DEMONSTRATION OF AN ALL-OPTICALLY DRIVEN SUB-KeV THz GUN *

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Abstract

The recent progress in the development of high power lasers in conjunction with novel techniques in nonlinear optics have led to the generation of intense ultrashort THz pulses with single-cycle pulse duration. The old scaling laws of damage threshold for materials and the more up-to-date rules governing the pulse heating of metals both predict the relaxation of damage probability when short pulses are exploited for electron acceleration. Consequently, using THz ultrashort pulses for electron acceleration offers a promising path towards increased acceleration gradients. In this contribution, we present the first experimental demonstration of an ultrafast THz gun. It is shown that strong-field of a single-cycle THz pulse focused by a parallel-plate waveguide accelerates electron bunches with 40 fC to peak energies of up to 0.8 keV. The achieved energy spreads are as low as 5.8%.

INTRODUCTION

The past century has witnessed the major role played by particle accelerators in achieving breakthrough discoveries in fundamental research using advanced instruments like high-energy colliders, x-ray light sources, and electron diffraction. The first and most critical stage of an accelerator facility is the gun, which accelerates particles initially at rest to relativistic speeds [1]. Therefore, many of limits in accelerator operation and particle beam quality are set by the gun properties. The conventional electron gun technology is based on either high DC voltages or RF radiation. Some examples of the difficulties in the construction of such guns are the bulky and expensive high voltage feedthroughs for DC guns, and high power klystrons needed to power RF guns. In addition, the synchronization challenges faced by RF guns hinders the progress to achieve faster and smaller devices. Both DC and RF guns show limitations in the accelerating field of about 10 MV/m and 200 MV/m, respectively, due to breakdown mechanisms [2, 3]. The need for more economical devices, in conjunction with the desire for higher field strengths, has propelled the development of compact IR- or THz-driven linear accelerator (linacs) structures with higher field breakdown thresholds and intrinsic synchronization [4–9].

The empirical studies done by Loew and Wang had initially shown that electron field emission, scaling as $f^{0.5}/\tau^{0.25}$ with f the operation frequency, and τ the pulse duration of the accelerating field, imposes a principal limit on device performance [2]. The above approximate scaling behavior justified research towards higher operating frequencies and ultrafast schemes to achieve compact accelerators. However, the recent comprehensive study on breakdown thresholds of various accelerators demonstrated that pulsed heating of the accelerator walls is the dominant factor limiting acceleration gradients [3]. This conclusion confirmed the observed lower operational gradients in existing facilities when compared with predictions from the previously derived scaling laws. The authors concluded that the pulse duration of the accelerating field plays the major role in the breakdown event, since it is directly linked to the pulse energy governing the pulsed heating in the device. This conclusion was the main motivation in [9] to focus efforts on efficient acceleration using short pulses, which opens new potentials to shrink down the size of such facilities.

Here, we implement a first-version of single-cycle THz-driven electron gun, which realizes a near-keV acceleration of a 40 fC electron bunch with energy spreads as low as 5.8% using a single-cycle THz field generated by a modest few-mJ laser [10, 11].

EXPERIMENTAL SETUP

Figure 1a-c illustrates the THz parallel-plate gun [9] configuration studied in this research. A parallel-plate waveguide (PPWG), made out of copper, consists of a thin-film copper photocathode (yellow) as the bottom plate, and an exit slit anode as the top plate. The tapered input of the THz gun performs as an efficient coupler for transferring energy from the THz beam to the TEM mode of the waveguide. The support for the propagation of a TEM mode without any cut-off frequency enables sub-wavelength confinement in the region between the two parallel plates, which has a thickness equal to 75 µm (Fig. 1c). A UV pulse illuminates the photocathode through the back side, producing an electron bunch inside the PPWG through a photoemission interaction. The vertically polarized electric-field subsequently

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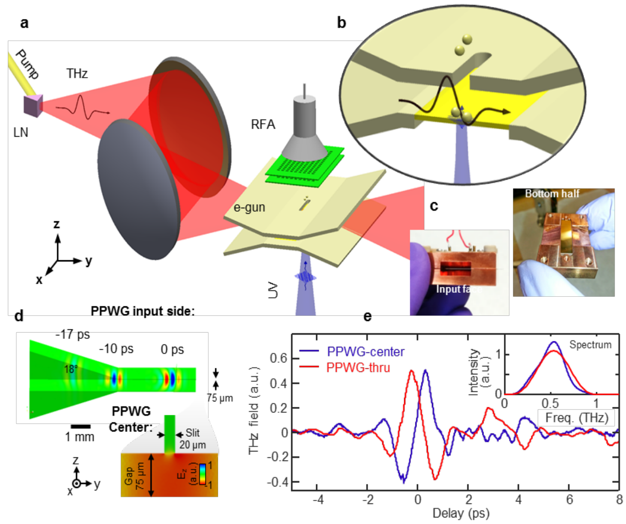

Figure 1: (a) Schematic of UV-triggered THz gun. (b) Photoemission method for electron injection. (c) Photos of the fabricated THz gun and (d) snap-shots of the simulated field profile within the proposed THz gun. (e) Temporal signature of the THz pulse used for electron acceleration.

accelerates the bunch, before it exits through the slit and is spectrally characterized by a retarding field analyzer (RFA) or counted by a Faraday cup. To generate the required high power THz pulses for the acceleration, optical rectification in lithium niobate using the tilted pulse front technique is employed. A maximum THz energy equal to 35.7 μJ is generated out of a Ti-Sapphire laser and led to the THz gun using parabolic mirrors. Temporal waveform measurements at the gun "entrance" corresponding to the focus of the parabolic mirror, with the gun removed, reveals single-cycle temporal waveforms of about 1.2 ps FWHM (Fig. 1d). Taking into account the energy, waveform, and beam spot size (Fig. 1e), the peak electric field of the THz beam at focus in free space is in the range of 150 MV/m. Assuming that the horizontal beam profile remains unaltered while the vertical profile is distributed uniformly across the 75 μm spacing, and taking into account the coupling efficiency, the confined THz pulse inside the PPWG has a peak field in the range of 350 MV/m.

RESULTS

To find the optimal operation point, which corresponds to the best emission phase of electrons in the THz pulse, the kinetic energy spectra and bunch charge as a function of delay between the THz and UV pulses should be recorded. Figure 2a-b shows the recorded energy spectrogram of electrons for various delays between the THz and UV pulses. When the emission does not overlap with the THz pulse ($t > 2$ ps or $t < -2$ ps), there is minimal variation in electron energy gain with delay. However, for the delays exhibiting an overlap between the photoemission laser and the terahertz pulse ($-2 > t < 2$ ps), a narrow energy spread with energy gain governed by the THz phase at the emission instant is observed. Between $t = 0.3$ ps and $t = 0.8$ ps, we observe suppression of photocurrent. This time interval corresponds with the positive half cycle of the THz field, which causes the emitted electrons to be pushed back to the cathode. Two delay positions were selected to be the operating points of the gun: the first delay, τ_1, produced the highest electron energy gains while the second delay, τ_2, produced the most monochromatic spectra. Determination of which operation point is superior depends on the application of interest, Fig. 2c-d shows the electron spectra at these two operating points for three THz energies. In each spectrum, a unimodal distribution is acquired with a peak increasing monotonically with THz field. The spectral shape is asymmetric with a peak yield toward higher energies, followed by a sharp cutoff, and a pedestal toward lower energies. The high yield near the cutoff indicates that most of the electrons are emitted at the optimal THz phase and concurrently experience equivalent acceleration. The lower-energy pedestal can be attributed to the electrons which are emitted away from the optimal phase, resulting in relatively less energy gain. For maximal THz energy, we achieve a peak energy gain of 0.8 keV for an output charge of 40 fC at τ_1. At τ_2, we achieve an energy spread of 5.8% with 0.4 keV energy gain for the output bunch with 32 fC charge.

By plotting the spectra as a function of THz energy on a 2D map in Fig. 3(a)-(b), it is observed that the energy gain increases monotonically with the THz energy. We also observe a monotonically decreasing the energy spread with accelerating energy. The lowest energy spreads achieved at τ_1 and τ_2 were 26% and 5.8% for THz energies of 35.7 μJ and 33.9 μJ, respectively.

CONCLUSION

The first demonstration of a high field (>300 MV/m), quasi-monoenergetic THz gun realizing sub-keV acceleration within an ultracompact and robust device is presented. The device shows no degradation in performance after one billion shots. In its current state, it can be used for time-resolved electron diffraction imaging and after further improvements on the gun structure and THz field relativistic electron guns will be potentially produced.

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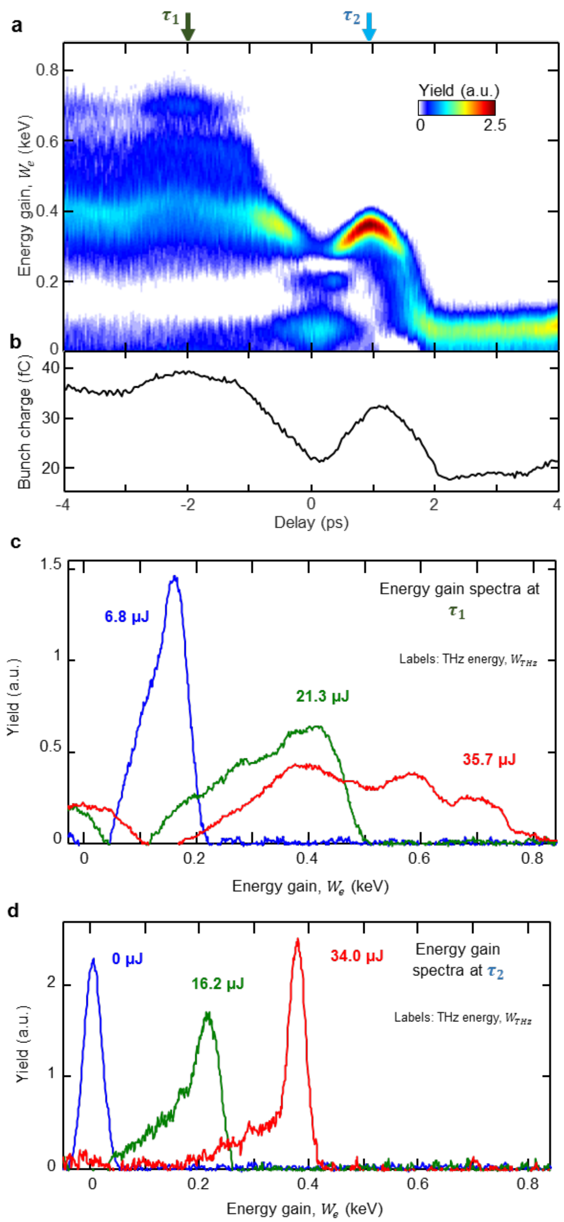

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Figure 2: (a)-(b) Spectrogram showing (a) energy gain spectra and (b) bunch charge as a function of delay between UV and THz, at max THz energy. (c)-(d) Accelerated electron spectra at delay (c) τ_1 and (d) τ_2 for several THz energies.

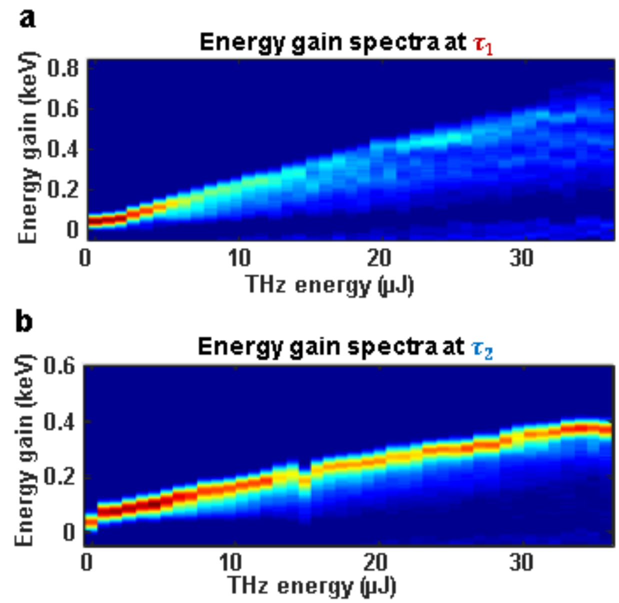

Figure 3: Accelerated electron spectra as a function of THz energy at delay (a) τ_1 and (b) τ_2.

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