Ultrafast time diagnostics
by
Electro-Optic Sampling

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relativistic electron bunch

ultrashort laser pulse (15 fs)

nonlinear crystal ZnTe

$\mathbf{E}$ field induces birefringence in ZnTe (Doppelbrechung)
optical anisotropy is sampled with ultrashort linearly polarized laser pulse
Electro-optic sampling (EOS) at the infrared FEL FELIX in Holland

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FIG. 2. The EO cross-correlation setup with two different detectors (a) and (b). In (a) the measured photodiode intensity is proportional to the FEL intensity. In (b) the measured photodiode intensity is proportional to the instantaneous electric field strength of the FEL pulse.

The signal from FEL several ps wide

<20 fs titanium-sapphire laser pulse

electric field induces birefringence
sampled with ultrashort
As the reference for the double-balanced mixer (DBM), a double-balanced mixer detects the electron beam that scatters from the sample. The diode (Si-PIN) detects the transverse and filters out the 1-GHz clock in the output signal. After filtering, the signal is sent to a driver for adjustment of the laser. The laser is used to control temporal tuning of the BPF, bandpass filter.

...variation in the two lasers in a population experiment. The sum of the two pulses is transmitted through a calcite polarizer to suppress background. As shown in Fig. 1, the delay line is used to vary the optical path difference. The average of the laser pulses, and the individual shots, corresponds to a 50-shot running average of the laser pulses. The laser pulses were measured with a Ti:sapphire laser pulses was measured with an autocorrelator that was sensitive enough to detect the individual shots (right-hand inset in Fig. 2). The laser pulse was similarly measured to be 180 fs FWHM (right-hand inset). The jitter of the laser was estimated to be 1-900 fs FWHM, assuming Gaussian 3). The degree of synchronization was present over many shots of the laser. The system was competitive with available systems that allow for synchronization to an external clock. For example, Coherent systems typically have less than 3 ps FWHM (10-6 ps FWHM). The time scale or shorter for table-top lasers. The FEL was located 40 m from the experiment site, and the excellent synchronization of the Ti:sapphire laser demonstrated the intrinsic time jitter of the Ti:sapphire laser at 600 fs FWHM. The laser pulse was 500 fs FWHM. The inset on the right-hand side shows the 10 fs fringe-resolved autocorrelation function of the Ti:sapphire pulse. The derived jitter is 400 fs FWHM (~900 fs FWHM). The scan took approximately 2 min to record.
Electro-optic effect in zinc-telluride

ZnTe is optically isohoric without $\vec{E}$-field

with electric field: refractive index ellipsoid

$\bar{E}_a = \bar{E}_{\text{THz}}$

$\cos 2\psi = \frac{\sin \alpha}{1 + \sqrt{1 + 3 \cos^2 \alpha}}$

optimum: $\alpha = 0$

$\Rightarrow \psi = \frac{\pi}{4} \approx 45^\circ$
Orientation of ellipse in (110) plane

Main refractive indices:

\[ n_{\text{slow}} = n_1 = n_0 + \frac{1}{4} n_0^3 \nu_{41} E_a \cdot (\sin \alpha + \sqrt{1 + 3 \cos^2 \alpha}) \]

\[ n_{\text{fast}} = n_2 = n_0 + \frac{1}{4} n_0^3 \nu_{41} E_a \cdot (\sin \alpha - \sqrt{1 + 3 \cos^2 \alpha}) \]

electro-optic coefficient of ZnTe:

\[ \nu_{41} = 4 \times 10^{-12} \frac{m}{V} \]

\[ n_1 = n_{\text{slow}} \]

\[ n_2 = n_{\text{fast}} \]

\[ n_1 - n_2 = \text{max for } \alpha = 0 \]
Consider horizontally polarized Ti:Sa laser pulse

\[ E_b = E_{Ti:Sa} \]

The projections of \( E_b \) on the \( m_1 \) axis and the \( m_2 \) axis receive different phase shifts.

\[ \Gamma = \frac{\omega d}{c} (m_1 - m_2) = \frac{\omega d}{2c} n_0^3 n_{41} E_a \sqrt{1 + 3\cos^2 \alpha} \]

\[ \frac{\Gamma(\alpha)}{\pi} \]

Phase advance \( \frac{\Gamma}{\pi} \)

Graph:

- \( \Gamma = 0.1 \pi \)
- \( \text{for } E_{THz} = 10^6 \text{V/m} \)
- \( d = 0.5 \text{mm} \)
- \( (d \alpha = 0) \)

The Ti:Sa beam is elliptically polarized behind the ZnTe crystal.
How to detect elliptic polarization?

a) Crossed polarizer

Detector signal

\[ S(\alpha) = E_{Ti:Sa}^2 \cdot \sin^2(2\psi_\alpha) \cdot \sin^2\left(\frac{\Gamma(\alpha)}{2}\right) \]

b) \( \frac{\lambda}{4} \) plate, Wollaston prism, balanced diode detector

\[ \text{difference signal} \approx E_{Ti:Sa}^2 \cdot \sin(\Gamma(\alpha)) \]

\( E_{7 \text{ Hz}} = 9.10 \frac{5 \text{V}}{\text{m}} \)
Titanium-Sapphire (Ti:Sa) laser
Femto source Compact by Femtolasers, Vienna

**Diagram:**
- Ti:Sapphire
- Pump beam
- Pieszo mirror
- Output coupler

**Specifications:**
- Bandwidth: 770 - 840 nm
- Pulse width: 15 fs (FWHM)
- Repetition rate: 81 MHz

**Graph:**
- Absorption
- Fluorescence

**Note:**
- Pump laser: 532 nm
- 5 W cw
- Verdi by Coherent
Figure 13: Vibrational noise in laser beam transport. Top and middle: two positions on a vertical I-beam in Hall 3. Bottom: vibrational noise at a mirror mounted on a vibration-damped vertical pillar.

Figure 14: Time variation of vertical laser beam position without and with feedback control.

crystal the Ti:Sa laser beam is guided into the box through a 100 mm long aluminium tube and its diameter is controlled by means of a feedback system.
synchronization Ti: Sa laser to rf
81 MHz = \frac{1}{16} \times 1300 MHz
Detector signal on 20 GS scope

(setup: crossed polarizers, photomultiplier as detector)
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Coincidence scan to find overlap of Ti:Sa pulse (<20 femtosec) with CTR pulse of e-bunch

Scan over 2000 ps

bunches missing

coincidence
Zoom of coincidence
Ti:Sa pulse / CTR pulse

amplitude [a.u.]

-2.6
-2.4
-2.2
-2.0
-1.8
-1.6
-1.4
-1.2
-1.0
-0.8
-0.6

-53
-52
-51
-50
-49
-48
-47
time [ps]
Experimental Setup

- direct measurement of the co-propagating electrical field
- nonintercepting

First attempt to measure directly electric field of the bunch

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Markus Hüning, May 15, 2001