A PROBE LASER SOURCE FOR SINGLE-SHOT EO-BASED 3D BUNCH CHARGE DISTRIBUTION MONITOR*

S. Matsubara, RIKEN/SPring-8, 1-1-1, Kouto, Sayo, Hyogo, 679-5148, JAPAN,
H. Tomizawa, JASRI/SPring-8, 1-1-1, Kouto, Sayo, Hyogo, 679-5198, JAPAN,
A. Maekawa, Nuclear Professional School, University of Tokyo, 2-22 Shirakata-Shirane, Tokai, Naka, Ibaraki 319-1188, JAPAN,

Abstract

High-brightness electron bunches are required with low slice emittance and bunch length of 30 fs (FWHM) in a targeting lasing part for XFEL/SPring-8. In order to obtain maximum brightness, it is very important to measure 3D bunch charge distribution (BCD) in real time for future X-ray light sources (XFEL, ERL, etc). Therefore, we are developing a single-shot, non-destructive, and real-time 3D-BCD monitor based on Electro-Optical (EO) Sampling with a manner of spectral decoding. The monitor system requires for a probe laser source to realize a higher temporal resolution. The laser source has broad bandwidth of 400 nm and a linear chirp of 3,000 fs^2 to achieve few-ps pulse duration. Then, the shape in the frequency regions is rectangular. The liner chirp is supplied by using a broadband AO-modulator (DAZZLER) which is possible to remove high order dispersions. The broadband probe laser pulses will be amplified to be micro-joule pulse-energy with a manner of NOPA (Non-collinear Optical Parametric Amplifier). The laser source with these properties is mentioned in this report. We expect the feasibility of 30-fs temporal resolution by using this laser source with an organic EO material such as DAST crystal.

INTRODUCTION

XFEL (X-ray Free Electron Laser) has been constructed at the SPring-8 site and it is planned to be in operation from 2010. 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 planning to install in XFEL [2]. It is, however, a destructive measurement and cannot be used in operation for SASE (Self-Amplified Spontaneous Emission) generation. Therefore, another 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 shape monitor is shown in Figure 1 [3-5]. This monitor is based on the EO detection with a manner of spectral decoding, which enables single-shot measurements using linear-chirped laser pulse [6]. The main function of this bunch monitor can be divided into longitudinal detection and transverse detection. Especially, this three-dimensional bunch shape monitor can detect the transverse charge distribution in a lasing slice shot-by-shot in real time, which is essential for SASE generation instead of the projected distribution. 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 transverse detection, see details in Ref. 7.

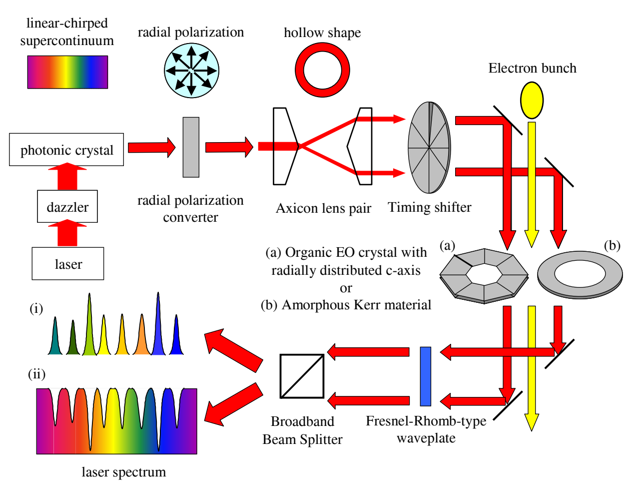

Figure 1: Schematic view of three-dimensional bunch shape monitor based on EO detection.

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 broadband square spectrum (> 400 nm at 800 nm of a central wavelength), the resolution is estimated to be < 30 fs if the pulse width of probe laser is 500 fs. In practice, the probe laser pulse must be longer than the timing jitter. Therefore, we will use few-ps probe laser for the rough beam tuning. Then 500-fs probe laser is used in order to achieve 30-fs temporal resolution for the precise tuning.

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 widely used EO crystals, have the absorption at 5 THz and 11 THz, respectively [8]. 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) [9], 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 3-D BCD monitor. The spectral range, which is required for this monitor is from 600 to 1100 nm. In this paper, we report the developing status of the broadband probe laser pulse and the optical components for its transportation.

GENERATING BROADBAND SPECTRA

Figure 2 shows the schematic drawing of the generation of the broadband probe laser pulse for 3D-BCD monitor. In the EO-Sampling measurements, the probe laser beam should be synchronized with the electron bunch. Therefore, we utilize the mode-locked Ti: Sapphire laser as an original source of the probe laser. In order to generate the broadband laser pulse, a femtosecond Ti: Sapphire laser pulse (~ nJ/pulse) is focused into a PCF (Photonic Crystal Fibers). Then, the spectrum of injected laser pulse is modulated inside PCF to be broadband spectrum by SPM (Self Phase Modulation). After PCF, broadband laser pulse is amplified by two-staged NOPA (Non-collinear Optical Parametric Amplifier); SHG of Ti: Sapphire and YAG laser are used as a pump laser at first and second NOPA, respectively. Between the first and second NOPA, DAZZLER modulates the amplitude and phase of the spectrum of the laser pulse so that the broadband probe laser has certain linear-chirped square spectrum. Without any modulation by the DAZZLER, the broadband laser pulse spreads temporally due to the GVD (Group Velocity Dispersion) of the material. Hence the negative chirp is applied by the DAZZLER, so that it is possible to adjust the pulse width of the broadband probe laser at the EO material.

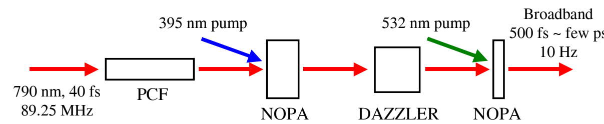

Figure 2: Schematic drawing of the generation of broadband linear-chirped laser pulse with rectangular-shaped spectrum.

As the first step, we use Ti: Sapphire laser (central wavelength: 790 nm, repetition rate: 89.25 MHz) and a PCF (SCG-800, Newport) in order to generate the broadband laser pulse. The laser power injected into PCF can be controlled from several mW to 50 mW using a polarizer and a half waveplate. Figure 3 shows the measured spectra using fiber spectrometer (USB-2000, Ocean Optics) which is available for the spectral range of 200– 900 nm. The spectrum of injected laser pulse is a Gaussian shape with about 30 nm bandwidth. After the PCF, the spectra were changed according to injected laser power. When the injected laser power becomes more than 20 mW, we found the strong peak at around 600 nm in the spectrum. And the broadband spectrum from 560 nm to 900 nm can be obtained when laser power is 50 mW. Because the spectrometer which we used here is not available for the spectral range of more than 900 nm, we are planning to measure the spectrum from 600 nm to 1100 nm by other spectrometer (HR4000, Ocean Optics) and check that this PCF is effective for our 3D-BCD monitor. We will also adjust the bandwidth and chirp of the incident laser pulse to PCF in order to obtain the rectangular –like spectrum.

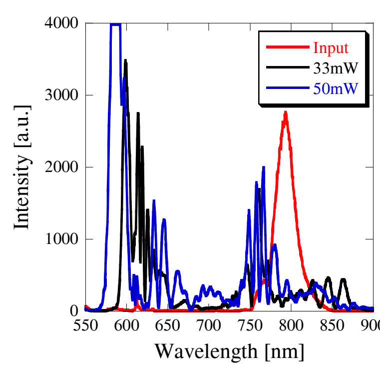

Figure 3: Spectra before and after the PCF. Red line is the original spectrum of Ti:sapphire laser, and black and blue lines are after the PCF with incident power of 33 mW and 50 mW, respectively.

GENERATING RECTANGULAR SHAPE SPECTRA

As the second step, we test the feasibility of the DAZZLER to modulate the amplitude of broadband laser spectrum. A fiber laser (SC450, Fianium) was used an original light source. It is a mode-locked laser generating broadband (450– 2400 nm) pulses. In these measurements, we used the spectrometer (HR4000) which is available for the spectral range 200– 1100 nm. Then, broadband rectangular-shaped spectrum was obtained by DAZZLER (UWB-650-1100, FASTLITE). The spectrum was modulated to be rectangular shape by using the DAZZLER which is a broadband AO-modulator as filtering effect on the first order of diffracted beam.

Figure 4 shows the measured spectra with and without modulation by the DAZZLER. The spectrum was almost Gaussian shape and had 90 nm bandwidth in FWHM without modulation. The spectrum is extremely broad, because of SPM inside the fiber which is the transmission line. With modulation, the spectrum was almost rectangular shape with flat plateau and had more than 300 nm bandwidth in FWHM. This flat-plateau region with a linear chirp is necessary for the real-time transverse detection, and broad bandwidth is important for the temporal resolution at 3D-BCD monitor. The transmittance of the filtering effect is 15 %.

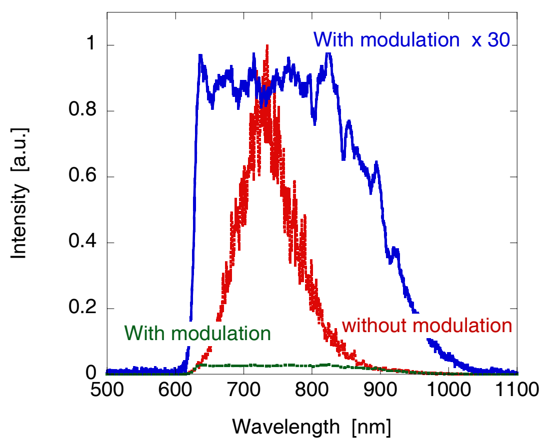

Figure 4: Spectra of the incident laser beam and the modulated laser beam with the DAZZLER. The incident laser beam with 90 nm spectrum bandwidth and moderated laser beam with 300 nm bandwidth in FWHM.

OPTICAL COMPONENTS

In our 3D-BCD monitor, the broadband laser pulse should be transported to the EO material without distortions, while small distortion can be compensated by the DAZZLER. Therefore, we have developed and tested the optical components for the broadband laser pulse (600 – 1100 nm); Fresnel-Rhomb waveplates and a broadband PBS (Polarizing Beam Splitter; separate angle: 106 degrees, contrast ratio: 1000:1). Figure 5 shows the schematic view of Fresnel-Rhomb waveplates (both a half waveplate and a quarter waveplate). A Fresnel-Rhomb waveplate utilized a retardation of λ/8 at a single total-internal-reflection, at which this retardation is inherently less sensitive to the wavelength. For the quarter waveplate, two glass elements (BK7) are connected by optical contact bonding so that high damage threshold for laser

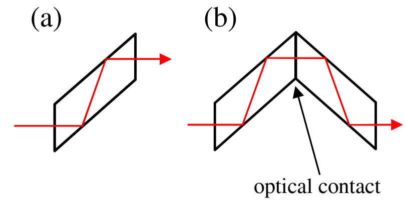

Figure 5: Fresnel-Rhomb waveplates. (a) quarter waveplate (QWP), (b) half waveplate (HWP).

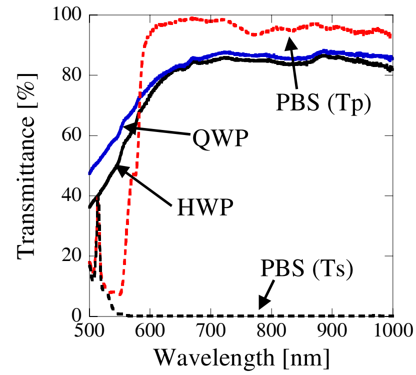

Figure 6: Results of transmittance measurements for the optical components. HWP: half waveplate, QWP: quarter waveplate, PBS: Polarizing beam splitter (Tp: p-polarization, Ts: s-polarization).

power can be obtained. Figure 6 shows the results of the transmittance measurements using the broadband fiber laser (SC450). It is verified that transmittance of each element is less sensitive to the wavelength in the spectral range of more than 600 nm.

We also checked that the polarization state of the laser pulse is varied by the Fresnel-Rhomb waveplate as designed. For this purpose, we utilized a conical refraction. When circularly polarized (or random polarization) laser enters a biaxial crystal in the direction of one of optic axes of the crystal, incident laser is refracted into a hollow cone inside the crystal and propagates as a hollow-shaped laser after the crystal. This phenomenon is known as a conical refraction. It is similar to the phenomenon that circularly polarized laser injected into the uniaxial crystal splits into ordinary and extraordinary beam inside the crystal; in conical refraction, each component of laser beam is refracted into different direction according to its polarization axis.

In this measurements, we use a $KGd(WO_4)_2$ (KGdW) as a biaxial crystal. It is transparent in wide spectral range of 350 – 5500 nm. Therefore we thought that it can be used as a polarization diagnostics of the broadband laser pulse. When the laser is focused and enters the crystal in the direction of the optic axis, laser profile at the focal point (outside the crystal) becomes hollow-shape and crescent-shape if incident laser is circular polarization and linear polarization, respectively [10].

Figure 7 shows the experimental results of the evaluation of the Fresnel-Rhom-type half waveplate (HWP). The broadband laser pulse from SC450 enters the HWP and then its polarization axis is rotated by rotating the HWP. The spatial profile after KGdW was detected by CCD camera (Model 4800, Cohu), which is available for 400 – 1000 nm. We also confirmed that spatial profile for band-passed beam (in the region of 600 – 800nm, spectral window with 50 nm) is the equivalent profile as shown in Figure 7 using several bandpass filters. When the angle of HWP is 0 degree, incident polarization to KGdW is vertical polarization. If the HWP is rotated from –45 to +45 degrees, incident polarization is rotated counterclockwisely from horizontal polarization, and return to horizontal polarization in the case of that the HWP angle becomes +45 degrees. In this case, crescent-like laser profile is also rotated counterclockwisely, and the profiles at HWP angle of +45 degrees is same as that of –45 degrees.

In the same way, we also evaluate the Fresnel-Rhom-type quarter waveplate (QWP) as shown in Figure 8. In this measurements, we use both HWP and QWP before KGdW. Because QWP cannot keep output laser position at the same point as described in Figure 5. it is difficult to rotate QWP in the experiments. Instead, we can rotate the incident polarization to the QWP by the HWP in order to change the output polarization from QWP. When circular polarization (the HWP angle is 0 degree in Figure 8)enters KGdW, hollow-shaped profile can be obtained. If the HWP is rotated and incident polarization to KGdW becomes ellipse polarization, laser profile becomes crescent-like shape. If the HWP angle is –22.5 and 22.5 degrees, incident polarization to KGdW becomes vertical

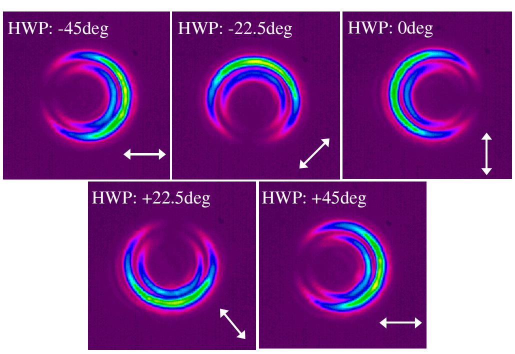

Figure 7: Evaluation of the Fresnel-Rhomb-type half waveplate (HWP) by a conical refraction. Inserted angles show the rotation angle of HWP, and arrows show the incident polarization states to KGdW.

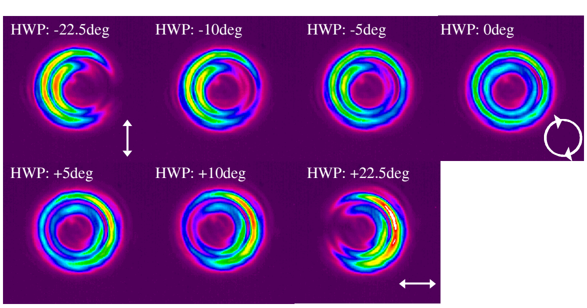

Figure 8: Evaluation of the Fresnel-Rhomb-type quarter waveplate (QWP) by a conical refraction. Inserted angles show the rotation angle of HWP, and arrows show the incident polarization states to KGdW.

and horizontal polarization respectively. In these cases, the same profiles as shown in Figure 7 are obtained. As a result, we can verify by a conical refraction that Fresnel-Rhomb waveplates work as it is designed.

FUTURE WORKS

Not only the rectangular shape, but a linear chirp is necessary to accurate measurement of electron bunches shot-by-shot in real time. The DAZZLER is possible to easy change dispersions with first-order to seventh-order dispersions. Therefore, we will add the linear chirp by the DAZZLER and check it by FROG system. Moreover, the laser pulses need to amplify to be micro-joule pulse-energy with a manner of NOPA. The NOPA is possible to amplify theses broadband spectrum regardless of the gain of the laser medium. As shown in Figure 2, we are planning to use two-staged NOPA with the DAZZLER. In the case of amplification with NOPA, negative chirp will be applied by the DAZZLER to obtain 500-fs square probe laser with linear chirp at the EO elements.

SUMMARY

We have been constructing the probe laser light source for the real-time 3D-BCD monitor. The broadband linear-chirped laser pulse is required for several-tens femtosecond resolution. We have generated the broadband laser pulse using a photonic crystal fiber from Ti: Sapphire laser, modulated the broadband spectrum to a rectangular shape by the DAZZLER, and developed the optical components for 3D-BCD monitor.

In the near future, we are planning to supply linear chirp into probe laser by the DAZZLER and detect it by the FROG, and amplify the laser pulse energy up to micro-joule with a multi-staged NOPA. Using all techniques which described in this paper, we will generate the broadband linear-chirped laser pulse with rectangular spectrum. This laser beam enables the single-shot real-time measurements of three dimensional charge distribution in femtosecond electron bunches.

REFERENCES

[1] T. Shintake, in Proceedings of EPAC 08, Genova, Italy (2008) 136.
[2] H. Ego et al., in Proceedings of EPAC 08, Genova, Italy (2008) 1098.
[3] H. Tomizawa, et al., in Proceedings of FEL 2007, Novosibirsk, Russia (2007) 472.
[4] H. Tomizawa, Japan Patent Application No. 2007-133046.
[5] A. Maekawa, et al., Phys. Rev. ST-AB (submitted).
[6] I. Wilke et al., Phys. Rev. Lett. 88 (2002) 124801.
[7] A. Maekawa et al., in Proceedings of PAC 09, Vancouver, Canada (2009) TH6REP045.
[8] G. Berden, et al., Phys. Rev. Lett. 99 (2007) 164801.
[9] Y. Takahashi et al., J. Photochem. Photobiol. A: Chem. 183 (2006) 247.
[10] T. K. Kalkandjiev et al., SPIE 6994 (2008) 69940B.