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

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Abstract

A combination of electro-optic detection of the Coulomb field of an electron bunch and single-shot cross-correlation of optical pulses, is used to provide single-shot measurements of the shape and length of sub-picosecond electron bunches. This so-called temporal decoding technique has been applied to the measurement of electron bunches at the Free Electron Laser for Infrared eXperiments (FELIX), where electric field profiles with a FWHM of 650 fs have been recorded. The measurement temporal resolution is limited primarily by the electro-optic crystal thickness and the relatively low energy of the electrons (50 MeV), and the bunch length is estimated to be around 635 fs. The single-shot electron bunch longitudinal profile measurement is real-time and non-destructive, and can therefore be used as an online diagnostic tool. The temporal decoding technique has also been used to measure the electric field profiles of single far-infrared laser pulses from the FELIX free electron laser.

INTRODUCTION

X-ray free electron lasers (FELs) require dense, relativistic electron bunches with bunch lengths significantly shorter than a picosecond. For operating and tuning these lasers, advanced electron bunch length monitors with sub-picosecond temporal resolution are essential. Ideally, non-destructive and non-intrusive monitoring of a *single* electron bunch should be available in real-time. A promising candidate for such monitors is the determination of the electron bunch longitudinal-profile via electro-optic (EO) detection of the co-propagating Coulomb field, an area subject to on-going research and development at the Free Electron Laser for Infrared eXperiments (FELIX) [1-7] and at other laboratories [8-12].

With the EO detection technique, the Coulomb electric field of the bunch induces birefringence in an EO crystal placed adjacent to the beam. The birefringence is determined through ellipsometry using a synchronized ultrafast Ti:sapphire (Ti:S) laser probe pulse. To enable a single-shot measurement, the Ti:S pulse is chirped to a duration exceeding the measurement window, and the induced birefringence is determined as a function of time within the probe pulse. In previously reported experiments, the timing was inferred from the wavelength-time relationship of the chirped probe pulse [2]. However, this spectral decoding method is intrinsically subject to limitations on the time resolution, and can introduce significant measurement artifacts [3, 13, 14, 15].

A recently demonstrated technique [5, 6, 13], which we refer to as temporal decoding, overcomes these limitations. The envelope of the probe pulse is measured directly in the time-domain, using single-shot second harmonic cross-correlation. In this contribution we report temporal decoding measurements of the longitudinal electric field of single electron bunches and of far-infrared FEL pulses.

ELECTRON BUNCH MEASUREMENTS

Measurements were performed on relativistic electron bunches (250 pC, 50 MeV) that are produced in the linear accelerator at the FELIX facility [16]. The electron bunch profile is measured inside the accelerator beam pipe at the exit of the undulator of the short wavelength IR FEL.

The setup is depicted schematically in Fig. 1. A near infrared 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 [17]. This pulse is split into a probe pulse and a reference pulse. The probe pulse is stretched to a length that is longer than the length of the electron bunch. Subsequently, the probe pulse is passed through an electro-optic crystal (ZnTe) that is placed between two crossed polarizers. In this way, the birefringence induced by the Coulomb field of a single co-propagating electron bunch is translated into an intensity modulation of the probe pulse. The temporal profile of this intensity modulation, and thus the temporal profile of the electric field of the electron bunch, is measured with a sub-50 fs resolution in a single-shot cross-correlator [13, 7] where the intensity modulated probe pulse is cross-correlated with the 30 fs reference pulse. The position dependent emission of the second harmonic light from the BBO crystal is imaged onto an intensified CCD camera.

Binning of the pixels of single-shot images along the direction perpendicular to the plane containing the probe and reference beams provides single-shot electron bunch mea-

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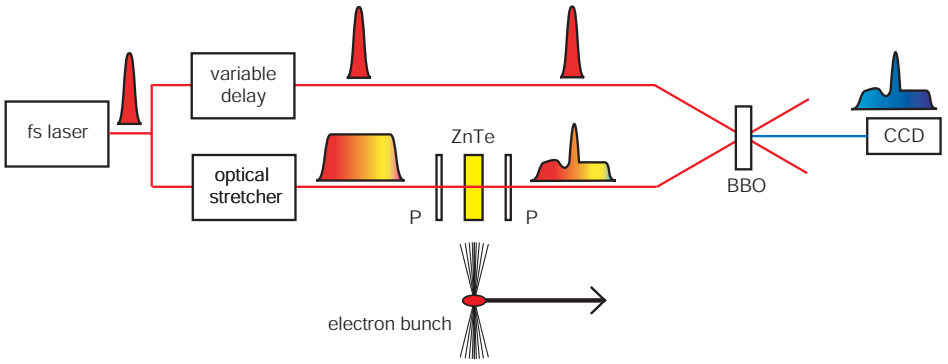

Figure 1: Scheme for single-shot measurements of the electric field profile of individual electron bunches. The electric field profile induces an intensity modulation onto a stretched optical pulse via the electro-optic effect. The electric field profile of the electron bunch is obtained with the temporal decoding method where the intensity modulated probe pulse is measured by a single-shot cross-correlation with an ultra-short optical pulse. For the experiments discussed here, the pair of polarizers P are crossed, with minimum transmission in the absence of the electron bunch.

surements. The position of the pixels in the parallel direction is proportional to time.

Examples of single-shot measurements are shown in the left hand panel of Fig. 2. As a result of the polarizer geometry used, the electro-optic signal scales quadratically with the electric field strength as has been experimentally verified (see Ref. [7] for more details). The traces shown in Fig. 2 correspond to electric field profiles with a FWHM of 650 to 700 fs, and have been recorded at the same settings of the accelerator. From the figure it is clear that the time jitter between the probe laser pulse and the electron bunch is of the order of the width of the electron bunch.

The right hand panel of Fig. 2 shows the temporal jitter of 108 electron bunches; the rms value is 390 fs. At FELIX, the timing jitter originates from the synchronisation of the probe laser pulses and the electron bunches to the rf clock. The former is determined by the quality of the active locking of the probe laser cavity round trip time to the rf clock. The latter is mainly determined by phase fluctuations of the klystron feeding the accelerator. Previous optical cross correlation measurements between 9 μm FEL radiation and the Ti:Sapphire laser at 800 nm in a 100 μm thick $AgGaS_2$ crystal showed a jitter of 400 fs rms [17], a value similar to that presently obtained with the electron bunch measurements.

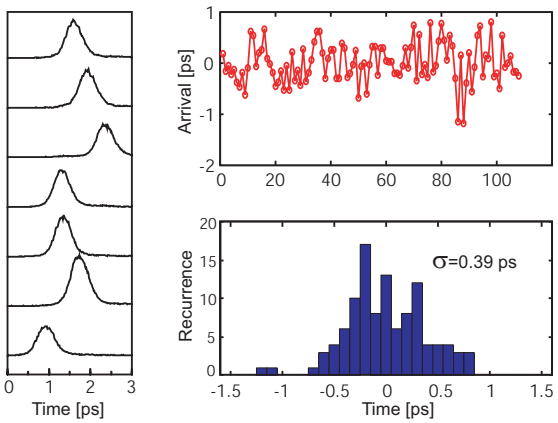

Figure 2: Left panel: a sequence of single shot electron bunch measurements. Right panel: a graph (top) and a histogram of the relative arrival time of 108 electron bunches. See text for further details.

For accelerators with a photo-injector, the laser which triggers the photo-cathode can be used for electro-optic detection of the electron bunches as well, which gives a method to directly monitor the time jitter introduced by bunchers and accelerators. The electro-optic detection method can also be used to produce accurate timing information (triggers) for user experiments.

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 [1]. 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 [3, 4, 18]. 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 contributions to the temporal resolution are present for all current electro-optic detection schemes. However, alternative EO materials, or deconvolution of material response in data analysis, both have potential for surpassing the material dependent limitations. An analogous single-shot auto-correlation technique routinely

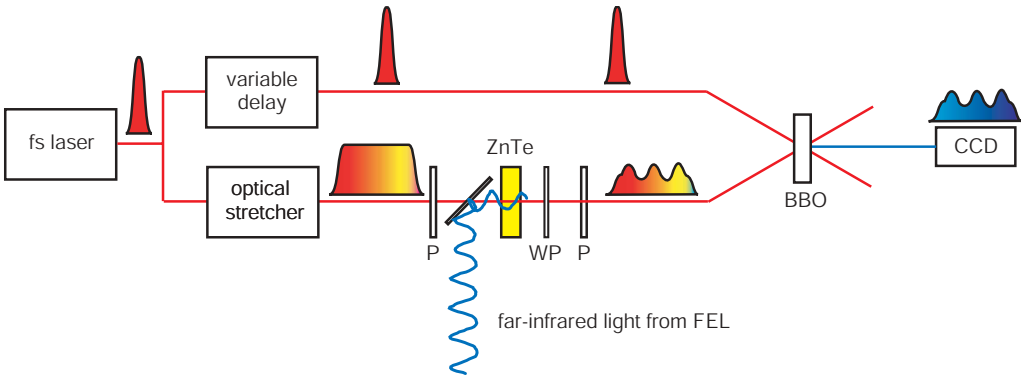

Figure 3: Scheme for single-shot measurements of the electric field profile of individual FEL optical pulses. The electric field profile induces an intensity modulation onto a stretched optical pulse via the electro-optic effect. The electric field profile of the FEL pulse is obtained with the temporal decoding method where where the intensity modulated probe pulse is measured by a single-shot cross-correlation with an ultra-short optical pulse. The polarizer (P) and quarter waveplate (WP) angles were varied according to specific experimental requirements.

characterises sub-50 fs optical pulses [19]. Ultimately, the time resolution is determined by the length of the reference optical pulse (30 fs).

FEL PULSE MEASUREMENTS

The output from a far-infrared FEL can be characterized with the electro-optic technique as well [20]. At a wavelength of 150 μm, a 20 ps long optical pulse consists of 40 optical cycles and is quasi-monochromatic. Since the timing jitter of the electron bunches ($\sim$400 fs, see Fig. 2) is of the same order of magnitude as the duration of one cycle of the far-infrared light, it is evident that one needs a single-shot detection technique to resolve the oscillating electric field.

Figure 3 shows the scheme for single-shot electro-optic detection with temporal decoding of the electric field of the FEL pulse. The laser system, the optical stretcher, and the cross-correlator are identical to those used in the electron bunch measurements. For the experiments described in this section, FELIX produces light at a wavelength of 130 μm at a macropulse repetition rate of 5 Hz. The micropulse repetition rate is 25 MHz, and the micropulse energy is about 1 μJ. The far-infrared laser beam and the 800 nm probe pulse are overlapped in space with an ITO coated glass plate acting as a far IR - optical dichroic mirror. Alternatively a gold coated mirror with a small hole for the probe pulse may be used to combine the two beams. A parabolic mirror with a focal length of 100 mm, not shown in the schematic diagram of Fig. 3, is used to focus the FEL pulse and the probe pulse onto the ZnTe electro-optical crystal.

The second harmonic light (400 nm) emerging from the BBO crystal is imaged onto an intensified CCD camera. The upper panel of Fig. 4 shows an image obtained by subtracting an image without the presence of an FEL pulse (background) from an image where an FEL pulse was present. The image shows a horizontal line because a cylindrical lens had been positioned in the probe pulse path, just before the BBO crystal. In the horizontal direction, the position in the image is proportional to time. The time axis can easily be calibrated since the duration of one cycle (one

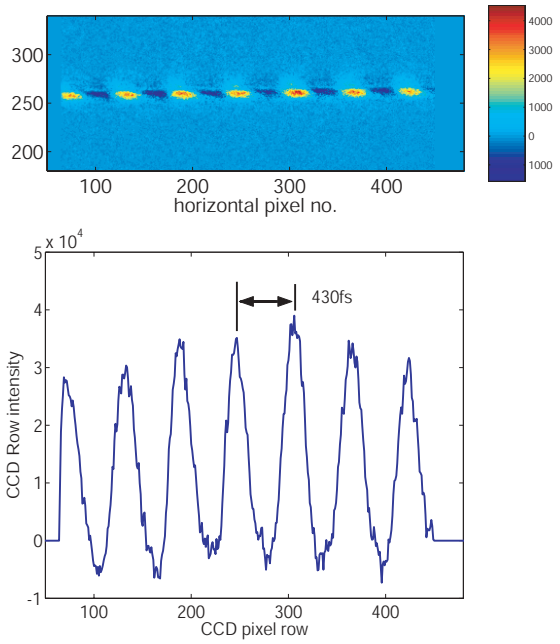

Figure 4: Electro-optic temporal decoding measurement of a quasi-monochromatic FEL pulse. The wavelength is 130 μm, and one cycle therefore corresponds to 430 fs. The image has been obtained by subtracting an image without the presence of an FEL pulse (background) from an image where an FEL pulse was present. The graph has been obtained by vertically binning the image.

oscillation of the electric field) is λ/c and the wavelength is known from the online spectrometer. By binning the image along the vertical direction, the electric field profile is obtained and is shown in the lower panel of Fig. 4.

The independently determined oscillating time structure of the FEL pulse measurements makes it attractive to use such FEL pulse measurements for the quantitative study of the capabilities of EO detection. At FELIX, we have used this approach to undertake initial experiments into alternative EO materials that may have the potential for improved time-resolution measurements. Furthermore, FEL measurements have been performed, outside the accelerator vault and with free access, to pre-align the cross-correlator and imaging setup before undertaking electron bunch measurements.

CONCLUSIONS

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-intercepting and non-destructive. It is largely non-intrusive, although it is expected that the modification of the beamline and induced wakefields will slightly influence beam properties. At FELIX we have measured femtosecond longitudinal electron bunch profiles using the new temporal decoding technique. The method has also been used to measure the electric field profile of the optical far-infrared FEL pulse, which is a convenient way to calibrate and test the experimental capabilities of the technique.

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