

SINGLE SHOT LONGITUDINAL BUNCH PROFILE MEASUREMENTS AT FLASH USING ELECTRO-OPTICS DETECTION TECHNIQUES

P.J. Phillips, W.A.Gillespie, Dundee University, Dundee, UK

S. P. Jamison, ASTEC, Daresbury, UK

V. Arsov, H. Schlarb, B. Schmidt, P. Schmüser, DESY, Hamburg, Germany

B. Steffen, PSI, Villigen, Switzerland

G. Berden, A.F.G. van der Meer, FOM Rijnhuizen, Nieuwegein, Netherlands

A.M. MacLeod, University of Abertay, Dundee, UK

Abstract

At the superconducting LINAC of FLASH, we have installed an electro-optic experiment for single shot, non-destructive measurements of the longitudinal distribution charge of individual electron bunches. The profile of the electron bunch field is electro-optically encoded onto a stretched Ti:Sa laser pulse. In the decoding step, the profile is retrieved either from a spectral measurement of the encoded pulse or from a cross-correlation of the encoded pulse with a 30 fs FWHM laser pulse, obtained from the same laser pulse. At FLASH, sub-100 fs electron bunches has been measured during FEL operation with an rms value of 60 fs (144 FWHM). The electro-optic measurements have been validated with transverse deflecting structure measurements.

INTRODUCTION

Short, intense relativistic electron bunches, with duration of less than 200 fs, are now produced in several accelerator facilities and laboratories. They are essential for femtosecond VUV and x-ray free electron lasers like, FLASH and XFEL at DESY, Hamburg. Ultra-short relativistic electron bunches are also produced in plasma wakefield accelerators. For all these accelerators, precise measurements of the longitudinal temporal profile of the electron bunch are essential for a detailed understanding of the physical processes and the operating principles. In this paper we present results of such a measurement using electro-optic technique and its comparison with simultaneous transverse deflecting structure (TDS) measurements.

SETUP

Two techniques currently play a leading role in the measurement of sub-ps relativistic electron bunches profiles, transverse deflecting structure and electro-optic measurements of the bunch coulomb field.

The principle of the Transverse Deflecting Structure is well understood and has been demonstrated as early as the 1960s [1]. The temporal profile of the electron bunch is transferred to a spatial profile through manipulation of the phase space by using a rapidly varying magnetic field. The spatial profile is viewed through a camera via a screen. Time resolution of this device can reach <15 fs. The size of the TDS structure is large and has to be designed into the accelerator. The diagnostic method also

destroys the electron bunch being measured. At FLASH a TDS has been installed and a detailed description can be found at [2].

The second technique, the Electro-Optic Temporal Decoding technique (EOTD) has demonstrated a high resolution profile measurement, with single shot measurements of sub-picosecond electron bunches first demonstrated in 2003 [3]. The underlying principle is that of using a non-linear process to convert the longitudinal electric field profile of a single bunch into a longitudinal intensity profile of an optical pulse. The EO technique has the advantage of being a non-destructive which offers the possibility of correlating the measurements with processes observed further downstream.

At FLASH we used a femtosecond Ti:Sa laser with a 30 fs FWHM temporal pulse width, 1kHz repetition rate and pulse energy of 1 mJ. This short laser pulse is split into two, where one part, called the probe beam, is stretched, sent through the EO crystal and then through an analyzing polarizer to a cross correlator. The second part

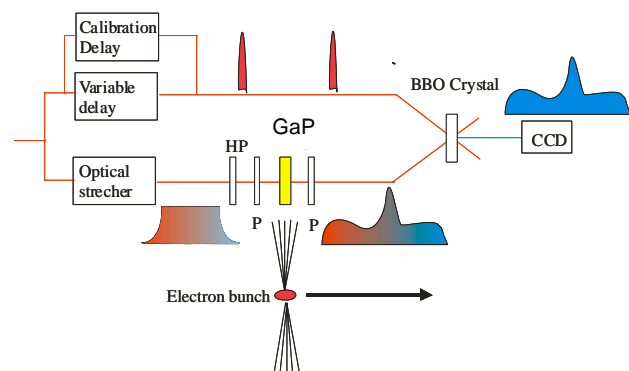


Figure 1 Schematic of the Electro Optical Temporal Decoding setup

of the pulse, the gate beam, is used to sample the probe beam in a correlator. This is shown in Fig 1. The cross correlator uses the technique of a non-collinear second harmonic generation (SHG) with expanded beam profiles.

When the pulses overlap spatially and temporally in the SHG crystal, a part of the pulse energy is converted into light of the double frequency of the incoming light. The second harmonic light leaves the crystal along the bisecting line two beam paths and the SHG intensity is

proportional to the product of the intensities of the two incoming pulses, the gate and probe beams.

Since the beams are expanded and they cross at an angle, different longitudinal slices of the probe beam coincide with the gate beam at different positions along the horizontal dimension of the SHG crystal. Light intensity from the crystal, which is imaged on to an ICCD camera, is proportional to a correlation of the intensities of the two beams. The temporal resolution of this detection scheme depends on the duration of the gate beam the thickness and phase matching of the SHG crystal, the spatial resolution of the imaging system and the camera. Using a Ti:Sa laser pulse of 30 fs FWHM duration and a 300 μm thick B-barium borate (BBO) crystal a resolution of better than 35 fs (rms) (86 FWHM) can be reached. Due to the low efficiency of the SHG process pulse energy of several 100 μJ was required in the gate pulse.

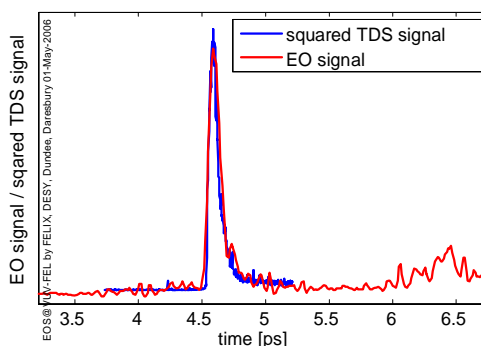


Figure 2 TDS comparison with EOTD setup. This shows the EO signal and the TDS signal squared

DISCUSSION

The EOTD measurements can be compared with measurements from the TDS which is located just before the EOTD experiment. This makes it impossible to observe the same electron bunch with both detection systems since TDS is destructive. In the experiments described here, TDS measurements were carried out on the last bunch in the macro pulse with EO measurements on the penultimate bunch. When FLASH is operated with long bunch trains it is expected that the fluctuations in bunch profile between the last pair of bunches will be small. As a result of the crossed-polariser geometry in the EOTD measurement, the EOTD signal scales quadratically with the coulomb field of the bunch. As shown in Fig 2 there is excellent agreement with the EOTD measurement and the squared TDS measurement.

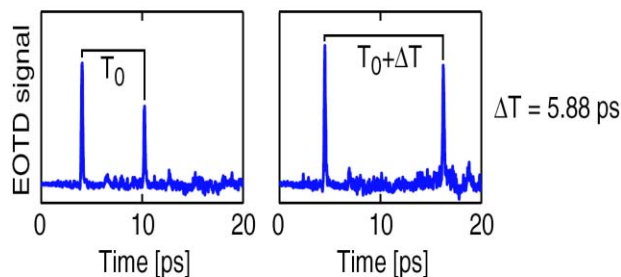


Figure 3 Time calibration of the electro-optic measurements is obtained by duplicating the gate pulse. The base T_0 is not precisely known, but the additional delay Δt can be varied with fs accuracy.

An approximate time calibration of the EOTD setup can be derived from the known laser geometry in the cross-correlator. We have devised an online calibration technique with much higher accuracy. Just before the cross-correlator, the gate pulse is duplicated by inserting two 50% beam splitters and a motorized delay line into the gate path. As a result, the probe pulse will be cross-correlated twice within several picoseconds, and the electron bunch will appear twice in the CCD image, as shown in Fig 3. Variation of the delay Δt between the two gates pulses provides a time calibration with femtosecond accuracy and which is not affected by the arrival time jitter of the electron bunches.

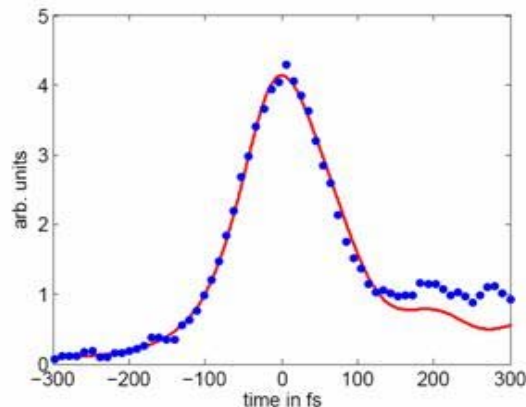


Figure 4 Comparison between simulation (red line) and the EOTD measurements (Blue dots). For a fitted Gaussian curve we get 60 fs (rms) for the measured bunch profile.

An important criterion for the choice of the EO crystal is its response to the THz pulse being created by the electron bunches. In all materials there are phonon resonances which act as a cut off to the interaction of the probe laser beam. In the material used in this experiment, GaP, there is a first phonon resonance at 11 THz.

We have simulated the response of a 65 μm GaP crystal to ultrashort electron bunches as characterised by the TDS. The equivalent THz pulse entering the EO crystal, which is identical to the Coulomb field of the electron bunch at a distance of 4.5 mm from the electron

beam, has an estimated rms width of 40 fs (96 FWHM). This pulse has been taken as an input for a numerical simulation of the electro-optical process in GaP [4], using published material data. The Fourier components of the THz pulse are multiplied by the complex electro-optic response function of the GaP crystal, which include and the EO coefficient $r_{41}(f)$, and then phase retardation between the orthogonal polarisation components of the laser beam is calculated. The computed EOTD signal has $\sigma = 55$ fs (rms). Note that the widening is entirely due to the first resonance of GaP at 11 THz. For the 65 μm GaP crystal, the cut-off arising from the frequency dependence of the EO coefficient $r_{41}(f)$ is lower than that from phase matching, and limits the useable frequency to about 8 THz.

As shown in Fig. 4 shows the temporal profile of the measured EOTD signal [5] agrees well with the predicted one except for a slight increase in width (55 fs rms (132 FWHM) to 60 fs rms (144 FWHM)), which is attributed to resolution of the optical cross correlator (35 fs rms), and a higher intensity in the tail of the bunch. The tail is enhanced by wakefields generated upstream of the EOTD crystal. Such wakefields are invisible to the TDS measurement because the TDS streaks the electric charge of the bunch and is totally insensitive to electromagnetic fields travelling down the beam pipe. The agreement in the width of the leading spike between measurement and prediction confirms that we have a quantitatively good understanding of GaP linear and non-linear properties. In this experiment as described earlier it is the cut off arising from the frequency dependence of the EO coefficient $r_{41}(f)$ is lower than that from phase matching, and limits the usable frequency from less than 8 THz, in the GaP.

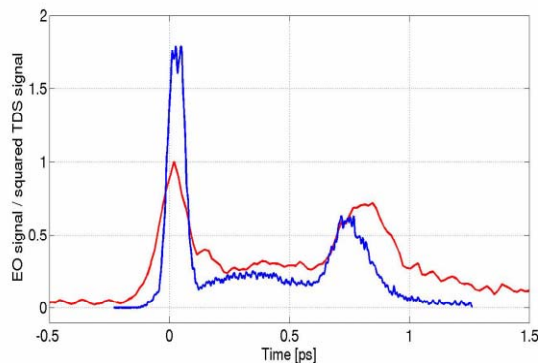


Figure 5 RF phase in the bunch compression was detuned to create two electron bunches which are displayed in both the signal EOTD and the squared TDS signal in very close agreement.

Electron bunches with an rms length of 30 fs (75 FWHM) range would appear thus broadened to about 55 fs (120 FWHM). Note however, that longer electron bunches ($\sigma \geq 90$ fs (rms)) will be faithfully reconstructed by this EOTD setup because the pulses do not contain Fourier components in the resonance region of GaP.

In different measurements, the rf phase in the bunch compression system was detuned from its optimal settings to generate wider bunches with a double peak structure. This allowed us to test the accuracy in the profile (as apposed to bunch length) measured with the EOTD technique. As shown in Fig 5 there is good agreement between the squared TDS and EOTD, for this bunch profile.

In summary, non-destructive, single-shot, longitudinal electron bunch profile detectors based on electro-optic detection with femtosecond lasers have been successfully implemented and calibrated at the soft x-ray FEL FLASH [5]. The best time resolution ever attained in the electro-optic analysis of ultra-short electron bunches has been achieved, and an absolute calibration of the EOTD process has been made using a delay line to measure the pulse twice. Furthermore, by using incident electron bunches that were characterised by a transverse deflecting structure of excellent time resolution, the EOTD technique has been benchmarked and we have confidence that it gives a reliable measurement of the electron bunch profile. EOTD has the considerable advantage of being non-destructive and can therefore provide trigger signals for pump-probe experiments at a FEL. Moreover, the EOTD setup covers a larger time window, yields valuable information on wakefields, require much less space in the LINAC, and is less expensive than TDS.

REFERENCES

- [1] O.H. Altenmueller, R.R. Larsen, G.A. Loew, *Rev. Sci. Instrum.* 35, 438 (1964)
- [2] M. Hüning et al., in *Proceedings of the 27th international Free Electron Laser Conference*, Stanford, CA, 2005 p538
- [3] G. Berden et al., *Phys. Rev. Lett.* 93, 114802 (2004)
- [4] S. Casalbuoni et al., *TESLA report no. 2005-01* and *Phys. Rev. STAB*, to be published
- [5] G. Berden et al, *Phys. Rev. Lett.* 99, 164801 (2007)