ELECTRO-OPTIC TECHNIQUES FOR LONGITUDINAL ELECTRON BUNCH DIAGNOSTICS

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Abstract

Electro-optic techniques are becoming increasingly important in ultrafast electron bunch longitudinal diagnostics and have been successfully implemented at various accelerator laboratories. The longitudinal bunch shape is directly obtained from a single-shot, non-intrusive measurement of the temporal electric field profile of the bunch. Furthermore, the same electro-optic techniques can be used to measure the temporal profile of terahertz / far-infrared optical pulses generated by a CTR screen, at a bending magnet (CSR), or by an FEL. This contribution summarizes the results obtained at FELIX and FLASH.

INTRODUCTION

Single shot electro-optic detection techniques have been successfully applied in electron-beam diagnostics. The longitudinal bunch profile of a single electron bunch can be determined in real-time by detecting its Coulomb field in an electro-optic crystal with a short optical laser pulse. The electro-optic method is not only single-shot and real-time, but also non-destructive and non-intrusive. For example, electro-optic measurements at the soft x-ray free electron laser FLASH show that the SASE process is not influenced by the bunch profile measurements [1].

The same electro-optic detection techniques have been used to measure the electric field profile of far-infrared optical pulses generated by a coherent transition radiation screen, a bending magnet, or by an FEL [2, 3].

This paper summarizes the results obtained at two rather different FEL facilities. FELIX produces picosecond electron bunches with an energy up to 50 MeV for the generation of FEL light in the range of 3-250 μm. The shortest bunches that have been observed are 650 fs FWHM (275 fs rms) [4]. FLASH produces bunches with an energy up to a GeV which are an order of magnitude shorter than those at FELIX, and are used to generate light with a wavelength down to 6 nm. The shortest electro-optic signals observed at FLASH have a width of 60 fs rms [1].

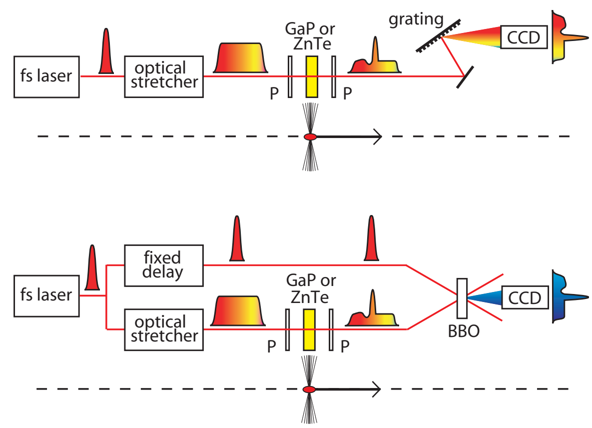

Figure 1: (color) Single-shot techniques for measuring the longitudinal electric field profile of single electron bunches using electro-optic encoding with spectral decoding (top) and temporal decoding (bottom).

PRINCIPLE OF SINGLE-SHOT ELECTRO-OPTIC DETECTION

For electron bunches, the electro-optic detection method makes use of the fact that the electric field of a highly relativistic electron bunch is almost entirely concentrated in a plane perpendicular to its direction of motion. An electro-optic crystal is placed inside the accelerator beam pipe close to the electron beam. Two methods for single-shot electro-optic detection of the electric field profile of single electron bunches are schematically depicted in Fig. 1 [5]. The time structure of the electric field of the bunch is electro-optically encoded onto a chirped laser pulse. The longitudinal electric field profile of the electron bunch is then obtained from the encoded optical pulse by a single-shot measurement of its spectrum (spectral decoding) [6] or by a single-shot cross correlation with a ultra-short laser pulse using a second-harmonic BBO crystal (temporal decoding) [4].

Details of the experimental setups can be found in the literature. Spectral decoding is described in references [4, 6] (FELIX) and [7] (FLASH). Temporal decoding is described in references [4] (FELIX) and [1, 7] (FLASH).

Both decoding techniques have their advantages and disadvantages. Spectral decoding needs a less powerful laser system and is easier to set up, while temporal decoding offers an intrinsically superior temporal resolution.

In order to measure the electric field profile of far-infrared (or THz) optical pulses, the same detection schemes can be applied. The optical pulse (CTR, CSR or FEL) is transferred to the electro-optic crystal by a suitable beamline. Both the far-infrared pulse and the probe laser pulse are focussed onto an electro-optic crystal in order to enhance the electro-optic effect. See references [2] (FELIX) and [3] (FLASH) for details.

ELECTRON BUNCH MEASUREMENTS

Figure 2 shows two electro-optic signals from single electron bunches recorded at FELIX (top) and FLASH (bottom). The electro-optic temporal decoding technique (see lower panel of Fig. 1) was used to record both traces since it has an intrinsically superior temporal resolution [4]. The Ti:Sa laser system, the grating stretcher for creating the chirped probe pulse, and the cross-correlator are identical for both measurements. The imaging optics for the 400 nm second harmonic light from the BBO crystal and the intensified CCD camera are different, which explains the large difference in the time windows. Measurements were performed in the so-called crossed polarizer regime. This means that no background signal is observed in the absence of the electron bunch. As a result, the electro-optic signal scales quadratically with the electric field strength [1, 7]. A crucial difference between the FELIX and FLASH measurements is the electro-optic crystal. For FELIX, a 500 μm thick ZnTe crystal was used, while for FLASH a 100 μm thick GaP crystal was used. The choice of the crystal is very important [1, 4, 9]. In summary, (i) the electro-optic response for ZnTe crystals is larger than that for GaP crystal, (ii) thick crystals give more signal than thin crystals, (iii) GaP crystals provide a better temporal resolution than ZnTe crystals, and (iv) thin crystals have a better time resolution than thick crystals. These rules of thumb show that one has to match the electro-optic crystal to the application. Bunches at FELIX are ‘long’, which allows the use of rather thick ZnTe crystals. Bunches at FLASH are short, which forces the use of thin GaP crystals, resulting in a poorer signal-to-noise ratio.

While the electro-optic signal of the measurements shown in figure 2 scales quadratically with the electric field strength, the linear regime is accessible as well by using the proper settings of the polarizer [1, 6, 7]. In the linear regime, the shortest electro-optic signals observed at FLASH have widths of 60 fs rms and were obtained by using a 65 μm thick GaP crystal [1]. Simultaneous measurements using a radiofrequency transverse deflecting structure [10] located adjacent to the electro-optic experiment at FLASH, show that the electro-optic electron bunch profile is slightly broader as a result of the electro-optic response of the 65 μm GaP crystal [1].

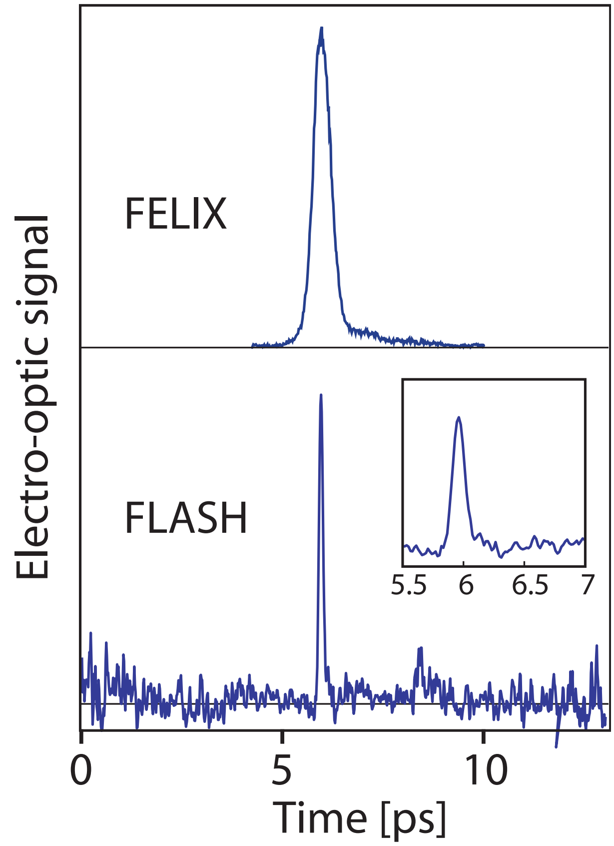

Figure 2: (color) Single-shot electro-optic bunch profile measurements recorded at FELIX (top) and FLASH (bottom). See text for details.

For optimum performance, the selection of the electro-optic crystal and the single-shot electro-optic detection scheme (Figure 1) should be matched to the application. The selection of the detection scheme is discussed in more detail in the paper by Jamison et al. [8], where a detailed comparison between spectral and temporal decoding is provided. For long bunches, spectral decoding and temporal decoding provide identical profiles. Spectral decoding is known to fail to reproduce short bunch profiles accurately, and the limiting bunch length, being defined as the length for which the measured bunch shapes are independent of the decoding method used, depends on the experimental parameters such as the electro-optic crystal and the durations of the laser pulses. For common experimental parameters, this limit is around a picosecond [8].

COHERENT RADIATION MEASUREMENTS

The electro-optic detection techniques are also suitable for measuring the temporal profile of the electric field of far-infrared (or THz) coherent radiation. While a measurement of the spectrum of the coherent radiation can be utilized for bunch duration measurements, there is an intrinsic problem in determining the bunch profile unambiguously

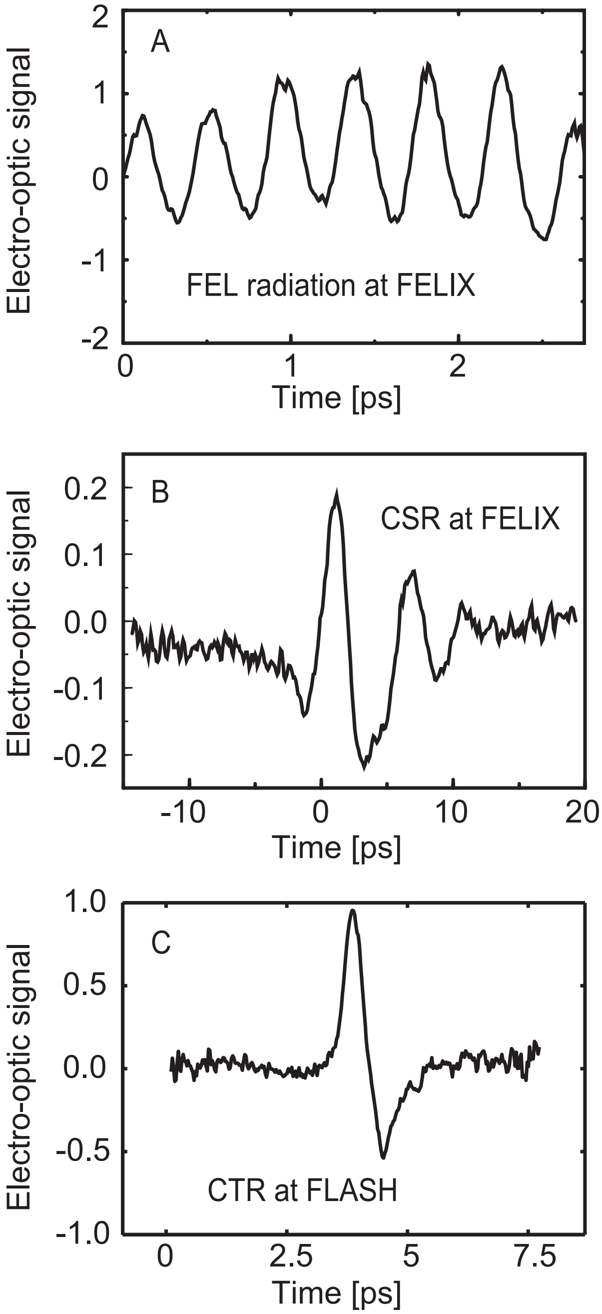

Figure 3: Single-shot electro-optic measurements of (A) FEL radiation, (B) CSR radiation and (C) CTR radiation. The leading edges of the pulses are on the left. Note the different time scales. See text for details.

due to the lack of spectral phase information. A direct measurement of the temporal profile of the coherent radiation avoids this ambiguity.

Single-shot electro-optic measurements of FEL radiation, coherent synchrotron radiation and coherent transition radiation are shown in Figure 3. In general, the coherent radiation and the probe laser beam are spatially and colinearly overlapped with an ITO coated glass plate acting as a THz dichroic mirror. A parabolic mirror is used to focus the THz pulse and the probe pulse onto the electro-optic crystal. The THz induced optical retardation is then measured using spectral decoding or temporal decoding.

The FEL pulse of Fig. 3A was measured at FELIX. Only part of the pulse is displayed. The full micro-pulse has an energy of 1 μJ and a length of around 30 cycles. The wavelength of this quasi-monochromatic FEL radiation was 130 μm, and one cycle therefore corresponds to 430 fs. This particular measurement was performed with a ZnTe crystal and temporal decoding as the detection scheme. Similar measurements have been performed using GaP crystals and spectral decoding. As the FEL radiation is transported to the laser laboratory via a beam line, these experiments can be performed outside the accelerator area. At FELIX, the FEL experiments have been primarily used for testing the electro-optic setup and practising the experimental procedures.

A measurement of a coherent synchrotron radiation (CSR) pulse is shown in Fig. 3B. The measurements was performed at FELIX, using electro-optic spectral decoding, about one meter distance from a bending magnet. The CSR radiation is coupled out of the beamline through a crystalline quartz window, collected and focussed onto a ZnTe crystal (see also Ref. [2]). Note that in these experiments, only the electro-optic crystal need be close to the accelerator. The stretched probe pulse can be sent from a remote laser system and, after passing through the electro-optic crystal, the pulse can be coupled into a fibre connected to a remote single-shot spectrometer.

The measurement of the coherent transition radiation (CTR) pulse shown in Fig. 3C were performed at FLASH. The CTR was generated from single bunches kicked to an off-axis screen. A diamond window was used to couple the radiation into the THz transfer line. There the radiation was coupled out via a crystalline quartz window and focussed onto a ZnTe crystal. Electro-optic spectral decoding was used as detection technique. For more details see Ref. [3]. Work is in progress to perform single-shot measurements directly in vacuum (avoiding the quartz exit window) and using a GaP crystal and temporal decoding to improve the temporal resolution.

SUMMARY

A short overview on the possibilities of electro-optic detection techniques in accelerator science has been provided by highlighting applications at FELIX and FLASH. The single-shot detection techniques provide the temporal profiles of electron bunches or coherent radiation pulses in real-time. Up to now, the shortest temporal profiles have been observed at FLASH, where 60 fs rms electric field profiles of electron bunches have been recorded.

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