

HIGH TEMPORAL RESOLUTION, SINGLE-SHOT ELECTRON BUNCH-LENGTH MEASUREMENTS

G. Berden*, B. Redlich, A.F.G. van der Meer,
FOM Institute Rijnhuizen / FELIX, Nieuwegein, The Netherlands

S.P. Jamison†, A.M. MacLeod, W.A. Gillespie,
School of Computing and Advanced Technologies, University of Abertay Dundee, Dundee, UK

Abstract

A new technique, combining the electro-optic detection of the Coulomb field of an electron bunch and the single-shot cross-correlation of optical pulses, is used to provide single-shot measurements of the shape and length of sub-picosecond electron bunches. As in our previous technique, spectral decoding [I. Wilke et al., Phys. Rev. Lett. 88, 124801 (2002)], the electric field of the electron bunch is encoded electro-optically on an optical pulse. The new method, which we term temporal decoding, offers a much better time resolution since it avoids the significant measurement artifacts that can arise in the spectral decoding technique. The temporal decoding technique has been applied to the measurement of electron bunches at FELIX, characterising single bunches of around 650 fs FWHM. The temporal resolution is limited primarily by the electro-optic crystal thickness and the relatively low energy of the electrons (50 MeV). This single-shot electron bunch shape measurement is real-time and non-destructive.

INTRODUCTION

Electro-optic detection of the electric field of electron bunches is a promising technique for the measurement of the bunch length and shape in the sub-picosecond time domain. The electro-optic detection method makes use of the fact that the local electric field of a highly relativistic electron bunch moving in a straight line is almost entirely concentrated perpendicular to its direction of motion. This electric field induces birefringence in an electro-optic crystal placed in the vicinity of the beam. The amount of birefringence depends on the electric field and is probed by monitoring the change of polarization of a short optical laser pulse.

Several electro-optic detection schemes have been proposed and/or demonstrated [1-9]. Single-shot measurements have been reported by Wilke *et al.* [4]. In such measurements the temporal profile of the Coulomb field-

induced birefringence in the electro-optic crystal is probed by a linearly chirped Ti:sapphire laser, with a pulse length longer than the electron bunch length. This optical probe pulse is passed through a polarizer in order to convert the time dependent phase retardation (birefringence) into an intensity modulation on the chirped pulse. In this way, the Coulomb field profile is encoded onto the spectrum of the probe pulse through the time-frequency relationship of the probe. The electric field profile of the electron bunch is determined through a single shot measurement of the probe spectrum.

Spectral decoding measurements at the Free Electron Laser for Infrared eXperiments (FELIX) [10] in Nieuwegein, The Netherlands, show single-shot electric field profiles with a FWHM of 1.7 ps [4]. The temporal resolution is determined by several factors. The increased duration of the Coulomb field at the probe position, when compared to the electron bunch duration, leads to a temporal resolution of $2R/(\gamma c)$ where R is the radial distance between the electron beam and the optical probe in the electro-optical crystal. For a 50 MeV beam and a distance of 1.5 mm this temporal resolution is 100 fs. The thickness and the material of the crystal contribute to the temporal resolution as well [4, 8, 9]. For a 0.5 mm ZnTe crystal, electric field Fourier components with a frequency lower than 2.8 THz will be detected with minimal distortions. These two contributions to the temporal resolution are present for all electro-optic detection schemes. For the aforementioned spectral decoding technique there are two other contributions: i) the resolution of the spectrometer and CCD array (300 fs for the single shot measurements reported in Ref. [4]) and ii) the intrinsic coupling between the frequency components of the intensity modulation (induced by the electron bunch) and the frequency components of the chirped optical pulse.

This intrinsic time resolution limitation of the spectral decoding technique has been studied in detail [11, 12]. For ultra-short electron bunches, the result is that the degree of distortion of the measured electric field profile depends on the actual length of the electron bunch. Therefore it is impossible to make a deconvolution of the measured electric field profile. A way to circumvent the time resolution problems of spectral decoding is to measure the intensity modulated probe pulse in the time-domain [12]. In this so-called temporal decoding method the chirped pulse car-

* berden@rijnh.nl

† also at: University of Strathclyde, Glasgow, UK

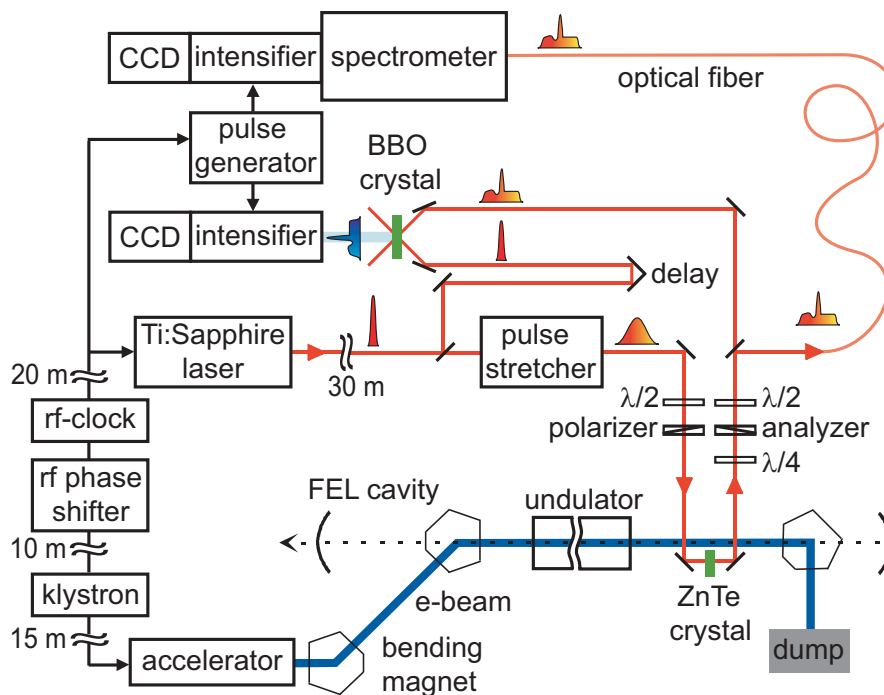


Figure 1: Setup for single-shot measurements of the longitudinal electric field profile of individual electron bunches. The electric field profile induces an intensity modulation onto a stretched optical pulse via the electro-optic effect. Two methods for decoding have been indicated: i) spectral decoding where the spectrum of the intensity modulated probe pulse is measured with a spectrometer-CCD combination, and ii) temporal decoding where the intensity modulated probe pulse is measured by a single-shot cross-correlation with an ultra-short optical pulse.

rying the modulation due to the presence of the electron bunch is cross-correlated with a part of the original optical pulse which has been split off before the optical stretching. Single-shot cross-correlation is based on the temporal to spatial conversion that occurs through the spatial overlap of non-collinear beams in a second-harmonic crystal.

In this contribution we show experimentally that the temporal decoding technique can measure single-shot electric field profiles under circumstances where the spectral decoding technique fails.

EXPERIMENTAL

Measurements were performed on relativistic electron bunches that are produced in the linear accelerator (250 pC, 50 MeV) at the FELIX facility [10]. The electron bunch shape is measured inside the accelerator beam pipe at the exit of the undulator of the FEL (see Fig. 1) [14]. A 0.5 mm thick $\langle 110 \rangle$ ZnTe crystal is used as an electro-optic sensor and is placed with its front face perpendicular to the propagation direction of the electron beam.

The probe laser pulse is obtained from a femtosecond Ti:Sapphire amplifier (wavelength 800 nm, pulse energy 1 mJ, repetition rate 1 kHz, pulse length 30 fs) which is actively synchronized to the accelerator rf clock [15]. The pulse passes through a grating-pair optical stretcher and is used to probe the birefringence in the electro-optical crystal. A half-wave plate and a polarizer are used to attenuate

the energy below the ZnTe damage threshold. The polarizer is oriented to maximize the phase retardation for the fixed ZnTe and Coulomb field orientation. Residual birefringence of the ZnTe crystal is removed with an appropriately adjusted quarter-wave plate. The analyzing polarizer is set to minimize the transmission of the probe laser pulse is the absence of the electron bunch.

The bunch profile could be measured by either spectral decoding or by temporal decoding. Spectral decoding takes place by coupling the probe pulse into a fiber that is connected to a spectrometer. The spectrum of the probe pulse is measured single shot with an intensified CCD camera. Temporal decoding with a resolution better than 50 fs is performed in a single-shot cross-correlator [13] where the probe pulse is cross-correlated with part of the (un-stretched) Ti:sapphire laser pulse. The position dependent emission of the second harmonic light from the BBO crystal is imaged onto an intensified CCD camera. Since we have only one intensified CCD camera we cannot record the temporal and spectral decoding signal at the same time.

RESULTS

For the relatively long bunches (~ 650 fs) available at FELIX, we have stretched the probe pulse to a length of 21 ps, in order to be in a regime where the spectral decoding method fails [4, 12] (identical spectral decoding limitations would apply for a 320 fs bunch length and a 5 ps chirped

probe). Measurements have been performed on 250 pC, 50 MeV electron bunches. Figure 2 shows the electro-optic signals recorded with the temporal decoding and the spectral decoding techniques. As a result of the cross-polarizer geometry in combination with the removal of the residual birefringence, the electro-optic signal scales quadratically with the electric field strength as has been experimentally verified [16]. Therefore, the temporal decoding trace corresponds to an electric field profile of a single electron bunch with a FWHM of 650 fs, while the spectral decoding trace would give a value of 2.5 ps for the same electron bunch. While the measurements were not performed simultaneously, they were carried out under the same experimental conditions, and it is believed that the true bunch profiles are very similar for each measurement.

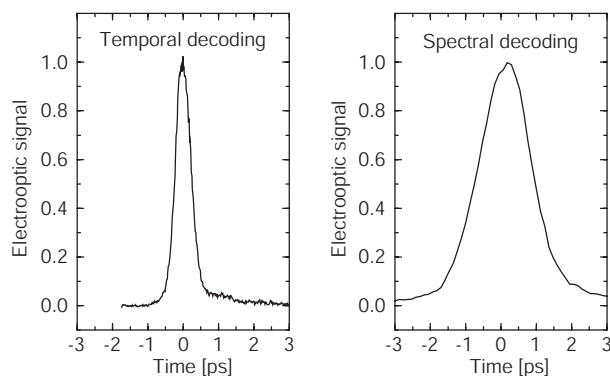


Figure 2: Electro-optic measurements of single electron bunches obtained with the temporal decoding and the spectral decoding technique. The leading edge of the bunch is on the left.

The broadening in the spectral decoding measurements is caused by the long chirped pulse duration in our measurements. A chirped pulse of 5 ps should be used in order to perform a reliable measurement with the spectral decoding method (see the results in Ref. [4]).

DISCUSSION

Spectral decoding is the simpler of the two electro-optic detection techniques discussed here. It can be used to determine the time jitter in the arrival time of electron bunches, and it can be used for real-time optimization of the accelerator settings. However, one has to keep in mind that there are certain limitations. Broadening and distortion effects, which depend on the actual length of the electron bunch, arise particularly when measuring short electron bunches with long probe pulses. Temporal decoding circumvents these problems as has clearly been demonstrated in Fig. 2. Temporal decoding, therefore, offers a better way to precisely determine the shape of the longitudinal electric field profile of electron bunches. At FELIX, we have used temporal decoding for real-time manipulation of the electron bunch shapes, and for measuring the timing jitter of the electron bunches [17].

REFERENCES

- [1] X. Yan, A.M. MacLeod, W.A. Gillespie, G.M.H. Knippels, D. Oepts, A.F.G. van der Meer, and W. Seidel, *Phys. Rev. Lett.* **85**, 3404 (2000).
- [2] T. Tsang, V. Castillo, R. Larsen, D.M. Lazarus, D. Nikas, C. Ozben, Y.K. Semertzidis, and T. Srinivasan-Rao, *J. Appl. Phys.* **89**, 4921 (2001).
- [3] M.J. Fitch, A.C. Melissinos, P.L. Colestock, J.-P. Carneiro, H.T. Edwards, and W.H. Hartung, *Phys. Rev. Lett.* **87**, 034801 (2001).
- [4] I. Wilke, A.M. MacLeod, W.A. Gillespie, G. Berden, G.M.H. Knippels, and A.F.G. van der Meer, *Phys. Rev. Lett.* **88**, 124801 (2002).
- [5] T. Srinivasan-Rao, M. Amin, V. Castillo, D.M. Lazarus, D. Nikas, C. Ozben, Y.K. Semertzidis, A. Stillman, T. Tsang, and L. Kowalski, *Phys. Rev. ST Accel. Beams* **5**, 042801 (2002).
- [6] L. Bentson, P. Bolton, E. Bong, P. Emma, J. Galayda, J. Hastings, P. Krejcik, C. Rago, J. Rifkin, and C.M. Spencer, *Nucl. Instrum. Methods Phys. Res., Sect. A* **507**, 205 (2003).
- [7] H. Loos, A. Doyuran, J.B. Murphy, J. Rose, T. Shaftan, B. Sheehy, Y. Shen, J. Skaritka, X.J. Wang, Z. Wu, and L.H. Yu, *Proceedings of the 2003 Particle Accelerator Conference (PAC)*, Portland (OR), 2003, p. 2455.
- [8] G. Berden, G.M.H. Knippels, D. Oepts, A.F.G. van der Meer, S.P. Jamison, A.M. MacLeod, W.A. Gillespie, J.L. Shen, and I. Wilke, *Proceedings of the 6th European workshop on beam diagnostics and instrumentation for particle accelerators (DIPAC)*, Mainz, Germany, 2003, 20.
- [9] G. Berden, G.M.H. Knippels, D. Oepts, A.F.G. van der Meer, S.P. Jamison, A.M. MacLeod, W.A. Gillespie, J.L. Shen, and I. Wilke, *Proceedings of the 2003 Particle Accelerator Conference (PAC)*, Portland (OR), 2003, p. 519.
- [10] <http://www.rijnh.nl/felix>
- [11] J.R. Fletcher, *Opt. Express* **10**, 1425 (2002).
- [12] S.P. Jamison, J. Shen, A.M. MacLeod, W.A. Gillespie, D.A. Jaroszynski, *Opt. Lett.* **28**, 1710 (2003).
- [13] F. Salin, P. Georges, G. Roger, and A. Brun, *Appl. Opt.* **26**, 4528 (1987).
- [14] Previous experiments at FELIX were performed at the entrance of the undulator [1, 4]. The ZnTe crystal and the two metal mirrors, which were in the beam pipe for more than 4 years (approximately 8000 hours of beam time), have been renewed when the crystal holder was moved to the exit of the undulator in the summer of 2003.
- [15] G.M.H. Knippels, M.J. van de Pol, H.P.M. Pellemans, P.C.M. Planken, and A.F.G. van der Meer, *Opt. Lett.* **23**, 1754 (1998).
- [16] Note that in Ref. [4] the spectral decoding technique has been used without using the quarter-wave plate to remove the residual birefringence. Therefore, the electro-optic signal scales linearly with the electric field.
- [17] G. Berden, S.P. Jamison, A.M. MacLeod, W.A. Gillespie, B. Redlich, and A.F.G. van der Meer, to be published.