ELECTRON BUNCH CHARACTERIZATION USING TEMPORAL ELECTRIC-FIELD CROSS-CORRELATION*

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Abstract

A new single-shot diagnostic is presented for mapping THz spatiotemporal waveforms with high temporal resolution for use in diagnostics of electron bunch temporal profiles. The THz waveform is encoded using electro-optic sampling onto either the phase or amplitude of a broadband chirped probe pulse, and is recovered using linear spectral interferometry with a temporally-short reader pulse. The technique was used to measure waveforms of coherent, ultrashort THz pulses emitted by electron bunches from a laser-plasma accelerator with sub-50 fs resolution. The presence of strong spatiotemporal coupling in the THz waveforms and of complex temporal electron bunch structure was determined.

INTRODUCTION

Recent progress in the field of laser-plasma acceleration has yielded millimeter- to centimeter-scale accelerators capable of producing electron beams with energies up to 1 GeV [1]. These devices, which have acceleration structures on the micron-scale are capable of producing electron bunches of extremely short durations in the range of a few femtoseconds [2]. This advancement has brought with it the necessity of developing new diagnostics capable of resolving such short bunches. Electro-optic sampling (EOS), which has seen great success in the field of THz time-domain-spectroscopy in a multi-shot, scanning configuration has recently been applied to electron-bunch temporal-profile diagnosis [3, 4, 5]. Here, either the transient electric-field of the electron bunch, or transition radiation generated by the electrons passing though a dielectric interface (such as a metallic foil or a plasma-vacuum boundary [6, 7]) is used to provide the strong electric fields required for the electro-optic effect. The low repetition rates and shot-to-shot variability that currently characterize laser-plasma accelerators (LPAs), however, necessitate a single-shot approach. In addition, strong spatio-temporal coupling in the transient electric fields requires a technique capable of resolving spatial variations in order to optimize sensitivity and to capture the full information of the THz waveform [8]. While single-shot techniques have been used to measure electron-bunch generated THz waveforms [3, 4, 5], single-shot temporal *and* spatial mapping of the waveforms has not yet been demonstrated in the femtosecond regime.

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A technique named Temporal Electric-field Cross-correlation (TEX) is presented which provides measurements of THz waveforms with high temporal resolution and simultaneously one dimension of spatial information. TEX is based upon measurement of the linear cross-correlation of a chirped probe with a compressed reader pulse using spectral interferometry. The full electric-field information of the optical probe, convolved with that of the short reader, is retrieved, allowing signals to be encoded onto either the phase or the amplitude of the probe or both. This dual capability is not present in previous EO methods, and makes TEX applicable to the measurement of a wide range of phenomena beyond EO sampling. Because the detection is linear, TEX can be implemented with low-cost, unamplified laser systems, and because it does not require focusing of the optical probe, spatial information can be recorded and retrieved. The temporal detection window is easily tunable in the several ps range by adjusting the chirp of the probe pulse, and the temporal resolution of the phase and amplitude retrieval is set by the duration of the short reader pulse pulse. Implementation of TEX to measure waveforms of intense THz pulses from an LPA is also demonstrated.

EXPERIMENTAL SETUP

Figure 1 shows the setup for TEX, implemented on an LPA-based THz source [6, 9, 10]. 400 mJ, 800 nm, 45 fs laser ("pump") pulses were focused into a 2 mm Helium gas jet, producing electron bunches with large energy spreads and sub-ps bunch durations. A portion of the coherent transition radiation (CTR) produced at the interaction was collected with an off-axis parabola (OAP) yielding a collimated beam in the range of $0-4$ THz with 90% of the energy vertically polarized. The beam was refocused with a second OAP onto a 200 μm thick gallium phosphide (GaP) crystal cut along $\langle 1, 1, 0\rangle$. A fully compressed ("reader") pulse with FWHM duration 45 fs and temporally chirped ("probe") pulse with FWHM duration 2 ps were split from the *pump* beam prior to the interaction, and used to sample the THz pulse. The *probe* and the THz pulses were spatiotemporally overlapped with a collinear geometry in the GaP. A polarizer was used to purify the polarization state of the incident *probe*, and a second polarizer (referred to as an "analyzer") was used to convert polarization rotations into amplitude modulations. A quarter wave plate (QWP) used to offset the transmission to the 50% level, allowed both positive and negative THz fields to be resolved. The transmitted probe pulse was then combined colinearly with, but temporally offset from the *reader* and sent into an imaging spectrometer, producing a spectral interferogram image ("TEXogram"). The interaction plane was imaged onto the spectometer slit which was used to select a spatiotemporal slice of the *probe*.

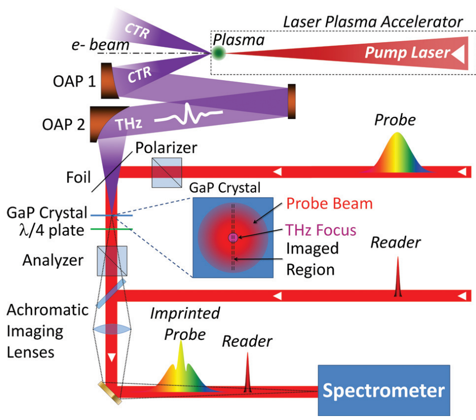

Figure 1: Schematic of the TEX detection scheme.

Selecting between amplitude and phase encoding is done by setting the polarization angle of the *probe* relative to the principal axes of the THz-induced index ellipsoid. If the polarization is aligned at $45°$ to the principal axes, it will be rotated in proportion to the THz field strength [8, 11, 12]. The *analyzer* then re-linearizes the polarization, and the phase-shift contribution from each of the axes will cancel, resulting in pure amplitude modulation. However, if the *probe* polarization is aligned *along* one of the principal axes, the *probe* will experience a temporally-varying phase-shift, but no polarization rotation, resulting in pure phase modulation. For other polarization states, the THz imprint is mixed between phase and amplitude with a strongly nonlinear dependence on the field strength, making waveform retrieval unreliable.

ANALYSIS

The first step of the *TEXograms* analysis is to recover the spatiotemporal amplitude and phase profile of the *probe* electric field (E_{pr}) onto which the signal is encoded. The signal is then extracted by comparing E_{pr} with and without the interaction. E_{pr} is obtained from the *TEXogram* by applying a single 1D Fourier Transform (FT) operation independently to each row of the spectral image. The FT of the *TEXogram* produces a broad side-peak in the time domain, at a position corresponding to the delay between the *reader* and the *probe*. The "convolution theorem" of FTs identifies this side-peak with the complex cross-correlation of the electric-fields of the *probe* and the *reader* in the time-domain. As the *reader* pulse is much shorter than the *probe*, it approximates a delta-function, and the side-peak may be taken as an approximation of the *probe* temporal field in both amplitude and phase.

The THz waveform is recovered by determining the modulation to either $\mathscr{E}(y,t)$, the spatiotemporal electric-field amplitude or $\Phi(y,t)$, the spatiotemporal phase of the *probe*, depending on the encoding method. The reconstructed waveform is given by: $E_{THz}(y,t) = \alpha^{-1}\arcsin[\mathscr{E}_T^2(y,t)/\mathscr{E}_{null}^2(y,t)-1]$ for amplitude encoding and by $E_{THz}(y,t) = 2\alpha^{-1}[\Phi_T(y,t)-\Phi_{null}(y,t)]$ for phase encoding, where the subscripts "T" and "null" refer to measurements in the presence and absence of the THz pulse, respectively. The temporal resolution was limited by the duration of the *reader*, which convolves the signal, and by phase matching considerations in the 200 μm GaP crystal, resulting in measurement sensitivity to THz frequencies below $\sim$ 8 THz. A more detailed description of the analytical method, as well as the limitations to the temporal resolution are described in Matlis et al. [8].

RESULTS

Figure 2 shows a nearly single cycle THz spatiotemporal waveform image acquired using TEX in the amplitude-encoding configuration. The waveform displays sharp temporal features of order 100 fs, illustrating the need for high temporal resolution. The waveform also exhibits strong spatiotemporal coupling, in the shape of an **X**, as was described by Jiang et al. [13], which can be understood in terms of a variation of the Gouy phase shift and focused-waist size with wavelength.

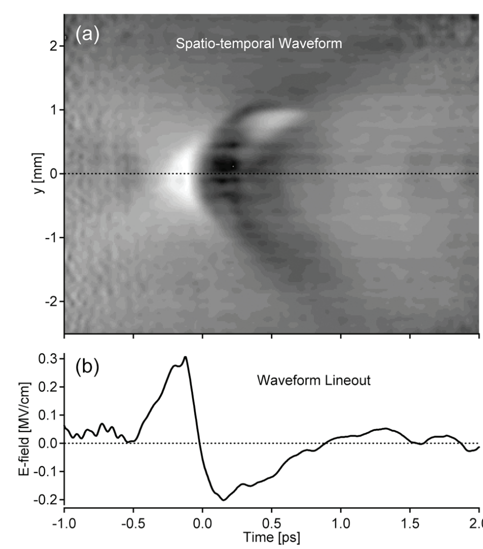

Figure 2: Data showing (a) THz spatiotemporal waveform extracted from the raw interferogram and (b) lineout of waveform at $y = 0$ mm.

To diagnose the structure of the electron bunch, the spectrum of the THz waveform shown in figure 2 was calculated and compared with theory. The spatial and temporal features of the spectral image were modeled (Fig. 3) by using CTR emission theory [9] with the inclusion of collection and propagation effects. To accurately model both the low- and high-frequency parts of the spectral image, two bunches of different duration and charge (90% of the charge in a 140 μm*-rms* bunch and 10% in a 50 μm bunch) were required. Comparison of a one-bunch model (containing only the longer bunch) with the two-bunch model shows that the contribution to the THz emission above ~ 0.75 THz comes entirely from the shorter bunch, in spite of its small relative charge (Fig. 3c). This high sensitivity to the presence of the shorter electron bunch is an important confirmation of the practicality of the THz-based diagnostic for characterizing LPAs, since the high-energy, low-charge electron bunch component of interest is often accompanied by a lower energy component containing the bulk of the charge. The electron energy spectrum, not shown here, also has a two-component distribution with a large thermal- and a smaller "quasi mono-energetic" component. The importance of recovering the spatial variations in the THz waveform is illustrated by the strong spatial dependence of the spectrum of the focused THz pulse: the higher-frequency component from the short bunch is more localized to the axis. A spatially-integrated technique would under-represent this component, thus diminishing sensitivity to the presence of the short bunch. In addition, because the transverse focal size of a given spectral component is strongly dependent on not only the wavelength but also the spectrally-varying far-field intensity distribution, the nice correspondence between data and model of the shape of the spectral image provides a confirmation of the THz emission patterns predicted by CTR theory.

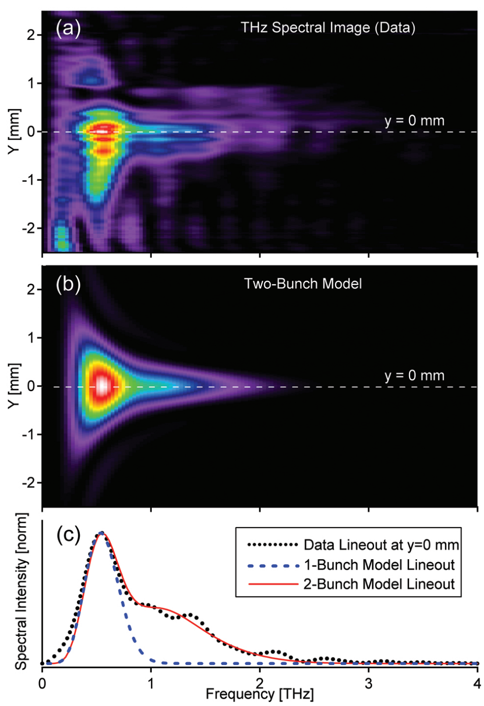

Figure 3: (a) Power spectrum of THz waveform in figure 2. (b) Spectral image calculated using a 2-bunch model (c) lineouts of spectral images for data (black-dotted line), 1-bunch model (blue-dashed line) and 2-bunch model (red-solid line). Comparison shows that a 2-bunch model yields a significantly better fit than a 1-bunch model.

CONCLUSION

A new single-shot technique (TEX) is demonstrated for measurement of ultrafast phenomena resulting in temporal phase or amplitude modulations. TEX provides high temporal resolution and one dimension of imaging simultaneously for the first time in EO sampling, enabling analysis of spatio-temporal and spatio-spectral coupling in the THz waveforms. TEX is significantly easier to setup than previous high-resolution EO techniques because it does not require the use of nonlinear processes other than the linear Pockels effect used for EO sampling. Because TEX is linear in the *probe* field strength, low-power, low-cost, unamplified laser systems may be used, making it highly accessible. In addition, the dual phase- and amplitude-encoding capability makes it applicable to a wide range of phenomena. The temporal resolution is set by the duration of the *reader* pulse, and can be made smaller than the intrinsic limitation set by phase-matching in the EO sampling process. The single-shot temporal detection window is tunable in the range of several to 10s of ps, and is limited by the bandwidth and spectral resolution of the spectrometer. Numerical analysis confirms the capability of TEX to reproduce THz waveforms in both temporal and spectral domains without significant distortion in both phase- and amplitude-encoding configurations. Waveforms of THz pulses generated as CTR from an LPA were measured using the amplitude-encoding configuration and were analyzed. The resultant THz spectral images were used to demonstrate the presence of heterogeneous electron bunch structure from the LPA. The dependence of the THz spectrum on the electron-bunch duration makes it possible to detect the presence of short electron-bunch substructure with high sensitivity.

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