DEVELOPMENTS OF 3-D EO BUNCH SHAPE MONITOR FOR XFEL/SPRING-8

A. Maekawa, M. Uesaka, The University of Tokyo, Ibaraki, Japan
H. Tomizawa, JASRI/SPring-8, Hyogo, Japan

Abstract

In XFEL/SPring-8, it requires ultra high-brightness electron bunches with ultralow slice emittance and bunch duration of 30 fs (FWHM) in a lasing part. In order to measure such bunches, we are developing a single-shot, non-destructive, real-time three-dimensional bunch shape monitor based on EO sampling with a manner of spectral decoding. It consists of a radially polarized probe laser and eight EO-crystals, which surround a beam axis azimuthally and their crystal-axes are radially distributed as well as Coulomb fields of electron bunches. The probe laser has a linear-chirped broad bandwidth (> 400 nm at 800 nm of a central wavelength) for higher temporal resolution, and a hollow shape to avoid interacting with electron bunches. As an EO crystal, we investigate the feasibility of an organic crystal such as a DAST for 20-fs temporal response. This monitor can measure not only longitudinal but also transverse charge distribution at the same time. These real-time three-dimensional bunch shape measurements are very important to optimize electron bunches for XFEL operation. We present the scheme of this monitor with its estimation in detail and report the developing status for probe laser.

INTRODUCTION

XFEL (X-ray Free Electron Laser) is now under construction at the SPring-8 site. It requires high-brightness electron bunches with an ultralow slice emittance of 0.7 – 1 mm-mrad and a bunch duration of 30 fs (FWHM) in lasing part [1]. In order to measure such ultrashort bunches, we are developing a single-shot, non-destructive, real-time three-dimensional bunch shape monitor based on Electro-Optic (EO) detection with a manner of spectral decoding [2,3]. This monitor enables the precise beam tuning in operation for SASE generation.

The schematic view of three-dimensional bunch shape monitor is shown in Figure 1. The main function of this bunch monitor can be divided into longitudinal detection and transverse detection. In the longitudinal detection, very high temporal resolution of several tens femtosecond in FWHM is required for XFEL. Temporal resolution of spectral decoding is limited by several factors as discussed in Ref. [4]; 1) geometrical limitation, 2) bandwidth of laser probe pulse 3) velocity mismatching within the EO material, 4) spectral characteristics of the EO material. The first is not crucial for XFEL due to its high energy; it is less than 4 fs if the EO material is placed within 10 mm from beam axis. The second is expressed as $T_{FL}\sim(\tau_0\tau_c)^{1/2}$, where τ_0 is the pulse width of a Fourier-transform limited pulse and τ_c is the chirped pulse width. With a broadband square spectrum (> 400 nm at 800 nm of a central wavelength), the resolution is estimated to be < 21 fs. The other limitations are inherent in the EO material. We are planning to utilize an organic EO material. A DAST crystal is one candidate because it has a large Pockels coefficient of r_{111} = 71 ± 8 pm/V and transparent at 600 – 2000 nm [5] and 2 – 30 THz (although small absorptions at several points are also reported) [6]. These details are discussed in Ref [3].

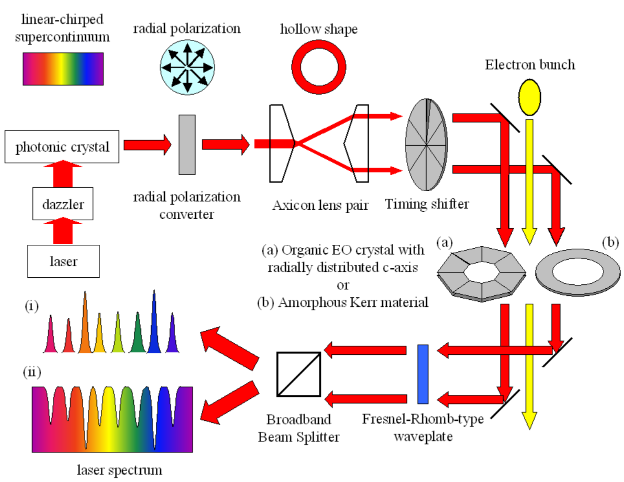

Figure 1: Schematic view of three-dimensional bunch shape monitor based on EO detection.

As well as the longitudinal detection, it is also necessary to monitor the transverse position and charge distribution of electron bunches for beam tuning. Especially, this three-dimensional bunch shape monitor can detect the transverse charge distribution in a lasing slice, which is essential for SASE generation instead of the projected distribution. In this monitor, 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 encode eight EO signals to different spectral components of the chirped probe laser pulse, the incident timing of the probe laser pulse to each crystal is adjusted by a timing-shifter, the thickness of which varies azimuthally.

In this paper, we report our developments and numerical estimations for transverse detection of electron bunches.

TRANSVERSE DETECTION

In order to evaluate the feasibility of this monitor, the intensity modulation between eight EO signals at each detection point are estimated numerically. 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 should be close to the beam axis. Hence, the detection points are fixed at r = 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 (Kerr effect is the lowest and dominant order in the amorphous material), it can minimize the background noise induced by the wakefield. The signal intensity with Kerr effect is expressed as

$$I_p = I_0 \sin^2\left(\frac{\pi}{\lambda}\frac{n_2 E^2}{2} L\right),$$

where I_0 is the intensity of the incident laser pulse, n_2 is the noninear refractive index, λ is the wavelength of probe pulse, L is the crystal thickness and E is the Coulomb field strength. The nonlinear refractive indices of several EO materials are on the order of 10^{-20} to 10^{-22} [m^2/V^2]. Assuming $n_2 = 10 \times 10^{-21}$ and crystal thickness L = 1 mm, the degree of polarization rotation is estimated to be θ_{rot} = ~19.1 degree at E = 97.6 MV/m.

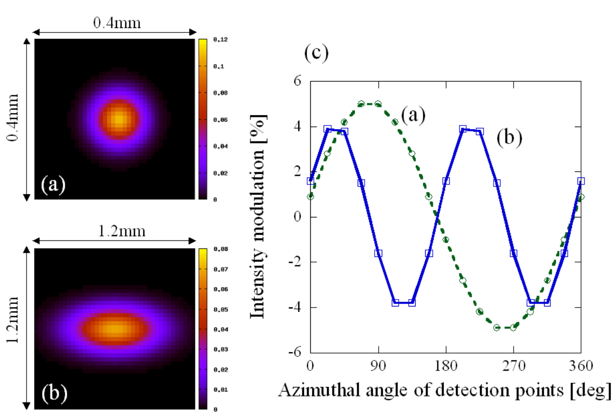

Figure 2: Numerical estimations of the azimuthal intensity modulation of EO signal; the calculated conditions are (a) a 10-μm transverse shift of the electron beam with a beam size of 40 μm (rms) and (b) an ellipse shape with a beam size of 150 μm (rms).

Figure 2 shows numerical estimations in the case that (a) the beam center (beam size of 40 μm in rms) shifts 10-μm away from the beam line, and (b) the transverse charge distribution becomes an ellipse shape (aspect-ratio is $r_{hol} : r_{ver}$ = 2 : 1, $\sqrt{r_{hol} \times r_{ver}} = 150\,\mu$m, where r_{hol} and r_{ver} are the horizontal and vertical beam size in rms, respectively). We can detect a beam position shift of 10 μm and an ellipse shape with a beam size of 150 μm in rms as a ten-percent intensity modulation of the EO signals. In this condition, the absolute signal intensity is 3% of the incident intensity, I_0.

Furthermore, this transverse detection can be applied for the energy distribution measurements. If the dispersion function η is relatively large, the electron bunch becomes chirped spatially according to its energy distribution. Hence, we can detect the energy distribution by the transverse detection. In XFEL, there is a plan to transport the ultrashort electron bunches into SPring-8 (storage ring), and therefore some bending magnets are planned to be installed. This section is favourable for the energy distribution measurements; designed parameters are β = 15 m, η = 0.6 m, $\Delta p/p = 4 \times 10^{-3}$. In this section, transverse beam size at this point is estimated to be 2.4 mm (horizontal) and 12.6 μm (vertical) in rms.

Figure 3 shows the numerical estimations of the intensity of EO signal; the calculated conditions are with various energy spreads (left) and with various peak energy shifts (right). In the latter case, the energy spread is fixed to be $\Delta p/p = 4 \times 10^{-3}$. The detection points are set at r =15 mm from the beam axis, where the electric field of the electron bunch is estimated to be ~ 4 MV/m. In this case, we can utilize a DAST crystal with the thickness of 0.1 mm. The signal intensity is expressed as

$$I_p = I_0 \sin^2\left[\frac{\pi}{2\lambda}(n_x^3 r_{111} - n_y^3 r_{221}) E_x L\right],$$

where n_x and n_y are the refractive indices in the x and y directions without an applied electric field, r_{111} = 77 pm/V and r_{221} = 42 pm/V [5] are Pockels coefficients. We can detect the energy spread of 2 – 8 × 10^{-3} as a 3 – 26 % intensity modulation, and the peak energy shift of ± 5 × 10^{-4} as a 30 % modulation of the EO signal, respectively. When we performed this transverse detection at the several points with/without bending magnets, we can measure both the spatial and energy distribution in real-time and single-shot measurements.

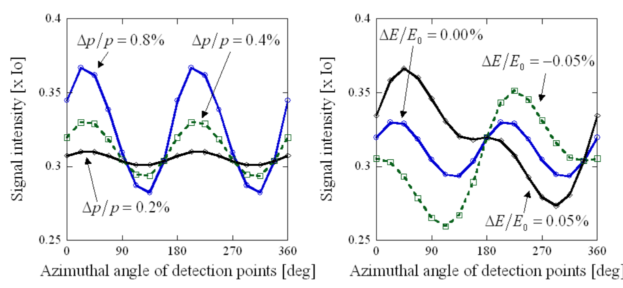

Figure 3: Numerical estimations of the intensity of EO signal; the calculated conditions are with various energy spreads (left) and with various peak energy shifts (right).

PROBE LASER GENERATION

Radially polarized hollow laser pulse is required for the transverse detection. We can generate such a probe laser with a radial polarization converter (ARCoptix, Switzerland) based on a nematic liquid crystal for radial polarization, and an axicon lens pair for the hollow shape. A radial polarization converter is favourable for our scheme because it can be utilize over a wide spectral range.

The experimental setup for the generation of a radially polarized hollow laser is shown in Figure 4. A He-Ne laser (633 nm) is used for a test light source. A radial converter converts the incident linearly polarized laser to a radial polarization. After a radial converter, we can utilize a spatial filter unit with a 50-µm pinhole, a focusing lens of f = 50 mm and a collimating lens of f = 25.4 mm in order to clean up the laser profile. The generated radially polarized laser is injected into an axicon-lens-pair unit with the cone angle of 140 degrees to generate a hollow-shaped laser. The obtained images of a radially polarized hollow laser are shown in Figure 5. The size and width of the hollow laser are 20.7 mm (horizontal) × 20.3 mm (vertical) and 0.56 mm, respectively. Figure 5 (b - e), which are images after a polarizer, prove the generation of a radial polarization. The hollow laser width is determined by the incident laser spot size, and the size can be controlled by changing the distance between two axicon lenses.

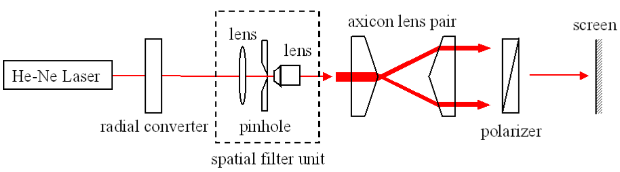

Figure 4: Experimental setup for the generation of a radially polarized hollow laser.

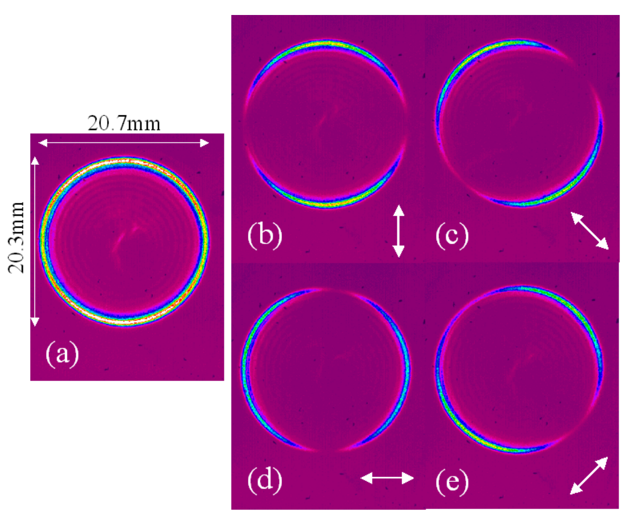

Figure 5: Radially polarized hollow laser after an axicon lens pair without a polarizer (a) and with a polarizer (b – e). The arrows in the images represent the direction of the polarizer axis.

In the three-dimensional bunch shape monitor, supercontinuum laser pulse is required for high temporal resolution. In this case, axicon lenses cannot be used due to chromatic aberration. Therefore, we are preparing the all-reflective system for the hollow laser generation using axicon-type metallic mirrors. We have also developed several optical elements for the supercontinuum laser pulse; Fresnel-Rhomb-type waveplates (both a quarter and a half waveplate), a PBS (Polarizing Beam Splitter), AR coating, and so on. These components can minimize the spectral dispersion in the intensity and the phase during broadband transport. Moreover, the AO-modulator (DAZZLER, UWB-650-1100, FASTLITE) can be utilized to compensate the residual dispersion. With this configuration, we can generate a radially polarized hollow laser pulse with broadband spectra.

SUMMARY

We have report the numerical estimation and developing status for the transverse detection of EO-based three-dimensional bunch shape monitor. Numerical estimations show it can detect a 10-µm transverse shift of the beam center (beam size of 40 µm in rms) as a ten-percent intensity modulation of eight EO signals. Moreover, it can also detect the energy distribution as a several-tens-percent intensity modulation. These spatial and energy resolutions are not superior to those of the RF-BPMs. However, non-destructive real-time measurements for both spatial and energy distributions enable fine beam tuning during XFEL operation.

We have generated a hollow probe laser with a radial polarization. Using this probe laser pulse, we are planning to verify the feasibility of the transverse detection of this three-dimensional monitor at the photocathode RF gun test facility (SPring-8/JASRI) and the VUV-FEL test accelerator (SPring-8 Compact SASE Source). As a next step, we will also perform the supercontinuum laser generation and investigate the feasibility of a DAST crystal for femtosecond temporal resolution.

REFERENCES

[1] T. Shintake, in Proceedings of EPAC 08, Genova, Italy (2008) 136.
[2] H. Tomizawa, et al., in Proceedings of FEL 2007, Novosibirsk, Russia (2007) 472.
[3] A. Maekawa, et al., Phys. Rev. ST-AB (submitted).
[4] I. Wilke, et al., Phys. Rev. Lett. 88 (2002) 124801.
[5] F. Pan, et al., Appl. Phys. Lett. 69 (1996) 13.
[6] Y. Takahashi, et al., J. Photochem. Photobiol. A: Chem. 183 (2006) 247.