

SINGLE-SHOT LONGITUDINAL BUNCH PROFILE MEASUREMENTS AT FLASH USING ELECTRO-OPTIC DETECTION: EXPERIMENT, SIMULATION, AND VALIDATION.

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Abstract

At the superconducting linac of FLASH at DESY, we have installed an electro-optic (EO) experiment for single-shot, non-destructive measurements of the longitudinal electric charge distribution of individual electron bunches. The time profile of the electric bunch field is electro-optically encoded onto a chirped titanium-sapphire laser pulse. In the decoding step, the profile is retrieved either from a cross-correlation of the encoded pulse with a 30 fs laser pulse, obtained from the same laser (electro-optic temporal decoding, EOTD), or from the spectral intensity of the transmitted probe pulse (electro-optic spectral decoding, EOSD). At FLASH, the longitudinally compressed electron bunches have been measured during FEL operation with a resolution of better than 50 fs. The electro-optic process in gallium phosphide was numerically simulated using as input data the bunch shapes determined with a transverse-deflecting RF structure. In this contribution, we present electro-optically measured bunch profiles and compare them with the simulation.

SINGLE-SHOT ELECTRO-OPTIC DETECTION

Precise measurements of the temporal profile of extremely short electron bunches are essential for a detailed understanding of the bunch compression and lasing mechanisms in a SASE FEL. Single-shot electro-optic (EO) detection techniques are ideally suited for this purpose since they are non-destructive and permit correlation studies between the time profile of electron bunches and the properties of FEL pulses produced by the same bunches.

The transverse electric field of a relativistic electron bunch passing close to an electro-optic crystal corresponds to a THz pulse traveling through the crystal. This THz pulse induces a transient birefringence in the EO crystal which can be sampled by a linearly polarized optical laser pulse. In this experiment we use gallium-phosphide (GaP) instead of the more common zinc telluride (ZnTe) as it offers a factor of two better time resolution. The electro-optic temporal decoding (EOTD) technique was applied [1, 2]

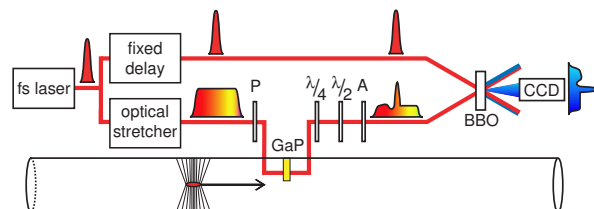


Figure 1: (color) Schematic drawing of the electro-optic temporal-decoding (EOTD) experiment at the FLASH linac. For details see text.

yielding the best time resolution of the single-shot EO detection methods.

The schematic setup is shown in Fig. 1. The titanium-sapphire (Ti:Sa) laser amplifier (pulse length 30 fs FWHM, central wavelength 795 nm, pulse energy 0.8 mJ, repetition rate 1 kHz) is synchronized to the 1.3 GHz accelerator RF. The laser beam is split into two beams: the probe beam and the gate beam. The probe beam is stretched to 20 ps with a grating-pair optical stretcher and guided through a polarizer P to set the polarization parallel to the [-1,1,0] axis of the EO crystal. It is then injected into the linac vacuum chamber and passes through the GaP crystal placed at a distance of 4-5 mm from the electron beam. The birefringence induced by the Coulomb field of the passing electron bunch is translated into a time-dependent elliptical polarization of the stretched probe beam. This in turn is converted into an intensity modulation with a half wave plate and an analyzer A that is orthogonal to the polarizer P. Any residual birefringence is removed by a quarter wave plate. The EO-induced intensity modulation of the probe pulse is measured through cross-correlation of probe and gate pulse in a frequency-doubling BBO crystal. By overlapping the two pulses non-collinearly, a spatially dependent time delay is introduced between the pulses. The BBO light ($\lambda \approx 400$ nm) is imaged by an intensified CCD camera, and the temporal profile of the electron bunch is derived from the light intensity as a function of position. The intrinsic time resolution of the optical cross-correlator is $\sigma = 25$ fs (rms).

The electric field of the bunch is also arranged to be parallel to the crystallographic [-1,1,0] axis (aligned in horizontal direction), so that the main axis of the refractive

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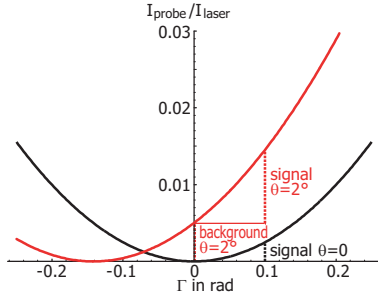


Figure 2: Normalized intensity of the probe beam as a function of the phase retardation Γ for $\theta = 0$, and $\theta = 2^\circ$.

index ellipsoid encloses an angle of 45° with the horizontal axis and hence 45° to the laser polarization. When passing through the birefringent GaP crystal its two polarization components along the main optical axes of the crystal acquire a relative phase retardation:

$$\Gamma = \frac{2\pi d}{\lambda_0} n_0^3 r_{41} E_{\text{THz}} \quad (1)$$

Here λ_0 is the optical wavelength, d the thickness of the crystal, $n_0 = n(\lambda_0)$ the optical refractive index of GaP in the absence of an electric field, r_{41} the electro-optic coefficient, and E_{THz} the amplitude of the THz field. Formula (1) is based on the simplifying assumption that THz and laser pulse have the same propagation velocity in the GaP crystal.

Note that in electro-optic sampling (EOS) experiments the delay between THz and probe laser pulse is varied in fine steps and the THz time profile is obtained by averaging over many THz pulses. This scanning method is inadequate at FLASH because the time jitter between the electron bunches and the Ti:Sa laser pulses is too large (> 100 fs). Therefore, single-shot methods are required, the best one being the EOTD technique described above.

The half wave plate shown in Fig. 1 can be used to obtain an EO signal that is either linear or quadratic in the THz field. The intensity of the laser probe pulse impinging on the BBO crystal depends on the phase retardation Γ and the orientation angle θ of the half wave plate in the form [3]

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

Here I_{laser} is the intensity of the incident laser beam. EO detection is frequently made at *crossed polarization*, corresponding to $\theta = 0$. For small values of Γ the EO signal is then proportional to Γ^2 , see the black curve in Fig. 2. Hence the EO signal is quadratic in the THz field. Rotating the half wave plate by a few degrees leads to a larger EO signal that is almost linear in E_{THz} , however, there is a non-vanishing background in the absence of an electron bunch (red curve in Fig. 2).

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SIMULATION OF THE ELECTRO-OPTIC PROCESS

For ideal electro-optic sampling conditions the THz pulse and the laser pulse should propagate through the EO crystal at the same speed. In reality the THz phase velocity $v_{\text{ph}}(f)$ is frequency dependent and differs from the group velocity v_{g} of the optical laser. A numerical simulation code for the EO process was written [4] to account for the velocity mismatch and to take also into consideration the frequency dependencies of the electro-optic coefficient $r_{41}(f)$ and of the THz amplitude transmission coefficient at the vacuum-crystal interface

$$A_{\text{tr}}(f) = \frac{2}{1 + n(f) + ik(f)} \quad (3)$$

Here $n(f) + ik(f)$ is the complex index of refraction. In the code the EO crystal is subdivided into thin slices of thickness $\delta d = d/N$ (typically $N = 10$ slices for a crystal thickness of $d = 100 \mu\text{m}$), and both the THz pulse and the laser pulse are propagated as wave packets through the crystal. Pulse spreading and attenuation are explicitly taken into account. In each slice the contribution $\delta\Gamma$ to the phase retardation is computed applying Eqn. (1) with the proper delay between the two wave packets in the respective slice. The overall phase retardation Γ is obtained by summation over all slices.

An alternative method is based on the so-called electro-optic response function:

$$G(f, d) = \frac{r_{41}(f) A_{\text{tr}}(f)}{d} \int_0^d \exp \left[i 2\pi f z \left(\frac{1}{v_{\text{ph}}(f)} - \frac{1}{v_{\text{g}}} \right) \right] dz \quad (4)$$

The phase retardation parameter can be computed from G by inverse Fourier transformation. Figure 3 shows the absolute magnitude of the EO response function of gallium phosphide calculated from published material data [5, 6, 7]. The strong oscillations are caused by the excitation of the lowest transverse-optical lattice resonance of GaP at 11 THz. The vanishing response at about 8 THz is due to the zero-crossing of r_{41} at this frequency. From these curves it is obvious that strong shape distortions will arise if the THz pulse has significant Fourier components in the resonance region of GaP. Moreover, the GaP crystal thickness must be less than $100 \mu\text{m}$ if one aims for excellent time resolution.

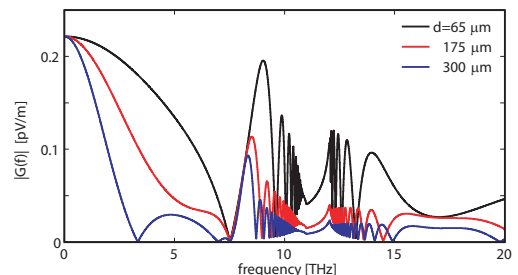


Figure 3: The EO response function of GaP for a crystal thickness of $d = 65 \mu\text{m}$, $175 \mu\text{m}$, and $300 \mu\text{m}$, respectively.

EXPERIMENTAL RESULTS

For benchmarking the EO process and determining its performance limitations we have carried out simultaneous measurements with the EOTD system and a transverse-deflecting rf structure (TDS), featuring excellent time resolution. The TDS was developed at SLAC [8] and was installed and commissioned at FLASH in cooperation with SLAC [9]. In the TDS, the temporal profile of the electron bunch is transferred to a spatial profile on a view screen by a rapidly varying electromagnetic field, analogous to the sawtooth voltage in conventional oscilloscope tubes. The TDS at FLASH is a 3.6 m long traveling wave structure operating at 2.856 GHz. The bunches pass the structure near zero crossing of the RF field and receive no net deflection but are streaked in the transverse direction. A single bunch out of a train can be streaked. With a fast kicker, this bunch is deflected toward view screen that is imaged by a CCD camera. The other electron bunches are not affected. The time resolution of the TDS for the measurements presented here is about 20 fs (rms).

An EOTD measurement on a longitudinally compressed electron bunch, such as needed for SASE FEL operation, is presented in Fig. 4. The TDS measurement on the adjacent bunch is also shown. The superior time resolution of the TDS is evident. EOTD signals as short as 55 fs (rms) could be measured using a 65 μm thick GaP crystal. The TDS signal shape was used as an input for the numerical simulation of the EO process. The predicted EO signal shape is as is shown in Fig. 4. Its main peak is in excellent agreement with the measured signal. Even the absolute normalization, not shown in the figure, agrees to within 20% to

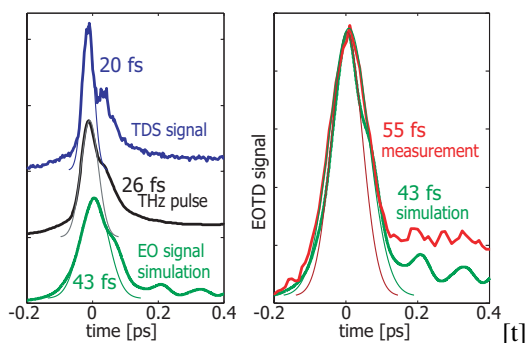


Figure 4: Steps in the comparison between TDS and EOTD signal shapes using a 65 μm thick GaP crystal at an angle $\theta = 2^\circ$ of the half wave plate. Left: From top to bottom: TDS signal, equivalent THz pulse at EO crystal, simulated EO signal. Right: Comparison between simulation and EOTD measurement. The simulated and the measured signals are normalized to the same peak height. The widths correspond to the rms values of the fitted Gaussian pulse shapes.

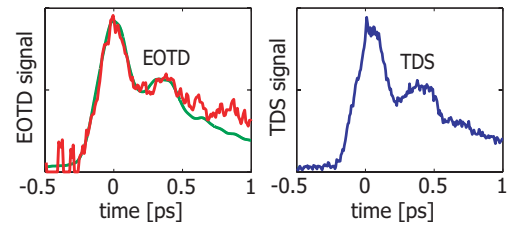


Figure 5: TDS and EOTD signals of bunches showing a double peak structure due to a detuned compression system. The simulated EO signal is shown as a green curve in the left panel.

30%, which is well within the expected fluctuations and the uncertainties of the EO material properties. The measured signal shows a higher tail than the predicted one, which can be attributed to wakefields trailing the electron bunch.

The observed broadening from $\sigma \approx 20$ fs in the TDS data to $\sigma \approx 55$ fs in the EO data is mainly due to the limitations caused by the lattice resonance in GaP. For sufficiently long electron bunches ($\sigma \geq 90$ fs) the time profile as measured by the TDS is faithfully reproduced by the EOTD signal, see Fig. 5.

In another measurement, we employed the simpler EOSD method [10] which does not require a laser amplifier but has the drawback of an inferior time resolution. A GaP crystal of 175 μm thickness was used. From Fig. 3, we infer that frequencies above 5 THz are strongly suppressed in such a thick crystal. As a result both the simulated and the measured EO signals are significantly longer than the real bunch, but both are in perfect agreement. The TDS measurement is shown in the left part of figure 6. The frequency dependent response function of the GaP crystal leads to a significantly stretched equivalent THz pulse inside the EO crystal. In spite of the stretching the THz pulse is still too short to be accurately reproduced by spectrally resolved detection with a Ti:Sa laser pulse chirped to 1.5 ps (rms). Frequency mixing of the effective THz pulse and the laser probe pulse leads to an additional broadening of the predicted EO signal (green curves in fig 6). In the right

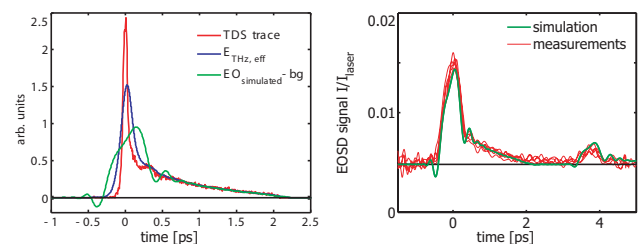


Figure 6: Left: TDS measurement, simulated effective THz pulse and simulated EO signal. Right: EOSD measurements of five consecutive compressed bunches in comparison with the simulated EO signal. Data were taken at $\theta = 2^\circ$ using a 175 μm thick GaP crystal. The laser pulses were stretched by chirping to $\sigma = 1.5$ ps.

part of figure 6 the predicted EO signal is compared to five EOSD electron bunch measurements. Excellent agreement is observed both in shape and amplitude. This indicates that the published GaP material properties and the resulting response function are correct. The comparison between the simulated effective THz pulse and the EOSD signal shows that in this case the signal width is not limited by the response function of the EO crystal but by frequency mixing between chirped laser pulse and THz pulse.

CONCLUSION

The temporal electro-optic decoding method has been benchmarked with a transverse-deflecting RF structure. Simulations based on published EO material data, and using the measured TDS electron bunch profiles as input data, are consistent in shape and amplitude with the EO measurements. Electron bunch profiles with a width of 55 fs (rms) are close to the resolution limit set by the GaP material properties. New electro-optic materials [11] with a broader frequency response than GaP will be needed to improve the temporal resolution.

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