SUB-PICOSECOND SHOT-TO-SHOT ELECTRON BEAM AND LASER TIMING USING A PHOTOCONDUCTIVE THz ANTENNA

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Abstract

Temporal synchronization systems, which measure electron beam time of arrival with respect to a laser pulse, are critical for operation of advanced laser-driven accelerators and light sources. State-of-the-art synchronization tools, relying on electronic e-beam response and photodetector laser response are limited to few GHz bandwidths in most practical configurations. This paper presents a temporal diagnostic instrumentation based upon a photoconductive THz antenna, which could offer an inexpensive and user friendly method to provide shot-to-shot relative time of arrival information with sub-picosecond accuracy. We describe the overall instrument design and proof-of-concept prototype results at the UCLA PEGASUS facility.

INTRODUCTION AND MOTIVATION

Many experiments today involve the careful coordination and synchronization between pulsed laser beams and accelerated charged particle beams. Examples include inverse Compton light generation, laser driven plasma wakefield acceleration, and plasma photocathode injectors. The two most widely used diagnostic systems for measuring synchronization which are capable of providing sub-ps or better timing resolution are BPM pick-ups [1] and fast photodiodes equipped with very high bandwidth oscilloscopes and electro-optical based encoding techniques [2]. The first method requires careful cable trimming and very expensive oscilloscopes. Electro-optic sampling (EOS) methods require careful optical alignment of birefringent crystals and many optical components and relatively high fields to induce non-linear processes.

THz photoconductive antenna (PCA) devices can both detect and produce single-cycle THz fields when used in conjunction with a pulsed laser system (typically < 100 fs pulse widths) [3]. The devices are comprised of a substrate wafer of photoconductive material, such as low-temperature GaAs, which is grown to have modified properties to enhance the carrier mobility in order to respond at ps and sub- ps timescales. Conductive metal is patterned onto the photoconductive substrate in the form of a resonant antenna (dipole, log-spiral, or other geometries) with a small gap left in the antenna structure. When the LT-GaAs in the antenna gap is illuminated with laser radiation with a photon energy above the photoconductive threshold, any incident THz fields will drive current on the antenna which can be measured with a transimpedance amplifier. The device will in this way be “gated” by the laser pulse, the width of which sets a lower limit on the temporal resolution of THz field amplitude detection.

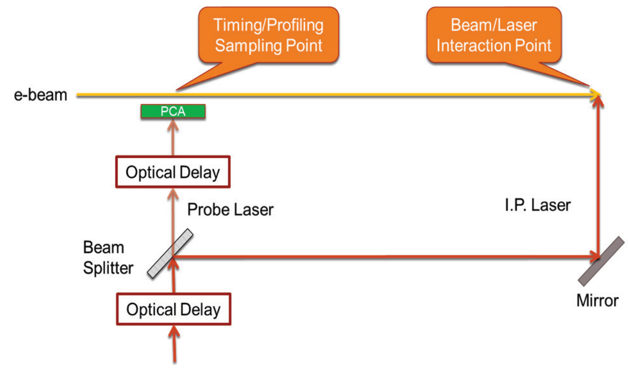

Figure 1: Schematic overview of a THz photoconductive antenna used as a timing synchronization instrument for short pulsed beams. The system could be used for longitudinal profile measurements for beams of longer bunch lengths

BENCH-TOP TESTS

For our proof of concept measurements, we have used the Menlo Systems Tera8-1 photoconductive antenna. The THz pulse used to test the detection capabilities of the PCA was produced through pulse-front-tilted optical rectification [4][5] of a 45 fs Ti:sapphire laser pulse centered at 800 nm with a 30 nm bandwidth. A beam splitter removed a fraction of the initial IR to act as the gating pulse for the PCA. Pulse-front tilting of the remaining IR was accomplished with a grating and then imaged onto stoichiometric lithium niobate to produce a picosecond-scale single-cycle THz pulse. The peak field of the THz pulse was set by the incident IR power and ranged from 300 kV/ m to 4.6 MV/ m. The THz pulse was collimated and then refocused down to a 2 mm spot size at the PCA using a pair of off-axis parabolic mirrors.

Initial measurements with the PCA varied greatly depending on the spot size of the IR pulse that illuminated the antenna. A 50 μm diameter pinhole was placed in front of the PCA to ensure a reproducible IR spot size and limit the IR illumination to the region of the antenna gap. Proper alignment of the pinhole with the antenna gap introduced a substantial challenge to the THz detection set-up, but resulted in significant improvement to the detection sensitivity and timing resolution. The pinhole was incorporated into the antenna mount design and alignment was optimized using the bench-top THz source. With the pinhole locked in place, the antenna mount could then be illuminated with a large (several mm) IR spot size, eliminating the challenge of precise optical alignment.

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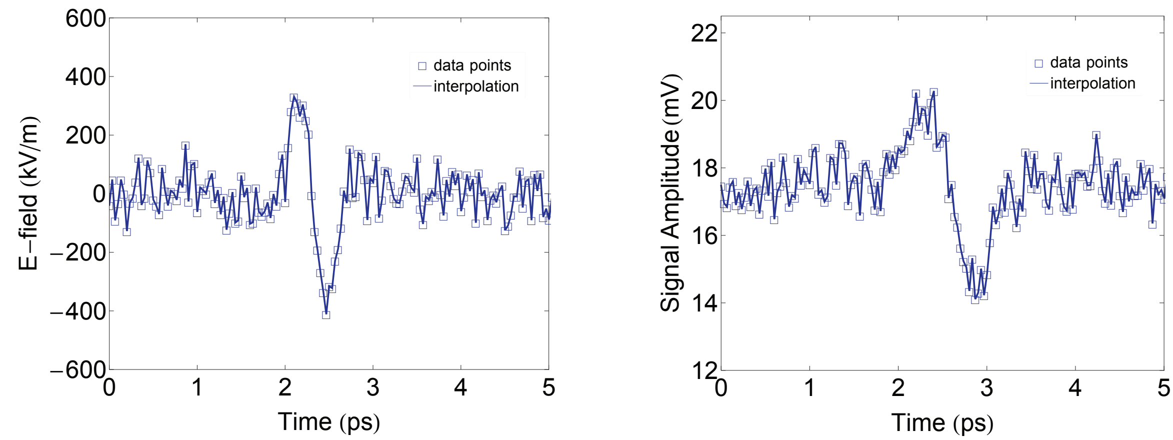

(a) (b)

Figure 2: (a) EOS measurement and (b) PCA measurement of the single-cycle THz pulse generated through optical rectification on the bench-top set-up. The temporal profiles obtained by the two methods show comparable sensitivity to low THz power.

The temporal field profile measured by the PCA was compared to an EOS measurement taken with zinc telluride at the focus of the THz pulse. The IR pulse that provided the gating for the PCA was used as the probe pulse for EOS. Within ZnTe, a THz field results in a rotation of the slow and fast axis of the crystal. When the THz pulse and linearly polarized probe pulse were coincident on the ZnTe, the polarization of the probe pulse was rotated. In the "balanced detection" configuration, after a quarter waveplate and Wollaston prism, a pair of photodiodes measured the orthogonal polarization components of the probe pulse to detect the rotation. The change in relative intensity was used to calculate the THz field.

Using the EOS diagnostic, we were able to determine the THz field seen by the PCA. At 350 kV/ m the PCA sensitivity was comparable to that of the EOS measurement, as shown in Fig. 2. The temporal profile and timing resolution of the two methods were also in good agreement.

INSTALLATION AND BEAM TEST AT PEGASUS

The PCA has been mounted on the beamline at the UCLA PEGASUS laboratory [6] [7]. A schematic of the facility is shown in Fig. 3. The antenna is situated perpendicular to the beamline with the polarization of the dipole oriented vertically in order to pick up the radially-polarized single-peaked THz pulse that is produced by the electron bunch passing above the detector. A manually operated actuator controls the proximity of the PCA mount to the beam axis, as seen in Fig. 4. The time of arrival of the IR gating pulse for the PCA has been measured and adjusted to match the expected arrival of the electrons. Fine tuning of the IR pulse delay will be made using a remotely operated translation stage. Measurements of the electron bunch charge produced at PEGASUS for this test by a downstream Faraday cup give

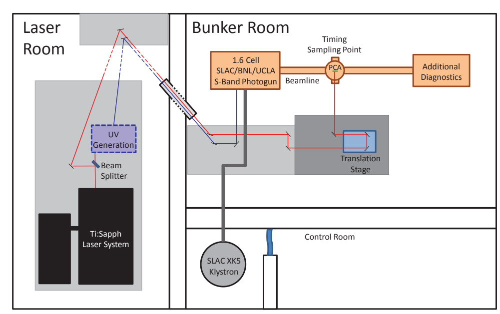

Figure 3: Simplified schematic of installation on the PEGASUS beamline.

an estimated charge of 50 pC. The electron beam can be steered and focused using the steering magnets and solenoid mounted on the beamline. The position of the electron beam relative to the PCA mount can be monitored using a YAG screen and CCD camera.

The operation of the klystron results in significant distortion of the PCA signal. While the photocurrent established by the IR pulse is distinguishable from background, indicating that we should be able to see the time-dependent THz signal, we are making additional modifications to the signal amplification equipment in order to filter the noise associated with the klystron. Once we have optimized the signal to noise ratio of the photocurrent, we will begin measurements of the PCA signal for varying IR pulse delay to detect the time-dependent THz signal.

CONCLUSION

Bench-top results using commercially available THz photoconductive antenna chips are promising, indicating temporal resolution on the order of several 100 fs and sub-ps synchronization. At the time of this publication, installation

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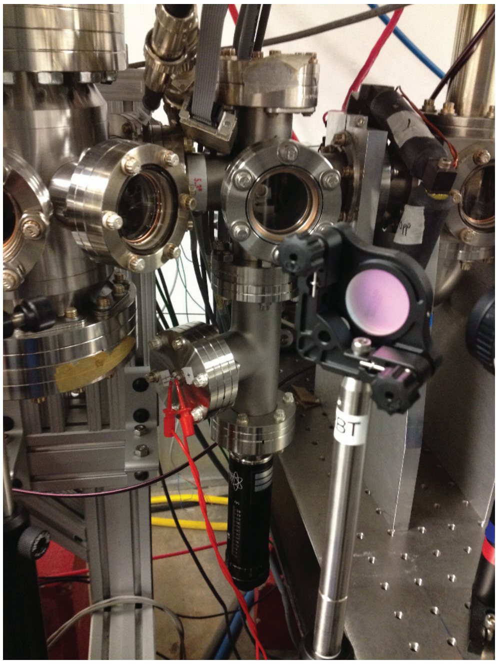

Figure 4: PCA mount with actuator installed in cross on PEGASUS beamline.

is complete and beam based measurements are underway. The first experimental runs have demonstrated THz and laser correlated signal, however noise from the accelerator system may be large enough to hinder acquisition of delay scans. In order to enhance sensitivity for optimal use in accelerator diagnostics in noisy environments, a collaboration with chip-level device manufactures producing customized photoconductive THz detectors is expected to yield up to 30 times sensitivity gain. Next generation detectors are expected in late October for testing. The results from these upcoming experiments at PEGASUS will serve to evaluate the use of photoconductive antennas for synchronization of GHz repetition rate accelerator diagnostic systems and for plasma photocathode injection requiring sub-picosecond time of arrival precision.

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