SINGLE SHOT ELECTRON-BEAM BUNCH LENGTH MEASUREMENTS

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Abstract

It is recognised by the instrumentation community that 4th generation light sources (like TESLA, LCLS) pose some of the most stringent requirements on beam diagnostics. Of these diagnostics, electo-optic detection of the electric field of electron bunches offers a promising single-shot technique for the measurement of the bunch length and shape in the sub-picosecond 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 chirped, synchronized Ti:sapphire laser pulse. This paper will provide details of the experimental setup at the Free Electron Laser for Infrared eXperiments (FELIX) in Nieuwegein, The Netherlands, where single shot images of 1.7 ps long electron bunches have been obtained (beam energy 46 MeV, charge per bunch 200 pC). Future upgrading possibilities will be discussed.

INTRODUCTION

An on-going research project at the Free Electron Laser for Infrared eXperiments (FELIX) [1] is the development of methods to measure the longitudinal shape of electron bunches via electro-optic detection of their transverse electric field. The electron bunch shape is measured inside the accelerator beam pipe at the entrance of the undulator of the FEL. A 0.5 mm thick <110> ZnTe crystal is used as an electro-optic sensor and is placed with its $4\times4\,\mathrm{mm}^2$ front face perpendicular to the propagation direction of the electron beam. The probe laser beam is linearly polarized and passes through the ZnTe crystal parallel to the electron beam.

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This paper describes three methods to measure the shape of an electron bunch with electro-optic detection. The electric field-induced birefringence in an electro-optic crystal is probed by

1. sweeping the pulse of the probe laser, with a probe pulse length that is shorter than the electron bunch length, over the electron bunch and recording the intensity of the light transmitted through a the crossed polarizer (analyzer) as a function of time [2]. Although this is not a single-shot method, it can be used for real-time monitoring.

2. using a linearly chirped pulse of the probe laser, with a pulse length longer than the electron bunch length, and recording the wavelength spectrum of the chirped pulse which is transmitted through an analyzer [3].

3. using a chirped pulse of the probe laser, with a pulse length longer than the electron bunch length, and recording the single-shot cross-correlation of the chirped pulse transmitted through an analyzer. An unchirped pulse is used as the reference in the cross-correlator.

DELAY-SCAN METHOD

The probe laser for the "delay-scan method" (method 1) 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 [5] (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. A balanced detection arrangement was used instead of a crossed-polarizer detection setup in order to increase the signal-to-noise ratio. The laser room, containing the femtosecond laser system and the detection system, is located approximately 30 meters from the FEL cavity. The probe pulse is relayed by means of lenses and mirrors to direct the pulse towards the ZnTe crystal (fibers would stretch the probe pulse). More details on the setup can be found in Refs. [2, 4].

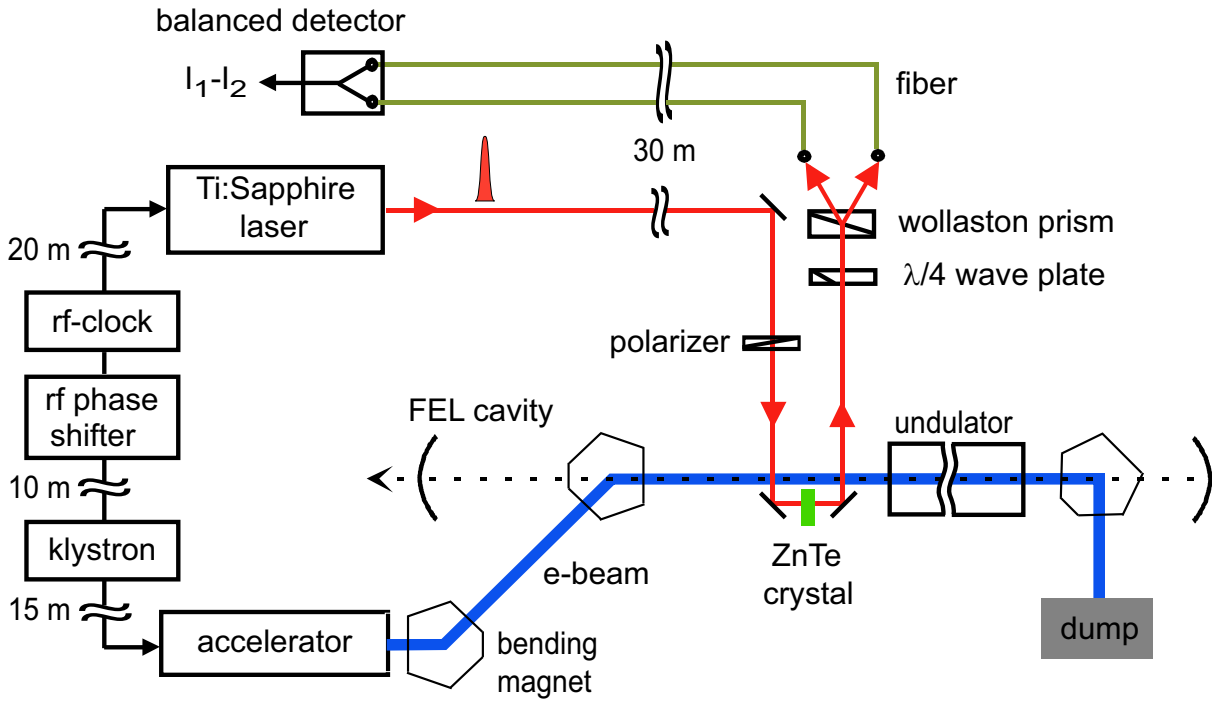

Figure 1: Experimental setup of the electro-optic "delay-scan method" (method 1).

Figure 2 shows a typical measurement. The 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.

The time resolution is determined by:

- the pulse length of the probe laser (in our case 15 fs);
- the time jitter in the synchronisation of the probe pulse to the electron bunch (in our case 50 fs in a few microseconds; on longer time scales 400 fs);

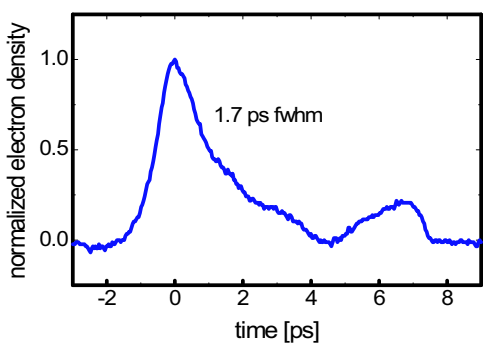

Figure 2: The electric field profile of the electron bunch measured at the entrance of the undulator. The leading edge is on the left. The pulse length is about 1.7 ps FWHM.

- the distance R from the electron beam to the electro-optic crystal, $\Delta t_d \approx 2R/\gamma c$ [6] (in our case $\Delta t_d \approx$ 0.4 ps for R=6 mm, γ=90);
- the material and the length of the electro-optic crystal, see below (the cut off for our 0.5 mm crystal is around 350 fs; thus electron bunches shorter than 350 fs are broadened and/or distorted).

WAVELENGTH DETECTION OF CHIRPED BEAM

In the "chirped-pulse spectrometer method" (method 2) a short probe pulse is stretched to 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 co propagate 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 onto the wavelength spectrum of the optical probe beam. This wavelength spectrum is dispersed in a spectrometer and recorded in a single shot with a linear diode array or a CCD camera (see Figure 3).

Figure 4 shows a single-shot image of the electric field profile of an individual electron bunch after on-line data

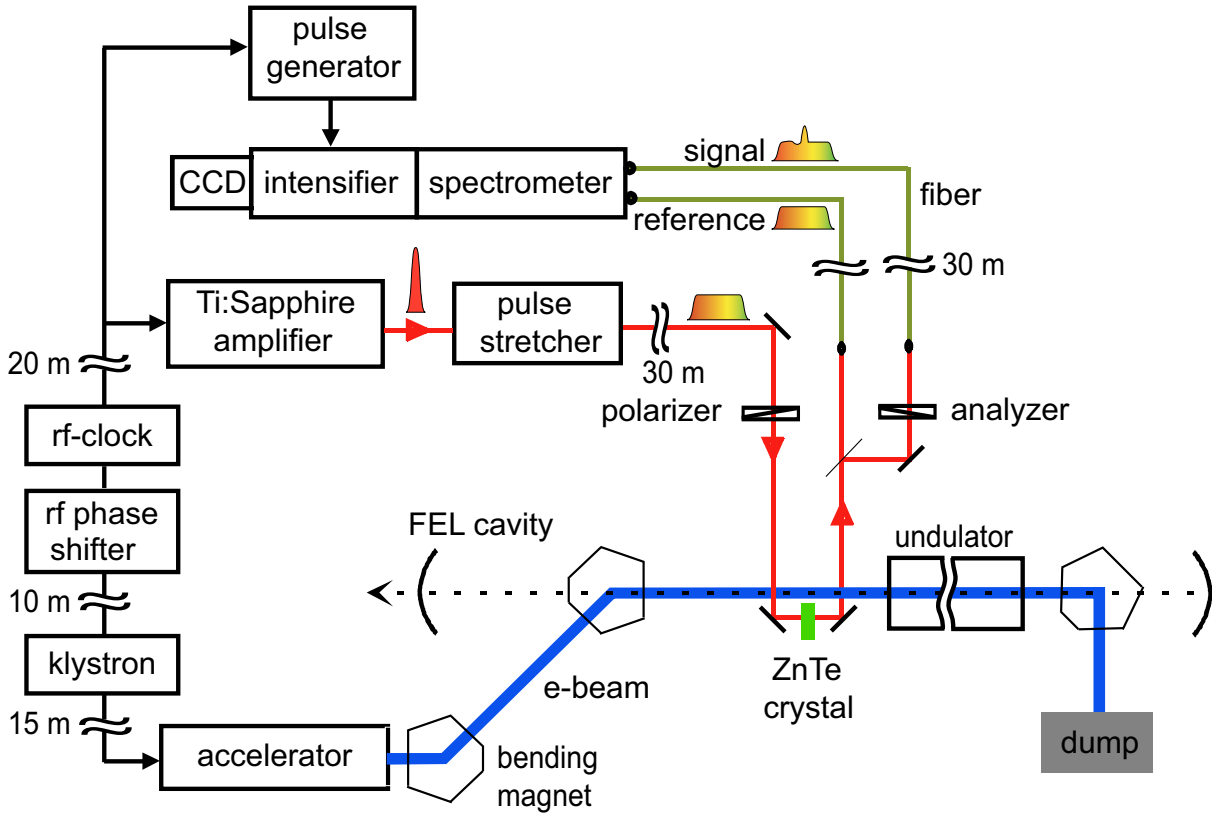

Figure 3: Experimental setup of the electro-optic "chirped pulse spectrometer method" for measuring single-shot images of the electric field profiles of individual electron bunches (method 2).

processing (details on the data processing can be found in Ref. [3]). The time resolution is determined by:

- the pulse length of the probe laser τ_0 and the length of the chirped pulse τ_c. For bunch lengths shorter than $(\tau_0\tau)^{1/2}$ the measured profile will be broadened and/or distorted (see below). In our case τ_0=30 fs and τ_c=4.48 ps, which gives $(\tau_0\tau)^{1/2}$ ≈370 fs while the bunch length is ≈1.5 ps. The broadening is expected to be less than 100 fs.

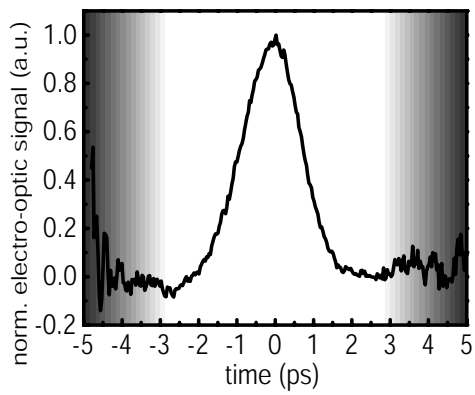

Figure 4: Single-shot measurement of the electric field profile of an individual electron bunch. The leading edge is on the right. The pulse length is about 1.7 ps FWHM. The shaded areas indicate the regions of increased noise introduced by the correction for the wavelength dependent variations in the intensity of the spectrum.

- the distance from the electron beam to the electro-optic crystal (in our case $\Delta t_d \approx 70$ fs for R=1 mm, γ=90);
- resolution of the spectrometer and diode array, in the present setup ≈300 fs.
- the material and the length of the electro-optic crystal, see below (the cut off for our 0.5 mm crystal is around 350 fs).

Since in our case the electron bunch length is on the order of 1.5 ps, the only improvements in resolution can come from an improvement of the spectrometer/diode-array setup, which can easily be done, and by replacing the crystal with a thinner one.

The time window in which the electron bunch is viewed can be changed as easily as the time scale of an oscilloscope, because the length of the chirped pulse may be altered simply by adjusting the optical path difference in the optical stretcher (which is controlled via one single translation stage). There is however an important limitation in increasing the length of the time-window due to

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 coupling introduces additional spectral modifications which cannot by themselves be distinguished from the desired spectral modulation. Experimentally this has been shown by Jamison et al. [7] in the chirped electro-optical detection of so-called optical half cycle pulses (see Fig. 5; theoretically this has been described by Fletcher [8] and more general by Jamison et al. [7]. Very generally, it can be concluded that there are no such problems if a time-window is chosen such that $(\tau_0 \tau_c)^{1/2}$ is smaller than the duration of the electron bunch.

CROSS-CORRELATION OF CHIRPED BEAM

The interference effects which can be present in the "chirped-pulse spectrometer method" appear because in the final step of this method the wavelength spectrum of the pulse is recorded. A way to circumvent these problems is to measure the chirped pulse in the time-domain, which is the third method: single-shot "chirped-pulse cross correlation". In this method the chirped pulse carrying 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. The results of such an experiment for a half-cycle pulse are shown in Fig. 5. At the moment of writing this contribution, the first test measurements have been performed on the cross-correlator set-up at FELIX and 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. Note that the cross-correlation method does not require a (linear) chirp of the probe pulse. Other related methods have been proposed such as auto-correlation and Frequency Resolved Optical Gating (FROG) measurements [9].

OTHER ELECTRO-OPTIC DETECTION VARIANTS FOR E-BEAM DIAGNOSTICS

Fitch et al. [10] 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. [11] 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

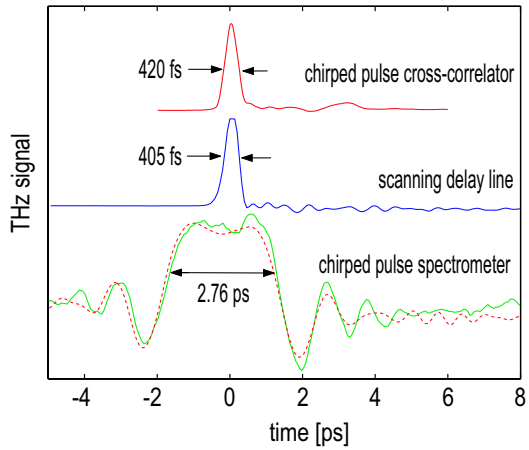

Figure 5: Electro-optic sampling of optical half cycle pulses. The length of the half cycle pulse is ≈300 fs, while the length of the probe laser pulse is ≈60 fs. The middle curve shows the result of the delay-scan method. The lower curve shows the result of the chirped-pulse spectrometer method, where the time-window (length of the chirped pulse) was 30 ps. If the time-window is too large compared to the length of the electric field, the signal is distorted. The dashed curve is a simulation [7]. The upper curve shows the result of the cross-correlator method, where the chirped pulse duration is also 30 ps.

is positioned at the waist of the laser beam which is directly below the electron beam. The intensity of the light transmitted 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. A difficulty in this experiment is the thickness of the crystal. A very thin crystal ($<30\mu$m) is needed because the directions of the electron beam and the probe laser beam are perpendicular to each other. Measurements have not yet been reported.

SOME NOTES ON ELECTRO-OPTIC CRYSTALS

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 (on 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. [12]). At a first glance the ideal crystal would be a long crystal with a high electro-optic coefficient. There are however a few limitations:

- Absorptions. It is clear that the crystal should be transparent for the probe laser, but the ideal crystal is transparent in a very broad THz spectral range as well. The ZnTe crystal has a strong transverse-optical phonon resonance at 5.3 THz, which means that components

of the electric field with a frequency higher than 5 THz (200 fs) are (partly) absorped which leads to a distortion of the measured electric field profile of the electron bunch. These absorptions can be modeled and it has been shown that ZnTe crystals can be used to measure frequencies up to 37 THz [13]. Other crystals might be even more suitable; GaP, for example, has a phonon absorption at 8.3 THz (115 fs).

- Dispersion. Two dispersion effects limit the length of the crystal: Group Velocity Mismatch (GVM) and Group Velocity Dispersion (GVD). Due to the wavelength dependence of the index of refraction (dispersion), the optical probe pulse and the electric field travel at a different velocity through the crystal. In the case of a long crystal, this means that the measured electric field profile will be smeared out. For ZnTe the group velocity of the 800 nm probe pulse is identical to that of the 2.3 THz frequency component of the electric field. The second effect, GVD, is a similar effect: the different frequency components of the electric field (but also of the probe laser) have different velocities in the crystal. It is clear that shorter optical pulses and shorter electron bunches require a thinner crystal.

Electro-optic sampling is a technique which originates from THz-science, and many details of this technique (crystal choice, measurement techniques, modelling, etc.) can be found in the literature.

An intriguing point is the effect of the difference in velocity of the electron bunch and the velocity of the electric field propagating through the crystal, which is lower by a factor of almost three. There has to be a region in the crystal where the field lines are not perpendicular to the propagation direction and are stretched over the length (thickness) of the crystal. However, there is still a one-to-one correspondence between the field and the electron density along the (narrow) probe laser path. A more detailed understanding of the progation of the Coulomb field through the crystal is desirable, although for practical purposes it should be sufficient to probe the electric field at a distance of d/n (d thickness of crystal, n refractive index) from the edge of the crystal.

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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