SPATIAL DECODING ELECTRO-OPTIC BUNCH MEASUREMENT AT TSINGHUA THOMSON SCATTERING X-RAY SOURCE*

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Abstract

Electron bunches with duration of sub-picosecond are essential in ultraviolet and X-ray free electron laser (XFEL) to reach the desired peak current. Electro-optic (EO) technique is suitable for temporal profile measurement of these ultrashort bunches which is one of the key diagnostics in FELs. An electro-optic monitor based on spatial sampling has recently been designed and installed for bunch profile diagnostic at Tsinghua Thomson scattering X-ray source (TTX). An ultrashort laser pulse is used to detect the field induced birefringence of the bunch Coulomb field in an electro-optic crystal and the monitor allows direct time-resolved single-shot measurement of bunch profile with an accuracy of 135 femtoseconds for a 40 MeV electron bunch in a non-destructive way, which can simultaneously record the relative time jitter between probe laser and electron bunch. This paper performs the layout of the setup and presents the current measurement results.

INTRODUCTION

Ultrashort relativistic electron bunches with high peak currents and duration of 100 fs or less are the key elements for X-ray free electron lasers, such as the Linac Coherent Light Source at SLAC and the European XFEL [1, 2]. Precise measurements with a high temporal resolution of the longitudinal profile including length and shape of an electron bunch are essential to confirm the beam quality. As a non-invasive measurement, the electro-optic detection technique with a resolution of sub-picosecond is a promising real-time profile monitor. Besides, it can simultaneously monitor beam arrival time between probe laser and electron bunch, which limits the temporal resolution of pump-probe technique and increases the jitter of photon yield in Thomson scattering X-ray source.

Single-shot EO measurement was first demonstrated in 2002 in the way of spectral decoding [3]. Several potential single-shot EO detection schemes were proposed and obtained exciting results [4-7]. All the EO methods share the same principle by detecting the field-induced birefringence of the bunch Coulomb field within an EO crystal. For a relativistic electron bunch, the Coulomb field distribution is almost equal to the longitudinal profile. We demonstrated the spatial decoding electro-optic detection in a non-destructive way for its relative simplicity of optics, high temporal resolution to the limits of EO crystal and pleasant application in arrival time measurement. In the spatial decoding detection, an ultrashort probe laser transfers across the crystal with an angle to the beam travel direction. Hence, the coulomb field at different moment modulates the corresponding section in the probe laser transverse profile. The longitudinal profile of Coulomb field is mapped to the space distribution of the laser and could be detected by a charge-couple device (CCD) camera. The maximum of relative phase retardation Γ of the probe laser passing through the crystal induced by the external field E_{ex} is given by [8]

$$\Gamma = \frac{2\pi d}{\lambda} n_0^3 r_{41} E_{ex}, \tag{1}$$

where d is the crystal thickness, λ is the wavelength of the probe laser, n_0 is the refractive index of the crystal at wavelength λ and r_{41} is the crystal electro-optic coefficient. In the crossed polarization setup where the vertically polarized component is detected after a horizontally polarized probe laser I_{laser} passing through the EO crystal, the laser intensity of signal $I_{\det}$ is given by [9]

$$I_{\det} = I_{laser} \sin^2\left(\frac{\Gamma}{2}\right) = I_{laser} \sin^2\left(\frac{\pi d}{\lambda} n_0^3 r_{41} E_{ex}\right). \tag{2}$$

For phase shift $\Gamma \ll 1$ the intensity is proportional to the square of bunch Coulomb field E_{ex}. The bunch charge profile can be obtained from the transverse intensity distribution of the laser pulse.

EXPERIMENTAL SETUP

Measurement was performed at Tsinghua Thomson scattering X-ray source [10]. A schematic drawing of the setup is shown in Fig. 1. The electron bunch is generated from a photocathode rf gun and exits the gun with energy of 4-5 MeV. The bunch is accelerated to approximately 40 MeV in a 3 m traveling wave accelerating section with a charge of 60 pC at a repetition rate of 10 Hz in the experimental situation. Length of the bunch is compressed by a magnetic chicane. The ultraviolet driven laser for the gun and the infrared probe laser for the EO detection are provided by two independent Ti:Sapphire laser systems. A

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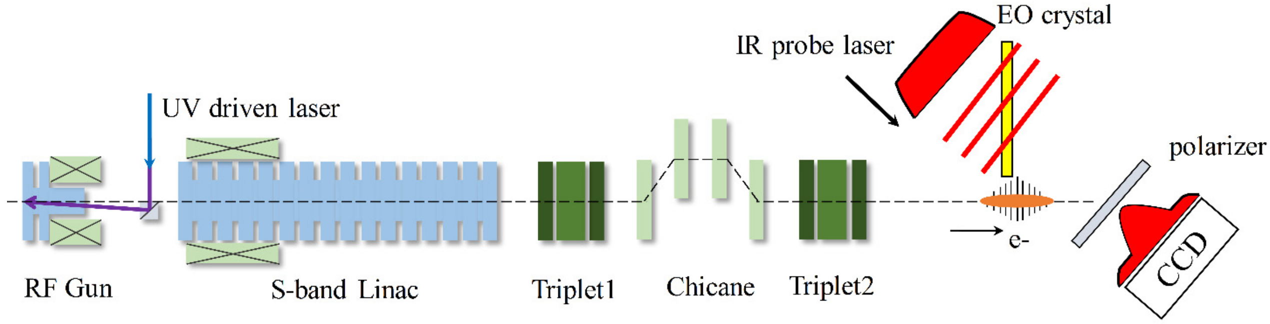

Figure 1: Schematic layout of the experimental setup.

more detailed description of the whole system can be found in Ref. [11,12]. The probe laser is compressed to 40 fs in a grating pair and is delivered to the crystal with an incidence angle of 40 degrees to the beam traveling direction. A zinc telluride (ZnTe) crystal with thickness of 0.3 mm is employed as the detection sensor, which is cut in [110] orientation plane with [-110] axis parallel to one marked edge. The EO signal is detected in a crossed polarizer setup and a quarter wave plate is placed before the polarizer to compensate the residual birefringence of the ZnTe crystal for crystal imperfection and mechanical stress.

Bunch Length Measurement

The typical single-shot spatial decoding electro-optic measurement result is shown in Fig. 2. Time calibration factor is obtained by changing the delay of probe laser and fitting the time delay to signal position. The signal shows a sharp leading spike following by a long decay tail which is in agreement with the actual distribution of an optimally compressed bunch. A Gaussian fit to the main peak excluding the long tail gives a signal width of 135 fs (rms).

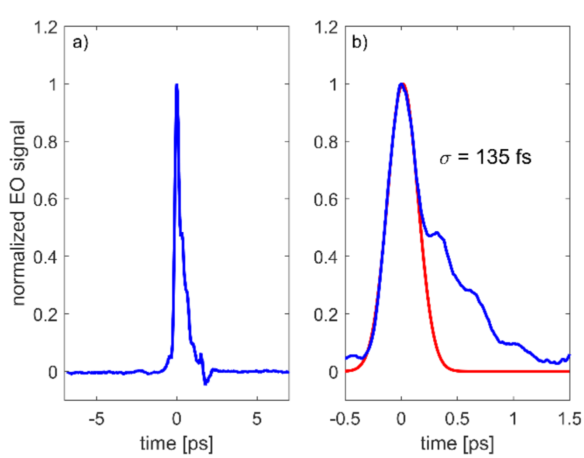

Figure 2: Single-shot spatial decoding EO bunch profile measurement. Head of the bunch is on the left. (a) EO signal on the whole time window of 14 ps. (b) Signal in expanding time scale, a Gaussian fit with $\sigma = 135$ fs to the main peak is plotted in red line.

Temporal resolution is limited by the length of probe laser, resolution of the imaging system, thickness of the ZnTe crystal and the distance between probe laser and electron bunch together with beam energy. In the current setup, the main limits are the response bandwidth of the EO crystal and the field broadening of low energy bunch with respect to charge density profile. As for 0.3 mm ZnTe, the upper limit of effective response frequency is ~3.75 THz corresponding to an rms bunch length of ~113 fs. The influence of distance (typically $D = 1$ mm) can be estimate by $2D/\gamma c \approx 83$ fs [13]. This was reproduced in the experiment.

Arrival Time Measurement

The spatial decoding EO setup is used to monitor the beam arrival time for its ability to measure the bunch profile in a single-shot and non-destructive way. The arrival time jitter discussed here is the time fluctuation of electron bunch relative to probe laser. Measurements of 5 consecutive bunches are presented in Fig. 3.

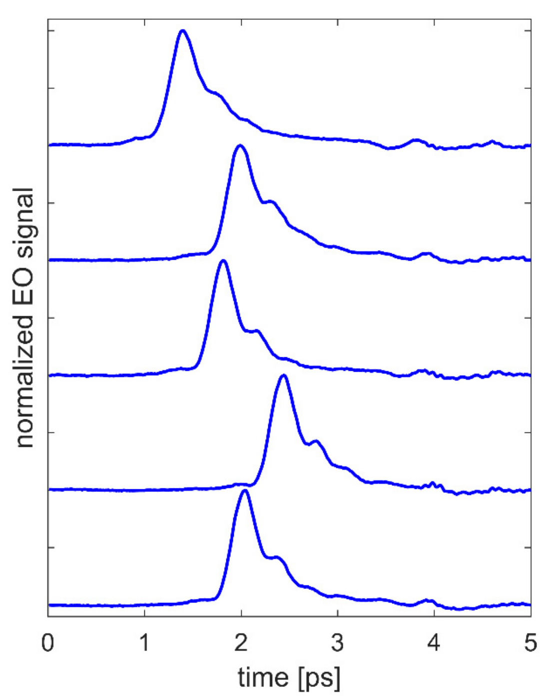

Figure 3: Profile measurements of 5 consecutive bunches.

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The position of EO signal in the probe laser profile varies from shot to shot as the fluctuation of arrival time. The time of peak position determined by a Gaussian fit to the main peak in the bunch profile is defined as the beam arrival time in our experiment. Measurement of the arrival time of compressed beam over 40 minutes is shown in Fig. 4. The entire time rms jitter is 589 fs including both the fast-term component and the slow drift. The slow drift plotted in solid red line is supposed to be introduced by the experimental environment. The period of slow drift is approximately 13.7 minutes which is in agreement with the temperature period of 13.2 minutes in the laser room. The variation of temperature would influence the working conditions of the two laser systems and the timing synchronization between laser oscillator and rf reference signal placed in the laser room. The rms jitter of fast-term component is 484 fs obtained by subtracting slow drift from the measured arrival time, seen in Fig. 5.

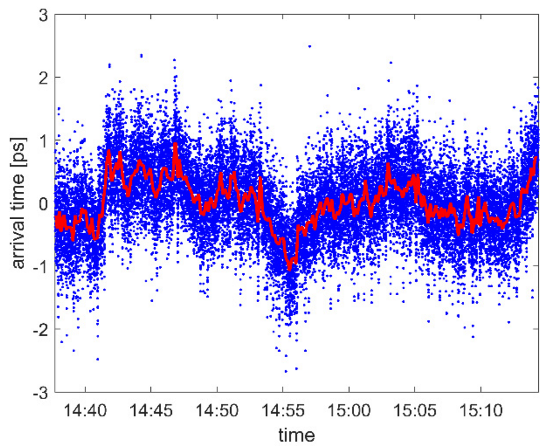

Figure 4: Beam arrival time measurement of compressed bunches over 40 minutes. The red line shows the slow drift.

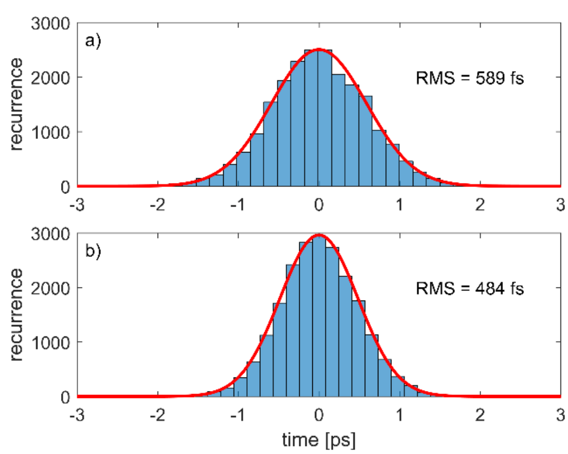

Figure 5: Arrival time histogram distribution. (a) Overall time jitter (data point in Fig. 4) with rms 589 fs. (b) fast-term component without slow drift, rms = 484 fs.

There are various sources contributing to the fast-term time jitter and the primary reason is the energy fluctuation for compressed bunch passing through the chicane under our experimental conditions. Energy jitter δ mainly caused by the amplitude and phase of the rf is approximately 0.3% and the parameter R_{56} of the magnetic chicane is about 40 mm. Thus, the arrival time jitter caused by energy fluctuation is approximately $R_{56}\delta = 400$ fs. Other sources include the synchronization jitter of the two laser oscillators to the reference rf signal. The synchronization accuracy of the UV driven laser and IR probe laser is approximately 100 fs and 200 fs, respectively. An online arrival time monitor with feedback control based on spatial electro-optic sampling is planned to be installed to remove the time jitter introduced by slow drift and increase the stability of photon yield in Thomson scattering experiment.

CONCLUSION

We have realized a single-shot time-resolved bunch profile monitor based on spatial decoding electro-optic detection. The monitor is able to measure beam longitudinal distribution in a non-destructive way which could simultaneously record the time jitter between laser pulse and electron bunch. EO signal as short as 135 fs rms has been observed with 0.3 mm ZnTe crystal for 40 MeV bunches. A long time monitor of time jitter between laser pulse and electron bunch has been achieved with rms jitter of 589 fs. Measurements of EO detection with higher accuracy by thinner ZnTe and new GaP crystal and practical application to decrease the time jitter will be published recently.

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REFERENCES

[1] B. Faatz *et al.*, *Nucl. Instrum. Methods Phys. Res.*, Sect. A 407, 302, 1998.
[2] L. Bentson *et al.*, *Nucl. Instrum. Methods Phys. Res.*, Sect. A 507, 205, 2003.
[3] I. Wilke *et al.*, *Phys. Rev. Lett.* 88, 124801, 2002.
[4] G. Berden *et al.*, *Phys. Rev. Lett.* 93, 114802, 2004.
[5] A. L. Cavalieri *et al.*, *Phys. Rev. Lett.* 94, 114801, 2005.
[6] G. Berden *et al.*, *Phys. Rev. Lett.* 99, 164801, 2007.
[7] B. Steffen *et al.*, *Phys. Rev. ST Accel. Beams* 12, 032802, 2009.
[8] S. Casalbuoni *et al.*, *Phys. Rev. ST Accel. Beams* 11, 072802, 2008.
[9] B. Steffen, "Electro-optic Methods for Longitudinal Bunch Diagnostics at FLASH", Ph.D. thesis, University of Hamburg, DESY-THESIS-2007-020, 2007.
[10] W. Wang *et al.*, *Nucl. Instrum. Methods Phys. Res.*, Sect. A 834, 183, 2016.
[11] Y. C. Du *et al.*, *Rev. Sci. Instrum.* 84, 053301, 2013.
[12] L. X. Yan *et al.*, *Nucl. Instrum. Methods Phys. Res.*, Sect. A 637, 127, 2011.
[13] X. Yan *et al.*, *Phys. Rev. Lett.* 85, 3404, 2000.