THE FIRST DEMONSTRATION OF EOS 3D-BCD MONITOR TO MAXIMIZE 3D-OVERLAPPING FOR HHG-SEEDED FEL

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Abstract

In FEL seeding as a full-coherent light source, a high hit rate of successfully seeded FEL pulses is required. Precise measurements of the electron bunch charge distribution (BCD) and its arrival timing are crucial keys to maximize and keep 3D overlapping between the high-order harmonics (HH) laser pulse and electron bunch. We constructed a relative timing drift monitor based on EO-sampling, which measured the timing differences between the seeding HH-laser pulse and the electron bunch, using a common external laser source of both HH-driving and EO-probing pulses. The feedback system of timing drift was realized with real-time data processing of EO-signal spectra. 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% effective hit rate during pilot user experiments. The 3D-BCD monitor enables non-destructive measurements of the longitudinal and transverse BCD at the same time. The transverse detection can be used to control the relative pointing between HH-pulse and electron bunch. We also verified this transverse detection with multiple EO crystals at the EUV-FEL accelerator. Our next target for temporal resolution is 30 fs (FWHM), with an octave-band EO-probing for DAST crystals, aiming FEL seeding in the soft X-ray region. For achieving the upper limit of temporal resolution, we are planning to combine high-temporal-response EO-detector crystals and an octave broadband probe laser pulse with a linear chirp rate of 1 fs/nm. We are developing an EO-probe laser pulse with ~10 μJ pulse energy and bandwidth over 300 nm (FWHM; flattop spectrum).

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, a high hit rate of successfully seeded FEL pulses is 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 Electro-Optic (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 (EOS) system can use timing feedback for continuous (without interruption) operation of HH-seeded FELs.

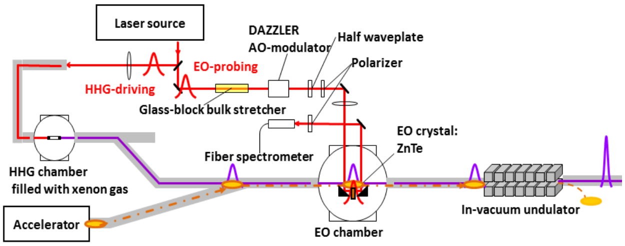

Figure 1: Experimental setup of seeded FEL with EO-sampling feedback at EUV-FEL accelerator: relative positioning in transverse and timing in longitudinal of electron bunch with respect to arriving timing of a seeding HH pulse are monitored at entrance of the first in-vacuum undulator to keep in a best seeding condition (Overlapping between HH-pulse and electron bunch in 6D phase space).

The R&D of a non-destructive 3D-BCD monitor (proposed in 2006 [2]) with bunch-by-bunch detection and real-time reconstructions has been extensively investigated at SPring-8. This ambitious 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 organic EO crystal (DAST) instead of conventional inorganic EO crystals (ZnTe, GaP, etc.). To realize HHG-seeded FEL in the soft X-ray region, the electron bunch will be compressed less than 50-60 fs (FWHM). The EOS monitor 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 [4].

In this paper, we describe the first demonstration of EOS 3D-BCD monitor as a real-time 3D-overlapping monitor in the feedback system for FEL seeding.

3D-BCD AND OVERLAPPING 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 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.

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. 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. Transverse detections of bunch slices are done by analyzing the higher order moments of the bunch slice charge density distributions (Ref. [3]). Newly applying this multi-track simultaneous detection, it can measure higher order charge moments without degrading temporal resolution. This method makes possible to eliminate a spiral timing shifter from our former system and be able to utilize the full spectral bandwidth for longitudinal EOS detection of each track.

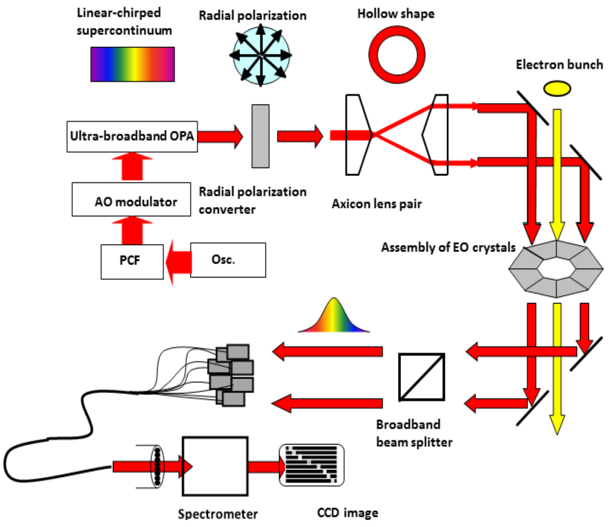

Figure 2: Schematic drawing of 3D-BCD monitor based on EO-multiplexing technique, utilizing simultaneous detection in imaging spectrographs with multi-track (eight tracks) of area array CCD of an image intensified (I.I.) camera.

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. 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.

In a 3D-overlapping monitor for FEL seeding, the probe pulse is split from the HH-driving Ti: Sapphire laser pulse (Fig. 1). For higher temporal resolution, the probe pulse is broadened by a photonic crystal fiber (PCF) up to over 300 nm. For real-time reconstructions of the 3D information, the octave broadband pulse is squarely shaped and linearly chirped by an Acousto-Optic (AO) modulator. 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). In addition, for a high S/N ratio of EO signals, over 1000 counts of signal intensity per channel are necessary.

FEASIBILITY TESTS WITH THE EUV-FEL ACCELERATOR

Pilot user experiments with seeded FEL were demonstrated with a high hit rate with the EUV-FEL accelerator, at SPring-8 in July 2012. The EOS 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 an effective 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 effective 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 (Ref. [5]).

We also verified this transverse detection with diagonal EO crystals at the EUV-FEL accelerator. We expected that the transverse detection can be used to control the relative pointing between HH-pulse and electron bunch. However, we couldn't apply the relative pointing control for the FEL seeding, because the EO-probe laser pointing was dominant for long-distance transportation in our seeding system.

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 a 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 a supercontinuum amplified with optical parametric amplification (OPA). Especially for amplification that maintains bandwidth >350 nm, a non-collinear OPA (NOPA) using BBO crystal and a pump source with a 460-nm wavelength must be prepared (Fig. 3, upper diagram).

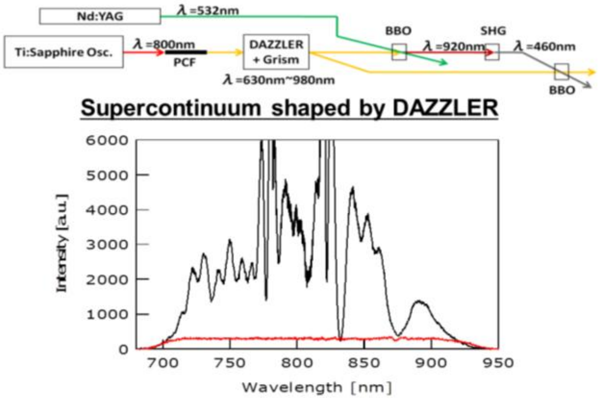

Figure 3: Schematic drawing of generation of broadband linear-chirped laser probe pulse with square-shaped spectrum (red line: 230 nm (FWHM), 660 fs (GDD introduced by DAZZLER: +1000 fs^2)). The 460-nm pump laser pulse is generated from Nd: YAG laser (SHG: 532 nm) pump pulse and the super-continuum signal pulse with additional NOPA stage.

The EO-probe pulse energy of 10 µJ provides a high S/N ratio per decoding (demultiplexing) 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 delay dispersion (GDD) 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 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 DAZZLER-based chirp scanning, the Fourier transform-limited (FTL) pulse is adaptively adjusted at the zero-crossing point. Adding pure GDDs, linear chirped pulses are prepared with arbitrary chirp rates (Fig. 4). 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 an adjuster of linear chirp rate.

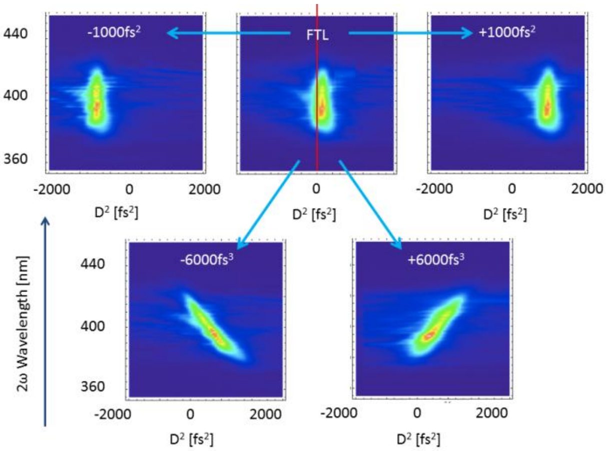

Figure 4: Chirp scan measurements of probe laser pulse. Adding GDD of +1000 fs^2 by DAZZLER, a linear chirped laser pulse was generated with a flattop spectrum (a wide spectral plateau region as shown in Fig. 3).

CONCLUSIONS

We successfully demonstrated the 3D-BCD monitor as the first application to monitor the 3D-overlapping condition of HH-seeded EUV-FEL. With timing feedback to the electrical delay unit of the common Ti:Sapphire laser source, the seeded FEL performance significantly improved for user experiments. The effective hit rate was improved from 0.3% to 20-30% (improvements of two orders). In addition, we generated linear-chirped laser pulse with a flattop spectrum to probe ultrafast DAST EO-crystal. The octave-broadband flattop spectrum of EO-probe laser gives not only the upper limit of temporal resolution, but also large dynamic range for arrival timing (trends in timing-drift and pointing data over time).

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