NON-DESTRUCTIVE SINGLE-SHOT 3-D ELECTRON BUNCH MONITOR WITH FEMTOSECOND-TIMING ALL-OPTICAL SYSTEM FOR PUMP & PROBE EXPERIMENTS

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Abstract

We are developing a non-destructive single-shot 3-D electron bunch monitor based on EO sampling, using the yearlong stable femtosecond laser source developed for the SPring-8 RF gun. The probe laser for spectral decoding EO sampling has been prepared as radial polarized and completely linearly chirped bandwidth (~500nm) supercontinuum generation. The EO-probe element is made of 8 EO-crystals with the assembling of each EO-crystal's optical axes along radial beam axes. The linearly chirped probe laser is longitudinally shifted in 8 transverse sectors for spectral decoding. We are planning to use organic polymer film as a femtosecond resolution EO-probe instead of crystals. This 3-D bunch monitor with spectrograph detects and analyzes the Coulomb field of electron bunches as longitudinally spectral decoding and transversely multi-pole expansion. Our single-shot bunch monitor can characterize the 3-D (both longitudinal (1D) and transverse (2D)) distribution and position of an electron bunch with femtosecond resolution. This non-destructive monitor can be used as an electron energy chirping monitor at a dispersive region for XFEL commissioning. Additionally, the EO-sampled probe laser pulse will be used as a femtosecond-timing signal pulse. This signal pulse is amplified with a NOPA, developing an all-optical timing system.

INTRODUCTION

At the SPring-8 site, construction of the XFEL project [1] has begun under a RIKEN and JASRI joint project. It will enter operation in 2010. For this project, it is necessary to monitor femtosecond electron bunch length for its commissioning. At the moment, the most promising femtosecond electron bunch monitor with an RF deflector, the LOLA cavity [2], is planned to be installed in the 1-GeV energy region of the 8-GeV SPring-8 XFEL linac. However, this monitor requires a few-meters-long cavity structure, and has to measure the bunch length on a fluorescent screen installed a few meters further downstream. The compactness is important in the XFEL project at SPring-8. Therefore, the shorter bunch monitor system is required for bunch length measurement, especially in the 8-GeV region.

In terahertz technology, femtosecond laser pulse duration has been measured utilizing the Pockels effect of ZnTe and so on. This method was the so-called electro-optical sampling (EOS). The variation of the Coulomb field of the electron beam bunch with a duration of less than 1 ps corresponds to terahertz (>10^{12} Hz) in frequency domain. Against this background, this EOS-based bunch monitor has been developed in the accelerator field [3-6]. The advantage of the EOS monitor is that it is non-destructive and has a high resolution of sub-picosecond. To use the laser as a probe allows a timing jitter of femtosecond, and a readout of the monitor head without signal cables. However, the temporal response of inorganic crystals like ZnTe is limited by 110 fs.

There are several types of EOS measurements. One is so-called spectral decoding, that decodes the longitudinal electron bunch structure on the spectrum of the chirped probe laser pulse. One of the others is so-called temporal decoding that is used as conventional pulse measurement with a correlation technique for a femtosecond laser.

The spectral decoding EOS makes possible single-shot measurement with a high repetition rate. Its encoding is simple to perform with a conventional spectrometer. Despite spectral decoding being a convenient method, it is well known that the sensitivity of the signal pulse is reduced because of certain interferences occurring between neighbouring wavelengths. Generally, the temporal resolution R_{res} is given by

$$R_{res} \cong \sqrt{t_0 t_c} ,$$

where the Fourier transform limit of the probe laser is t_0, and the probe chirped laser pulse duration is t_c [5-6]. Therefore, it is the tendency for measurement with high precision to use the temporal decoding method, which is superior in resolution. With a broadband (> 400 nm) laser square pulse chirped linearly, for instance, if t_0=2.5 fs, t_c=160 fs, R_{res} is improved around 20 fs.

In our point of view, spectral decoding is simple to encode and useful for measuring more information about the electron bunch. If the three-dimensional charge distribution of the electron bunch is measurable, it is quite useful for many applications. We investigated the bunch-by-bunch measurement possibility of the transverse charge distribution of the electron bunch with spectral decoding. In our strategy, temporal decoding, AO-modulator-based SPIDER [7] (Spectral Phase Interferometry for Direct Electric field Reconstruction) measurement will be used as a precise calibration for our spectral decoding EOS 3-D bunch monitor.

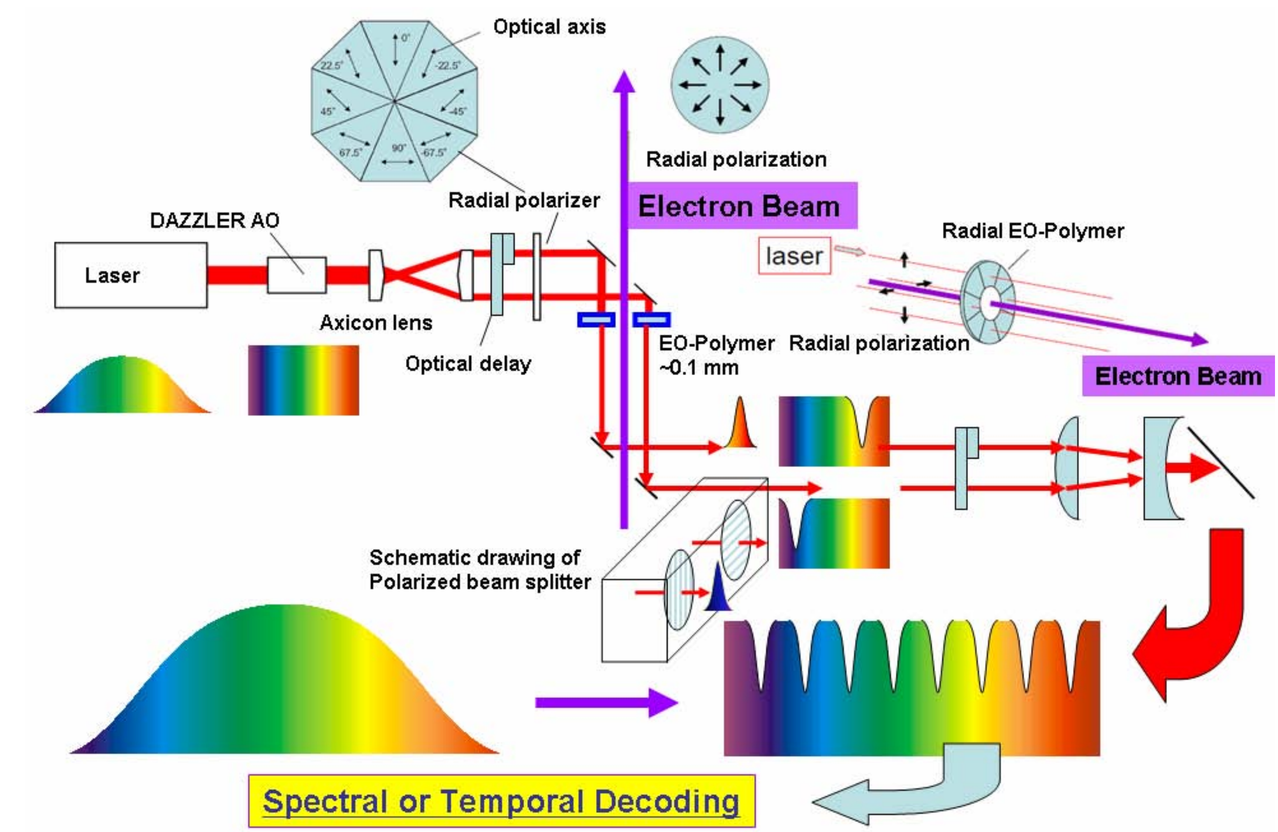

Figure 1: 3-D bunch structure monitor and its probe laser optics:
The probe laser for spectral decoding EOS is prepared as radial polarized and completely linearly chirped bandwidth (~500nm) supercontinuum generation. The EO-probe element is made of 8 EO-crystals (organic films) with the assembling of each EO-crystal's optical axes along radial beam axes. The linearly chirped probe laser is longitudinally sifted in 8 transverse sectors for each spectral decoding to analyze transversely multi-pole expansion.

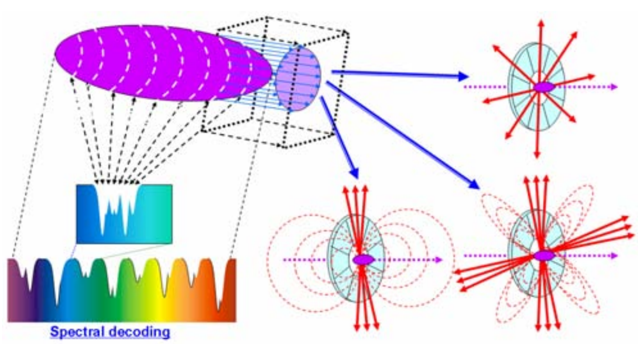

Figure 2: The principle of single-shot EOS-based 3-D bunch monitor: This 3-D bunch monitor with spectrograph detects and analyzes the Coulomb field of electron bunches as longitudinally spectral decoding and transversely multi-pole expansion. In the figure, the Coulomb fields of monopole, dipole, and quadrupole in the bunch slice are shown.

The probe laser will be generated with a photonic crystal, using the yearlong stable femtosecond laser source [8] developed for the SPring-8 RF gun. Recently, the photonic crystal has generated supercontinuum with a broad bandwidth of more than 500 nm. This broadband laser source is linearly chirped and temporally (spectrally at the same time) squared by a broadband AO-modulator (DAZZLER: UWB650-1100; FASTLITE). The squared linear-chirped broadband pulse is radial polarized and converted to a hollow laser pulse with optics we invented [9]. This hollow laser pulse is used as the probe laser for EOS as shown in Figure 1. Using this probe hollow laser pulse, the single-shot 3-D bunch monitor shown in Figure 2 is possible. We propose a single-shot EOS-based 3-D bunch monitor and report the optics for generating a hollow broad-bandwidth laser probe pulse.

CONFIGRATION AND COMPONENTS OF EOS-BASED 3-D BUNCH MONITOR

Radial polarizer for hollow broad-bandwidth laser beam as EOS probe

A radial polarized beam can be generated with 8-divided waveplates [10] as shown in Figure 1. However, the divided type has difficulty being utilized for broad bandwidth (500 nm) supercontinuum. For a broadband source, it is possible to use a radial polarizer based on liquid crystal. In Figure 3, the radial polarization test samples with 90-degree rotation of an additional polarizer for a white light source are shown, using the radial polarization converter based on liquid crystal.

It is necessary to generate the hollow laser beam for the probe laser, avoiding interaction with the electron beam bunch. The hollow laser beam is generated by an axicon lens pair, and then reflected in and out at the hollow mirrors in a vacuum. The ring width of the hollow probe beam is half of the incident beam radius at the axicon lens pair. The width should be as narrow as possible for accuracy to decode the field of the electron bunch slice.

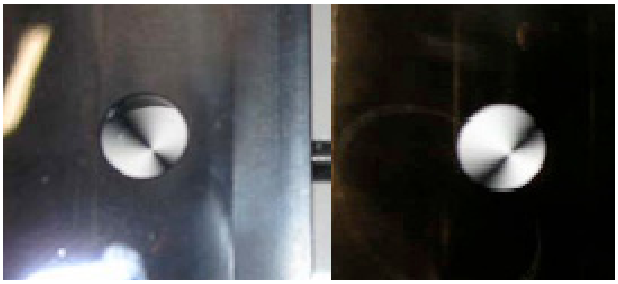

Figure 3: Radial polarization converter (ARCoptix, Switzerland) based on liquid crystal: Comparing the right and left (rotated 90 degrees from each other), it is clear that the converter generates a radial polarization.

Supercontinuum generation and transport

In order to generate supercontinuum (650-1100 nm) with a femtosecond laser oscillator, we selected a photonic crystal. The generated broadband laser has to be transported with optics without distortion in intensity and phase over the spectral range. It is difficult to maintain the whole spectral range, especially for a polarizer. The present status of the optical configuration is shown in Figure 4. At the moment, we have chosen the Glan-Laser Carsite Polarizer limited by the upper limit wavelength of 1000 nm. To maintain the entire supercontinuum spectrum, we are designing a Fresnel-Rohm and apochromatic waveplate.

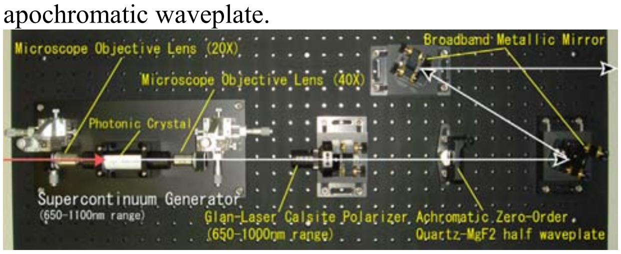

Figure 4: Supercontinuum generator (650-1100 nm) and broadband transport optics

Squared linear-chirped supercontinuum with compensation of transport distortion

The generated broadband laser is distorted in intensity and phase spectra. However, by introducing an AO-moderator, such distortion on intensity and phase spectra can be compensated. We want to prepare the probe laser pulse as a squared linear chirped pulse because it avoids computation to encode the electron-bunch-information-decoded spectra through detection with a spectrometer. Without complex computation to encode, it helps to detect the 3-D bunch structure at a high repetition rate.

We tested spectrum shaping with the AO-modulator DAZZLER, which can compensate optical dispersion up to 4th order in the phase spectrum and gain-narrowing in the intensity spectrum. We installed DAZZLER after the stretcher of the CPA configuration of the Ti: Sapphire terawatt laser. Because of too large a stretching factor of ~19000, it is beyond DAZZLER's capability to compensate GDD (Group Delay Dispersion) in this test. Therefore, we compensated just the gain-narrowing of spectrum for squared pulse generation. Streak spectrographs (streak image in spectrum) are shown in Figures 1 (initial) and 2 (square-shaped). It clearly shows that a square shape is generated successfully.

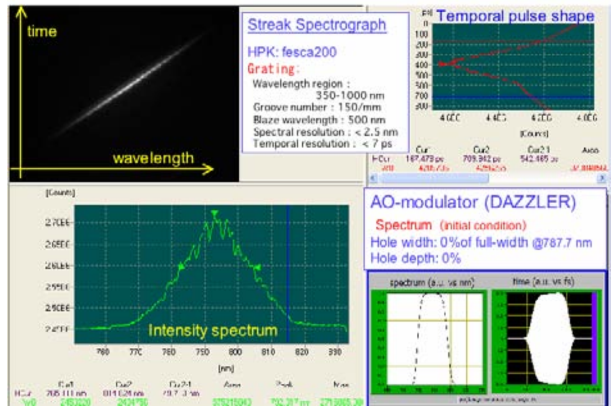

Figure 5: Initial intensity spectrum and chirp of the fundamental of Ti: Sapphire laser (after the stretcher): The linear chirp is measured by monochrometer combined with streak camera (Hamamatsu Photonics K.K.)

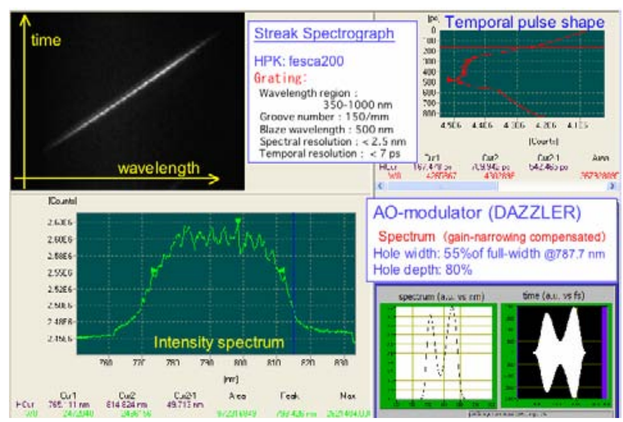

Figure 6: Squared intensity spectrum with a hole made on its spectrum by DAZZLER

EOS BUNCH MONITOR CHAMBER

It is possible to make several configurations of EOS-monitors with different functions and with different boundary conditions (3-D monitor shown in Figure 7, BPM-function shown in Figure 8). Besides, the temporal resolution τ that depends on the distance r between the monitoring probe laser position at the EO element and the charge centre of the electron bunch slice is given by

$$\tau = r/\gamma c\,,$$

where the Lorenz factor is γ, and the light speed is c. At the energy region of 8 GeV, with monitoring position r of 1 cm, temporal resolution τ will be 2 fs. The broad bandwidth of 400 nm determines the resolution of 20 fs (already mentioned). At the beginning of the test, the radial EO-probe element will be made of 8 EO-crystals with the assembling of each EO-crystal's optical axes along radial beam axes as shown in Figure 7. We are planning to use organic polymer film [11] for a femtosecond resolution EO-probe instead of inorganic crystals. The existing π-bonding in organic polymer causes a higher response of electrons for Pockels effect than inorganic crystals with only σ-bonding.

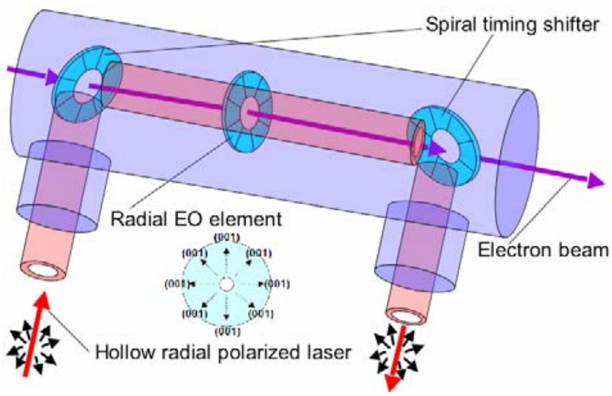

Figure 7: EOS bunch monitor for 3-D electron distribution monitor function: The linearly chirped hollow probe laser is shifted by the spiral timing shifter in 8 transverse sectors for spectral decoding. It has also function of total timing delay of the hollow probe laser, avoiding interaction with the electron beam bunch.

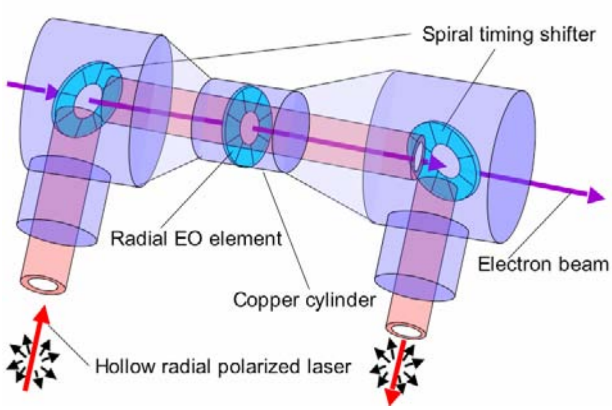

Figure 8: EOS monitor for BPM function: The 3-D monitor EOS chamber shown in Figure 7 is installed between two BPM EOS chambers.

With variation of distance r and boundary condition of a cylindrical metal wall, the combined EOS bunch monitor should be optimized in their geometry. The 3-D monitor function EOS chamber is installed between two BPM function EOS chambers. Analysis of three-dimensional charge distribution requires the charge centre position of the electron bunch slice at the EO element (see Figure 2). A spectrograph encoder detects and analyzes the Coulomb field of the electron bunches as longitudinally spectral decoding and transversely multi-pole expansion. The analysis of transversely multi-pole expansion can be done with the similar manner of a multi-strip-line-electrodes-type BPM [12].

SUMMARY AND DISCUSSION

We discussed a new concept of a 3-D electron bunch monitor based on EOS (spectral decoding), and showed the method for its optical configuration. Our single-shot bunch monitor can characterize the 3-D distribution and position of an electron bunch with femtosecond resolution. This EOS 3-D bunch monitor with spectrograph detects and analyzes the Coulomb field of electron bunches as longitudinally spectral decoding and transversely multi-pole expansion. This non-destructive monitor can be used as an electron energy chirping monitor at a dispersive region for XFEL commissioning.

The probe laser for EOS has been prepared as radial polarized and completely linearly chirped broadband (limited by 350 nm) supercontinuum generation. We are planning to use organic polymer film for a femtosecond resolution EO-probe instead of inorganic one.

At the encoding with the spectrometer the interferences will make resolution worse. Defusing techniques should be applied with the spectrometer.

In addition, we are developing an all-optical system for femtosecond-timing pump & probe experiments. The EO-sampled probe laser pulse will be used as a femtosecond-timing signal pulse. This signal pulse is amplified with a NOPA (noncollinear optical parametric amplifier), using an SHG of Yb fibre laser as a pump laser.

The total design of the EOS-monitoring and all-optical timing system can be improved and simplified with the recent progress of laser technologies.

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