SINGLE SHOT LONGITUDINAL BUNCH PROFILE MEASUREMENTS BY TEMPORALLY RESOLVED ELECTRO-OPTICAL DETECTION

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Abstract

For the high gain operation of a SASE FEL, extremely short electron bunches are essential to generate sufficiently high peak currents. At the superconducting linac of FLASH at DESY, we have installed an electro-optic measurement system to probe the time structure of the electric field of single ~100 fs electron bunches. In this technique, the field induced birefringence in an electro-optic crystal is encoded on a chirped picosecond laser pulse. The longitudinal electric field profile of the electron bunch is then obtained from the encoded optical pulse by a single shot cross correlation with a 35 fs laser pulse using a second harmonic crystal (temporal decoding). An electro-optical signal exhibiting a feature with 118 fs FWHM was observed, and this is close to the limit of resolution due to the material properties of the particular electro-optic crystal used. The measured electro-optic signals are compared to bunch shapes simultaneously measured with a transverse deflecting cavity.

INTRODUCTION

Precise measurements of the longitudinal temporal profile of extremely short electron bunches are essential for a detailed understanding of the lasing and operating principles of a SASE FEL [1]. At FLASH (DESY), several monitors for the longitudinal profile of the compressed beam are located within a few meters of each other: the LOLA transverse deflecting RF structure [2], and the single shot electro-optic detection monitor [3] measuring the Coulomb field of the bunches as described in this paper.

MEASUREMENT SETUP

The temporal decoding method for single shot electro-optic detection of the electric field of electron bunches [4] is schematically depicted in Fig. 1. The time structure of the electric field of the electron bunch is encoded onto a chirped laser pulse. In the electro-optic crystal the stretched laser pulse acquires an elliptic polarization with an ellipticity which is proportional to the electric field of the electron bunch and encodes its temporal structure. The analyser, A, turns the elliptical polarization into an intensity modulation, which is then sampled by the gate pulse in a single-shot cross-correlator, using a second harmonic BBO crystal.

The femtosecond laser consists of a Ti:Sa oscillator, which is synchronised to the rf of the accelerator, and a Ti:Sa amplifier, which delivers pulses of 35 fs duration at a central wavelength of 792 nm with an energy of 1 mJ. A full description of the electro-optical temporal decoding has been given elsewhere [3,4,5]. The laser pulse is transported 20m to an optical table near the beam pipe where it is injected into the beam pipe and through an electro-optic crystal. It is then coupled out of the pipe and into the temporal decoding setup comprising the polarisers, electro-optic crystal and cross-correlator shown in figure 1.

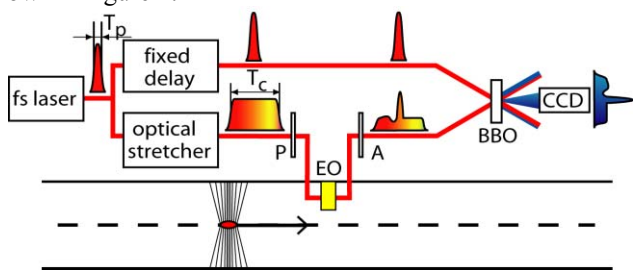

Figure 1: The single-shot technique for measuring the longitudinal electric field profile of electron bunches using electro-optic encoding and temporal decoding. P and A are polarizers, BBO is the second-harmonic crystal of the cross-correlator and the signal is recorded by the CCD.

There are four main factors which influence the accuracy of temporal decoding measurements: the material properties of the electro-optic crystal, the energy of the electron beam, the geometry of the electro-optic interaction and the geometry of the cross correlator.

The Coulomb field of the electron bunch behaves as a single cycle terahertz pulse which, for maximum time resolution and electro-optic signal strength, must propagate through the electro-optic crystal with the same group velocity as the laser pulse. This condition is evidently not met when the signal has significant components near a phonon resonance of the electro-optic crystal, where the refractive index changes rapidly with frequency. We have, in the past, used ZnTe, which has a phonon resonance around 5.3 THz, as an electro-optic crystal. In the experiments described here we use GaP as the electro-optic crystal: the higher resonance frequency of 11 THz should give a corresponding improvement in time resolution. We note that the details of the phonon resonances strongly depend on the material quality and manufacturing parameters. Figure 2 shows theoretical calculations made on both ZnTe and GaP [5].

The electric field of a charge moving at relativistic fields is compressed in the longitudinal direction and has an opening angle of $2/\gamma$ [5]. This small opening angle leads to a slight temporal broadening of the electric field pulse at a finite distance, which results in a reduction of the high frequency parts of electric field at the electro-optic crystal.

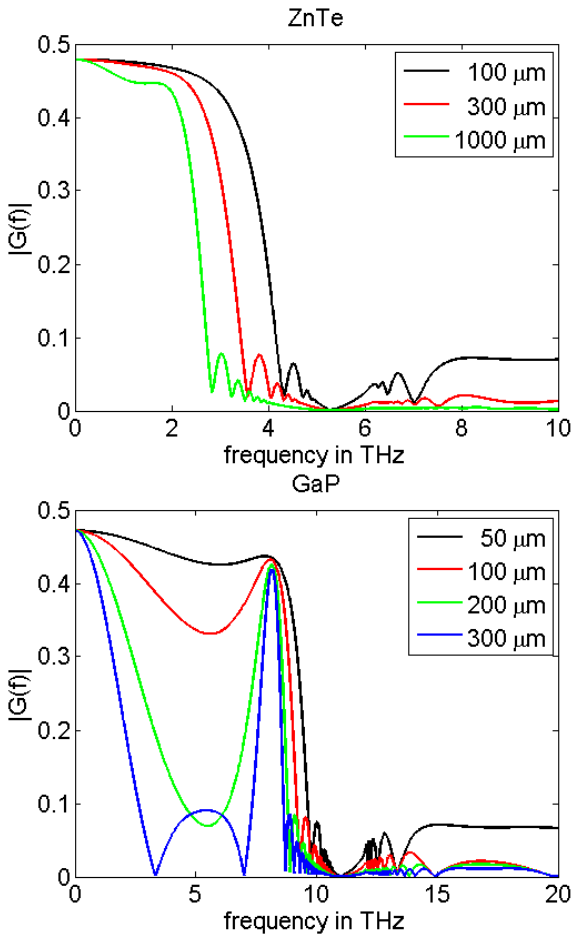

Figure 2: Electro-Optic response function for ZnTe (upper) and for GaP (lower) for different thickness of crystal.

While the THz pulse travels perpendicular to the surface through the crystal, the laser beam is inclined by a small angle. The right hand part of the laser arrives earlier at the crystal surface then the left hand part. Therefore the phase retardation resulting from the interaction of the THz pulse laser field is not distributed perpendicular to the direction of travel of the laser but tilted by the small angle. This effect is leads to a broadening of the electro optical signal (approximately a Gaussian convolution of 35 fs).

An upper limit for the time resolution of the cross-correlator was experimentally determined to be better then 50 fs (rms), including in the response of the BBO crystal, the imaging optics and the length of the gate pulse.

In these experiments we also compared the electro-optic detection with results from a Transverse Deflecting Cavity (TDC), which currently produces the highest resolution of all the longitudinal diagnostics at FLASH. The TDC streaks the longitudinal phase space of the bunch transversely without producing any mean deflection, and is preceded by a kicker that adds an additional mean deflection, so that a single bunch can be deflected onto an off-axis OTR screen. A number of electro-optic temporal decoding traces have been taken in parallel with longitudinal bunch profile measurements with high temporal resolution using TDC. Owing to space constraints, the electro-optic experiment had to be mounted downstream of the TDC. Although it was not possible to measure using both techniques simultaneously, we were able to use the electro-optic detector to measure the bunch immediately preceding or immediately following the bunch deflected by the TDC.

RESULTS AND DISCUSSION

The data is obtained directly from the CCD camera in real time and is displayed in the format as shown in Figure 3. The camera image, which is in false colour representation, clearly shows a reflection from the electro-optic crystal. The lower panel shows the electro-optic signal obtained after binning, background subtraction, and normalisation of the image. Using a 100mm thick GaP crystal in the temporal decoding setup of Figure 1, a pulse of 118 fs FWHM in a 12 ps measurement window was observed. The leading edge of the electron bunch is on the left. The small peak around 8.5 ps is due to the reflection of the THz field in the electro-optic crystal.

Simultaneous TDC and the electro-optic measurements, not presented here, show a good correlation between the shapes of the electron bunch profiles.

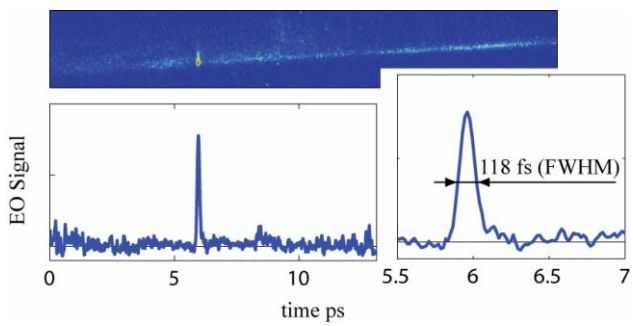

Figure 3: A typical measurement from temporal decoding showing the camera image and a binned image. The insert displays an exploded view of the peak.

The CCD camera which captures the images in the electro-optic experiment is part of the FLASH control system. This makes it possible to tune the accelerator

while observing the electron bunch shape. Electro-optic measurements have been performed during the SASE output. These measurements did not adversely influence the SASE process.

CONCLUSION

Electro-optic detection of single electron bunches with a FWHM of 118 fs has been observed. The response of the electro-optic material, GaP in our case, is the dominant temporal limitation in these measurements. Simultaneous TDC and electro-optic measurements show a good agreement in the shapes of the electron bunch profile. The non-invasive property of the electro-optic measurement allowed it to be used as a diagnostic tool during SASE operation.

We are currently designing a robust version of the electro-optic diagnostic with a reduced footprint, a better temporal resolution and increased measurement stability. Such a setup will be installed at FLASH and at the Energy Recovery Linac Prototype (ERLP) at Daresbury laboratory. Furthermore, the setup will be readily transportable to other laboratories.

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