TEMPORAL PROFILES OF THE COHERENT TRANSITION RADIATION MEASURED AT FLASH WITH ELECTRO-OPTIC SPECTRAL DECODING

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Abstract

We present absolute electric field time-profiles measured on the coherent transition radiation (CTR) beamline at FLASH using electro-optic spectral decoding (EOSD) in near crossed-polarizers scheme with a (20-200) µm thick GaP crystal in vacuum. The CTR spectrum is in the range 200 GHz - 100 THz and the pulse energy in the focus is over 10 µJ. The measured narrow CTR temporal profiles in the range 400 - 500 fs FWHM demonstrate that the short THz-pulses emitted by the compressed electron bunches are transported through the 19 m long beam line without significant temporal broadening.

INTRODUCTION

The reliable operation of the ultraviolet and x-ray free electron lasers require precise and non-destructive measurement of the electron bunch structure in the sub-100 fs scale. Recent numerical [1] and experimental [2], [3] works reveal the potential of the electro-optic detectors for such time-profile monitors. For even shorter, sub-10 fs structures, spectroscopy of coherent transition radiation (CTR) offers an alternative, although not allowing direct reconstruction of the longitudinal profile. For such diagnostic purposes 200 GHz - 100 THz broad-band CTR beamline is constructed and characterized [4]. The ability of the CTR beamline at FLAHS to preserve the narrow CTR pulses was first demonstrated using electro-optic balanced detection with 0.5 mm thick ZnTe crystal in air [5], followed by measurements with the same crystal in vacuum in near crossed-polarizers scheme [6]. To fully utilize the resolution of the electro-optic spectral decoding method, thinner crystals with better optical properties, such as GaP should be used. In this paper, we report electro-optic spectral decoding measurements at the CTR beamline of FLASH using a (20-200) µm wedge GaP crystal in vacuum.

EXPERIMENTAL SETUP

The setup for measurement of the CTR electric field temporal profiles is shown in Fig. 1.

The CTR beamline is installed in the straight section between the last accelerating module and the undulator at the 140 m of FLASH. The generation and transport of the ultrabroadband CTR radiation in the range of 200 GHz - 100 THz with energies more than 10 µJ is described thoroughly in [4]. The CTR is produced by kicking of a single bunch from a pulse train on an off-axis screen, inclined at 45° with respect to the accelerator axis. The 18.7 m long beam line is designed specially to minimize diffraction and to avoid waveguide effects, by using focusing mirrors and corrugated bellows. The pressure in the beamline is below 0.1 mbar and is isolated from the accelerator vacuum by a wedge diamond window.

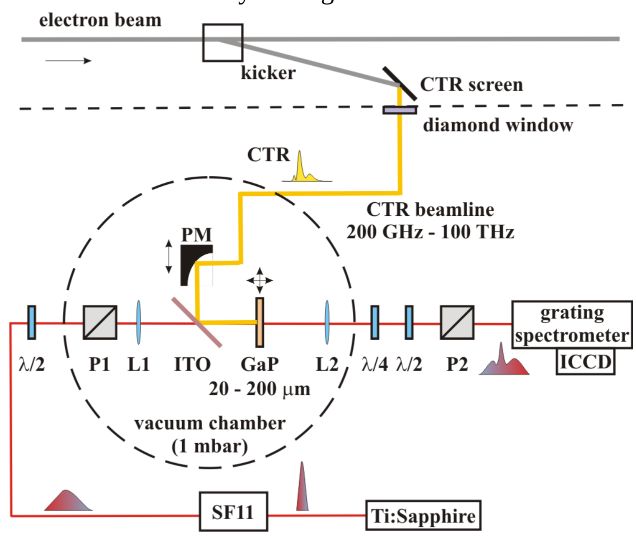

Figure 1: Schematic layout of the setup for EO detection of coherent transition radiation (CTR) transported from the linac to the laboratory through a 19 m beamline.

In a laboratory outside the linac tunnel, the beamline ends in a large vacuum vessel hosting several diagnostic experiments, taking full advantage of the broad band THz spectrum - interferometric, spectroscopic and electro-optic (EO).

The principles of single-shot electric field profile measurements using EO techniques is described in [3]. In this experiment, we apply the spectral decoding method. A τ_0 = 16 fs (Fourier-limited) pulse from a commercial Ti:Sapphire oscillator (Micra-5 from Coherent) is linearly chirped in a 10 cm long glass block (SF11) to $\tau_c \approx$ 5ps. The EO signal broadening, imposed by the chirp is $\sqrt{\tau_0 \cdot \tau_c} \approx 280\ fs$. The laser center wavelength is 800 nm, the bandwidth 60 nm and the repetition rate 81 MHz. The typical output power of the laser is 500 mW.

Except for the first polarizer P1 and the lenses for the crystal, all other elements are placed on the same optical table. Shortly before the entrance port of the vacuum chamber, there is a half-wave plate, which in combination with the first polarizer P1 serves as a power attenuator. The energy on the EO the crystal is 2.5 nJ. The EO crystal

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is placed between the foci of two lenses with f = 300 mm. The laser focal spot radius is estimated to be 10 μm.

The distance between the last focusing mirror of the THz beamline (f_5 = 200 mm) and the parabolic mirror in the vacuum vessel (f = 150 mm) is 1.65 m. The distance between the center of the parabolic mirror and the EO crystal is 17.5 cm. According to simulations at this geometry for 2 THz the focal spot has a doughnut shape with outer radius 2 mm and inner radius 1 mm.

Both the EO crystal and the parabolic mirror are placed on motorized translation stages, allowing longitudinal tuning. In addition the EO crystal can be also translated horizontally (motorized) and turned azimuthally (manually). An indium-tin oxide (ITO) slab is used as a beam combiner.

For the present experiments a (20-200) μm wedge GaP crystal is used and results for thicknesses 175, 130, 70 and 20 μm are obtained. All measurements are made in vacuum below 0.1 mbar. For crystal thicknesses below 100 μm the THz pulse broadening is negligible [4], thus the overall system resolution is limited only by the chirp broadening (~300 fs).

The spectra are resolved with a 150 mm focal length spectrometer, a 600 l/mm grating and an intensified CCD camera with 1280 pixel. The spectral resolution is 0.122 nm/pix. The temporal calibration of the spectra is made before each data acquisition by sweeping the phase of the laser relative to the 1.3 GHz reference with 10 fs steps. The calibration constant is 8.6 fs/pix. Acquisition is made near crossed-polarizers, for which the EO signal is almost linear with the electric field [3].

The measurements are made with two bunches in the machine at 500 kHz repetition rate (second bunch kicked), energy 906 MeV and charge 0.8 nC.

RESULTS AND DISCUSSION

Typical raw CTR signals measured with 130 μm thick GaP crystal in vacuum are shown in Fig. 2. Each curve is an average of 20 acquisitions. In this example the EO signals are taken at Θ = –1° off-crossed polarizers. Four data sets are always saved: I(dark)-spectrum without laser and without THz, I(0,0)-spectrum at crossed polarizers and without THz, I(0,Θ)-spectrum at Θ° off-crossed polarizers and without THz, I(Γ,Θ)-spectrum at Θ° off-crossed polarizers and with THz.

Similar narrow signals in the range (420-520) fs are observed also for the rest of the measurements independent on the GaP thickness (20-175) μm. Within the accuracy of the setup resolution of ~300 fs these widths demonstrate the ability of the THz beamline to preserve the temporal structure of the CTR radiation produced by the sub-100 fs short electron bunches.

The measured electro-optic signals allow determination of the phase retardation Γ(τ) in the GaP crystal in the time domain and thus calculation of the absolute electric field profile of the CTR pulse. Near crossed polarizers the signal on the detector is [3]:

$$I_{det}(\Gamma,\Theta)=\frac{I_{laser}}{2}\cdot\left[1-\cos(\Gamma+4\Theta)\right]+I_{offset} \quad (1)$$

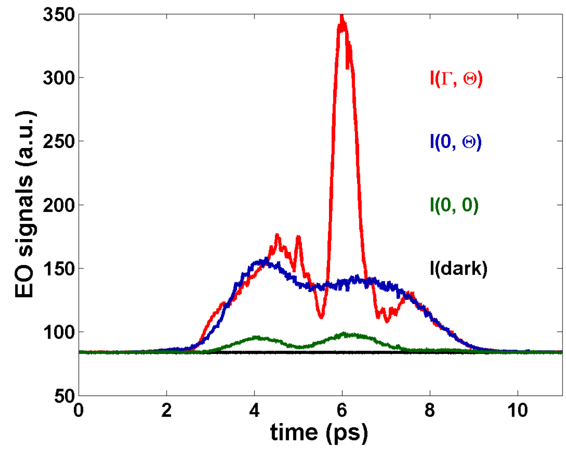

Figure 2: Raw single-shot EO signals of a CTR pulse, taken with 130 μm thick GaP crystal in vacuum. The deviation of from crossed polarizers is Θ = –1°.

Here it is assumed, that the quarter-wave plate is set for minimum transmission (crossed-polarizers, ϕ ≡ 0). The different backgrounds (Fig. 1) correspond to Γ and/or Θ set to zero, which allows solving (1) for Γ:

$$\Gamma_{\exp}(\tau)=\arccos\left[1-I_N(\tau)\right]-4\Theta \quad (2)$$

where I_N is the normalized signal:

$$I_N(\tau)=\frac{I(\Gamma,\Theta)-I(0,0)}{I(0,\Theta)-I(0,0)}\cdot(1-cos4\Theta) \quad (3)$$

On the other hand the phase retardation in the time domain can be computed using the electro-optic properties of the material in the frequency domain [3]:

$$\Gamma(\tau)=\frac{n_0^3 d}{\lambda_0}F^{-1}\left\{E(\omega)A_{tr}(\omega)G(\omega)r_{41}(\omega)\right\} \quad (4)$$

where n_0 is the refraction index for the optical group velocity (wavelength l_0), d is the crystal thickness. For GaP and l_0 = 800 nm n_0 = 3.568. F denotes a Fourier transformation. E(ω) is the THz Coulomb field in the frequency domain, $A_{tr}(\omega)$ is the frequency dependence of the amplitude transmission coefficient for the Coulomb field from vacuum into the EO crystal, G(ω) is the geometric response, which accounts the velocity mismatch between the THz and the optical pulses in the crystal and $r_{41}(\omega)$ is the electro-optic coefficient. The product of the last three factors is the effective response function, which is plotted on Fig. 3 for three different crystal thicknesses, used in the experiment.

Combining (2)-(4) one obtains an expression for the electric field in the time domain:

$$E(\tau)=F^{-1}\left\{\frac{\lambda}{n_0^3 d}\frac{F(\Gamma_{\exp}(\tau))(\omega)}{A_{tr}(\omega)G(\omega)r_{41}(\omega)}L(\omega)\right\} \quad (5)$$

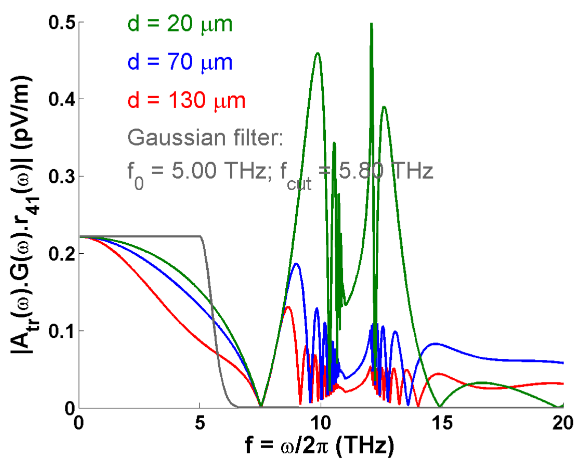

Figure 3: Effective response function of GaP and a Gaussian filter used for the retrieval of the Coulomb field

L(ω) is a low-pass filter, necessary to smoothly exclude the zeroes of the response function near the resonance. Here a Gaussian filter is used (Fig. 3). The choice of the central f_0 and the cut-off f_{cut} frequencies depends on the crystal thickness and the duration of the pulses. In order to fine-tune the filter for a given thickness, a model pulse is transformed according to equation (5) (Fig.4). In the shown example the GaP is 70 μm thick. Pulses with duration above 150 fs FWHM are reconstructed without distortion for Gaussian filter with f_0= 5 THz and f_{cut}=5.8 THz. For GaP thickness 130 μm the corresponding filter values are f_0= 3 THz and f_{cut}=3.8 THz. With the above parameter set, the absolute electric field profiles of the CTR pulses are calculated providing amplitudes 4 MV/m (Fig. 5a) for the 70 μm thick GaP crystal and 6 MV/m (Fig. 5b) for the thickness 130 μm. The obtained amplitudes can be attributed to the fact that different points in the focal plane have been sampled by the laser. The excellent agreement between the measured phase retardation Γ and the recovered with the above described numerical procedure electric field (Fig. 5) confirms the correctness of the method .

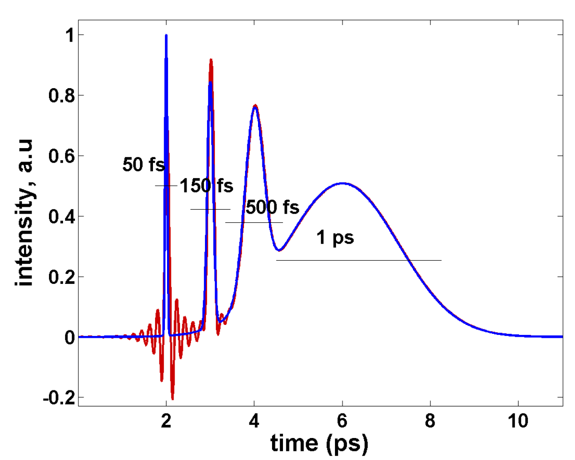

Figure 4: A model pulse Γ(τ) (blue curve) transformed according to eq. (5) (red curve) for GaP thickness 70 μm and Gaussian filter with f_0= 5 THz and f_{cut}=5.8 THz . The widths are FWHM.

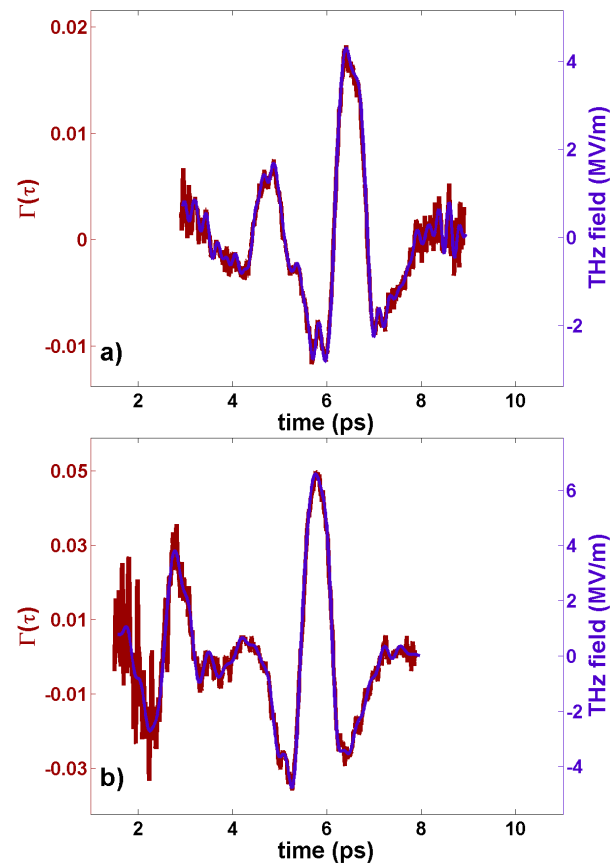

Figure 5: Phase retardation Γ and and recovered absolute electric field profiles for GaP thicknesses 70 μm (a) and 130 μm (b).

CONCLUSION AND OUTLOOK

Narrow CTR temporal profiles in the range 420-520 fs FWHM are measured with electro-optic spectral decoding with GaP in vacuum at crystal thickness 20-175 μm. Within the accuracy of the setup resolution of ~300 fs, these widths demonstrate that the THz beamline at FLASH preserves the narrow shape of the CTR pulse, produced by the compressed electron bunches. The measured profiles allow calculation of the absolute electric field. There is an excellent agreement between the measured phase retardation Γ and the numerically recovered electric field profile.

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