ELECTRO-OPTIC SAMPLING OF LOW CHARGE LOW ENERGY RELATIVISTIC ELECTRON BUNCHES AT PEGASUS LABORATORY*

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Abstract

Electro-optic sampling (EOS) has been developed as a timing monitor at Pegasus photoinjector laboratory for 100-fs electron bunches. A geometrically simple 2-dimensional spatially encoding scheme is used to measure time-of-arrival (TOA) of these ultrashort electron bunches in a 20 ps window down to < 50 fs resolution. The setup described here has successfully observed EOS signals for low energy (~ 4 MeV) and low charge (< 10 pC) bunches, both parameters being lower than electro-optic TOA monitors currently used in other labs. Experimental 2-d EOS images are compared to particle-in-cell plasma simulations (OOPIC) of electron bunch transient electric fields in ZnTe and to theoretical field propagation in dielectric crystals.

INTRODUCTION

While electro-optic sampling (EOS) was initially used as a temporal diagnostic to study THz radiation pulses, it has been readily applied to detecting sub-picosecond relativistic electron bunches since they tend to produce transient electric fields mimicing a single THz cycle. The non-destructive nature of electro-optic methods has made them invaluable for single shot beam monitoring. The proliferation of ultrafast laser techniques in modern accelerator labs makes the tools to apply EOS as a beam diagnostic readily available.

Though much work has been done at other labs developing the time resolution of EOS as a bunch profile monitor (BPM) for sub-picosecond bunch sources, the relative laser-bunch time of arrival (TOA) is an equally important parameter for experiments dealing with laser pulse-electron bunch interactions such as FEL, inverse Compton scattering, and pump-probe diffraction. Precise timing between beams is desired in these experiments. In reality, the mechanical- or phase-scanning ability of a relative delay is limited to a few hundred fs. By letting TOA jitter randomly delay laser-bunch interactions, it has been shown [1] that much shorter processes can be monitored. To take advantage of TOA jitter, it is necessary to have an EOS-TOA setup that can record bunch position in a single shot with sufficient resolution.

A novel single shot geometry for EOS was proposed [2] to fully encode the time profile of a single bunch on the transverse profile of a probe laser beam. This technique is easier and less costly to implement than spectrally encoding single shot EOS setups. The design has been realized at Pegasus lab as a TOA timestamp mechanism for time resolved relativistic electron diffraction.

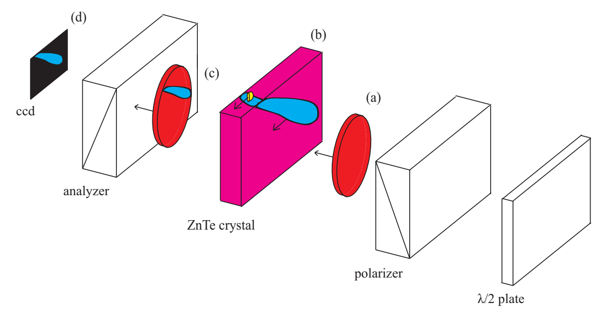

Figure 1: Interaction geometry of spatially-encoding 2-d EOS setup with crossed polarizers. (a) A linearly polarized laser pulse enters the ZnTe crystal. (b) Meanwhile, a passing electron bunch's electric field induces a transient birefringence in the ZnTe. (c) The transient field is imprinted as a phase modulation on the transverse profile of the laser pulse. (d) An analyzer removes all except the modulated region which is read out on a CCD as an intensity modulation.

UCLA Pegasus laboratory is a high brightness photoinjector test facility. The lab is currently researching the longitudinal "blowout" regime of photoinjection to produce ultrashort ellipsoidal electron bunches. Project goals include full characterization of these bunches as well as finding new applications for beams of this nature. One demonstrated use of ultrashort bunches has been diffraction of static metal foils [3]. Pump-probe experiments requiring EOS-TOA have begun, but are beyond the scope of this paper.

Bunch parameters that are ideal for electron diffraction present challenges for EOS monitoring at Pegasus. When in diffraction mode, Pegasus runs a 20 pC beam at 3.5 MeV. Additionally, the beam is collimated giving a betatron spot size of 600 μm at the EO crystal. The expected fields with these parameters are weak compared to other EOS accelerator experiments, providing an additional challenge. A particle-in-cell simulation has been used to try to estimate the fields in the EO crystal given these parameters.

This paper will characterize the Pegasus EOS setup in terms of the timing resolution and beam parameters. Comparison will be made between simulation and data.

EXPERIMENTAL SETUP

A single 40-fs 800-nm laser pulse is split; one part is the EOS probe pulse and the other part is frequency-tripled to

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266 nm and serves to create the charge at the photocathode. Using a single laser source for both bunch and EOS probe eliminates a source of overall timing jitter. The laser oscillator is phase locked to the rf amplifier to ensure the UV pulse arrives at the cathode while the rf gun is at the proper accelerating phase.

The EO crystal used for this experiment is $10 \times 10 \times 0.5$ mm (110)-cut zinc telluride (ZnTe) from Del Mar Photonics, Inc. A standard 6-way vacuum cross is chosen for the EOS chamber. The EO crystal is lowered to a position just above the design trajectory of the electron bunch through the cross. The bunch is steered to pass directly below and along the (110) edge of the ZnTe crystal. The linearly polarized probe laser pulse enters the cross perpendicular to the electron bunch and passes through the EO crystal. Using polarization encoding [2], the bunch electric field is impressed onto the laser pulse, decoded with a polarization analyzer, and detected with a 640×480 CCD as shown in Figure 1. The horizontal dimension calibration of the CCD has been measured [4] to be 29 fs/pixel, giving an observing window of 19 ps in a single shot .

A $\lambda/2$ plate before the polarizer allows us to rotate the probe laser input polarization to an arbitrary axis in the $<$110$>$ plane containing the EO crystal's induced optical axes. The EOS transmitted intensity I_{tr} depends on the laser polarization axis with respect to the induced optical axis in the ZnTe. We found experimentally that an input polarization of 20° gives the maximum EOS signal. The calculation and measurement of this angle will be presented in a future paper.

EXPERIMENTAL RESULTS

In a typical EOS characterization run at Pegasus data from hundreds of consecutive shots is collected. The electron beam is then blocked and several laser background shots are taken. The background image is subtracted from the signal images. Figure 3(a) shows a typical subtracted shot.

The 2-d EOS signal exhibits both a direct field component as well as an induced wakefield [4]. This paper will focus only on the observed direct field.

For timing analysis, a horizontal lineout is taken from the subtracted image to obtain a signal intensity trace in time. The time calibration is applied to the horizontal axis of the trace. A Gaussian fit to the peak is used to find the peak center.

EOS Charge Dependence

Varying the bunch charge causes a significant change in the amplitude of the measured EOS signal. Figure 2 shows the dependence of the measured signal intensity on bunch charge. Each intensity point is the mean obtained from 100 consecutive shots. The error bars are the standard deviation from the mean. A quadratic fit is used to guide the eye. Future work will analytically explore the signal dependence on bunch charge. With more favorable steering and focusing (i.e., not during diffraction runs) a signal could be obtained with even less charge. High charge scans are planned.

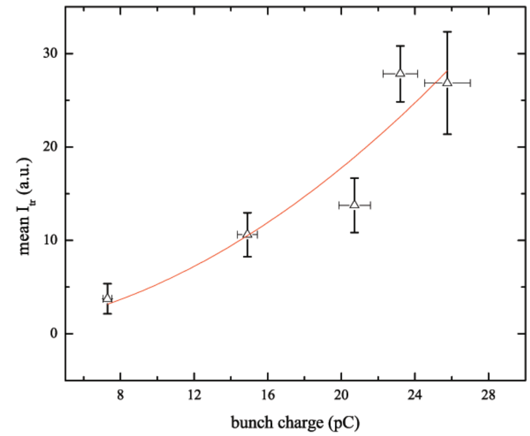

Figure 2: EOS transmitted intensity as a function of electron bunch charge. The minimum charge for which an EOS signal was measured here is 7.3 pC.

Peak Finding Resolution

The horizontal dimension of the CCD helps to establish the reliability of finding a peak from shot to shot, i.e. the TOA resolution. We have observed that the slope of the 2-d EOS signal is highly steering dependent. In addition to timing jitter, there is a high degree of beam pointing jitter from the rf gun. This fluctuation in steering results in a variation in the 2-d EOS slope. Thus, there can be a large difference in the trace peak center from shot to shot that depends on how far up the trace is taken from the lower edge of the crystal where the bunch passes. Assuming the lowest point is fixed in TOA, we measure the rms of the peak-to-peak center difference over 100 consecutive shots . This shows that traces farther up from the beam axis exhibit more uncertainty due to pointing jitter. The least positional uncertainty occurs for pixels closest to the edge. The resolution is the rms of the peak to peak position difference at that point, which is found to be < 46 fs.

TERAHERTZ PULSE PROPAGATION IN DATA AND SIMULATION

A bonus of the novel geometry presented here is that one can observe the propagation of the THz pulse into the ZnTe crystal in a single shot. The vertical axis of the signal shots represent the distance into the crystal that the pulse has traveled. An immediately apparent feature of the data, as in Figure 3(a), is that the pulse begins to broaden and distort as it travels farther from the edge of the passing bunch. For timing studies, we choose to stay as close as possible to the crystal's bottom edge to avoid this effect.

The angle that arises in the experimental 2-d shot (θ_{sim}) is due to the bunch vacuum electric fields bending at the di-

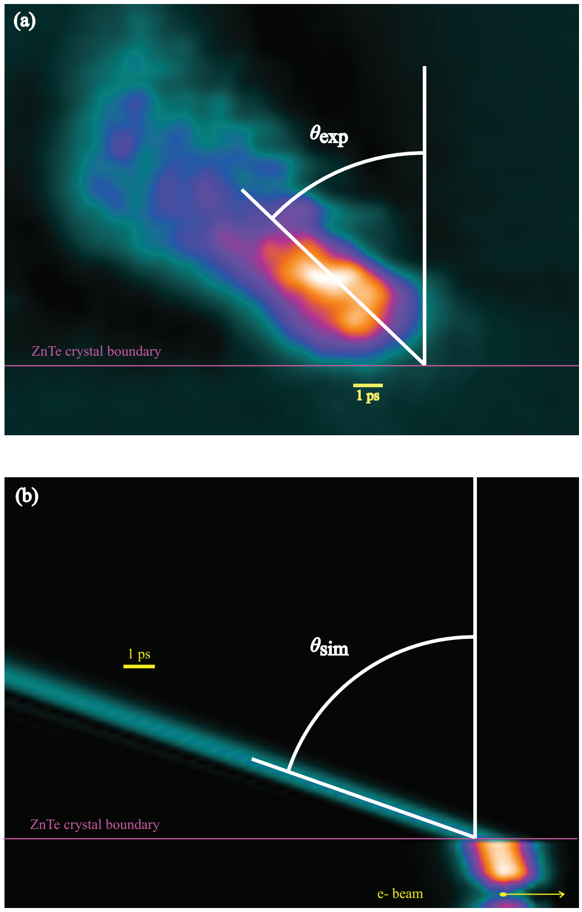

Figure 3: (a) Experimental transmitted intensity for a typical shot showing a Cerenkov-like pulse wavefront propagation. (b) Simulated electric field inside ZnTe for a typical shot a Cerenkov pulse (θ_{sim}).The e- beam passes left to right along the bottom edge of each image. In both images, the entire horizontal window is 19 ps and the horizontal dimension is 3.8 mm.

electric interface. In a 2-d infinite slab geometry, this angle can be theorized to be the Cerenkov angle. In comparison, one finds that the angles obtained in theory and simulation (OOPIC) are significantly bigger (measured from the vertical) than observed in the data. In the OOPIC result, the ZnTe crystal, bunch, and beam pipe are modeled in a 2-d slab geometrical approximation such that the simulated crystal and electron bunch extend infinitely in the direction of the laser propagation. This model does not take beam steering into account. A full 3-D time-domain field solver may be necessary to answer the question about the observed field angle, since large changes in angle arise by changing the bunch steering only a small amount.

The bunch profile is not represented since our simulation lacks THz dispersive and absorptive modeling. Thus the FWHM of the simulated and experimental bunch profiles should not agree, as the ZnTe index of refraction has a resonance in the THz spectrum [5]. However, comparing lineouts of the simulation and the data in Figure 4 shows a FWHM difference of only a few hundred fs. It should be noted that the y-axis measures different quantities, comparing the experimental EOS intensity I_{tr} with the simulated THz field magnitude $|E_{\text{sim}}|$, so the vertical scaling may change. I_{tr} is a function of the bunch electric field. The rms bunch length given to OOPIC is only 200 fs. The large width of the calculated field (0.89 ps FWHM) may indicate that this setup as a profile monitor is limited by low bunch energy, not by dispersion in the EO crystal. This will be investigated to develop an EOS BPM at Pegasus.

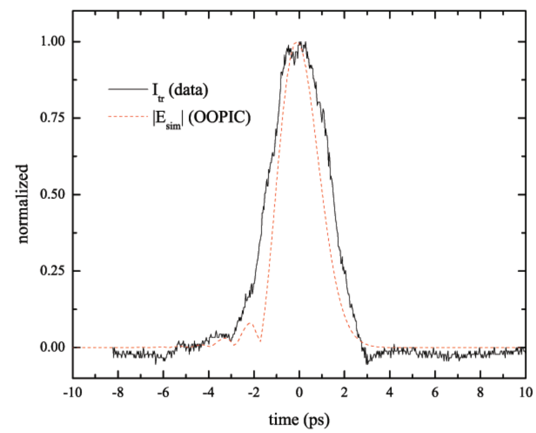

Figure 4: Horizontal lineouts of the EOS transmitted intensity (taken from a typical experimental shot, solid line, $\sigma_t = 1.2$ ps) compared to the calculated electric field (OOPIC, dashed line, $\sigma_{t,\text{ sim}} = 0.89$ ps). Note that the normalized y-axis measures differently for the simulated and experimental traces.

CONCLUSION

A novel single shot spatial encoding scheme has been proven at Pegasus lab. The time-of-arrival resolution has been shown to be < 50 fs. A 3-d model including THz dispersion in ZnTe will be sought in future calculations to explore EOS as a profile monitor. EOS-TOA will be implemented to timestamp dynamic relativistic electron diffraction at Pegasus.

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