TIME RESOLVED SINGLE-SHOT MEASUREMENTS OF TRANSITION RADIATION AT THE THZ BEAMLINE OF FLASH USING ELECTRO-OPTIC SPECTRAL DECODING

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Abstract

Single-shot electro-optic detection was used to measure the temporal profile of coherent transition radiation (CTR) pulses at FLASH, the VUV-FEL at DESY. The CTR was generated from single bunches kicked to an off-axis screen, and transported through a 20 m long transfer line from the radiation screen to an experimental station outside the accelerator tunnel, where it is imaged. Bipolar pulses with a FWHM less than 1 ps have been measured and are consistent with simulations of the propagation of radiation through the transfer line.

INTRODUCTION

X-ray free electron lasers require short, intense, relativistic electron bunches. Precise measurements of the longitudinal temporal profile of these compressed electron bunches are essential for a detailed understanding of the lasing and operating principles. At FLASH, the VUV-FEL at DESY, three monitors for the longitudinal profile of the compressed beam are located within a few meters of each other: the LOLA transverse deflecting RF structure [1], the single-shot electro-optic detection monitor which measures the Coulomb field of the bunches [2, 3], and the broadband single shot spectrometer which measures the infrared and far-infrared (or THz) transition or diffraction radiation [4, 5]. For this spectrometer, a 20 meter long THz beamline has been constructed which transports the radiation from the diffraction and transition radiation screen to the experimental hut [6]. The same experimental hut contains the laser system which is used for electro-optic detection of the Coulomb field of the electron bunches [2]. This gives the opportunity to directly measure the temporal profile of the CTR via electro-optic detection as well. Single-shot electro-optic detection of CSR radiation has been reported before at the FELIX FEL facility [7, 8]. This paper reports the first results obtained at FLASH.

EXPERIMENT

A diagram of the experimental setup is shown in Fig. 1. The CTR was generated from single bunches kicked to an off-axis screen. A diamond window was used to couple the radiation from the ultra high vacuum environment of the accelerator into the THz transfer line. All optical components in the transfer line are reflective, and the line is evacuated to avoid water absorption. The CTR radiation was coupled out from the beamline through a crystalline quartz window, collected and focussed onto a ZnTe electro-optic crystal with a 90° off-axis parabolic mirror. An indium tin oxide (ITO) beam combiner was used to overlap the THz beam and the optical probe beam.

The probe pulse is the uncompressed optical pulse from a Ti:S amplifier which is synchronised to the accelerator. Alternatively, a stretched pulse from a Ti:S oscillator could be used as is shown in Fig. 1 and described in Ref. [3]. For the experiments described in this paper, the probe pulse was a linearly chirped 4 ps FWHM long pulse with a central wavelength of 792 nm, a bandwidth of 40 nm FWHM, and an energy of less than a microJoule. In a linearly chirped optical pulse, the instantaneous wavelength is proportional to time. Such a probe pulse is needed since we use the

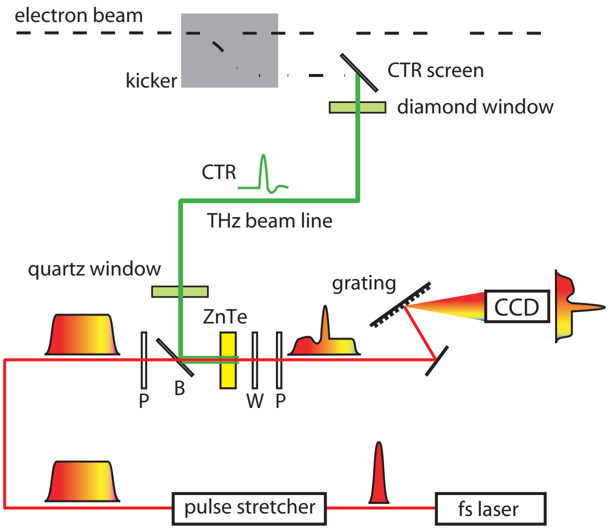

Figure 1: (color) Electro optic spectral decoding measurements of coherent transition radiation (CTR). See text for details; abbreviations: polarizer (P), quarter wave plate (W), ITO beam combiner (B).

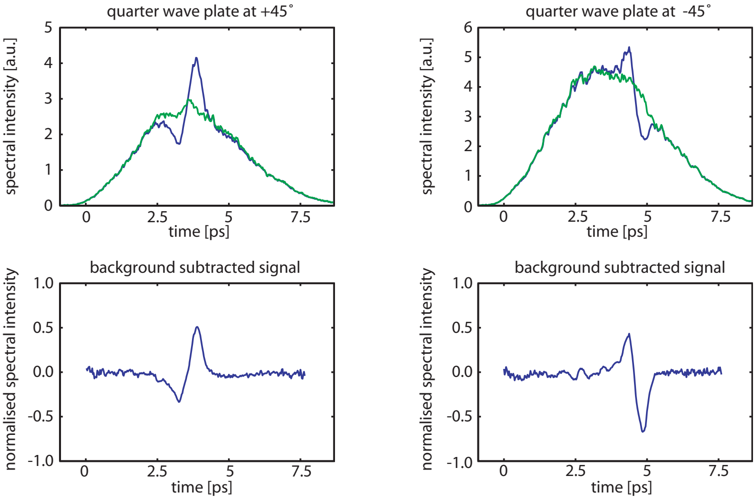

Figure 2: (color) Spectral decoding results for different settings of the quarter wave plate. Upper panels: raw data. Green traces are without CTR radiation, blue traces are with CTR radiation. Lower panels: normalised data. The leading edge of the CTR pulse is on the right.

technique called spectral decoding [9, 3, 7] for retrieving the electric field profile of the CTR pulse. The length of the probe pulse has to be larger than the length of the CTR pulse in order to be able to measure the whole electric field profile of the CTR pulse. The first polarizer (see Fig. 1) defines the correct polarization. The ITO beam combiner overlaps the THz beam and the probe pulse. In the 500 μm thick ZnTe crystal, the electric field profile of the THz CTR pulse is encoded electro-optically onto the chirped probe pulse. In this way, the various wavelength components of probe pulse experience a different amount of birefringence dependent of the actual phase of the electric field of the CTR pulse. A quarter waveplate and a second polarizer (the analyzer) are used to translate the amount of birefringence into a modulation depth of the intensity of the probe pulse. The temporal electric field profile of the CTR pulse is now obtained from a single shot measurement of the wavelength spectrum of the intensity modulated probe pulse. This can easily be done with a grating spectrometer and a linear array detector. In present experiments, the detector is a gated intensified CCD camera. Raw spectral decoding traces are obtained by proper binning the images.

RESULTS AND DISCUSSION

The upper panels of Fig. 2 show raw spectral decoding results obtained with two different settings of the quarter wave plate. Green traces are obtained by blocking the CTR at the exit window of the THz beam line, and represent measurements without CTR radiation present. Blue traces are obtained with CTR radiation present. The green traces represent a direct measurement of the wavelength spectrum of the probe pulse as well and can be used to convert the horizontal axes into time, since the probe pulse is linearly chirped and the duration of this pulse is know. The spectral decoding signal is obtained by taking the difference between spectra recorded with and without CTR present and normalising by the laser spectrum, and is shown in the lower panels of Fig. 2. The leading edge of the CTR pulse is on the right as confirmed by changing the delay between the CTR pulse and the optical probe pulse.

The quarter wave plate at a position of $\pm 45°$ corresponds to a so-called balanced detection configuration. This means that the probe pulse, in the absence of the CTR pulse, is left- or right-handed circularly polarized just before the analyzing polarizer. Therefore, the positive and negative parts of the electric field of the CTR induce opposite intensity changes after the analyzing polarizer, allowing the observation of bipolar CTR pulses.

In the balanced detection configuration, the signal $S^{BD}(\omega)$ is conventionally taken as the difference in intensity of two orthogonal polarisations, $S^{BD}(\omega) \equiv I_y - I_x$. In Fig. 2, the signal was defined as the difference in intensity of the measured signals with and without CTR present, which is in the small signal limit proportional to the conventional balanced detection signal. Jamison *et al.* [10] showed that the balanced detection signal in the case of spectral decoding can be described as

$$S^{BD}(\omega) \propto \left\{ E_{CTR}(\tau + t_0) * \cos(\frac{\tau^2}{4\beta} - \frac{\pi}{4}) \right\}, \quad (1)$$

where $\tau \equiv 2\beta(\omega - \omega_0)$, ω_0 is the central frequency of the optical probe pulse, and β is the chirp parameter of the optical probe pulse. The signal depends linearly on the electric field strength, which means that the normalised spectral decoding traces in the lower panel directly represent the electric field profile of the CTR pulses. It is also apparent that through its convolution with the CTR field $E_{CTR}(t)$ the function $\cos(\tau^2/4\beta - \pi/4)$ plays the role of a time-resolution function. A temporal-limitation τ_{lim} can be defined as the separation of the first zeros of $\cos(\tau^2/4\beta - \frac{\pi}{4})$

centered around $\tau = 0$; τ_{lim} can be approximately interpreted as the minimum THz pulse duration that can be measured without distortion arising from the cosine time resolution function. For our experimental conditions we obtain

$$\tau_{\mathrm{lim}} = \sqrt{12\pi\beta} \approx 2.6\sqrt{T_c T_0}, \qquad (2)$$

where the approximation on the right hand side is obtained from an assumption of a Gaussian probe. T_c is the FWHM of the chirped probe pulse duration and T_0 the FWHM of the duration in case the probe pulse was unchirped. For the experiments described here, τ_{lim} is 900 fs, which indicates that the CTR measurements shown in Fig. 2 are close to the limit of distortion-free detection for spectral decoding with the used chirp parameters. Fully distortion free detection can be achieved using temporal decoding [11, 12] as the detection scheme. Note that the time resolution for the electro-optic measurements also depends on the material and thickness of the electro-optic crystal; for the experiment shown here, the resolution limit is about 300 fs (see for example Ref. [13]).

CONCLUSION

The first electro-optic CTR results at FLASH are very promising. Work is in progress to perform single-shot electro-optic spectral decoding and temporal decoding measurements of the CTR pulse directly in vacuum (eliminating the quartz exit window of the THz beam line) and compare the results with spectral measurements of the CTR pulse. Furthermore, the CTR measurements will be compared with measurements obtained from single-shot electro-optic detection of the Coulomb field of electron bunches and from the LOLA transverse deflecting rf structure.

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