DEVELOPMENT OF 3D EO-SAMPLING SYSTEM FOR THE ULTIMATE TEMPORAL RESOLUTION

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Abstract

We have developed a set of key components for ultrafast electron-bunch measurement using Electro-Optic (EO) sampling technique. The key components are a highly-qualified EO-probe laser pulse with an octave bandwidth, an ultrafast organic EO crystal, and a spectrographic EO-demultiplexing (EO-decoding) system. In addition, we developed three-dimensional bunch charge distribution (3D-BCD) monitor with arrival timing for an FEL seeded with a high-order harmonic (HH) pulse. A 3D-BCD monitor is used multiple EO crystal. In our EUV-FEL accelerator, we prepared a seeded FEL with an EO-sampling based feedback system for user experiments. For obtaining a higher seeding hit rate, 3D overlapping between the electron bunch and the seeding HH-pulse must be maximized and kept at a constant optimal seeding condition. Keeping the peak wavelength of EO signals at the same wavelength with our feedback system, we provided seeded FEL pulses (intensity >4σ of SASE) with a 20-30% hit rate during pilot user experiments. For achieving the upper limit of temporal resolution, we are planning to combine high-temporal-response EO-detector crystals and an octave broadband laser pulse with a linear chirp rate of 1 fs/nm. We are developing the EO-probe laser pulse with ~10 μJ pulse energy and bandwidth over 300 nm (FWHM). In 2011, we successfully demonstrated the first electron bunch measurement with an ultrafast organic EO crystal in the FEL accelerator at SPring-8.

INTRODUCTION

Since 2010 at SPring-8, we have been demonstrating a seeded free-electron laser (FEL) in the extreme ultra violet (EUV) region by high-order harmonics (HH) generation from an external laser source in a prototype test accelerator (EUV-FEL) [1]. In FEL seeding as a full-coherent high-intensive light source for EUV user experiments, high hit rates of successfully seeded FEL pulses are required. Precise measurements of the electron bunch charge distribution (BCD) and its arrival timing are crucial keys to maximize and keep 3D (spatial and temporal) overlapping between the high-order harmonics (HH) laser pulse and the electron bunch. We constructed a timing drift monitor based on EO-sampling, which simultaneously measures the timing differences between the seeding laser pulse and the electron bunch using a common external pulsed laser source (Ti:Sapphire) of both the HH-driving and EO-probing pulses (Fig. 1). The EO-sampling system can use timing feedback for continuous operation of HH-seeded FELs.

The R&D of a non-destructive 3D-BCD monitor (proposed by H. Tomizawa in 2006 [2]) with bunch-by-bunch detection and real-time reconstructions has been investigated at SPring-8. This innovative monitor is based on an EO-multiplexing technique that resembles real-time spectral decoding and enables simultaneous non-destructive measurements of longitudinal and transverse BCDs. This part of the monitor was simultaneously materialized for probing eight EO crystals that surround the electron beam axis with a radial polarized, hollow EO-probe laser pulse. In 2009, we verified the concept of a 3D-BCD monitor through electron bunch measurements in the photoinjector test facility at SPring-8 [3].

As part of the Self-Amplified Spontaneous Emission (SASE) XFEL project at SPring-8, an additional target of temporal resolution is ~30 fs (FWHM), which utilizes an ultrafast organic EO crystal (DAST) instead of conventional inorganic EO crystals (ZnTe, GaP, etc.). EO sampling with DAST crystals is expected to measure a bunch length that is less than 30 fs (FWHM). In 2011, we demonstrated the first EOS bunch measurements with DAST crystal in the EUV-FEL accelerator.

In this paper, we describe the development status of ultrafast EO-sampling decoding system and octave broadband EO-probe laser pulse for application of 3D-BCD as a 3D-overlapping monitor for FEL seeding.

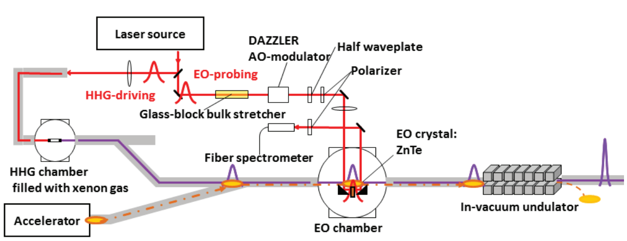

Figure 1: Experimental setup of seeded FEL with EO-sampling feedback at EUV-FEL accelerator: relative positioning in transverse and timing in longitudinal of electron bunch with respect to arriving timing of a seeding HH pulse are monitored at entrance of the first in-vacuum undulator to keep in a best seeding condition.

3D-BCD MONITOR

EO-sampling measures a probe-pulse's retardation by changing the refraction index of a non-linear optical crystal by the radial Coulomb field of relativistic electron bunch slices. The EO-probe laser pulse is injected into the EO crystal at the same time as the electron bunch arrives at the EO crystal. The BCDs are bunch-by-bunch encoded

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as polarization modulations on the spectra of the EO-probe pulses. In spectral decoding to detect with a multi-channel spectrometer in real-time, the polarization modulations are converted into spectral intensity modulations by a polarized beam splitter.

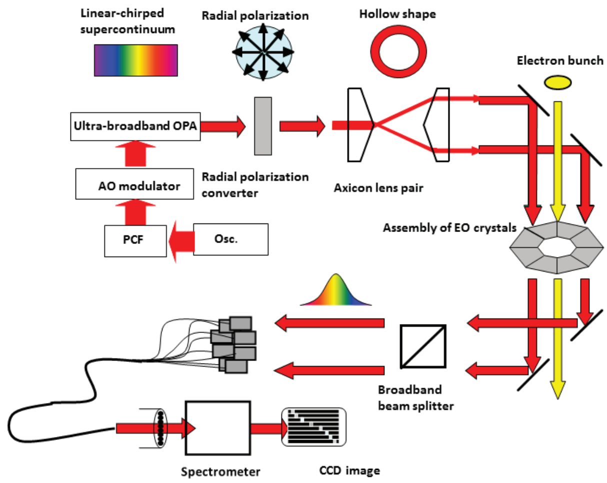

Figure 2: Schematic drawing of 3D-BCD monitor based on EO-multiplexing technique, utilizing simultaneous detection in imaging spectrographs with multi-track (eight tracks) of area array CCD of an image intensified (I.I.) camera.

A 3D-BCD monitor evolved from simple encoding of EOS into a multiplexing technique with a single probe laser pulse for multiple EO crystal detectors in a manner of spectral decoding (demultiplexing). A schematic drawing of a 3D-BCD monitor with eight EO crystals that surround the electron beam axis is shown in Fig. 2. It is applied for a multiplexing technique to simultaneously probe eight EO crystals with a radial polarized, hollow (ring beam) laser pulse. For higher temporal resolution, the EO-probe pulse is broadened by a Photonic Crystal Fiber (PCF) up to over 300 nm. For real-time reconstructions of the 3D-bunch information, the octave broadband pulse is squarely shaped and linearly chirped by an Acousto-Optic (AO) modulator and amplified with bandwidth by Optical Parametric Amplification (OPA) technique. Then the probe pulse passes through the radial polarization converter and an axicon lens pair to obtain a ring beam shape with radial polarization. This ring beam is simultaneously injected into eight EO crystals. As the spectral decoding of conventional EOS, the demultiplexing of the probe pulse is measured through eight-bunched bundle fibers that are matched to the f-number of the grating optics of a spectrometer (imaging spectrograph). We realized demultiplexing as an imaging spectrograph with eight-track simultaneous detection in the area array CCD of a high-speed gated I.I. camera. In addition, for a high S/N ratio of EO signals, over 1000 counts of signal intensity per channel are necessary.

For obtaining a higher hit rate of FEL seeding, 3D overlapping between the electron bunch and the seeding laser pulse is necessary to maintain a constant seeded FEL pulse. In a 3D-overlapping monitor for FEL seeding, the probe pulse is split from the HH-driving Ti:Sapphire laser pulse (Fig. 1). Utilizing this multiplexing EOS technique, relative positioning in the transverse and the timing in the longitudinal of the electron bunch with respect to arriving timing of the seeding HH pulse is obtained at the entrance of the first in-vacuum undulator in real-time with a non-destructive measurement. Transverse detections of bunch slices are done by analyzing the multipole moments of the bunch slice charge density distributions (Ref. [3]).

FEASIBILITY TESTS WITH THE EUV-FEL ACCELERATOR

Test experiments with seeded FEL were demonstrated with a high hit rate with the EUV-FEL accelerator, at SPring-8 in July 2012. The EO-sampling system shown in Fig. 1 was used for feedback to the timing delay unit of a common laser source as a real-time monitor for the relative difference of arrival timing between an electron bunch and a seeding HH pulse. We realized a sophisticated feedback system of timing drift with real-time data processing of EO-signal spectra that encoded the arrival timing as the central wavelengths of the peak signals of spectra and the BCD of the electron bunches. Maintaining the peak wavelength of EO signals at the same wavelength is the most optimal timing for HH seeding. Our feedback system realized a half-day seeded FEL operation with a hit rate of 20-30% (Seeded FEL pulse intensity >4σ of SASE). Compared with a hit rate of seeded FEL operation without EOS feedback [1], the hit rates became 100 times higher. This result shows that only keeping a temporal-overlapping constant at the optimal condition is effective to seed a single-pass SASE FEL pulse shot-to-shot with a HH pulse.

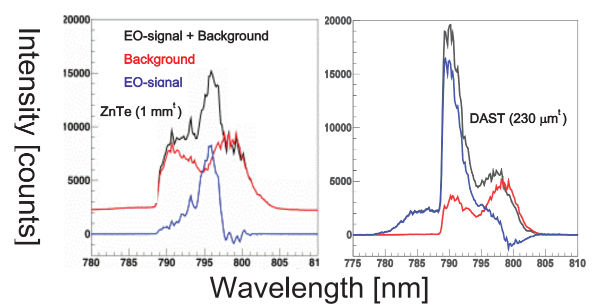

Figure 3: First BCD measurements with 230-μm thick organic DAST crystal compared with EO signals with a 1-mm inorganic ZnTe crystal. The both of the crystals were set 2.0 mm from the electron beam axis.

The other feasibility tests were done by bunch measurements with an ultrafast organic EO crystal (DAST) in the EUV-FEL accelerator. DAST-EOS allows a few tens of femtosecond temporal resolution in the 3D-EO-sampling measurements. In 2011, we successfully demonstrated BCD measurements with a bunch charge of 0.28 nC by a 230-μm thick ultrafast organic DAST crystal. The edges of the EO crystals were set 2.0 mm from the electron beam axis. In a comparable EOS condition,

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double EO-signal intensity was observed by DAST over a conventional, 1-mm thick inorganic ZnTe crystal. The comparison of EO signals is shown in Fig. 3.

OCTAVE BROADBAND LASER PROBE PULSE GENERATION TAWARD ULTIMATE TEMPORAL RESOLUTION

For obtaining higher resolution feasible with DAST EO crystal, we developed an octave broadband probe pulse with an ultimate linear chirp rate of 1 fs/nm using a high pulse energy oscillator (FEMTOSOURCE scientific XL 500 (550 nJ/pulse; Femtolasers GmbH) and a PCF to generate a 5-MHz supercontinuum pulse train.

In spectral decoding (demultiplexing), temporal resolution T_{Res} depends on the bandwidth of the probe pulse, as in the following relationship $T_{Res} \sim (\tau_0 \tau_c)^{1/2}$, where τ_0 is the pulse width of a Fourier transform limited pulse and τ_c is the chirped probe pulse duration. If we utilize a laser pulse with 300 nm of square spectrum bandwidth (FWHM) at a center wavelength of 800 nm and 300-fs pulse duration as an EO-probe pulse, we can obtain temporal resolution of 30 fs (FWHM).

We are developing an EO-probe laser pulse with a few tens of micro-Joules and bandwidth over 300 nm (FWHM). For obtaining such bandwidth and pulse energy, this EO-probe pulse is initiated a supercontinuum generated with PCF and amplified with ultra-broadband OPA. Especially for amplification that maintains bandwidth >300 nm, a non-collinear OPA (NOPA) using BBO crystal and a pump source with a wavelength of 460 nm is preparing (Fig. 4, upper diagram). 460 nm pump wavelength made amplification from 630 nm possible.

The EO-probe pulse energy of 10 μJ provides a high S/N ratio per decoding (demultiplexing) detector. This pulse energy is estimated to be over 1000 counts at detector. In addition, the probe laser spectrum is shaped adaptively as a square spectrum by a broadband AO-modulator, DAZZLER (UWB-650-1100, FASTLITE) at the detectors. The octave-broadband supercontinuum pulse is temporally stretched with nonlinear chirping due to the Group Velocity Dispersion (GVD) and even higher dispersion of the material of transparent optics, including the DAZZLER crystal. Hence, since dispersion controls are applied to roughly compress laser pulses by a Grism (consisted of grating and prism) pair and linearly chirped by DAZZLER, we can finely adjust the pulse duration of the broadband probe laser with a linear chirp rate of 1 fs/nm for probing EO crystals. Owing to the characterization of the nonlinear chirp of the laser pulse with chirp scanning measurement, DAZZLER works as adaptive optics with two functions that provide control of spectral amplitude and phase up to 7th order dispersions: an intensity spectrum shaper and a linear chirp keeper.

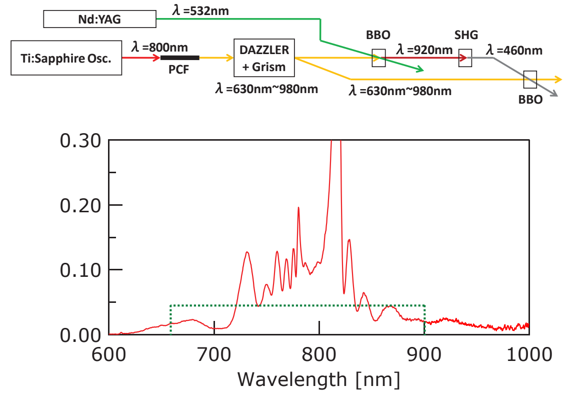

Figure 4: Schematic drawing of generation for broadband linear-chirped laser pulse with square-shaped spectrum. The spectrum of red solid line is generated supercontinuum with large mode area PCF (5 μm diameter) and 100 nJ input pulse energy. Shaping region is shown as green dotted lines on supercontinuum spectrum. Pump source with 460 nm is not available commercially. It is generated from Nd: YAG laser (SHG: 532 nm) pump pulse and the super-continuum signal pulse with additional NOPA stage.

CONCLUSIONS

In several experiments, we successfully demonstrated and proved that the principle of the 3D-BCD monitor as an application for an HH-seeded EUV-FEL is completely feasible. In addition, we successfully demonstrated BCD measurements with ultrafast organic DAST crystal (230-μm thick) by the EO-sampling method. We made the world's first electron bunch measurements by organic EO crystals. This crystal makes a few tens of femtosecond temporal resolution in 3D-BCD measurements possible with our octave broadband EO-probe pulse with a linear chirp rate of 1 fs/nm. The complete version of a 3D-overlapping monitor with a feedback system is going to be demonstrated in seeded EUV-FEL. In the following step, the ultimate temporal resolution of DAST EO-sampling will be tested in SACLA-XFEL.

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