COMPARATIVE STUDY OF ELECTRO-OPTIC EFFECT BETWEEN SIMULATION AND MEASUREMENT *

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Abstract

Electro-Optic Sampling (EOS) is a promising method to measure various properties of the electron beam non-destructively. In this Letter, a rigorous analysis procedure of the electro-optic (EO) measurement is introduced. The measured data of electron beam by electro-optic technique is analyzed in terms of the relative phase shift between the horizontal and the vertical components of the laser. A simulation study is done with the pulse propagation method, which utilizes Fourier transform to investigate the evolution of an electromagnetic pulse inside the EO crystal. The analysis result of the EO measurement expressed in terms of the relative phase shift is compared with the simulation, and they show a good agreement.

INTRODUCTION

Non-destructive measurement of the electron bunch length with femtosecond resolution is one of essential issues to operate XFEL facilities successfully [1]. During last several years, the EOS method has been successfully implemented to measure femtosecond electron bunches and arrival time at FELIX, SPPS, and FLASH facilities [2-8].

THEORY

EO crystals such as ZnTe and GaP have a character of birefringence materials when the electric field is applied to the crystal. The refractive index of the crystal can be calculated from the constant energy surface in the electric displacement vector space and the impermeable tensor that is linear to the electric field strength. The refractive index can be found from the refractive index ellipsoid equation by a principal-axis transformation [9, 10]. The two main refractive indices n_1, n_2 of the crystal along the principal axes are given by

$$n_1 = n_0 + \frac{n_0^3 r_{41} E}{2} \qquad (1)$$
$$n_2 = n_0 - \frac{n_0^3 r_{41} E}{2}$$

where n_0 is the initial refractive index, r_{41} is the electro-optic constant, and E is the electric field applied to the crystal. The difference in the propagation speeds, which is due to the different refractive indices, changes the polarization of the incident laser pulse. This brings the relative phase shift, Γ, between the horizontal component of the laser pulse and the vertical one, which is given by

$$\Gamma = \frac{\omega_0 d}{c}(n_1 - n_2) = \frac{\pi d}{\lambda_0} n_0^3 r_{41} E \qquad (2)$$

where d is the crystal thickness, ω_0 is the mean angular frequency of the laser pulse, c is the speed of light, λ_0 is the mean wavelength of the laser pulse, and E is the electric field applied to the crystal.

Detection scheme

A new method called Near Crossed Polarizer (NCP) scheme is developed. In the new detection scheme, the laser intensity is measured by a quarter wave plate, a half wave plate, a polarizer, and a detector. The intensity with NCP scheme is calculated by the multiplication of the Jones matrices of the each wave plate [11]. The calculated intensity is given by

$$I(\theta, \varphi, \Gamma)\ /I_0 = \left[1 - \cos(\Gamma)\cos(4\theta - 2\varphi)\cos(2\varphi) + \sin(\Gamma)\sin(4\theta - 2\varphi)\right]/2 \qquad (3)$$

where θ is angle of the half wave plate, φ is angle of the quarter wave plate, and I_0 is the initial laser intensity incident on the EO crystal. The signal level and the background are also changed according to the angles of the half and the quarter wave plates. The signal to noise ratio can be increased by the control of the angle of the plates [12].

EXPERIMENT

At the FLASH facility in DESY, there is an EO diagnostic section called Timing Electro-Optic (TEO) setup to measure the electron beam properties. The TEO setup is used to measure the bunch length and the timing jitter of the electron beam by the spatial decoding method with GaP crystal as shown in Fig. 1 [8].

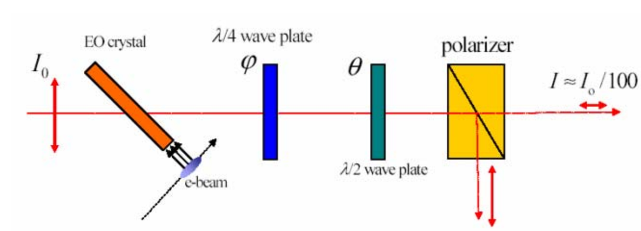

Figure 1. Layout of the electro-optic sampling.

In the spatial decoding method, the laser pulse is propagated through the EO crystal with 45° angle, and the timing information of the electron beam is converted to the spatial information of the image measured by the ICCD camera [5, 8].

In order to study the electro-optic effect induced by the electron beam, it is necessary to know the initial intensity of the laser as shown in Eq. (3). Normally, the initial intensity of the laser for the EO diagnostic is so high to be measured by ICCD camera directly without damaging ICCD itself. Thus, the initial intensity of the laser is extrapolated from the measured data with several angles of the half wave plate using Eq. (3), where ICCD can detect the intensity of the laser passing through the EO crystal and polarizer safely. If the angle of the quarter wave plate is fixed, the laser intensity at the ICCD is controlled by the half wave plate in front of the polarizer as shown in Fig. 1. The extrapolated initial intensity of the laser is 4466 which will be shown elsewhere.

A measurement result is shown in Fig. 2 which shows a signal with 47.6 unit of the ICCD at 12.6 ps position in the measurement window.

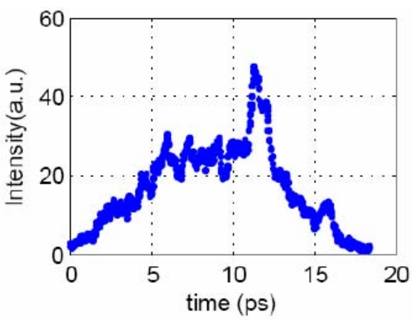

Figure 2. Electron beam measurement by TEO setup at FLASH. The GaP crystal thickness is 180 μm. The distance between the electron beam and the laser at the crystal is 2 mm on average. The half wave plate angle is 0^o. The quarter wave plate angle is -2^o.

There is a small peak at 16 ps position, which is generated by the reflection of THz radiation at the back surface of the EO crystal [10]. The time duration between the main peak and the small one is determined by the thickness of the EO crystal and the speed of THz radiation in the EO crystal. The GaP crystal thickness used in this experiment is 180 μm. It makes the travel distance of THz radiation 360 μm which corresponds to 3.4 ps travel time. The radial distance from the electron beam and the EO crystal can be controlled by a remote control system. The radial distance between the electron beam and the crystal in the measurement is 2 mm on the average which can be known from the radiation detection by glass optic fibers in FLASH [13].

The maximum relative phase shift Γ of the measured pulse can be calculated from Eq. (5) with the peak value of the measured data in Fig. 2. In the measurement, the angle θ of the half wave plate is set to 0^o and the angle φ of the quarter wave plate is set to -2^o. Analysis of the peak in Fig. 2 with the initial laser intensity I_0 = 4466 is shown as

$$\begin{aligned} &I\left(\theta=0^\circ,\ \varphi=-2^\circ,\ \Gamma\right)=47.6 \\ &=\frac{4466}{2}\left[\begin{matrix}1-\cos(\Gamma)\cos\left(-2\times(-2^\circ)\right)\cos\left(2\times(-2^\circ)\right)\\ +\sin(\Gamma)\sin\left(-2\times(-2^\circ)\right)\end{matrix}\right] \end{aligned} \tag{4}$$

From the solution of Eq. (4), we can get the relative phase shift Γ = 7.13^o which represents that the laser passing through the EO crystal is elliptically polarized.

SIMULATION

In the simulation, the electric field inside the crystal is calculated from the longitudinal profile of the electron beam. The pulse propagation method, which utilizes Fourier transform of the electric field to investigate the evolution of the electric field inside the EO crystal, is used in this simulation.

An electron beam with Gaussian charge distribution is generated to simulate the measurement. The beam charge Q is set as 0.06 nC and the rms pulse width σt of the electron beam is set as 40 fs which corresponds to the bunch length of the electron beam 12 μm. The thickness of GaP is the same 180 μm as the experimental condition. Simulation results for different distances between the electron beam and the crystal are shown in Fig. 3, and the peak values for different distances are shown in Fig. 4.

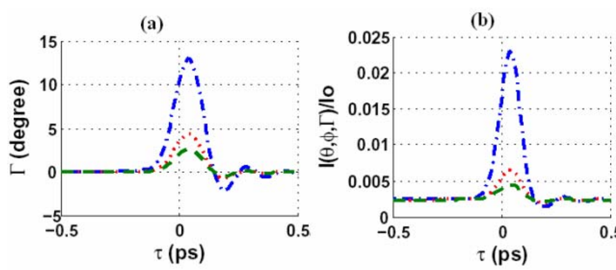

Figure 3. Simulation results: (a) The relative phase shift Γ, and (b) the intensities from NCP scheme are shown. The dash-dot line (top) represents the result of the distance between laser and the EO crystal R = 1 mm, the dotted line (middle) represents the result of the R = 3 mm, and the dashed line (bottom) represents the result of the R = 5 mm. The charge of the electron beam is 0.06 nC and the rms pulse width is 40 fs. The half wave plate angle θ is 0^o and the quarter wave plate angle φ is -2^o.

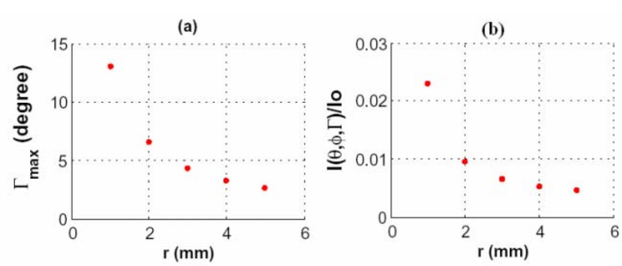

Figure 4. Simulation result for different distance R. (a) Maximum points of Fig. 6 (a) are plotted along R. The data is fitted by Eq. (10) shown as a solid line. (b) Maximum points of Fig. 6 (b) are plotted along R. The curve is the fitting result with Eq. (11).

SUMMARY

This Letter introduces a rigorous procedure to analyse the EO technique to measure the electron beam non-destructively. The initial intensity of incident laser is obtained by the extrapolation of the data measured at lower intensity. Accurate relative phase shift obtained by precisely estimated incident laser intensity and NCP scheme provides EOS as a tangible technique for non-destructive measurement of electron beams. Simulation results with the pulse propagation method are well matched with the analysis result of the measurement.

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