FEASIBILITY STUDY OF RADIAL EO-SAMPLING MONITOR TO MEASURE 3D BUNCH CHARGE DISTRIBUTIONS

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Abstract

We are developing a single-shot and non-destructive 3D bunch charge distribution (BCD) monitor based on Electro-Optical (EO) sampling with a manner of spectral decoding for XFEL/SPring-8. For fine beam tuning, 3D-BCD is often required to measure in real-time. The main function of this bunch monitor can be divided into longitudinal and transverse detection. For the transverse detection, eight EO-crystals (Pockels effect) surround the beam axis azimuthally, and a linear-chirped probe laser pulse with a hollow shape passes thorough the crystal. We are planning to use an amorphous material which has only an even-order field dependence (Kerr effect) in donut shape without assembling eight conventional EO-crystals. The polarization axis of the probe laser should be radially distributed as well as the Coulomb field of the electron bunches. Since the signal intensity encoded at each crystal depends on the strength of the Coulomb field at each point, we can detect the transverse BCD. In the longitudinal detection, we utilize a broadband square spectrum (> 400 nm at 800 nm of a central wavelength) so that the temporal resolution is less than 30 fs if the pulse width of probe laser is 500 fs. In order to achieve 30-fs temporal resolution, we have a plan to use an organic EO material, DAST crystal, which is transparent up to 30 THz. We report the first experimental results of this 3D-BCD monitor with a 200-ps linearly chirped probe laser pulse and two ZnTe crystals installed diagonally.

INTRODUCTION

XFEL (X-ray Free Electron Laser) has been constructed at the SPring-8 site and it is planned to be in operation from 2011. It requires high-brightness electron bunches with a slice emittance of 0.7 - 1 π mm-mrad and bunch duration of 30 fs (FWHM) [1]. In order to measure the temporal distribution of several-tens-femtosecond bunches, the measurement with an RF deflector is the most reliable method at present and it is being installing in XFEL [2]. It is, however, a destructive measurement and cannot be used in operation for SASE (Self-Amplified Spontaneous Emission) generation. Therefore, another compact measurement system without destruction of the electron bunches is also required for a beam tuning to generate stable SASE radiation for user experiments.

The schematic view of three-dimensional bunch charge distribution (3D-BCD) monitor is shown in Figure 1 [3]. This monitor is based on the EO-sampling (EOS) with a manner of spectral decoding, which enables single-shot measurements using linear-chirped laser pulse [4]. The main function of the bunch monitor can be divided into longitudinal detection and transverse detection. For the transverse detection, eight EO-crystals surround the beam axis azimuthally, and a linear-chirped probe laser pulse with a hollow shape passes thorough the crystal. The crystal axes of EO crystals and the polarization axis of the probe laser should be radially distributed as well as the Coulomb field of the electron bunches. The signal intensity encoded at each crystal depends on the strength of the Coulomb field at each point. Therefore, the signal intensity becomes different each other when the transverse charge distribution of electron bunches becomes asymmetric. In order to detect the intensity modulation of each signal in real time, the laser spectra should be a rectangular shape with a linear chirp. For the principle of transverse and energy chirp detection see details in Ref. [5].

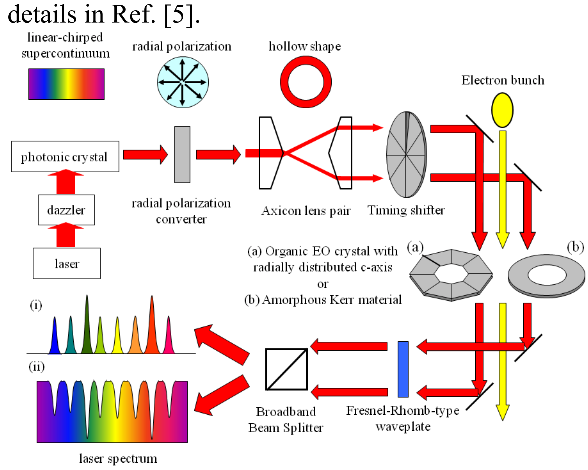

Figure 1: Schematic view of 3D-BCD monitor based on EOS: Decoding eight EO signals in 3D-BCD to keep S/N higher at the same time, the spectra (i) divided from a polarized splitter are measured together with eight-branched fibre of one spectrometer (HR4000; Ocean Optics).

In the longitudinal detection, very high temporal resolution of several tens femtosecond in FWHM is required for XFEL. In the spectral decoding, one of the main factors limiting temporal resolution is the bandwidth of a probe laser. It is expressed as $T_{Res} \sim (\tau_o \tau_c)^{1/2}$, where τ_0 is the pulse width of the Fourier-transform limited pulse of the probe laser and τ_c is pulse width of the probe laser with liner chirp. With a probe laser pulse width of 500 fs and a broadband square spectrum (> 400 nm at 800 nm of a central wavelength), the resolution is estimated to be less than 30 fs. In practice, probe laser pulse must be longer than the timing jitter. Therefore, we will use fewpicosecond probe laser for the rough beam tuning. Switching with DAZZLER (AO-modulator for spectral and temporal shaping), 500-fs probe laser is used in order to achieve higher temporal resolution for the precise tuning. For the principle of tuneable octave-broadband laser probe, see details in Ref. [6].

Other limiting factor for the temporal resolution is the spectral characteristics of an EO material; i) absorption in THz range, ii) velocity mismatching inside the material between a THz pulse (the Coulomb field) and a probe laser pulse and iii) velocity mismatching between the different spectral components of probe laser. In EO-based bunch duration measurements, the temporal resolution is limited to 120 fs (FWHM) at present because ZnTe and GaP, which are commonly used EO crystals, have the absorption at 5 THz and 11 THz, respectively [7]. In order to achieve 30-fs temporal resolution, EO material should be transparent up to 30 THz. One candidate for such a material is DAST crystal, which is an organic EO material. Because the DAST crystal is used as the broadband THz source (more than 20 THz) [8], it is also expected to be effective for the ultrashort bunch duration measurements. DAST crystal is transparent in the spectral range of more than 600 nm. This is the reason why we are planning to generate the broadband laser pulse with the spectral range of 600 – 1100 nm. The effect of the velocity mismatching due to the dispersion of the refractive index is evaluated by numerical estimations. Although its effect becomes strong in the case of the broadband laser pulse, we confirmed the broadband laser pulse enables higher temporal resolution.

As mentioned above, the broadband linear-chirped laser pulse with rectangular shape spectrum is required for our 3D-BCD monitor. The spectral range required for this monitor is from 600 to 1100 nm. Besides, the laser should be a hollow beam with a radial polarization over the whole spectral region. In this paper, we report the first experimental result of 3D-BCD monitor.

EXPERIMENTAL SETUP

We have generated a hollow probe laser with a radial polarization at the fundamental wavelength of Ti:Sa laser (792 nm). Using the 0th order of diffraction at the compressor grating of the photocathode illuminating UV-laser source, we can measure the timing jitter and the relative beam pointing fluctuations between probe laser and electron beams at the same time. Therefore, the first test bench of 3D-BCD has been constructed to investigate several EO-materials and fundamental technologies of EOS. As a next step, we are preparing the supercontinuum laser generation with two-staged NOPA amplifiers [6] as a laser probe and investigate the feasibility of a DAST organic crystal for femtosecond temporal resolution in the equivalent setup with a reflective axicon mirror pair at the VUV-FEL test accelerator (SPring-8 Compact SASE Source: SCSS).

The schematic drawing of the current 3D-BCD monitor setup at the advanced photocathode test facility in SPring-8 is shown in Fig. 2. The radially polarized laser is injected into an axicon-lens-pair unit with the cone angle of 140 degrees to generate a hollow-shaped laser. Optimizing half and quarter waveplates, a sufficient radial polarization on the EO-crystals surround the electron bunch. For the preparation of fine linear polarization as an incident laser for the radial polarizer, a polarized splitter with a high extinction ratio (~ 10000:1) is required. It required fine alignments for incident laser beam to the axicon lens pair. A pair of Risley prisms is mounted in remote-controlled rotation stages to align the laser automatically with Advanced Tactical Aligner [9] (ATA system, developed with Photo-Physics Laboratory Inc.) Guiding a merit function calculated from laser profile data, ATA system aligns a laser to the optimal path automatically to generate a fine hollow laser beam. The timing shifter is a 120-mm long rod consisted of eight different optical glasses with different refractive indices. This timing shifter makes encoding time differences on each EO-crystal. In our spectral decoding in 3D-BCD monitor, the signals encoded at each EO-crystal appear in the different wavelength region.

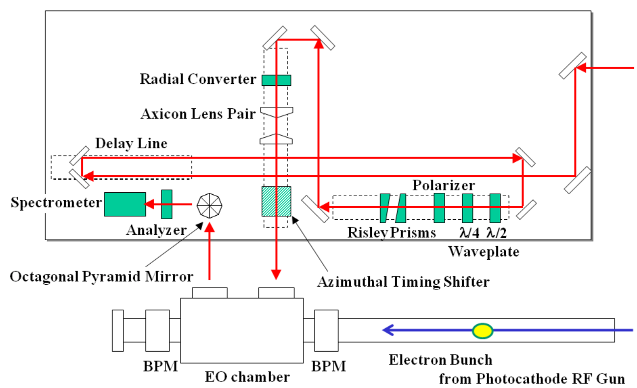

Figure 2: 3D-BCD monitor setup at the advanced photocathode test facility in SPring-8: Radially polarized hollow laser is generated after an axicon lens pair with an eight-segmented waveplate (radial polarizer). It requires fine alignments for the incident laser beam to the axicon lens pair. A pair of Risley prisms is mounted in rotary stages to align the probe laser automatically with ATA based on a hill climbing method extended with fuzzy set theory.

Decoding eight EO signals in 3D-BCD to keep S/N higher at the same time, the spectra of p-polarized components from a polarized splitter are measured together with eight-branched fibre of one spectrometer (HR4000; Ocean Optics). The resolution of the spectrometer is 0.2 nm. The probe laser operated with a pulse width (FWHM) of 200 ps and a spectral band width of 20 nm for the first test run. According to $T_{Res} \sim (\tau_o \tau_c)^{1/2}$, the temporal resolution of bunch width (FWHM) is ~3 ps.

THE FIRST EXPERIMENTAL RESULTS OF 3D-BCD MONITOR

At SPring-8, photocathode is illuminated by UV-laser pulse shaped with 3-stage UV-pulse stacker [10]. Eight pulses stacked with an optical delay of 2.5 ps between neighbouring pulses to generate a 20-ps square combined pulse. In this experiment, we fixed a laser spot diameter of 1.5 mm and a charge generated by each micro pulse of 0.25 nC. The total bunch charge generated by the 20-ps square combined pulse was 1.4 nC. When the absolute RF phase of laser incidence is 80 degrees in these laser conditions (20-ps square combined pulse), our simulation results show that the bunch width becomes 10 ps.

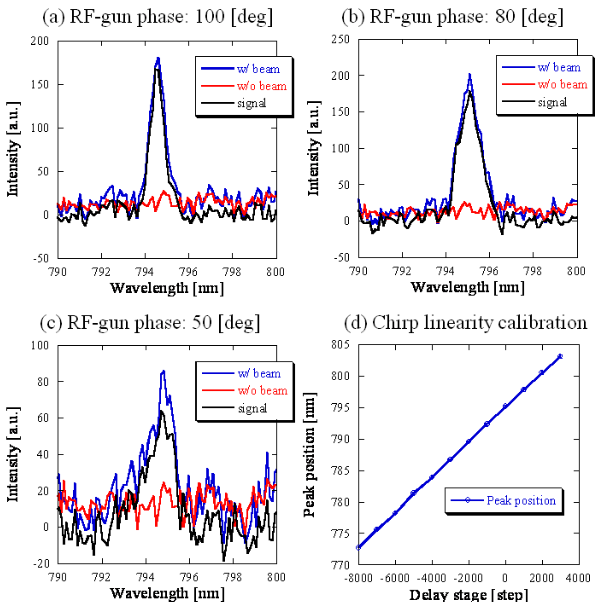

Figure 3: Experimental results of EO signals at the different absolute RF phases of laser incidence at the photocathode and chirp linearity of the probe laser (One of the EO-crystals probed with a hollow laser); Measured electron bunches' width (FWHM) calibrated with (d) 9.58 ps/nm: (a) 6.13 ps, (b) 10.8 ps (c) 11.5 ps.

We performed EOS experiments with two ZnTe crystals installed diagonally. The probe laser was a hollow laser with linear polarization. The chirp linearity of this probe laser is measured as a wavelength shift at EO signal peaks with changing a delay time of the probe laser pulse. In the delay line, one step of the stage shifts 8 µm. Fitting result of (d) in Fig.3 gives a conversion factor of 9.58 ps/nm. The experimental results of EO signals at the different absolute RF gun phase of laser incidence are shown in Fig. 3. The measured electron bunch width is 10.79 ps at the RF phase of 80 degrees. It is good agreements with our simulation results.

Each of EO-signals (double peaks with a timing shift of 100 ps) was measured at each EO-crystal simultaneously, as shown in Fig. 4. The peak count of both of EO-signals fluctuates shot-to-shot, because a bunch charge, a probe laser pulse intensity, or the laser pointing are fluctuating independently (as a simple model). In our measurements, the peak count ratio (i) / (ii) was 13 % fluctuation (rms), the count (i), 13 %, and the count (ii), 12 % as well. Therefore, the bunch charge fluctuation was estimated to be negligible. The peak summation (i) + (ii) was 10 % fluctuation (rms). It related to the fluctuation of the probe laser intensity. It indicates that a relative beam pointing fluctuation between the electron and the probe laser is ~8% (rms). It means that the pointing fluctuation was ~80 µm (rms). It is about twice larger magnitude of the UV-laser pointing fluctuation at the cathode.

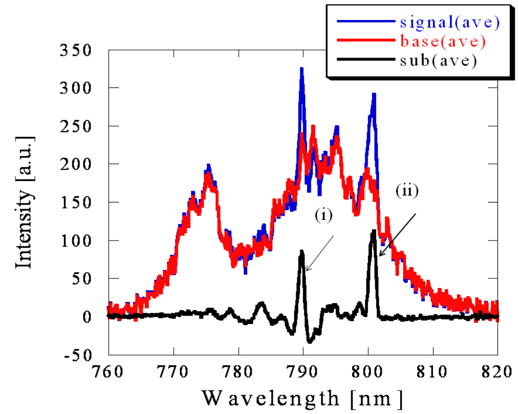

Figure 4: Experimental results of EO signals (Both of the EO-crystals probed with a hollow laser); Measured electron bunches' width (FWHM) : (i) 10.7 ps, (ii) 11. 8 ps.

SUMMARY

We reported the first experimental results of this 3D-BCD monitor with a 200-ps linearly chirped probe laser pulse and two ZnTe crystals installed diagonally. We could characterize an electron bunch with a temporal charge distribution and a relative beam pointing between the electron and the probe laser beams successfully. It indicates that this concept of 3D-BCD is feasible. Using EO-crystals more than eight, it can characterize three-dimensional charge distribution in an electron bunch.

In the calculations, the beam energy is 8 GeV, the charge is 100 pC, and longitudinal charge distribution is the square shape with 30-fs bunch duration. To detect the transverse distribution, the detection points will be fixed at 2 mm from the beam axis. In this configuration, the electric field of the electron bunch is estimated to be ~ 98 MV/m. For such a strong electric field, the Kerr effect can be utilized instead of the Pockels effect. Since an amorphous material has only an even-order field dependence, it can minimize the background noise induced by the wakefield.

REFERENCES

[1] T. Shintake, *Proceedings of EPAC 08*, Genova, Italy (2008) 136.
[2] H. Ego, et al., *Proceedings of EPAC 08*, Genova, Italy (2008) 1098.
[3] H. Tomizawa, et al., *Proceedings of FEL 2007*, Novosibirsk, Russia (2007) 472.
[4] I. Wilke, et al., *Phys. Rev. Lett.* 88 (2002) 124801.
[5] A. Maekawa, et al., *Proceedings of PAC 09*, Vancouver, Canada (2009) to be published.
[6] S. Matsubara, et al., *Proceedings of FEL 2009*, Liverpool, UK, 2009 to be published.
[7] G. Berden, et al., *Phys. Rev. Lett.* 99 (2007) 164801.
[8] Y. Takahashi, et al, *J. Photochem. Photobiol. A: Chem.* 183 (2006) 247.
[9] H. Tomizawa, *Synchrotron Radiation in Natural Science Vol. 9, No. 1 – 2* (2010) 24.
[10] H. Tomizawa, et al., *Russian Journal of Quantum Electronics*, (2007) 697.