COMPACT TERAHERTZ-POWERED ELECTRON PHOTO-GUN

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Abstract

We present a modular THz-driven electron gun with both tunable interaction length and output orifice allowing optimization of the sub-mm interaction volume. First extraction of multi-keV electrons is demonstrated and the parameter space as well as resulting performance of the THz-driven gun by varying the timing of the two single-cycle THz pulses and the UV photo-excitation pulse are explored. Such compact photo-gun prototypes are not only promising as injectors for compact THz-based linear accelerators (LINACs) but also as source for ultrafast electron diffraction experiments.

INTRODUCTION

Novel accelerator concepts such as all-optical terahertz (THz) based compact accelerators promise to enable new science due to unique features such as reduced timing-jitter and improved space-charge broadening of the generated electron bunches [1]. While practical prototypes of THz based devices have been demonstrated and showed exceptional capabilities to accelerate and manipulate electron beams on sub-ps timescales [2-4], development of practical THz-powered photoguns, however, has lagged due to challenges associated with the physical miniaturization and the larger THz energies required for the driving pulses [5, 6]. Here, we present a modular THz-driven electron gun transversely pumped by single-cycle pulses. Both the interaction length and output orifice are tunable and allow optimization of the sub-mm interaction region. The maximum electron energy from the THz photogun prototype reached up to ~ 3 keV which sets a record energy for such a compact photo-triggered device. The demonstrated concept is scalable to higher energies and thus is promising for powering compact THz driven accelerators or for ultrafast probe-beams in electron diffraction experiments.

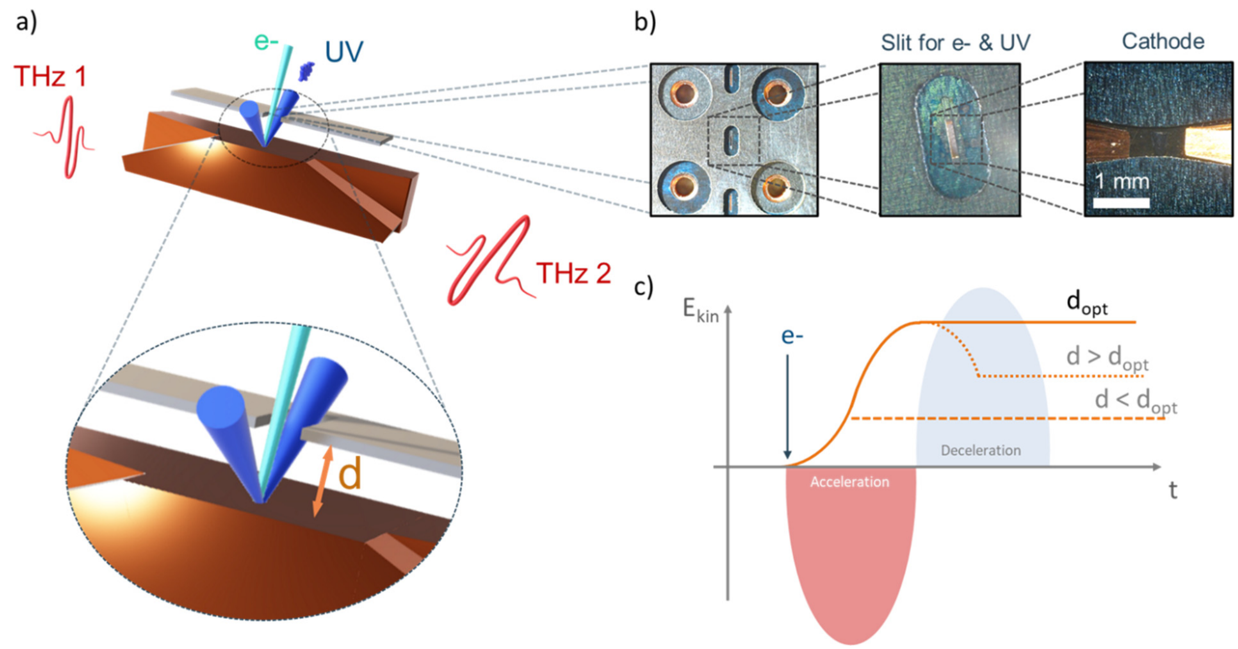

Figure 1: (a) 3D-sketch of the compact gun structure pumped transversely by two single-cycle THz pulses (red). The THz pulses interfere at the cathode area which they are confined into by copper waveguides. Electrons are photo-generated by a UV pulse (blue) illuminating the cathode through the exit slit for the electrons (green). (b) Close-up picture of the output orifice and copper cathode area. (c) The maximum reachable electron-energy depends on the spacing *d* between cathode and exit slit, as it needs to be matched to the accelerating half-cycle of the superposed THz fields.

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RESULTS

The THz photogun (Fig. 1a) is a single-layer version of the segmented THz electron accelerator presented in [3], with the additional difference that the bottom of the acceleration volume is also used as the photocathode for generating the electrons, as described in [7].

Working Principle and Experimental Setup

As in [2, 3], the acceleration volume is pumped transversely from both sides simultaneously by two single-cycle THz pulses whose relative delay can be finely adjusted. The THz pulses were generated in two twin setups [8] based on the tilted-pulse-front scheme [9]. After transport and balancing of the two pulses ~ 22 µJ THz pulses were coupled into each horn coupler of the device. These two tapered horn couplers confined the THz pulses into the cathode region with a cut-off frequency of ~ 220 GHz. The photoemission of the electrons is achieved via a 130 nJ UV-pulse (254 nm, 1 ps duration) that illuminates the cathode via a 120 x 600 µm wide slit in the covering foil of the acceleration volume (Fig. 1b). A circular mirror with an on-axis hole for the electrons to pass through was integrated into the gun to allow injection of the UV pulse from behind at an incident angle of 30°. The generated electrons are intrinsically synchronized to the laser system [10], that was used to generate both THz and UV pulses.

The acceleration length *d* can be adjusted to match the available THz energy and frequency via a spacer-layer of thickness *d*. This spacer layer can for example be optimized such that an electron launched into the THz field experiences the strongest negative half-cycle for maximum acceleration (Fig. 1c).

Field-Emission and Photo-Injection

The temporal dynamics involving the three optical pulses and the electrons were studied using a Channeltron detector closely placed to the output orifice of the THz photogun.

Field-emission To check the coupling of the THz pulses to the cathode area, the field-emitted electron yield was recorded vs the relative delay between the two driving THz pulses τ_{THz} while the UV beam was blocked (Fig. 2a). The Fourier-transform of this signal indicates the frequency-content of the THz pulses above the cut-off frequency (~ 220 GHz) coupled into the interaction volume as intended (Fig. 2b).

Photo-injection To verify that electrons were produced by photoemission, the relative timing between the UV pulse and the single-cycle THz pulses τ_{UV} was scanned (Fig. 2c). Via simultaneously scanning the delay between the THz pulses the complete temporal dynamics in the structure could be studied (Fig. 2d). While the THz delay sets the accelerating field for the electrons, the UV delay controls the injection phase into the THz field. The points with high signal correspond to injection phases such that the overlap of the electrons with the accelerating phase of the THz, integrated over the interaction, is maximized.

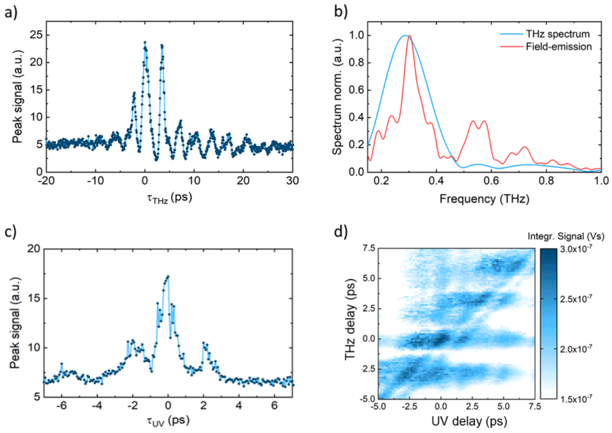

Figure 2: (a) The field-emission caused by the accelerating THz field in the gun structure vs. the relative delay between the THz pulses. (b) The Fourier-transformed field-emission signal (red) indicates the THz pulses were properly coupled from free space (spectrum in blue) into the gun and indicate a low-frequency cut-off by the coupler at ~ 220 GHz. (c) The modulation of the electron yield with the relative delay of the UV pulse verifies that control over the photo-injection into the THz accelerating field was achieved. (d) The emitted electron yield sensitively depends on both the relative delay of the THz pulses (which set the accelerating field) and the relative delay of the UV pulses (which determine the time of injection into the accelerating field).

Bunch-Profile and Energy

The energy and spatial profile of the accelerated electrons were analyzed using a microchannel plate (MCP) and phosphor screen stack that was monitored by a CCD camera (see Fig. 3a). The profile of the focused electron bunch is shown in the inset of Fig. 3a. The ≈ 1 mm wide center-spot was found to be surrounded by a star-shaped structure, which could be attributed to misalignment of the focusing solenoid in combination with the spatial energy distribution of the ejected electron bunches.

The electron energy was determined via the angle of deflection observed for the beam on the MCP introduced by a tunable magnetic steerer (Fig. 3b). This steerer [11] was calibrated on a DC electron gun with known parameters. Upon optimization of the injected THz energy and timing, a maximum energy of 2.4 keV was determined for the center spot of the electron beam on the screen. In addition, the energy of the electrons was probed via setting a retarding potential to the front-side of the MCP-detector stack such that only electrons with energies exceeding the retarding potential could reach the screen. The measurement, shown in Fig. 3c, shows evidence of electron energies reaching up to 3 keV.

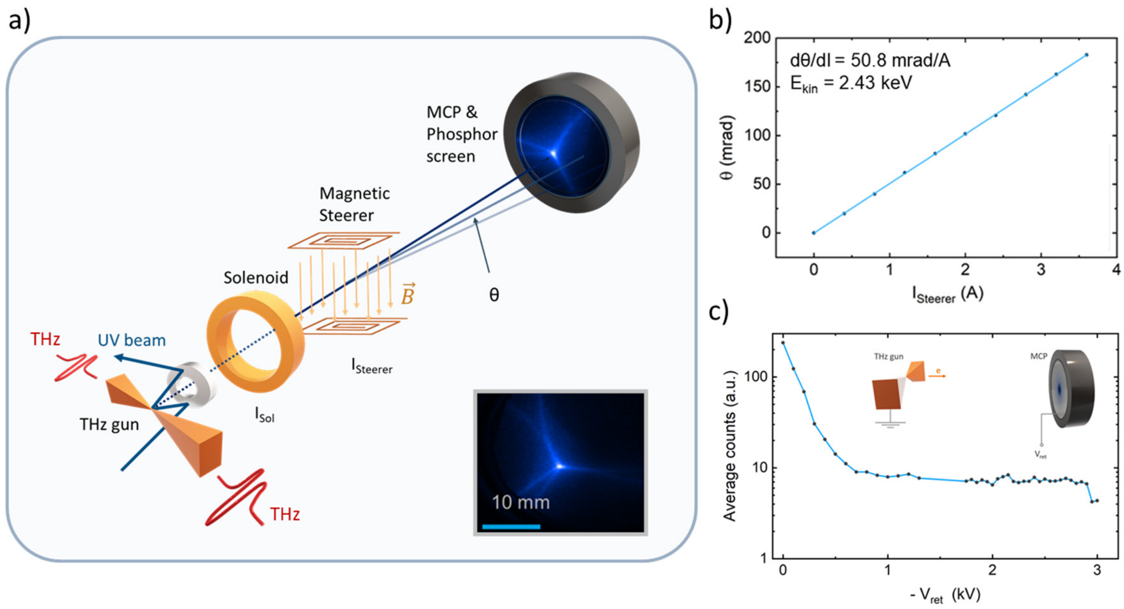

Figure 3: (a) Schematic of the experimental setup: The electron bunches (see inset) are focused onto a MCP and phosphor-screen stack monitored by a camera. (b) A tunable magnetic steerer, calibrated at a DC gun with known beam parameters, was added to determine the electron energy via the deflection angle per steerer current. (c) In another experiment to characterize the electron energy, a retarding potential was applied to the front side of the MCP detector stack (see inset). The amplitude of the potential barrier for the electrons was scanned via the applied retarding voltage V_{ret}.

CONCLUSION

We present the design and first tests of an ultrafast THz-powered photogun with potential for reaching multiple tens of keV electron energy. Preliminary energy measurements and signal dependence on UV timing confirm achievement of a THz photogun with electron energies of multiple keV. This result represents a record of electron energy obtained from a triggerable THz photogun. Ongoing work focuses on scaling the electron energy towards higher energies such that the device will be interesting both as injector for subsequent LINACS and for performing ultrafast electron diffraction experiments.

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REFERENCES

[1] F. X. Kärtner *et al.*, "AXSIS: Exploring the frontiers in attosecond X-ray science, imaging and spectroscopy", *Nucl. Instr. Methods. A*, vol. 829, pp. 24- 29, 2016.
`doi:10.1016/j.nima.2016.02.080`

[2] A. Fallahi *et al.*, "Short electron bunch generation using single-cycle ultrafast electron guns", *Phys. Rev. Accel. Beams*, vol. 19, p. 081302, 2016.
`doi:10.1103/physrevaccelbeams.19.081302`

[3] D. Zhang *et al.*, "Segmented Terahertz Electron Accelerator and Manipulator (STEAM)", *Nat. Photonics*, vol. 12, pp. 336-342, 2018. `doi:10.1038/s41566-018-0138-z`

[4] E. Nanni *et al.*, "Terahertz-driven linear electron acceleration", *Nat. Com.*, vol. 6, p. 8486, 2015.
`doi:10.1038/ncomms9486`

[5] W. R. Huang *et al.*, "Terahertz-driven, all-optical electron gun", *Optica*, vol. 3, pp. 1209-1212, 2016.
`doi:10.1364/optica.3.001209`

[6] S. Li and R. R. Jones, "High-energy electron emission from metallic nano-tips driven by intense single-cycle terahertz pulses", *Nat. Com.*, vol. 7, p. 13405, 2016.
`doi:10.1038/ncomms13405`

[7] A. Fallahi and F. X. Kärtner, "Design strategies for single-cycle ultrafast electron guns", *J. Phys. B: At. Mol. Opt. Phys.*, vol. 51, p. 144001, 2018.
`doi:10.1088/1361-6455/aac6f0`

[8] T. Kroh *et al.*, "Robust optimization of single-cycle THz setups based on phase-matching via tilted pulse fronts using an incident-fluence metric", in *Proc. SPIE 11264,* San Francisco, USA, Mar. 2020, paper 1126416.
`doi:10.1117/12.2545145`

[9] J. Hebling *et al.*, "Velocity matching by pulse front tilting for large-area THz-pulse generation", *Optics Express*, vol. 10, pp. 1161-1166, 2002. `doi:10.1364/OE.10.001161`

[10] H. Cankaya *et al.*, "190-mJ cryogenically-cooled Yb:YLF amplifier system at 1019.7 nm", *OSA Continuum*, vol. 2, pp. 3547-3553, 2019. `doi:10.1364/OSAC.2.003547`

[11] K. Floettmann, "Design and performance of printed circuit steering magnets for the FLASH injector", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper MOPEB003, pp. 277–279.