Terahertz-driven, sub-keV electron gun

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Abstract: Strong-field, single-cycle THz fields accelerate electrons with peak energies of up to 0.75 keV in a millimeter-sized THz gun with bunch charge of 45 fC. Energy spreads as low as 5.8% were also achieved.

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1. Introduction

Ultrafast electron guns are an enabling technology for femtosecond electron diffraction and compact free electron lasers. Guns accelerate electrons either by DC electrostatic fields or by synchronized RF fields. Current hurdles facing the construction of guns include the bulky, expensive high voltage feedthroughs or high power klystrons needed to power DC or RF guns, respectively, as well as the synchronization challenges faced by RF guns. Further, 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 in common accelerator materials [1]. It is well known in accelerator physics that electron beam size and bunch duration directly achieved from the gun is inversely proportional to the accelerating electric field. The need for more economical devices, coupled with the desire for higher field strength, has propelled the development of compact NIR- or THz-driven linear accelerator (linacs) structures with higher field breakdown thresholds [2,3] and intrinsic synchronization. The enormous potential advantages of light-driven linacs, however, has not extended to guns [4], which are essential to determining beam quality. Here we implement a first-version of THz-driven electron gun based on a parallel plate waveguide (PPWG) structure with subwavelength field confinement. We report on the demonstration of keV-scale acceleration of a 45 fC electron bunch using a single-cycle THz pulse generated by a modest mJ-scale NIR laser. Energy spreads as low as 5.8% were achieved.

2. Experimental setup

Figure 1: Schematic of setup (a) zoomed out and (b) cross-section zoomed in. (c) THz electric waveform and spectrum (inset) at the entrance and exit of the PPWG gun structure. (d) THz intensity profile at free-space focus.

The THz Gun structure, schematic in Fig. 1(a)-(b), consists of a copper PPWG, an angled coupling taper, a thin-film copper photocathode, and an exit anode. A THz beam, polarized perpendicularly to the PPWG walls, is coupled into it by the assistance of the angled taper. Once inside the waveguide, the THz electric field accelerates an electron bunch, produced via photoelectric emission by UV back-illumination of the photocathode. Accelerated electrons travel across the vertical extent of the waveguide and exit through a narrow slit on the anode. Afterward, they are detected and spectrally characterized by a retarding field analyzer (RFA). The THz pulses are generated by optical rectification in lithium niobate using the tilted pulse front technique. The energy impinging the gun was 33 μJ after relaying off parabolic mirrors. Electro-optic sampling (EOS) at the gun “entrance” (at the focus of the parabolic mirror with the gun removed) and at the gun “exit” (at the focus of a second relay after the THz travels through the waveguide—not shown in schematic) reveals single-cycle temporal waveforms of about 1.2 ps FWHM (Fig. 1(c)). A horizontal beam waist of 0.74 mm at the gun (Fig. 1(d)). Taking into account the energy, waveform, and beam waist, the focused THz has a calculated peak field in the range of 100 MV/m in free space. Assuming 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 300 MV/m.

3. Results

We record the kinetic energy spectra as a function of delay between the THz wave and UV photoemitter, producing a streaking spectrogram in Fig. 2(a). When the emission occurs before the terahertz pulse (<-2 ps), we observe a large spread of kinetic energies, resulting from UV emission combined with THz field emission, a phenomenon observed and investigated in [5]. Conversely, when the emission occurs during the terahertz pulse (-2 to 2 ps), we observe a narrow energy spread with energy gain governed by the THz phase at which emission occurs. Between 0.3 - 0.8 ps, we observe suppression of photocurrent resulting from the fact that emission occurs at the highest downward force of the THz field. Two delay positions were selected to analyze the THz energy dependence, plotted in Fig. 2(b)-(c). The first delay, τ_1 , produced the highest electron energies while the second delay, τ_2 , produced the most monochromatic spectra. Each spectrum exhibits a unimodal distribution 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 indicate that most of the electrons are emitted at the optimal THz phase and concurrently experience the same acceleration. The pedestal can be attributed to the electrons which are emitted away from the optimal phase, resulting in relatively less energy gain. At τ_1 , we achieve energy gain of 0.75 keV for maximal THz energy. The bunch charge was measured to be 45 fC at this setting.

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

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 percent RMS 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.

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

4. Conclusion

We have built a first electron gun driven by strong THz fields, with close to 1 keV-scale acceleration. The gun was operated over the entire 4 days of period without noticeable degradation.

5. References

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