CHIRPED-LASER BASED ELECTRON BUNCH LENGTH MONITOR

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Abstract

An electron bunch length monitor will be discussed which is based on the birefringence induced by the Coulomb field of the bunch in an electro-optically active crystal that is placed in close proximity of the beam. This birefringence is used to change the polarization of an external laser probe pulse. Measurements, performed at the FELIX facility, both in sampling mode (where the 1 GHz micropulse repetition rate of the accelerator was used) and in single-shot mode, will be described. In the latter case, the laser pulse is stretched and chirped, which allows the longitudinal bunch profile to be encoded on its spectral content. Issues related to the (sub-picosecond) time resolution will be discussed.

INTRODUCTION

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 makes an electro-optic crystal placed in the vicinity of the beam birefringent. The amount of birefringence depends on the strength of the electric field and is probed by monitoring the change of polarization of the light from a short pulse laser system.

At the Free Electron Laser for Infrared eXperiments (FELIX) [1] the electro-optic detection technique has been used to measure the electron bunch shape inside the accelerator beam pipe at the entrance of the undulator of the FEL [2, 3]. In this paper we describe two methods, which differ in the way the electric field induced birefringence is detected.

In the first method, the "delay-scan method" [2], a short laser pulse (shorter than the duration of the electron bunch) is used to sample the amount of birefringence. The delay between probe laser pulse and electron bunch is swept, and the intensity of the light transmitted through a crossed polarizer (analyzer) is measured as a function of delay.

In the second method, the "chirped-pulse spectrometer method" [3], a short probe pulsed is stretched into a pulse with a linear chirp and with a length longer than that of the electron bunch. In a linearly chirped pulse the instantaneous wavelength is proportional to time. When the electric field of an electron bunch and the chirped optical pulse copropagate in the electro-optic crystal, the various wavelength components of the chirped pulse passing through the crystal obtain different phase retardations, corresponding to different portions of the local electric field. By placing the crystal between crossed polarizers, the phase retardation in the wavelength spectrum is converted into an intensity modulation of this spectrum. Thus, the time profile of the local electric field of the electron bunch is linearly encoded on the wavelength spectrum of the optical probe beam. This wavelength spectrum is recorded single-shot with a linear diode array or a CCD camera after dispersing the optical pulse by a grating.

The electro-optic detection technique has been used in other laboratories as well. For example, Fitch et al. [4] have used the delay-scan method to measure the wake fields in the Fermilab high-brightness photo-injector (charge per bunch: 12 nC, bunch length 4.2 ps). They used a $LiTaO_3$ crystal as sensor which was oriented in such a way that they were able to probe longitudinal and radial components of the electric field. The measurements were related to the wall impedance.

Srinivasan-Rao et al. [5] proposed a method to encode the electron bunch profile on the *spatial* intensity distribution of the probe laser pulse. In this method the probe laser pulse is focused to form a line focus which is parallel to the direction of the electron beam. A thin electro-optic crystal is positioned at the waist of the laser beam which is directly below the electron beam. The intensity of the light trans-

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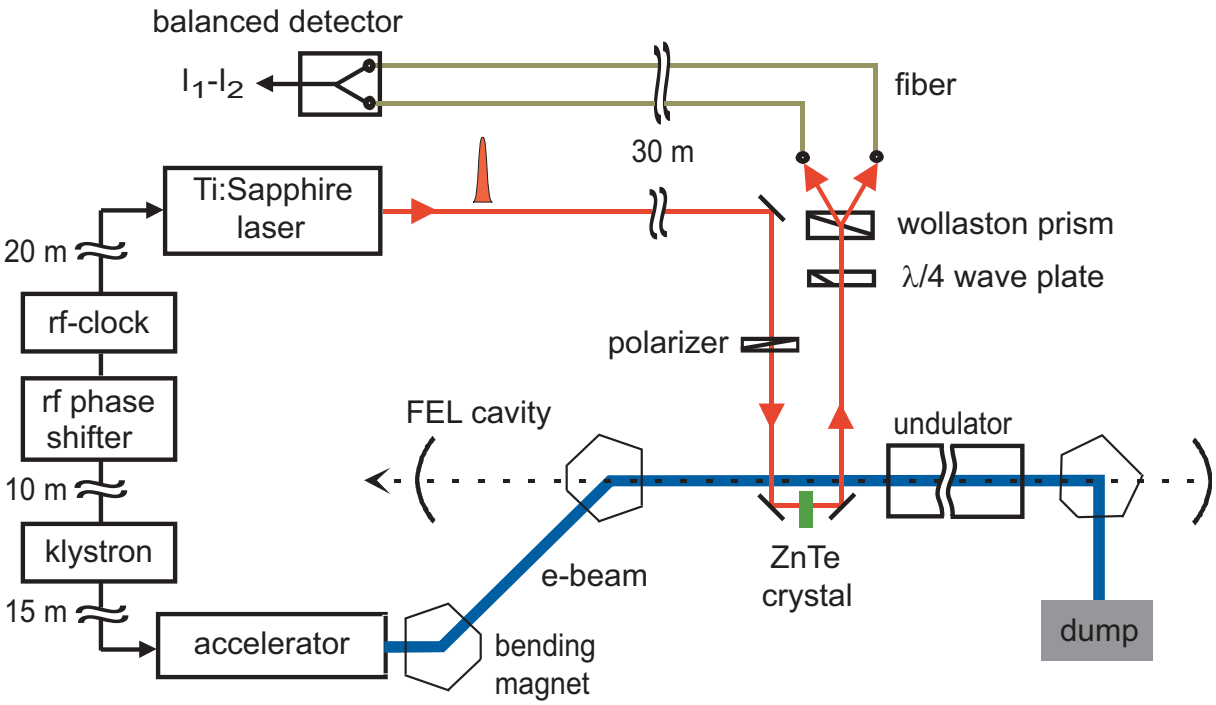

Figure 1: Experimental setup of the electro-optic "delay-scan method".

mitted by the crystal and a crossed analyzer is detected by a linear array. This spatially resolved intensity distribution is a measure of the temporal distribution of the charge in the electron beam. Measurements have not yet been reported.

THE ELECTRO-OPTIC CRYSTAL IN THE FELIX BEAMLINE

At FELIX, the electron bunch shape is measured inside the accelerator beam pipe at the entrance of the undulator. A 0.5 mm thick <110> ZnTe crystal is used as an electro-optic sensor and is placed with is 4×4 mm^2 front face perpendicular to the propagation direction of the electron beam (Figure 1). The probe laser beam is linearly polarized and passes through the ZnTe crystal parallel to the electron beam. A photograph of the part of the beamline containing the ZnTe crystal is shown in Figure 2. A small optical table is attached to the wall of the accelerator hall. It contains the last steering mirror to bring the laser beam from the laser room to the ZnTe crystal, a polarizer, the mirror which picks up the laser beam comming back from the crystal, the analyzer (in Fig. 1 this is a $\lambda/4$ waveplate / Wollaston prism combination), and fibers which bring the laser pulse back to laser room where the detection system is located. The laser beam enters and leaves the vacuum pipe through the same window. On the other side of the electron beam, the ZnTe crystal and two small mirrors are mounted on a translation stage.

The choice of the material and size of the crystal depends on many things. The phase retardation experienced by the probe laser passing through an electro-optic crystal is proportional to the length of the crystal, the electro-optic coefficient (of the order of pm/V) and the local electric field. The actual expression for the phase retardation depends on the orientation of the crystal with respect to the direction of the electric field and the polarization of the probe laser, and can be found in literature (see e.g. [6]). At a first glance the ideal crystal would be a long crystal with a high electro-optic coefficient. There are however a few limitations due to absorption and dispersion of the various frequency components of the electric field and probe

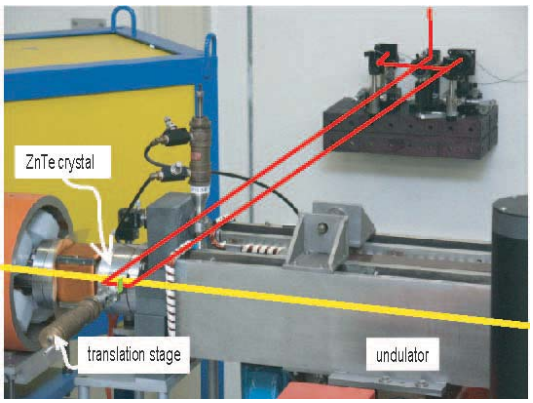

Figure 2: Photograph of the section of the electron beampipe containing the electro-optic crystal ZnTe. A small optical table is attached to the wall. The yellow and red lines indicate the electron beam and laser beam, respectively. The ZnTe crystal (in green) is mounted on a translation stage.

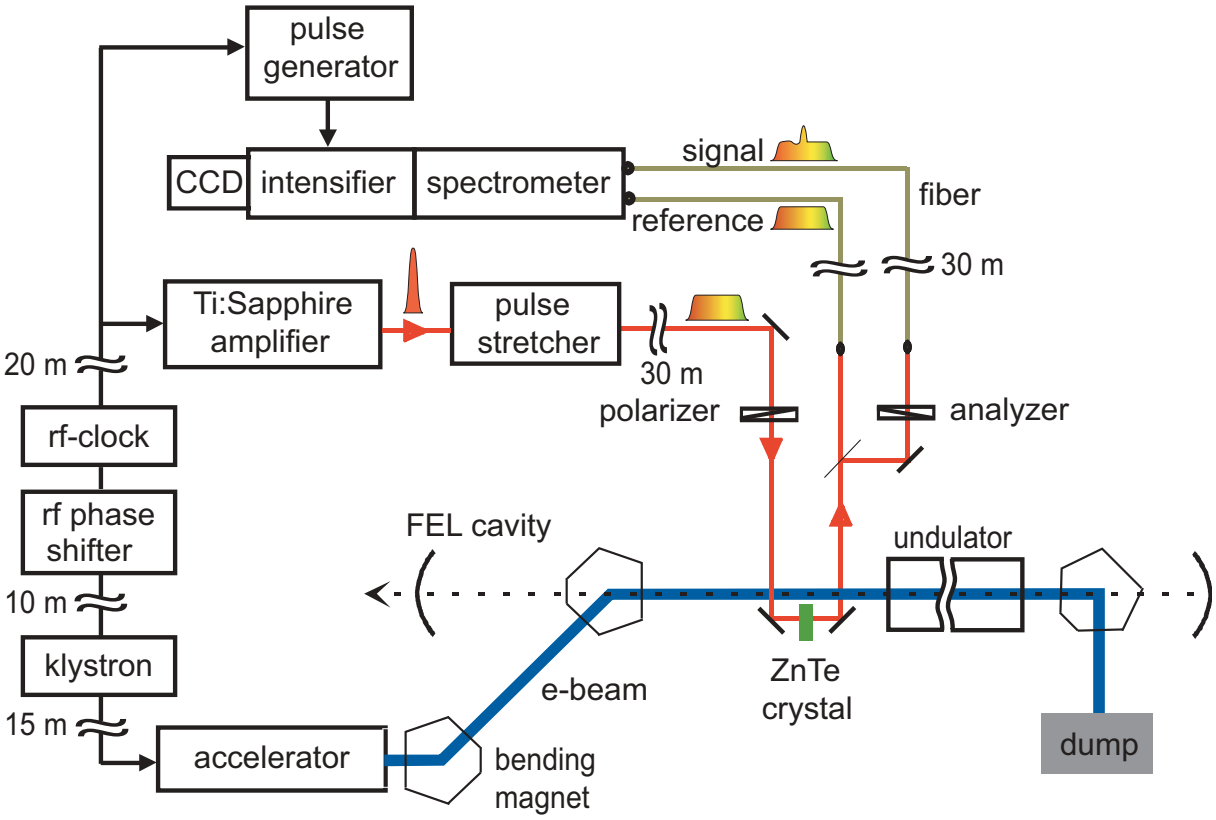

Figure 3: Experimental setup of the electro-optic "chirped pulse spectrometer method" for measuring single-shot images of the electric field profiles of individual electron bunches.

laser in the crystal (see also [7]). In ZnTe the velocity of a 800 nm probe pulse is identical to that of the 2.3 THz frequency component of the electric field; other frequency components of the electric field have different velocities, which means that the measured electric field profile will be distorted if the crystal is too long. Absorptions in the crystal lead to a distortion of the measured beam profile as well; ZnTe, for example, has a strong phonon absorption at 5.3 THz, limiting the temporal resolution to about 200 fs. These absorptions can be modeled and it has been shown that ZnTe crystals can be used to measure frequencies up to 37 THz [8]. Electro-optic sampling is a technique which originates from THz-science, and many details of this technique (crystal choice, measurement techniques, modeling, etc.) can be found in the literature.

DELAY-SCAN METHOD

The probe laser for the "delay-scan method" is a femtosecond Ti:Sapphire laser (wavelength 800 nm, pulse energy 5 nJ, repetition rate 100 MHz, pulse length 15 fs) which is actively synchronized to the accelerator rf clock [9] (see Figure 1). The delay between optical pulses and the electron bunches (beam energy 46 MeV, bunch charge 200 pC, micropulse repetition rate 25 MHz or 1 GHz, bunch length $\sim$1.5 ps) can be varied with a phase shifter. This rf-phase shifter can sweep the probe laser pulses over the electron bunches with a rate of a few picoseconds per microsecond. Since there is an electron bunch every 1 or 40 ns and a probe pulse every 10 ns, this means that the complete electric field profile is measured in a few microseconds. This delay-scan method can therefore be used for real-time monitoring, although the measured profile is sampled from a few hundred individual electron bunches. A balanced detection arrangement was used instead of a crossed-polarizer detection setup in order to increase the signal-to-noise ratio. Electric field profiles of electron bunches with a FWHM of 1.7 ps have been measured by limiting the delay-scan to about 10 ps [2]. Longer

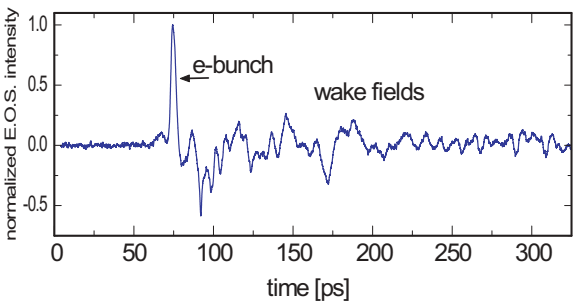

Figure 4: The electric field profile of the electron bunch measured at the entrance of the undulator. The leading edge is on the left.

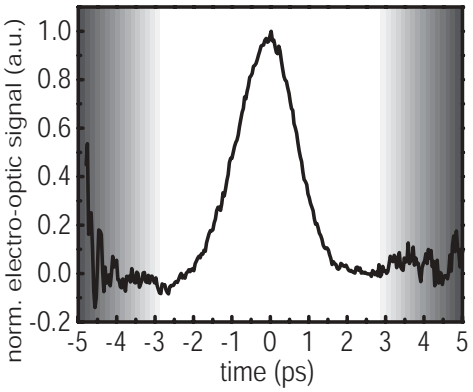

Figure 5: Single-shot measurement of the electric field profile of an individual electron bunch. The leading edge is on the right. The pulse length is about 1.7 ps FWHM. The shaded areas indicate the regions of increased noise introduced by the correction for the wavelength dependent variations in the intensity of the spectrum.

delay scans, of a few hundred picoseconds, have been made as well; these electric profiles show the effects of wake fields after the electron bunch. Figure 4 shows a typical measurement.

CHIRPED PULSE SPECTROMETER METHOD

The probe laser for the "chirped-pulse spectrometer method" is 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 [10]. Laser pulses are linearly chirped in an optical stretcher [3]. The length of the pulse can easily be varied over a range of 30 fs to 20 ps with a single translation stage. The chirped beam leaving the beampipe is split into a signal beam and a reference beam that is used to monitor possible laser fluctuations (see Figure 3). The signal beam passes through an analyzer (a second polarizer) which is (nearly) crossed with respect to the first polarizer. Subsequently, the spectra of the chirped laser pulses are dispersed with a grating spectrometer and the line spectra are focussed onto a CCD camera. The intensifier in front of the CCD camera acts as a shutter (minimum gate 10 ns).

Figure 5 shows a single shot image of the electric field profile of an individual electron bunch after on-line data processing (details on the data processing can be found in Ref. [3]). By increasing the chirp, a larger time window is obtained, which allows monitoring of the electron bunch and wake fields (see [3]).

TEMPORAL RESOLUTION

The time resolution of the two electro-optic methods is determined by:

- the material and the length of the electro-optic crystal. The cut off for our 0.5 mm crystal is around 350 fs [11]; thus electron bunches shorter than 350 fs are broadened and/or distorted. Higher resolution can be obtained with a thinner crystal.

- the distance R from the electron beam to the electro-optic crystal, $\Delta t_d \approx 2R/\gamma c$ [12]. For our "delay-scan method" this is $\Delta t_d \approx 400$ fs for R=6 mm and γ=90, and for our "chirped-pulse spectrometer method" this is $\Delta t_d \approx 70$ fs for R=1 mm and γ=90.

- the length of the probe laser pulse, τ_0. In our "delay-scan method" τ_0=15 fs. For the "chirped-pulse spectrometer method" the length of the chirp τ_c plays a role as well. For bunch lengths shorter than $(\tau_0\tau_c)^{1/2}$ the measured profile will be broadened and/or distorted [13, 14]. In our case τ_0=30 fs and τ_c=4.48 ps, which gives $(\tau_0\tau_c)^{1/2}$ ≈370 fs while the bunch length is ≈1.5 ps. The broadening is expected to be less than 100 fs.

- time jitter in the synchronization of the probe pulse to the electron bunch. In our case 50 fs in a few microseconds, on longer time scales 400 fs. In the single-shot measurement in Figure 5 time-jitter can be neglected since the profile has been recorded in about 10 ps (more about the synchronization can be found below).

- resolution of the spectrometer and diode array in the case of the "chirped-pulse spectrometer method". In our case this was about 300 fs. This can easily be improved by using a better spectrometer with a larger diode array.

SYNCHRONIZATION

For the study of very short electron bunches, the synchronization between the electron bunches and the probe laser pulses becomes more important. For the "delay-scan method" this is obvious, since time-jitter gives a broadening of the observed electric field profile. But also for the single-shot "chirped-pulse spectrometer method" the time-jitter is of great concern, although it does not give rise to a broadening of the profile. Let us consider an example: suppose we have an electron bunch of 100 fs, a very high resolution-spectrometer/diode array combination, a very thin ZnTe crystal and a short distance between electron beam and crystal. With a 15 fs laser, a time-window of about 170 fs is needed (thus $(\tau_0\tau_c)^{1/2}$ ≈50 fs). If the jitter in the synchronization is on the order of 100 fs, the electric field profile would frequently lie partially outside the time window.

In our case the jitter is about 50 fs on a microsecond time scale, but 400 fs on a longer time scale. This jitter has been measured by cross correlating the FEL output with the optical pulse (see Ref. [9]; and qualitatively confirmed by our electron bunch experiments). An interesting question is where the dominant part of the jitter is originating from,

since both the laser and the electron bunches (and thus the FEL radiation) are locked to same the rf-clock. Most probably, the jitter is caused by fluctuations in the voltage of the power supply feeding the klystron.

Synchronization of a modelocked Ti:Sapphire laser, which is used to drive a photocathode, to a 3 GHz RF oscillator with a jitter of less than 29 fs has been reported [15]. But how well do the electron bunches remain synchronized to the laser after they have passed devices such as bunchers and accelerators?

FUTURE

It has been shown experimentally, by Jamison et al. [14], in the "chirped pulse spectrometer" detection of so-called optical half cycle pulses, that the measured profile is distorted and broadened when the duration of the electric field is larger than $(\tau_0\tau_c)^{1/2}$. This effect is caused by interference between spectral components of the modulation (induced by the electric field) and the spectral components of the chirped pulse [13, 14]. A way to circumvent these problems is to measure the chirped pulse in the time-domain, which can be done with a (single-shot) cross-correlator.

At the moment of writing this contribution, the first test measurements have been performed with a "chirped pulse cross-correlator" set-up at FELIX although we have not yet obtained a single shot cross-correlation measurement of the electron bunch. It is clear that the optical alignment of a cross-correlator is more complex than the alignment of a spectrometer. Other related methods have been proposed such as auto-correlation and Frequency Resolved Optical Gating (FROG) measurements [16].

CONCLUSION

Electro-optic sampling of the Coulomb field of the electron bunch is a promising method for real-time monitoring of the electron bunches. The method is non-destructive (it does not intercept the electron beam) and non-intrusive (although it is expected that the modification of the beamline will slightly influence beam properties, this has not yet been investigated in detail). At FELIX we have measured the length and shape of individual relativistic electron bunches with a subpicosond time resolution.

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