AN ULTRAFAST LASER-WIRE SCANNER BASED ON ELECTRO-OPTICS*

A. Bosco#, G. A. Blair, S. T. Boogert, G. Boorman,
John Adams Institute at Royal Holloway University of London, Egham, UK.

Abstract

A complete optical characterization of an electro-optic deflector to be used for fast laser-wire electron beam profilers performed using a 130 kHz repetition rate mode-locked laser, is presented. Incorporation of the device into the 2D laser-wire at PETRA III synchrotron at DESY is discussed.

INTRODUCTION

Laser-based beam profile monitors, and in particular the laser-wire (LW), will be standard tools for electron beam sizes measurements in future synchrotron light sources [1] and electron–positron colliders [2].

One of the main advantages in using such a technique is that the LW is inherently a non-invasive profiling system [3]. Furthermore, it allows sub-micrometric resolution [4], and fast profiling speed [1], [5].

In [5], an extensive analysis of an original design of a large aperture electro-optic (EO) scanner was presented and in [6] experimental measurements of its deflection strength and on the preservation of the laser mode quality were performed using a laser operating at 2 kHz repetition rate. This work is the natural continuation of [5] and [6]; it presents in fact, the latest experimental results from the same EO prototype using a fast laser at 130 kHz repetition rate.

PRINCIPLE OF OPERATION

The principle of operation of the presented device is based upon the generation of a linear gradient of refractive index across the transversal laser beam cross-section obtained through the linear EO effect. In fact, an EO material experiences a change Δn in the refractive index n_0 that is directly proportional to an applied static electric field, according to [6]:

$$\Delta n = \frac{1}{2} n_0^3 r_{33} E_z , \quad (1)$$

where r_{33} is the EO coefficient which couples a linearly polarized laser beam to a parallel electro-static field along the crystallographic c-axis E_z [note that the more general coupling formula is tensorial and eq. (1) is valid only for a particular class of materials such as the one treated in the text]. Now, if the static electric field is applied through an arrangement of alternated electrodes hyperbolically shaped, as shown in Fig. 1, the component E_z (and therefore Δn according to Eq. 1) will vary along the transversal coordinate from a positive to a negative maximum amplitude, with a nil value in the centre of the crystal.

The effect of such modulation of the refractive index on a laser beam that propagates through the EO crystal will be that the right side will travel at a different speed than the left one. Thus the laser beam wave-front will deflect in a measure proportional to the refractive index difference and the propagation length [5].

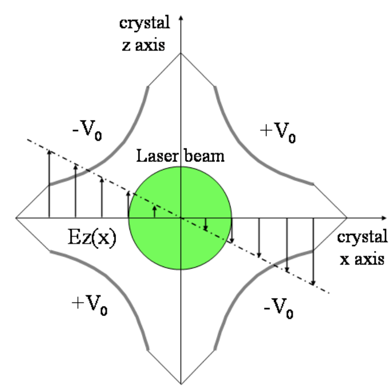

Figure 1. Schematic picture of a quadrupole EO deflector. The value of the refractive index changes from left to right by $2\Delta n$ given by Eq.1.

PROTOTYPE DETAILS

A type of EO scanner based upon the principle described in the previous section is already available on the market but there is a fundamental limitation on the optical aperture (and a consequent limit in its use with high power lasers), due to the fact that the electrodes are shaped directly on the EO crystal (the largest clear aperture available in the market is around 3 mm diameter). In fact, to obtain a device with large clear aperture, it would require growing a good (homogeneous) crystal with extremely large dimensions (16x16 mm^2 for a clear aperture of 6 mm) with obvious technical growth problems.

In [5], in order to overcome this problem, we proposed a hybrid solution in which the electrodes were shaped on a holder made of Perspex, a common polymer (a picture of the device is shown in Fig. 2). A 8.6 mm hole was drilled through the holder in order to accommodate the EO medium. The chosen EO material was a 90 mm long

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alessio.bosco@rhul.ac.uk

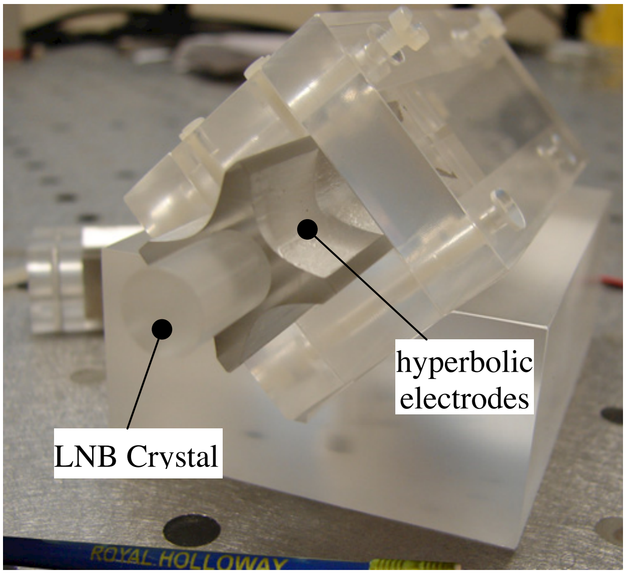

Figure 2. Picture of the realized crystal holder with hyperbolic shaped electrodes.

cylinder of Lithium Niobate doped with MgO to decrease the unwanted photo-refractive effect that would otherwise be strong at the interesting wavelength of 532nm.

The obvious advantage of this configuration is that the clear aperture coincides with the diameter of the EO crystal cylinder. The realized prototype had a clear aperture of 8.6 mm, capable to accept a beam diameter up to 5.5 mm (within the diffraction limit 8.6 mm/1.57 [7]). On the other hand, the electric field that generates the refractive index has to propagate through an interface between two media with different dielectric properties. This might result in an actual electric field that is distorted from the ideal case of Fig. 1. This problem was treated analytically in [5] where it is shown that the distortions of the electric field at the interface are localized at the interface. Moreover, these distortions can be reduced further in two different ways: first, by choosing materials for the holder and the EO core with better dielectric matching; and second by optimizing the shape of the electrodes.

EXPERIMENTAL TESTS

The experimental setup used to test the device is sketched in Fig. 3. The laser used for these tests was a frequency doubled mode-locked Nd:YVO_4 laser emitting 10 ps pulses with a repetition rate of 130 kHz and wavelength of 532 nm. A TTL signal from the laser synchronization box was then input to a National Instruments^{TM} PC card in order to generate a subharmonic signal locked to the laser for triggering the CCD camera.

The laser beam profiles were recorded using a Gentec^{TM} CCD camera (model WincamD) externally triggered. The CCD camera was placed after a plano-convex lens with a focal length of 1 m, for recording the beam shift at the focal plane in order to calculate the deflection.

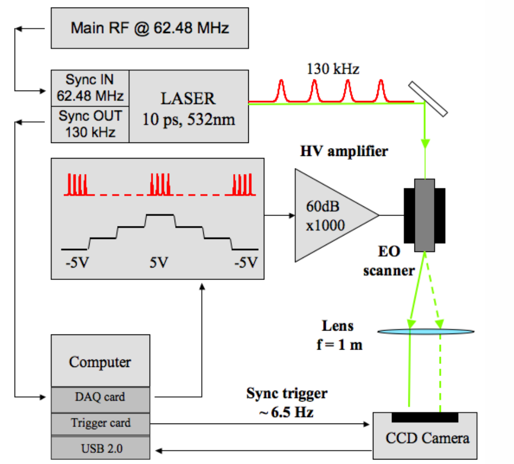

Figure 3. Experimental setup.

An amplifier with a gain of 60dB (1000X) and bandwidth of 75 kHz, fed by a stepped ramp function from -5V to +5V, was used to supply the high voltage to the EO device. The synchronization and control signal generation was managed by a DAQ software written in a Labview platform.

In Fig. 4 is reported a series of images of the laser profile for applied voltages from -5kV and +5kV in 2kV steps. The HV driving functions consisted of a series of stepped ramps from -5kV to +5kV and then back to -5kV, with a step of 1kV (as illustrated in Fig. 3). Each step contained 3 laser pulses and was 25 μs long. A trigger, obtained by dividing the TTL signal from the laser by an appropriate factor, was used to gate the CCD camera, in order to record the beam at different voltages within each cycle. We could measure, using the profiles in Fig 4, a beam displacement at the focal plane of 1.2 mm, i.e. an angular scan range of 1.2 mrad. From this measurement we could quantify a deflection factor of 120 μrad/kV. The laser beam is focused down to $\sigma = 37$ μm (see Fig. 4), therefore the total deflection is about 32 times σ.

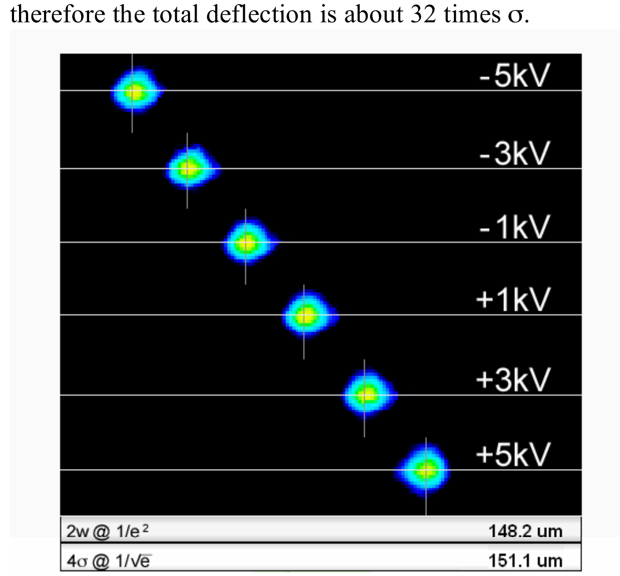

Figure 4. Images of the laser pulses during scan operation.

FUTURE TESTS AT DESY

The described device will be incorporated within the 2D LW currently being installed in the PETRA III synchrotron accelerator at DESY for tests of LW scanning operation at 130 kHz repetition rate (matching the accelerator's round trip frequency).

The layout of the 2D LW breadboard is pictured in Fig. 5. The mirror SM is mounted on a motorized translation stage and it is used to select the path of the laser for either vertical or horizontal profiling. The vertical profiler's lens (LV) focal length is 250 mm whereas the horizontal one's (LH) is 750 mm. The normal operation of the scanner will be similar to the previous version (extensively described in [1]), and it will use the same Q-switched laser emitting 5 ns long pulses at 20 Hz repetition rate with a peak power of 5 MW. The upgraded version was designed to measure electron spot sizes down to 10 μm (5 times smaller than achieved in [1]).

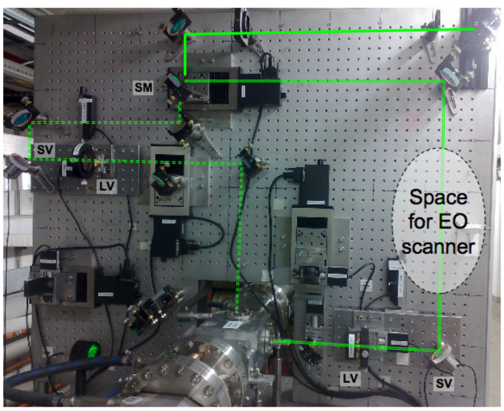

Figure 5. Picture of the 2D LW installed at PETRA III.

The fast deflector will be installed within the vertical profiler laser path (solid lines in Fig. 5). Both the focused waist and the scan range scale linearly with the focal length of the lens; therefore, with the values reported in the previous section, the dimension at the interaction point is expected to be about 9 μm and the scan range approximately 400 μm, both useful value for a full scan of a 10 μm electron beam.

CONCLUSIONS

In conclusion, we realized and tested an EO device capable of deflecting a pulsed laser beam (test were done using a repetition rate of 130 kHz using a step function with 70 μs long steps). The clear aperture of the device was 8.6 mm, 3 times bigger than what is available on the market.

The obtained deflection, which was 32 times σ, makes the device suitable for use within a LW profiler [1].

The next experimental tests on the same device will be performed at the PETRA III synchrotron machine within the already installed 2D LW breadboard.

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