ELECTRO-OPTIC SAMPLING OF TRANSIENT FIELDS FROM THE PASSAGE OF HIGH-CHARGE ELECTRON BUNCHES*

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Abstract

When a relativistic electron bunch traverses a structure, strong electric fields are induced in its wake. We present measurements of the electric field as a function of time as measured at a fixed location in the beam line. For a 12 nC bunch of duration 4.2 ps FWHM, the peak field is measured > 0.5 MV/m. Time resolution of ∼5 ps is achieved using electro-optic sampling with a lithium tantalate ($LiTaO_3$) crystal and a short-pulse infrared laser synchronized to the beam. We present measurements under several different experimental conditions and discuss the influence of mode excitation in the structure.

1 INTRODUCTION

Since the pioneering experiments [1–3], electro-optic sampling (EOS) has been shown to be a powerful technique for fast time-domain measurements of electric fields [4, 5].

The use of electro-optic sampling for accelerator applications has been previously suggested by [6–8] and others. Detection of the beam current by magneto-optic effects has been demonstrated by [7] with a time resolution that is sub-nanosecond.

Recently, at Brookhaven, electro-optic detection of a charged particle beam was reported by detecting a faint light pulse through crossed polarizers as the beam passed by an electro-optic crystal [9]. The time resolution possible here is limited by the speed of the photodetectors and amplifiers, which similar to that available with capacitive beam pickups (∼100 ps). Earlier at Brookhaven, an RF phase measurement using the electro-optic effect and phase stabilization by feedback was demonstrated [10].

We have used electro-optic sampling to measure the electric field waveforms in vacuum induced by the passage of electron bunches with an estimated time resolution of ∼5 ps, limited by the laser pulse length [11, 12].

Independently of our work, a group at FOM Rijnhuizen (Nieuwegein, The Netherlands) has used electro-optic sampling in ZnTe to resolve the sinusoidal electric field of the free electron laser FELIX at the optical frequency ($\lambda = 150$ μm) [13]. Of note is the rapid-scanning cross-correlation technique (a fast data-acquisition trick). The same group has sampled the electric field of the transition radiation from the electron beam exiting a beryllium window [14] and the electric field in vacuum [15] from which the bunch length is measured.

We have thus far been unable to reproduce their results with ZnTe; we suspect a problem with our crystal.

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2 EXPERIMENT

The linear electro-optic effect (or Pockels effect) is one of several nonlinear optical effects that arise from the second-order susceptibility tensor $\chi^{(2)}$, and is described in many standard texts, such as [16]. For our purposes, it suffices that the polarization of light is altered by an electric field applied to the crystal. By analyzing the polarization change, the electric field can be measured. Using a short laser pulse and a thin crystal, the electric field is sampled at a particular time T_i when the laser pulse arrives at the crystal. By changing the delay of the probe laser arrival time, and repeatedly measuring the electric field, the electric field waveform is recovered by electro-optic sampling. The data acquistion is handled by LabVIEW and a digital oscilloscope.

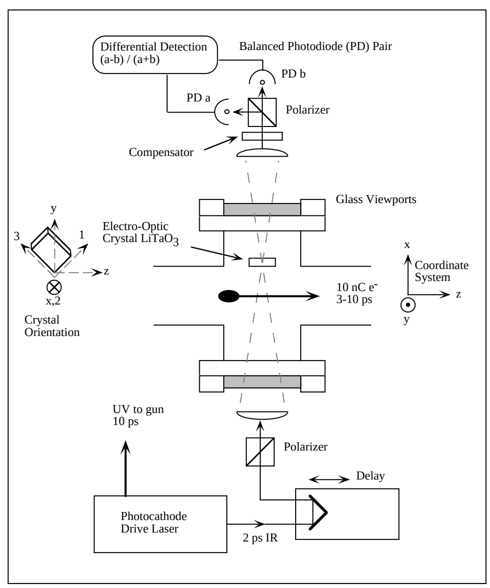

Figure 1: EOS configuration, sensitive to $(E_z + E_\theta)/\sqrt{2}$.

Experiments were performed at the AØ Photoinjector of Fermilab [17, 18]. A lamp-pumped Nd:glass laser system built by the University of Rochester is quadrupled to UV ($\lambda = 263$ nm) for photocathode excitation. The UV pulses are temporally shaped to an approximate flat-top distribution with a 10.7 ps FWHM. Unconverted infrared light is the probe laser for the electro-optic sampling, so that jitter between the beam and the probe laser vanishes to first order. The photoinjector produces 12 nC bunches with normalized emittance of 20π mm-mrad (uncompressed) in pulse trains up to 200 pulses long with interpulse spacing 1 μsec. A chicane of four dipoles was used for magnetic compression. In a companion paper in these proceedings we present some compression studies. The best compression to date is $\sigma_z = 0.63$ mm (1.89 ps) for a charge of 13.2 nC, which gives a peak current of 2.8 kA.

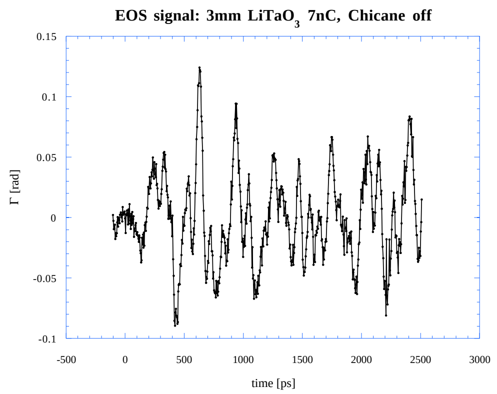

Figure 2: EOS waveform, sensitive to $(E_z + E_\theta)/\sqrt{2}$.

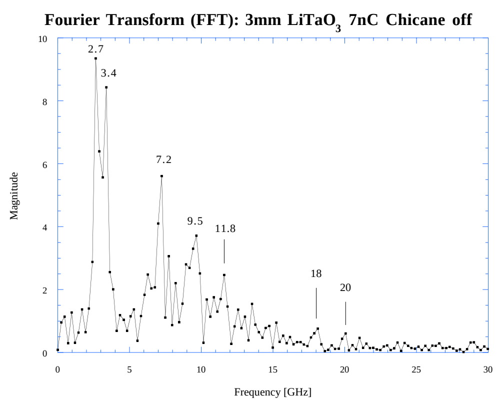

Figure 3: FFT of waveform in Figure 2

We have taken data using several different configurations. The elements common to all of the setups are a polarizer, the crystal, the compensator, and another polarizer (analyzer). The ellipsometry can be simplified for perfect polarizers and small polarization changes in the crystal. For two detectors A and B (silicon photodiodes) after the analyzer, the intensity measured at $I_A \equiv A$ is:

$$A = I_o \sin^2(\delta\Gamma + \phi) \tag{1}$$

where the intensity incident on the analyzer is I_o, and ϕ is a constant which represents the compensator and/or the static birefringence of the crystal ($\phi_s = \omega(n_o - n_e)L/c$). The term proportional to the electric field is $\delta\Gamma = \omega\delta n\, L/c$, and putting in the electro-optic coefficient for $LiTaO_3$ with the electric field along the 3-axis, we find

$$\delta\Gamma = \frac{\omega}{c}(n_o^3 r_{13} - n_e^3 r_{33})E_3 L. \tag{2}$$

For the electric field along the 2-axis of $LiTaO_3$, the electro-optic coefficient is $\delta\Gamma = \omega n_o^3 r_{22} E_2 L/c$. It is clear from Equation 1 that if $\phi = 0$, then for small signals, $A \propto I_o(\delta\Gamma)^2$.

The second detector B measures the orthogonal polarization component, so $B = I_o \cos^2(\delta\Gamma + \phi)$. It is seen that for a choice of $\phi = \pi/4$,

$$\frac{A - B}{A + B} = \sin\delta\Gamma \sim \delta\Gamma \propto E \tag{3}$$

independent of I_o. The compensator then is used to balance the detectors in the absence of electro-optic modulation. However, the static birefringence is a function of temperature, so we make one further subtraction to cancel drifts to form the experimental Γ.

$$\Gamma = \left(\frac{A - B}{A + B}\right)_{\rm signal} - \left(\frac{A - B}{A + B}\right)_{\rm background} \tag{4}$$

For the background points, a shutter is closed which blocks the UV for the photocathode but allows the infrared probe laser to go to the crystal. The field magnitude is estimated by calibrations on a duplicate crystal on the bench. A field $E_3 = 100$ kV/m induces a rotation $\Gamma = 0.046$ rad, while $E_2 = 100$ kV/m induces $\Gamma = 0.003$ rad, all for the 7×8×1.5 mm $LiTaO_3$ crystal (thickness $L = 1.5$ mm).

3 RESULTS

With the sensitive axis of the crystal oriented so that $E_3 = (E_z + E_\theta)/\sqrt{2}$, using the convention that the electron beam velocity defines the $+z$ direction, the measured waveform in shown in Figure 2. The initially surprising feature is the presence of strong oscillations that persist beyond the end of the delay stage (3 ns). These are attributed to excitation of modes in the structure, and an FFT of the waveform is shown in Figure 3. We can, for example, identify the frequencies near 3 GHz as trapped modes in the 6-way cross [19].

With the sensitive axis of the crystal oriented so that $E_3 = E_r$, the measured waveform is quite different, being nearly sinusoidal (Figure 4). In the cylindrical beam pipe (radius $b = 2.2$ cm), there is a propagating (waveguide) $TM_{1,1}$ mode with frequency $\nu = (3.83)c/2\pi b = 8.4$ GHz, and it may be the origin of the observed 8.8 Ghz component. The slow build-up (and beat near 1900 ps) in the envelope could be explained by a small splitting of this mode into two frequencies, which are initially out of phase. The FFT (figure 5) suggests a splitting, but the resolution (limited by the length of the scan) is poor. More will be presented and discussed in a future publication. A second round of experiments is planned with the goal of detecting the direct Coulomb field of the bunch.

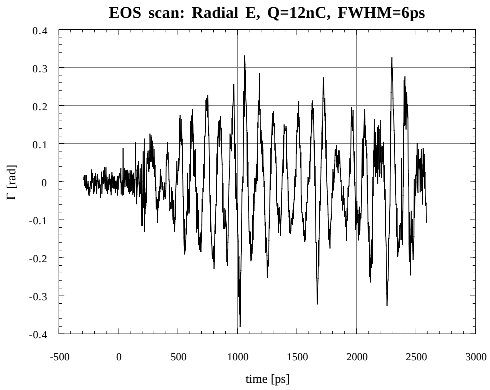

Figure 4: Electro-optic sampling waveform, sensitive to E_r.

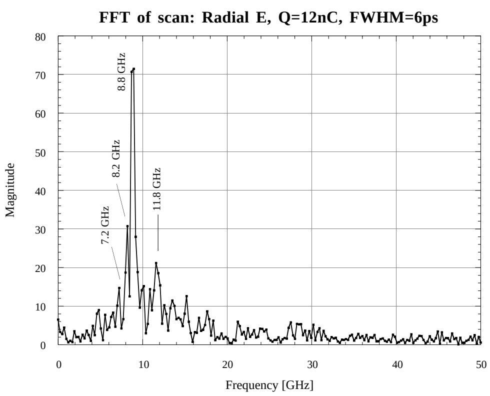

Figure 5: FFT of waveform in Figure 4

The direct Coulomb field of the bunch, if detected, is simply connected with the charge distribution $\rho(z)$ with sensitivity to head-tail asymmetries. As the electro-optic effect has a physical response at the femtosecond level, the technique of electro-optic sampling could be a valuable method for bunch length measurements at the < 100 fs level. The transient (wake) fields we measured off-axis could be applied to on-axis measurements of the wake function and beam impedance. Higher-order mode coupling and damping in structures may also be of interest.

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