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Electro-optic techniques for temporal profile characterisation of relativistic Coulomb fields and coherent synchrotron radiation

S.P. Jamison[a,b,*], G. Berden[c], A.M. MacLeod[a], D.A. Jaroszynski[b], B. Redlich[c], A.F.G. van der Meer[c], W.A. Gillespie[d]

[a]*School of Computing and Advanced Technologies, University of Abertay Dundee, Dundee DD1 1HG, UK*
[b]*Department of Physics, John Anderson Building, 107 Rottenrow, University of Strathclyde, Glasgow G4 0NG, UK*
[c]*FOM Institute for Plasma Physics 'Rijnhuizen', Nieuwegein, The Netherlands*
[d]*Division of Electronic Engineering and Physics, University of Dundee, Dundee DD1 4HN, UK*

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Abstract

Electro-optic (EO) detection of relativistic Coulomb fields offers a method for non-destructive longitudinal profile measurements of ultrashort bunches. Techniques for single-shot EO characterisation of Coulomb fields which have been developed or demonstrated at the FELIX free electron laser (FEL) facility are discussed. In addition, recent FELIX experiments have used single-shot electro-optic detection to measure the temporal profile of the far-infrared electric field pulse of coherent synchrotron radiation (CSR), initial results of which are reported here. Such time-resolved CSR measurements have the potential for a completely non-invasive bunch longitudinal profile determination, without the ambiguity in profile that is present in CSR spectral measurements.
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1. Introduction

Electro-optic (EO) detection techniques have great promise for the characterisation of the longitudinal profiles of ultrashort electron bunches, and for the non-destructive measurement of bunch arrival times with ultrafast time resolution [1–4]. A number of variations of the EO detection concept have been proposed or undertaken for electron bunch measurements, and each technique has its relative merits; at the FELIX free electron laser (FEL) facility recent experimental work has been particularly focused on single-shot (single bunch) longitudinal bunch profile measurements with chirped laser probes. While much emphasis has been on bunch profile measurements through the EO charactersiation of the bunch Coulomb field, the same single-shot EO techniques can also be applied to the detection of coherent synchrotron radiation (CSR) or edge radiation. Recently, such measurements have been performed at the FELIX facility. This has the potential for a less direct, but also less invasive, measurement of the bunch profile and timing. This paper provides an overview of the single-shot EO experiments at the FELIX facility.

2. Electro-optic detection of Coulomb fields

In considering the various EO techniques, it is useful to make a distinction between the encoding of the Coulomb field, or the THz electric field, into an optical signal, and the decoding of this optical signal in such a way as to infer the temporal profile of the transient electric field pulse. For the encoding process, it is sufficient here to consider the

*Corresponding author. Department of Physics, John Anderson Building, 107 Rottenrow, University of Strathclyde, Glasgow G4 0NG, UK. Tel.: +44 141 548 3103; fax: +44 1414 552 2891.
E-mail address: steven.jamison@strath.ac.uk (S.P. Jamison).

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instantaneous electric field as inducing a birefringence in an EO material. As the electric field propagates through the crystal, the birefringent properties of the crystal also propagate. This birefringence can be probed by a co-propagating optical laser pulse.

The influence of material properties on the electric field propagation is most easily considered from the decomposition of the time-varying electric field into its frequency components; Fourier transformation provides the required spectral phase and amplitude information. Propagation of the field spectral components can be treated independently, and is determined by the frequency-dependent refractive index and absorption coefficient. In ZnTe, a common EO material, the refractive index and absorption for frequencies below ~4 THz can, to a first approximation, be considered frequency independent. Consequently, the temporal profile of the field is maintained during propagation whenever the upper limit of the spectrum is below ~4 THz. For a Gaussian Coulomb field longitudinal profile, this limit would correspond to a FWHM length of ~300 fs. The propagation distortion expected for shorter Coulomb field profiles has recently been addressed in depth by Casalbuoni et al. [5].

The above comments refer to propagation within the EO material, and are applicable to any THz source (e.g. CSR). For Coulomb field measurements we need to consider the relationship between free-space and dielectric Coulomb fields. In Fig. 1, the electric field profile of an electron is shown as it penetrates an EO material. For this calculation, the EO material was approximated with a constant refractive index ($n = 3$) throughout the THz spectral region, an approximation that allows us to work directly with fields in the time domain, rather than the field spectral decomposition. The field at any coordinate within the crystal was inferred by evaluating the electromagnetic (EM) field retardation, including the boundary refraction and reduced EM propagation velocity within the crystal, and then mapping the free-space Coulomb field of an equivalent free-space co-ordinate onto this crystal coordinate. As shown in Fig. 1, the Coulomb field has two structures: the first propagates from the vertical boundary collinear with the electron bunch, but with a reduced velocity. The second field region originates from the horizontal boundary, propagates obliquely to the crystal boundary, and is similar to Cherenkov radiation. It is only the first of these propagating fields that is sought to be probed in EO measurements. The probe laser propagates collinearly with the electron bunch, overlapping the desired propagating Coulomb field. In ZnTe there is a close match in the group velocity of the laser pulse and the THz pulse phase velocity. In the case of perfect velocity matching the laser continues to probe the same part of the THz pulse during propagation. For imperfect velocity matching, the temporal shift between THz and probe pulses gives rise to a blurring of the measured THz profile, an effect that is minimised by using very thin crystals.

For the decoding process, in all its variety of forms the principle is to convert the optical phase retardation induced by the birefringence into a measurable intensity change. In this paper, we restrict attention to the single-shot measurement techniques which have been experimentally demonstrated at FELIX: spectral decoding (SD) and temporal decoding (TD). These techniques are shown schematically in Fig. 2.

Electron bunches of $\leqslant 50$ MeV, $\leqslant 300$ pC are produced at the FELIX FEL facility, and have been used as a test-bed for EO techniques for several years now. In the earliest measurements, a temporal scanning measurement over successive bunches in a bunch train was used [1]. The first single-shot measurements using SD were also undertaken at FELIX [2]. Most recently, the high temporal resolution of TD has been demonstrated with the profiling of 650 fs FWHM electron bunches [3].

In SD [2], the probe pulse is chirped to provide a time–wavelength relationship within the optical spectrum. The intensity variation occurring at a specific temporal position within the probe can then, under well-defined constraints [6], be determined from the intensity modulation at the corresponding wavelength.

In TD [3,6], a chirped optical pulse is similarly used; however, the temporal intensity profile of the probe is determined directly through a cross-correlation with a second $\leqslant 50$ fs optical "gate" pulse in a non-linear optical

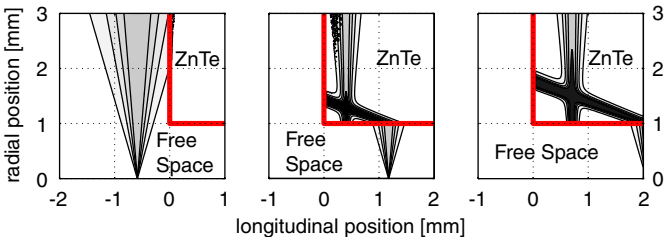

Fig. 1. The Coulomb field of a low γ electron as it passes a dielectric slab. The contours are for field scaled by radial position, $r^2 E_{\text{Coulomb}}$. The field outside the crystal region is as calculated in the absence of the crystal.

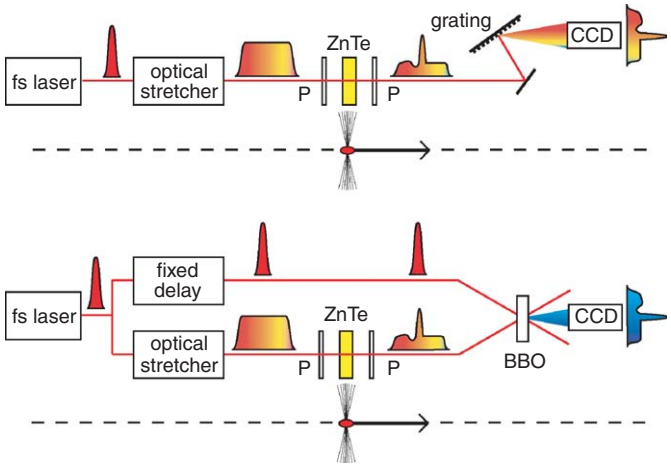

Fig. 2. The general layout for the techniques of spectral decoding (top), and temporal decoding (bottom). Only the ZnTe crystal is within the beamline.

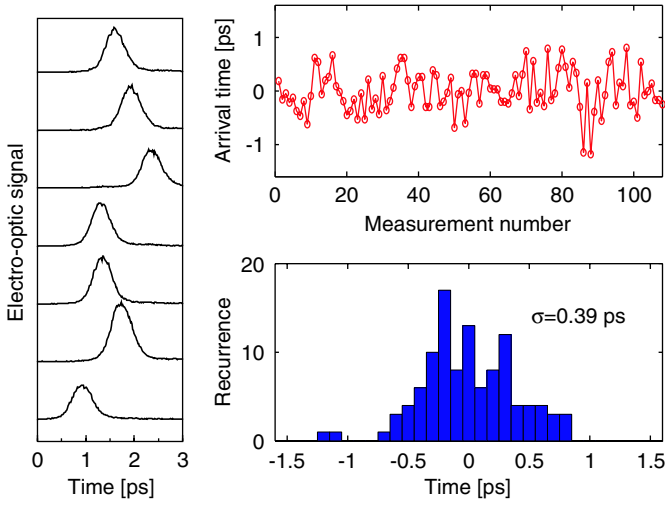

Fig. 3. A series of single-shot temporal decoding measurements of FELIX electron bunches (50 MeV, 300 pC), showing the timing jitter between the laser and electron bunch. The rms timing jitter of 390 fs is comparable to the bunch length of 275 fs rms (650 fs FWHM) [3].

material such as BBO. This cross-correlation is accomplished in a single-shot through cross-correlation of probe and gate pulses which are propagating non-collinearly; the angle between propagation directions introduces a spatially dependent time delay between gate and probe, and hence a spatially resolved measurement of the cross-correlation signal is in effect a temporally resolved measurement [7]. An alternative approach in which the encoding and decoding are physically combined has been demonstrated at the Sub-Picosecond Pulse Source (SPPS) by Cavalieri et al. [4], and has the potential to provide the same time resolution as TD.

At FELIX, 0.8 mJ 30 fs pulses with a central wavelength of 800 nm are used for TD and SD experiments. A 0.5 mm ZnTe crystal placed in the beamline serves as the EO medium. With the TD technique, experiments have been undertaken for: examination of the temporal profile; observation of the bunch timing jitter; examining the charge dependence of the EO signal; observing the EO signal as a function of the electron beam position with respect to the probe laser; and for realtime monitoring of the bunch profile during modification with accelerator and buncher phase adjustments [3]. An example of the bunch timing jitter measurements is shown in Fig. 3. Comparison of SD and TD for Coulomb field measurements has also been examined at FELIX. The superior time resolution of TD (for the chosen laser parameters) was clearly demonstrated, and the differences in the two measurements were shown to be as expected from calculation [3].

3. Electro-optic detection of CSR

There is a growing interest in the THz CSR emitted by ultrashort electron bunches, both for use as a non-invasive diagnostic, and also as a far-infrared light source [8]. While a measurement of the CSR spectrum can be utilised for bunch duration measurements [9], there is an intrinsic problem in determining an unambiguous bunch profile due to a lack of spectral phase information [10]. A measurement of the temporal profile of CSR avoids this ambiguity.

At FELIX the CSR emitted from the entrance to a switching magnet [11] has been measured with EO detection. Bunches with ~200 pC charge, and 45 MeV energy are bent through a 38 cm radius, 45° bend. The THz CSR is coupled from the beamline vacuum through a quartz window. At a distance of ~1 m from the magnet entrance, the THz radiation is collected by an 90° off-axis parabolic (focal length 10 cm) and focused onto a ZnTe EO crystal. To enable collinear propagation of the THz CSR with the optical probe pulse, an indium titanium oxide coated glass flat was used as a beam combiner, reflecting the THz pulse while transmitting the ~20 ps chirped probe pulse. A pyroelectric array on XYZ stages was used to measure transverse beam profiles of the far-infrared CSR beam at positions before and after optical components. With these transverse beam profiles the CSR and probe pulse could be easily co-aligned through the EO crystal.

The SD technique was used for the CSR experiments; the lower time resolution that is achievable with SD is sufficient for these measurements, with high-frequency THz components $\geqslant$3 THz limited by absorption in the quartz window. After passing through the ZnTe crystal, the probe was sent via a fibre optic to an optical spectrometer located outside the beamline vault. The SD signal, examples of which are shown in Fig. 4, is obtained as the difference between probe spectra recorded with and without electron bunches present, and normalised by a reference spectrum.

An important distinction between CSR and Coulomb fields is that the CSR will contain both field polarities. The arrangement of optical polarizers was chosen to produce a EO signal linearly proportional to the CSR electric field. This differs from that used in the Coulomb field measurements (Fig. 3 and Ref. [3]) where the signal was proportional to the field squared. The signal shown in

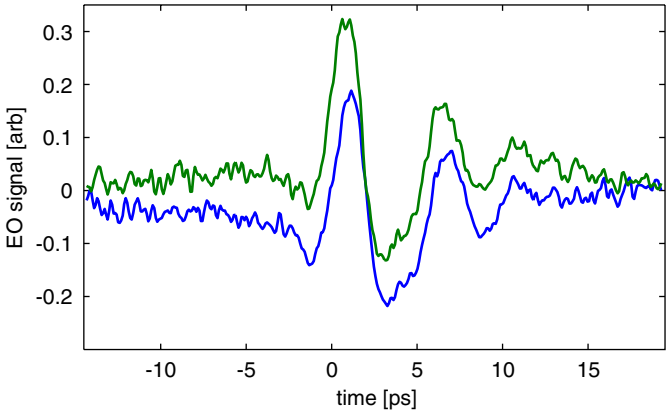

Fig. 4. The electro-optic signal of the CSR emitted from the entrance to the dipole magnet. Two separate measurements are shown to demonstrate the level of reproducibility.

Fig. 4 was obtained with 182 pC bunches, and a measured THz pulse energy of ~50 nJ, although there were indications that the energy could be higher due to uncalibrated reflection losses at the surface of the pyroelectric detector. The same detector measured ~330 nJ THz pulse energy directly after the beamline exit window.

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[11] Strictly speaking, this should be termed the coherent edge radiation, although our imaging setup would be unlikely to resolve the CSR and edge radiation regions.