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COMPACT FIELD EMISSION ELECTRON GUN DRIVEN BY THz WAVE*

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Abstract

Accelerator-based light sources require high brightness electron beams to improve performance in exploring structure of matter. Higher acceleration gradient is the key to generate high brightness electron beams and is more feasible with higher frequency and shorter pulse length electromagnetic wave according to previous empirical formulas. A tapered rectangle waveguide structure driven by terahertz (THz) wave is designed as a compact electron gun. A nanotip is fabricated by focused ion beam (FIB) in the centre to enhance the field and to emit electrons. The average emission charge per pulse is measured by a Picoammeter, and the peak value reaches 10 fC. The max electron energy beyond 4 keV is measured from the signal of channel electron multiplier behind a -4 kV metal girds, revealing that maximum acceleration gradient is beyond 100 MeV/m. These results indicate promising performance of compact THz electron gun in high brightness electron injection. Further research will be done in the future.

INTRODUCTION

Compact terahertz (THz) electron accelerators and injectors have emerged as an active research focus with the development of strong-field THz technologies, providing the potential for high-gradient acceleration as suggested by previous empirical formulas [1, 2]. This capability is beneficial to generating high-brightness electron bunches, thereby enhancing the performance of accelerator-based light sources for the investigation of matter's structure. THz-driven acceleration of electron beams has been achieved with an effective acceleration gradient of 85 MeV/m and an energy gain of up to 204 keV [3]. The electron beam emitted by THz photocathode electron gun, with a charge of approximately 10 fC, achieves a maximum electron energy of 14 keV [4]. This corresponds to an acceleration gradient of approximately 280 MeV/m, which is much higher than that of an X-band photogun, yet the maximum electron energy is significantly lower. Further research is required to enhance the performance of THz accelerators and electron guns.

In this paper, we report on the setup of experimental platform for THz electron guns research in Tsinghua University. Beam experiments were carried out using the designed compact THz field emission gun. Emission charges up to 10 fC were obtained with the maximum energy detected exceeding 4 keV. This corresponds to an acceleration gradient over 100 MeV/m, which was limited by our available THz pulse energy. Despite the limitation, it shows promising high-gradient acceleration capabilities.

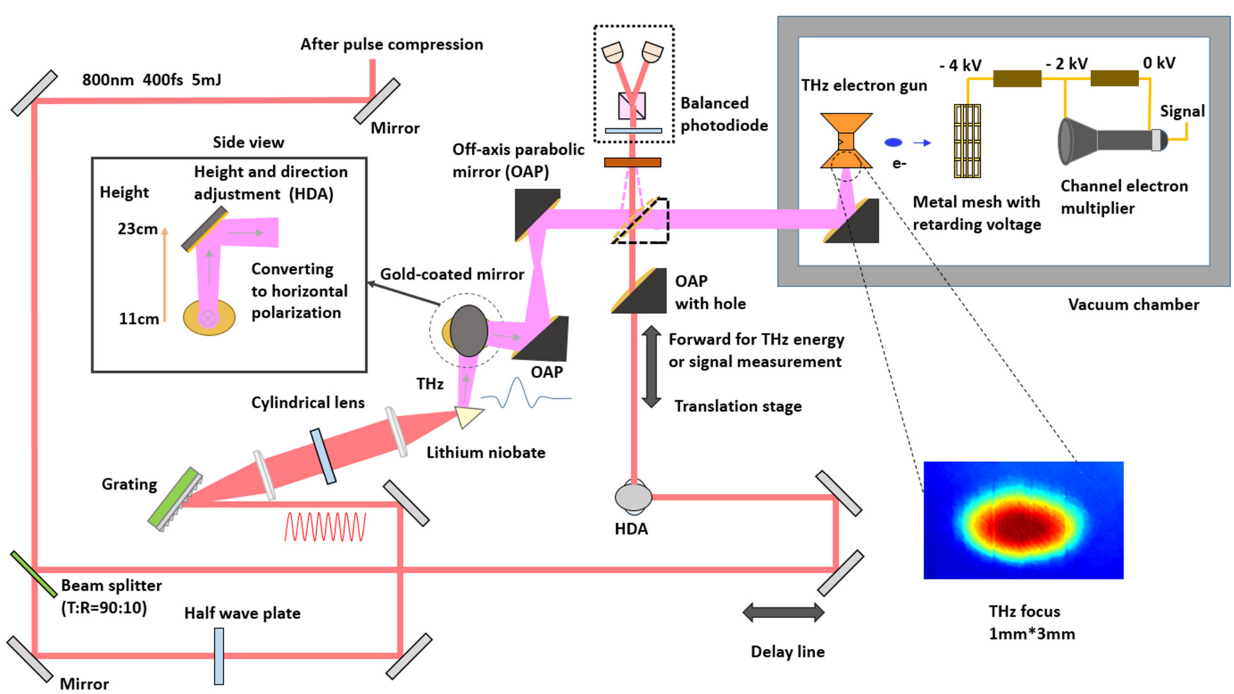

Figure 1: The schematic layout of the experiment.

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EXPERIMENTAL SETUP

The optical path design for generating strong-field THz radiation based on optical rectification method is shown in Fig. 1. The initial near-infrared laser pulse with a width of several hundred picoseconds is compressed by a dual-grating system. After pulse compression the laser pulse width is reduced to approximately 400 femtoseconds. The laser pulse first passes through a beam splitter. The reflected light, a small portion of the laser pulse, serves as the probe for THz electric field electro-optic measurements. The transmitted light passes through three reflective mirrors to adjust its direction and a half-wave plate to tune the energy of the diffracted pulse. It then incidents onto a diffraction grating with a line density of 1800 lines/mm at an angle of approximately 38°, producing a laser pulse with a tilted wavefront. The -1st order diffracted laser pulse passes through a double-lens imaging system composed of two cylindrical lenses with focal lengths of f_1 = 100 mm and f_2 = 60 mm, respectively, which images the wavefront tilt generated at the grating surface onto the congruent lithium niobate (cLN) crystal surface with an image reduction factor of 0.6. Since the cylindrical lenses only focus in the horizontal divergence direction of the diffracted light, the final laser spot on the cLN crystal is laterally distributed in an elliptical shape. The half-wave plate placed between the grating and the cLN crystal is used to alter the laser polarization direction to align it with the crystal axis, thereby enhancing the THz conversion efficiency. In the experiment, the diffraction grating, the cylindrical lenses, and the cLN crystal are all mounted on a multi-dimensional mirror frame to facilitate the optimization of THz conversion efficiency. The highest conversion efficiency achieved is approximately 2‰. Table 1 summarizes the parameters of the pump laser and main optical components for THz generation via optical rectification.

Table 1: Summary of Parameters for THz Generation

Parameters	Value
Laser energy	5 mJ
Pulse width	400 fs
Diffraction grating	1800 l/mm
cLN crystal	25mm*25mm*35mm, 63°
Cylindrical lenses	f_1 = 100 mm, f_2 = 60 mm
Half wave plate	d=25.4 mm@800 nm

The THz transmission optical path and electron beam experimental layout are also shown in Fig. 1. The THz wave radiated from the cLN crystal first passes through two assembled gold-coated mirrors to adjust the transmission height and direction. This step is primarily aimed at converting the polarization of the THz wave to a horizontal direction, which is beneficial to the subsequent arrangement of the electron gun beamline. This method is more efficient than THz half wave plate in polarization conversion. The THz wave then passes through two gold-coated off-axis parabolic (OAP) mirrors. The first one is used to form a THz focus for the purpose of using a THz camera to observe the THz transmission direction and transmission efficiency. The second one is used to form a parallel THz beam to achieve efficient transmission over long distances. An OAP with hole is mounted on an electrical translation stage for THz measurement when it's in the transmission path of the THz wave, using a ZnTe crystal and the balanced photodiode for THz time signal measurement or Golay Cell for THz energy measurement. A CF63 TPX window is mounted on the vacuum chamber for its high transmission for THz wave. The final OAP is used to form a THz focus which is coupled into the THz electron gun for field emission and acceleration of electrons.

In the vacuum chamber, the THz electron gun is positioned at the THz focal point with the nanotip axis parallel to the direction of the terahertz electric field. This nanotip as shown in Fig. 2 is fabricated by utilizing an annular focused ion beam (FIB) to etch a small cylindrical substrate. Field emission is determined by the main tip according to simulations. The peak electron energy is roughly measured via a channel electron multiplier (CEM) positioned around 2 cm away from the tip along the emission axis with a stopping potential (-4 kV) applied to a grid placed before the CEM. By replacing the energy analysis setup with a metal plate connected to a Picoammeter, the emitted charge can be quantitatively measured.

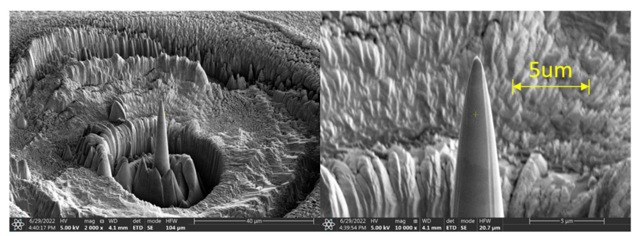

Figure 2: Nanotip fabricated by annular FIB.

THz ELECTRON GUN DESIGN

The THz electron gun in our experiment as shown in Fig. 3 is designed as a horn gun [5] to enhance the field both in the electric field direction and the magnetic field direction. This structure will induce dispersive effects, and to suppress dispersive effects the length of the rectangular waveguide interaction region l is reduced to 100 µm. The length of the broad side of the rectangular waveguide is a for the tapered coupler and a_0 for the interaction region, and the length of the narrow side of the rectangular waveguide is b and b_0 respectively. The narrow side b_0 is equivalent to the sum of the tip height h adding the electron flight gap d. The tip height $h{\sim}30\ um$ is selected to be the effective length which is ~0.06λ [6]. $\lambda{\sim}670\ um$ is the THz central wavelength used here. $d{\sim}30\ um$ is chosen as the optimal flight distance through simulation using CST [7]. The electrons emitted at the strongest field time travels the whole distance without experiencing the deceleration cycle in the condition that the THz energy is 4 µJ and the tip radius is around 400 nm. Then we get $b_0{\sim}60\ um$. $a_0{\sim}\frac{\sqrt{2}}{2}\lambda$ is used for the trading off between coupling efficiency and field enhancement. Within the tapered waveguide coupling section, the dimension b conforms to the variation law of Gaussian beam envelope. The equivalent

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Rayleigh length is chosen to achieve the highest coupling efficiency. To minimize reflection, we maintain a constant characteristic impedance throughout the tapered section, and the wave impedance at the entrance is designed to be approximately equal to the vacuum wave impedance.

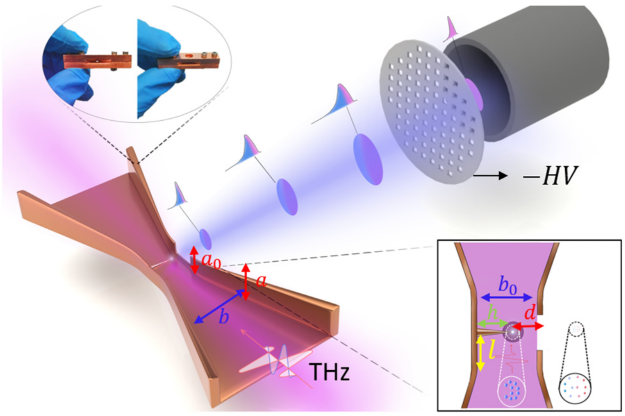

Figure 3: Schematic diagram of the THz electron gun.

RESULTS AND SIMULATION

The THz signal we measured in the experiment is shown in Fig. 4. Different from the THz signal that we use in THz gun design, the central frequency is ~300 GHz. We use the measured THz signal in subsequent CST electron dynamics simulations.

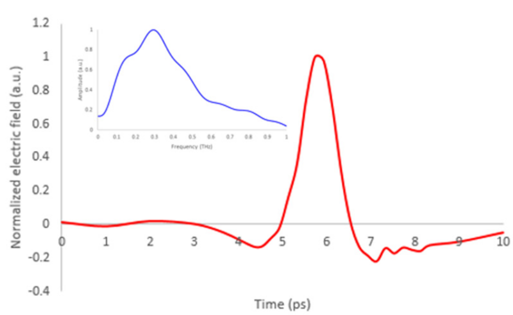

Figure 4: THz signal in experiment.

Emission charge are measured using a metal plate connected to a Picoammeter. Results are shown in Fig. 5. The dashed line illustrates the result calculated by Fowler-Nordheim (F-N) field emission formula. In other research [6, 8], THz field emission also roughly obeys F-N formula. These discrepancies require further analysis.

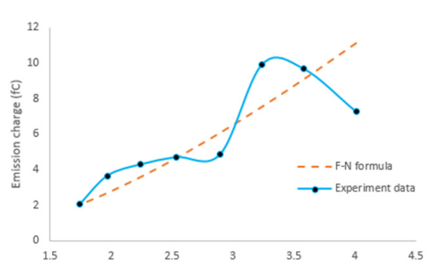

Figure 5: Measured and calculated emission charge.

We show distinct CEM signals with THz on and off in Fig. 6(a). This is the evidence of electrons energy exceeding 4 keV, corresponding to an acceleration gradient over 100 MeV/m across the flight distance $d{\sim}30\,um$. Fig. 6(b) shows the simulated electron spectrum.

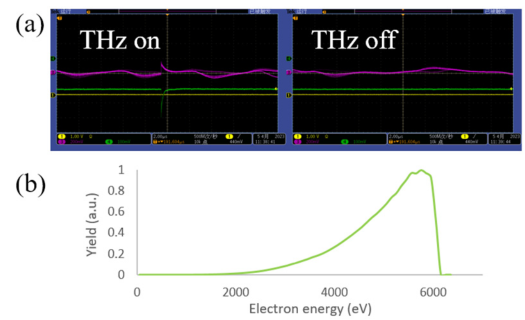

Figure 6: (a) CEM signals with THz on and off, (b) The simulated electron spectrum.

CONCLUSION

In this paper, we report on the THz electron gun experiment setup in Tsinghua University. THz wave is generated using a tilted wavefront laser pulse with central wavelength at 800nm and then transported to the vacuum chamber. Principle and parameter for designing an electron gun driven by single cycle THz are presented. Beam characterization experiments are carried out. Average emission charge per pulse reaches 10 fC, and the max electron energy exceeds 4 keV. Considering an acceleration gap of around 30 μm, this corresponds to an acceleration gradient over 100 MeV/m. The result shows promising high-gradient acceleration capabilities of such THz compact field emission gun. More work will be done in the future.

REFERENCES

[1] J. W. Wang and G. A. Loew, "RF breakdown studies in copper electron linac structures," in *Proc. of the 1989 IEEE Particle Accelerator Conference*, Chicago, IL, USA, 1989, vol. 2, pp. 1137-1139. doi:10.1109/PAC.1989.73374.

[2] A. Grudiev, S. Calatroni, and W. Wuensch, "New local field quantity describing the high gradient limit of accelerating structures," *Phys. Rev. Spec. Top. Accel Beams*, vol. 12, no. 10, p. 102001, Oct. 2009. doi:10.1103/physrevstab.12.102001

[3] H. Xu *et al.*, "Cascaded high-gradient terahertz-driven acceleration of relativistic electron beams," *Nat. Photonics*, vol. 15, no. 6, pp. 426–430, Mar. 2021. doi:10.1038/s41566-021-00779-x

[4] J. Ying *et al.*, "High gradient terahertz-driven ultrafast photogun," *Nat. Photonics*, vol. 18, no. 7, pp. 758–765, May 2024. doi:10.1038/s41566-024-01441-y

[5] A. Fallahi and F. Kärtner, "Design strategies for single-cycle ultrafast electron guns," *J. Phys. B: At. Mol. Opt. Phys.*, vol. 51, no. 14, p. 144001, Jun. 2018. doi:10.1088/1361-6455/aac6f0

[6] S. Li and R. R. Jones, "High-energy electron emission from metallic nano-tips driven by intense single-cycle terahertz pulses," *Nat. Commun.*, vol. 7, no. 1, p. 13405, Nov. 2016. doi:10.1038/ncomms13405

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-THPB094

[7] CST Studio Suite, 2019, `http://www.cst.com/`.

[8] D. Matte *et al.*, "Extreme lightwave electron field emission from a nanotip," *Phys. Rev. Res.*, vol. 3, no. 1, p. 013137, Feb. 2021. `doi:10.1103/physrevresearch.3.013137`