PICOSECOND ELECTRON BUNCH LENGTH MEASUREMENT BY ELECTRO-OPTIC DETECTION OF THE WAKEFIELD.

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Abstract

The longitudinal profile of an 10 nC electron bunch of a few picoseconds duration will be measured by electro-optic detection of the wakefield. The polarization of a short infrared probe laser pulse (derived from the photocathode excitation laser) is modulated in a $LiTaO_3$ crystal by the transient electric field of the bunch. The bunch profile is measured by scanning the delay between the laser and the bunch, and is sensitive to head/tail asymmetries. A single-shot extension of the technique is possible using a longer chirped laser pulse.

1 PICOSECOND BUNCH LENGTH MEASUREMENTS

The generation and manipulation of very short electron bunches is important for many applications including future linear colliders, free electron lasers (FELs), and plasma wakefield acceleration. Consequently, methods of measuring the bunch length and temporal profiles of charged particle beams on picosecond and sub-picosecond time scales have attracted great interest.

Notable recent efforts have used coherent radiation from an electron bunch. Coherent transition radiation (CTR) has been analyzed with far-infrared interferometry [1, 2] with impressive results. Since the measured signal is an autocorrelation, it is symmetric in time and insensitive to head-tail asymmetries. Cherenkov radiation has been examined with a 200-fs streak camera [3]. Below 1 ps, streak cameras are increasingly costly and inefficient. A Hilbert tranform spectrometer employing a Josephson junction detector [4] can also be used to analyze the millimeter and submillimeter radiation from CTR.

Ideally, it is desirable to know the longitudinal phase space distribution function, not just the rms width (the bunch length) of this distribution. Frequency-domain techniques may suffer from the problem of missing phase information, though recontructing the charge density from the form factor using Kramers-Kronig relations [5] may be an improvement. Time-domain techniques do not suffer from requiring *a priori* assumptions on the longitudinal bunch shape. A recent example of a time-domain study using an rf zero-phasing method is Wang, *et al.* [6]. The imposed longitudinal momentum spread of the zero-phasing cavities is transformed into a horizontal position spread in a spectrometer bend. However, the intrinsic energy spread of the bunch must be small compared with the correlated energy spread from the zero-phasing cavities. This condition is well satisfied by the DC thermionic beam of Wang, *et al.*, and they achieve 100 fs resolution. For a high-brightness photoinjector beam, this condition seems difficult to satisfy.

For beams of high average power, such as the TESLA design [7], non-interceptive, minimally invasive measurement techniques are desired. Our current effort is to develop a time-domain longitudinal profile measurement based on electro-optic sampling at Fermilab's AØ Photo Injector (AØPI), made possible by the combination of a high-charge (10 nC) high-brightness electron beam and synchronized picosecond laser pulses.

2 ELECTRO-OPTIC SAMPLING

In a nonlinear optical crystal, an applied electric field modulates the polarization of light passing through the crystal. This electro-optic, or Pockels effect has wide-ranging applications.

The principle of electro-optic sampling (EOS) is to use a short laser pulse as a probe of the fields in the crystal by measuring a polarization change as the relative delay is scanned. Since the first studies of EOS on an electric field injected into a crystal [8, 9], EOS has been demonstrated in various materials to have multi-THz bandwidths [10, 11]. Electro-optic detection of field transients propaging in free space has been demonstrated in the far-infrared [12] and also in the mid-infrared [13].

The passage of a very short, high-charge, relativistic electron bunch is accompanied by a strong transient electric field–the wake field. In the lab frame, the electric field is relativistically flattened to a radial pancake. A simple estimation of the magnitude of the field may then be obtained using Gauss' law. Treating the electron bunch as a line charge ($Q = 10$ nC), the radial field is

$$\int_S \vec{E} \cdot d\vec{A} = \frac{q}{\epsilon_0} \tag{1}$$

$$|E_r| = \frac{q}{2\pi\epsilon_0 al} = 3 \text{ MV/m}. \tag{2}$$

where we have taken the bunch length to be $l = 3$ mm for a 10 ps bunch, and have evaluated the field at a radius $a = 2$ cm.

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Calculating wake fields or the Fourier transform beam impedances [14] is an important research activity. A more accurate calculation including the boundary conditions of the beampipe walls can be made with various computer codes. For example, ABCI gives for the iris of the AØPI gun a field magnitude $|E_r| = 1.5$ MV/m.

2.1 *The Photo Injector Beamline*

Fermilab's AØPI is a TESLA prototype injector [15, 16] with a Cs_2Te photocathode in a 1.625-cell L-band Cu gun with a solenoid lens. A superconducting Nb 9-cell "capture" cavity [17] accelerates the beam to 18 MeV followed by magnetic compression in a dipole chicane.

The laser system is described elsewhere [18, 19]. Briefly, an actively modelocked Nd:YLF oscillator at 81.25 MHz is phase-locked to the rf with $\sim$ 1–2 ps rms jitter. These pulses are stretched and chirped in a 2 km single-mode fiber. A fast electro-optic pulse picker selects a 1 MHz pulse train for amplification in a chain of Nd:glass amplifiers. After grating compression to 1–2 ps FWHM, the 1054 nm infrared pulses pass through two BBO crystals, generating the second and fourth harmonics to green (532 nm) and UV (263.5 nm). Full charge operation requires 3–5 μJ UV per pulse for quantum efficiencies of order 1% , and the laser can provide 200 μsec pulse trains adequate for full charge, and longer 800 μsec trains at reduced charge.

After the harmonic generation crystals, a dichroic beamsplitter separates the colors: the unconverted infrared passes through a delay stage (with a stepper motor) and is expanded and transported to the beamline enclosure as a probe beam; the UV is expanded and transported to the cathode. Since the $\sim$1 ps UV pulse is undesirably short, it will be temporally manipulated to a 10 ps quasi-flattop by a pulse stacker. The pulse stacker is a compact arrangement of multiple delay lines arranged around a single UV beamsplitter [20] and this work in progress will be described separately. Both the infrared and UV beams share the same evacuated transport line, and so are combined and separated at either end with dichroic beamsplitters. From the first dichroic to the cathode, the UV transmission is measured to be 78 ± 2%.

2.2 *Expected Signal*

We have chosen a crystal of lithium tantalate ($LiTaO_3$) based on the high electro-optic coefficient and good transparency at our infrared laser wavelength and at the millimeter waves of the transient field. The crystal is 7 mm $\times$ 8 mm $\times$ 1.5 mm, and is cut with the $\vec{c}$-axis (with extraordinary index of refraction n_e) parallel to the longest dimension, and the $\vec{b}$-axis the shortest dimension (ordinary index n_o for this and the $\vec{a}$-axis). See Fig. 1.

To avoid conductors which perturb the electric fields, the crystal is mounted in a vacuum cross with a machined Macor ceramic holder, and is just recessed into the cross to avoid behind hit by the beam.

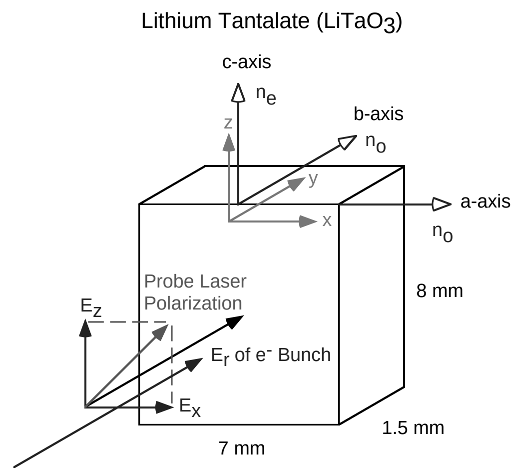

Figure 1: Electro-Optic Crystal: Detailed Axis Geometry

The probe laser is linearly polarized at $45°$ with respect to the ordinary and extraordinary optic axes. The laser and the transient pulse propagate colinearly in the y-direction, which coincides with the crystal $\vec{b}$-axis. Due to the static birefringence, the laser ($\hbar\omega$) becomes elliptically polarized:

$$\delta\phi_{nat} = \frac{\omega}{c}(n_e - n_o)\,\delta y, \tag{3}$$

An additional phase shift is acquired in the presence of the transient field:

$$\delta\phi_{tra}(T) = \frac{\omega}{c} n_o^3\, r_{22}\, E_{tra}(T)\,\delta y. \tag{4}$$

where the appropriate electro-optic coefficient is $r_{22} = 1 \times 10^{-12}$ m/V and the index is $n_o = 2.154$, so that a 1 MV/m field accumulated over 2 ps ($ct = 0.6$ mm) gives a phase shift of 36 mrad, or $\sim 2°$.

This phase shift is analyzed by a polarizing cube beamsplitter and two photodiodes (see Fig. 2). The static birefringence is compensated by a waveplate which balances the current in the two photodiodes. By detecting the difference current between the pair of photodiodes, small photomodulation depths can be observed, particularly with the signal averaging of a lock-in amplifier. While it may be possible to use a lock-in with our 1 MHz pulse trains, we have concentrated on single-shot difference current measurements. While 10^{-3} is adequate for the above estimate ($\sim 1\%$), and increased signal-to-noise ratio is greatly desired.

Group velocity mismatch between the probe laser and the transient field causes slippage, and degradation of the time resolution. The common approach is to use a very thin crystal, or a complicated geometrical phase matching.

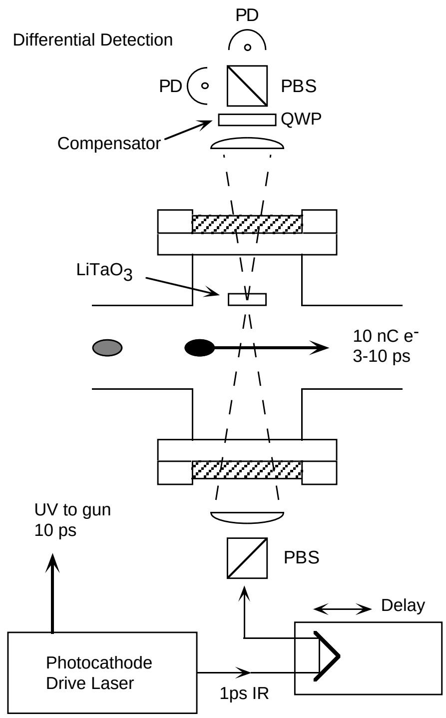

Figure 2: The probe laser passes completely through a vacuum cross with the $LiTaO_3$ crystal mounted in a Macor holder (not shown). The polarization change is analyzed by a polarizing beam splitter (PBS), balanced with a quarter-wave plate (QWP) and detected with a balanced pair of photodiodes (PD).

We have chosen a simple colinear geometry [21, 22] since for the large group velocity mismatch of $LiTaO_3$, the transient field is nearly stationary so that the laser sweeps over the entire portion of the waveform that is inside the crystal. The desired waveform is recovered by numerical differentiation.

3 EXPERIMENTAL PROGRAM

Once the issues of signal detection, timing, data acquisition, *etc.* are resolved, there are several interesting studies that can be done. A careful study of magnetic bunch compression in the dipole chicane would allow comparison of the bunch length (and profile) measured with electro-optic sampling to traces of a streak camera. Since the UV pulse length on the cathode has some degree of adjustability, the optimum can be found.

An extension of this scheme to a single-shot measurement using a longer chirped laser pulse and a grating spectrograph [23] is under consideration. In this case, the correlation of frequency versus time (the chirp) replaces the scanning delay, although the time resolution is broadened due to a convolution effect. As the technology of picosecond semiconductor diode lasers improves [24], it may be possible to greatly reduce the size, cost, and complexity of the laser, so that a stand-alone electro-optic bunch length monitor might be realized.

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