Electro-optical sampling non-synchronous delay scanning measurement of electron beam bunch length at BFEL *

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Abstract The Electro-optical sampling delay scanning technique can be used for electron beam bunch length measurement. A novel non-synchronous delay scanning technique based on the electro-optical sampling measurements is presented. Based on Beijing Free Electron Laser (BFEL), the electron beam bunch length was measured with the electro-optical sampling technique for the first time in China. The result shows that the electron beam bunch length at BFEL is about 5.6±1.2 ps.

Key words electro-optical sampling, measurement of electron beam bunch length, non-synchronous delay scanning technique

PACS 29.27.Fh

1 Introduction

The advanced synchrotron radiation source, the fourth generation light source such as X-ray Free Electron Laser (XFEL) and Energy Recovery Linac (ERL), and high energy linear collider are all required to produce subpicosecond ultrafast high peak-current relativistic electron bunch. The diagnostics of relativistic electron beam are focused on the bunch length measurement and real-time monitoring with subpicosecond and even femtosecond temporal resolution. There are several diagnostics available to measure the length of short electron bunches, for example, the streak camera technique, the RF defecting cavity, the coherent transition radiation measurement, the electro-optical measurement, and so on [1–2]. The electro-optical measurement is non-destructive and non-intrusive, and can be used for real-time monitoring [3]. It is a promising single-shot technique to measure the length and the shape of the electron beam bunch in the subpicosecond domain.

Employing different probe laser pulses and different detection methods, the electro-optical measurements can be classified as delay scanning detection, spectrally resolved detection, chirped-pulse cross correlation detection and spatially resolved detection [3]. The last three detection methods belong to single-shot technique, while they all need higher probe laser energy and more expensive detector compared with delay scanning detection. The electro-optical delay scanning technique can finish the electron beam bunch length measurement once within a macropulse [4]. Based on Beijing Free Electron Laser (BFEL) facility, the experimental setup to measure the bunch length of relativistic electron beam by using the electro-optical sampling technique was built up for the first time in China. A novel non-synchronous delay scanning technique based on the electro-optical measurements is employed which can work without the synchronization system for the probe pulse and the electron bunch.

2 The principal of the electro-optical delay scanning measurement

The principal of the electro-optical delay scanning measurement is given in Fig. 1. The Coulomb field of the relativistic electron beam is concentrated perpendicular to the direction of the electron beam propagation, which represents the length and the longitudinal

Received 24 June 2009

* Supported by National Natural Science Foundation of China (10575116)

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shape of the beam bunch. When a piece of ⟨110⟩ cut ZnTe crystal is mounted in the beam vacuum pipe of an accelerator with the edge of the crystal a few millimeters away from the electron beam, the Coulomb field of the electron beam will induce a birefringence in the ZnTe crystal, and the polarization of the probe laser will be modulated by the crystal. Changing the delay between the beam bunch and the probe laser pulse, the Coulomb field at different longitudinal positions can be probed by the probe laser. The balanced detection is used in order to increase the signal-to-noise ratio. A quarter wave plate is used in the setup of balanced detection to transform the slightly elliptically polarizing beam into an almost circularly polarized beam, and a polarizing beam splitter (Wollaston prism) splits the almost circularly polarized beam into two linearly polarized beams, which are measured by a balanced diode detector. The difference intensity signal in the balanced diode detector is given by [5]:

$$\Delta I = I_0 \frac{2\pi}{\lambda_0} L n^3 \gamma_{41} E_b \,. \qquad (1)$$

where I_0 is the initial intensity of probe laser, λ_0 is the wavelength in vacuum, L is the thickness of the ZnTe crystal, n is the refractive index of the ZnTe crystal, γ_{41} is nonzero element of the linear electro-optic tensor of the ZnTe crystal, and E_b is the Coulomb field of the beam bunch at the detected position. The difference intensity signal ΔI is proportional to the Coulomb field of the electron beam bunch E_b, therefore, the pulse duration of the difference intensity signal envelope, which is detected by delay scanning the beam bunch, is the electron beam bunch length, and the pulse shape is the longitudinal distribution of the charges in the bunch.

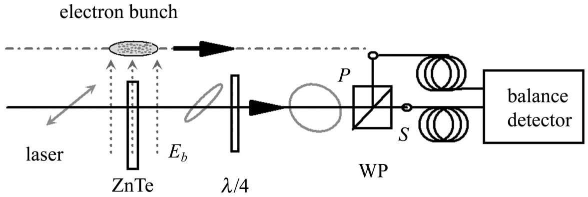

Fig. 1. Scheme of the electro-optic sampling electron bunch length measurement.

3 Experiment setup

BFEL is a low-gain middle and far infrared free electron laser facility with wavelength at 7–19 μm. The parameters of the electron beam used for the electro-optical measurements at BFEL are given in Table 1.

Table 1. Parameters of the electron beam used for the electro-optical measurements at BFEL.

parameters	values
beam energy	26 MeV
energy spread/rms	±0.5%
normalized emittance	70 πmm·mrad
bunch charge	80 pC
macropulse frequency	3.125 Hz
macropulse duration	5 μs
micropulse frequency	2856 MHz
micropulse duration(designed)	4 ps

The setup of the electro-optical delay scanning electron beam bunch length measurement system at BFEL is shown in Fig. 2. A mode-locked femtosecond Ti:sapphire laser producing a 35 fs pulse at 800 nm with horizontal polarization is employed as a probe laser of the measurement system. The repetition rate of the laser is nearly 102 MHz. The probe laser beam is expanded by a Galileo telescope system, and then it is propagated from the clean room to the accelerator hall at BFEL. After an inverted telescope the probe laser is focused into the electron beam vacuum pipe. A 2 mm thick ZnTe crystal and two mirrors are mounted in the pipe, in which the electron beam is propagated upon the edge of the crystal, while the probe laser is transmitted from the crystal paralleling to the electron beam with 3 mm distance. The probe laser beam carrying the information of the electron beam bunch is educed from the vacuum pipe by a mirror, and after transmitting from a quarter wave plate, it is split into two beams with orthogonal polarization states by a Wollaston prism. Using two 20 m multimode optical fibers, the two beams are respectively propagated back to the clean room, and then measured by the balanced diode detector to obtain the difference intensity signal.

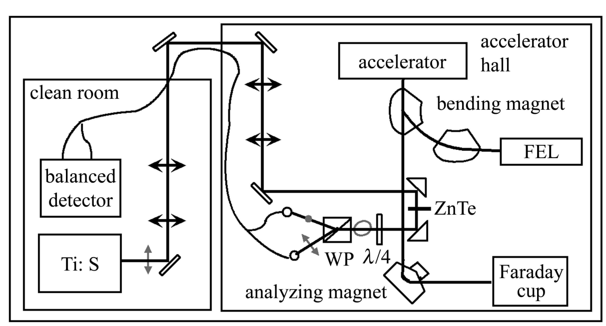

Fig. 2. Experimental setup of the electro-optical delay scanning measurement of the electron bunch length at BFEL.

4 The timing of the non-synchronous delay scanning

Usually, the probe laser pulses should be actively synchronized to the accelerator RF clock in the electro- optical electron bunch length measurements. The repetition rate of the electron bunch can be changed via an RF-phase shifter which sweeps the electron bunch over the probe laser pulse train, and the complete electric field profile is thereby measured.

In this paper, a novel non-synchronous delay scanning technique is presented. The timing of the non-synchronous delay scanning is in Fig. 3. Fig. 3(a) shows the electron beam bunches with 2856 MHz repetition rate, and Fig. 3(b) shows the probe laser pulse train with a repetition rate of about 102 MHz, which is nearly 1/28 of the 2856 MHz. When 28 electron bunches pass through, there is a probe laser pulse which transmits the ZnTe crystal, and the delay time between the laser pulse and the 28th electron bunch is ΔT longer than the delay time of the previous one, where ΔT is the delay scanning step between the probe laser and the electron bunch. If the repetition rate of the probe laser pulses is suitable, the electron bunch is swept over the probe laser pulse train, and the envelope of the difference intensity signal will illustrate a pulse structure, which is shown in Fig. 3(c). Thus the bunch length can be read from the difference intensity signal envelope, and the electric field profile is thereby measured. Furthermore, the complicated synchronization system is not needed in the non-synchronous delay scanning technique, which greatly simplifies the measurement. And the delay scanning is automatically accomplished without RF-phase shifting, so the measurement will not disturb the operation of the facility.

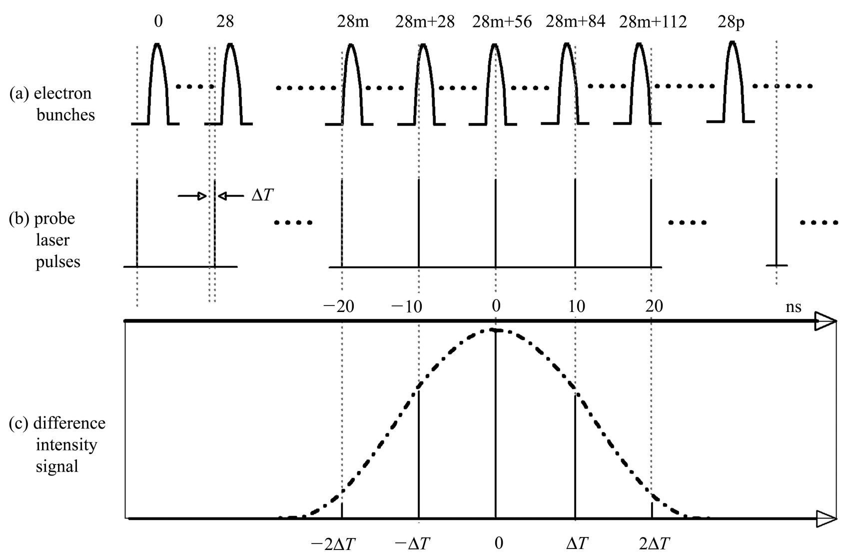

Fig. 3. Timing of the non-synchronous delay scanning technique.

5 Measurement of electron beam bunch length at BFEL

Figure 4 shows the measurements of the electron field profile and its Gaussion fit with different delay scanning steps. From Fig. 4(a) to (c), the delay scanning step is 0.9 ps, 1.2 ps and 2.3 ps respectively, and the measured electron beam bunch FWHM length is 6.3 ps±0.9 ps, 6.0 ps±0.9 ps, and 4.8 ps±0.9 ps correspondingly. The measurements of the electron bunch length at BFEL coincide well with the designed value. When the delay scanning step is shorter, the sampling points are denser, and more details of the longitudinal profile of the charge distribution in the electron beam bunch can be achieved.

To verify the non-synchronous delay scanning technique, a set of contrast experiments were made. The results are given in Fig. 5, and the grey curve marked with squares in the figure is just the curve in Fig. 4(a) to compare. In the case of Fig. 5(a), the black curve marked with triangles was measured when the electron beam was intercepted by a profile before the ZnTe crystal. When no electron beam passes through, there are not any pulse structures which occur in the envelope of the difference intensity signal. If the repetition rate of the probe laser pulses is equal to 102 MHz, the relative temporal

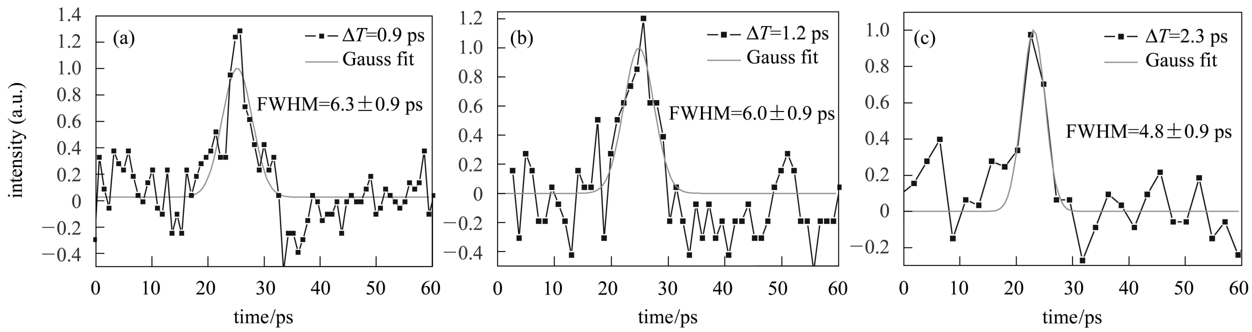

Fig. 4. Electro-optical sampling measurements of the electron bunch length at BFEL.

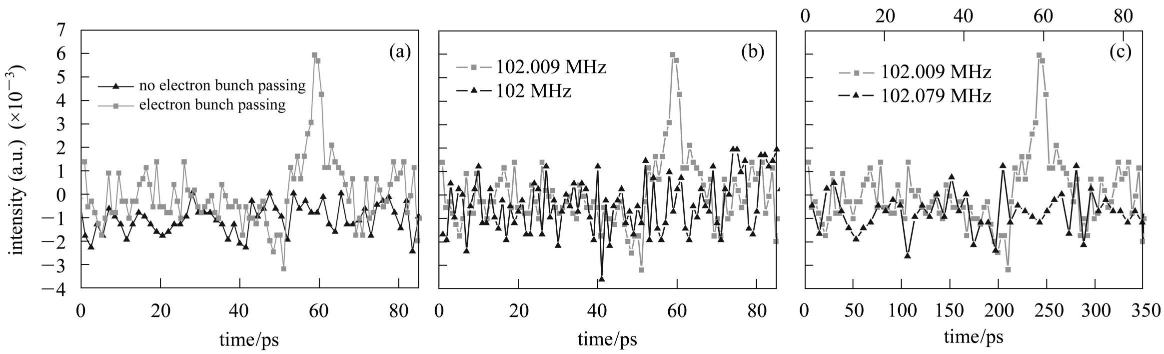

Fig. 5. Results of the contrast experiments.

relation of the probe laser pulse and the electron bunch is invariable. Therefore, it is impossible for the probe laser pulses to sweep the electron bunch with 0 delay scanning step. The envelope of the difference intensity signal also has no pulse structure, which is the black curve marked with triangles in Fig. 5(b) (For careful observation the time interval of the sample points is set at 1 ps). On the other hand, when the repetition rate of the probe laser pulses deviates from 102 MHz too much, the delay scanning step will be too large to accomplish the measuring. Fig. 5(c) illustrates the curves measured with 102.079 MHz and 102.009 MHz repetition rate probe laser pulses, which means that the delay scanning step is 7 ps and 0.9 ps respectively. The 7 ps delay scanning step is almost equal to the length of the electron bunch at BFEL, hence, the pulse structure can not be observed from the envelope of the difference intensity signal.

The average value of the electron beam bunch length FWHM at BFEL is 5.6 ps in the measurements, and the measurement error is 1.2 ps, by analyzing a set of measurement results under the same condition on the same day. The time resolution is about 0.5 ps in the configuration, depending on the 0.9 ps delay scanning step.

6 Summary

In conclusion, electro-optical non-synchronous delay scanning measurements of the length of relativistic electron bunches have been performed based on the BFEL facility. A novel delay scanning technique is employed to avoid the synchronization system and the disturbance of the facility operation. The measured electron beam bunch FWHM length at BFEL is 5.6±1.2 ps.

We would like to thank our colleagues Yang Xue Ping, Wang Zi Hua and Wu Gang for operating the BFEL facility and their other helps.

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