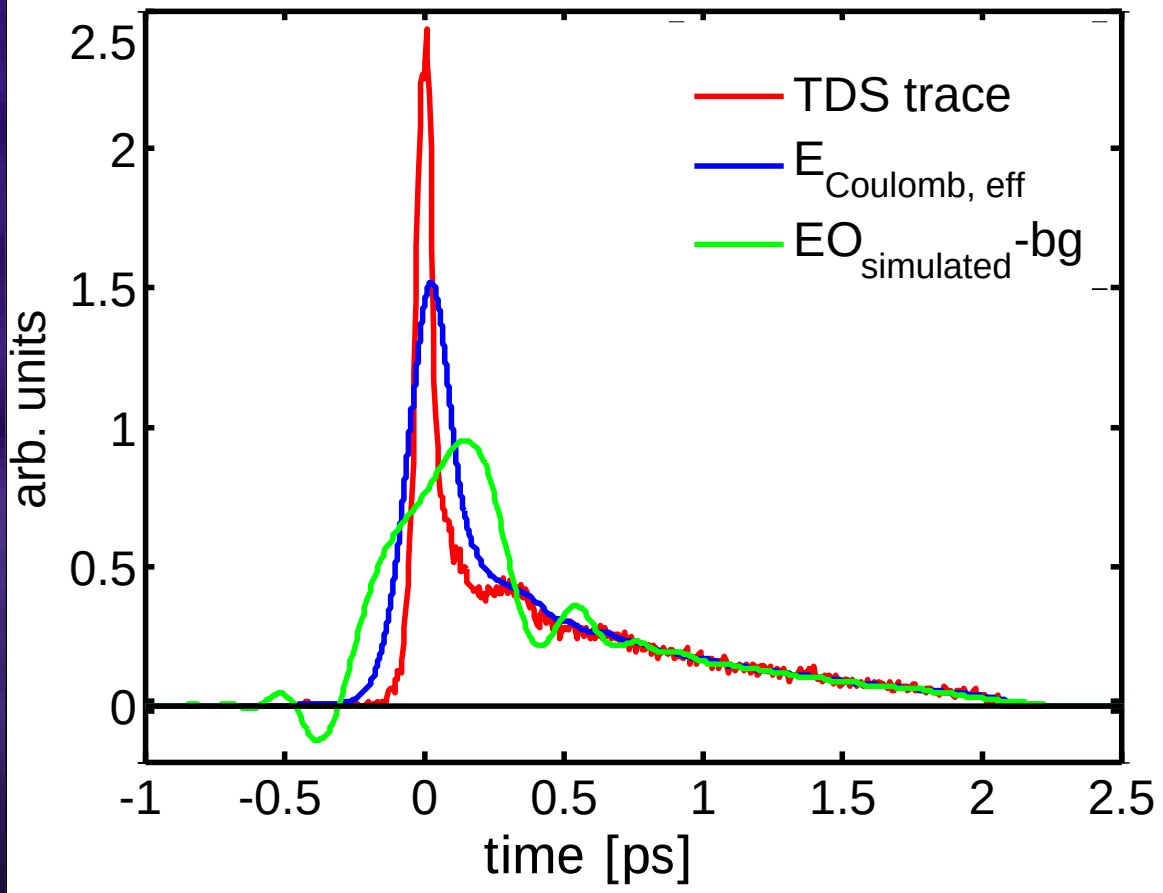
EOSD: Distortions due to frequency mixing for thin crystal and large chirp



GaP 175 μm thick

Laser σ_0=6 fs
chirped to: σ_c=1.5 ps

θ=2°

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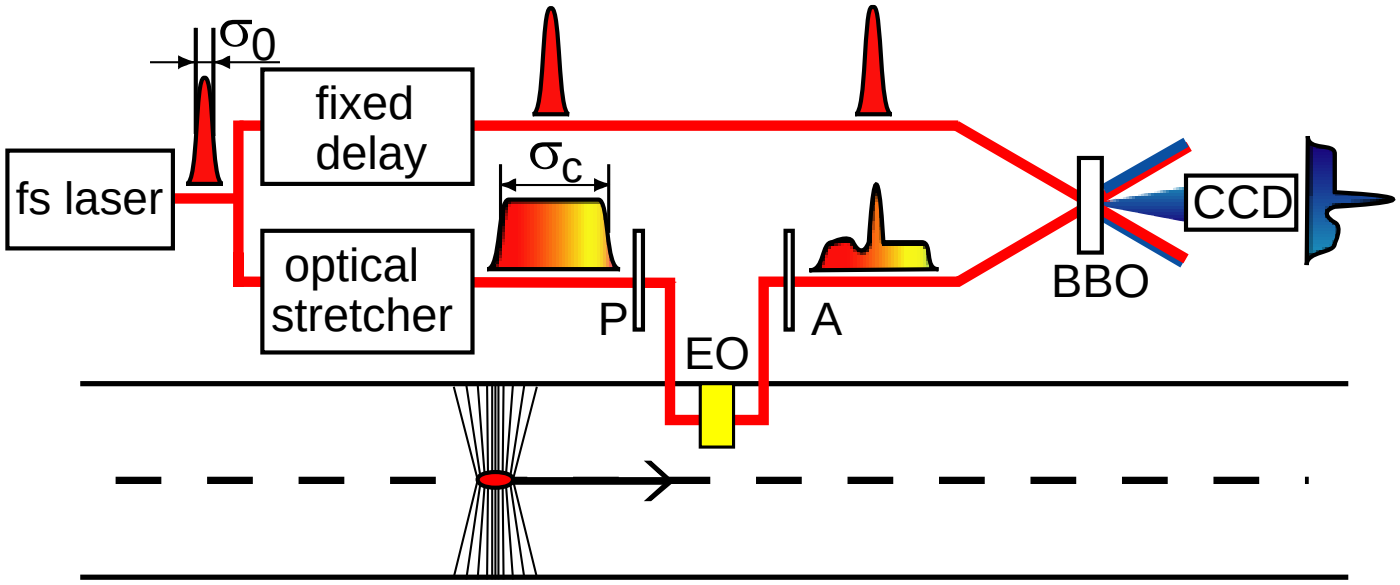
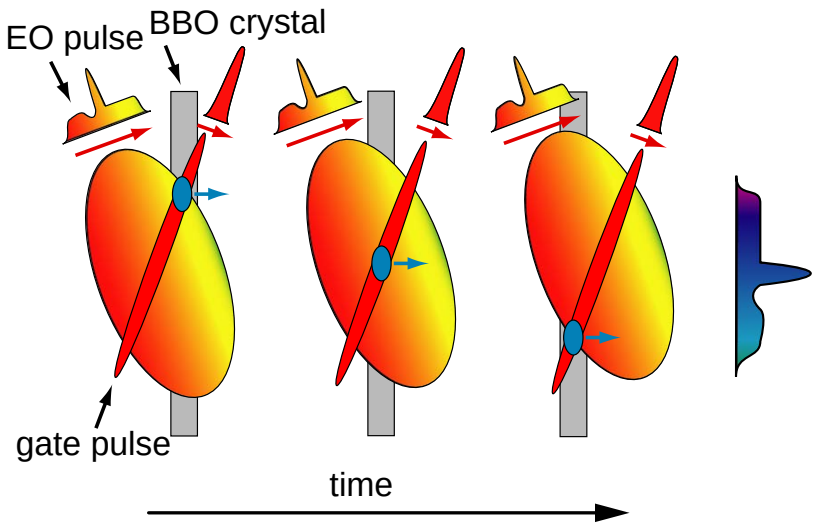
EO Temporal Detection





- Single shot 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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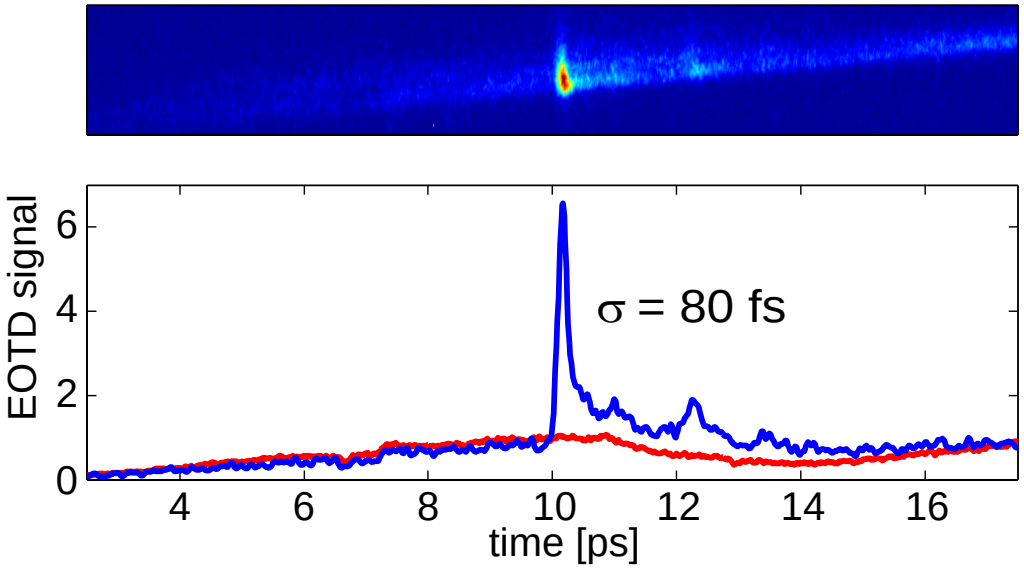
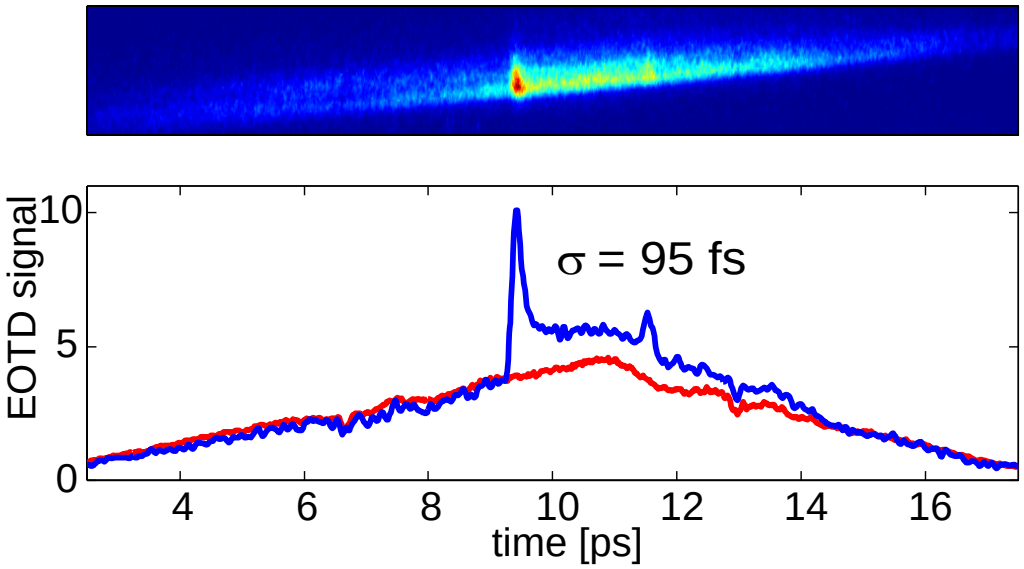
EO Temporal Detection



$\theta = 0$

EO signal $\propto E^2_{Coul}$



$\theta = 1°$

EO signal $\propto E_{Coul}$

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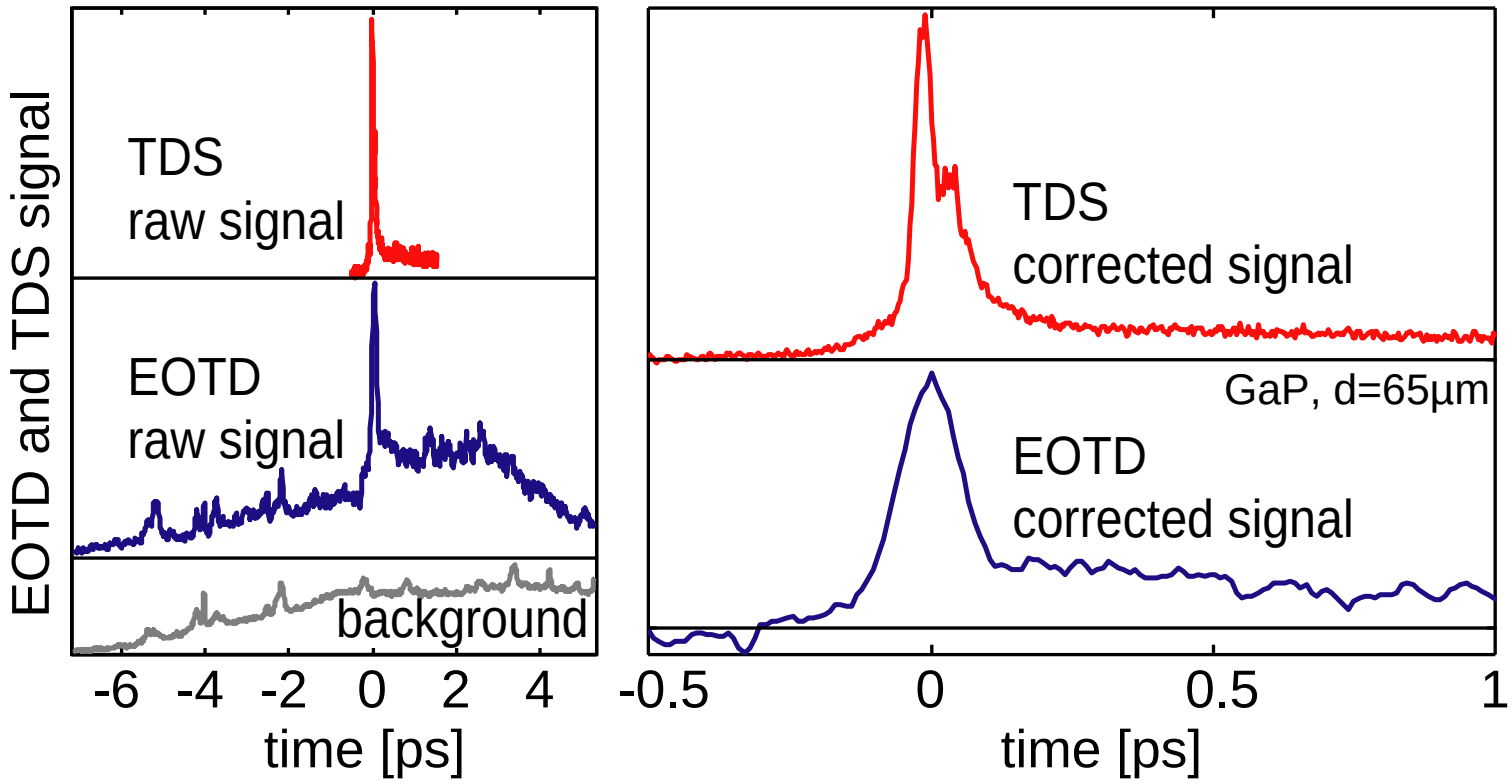
Comparison of EOTD vs. TDS measurements



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

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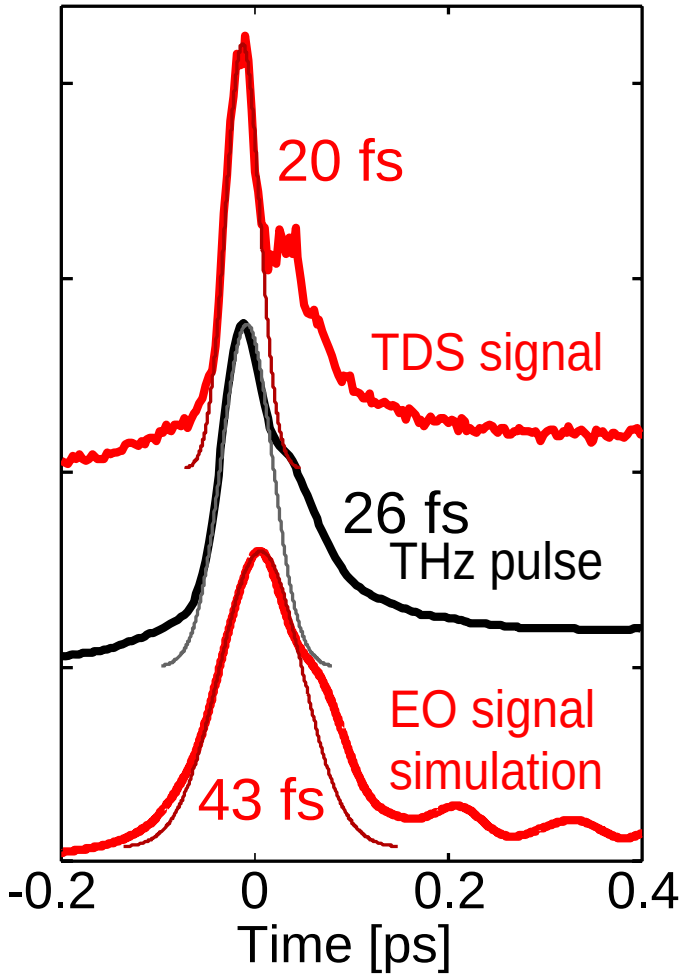
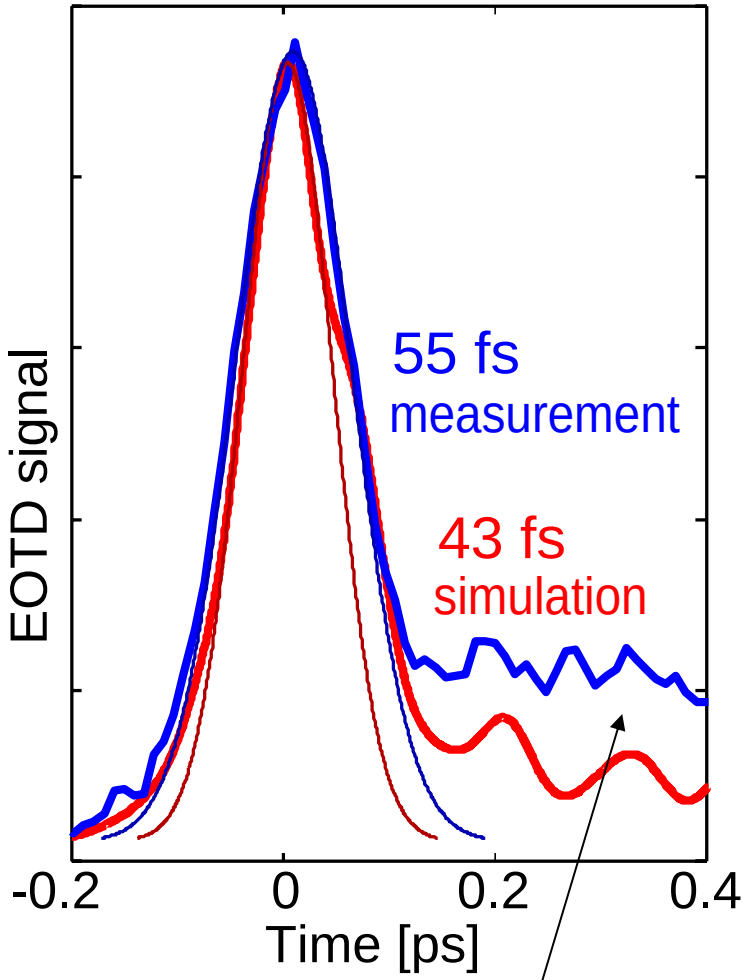
Comparison of EOTD vs. TDS measurements





- **Good agreement between measurement and simulation**
- **close to the resolution limit of GaP**

Signal due to wake fields?

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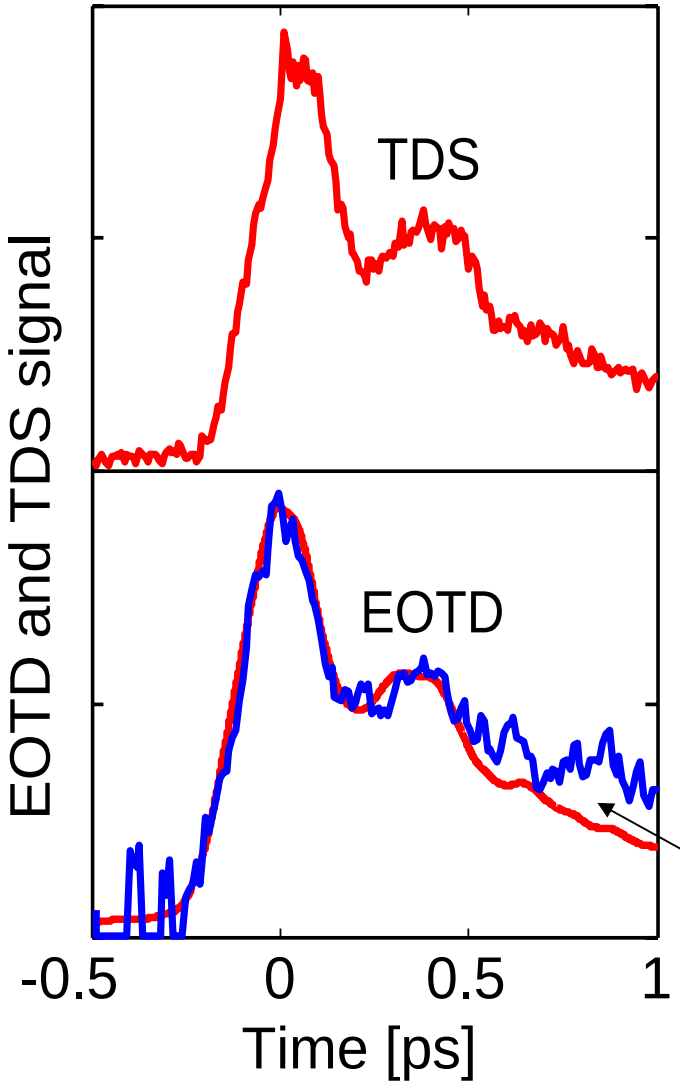
TDS and EOTD measurement of overcompressed bunches



In good agreement with the electron bunch shape

Signal due to wake fields?

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Conclusions

- Benchmarked EO detection against TDS
- Simulations based on published material data are consistent in shape and amplitude with measured signals for GaP
- EOTD 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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Thanks to

- G. Berden, A.F.G. van der Meer (FELIX)
- S. Jamison (ASTeC, Daresbury Laboratory)
- P.J. Phillips, W.A. Gillespie (University of Dundee)
- A.M. MacLeod (School of Computing and Advanced Technologies, University of Abertay, Dundee)
- V. Arsov, E.-A. Knabbe, H. Schlarb, B. Schmidt, P. Schmüser (DESY)

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