OPTIMIZATION AND SINGLE-SHOT CHARACTERIZATION OF ULTRASHORT THz PULSES FROM A LASER PLASMA ACCELERATOR*

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Abstract

Spatiotemporal characterization of μJ-class ultrashort THz pulses generated from a laser plasma accelerator (LPA) is presented. Accelerated electrons [1], resulting from the interaction of a high-intensity laser pulse with a plasma, emit high-intensity THz pulses as coherent transition radiation [2]. Such high peak-power THz pulses, suitable for high-field (MV/cm) pump-probe experiments [3], also provide a non-invasive bunch-length diagnostic [4] and thus feedback for the accelerator. The characterization of the THz pulses includes energy measurement using a Golay cell, 2D sign-resolved electro-optic measurement and single-shot spatiotemporal electric-field distribution retrieval using a new technique, termed temporal electric-field cross-correlation (TEX). All three techniques corroborate THz pulses of ~ 5 μJ, with peak fields of 100's of kV/cm and ~ 0.4 ps *rms* duration. Single-shot measurement of the THz spatiotemporal waveform demonstrates a dependence of the THz spectrum on the electron bunch properties and dynamics in the LPA.

INTRODUCTION

Terahertz waves, or T-rays, associated with the far-infrared region of the electromagnetic spectrum, have gained interest as a source in recent years due to promising applications in imaging, spectroscopy and communications. T-rays have also been proven [4] to be uniquely suited for temporal characterization of electron bunches produced by a laser plasma accelerator (LPA). As the bunch propagates through the plasma-vacuum interface, it produces coherent transition radiation (CTR) in the $0.3-6$ THz range [5, 6]. Theoretical analysis [2] of the generation of CTR by the electron bunch reveals a strong dependence of the THz peak power on the bunch charge, plasma size, bunch length and electron energy. Since each electron in the bunch emits independently, the radiation only interferes constructively if the bunch is shorter than the emitted wavelength. The bunch length (< 50 fs) thus sets the cut-off frequency of the THz spectrum (typically a few THz), providing a practical way to measure the bunch duration. The power spectrum of the THz is determined by Fourier transformation of the temporal waveform. In this paper, three different techniques are used to characterize the THz pulses: pulse energy integration using a Golay cell; spatially-resolved sign-sensitive electro-optic (EO) sampling, in which the delay of a probe beam is scanned to recover the temporal electric-field structure; and a new single-shot technique named temporal electric-field cross-correlation (TEX) based on frequency-domain interferometry.

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OPTIMIZATION AND ENERGY MEASUREMENT

In the LOASIS facility at the Lawrence Berkeley National Laboratory, an 800-nm laser pulse ($\geqslant 40$ fs, up to 0.5 J) was focused ($w_0 \simeq 6$ μm, $> 10^{19}$ W/cm^2) into Helium or Hydrogen gas ($n_e \sim 4 \cdot 10^{19}$ cm^{-3}) from a supersonic nozzle [7, 8]. The laser pulse excited a plasma density wave which trapped and accelerated to 10's of MeV electron bunches with ~ 1 nC of charge. The bunches produced CTR (THz) pulses at the plasma-vacuum interface [5]. T-rays were collected and refocused outside the vacuum chamber by two off-axis parabolas, to where diagnostics were mounted.

The main LPA parameters determining the amount of THz radiation generated are the bunch duration, the plasma size, and both the charge and energy of the electron bunch. As the plasma size is difficult to vary, the approach was to maximize the charge and energy of the electron bunch by optimizing the temporal intensity profile of the driver beam (pre-pulse control), hence the interaction between laser and plasma. In addition, the correlation between LPA performance and THz emission was explored by scanning the compression and the power of the driver beam.

Pre-pulse control for the laser was based on the cross-polarized wave (XPW) technique [9, 10]. After implementation, experiments showed a dramatic increase in the production of charge, THz (a factor ~ 4), and a dramatic decrease in shot-to-shot fluctuations, from 100% to 10%.

To measure the THz pulses energy, a Golay cell was used. Based on a calibration obtained at the FELIX facility in the Netherlands [11], the full-scale detection limit of a Golay cell is 0.85 μJ. At the focus of the THz beam, the collected energy was sufficient to strongly saturate the Golay cell. Thus, to recover the energy a narrow (0.9 mm) slit aperture was scanned across the THz beam at a plane

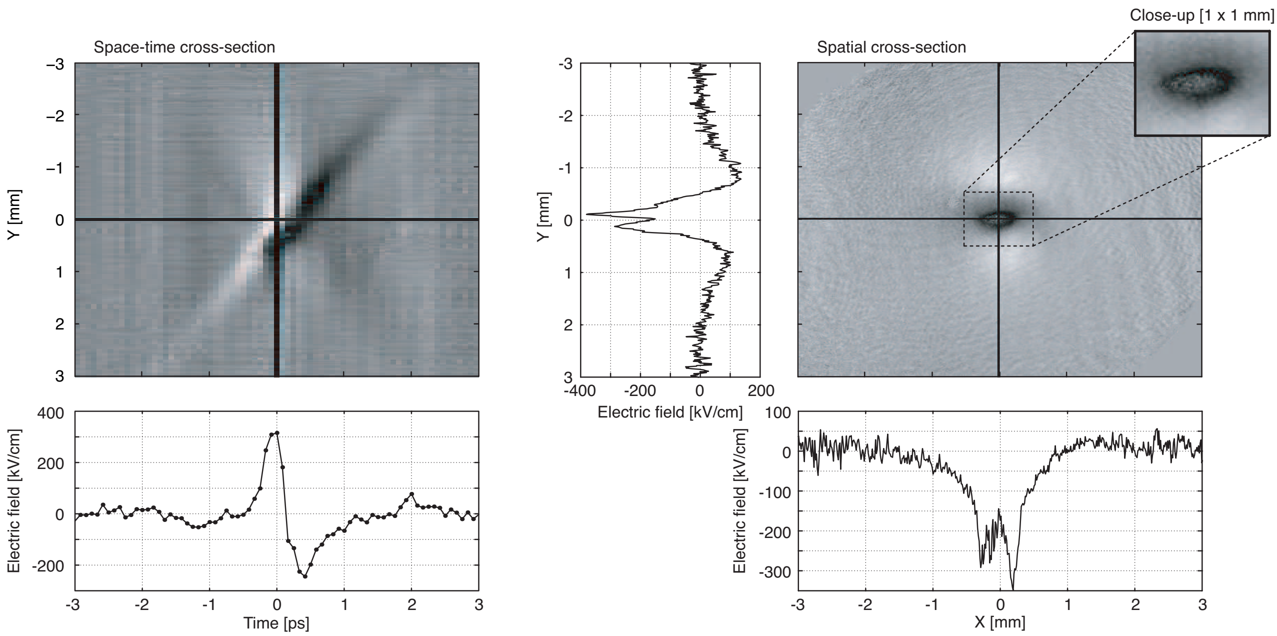

Figure 1: Space-time cross section (*left*) of the THz pulse electric fields reconstructed from a delay scan using 2D sign-resolved EO sampling. Spatial cross-section (*right*) showing inversion (close-up).

3.8 cm upstream of focus. The resulting distribution of energy density was then integrated to yield the energy in the whole beam, which was 5.1 μJ.

The Golay cell was also used to characterize the dependence of the THz pulse energy on the laser compression and power. As expected, THz generation is maximum at peak compression and at maximum power. More interesting is the change in the power-law dependence of THz energy on the charge of the electron bunch. For pulse compression, THz energy is proportional to charge to the power 1.4, whereas for pulse energy it is to the power 2.3.

2D SIGN-RESOLVED ELECTRO-OPTIC SAMPLING

The spatiotemporal profile of the THz pulses was measured using spatially-resolved electro-optic sampling. The technique relies on the interaction of a THz pulse with a short ($\sim$ 50 fs) diagnostic laser pulse in an EO crystal. The collimated, linearly polarized probe beam overlaps with the focused T-rays inside the active crystal (GaP $\langle 110 \rangle$). The high amplitude, low frequency field of the T-rays acts as an electrical bias on the crystal, inducing local birefringence. The probe pulse thus experiences a polarization rotation proportional to the THz electric field, which is translated to an amplitude modulation by using a second polarizer, termed "analyzer". By introducing a quarter-wave plate (QWP) before the analyzer, polarization rotation by the THz can either add to or subtract from the base level of rotation provided by the QWP. Positive and negative THz fields are thus distinguished as an increase or decrease, respectively, of the transmission through the analyzer.

The maximum measurable field strength is set by the field required to rotate the polarization by $\pi/2$. For these experiments, the upper limit (200 μm thick GaP crystal) was $\sim$ 260 kV/cm. Since the probe pulse duration was much shorter than the THz pulse, temporal structure of the THz electric field was retrieved by simply scanning the arrival time of the probe pulse. The sequence of images collected were used to reconstruct a space-time cross-section of the shot-averaged THz pulse electric field (Fig. 1). For phase retardation greater than $\pi/2$ an inversion of the transmission was observed. In the experiments described here, the inversion was determined to occur at approximately 200 kV/cm, in reasonable agreement with the theoretical value, providing a benchmark for the field strength measurement. Accounting for the over-rotation of the polarization, the corrected peak electric field was $\sim$ 300 kV/cm and the pulse duration $\sim$ 0.4 ps *rms*.

The space-time cross-section in Fig. 1 shows strong spatiotemporal coupling, which manifests itself as a time-dependent beam diameter and wavefront. This spatiotemporal coupling is attributed both to double Fresnel diffraction of the T-rays on the collection optics (OAP) and to the few-cycle nature of these pulses [12]. Theoretical model and simulations are currently in progress.

TEMPORAL ELECTRIC-FIELD CROSS-CORRELATION

Real-time optimization and characterization of the T-rays generated by a laser plasma accelerator requires techniques capable of measuring the temporal electric profile of these THz pulses on a single-shot basis. The retrieval

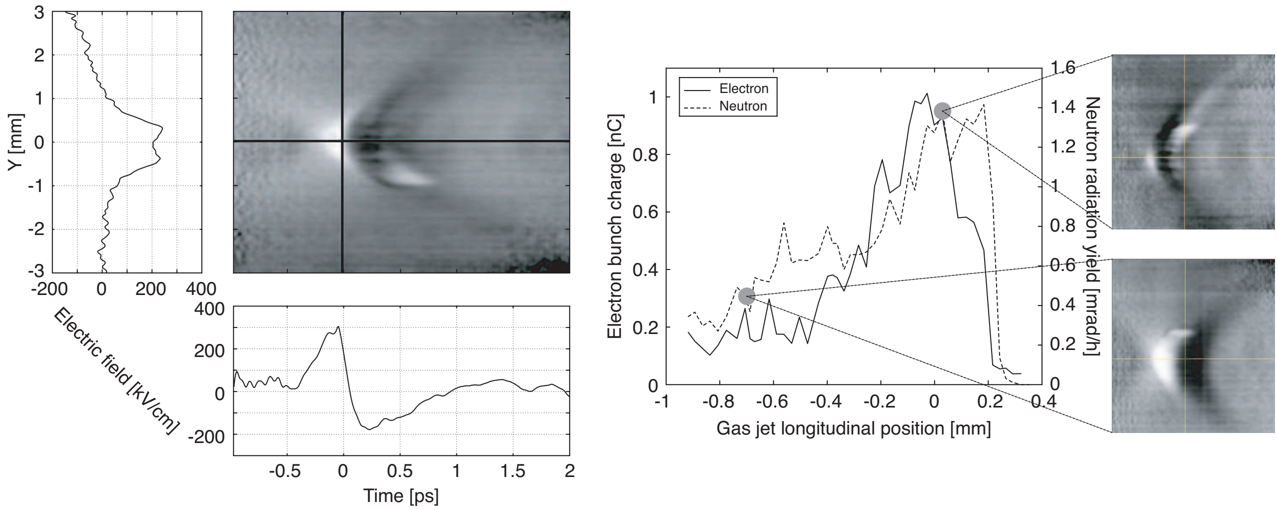

Figure 2: Space-time cross section obtained in a single-shot (*left*) by Temporal Electric-field Cross-correlation (TEX). Electron and neutron yield versus gas jet position (*right*). Spatiotemporal waveforms of the THz correlate with the accelerator performance.

of a space-time cross-section using 2D sign-resolved EO sampling is time-consuming and susceptible to shot-to-shot fluctuations. Although several techniques exist to capture THz waveforms in a single-shot [6, 13], a new method was developed. The technique overcomes the temporal resolution limitations of "spectral encoding" [14], and avoids the difficulties associated with a secondary nonlinear process (*e.g.* second-harmonic generation), while combining the advantages of both.

This new technique [15] is a variation of the single-shot temporal cross-correlation technique [6]. A chirped pulse (few picoseconds long) overlaps the THz pulse in an EO crystal and experiences both amplitude and phase modulation, providing two simultaneous retrievals of the full temporal electric-field distribution. Because the accumulated phase shift scales linearly with the electric-field, the phase modulation provides a benchmark for the "over-rotation" occurring in the amplitude modulation. Preliminary results (Fig. 2) corroborate all the observations described in the previous section, *i.e.* pulse duration, peak electric-field and spatiotemporal coupling at the T-rays focus.

In Fig. 2, electron and neutron yield for different longitudinal positions of the gas jet is shown. As can be seen, the THz spectra correlate with the accelerator performance. As the neutron yield and charge of the electron bunch increase, the spatiotemporal waveforms of the T-rays show sharper features, shorter pulse duration and, hence, higher THz frequencies.

CONCLUSION

Generation of 0.4 ps *rms* THz pulses with $> 5\ \mu$J of energy and $\sim$ 0.3 MV/cm peak electric-fields have been demonstrated. It is shown that these few-cycle T-rays experience a strong spatiotemporal coupling which impacts its properties and, therefore, the interpretation of the LPA characteristics. Finally, the ability to provide both amplitude and phase of the THz pulses in a single-shot has been demonstrated, providing valuable shot-to-shot information on the electron bunch duration for LPA experiments.

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