NOVEL NONDESTRUCTIVE SHOT-BY-SHOT MONITOR TO MEASURE 3D BUNCH CHARGE DISTRIBUTION WITH FEMTOSECOND EO-SAMPLING

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Abstract

In linac-based high brightness light sources, it is necessary for high-precision experiments to characterize the light emission bunch-by-bunch. It is essential for precise characterizations of an X-ray FEL's beam to monitor ever-changing charge distribution of electron bunches by single-shot measurement with high resolution. Therefore, a single-shot and non-destructive 3D bunch charge distribution (BCD) monitor was developed to characterize longitudinal and transverse BCDs simultaneously. It is based on Electro-Optical (EO) multiple sampling with a manner of spectral decoding. For transverse detection, eight EO crystals surround the beam axis azimuthally, and a linear-chirped probe laser pulse with a hollow shape and spirally temporal shift passes through the EO crystals. The polarization axis of the probe laser is radially distributed as is 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, the longitudinal BCDs are encoded as independent intensity modulations at eight different wavelength regions. The encoded information of 3D BCDs is decoded by a multichannel spectrometer with an eight-branched fiber-optic input. We report the first feasibility test of this 3D-BCD monitor done with two ZnTe crystals installed diagonally. These two EO crystals were probed at the same time with a radially polarized hollow-shaped laser pulse with a 200-ps linear chirp. As future development directions, we are preparing a conerefringent probe laser with Kerr-EO amorphous material (polymer) for precise detection of transverse BCDs and a broadband laser probe pulse (> 400 nm @ 800 nm) with an organic DAST EO-crystal to achieve a temporal resolution of < 30 fs.

INTRODUCTION

The SPring-8 XFEL (X-ray Free Electron Laser) has been constructed and is planned to be in commission in 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]. To measure the temporal distribution of several-tens-of-femtosecond bunches, using an RF deflector is the most promising method at present, and one is being installed at the 1.3-GeV energy region of the SPring-8 XFEL [2]. It requires 5-m-long RF structures and 5 m more distance to put a screen monitor downstream. However, it is a destructive measurement and cannot be used in operation for SASE (Self-Amplified Spontaneous Emission) generation. Also, a compact bunch monitor is required when we monitor ultrashort electron bunches at 8-GeV energy regions (just before the undulator section) of the XFEL. Therefore, another compact measurement system without destruction of the electron bunches is also required for a diagnosis of bunch parameters to generate stable SASE radiation for user experiments.

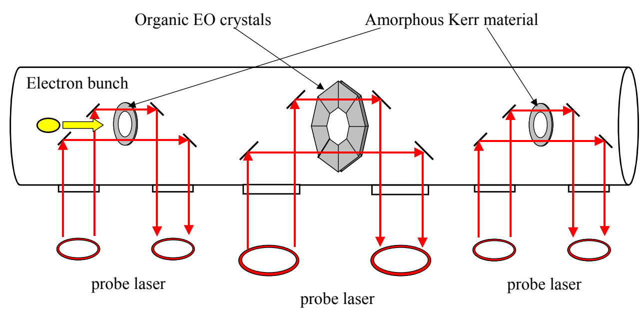


Figure 1: Schematic drawing of 3D-BCD monitor setup. Amorphous Kerr EO materials are placed at both sides as beam position monitor (BPM) functions and an organic Pockels EO crystal is at the center for 3D-BCD measurements of the electron bunch. The total size of this monitor is 50 cm. We are planning to install this diagnostics system before the undulator section. At this section, the beam halo is suppressed to avoid any radiation damage to the permanent magnets of in-vacuum undulators, which is also a reliable condition for EO detection.

A schematic view of the three-dimensional (3D) bunch charge distribution (3D-BCD) monitor is shown in Figure 1, and one of the detectors of the 3D-BCD is shown in Figure 2 [3]. The 3D bunch monitor consists of three detector sections. The electron bunch's center of mass and incident angle at the central detector are defined with detections at both ends. The 3D-BCDs of the electron bunch are monitored at the central detector. Each detector section of this monitor is based on EO-sampling (EOS) with a manner of spectral decoding, which enables single-shot measurements using linear-chirped laser pulses [4]. The main function of the bunch monitor can be divided into longitudinal detection and transverse detection. For transverse detection, eight EO crystals surround the beam axis azimuthally, and a linear-chirped probe laser pulse with a hollow shape passes through 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 when the transverse charge distribution of electron bunches becomes asymmetric. To detect the intensity modulation of each signal in real time, the laser pulse spectra should be a rectangular shape with a linear chirp. For details of the principle of transverse and energy chirp detection, see Ref. [5].

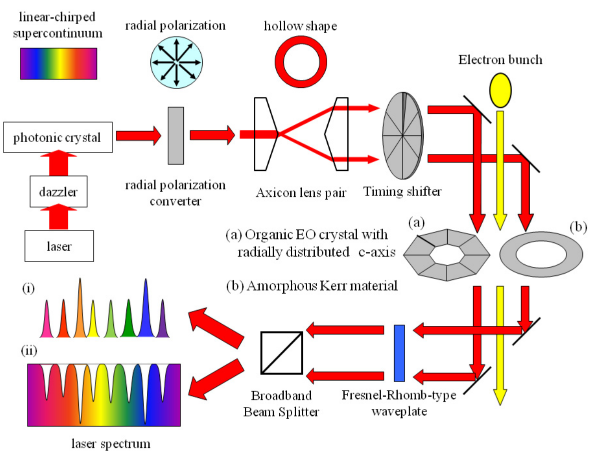


Figure 2: Schematic view of 3D-BCD monitor based on EOS: Decoding eight EO signals in 3D-BCD to keep S/N higher at the same time, the spectra (i) divided from a polarized splitter are measured together with eight-branched fiber of one spectrometer (HR4000; Ocean Optics).

In the longitudinal detection, very high temporal resolution of several tens of femtoseconds in FWHM is required for the 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 the pulse width of the probe laser with linear chirp. With a probe laser pulse width of 400 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, a probe laser pulse must be longer than the timing jitter. Therefore, we will use a few-picosecond probe laser for the rough beam tuning. Switching with DAZZLER (AO-modulator for spectral and temporal shaping), a 400-fs probe laser is used to achieve higher temporal resolution for precise tuning. The probe laser is tuned as a perfectly linearly chirped pulse under precisely controlled dispersion up to seventh order and has a rectangular-shaped spectrum with a broadband DAZZLER (UWB-650-1100, FASTLITE). For details of the principle of the tuneable octave-broadband laser probe pulse (generation and amplification), see Ref. [6].

Other limiting factors for the temporal resolution are the spectral characteristics of an EO material:

i) Absorption of EO material in the THz range,
ii) Velocity mismatching (dispersion) inside the EO material between a THz pulse (the Coulomb field) and a probe laser pulse,
iii) Dispersion of EO material in a spectral range of a broadband probe laser (650 -1100 nm).

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 inorganic crystals, have absorption at 5 THz and 11 THz, respectively [7]. To achieve 30-fs temporal resolution, EO material should be transparent up to 30 THz. One candidate for such a material is DAST organic crystal, which is an organic EO material. Because the DAST crystal is used as the broadband THz source (0.3–30 THz; a sharp and narrow absorption due to optical photon resonance at 1.1 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 why we are planning to generate a broadband laser pulse with a 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 that the broadband laser pulse enables higher temporal resolution.

As mentioned, a broadband linear-chirped laser pulse with rectangular-shaped spectrum is required for our 3D-BCD monitor. The spectral range required for this monitor is from 600 to 1100 nm. In addition, 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 for the 3D-BCD monitor.

EXPERIMENTAL SETUP

We have generated a hollow probe laser with a radial polarization at the fundamental wavelength of a Ti:Sa laser (central wavelength: 792 nm). The first test bench for the 3D-BCD has been constructed to investigate several EO materials and fundamental technologies of EOS at the advanced photocathode test facility at SPring-8. 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 the probe laser and electron beams at the same time. Our photoinjector generates a 10-ps electron bunch up to 24 MeV. We performed the first feasibility test for the 3D-BCD monitor with this beam.

The schematic drawing of the current test bench for the 3D-BCD monitor at the advanced photocathode test facility at SPring-8 is shown in Fig. 3. The radially polarized laser is injected into an axicon-lens-pair unit with a cone angle of 140 degrees to generate a hollow-shaped laser. A waveplate divided into eighths is used as a radial polarizer [3]. Optimizing half and quarter waveplates, a sufficient radial polarization on the EO crystals surrounds 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 (~ 10,000:1) is required, as are fine alignments for the 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 the Advanced Tactical Aligner [9] (ATA system, developed with Photo-

Physics Laboratory Inc.) Guiding a merit function calculated from laser profile data, the 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 consisting of eight different optical glasses with different refractive indices as shown in Fig. 4. This timing shifter makes it possible to encode time differences on each EO crystal. In our spectral decoding in the 3D-BCD monitor, the signals encoded at each EO crystal appear in a different wavelength region.

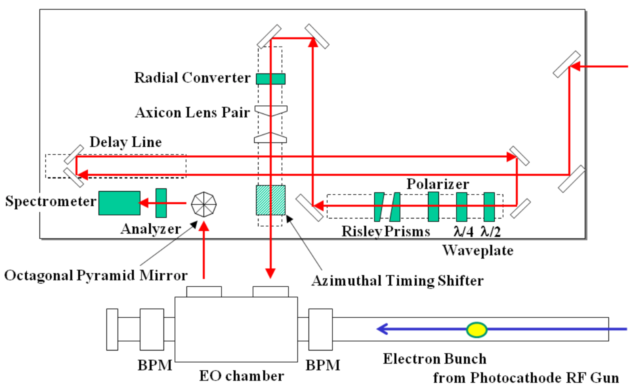
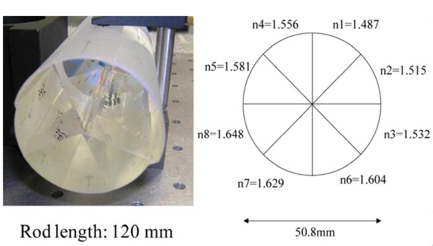


Figure 3: 3D-BCD monitor setup at the advanced photocathode test facility at SPring-8: Radially polarized hollow laser is generated after an axicon lens pair with a waveplate (radial polarizer) segmented into eighths. It requires fine alignments for the incident laser beam to the axicon lens pair. A pair of Risley prisms is mounted in rotary stages to align the probe laser automatically with the ATA system (fuzzy set theory) [9].

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 fiber of one spectrometer (HR4000; Ocean Optics). The resolution of the spectrometer is 0.2 nm (It corresponds to the geometrical resolution of 1.2 ps in the temporal domain). The probe laser was operated with a pulse width (FWHM) of 200 ps and a spectral bandwidth of 20 nm for the first test run. According to $T_{Res} \sim (\tau_0 \tau_c)^{1/2}$, the temporal resolution of the bunch width (FWHM) was ~3 ps.



	Glass	n @768nm
n1	S-FSL5	1.483
n2	S-NSL5	1.517
n3	S-BAL12	1.534
n4	S-BAL41	1.558
n5	S-BAL35	1.583
n6	S-BSM4	1.606
n7	S-BSM18	1.631
n8	S-BSM25	1.650

The names of optical glass are from the catalog of OHARA Inc.

Figure 4: Timing shifter of 3D-BCD for 10-ps bunch.

The timing shifter requires more than 10-ps temporal shifts between neighboring optical glasses because we measure the photoinjector's beam with a bunch length of 10 ps as a feasibility test. Eight different optical glasses were chosen with least different refractive indices of 0.02.

FIRST EXPERIMENTAL RESULTS AND ANALYSIS OF 3D-BCD MONITOR

In the SPring-8 single-cell RF gun (pill-box type), the photocathode is illuminated by a UV-laser pulse shaped with a three-stage UV-pulse stacker. Eight pulses were stacked with an optical delay of 2.5 ps between neighboring pulses to generate a 20-ps square combined pulse. In this experiment, we fixed a laser spot diameter of 1.5 mm and an equivalent charge generated by each micro pulse. The total bunch charge generated by the 20-ps square combined laser pulse was 0.85–1.4 nC. It depends on the initial RF phase of the RF gun. The initial RF phase is defined as θ in the following formula of the cathode surface field of RF; $E_{RF} = E_0 \cos(\omega t - \theta)$, when the time of the electron bunch head or laser pulse head at the cathode surface is zero.

When the RF-gun phase (initial RF phase of the RF gun) is 80 degrees in the laser conditions (20-ps square combined pulse), our simulation results show that the bunch width becomes 11 ps after the acceleration on the top RF phase with an RF accelerating structure.

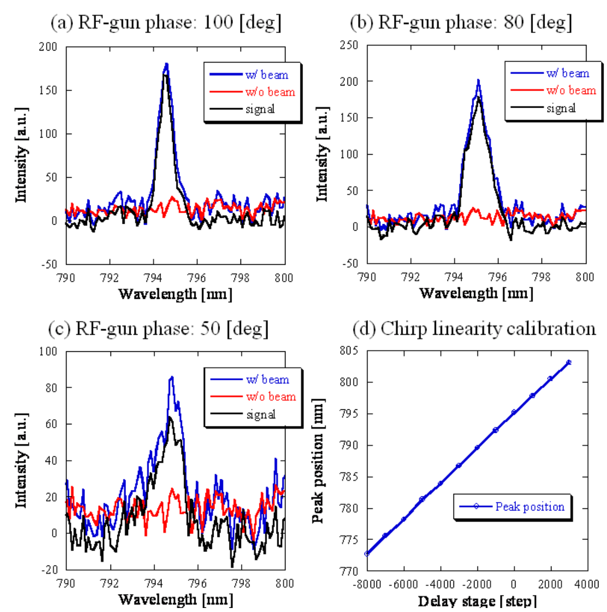


Figure 5: Experimental results of EO signals at the different initial RF phases of the photocathode and chirp linearity of the probe laser (one of the EO crystals probed with a hollow laser); Measured electron bunches' width (FWHM) calibrated with (d) 9.58 ps/nm (linear chirp region over 180 ps): (a) 6.13 ps (0.85 nC), (b) 10.8 ps (1.22 nC), (c) 11.5 ps (0.95 nC).

We performed 3D-EOS feasibility studies with two ZnTe crystals with a thickness of 1 mm installed diagonally. Both crystals were placed at 4 mm from the electron beam axis. The birefringence induced by the transverse electric field of the electron beam bunch was probed 4~5 mm from the axis by a hollow laser beam with a 1-mm ring width. In the 3D-EOS monitor, Pockels EO crystals are installed in the number of 2^n surrounding the electron beam axis azimuthally for transverse detection. This feasibility study is the simplest case, n=1. The probe laser is a hollow laser with linear polarization. Note that a radial polarization is required when we probe more than eight EO crystals (n= 3) at the same time.

As the first step, a single EO signal was measured with one of the ZnTe crystals at different RF-gun phases, and these results are shown in Fig. 5. The chirp linearity of this probe hollow laser is measured as a wavelength shift at EO signal peaks while changing the delay time of the probe laser pulse. In the delay line, one step of the stage shifts 8 μm. The fitting result of (d) in Fig. 5 gives a conversion factor of 9.58 ps/nm. The experimental results of EO signals at the different initial RF-gun phase are shown in Fig. 5. In the phase shifting in the RF-gun phase, we always put an electron bunch on the RF top phase of RF accelerating structures. The measured electron bunch width is 10.8 ps at the RF-gun phase of 80 degrees ((b) in Fig. 5). It agrees well with our simulation results. At the RF-gun phase of 50 degrees ((c) in Fig. 5), an electron bunch with tailing was measured. This tailing comes from a larger energy spread of the electron beam at this RF-gun phase. This temporal bunch shape also agrees well with our simulation results.

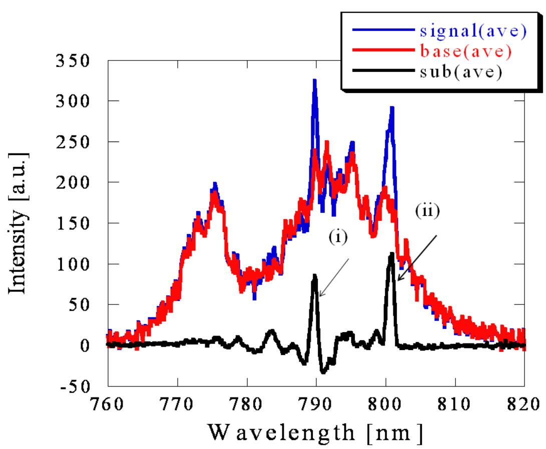


Figure 6: Experimental results of EO signals (Both EO crystals probed with a hollow laser). Measured electron bunches' width (FWHM) 1.3 nC: (i) 10.7 ps, (ii) 11. 8 ps.

As the second step, double EO signals were measured with both ZnTe crystals, and these results are shown in Fig. 6. Each of the EO signals (double peaks with a timing shift of 100 ps) was measured at each EO crystal simultaneously, as shown in Fig. 6. The peak count of both EO signals fluctuates shot-to-shot because bunch charge, probe laser pulse intensity, and the laser pointing are fluctuating independently (as a simple model). In our measurements, the peak count ratio (i) / (ii) was 13% fluctuation (rms), count (i) was 13%, and count (ii) was 12%. This indicates that all fluctuations, except the bunch charge fluctuation, were 13%. The peak summation (i) + (ii) was 10% fluctuation (rms). This is related to the fluctuations of the probe laser intensity. Consequently, the relative beam pointing fluctuation between the electron and the probe laser is ~8% (rms). This means that the pointing fluctuation was ~80 μm (rms) at the EO crystals.

SUMMARY

The first test bench for the 3D-BCD was constructed to investigate several EO materials and fundamental technologies of EOS. 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 longitudinal BCDs, and a relative beam pointing between the electron and the probe laser beams successfully. This indicates that this concept of 3D-BCD is feasible. Using more than eight EO crystals, it can characterize 3D-BCD in an electron bunch. As a next step, we are planning supercontinuum laser generation with two-staged NOPA amplifiers [6] as a laser probe and will investigate the feasibility of a DAST organic crystal and an amorphous EO polymer for femtosecond temporal resolution. The next hollow broadband laser probe pulse is generated with a reflective axicon mirror pair. We are preparing a new encode-decode system for precise detection of transverse BCDs with a conerefringent probe laser pulse for Kerr-EO amorphous materials with femtosecond response.

In the calculations, the beam energy is 8 GeV, the charge is 100 pC, and longitudinal BCD is a square shape with 30-fs bunch duration. To detect the transverse BCD, 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 (the Kerr effect is the lowest and dominant order in the amorphous material), it can minimize the background noise induced by the wakefield. Kerr EO coefficient n_2 is on the order of 10^{-20} to 10^{-22} $[m^2/V^2]$. Assuming $n_2 = 1.0 \times 10^{-21}$ $[m^2/V^2]$ and crystal thickness L = 1 mm, the degree of polarization rotation is estimated to be θ_{rot} = ~19 degrees at E = 98 MV/m. The quadratic dependence of the Kerr effect contributes to an enhancement of the intensity modulation for transverse BCD detections compared with the Pockels effect.

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