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Ultrafast laser-wire scanning with Electro-Optics

A. Bosco, G.A.. Blair, G. Boorman, C. Driouichi, M. Price
Dept. of Physics, Royal Holloway, Univ. of London, Egham, Surrey. TW20 0EX. UK

The possibility is presented of using electro-optics techniques to increase laser-wire scanning rates for intra-train scanning at the international linear collider (ILC). The requirements include the preservation of the laser beam mode quality and the ability to work with laser beam powers of order 10 MW. The first ideas of a possible device configuration are presented together with a survey of EO materials and first experimental results using linear prisms.

1. INTRODUCTION

The Laser-wire (LW) is a very important tool for non-invasive electron beam profile measurements. The LW works by scanning a focussed laser beam across an electron (or positron) beam. The number of Compton-scattered photons as a function of laser spot position then provides information on the bunch transverse profile. In recent years many issues relating to these devices have been tackled and partially solved. For instance, much effort has been spent improving their resolution by focussing the laser beam down to a waist comparable with the electron beam size while maintaining a sufficient scanning range of approximately 5 times the size of the bunch [1, 2].

Another important issue related to a real-time LW monitor is the scanning speed. So far, two different scanning techniques have been considered; moving the entire LW optical system [1] and deflecting the laser beam with piezo-driven mirros [2]. Piezo driven mirrors preserve the beam quality but their speed is limited by the load (scanning mirror) attached to the piezo driver. The first idea to improve the scanning speed was to use acousto-optic devices, whose time response could be as fast as 500 ns [3]; however their major limitations are a very low damage threshold and a low diffraction efficiency (< 40%) , which dramatically affects the beam quality. Electro-optic (EO) techniques may be the key for reaching scanning rates of ~100 kHz, such as are needed for scanning bunches within an ILC train.

2. ELECTRO-OPTIC EFFECT

Consider the parameters of the ILC [4], with trains of about 2800 electron bunches spaced by 337 ns, giving a bunch repetition rate of ~3 MHz. A scanner capable of running at a rate of ~100 kHz would then provide information about the particle beam size in about one hundred different positions along the train. Such high frequencies might be reached by exploiting the EO effect, where a refractive index change is induced by an applied electric field:

$$\Delta n = \frac{1}{2} n^3 \overleftrightarrow{r} \bullet \vec{E}$$

where n is the linear refractive index, $\vec{E}$ is the E-field vector and $\overleftrightarrow{r}$ is the EO tensor, whose form and magnitude depends on the material. This refractive index modulation will change the refraction direction through an interface between the EO medium and the output (linear) medium.

Although being very fast, the EO refractive index change remains relatively small ($\Delta n \sim 10^{-5}$ with E = 1kV/cm). Moreover, the transverse dimension of the EO crystal, defining its optical aperture, should be sufficient to accommodate larger laser spot sizes both to enable working with lower laser intensities and to focus the beam down to a smaller waist. On the other hand, the applied E-field is inversely dependent on the thickness of the crystal so that the thicker the crystal, the higher must be the applied voltage. A set of test facilities are in operation (or in advanced planning) with a view to addressing the key technological challenges fast LW scanning. These are now outlined in turn.

2.1. Material

A survey and analysis of EO materials available on the market is presented here. The chosen material should be easily available, with a relatively high nonlinear EO coefficient and, most of all, possess a very high optically induced damage threshold. A list of EO crystals is given in Table. I.

Table I: A list of EO crystals with properties relevant to Ultra-fast LW scanning

Material	EO coefficient [pm/V]	Linear refr. ind.	$\Delta n = 0.5 n_3 r_{ij} E_j$ (E=2.5kV/cm)	Damage Threshold [MW/cm^2]
$KNbO_3$	$r_{42} = 380$	$n_2 = 2.28$	4.5×10^{-4} (E_y)	350 (10ns)
$LiNbO_3$	$r_{33} = 30$	$n_3 = 2.15$	3.73×10^{-5} (E_z)	200 (10ns)
$LiTaO_3$	$r_{33} = 32$	$n_3 = 2.19$	4.2×10^{-5} (E_z)	500 (10ns)
SBN75	$r_{33} = 1340$	$n_3 = 2.27$	1.96×10^{-3} (E_z)	-
$KTiOAsO_4$	$r_{33} = 40$	$n_3 = 1.86$	3.11×10^{-5} (E_z)	10^4 (100ps) 10^3 (8ns)
$KTiOPO_4$	$r_{33} = 35$	$n_3 = 1.90$	3×10^{-5} (E_z)	500 (20ns)

At first sight, it seems that the SBN75 would be the best choice; nevertheless, it has a very low damage threshold due to a strong photorefractive effect. For the same reason, $LiTaO_3$, $KNbO_3$ and also $LiNbO_3$ (LNB) cannot be used. For high power application the best candidate is $KTiOAsO_4$ (KTA). Nevertheless, we decided to start our experimental investigation using LNB since it is a material that is readily available and, by doping it with magnesium, its photorefractive properties can be strongly reduced. According to Tab.1, both LNB and KTA would experience a similar refractive index change under the same E-field. In Tab. 1 Δn has been calculated for an electric field of 1 kV across a thickness of 4 mm (2.5 kV/cm); a variation of refractive index of approximately 4×10^{-5} is predicted.

2.2. Configuration

According to Snell's law, the variation of refractive index corresponds to a variation $\Delta\theta$ of the output direction that is linear in Δn. Moreover, for output angles close to the normal direction, this $\Delta\theta$ is equal to Δn. Such a tiny refractive index modulation would then give $\Delta\theta$ as small as 40 μ rad. The chosen configuration for the scanning device is a prism shaped EO crystal as shown in fig. 1. In this case, Δn would apply to both input and output refractions giving a total deflection $\Delta\theta = k \cdot \Delta n$, where the coefficient k depends on the prism angle α and increases rapidly when approaching total internal reflection. However the prism also acts as a focussing lens in the horizontal direction, turning the circular beam into an elliptical beam, and this effect also becomes stronger close to total internal reflection. A compromise between beam quality and prism steering efficiency must therefore be found.

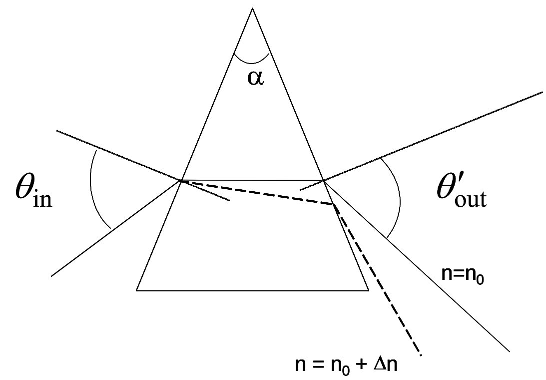

Fig. 1. Electro-optic prism. The dashed line represent the beam path when the refractive index is changed

Maintaining the output direction θ' at around 65°, it is possible to have an acceptable (or at least correctable) beam ellipticity. If the prism is embedded in a medium with intermediate refractive index, as shown in fig. 2, there are two refractions: prism-medium and medium-air which together may increase the *k* coefficient by about a factor of 4. The resulting deflection ($\approx 150\,\mu$rad) is still fairly small; focussing the beam with a 250 mm lens results in a total scan range $\Delta = f\Delta\theta$ of approximately 35 μm, which is comparable with the waist dimension. The proposed solution for increasing the angular deflection is to use additional linear prisms to amplify the change of output angle from the nonlinear one.

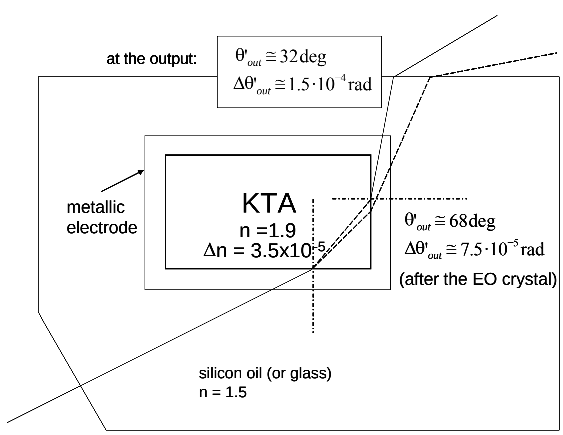

Fig. 2. EO prism embedded in an intermediate medium. The deflection is increased by the second interface

2.3. Experimental Studies

A study has begun at RHUL of the effect of a prism on light deflection and the resulting introduced ellipticity. The experimental setup is sketched in Fig. 3. A mirror mounted on a rotary stage with 500 μrad sensitivity simulates the effect of the EO prism. A focussing lens with focal length of 250 mm transforms the deflection into a translation of the focal point according to $\Delta = f\,\Delta\theta$, which is measured by a CCD camera plus a ×7 magnification system.

The position of the focus and the beam ellipticity were then measured as a function of angle of incidence. Without a prism the beam is circular (ω_x = 33 μm, ω_y = 26 μm) and a translation of 250 μm was obtained. Using a prism with an output angle of 61°, the translation increases to 410 μm but the beam become elliptical (ω_x = 60 μm, ω_y = 30 μm).

Going to an output angle of 71° the beam shift at the focus increases to about 600 μm but the beam distortion become very large (ω_x = 85 μm, ω_y = 30 μm).

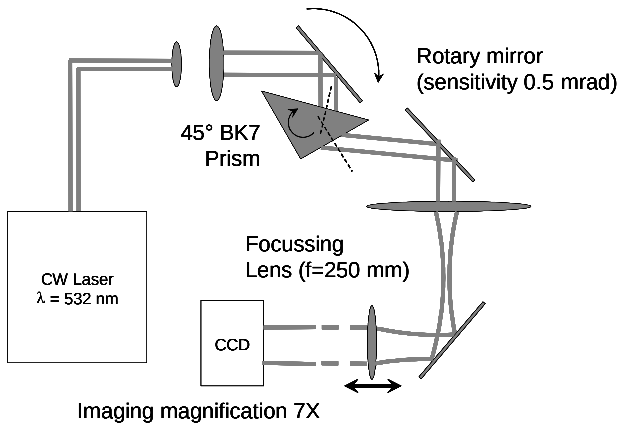

Fig. 3 Experimental set-up for measurements of prism-induced laser beam properties.

3. CONCLUSION

As expected, the use of prisms to change the beam direction affects the beam quality. Nevertheless, it may be possible to correct this ellipticity, for instance by using an (oppositely) elliptical incident beam. A second possibility is to increase the driving voltage in order to increase the EO deflection and work far from the critical angle. This would of course decrease the speed of the device, but it would still be faster than the piezo-scanners.

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