A STUDY OF DETECTION SCHEMES IN ELECTRO-OPTIC SAMPLING TECHNIQUE*

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Abstract

Electro-Optic Sampling (EOS) is the ingenious tool for the measurement of the electron beam. There are two traditional detection schemes: one is the crossed polarizer scheme and another is balanced detection one. A new detection scheme called 'Near Crossed Polarizer' (NCP) scheme in the EOS technique is developed to increase the signal to noise ratio (SNR) in the experiment. The new detection scheme is studied in detail and the 3D scanning result with electron beam in FLASH is compared with the detection scheme.

INTRODUCTION

The detection schemes for EOS measurement are studied in theoretically and experimentally also. Two traditional detection schemes are the crossed polarizer and the balanced detection scheme. Those have each difficulty to be applied in real diagnostic in the EOS measurement of the electron beam. To overcome those difficulties, new detection scheme called 'Near Crossed Polarizer' scheme is developed. In this letter, the detail study of the NCP scheme is shown with 3D scanning result of the EOS measurement.

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 [1, 2]. The two main refractive indices n_1, n_2 of the crystal along the principal axes are given by

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

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 of the propagation speeds of each laser component, 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

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

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 schemes

There are two traditional methods to detect the polarization change; the crossed polarizer scheme and balanced detection one. In the crossed polarizer scheme, the laser intensity is measured by a polarizer and a detector. The analytic expression of the intensity difference ΔI in the case of the crossed polarizer scheme is given by [1, 2]

$$\Delta I = I_0 \sin^2\left(\Gamma / 2\right) \qquad (3)$$

where Γ is the relative phase shift between the two polarized parts of the laser field and the I_0 is the initial intensity of the laser pulse. There is another method to detect the polarization change called balanced detection scheme. In the balanced detection scheme, the laser intensity is measured by a quarter-wave plate, a polarizer and two detectors. The quarter-wave plate enhances the relative phase shift by a quarter of one wave length. The analytic expression of the intensity difference ΔI in the case of balanced detection scheme is given by [1, 2]

$$\Delta I \equiv I_h - I_v = \left|\mathrm{E}_h\right|^2 - \left|\mathrm{E}_v\right|^2 = I_0 \sin\left(\Gamma\right) \qquad (4)$$

where all parameters are same with above Eqs., h and v represent 'horizontal' and 'vertical' each. When the relative phase change Γ is 7^o in the crossed polarizer scheme, the change of the initial laser intensity is merely 0.37% from Eq. (3). This signal change is too low to be detected in real diagnostics setup. However, in the balanced detection scheme, there is 12% change of the initial laser intensity from Eq. (4) for the same Γ. The signal level is high enough to detect, but the balanced method is difficult to apply in real diagnostic setup. To overcome those difficulties, 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 [3]. The calculated intensity is given by

$$
\begin{aligned}
I(\theta,\ \varphi,\ \Gamma) \\
&= \left[1\ +\ \cos(\Gamma+2\varphi-4\theta)\sin^2\varphi-\cos(\Gamma-2\varphi+4\theta)\cos^2\varphi\right]/2 \\
&= \left[1-\cos(\Gamma)\cos(4\theta-2\varphi)\cos(2\varphi)+\sin(\Gamma)\sin(4\theta-2\varphi)\right]/2
\end{aligned}
\qquad (4)
$$

where the θ is angle of the half wave plate, φ is angle of the quarter wave plate and the I_0 is the initial laser intensity incident to the EO crystal. The signal level and background also are changed according to the angles of the half and quarter wave plates. In Fig. 1, the experimental layout with the NCP scheme is shown.

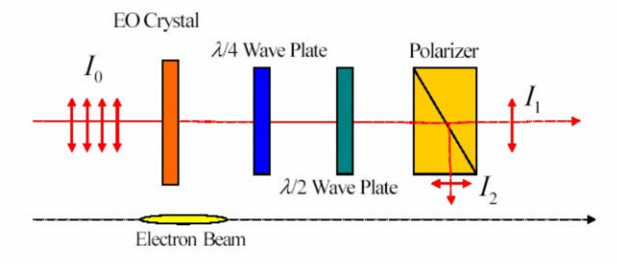

FIG. 1. Layout of the electro-optic sampling.

In Fig. 2, there is a measurement result of the electron beam with the NCP scheme in FLASH [4].

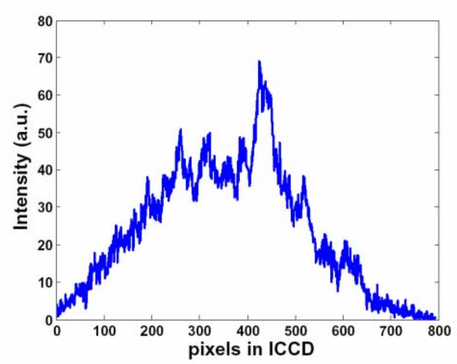

Fig. 2. The typical measurement of the electron beam in FLASH. In this measurement, the quarter wave plate is set as -4 degree and the half wave plate is set as -2 degree. The GaP crystal thickness used in this measurement is 180 μm. The distance between the electron beam and the crystal is 1.5 mm on average. The electron beam energy is 800 MeV and the total electron beam charge is 0.8 nC.

3D view of the signal in NCP scheme

In Fig.3, the theoretical intensity change of EO signal by half and quarter wave plate is shown with 3D plot when Γ is 2 degree. The background intensity change which means Γ is 0 degree is not shown in this paper, however the behaviour of the two graphs is similar.

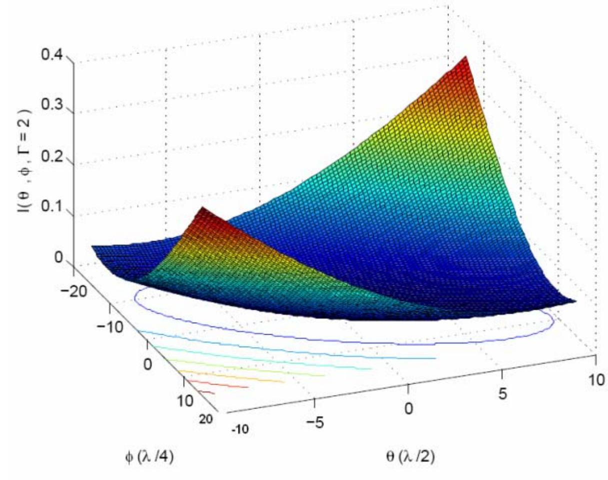

Fig. 3. The intensity with 'crossed polarizer scheme' when Γ is 2 degree. θ is the angle of half wave plate for compensation and φ is the angle of quarter wave plate. Note that y axis is normalized by the initial laser intensity.

In Fig. 4, the measurement result of the theoretical prediction shown in Fig. 3 is plotted.

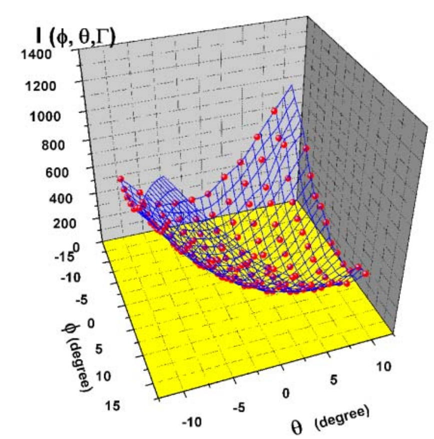

Fig. 4. The intensity with 'crossed polarizer scheme' measured in FLASH. θ is the angle of half wave plate for compensation and φ is the angle of quarter wave plate. Note that y axis is not normalized by the initial laser intensity. The unit is same with the Fig. 2 i.e. the ICCD unit.

SCANNING RESULT IN TEO SETUP IN FLASH

The half and quarter wave plates are scanned to find the best condition to measure the electron beam. In Fig. 5, the theoretical prediction of the SNR function in 3D view is shown, in which the peak position is where the θ = 0 and φ = 0 because the theoretical background is 0.

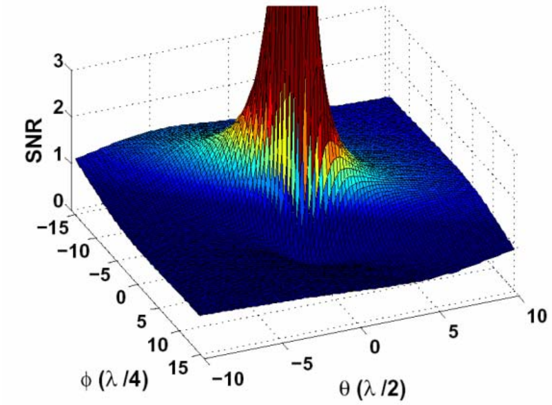

Fig. 5. Theoretical prediction of SNR. θ is the angle of half wave plate for compensation and φ is the angle of quarter wave plate.

There is a region lower than 1 which means the signal is lower than the background. This can be occurred at certain angles of the half and quarter wave plate, because the changed polarization of the laser pulse with the angles is decreased by the modulation of EO crystal.

In Fig. 6, the experimental result of the SNR function in 3D view is shown.

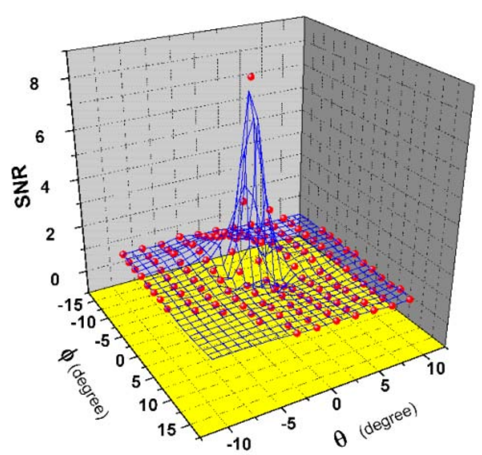

Fig. 6. SNR measured in FLASH. θ is the angle of half wave plate and φ is the angle of quarter wave plate.

In Fig. 6, the peak position is not at θ = 0 and φ = 0 point due to the leakage of the laser due to the imperfection of the polarizer. The background is not 0 even at θ = 0 and φ = 0, so the denominator of the SNR function is not 0. That makes the shift of the maximum position of SNR. With θ = 0 and φ = 0, the NCP scheme is same with the CP scheme, that means the level of signal is quite low to be detected in some situation. In the real diagnostics experiment, the maximum SNR point should be searched in each diagnostics setup to make balance between the SNR and the absolute signal level to be detected with good resolution.

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