SINGLE-SIDED PUMPED COMPACT TERAHERTZ DRIVEN BOOSTER ACCELERATOR

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Abstract

Here, we present on the progress of developing a multi-layered accelerator structure designed to boost the 50 keV output of a DC electron gun to energies of $\sim$ 400 keV powered by a single high-energy terahertz ("THz") pulse. An integrated piezo-actuated mirror inside the matchbox sized structure enables fine-tuning of the electric field in the interaction region for efficient acceleration and helps reduce the complexity of the optical setup. Such a compact booster accelerator is very promising as electron source in ultrafast electron diffraction experiments and as booster stage prior to THz based LINACs.

INTRODUCTION

Scaling the RF-accelerator concept to terahertz ("THz") frequencies brings several compelling advantages, including compactness, intrinsic timing between the photoemission and driving field sources, and high field gradients associated with the short THz wavelength and high breakdown threshold [1]. Some recent demonstrations of such THz powered accelerators and beam manipulators relied on two counter-propagating single-cycle THz pulses [2-4]. However, to achieve high energy gains in the acceleration process THz pulses of high energy are needed which in turn require complex optical setups and optimization procedures [5-7]. Here, we present on the development of a multi-layered accelerator structure which only requires a single THz pulse to be powered and is designed to boost the 50 keV output of a DC electron gun to energies of up to $\sim$ 400 keV. An integrated tunable mirror inside the matchbox sized structure interferes the front of the driving THz pulse with its rear part such that the magnetic field in the interaction region is cancelled and the electric field is optimized for efficient acceleration. This approach reduces the required number of driving THz pulses from two to one and consequently reduces the complexity of the optical setup.

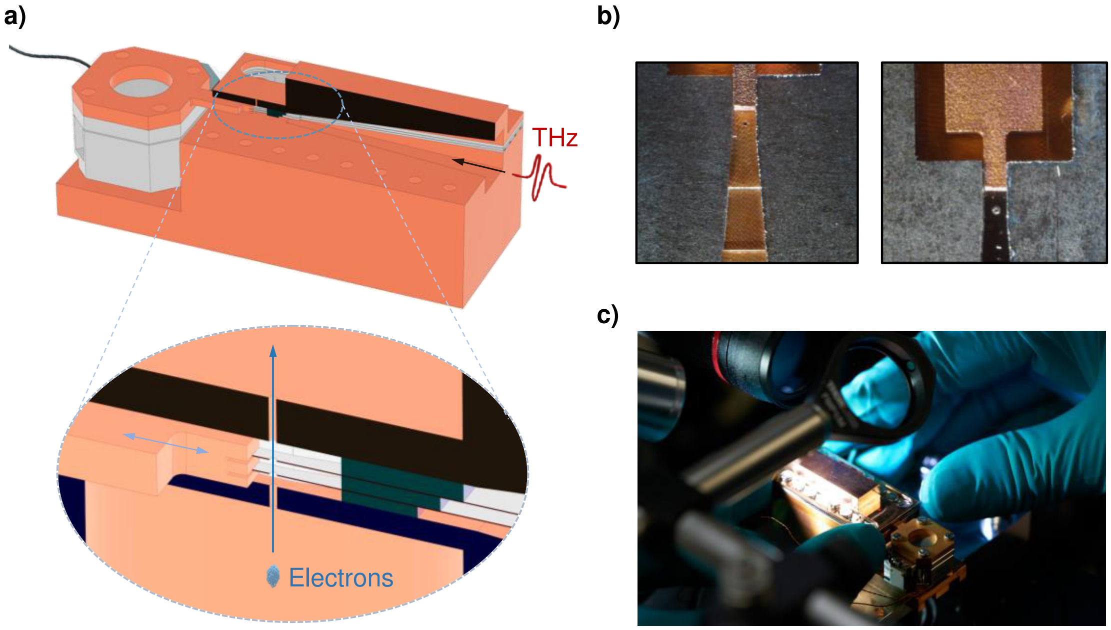

Figure 1: (a) 3D-model of the compact booster accelerator pumped transversely by a single-cycle THz pulse (red). This pumping scheme is enabled by a piezo-actuated mirror integrated into the device. (b) Top-view close-up pictures of the 1st and 2nd layer. Fused silica inserts delay the THz pulse in each consecutive layer such that efficient acceleration is achieved. (c) Assembly of the booster device under an optical microscope with an integrated alignment laser.

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The concept is scalable towards higher THz pulse energies and, paired with an optically triggered electron gun, offers intrinsic synchronization due to the all-optical approach. Therefore, such compact THz-based accelerators are not only promising as booster stage in compact THz driven accelerators but for delivering ultrafast-probe beams in electron diffraction experiments.

RESULTS

The THz booster accelerator (Fig. 1a) is a 3-layer version of the segmented THz electron accelerator presented in [3], with the additional difference that a piezo-actuated mirror is integrated such, that the device can be powered by a single terahertz pulse instead of two counterpropagating pulses.

Working Principle & Experimental Setup

As in [2, 3], the acceleration volume is pumped transversely by a high-energy single-cycle THz pulse, whose relative delay to the electron bunches can be finely adjusted. The THz pulses are generated by optically rectifying high-energy laser pulses (1030 nm, 400 fs, up to 200 mJ) in a cryogenically cooled lithium niobate prism utilizing the tilted-pulse-front method [5]. The high-energy THz pulses (~ 400 µJ) are focused into a tapered horn-coupler that confines the pulse into the interaction volume. Beforehand, a 90°-periscope is used to rotate the polarization of the THz pulses such that the electric field component aligns with the propagation of the electron bunches.

Single-sided pumping scheme. The dispersion of the waveguide causes the single-cycle THz pulse to stretch to a few-cycle pulse inside the structure. This allows an integrated mirror to retroreflect the THz pulse back onto itself, such that its front and rear part can constructively interfere. This mirror is piezo actuated which enables precise tuning of the mirror position relative to the electron beam and, therefore, to finely adjust the accelerating field. Such a single-sided pumping scheme enables to reach comparable field strengths as in a double-sided pumped approach, but with half the energy. Thus, the single-sided scheme has the advantage that the available THz pulse energy is used more efficiently, and the complexity of the optical setups is significantly reduced. However, this benefit comes at the cost of a more complex accelerator device which is harder to assemble. Furthermore, if the interfering half-cycles of the THz pulse are not equal in amplitude, a non-vanishing magnetic field component can induce deflection of the electron beam, which then needs to be compensated for using an external electromagnetic steerer or by adjusting the THz pulse carrier-envelope phase (CEP) [8].

Multi-layer approach. Efficient acceleration requires the interaction between electrons and THz field to be restricted to a duration shorter than a half-cycle of the THz field. Here, this is circumvented by stacking several interaction layers within which the THz pulse is delayed by a fused silica piece (Fig. 1b) such that repeated acceleration is possible. In each layer, the interaction length between electrons and transversely propagating THz pulse can be adjusted to match the electron kinetic energy, THz field strength and centre-frequency via the thickness of spacer layer foils. Adding more layers allows to scale the concept to arbitrary THz pulse energies but is ultimately limited by the complexity of the assembly process. Our prototype consists of 3 consecutive layers of which the layer thicknesses (250 µm, 300 µm, 400 µm) were optimized to achieve maximum possible acceleration.

Device assembly. For the assembly of the device (see Fig. 1c), an optical microscope was used to ensure gaps between parts and vertical layers were kept within specified tolerances of ~ 10 µm to minimize leakage of THz energy from one layer into another or out of the structure. Simultaneously, the piezo-actuated mirror was ensured to move without mechanical friction such that its front facets could penetrate each individual layer. The relative distance between mirror and through-holes for the electrons was calibrated to the encoded position of the piezo-motor. A HeNe laser was used to ensure alignment of the electron through-holes in all layers.

Electron source and detection. The booster accelerator is seeded with electron bunches of ~ 10 fC charge and 55 keV energy from a table-top DC electron photo-gun [9] equipped with a THz-driven buncher to compress the bunch duration down to the 100-fs level. Since the same laser system is used to photo-generate the electrons and the accelerating THz pulses, the electron bunches and their driving field are intrinsically synchronized to the laser system. The match-box sized booster accelerator is mounted on a high-precision stage assembly to precisely tune it such that the electron beam can pass through the orifice in the individual layers of 80 µm diameter. The profile of the electron bunches exiting the booster are then detected using a phosphor screen monitored by an amplified CCD camera. Additionally, the electron energy can be measured by a custom-made compact electromagnetic spectrometer.

Initial Characterization

In a first experiment, spatio-temporal overlap and initial interaction between THz pulses and electron bunches was verified. The setup was operated with uncompressed electron bunches and low THz pulse energies with the integrated mirror set to a fixed distance from the interaction region of 420 ± 10 µm. Figure 2a shows the radius (FWHM) of the electron bunch as a function of the injection timing of the electrons into the THz field. Around time-zero, the electron bunch is caused to diverge which leads to a reduced peak signal on the screen, confirming first interaction inside the booster accelerator. The profile of the transmitted electron beam is shown in the inset.

The next round of testing will target scanning both the injection timing as well as the integrated mirror position while increasing the amount of injected THz energy into the structure to reach nominal internal field strengths. Simulations performed with CST Studio [10] predict the electron energy to increase up to 420 keV as the electron bunch propagates through the 3-layered device (see Fig. 2b) driven with THz pulses of ~ 400 µJ energy with a center frequency of 300 GHz for optimized injection timing and CEP of the THz pulse.

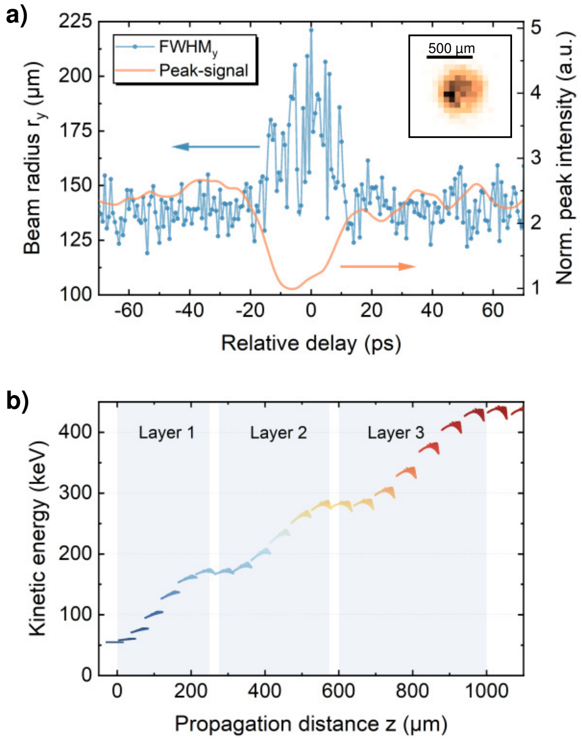

Figure 2: (a) Confirmation of interaction between the uncompressed electron bunch and THz field inside the booster at time-zero. The inset shows the recorded profile of the electron bunch ~ 8 cm after exiting the device. (b) Simulated energy distribution of the electron bunch as it transitions through the 3 layers of the THz-driven booster. Under optimum conditions, the electron output energy can reach up to ~ 430 keV.

CONCLUSION

We present on the design and implementation of an ultrafast THz-powered booster accelerator with potential for boosting electron bunches of a conventional DC electron gun to multiple hundreds of keV electron energy. The use of a tunable integrated mirror for the transversely injected THz pulses allows to significantly simplify the optical setup as it can be powered by a single high-energy THz source. Spatio-temporal overlap between electron bunches and accelerating terahertz pulses was verified in initial experiments with ongoing efforts to scale up the accelerating field to reach nominal performance. The next round of testing will then target characterization of bunch charge, energy spread and emittance of the beam. Such compact accelerator device is promising both as injector for subsequent LINACS and for performing ultrafast electron diffraction experiments.

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