ELECTRO-OPTIC SPECTRAL DECODING FOR SINGLE-SHOT CHARACTERISATION OF THE COHERENT TRANSITION RADIATION PULSES AT FLASH

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Abstract

We report preliminary single-shot electro-optic spectral decoding (EOSD) measurements of coherent transition radiation (CTR) pulses, generated by the electron bunches of the free-electron laser (FLASH) at DESY, Hamburg. The THz radiation is transported through a 20 m long beam-line from the accelerator tunnel to an experimental station outside. The measurements are performed in vacuum with a 0.5 mm ZnTe crystal in crossed-polarizer and near crossed-polarizer detection schemes. Pulses with complex structure and sharp peaks have been detected. The different components have full width at half maximum in the range 400-900 fs.

INTRODUCTION

Intense relativistic electron bunches with a duration less than 100 fs are needed in contemporary light source accelerators, such as the ultraviolet and soft x-ray free-electron laser at Hamburg (FLASH) [1], as well as the future x-ray FELs like the Linac Coherent Light Source at SLAC [2] and the European XFEL [3]. With this there is a growing demand for ultra-fast characterisation of the electron bunches. Some of the leading longitudinal diagnostic techniques with fs abilities are the spectral, the electro-optic (EO), the transverse deflecting cavities and, since recently, the optical replicas [4]. The spectral techniques refer to spectrum measurements of the coherent transition radiation (CTR), diffraction and synchrotron radiation, etc. A Fourier transformation of the measured spectrum has resolved structures with less than 10 fs duration in a single-shot acquisition [5]. In the case of FLASH the single shot CTR spectrometer is situated outside the accelerator tunnel, which is convenient from experimental point of view, but requires knowledge of the transfer function of the beam line. Therefore an independent CTR pulse length measurement, such as an EO technique applied inside the spectrometer can facilitate the interpretation of the CTR spectra.

The EO techniques allow direct characterization of THz fields both in the spectral and in the time-domain. Depending on the analyzer orientation, the measured signal is either linear or quadratic with the THz field [5],[6]. Recently EO signals as short as 55 fs (rms) have been observed, which is a new record in the EO detection of single electron bunches and close to the limit imposed by the properties of the EO material [7].

The temporal profiles of the CTR pulses at FLASH have been measured for the first time by Berden et. al. [8]. Their measurements were carried out in air with ZnTe, using electro-optic spectral decoding (EOSD) in the so called balanced detection scheme. Here we present similar EOSD measurements with ZnTe, but carried out in vacuum, using crossed-polarizer and near crossed-polarizer detection schemes [6].

EXPERIMENTAL SETUP

The CTR electric field temporal profiles are resolved with a spectral decoding electro-optic technique [6], [9]-[11].

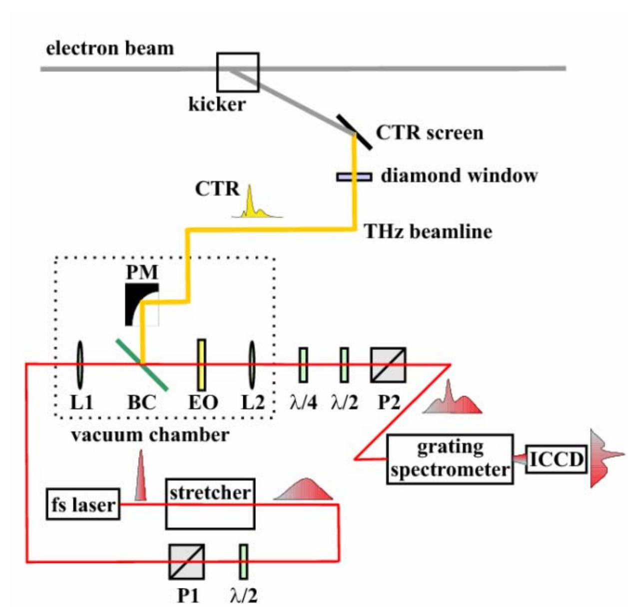

Figure 1: Set-up for electro-optic spectral decoding measurements of coherent transition radiation (CTR). Notations: (l/2), (l/4) – half and quarter wave plates; (P1,2) – polarizers; (L1,2) – lenses; (BC) – indium tin oxide beam combiner; (EO) – 0.5 mm thick ZnTe electro-optic crystal; (PM) – parabolic mirror

A diagram of the experimental setup is shown on Fig. 1. The CTR is generated from single bunches, kicked to an off-axis screen. A diamond window is used to couple the radiation from the ultra high vacuum environment into a 20 m long transfer line, where the pressure is lower than 0.1 mbar. The beam line is equipped with high reflectivity focusing mirrors, designed specially to minimize the diffraction. Special care has been taken to avoid wave guide effects in the pipe by using corrugated bellows. The lowest frequency (ca. 300 GHz) is determined by the diameter of the pipe, which is ca. 200 mm [12]. Outside the accelerator runnel the THz beam line is connected to an evacuated vessel containing several diagnostic experiments, including a single-shot THz grating spectrometer and an EO setup. Alternatively, the radiation can be coupled out of the vacuum pipe of the transfer line through a single-crystal quartz window for experiments in air. However this is at the expense of suppression of CTR frequencies above 4 THz due to the absorption in quartz and especially by the broad band absorption in air. The CTR radiation is focused on the 0.5 mm thick ZnTe crystal with an off-axis parabolic mirror. The spatial overlap with the probe laser beam is achieved with an indium tin oxide (ITO) beam combiner.

The probe optical pulse is produced by a titanium-sapphire laser (center wavelength 790 nm, bandwidth 36 nm, pulse length 40 fs and repetition rate 1 kHz), synchronized to the 1.3 GHz accelerator frequency. The probe beam is stretched to 7.7 ps in a 40 cm long SF11 glass block (stretcher on Fig. 1). The length of the probe pulse is chosen to be larger than the length of the CTR pulse in order to encompass the whole CTR electric field temporal profile. The chirp of the optical pulse is linear and so is the time-frequency mapping of the corresponding intensity profiles. The probe optical pulse and the THz radiation propagate collinearly in the EO crystal. For ZnTe there is a close match in the group velocities of the THz and the optical pulses. In the ideal case the instantaneous frequency of the probe laser pulse interacts with the same portion of the THz field, thus experiencing a phase retardation in the EO crystal proportional to the local electric field. The specific phase retardation is made apparent by an analysing polarizer P2. Thus the CTR temporal profile is imprinted on the spectrum of the optical pulse and can be resolved with a spectrometer.

The half wave plate preceding the input polarizer P1 (Fig. 1) serves to attenuate the energy of the probe laser pulse below the damaging threshold of the EO crystal (~ 5 mJ)

In the absence of a CTR pulse the transmittance through the polarizer P1 and P2 is minimized. This is the so called acquisition at crossed polarizer. In this arrangement the measured intensity is proportional to the square of the THz electric field. The advantage of this arrangement is the low background in comparison to the balanced detection scheme. The residual birefringence due to mechanical stress in the EO crystal is removed by the quarter wave plate. In the present experiment also measurements at few degrees off-crossed polarizer have been made. The advantage is the higher sensitivity and lower signal to noise ratio at the expense of a slightly higher background [6]. An additional advantage is that the EO signal is linear with the CTR field. The corresponding polarizer arrangement is chosen with the half wave plate in front of P2.

The spectra are resolved with a 0.15 m spectrometer, equipped with a 600 grooves/mm grating. The images are recorded with a 1280x1024 pixel intensified CCD camera (ICCD). The time axis is along the longer side of the sensor. In the other direction the spectra occupy ~ 90 pixels, which is used for binning.

RESULTS AND DISCUSSION

The upper panels of Fig. 2 show the raw CTR signals, measured with 0.5 mm thick ZnTe at different polarization schemes. The leading edge is on the left. The green traces represent the spectral intensities of the probe laser pulse with CTR being blocked (spectrum *A*). These traces are averaged along 20 laser shots. Since the laser pulse is linearly chirped and its duration is known, these traces are also used for time-calibration of the horizontal axis. The blue traces are taken with the presence of the probe laser and CTR radiation (spectrum *B*) and represent a single-shot measurement. At the beginning and the end of each measurement series separate background spectra have been taken without the presence of laser and CTR (spectrum *C*). These traces are not represented on Fig 2, but are used for the signal normalization. The lower panels of Fig. 2 show the normalized electro-optic signals. For the case near crossed polarizer the following relation is used for normalization: $\frac{B-A}{A-C}$, where *A*, *B* and *C* are the above mentioned spectra. For the case of crossed polarizer the normalizing relation is: $\frac{B-A}{D-C}$, where is *D* the laser spectrum taken at few degrees off-cross polarization without the presence of CTR.

The left panel of Fig. 2 represents measurements with 0.5 mm ZnTe in vacuum at crossed polarizer. The measured EO signal has a complex structure. The most pronounced one has a broad base with width 3.3 ps and amplitude 0.4, followed by a sharp peak with normalized amplitude 1.15 and 440 fs width. The rest of the signal is hardly distinguishable from the noise.

The right panel of Fig. 2 shows similar measurements with 0.5 mm ZnTe in vacuum, but with -2° deviation from crossed polarizer. This increases the sensitivity at the expense of slightly increased background. The normalized signal amplitude is also higher. Again a complex CTR structure is observed with two pronounced peaks. The highest peak is 700 fs wide. Its normalized amplitude is 1.6. The preceding lower peak has a normalized amplitude 0.5 and width 900 fs.

The data of Fig. 2 shows the clear difference between the measurements in crossed- and near crossed polarization. In the first case the EO signal is proportional to the square of the CTR electric field. This is the reason for the observed broader step preceding the sharp peak on the left image of Fig. 2. In the case of measurements near crossed polarizer, the EO signal depends linearly on the CTR electric field. As seen from the right image of Fig. 2, there is a negative swing with smaller amplitude at the position, where a broad step in crossed polarizer is observed.

As pointed out by [4] and [8], pulse lengths shorter than $2.4\sqrt{T_0 T_C}$ should be distorted with EOSD measurements. T_0 is the initial length of the laser pulse, which in our case is 40 fs; T_C = 7.7 ps is the length of the chirped laser pulse. For the lower limit of the CTR pulse one obtains 1.3 ps. The measured pulse widths are near this limit. The choice of the chirped pulse length is a compromise between the possibility to have wide enough time-window and the ability to resolve narrow temporal components. In our case a clear structure in the CTR signal is distinguishable. A distortion free measurement would require temporal decoding set-up [4],[6], [7],[13].

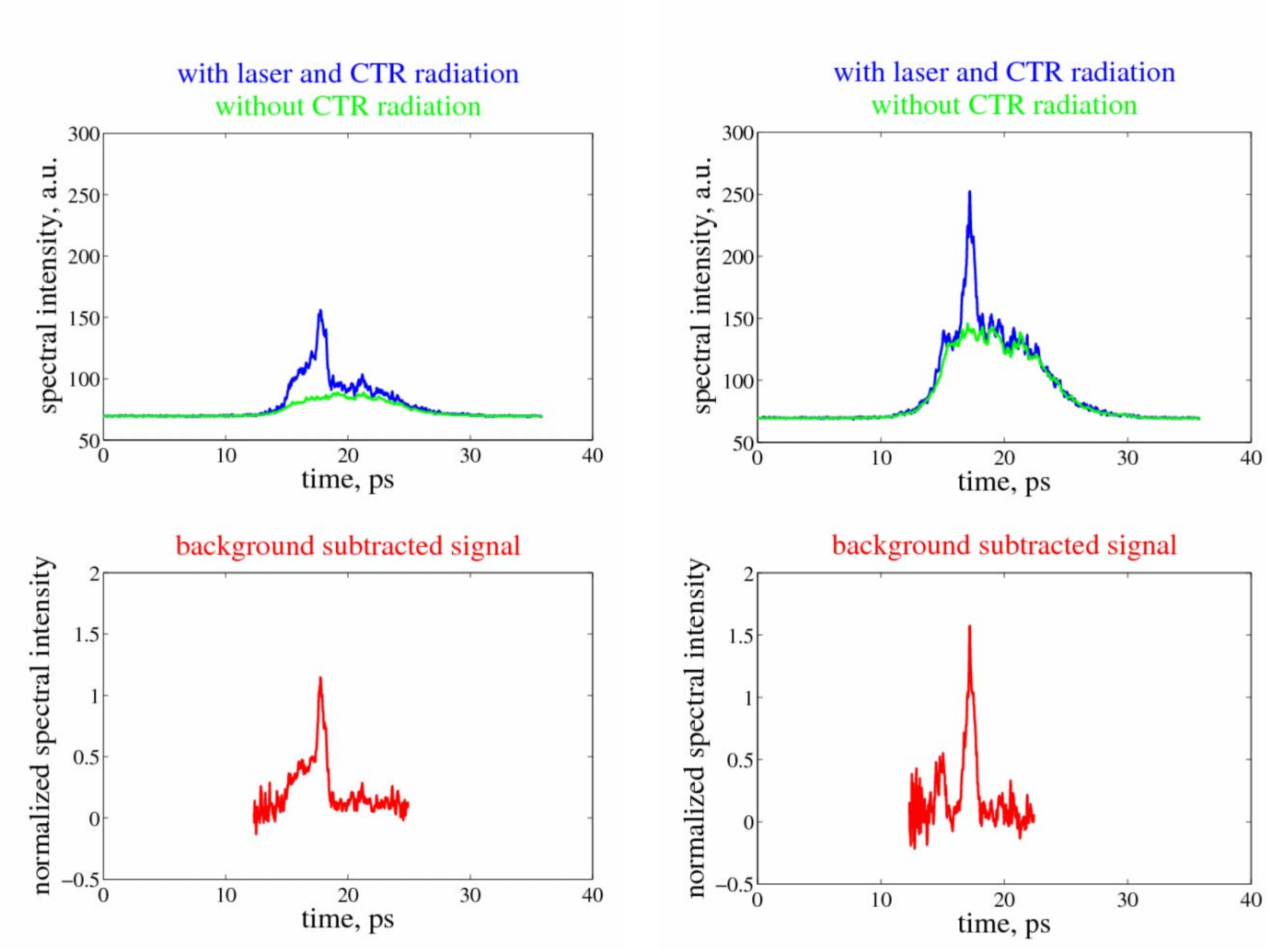

Figure 2: Electro-optic spectral decoding signals of coherent transition radiation (CTR), measured with 0.5 mm ZnTe in vacuum. Upper panels: raw data; the green traces are the laser spectral intensities without CTR radiation; the blue traces are the corresponding intensities with CTR radiation. Lower panels: normalized spectral intensities. The leading edge of the CTR is on the left. Left panel: measurements at crossed polarizer. Right panel: measurements at -2° off- crossed polarizer.

An important result are the sharp and high CTR peaks, despite the lower cut-off frequency (4THz) of ZnTe. Such peaks are familiar from EO measurements of the electron bunch lengths directly in the FLASH tunnel [6],[7],[10]. This demonstrates, that the optics of the THz beam line maintains the amplitude and the phase information in this wavelength range and properly images the electrical field from the CTR screen to the experimental station outside the tunnel. These results are rather preliminary and a more systematic study is necessary with the use of GaP, which has a higher cut-off frequency (11 THz) and better optical properties.

CONCLUSION AND OUTLOOK

A comparison between electro-optic spectral decoding measurements of CTR radiation with crossed polarizer and near crossed polarizer arrangements in ZnTe has been made. In both cases the ability to resolve structure in the CTR signal and sharp peaks is quite promising. Since the THz diagnostics are situated outside the DESY-FLASH tunnel, it is necessary to verify experimentally the transfer function of the THz beam line, which at this point is known through simulation. For this purpose more systematic EO studies with GaP in vacuum with variation of the THz focus are necessary. In addition temporal decoding measurements are foreseen in order to resolve shorter time structures and to avoid a possible signal distortion.

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