Powering a Photogun using Single-Cycle Terahertz

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***Abstract*—Development of THz-powered photoguns promises to bring benefits to many applications by scaling down the size and cost of these devices as well as creating new capabilities. In particular, THz photoguns producing MeV beams are desired as the front end for THz-powered LINACs. Generating sufficient THz energy, however, is challenging, as is transporting and coupling the THz into the gun. We present initial results on development of the THz source and transport for an MeV gun.**

I. Introduction

SINGLE-CYCLE terahertz (THz) radiation with pulse energies reaching 1 mJ and field strengths reaching 1 GV/m are now possible due to the development of the tilted pulse front concept for difference frequency generation using lasers [1]. Such THz pulses are attractive for a range of ultrafast experiments and have recently been applied to the development of compact, high-gradient THz-powered accelerators [2]. Practical prototypes of these devices have now been demonstrated and show the capability to accelerate and manipulate electron beams with exceptional capabilities [3, 4]. Development of practical THz-powered photoguns, however, has lagged behind due to challenges associated with the physical miniaturization and the short wavelength of the THz driver. In particular, generating high energy THz pulses with the correct spectrum and transporting and coupling this energy into the interaction region of the photogun stand out among these challenges. Here, we describe the optimization of single-cycle sources for powering THz photoguns, development of the optical system to transport and shape the THz mode, as well as first measurements evaluating coupling of the THz into a photogun prototype based on the technology presented in [3, 4].

II. Results

A. Single-cycle THz generation to power the photogun

The single-cycle THz generation was driven by a custom developed Yb:YLF laser system producing pulses of energy up to 60 mJ at a central wavelength of 1020 nm, with a bandwidth of 2 nm and a repetition rate of 10 Hz (Fig. 1a). The THz-generation setup, based on the tilted pulse front concept [1] utilizing lithium niobate as a nonlinear crystal, was designed specifically to enable a robust and independent optimization of each of the primary parameters affecting the efficiency of the conversion process [5]. Optimal performance of the cryogenically cooled setup was found for a pulse front tilt of 63.7° yielding THz pulses with usable energies reaching up to ~ 100 µJ corresponding to a conversion efficiency of ~ 0.35% (Fig. 1b). Two mirror-image but otherwise identical setups were built to provide the twin single-cycle THz pulses to power each side of the photogun. A delay line for the optical pump was installed to adjust the relative timing of the THz pulses at the interaction point. Prior to the design of the THz transport system, the divergence of the THz beam was measured via raster-scanning a sensitive THz detector with small aperture across the beam at several distances from the crystal surface.

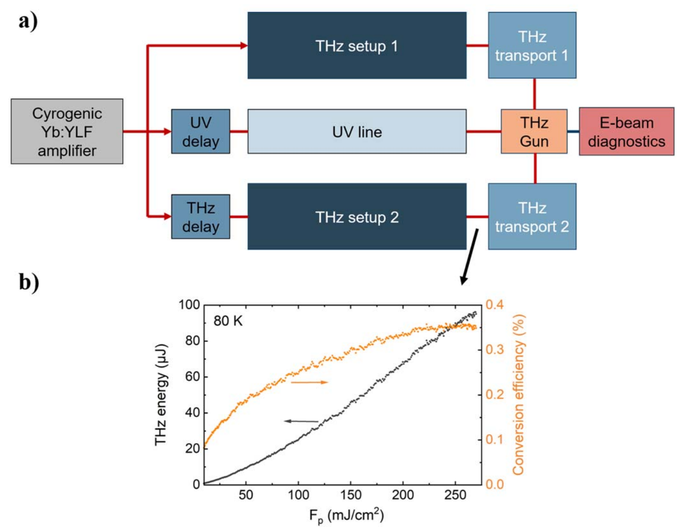

Fig. 1. (a) Setup and individual modules to generate THz and UV pulses for powering the compact photogun prototype. (b) Generated THz energies and corresponding conversion efficiency of the tilted-pulse-front THz setups.

B. THz transport system

To transport the THz from the source to the gun, an optical setup was developed using two TPX lenses to limit the size of the THz mode during transport and create the desired convergence at the gun. In addition, a custom periscope was fabricated to allow independent adjustment of the three spatial and two angular coordinates of the transported THz focus (Fig. 2a). This periscope rotates the polarization of the THz fields to match the direction of electron acceleration in the

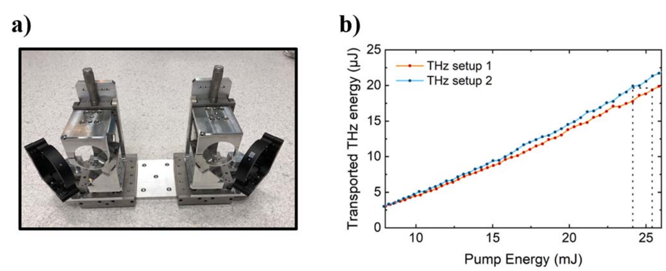

Fig. 2. (a) Custom periscope used for THz transport and independent adjustment of the degrees of freedom of the THz focus. (b) Pump-energy dependent transported THz for both setups. Dashed lines indicate the pump energy selected for balancing the two setup energies.

photogun. The THz transport setup was designed for the frequency range (220 – 500 GHz) that the horn-coupler of the photogun allows to couple to the acceleration volume efficiently. Frequencies below the cut-off (~ 220 GHz) are mostly reflected by the horn-coupler. A tight-focusing scheme was employed to ensure an almost constant angle of convergence of the relevant frequencies contained within the transported THz pulses. Slight variations in the transport efficiency between the two arms were balanced via the pump energy incident on the lithium niobate crystals in the THz setups. The balanced transported THz energies at the input to the gun reached ~ 20 µJ (see Fig. 2b), corresponding to a transportation efficiency of ~ 35%. The diameter of the focused transported THz beam was set to ~ 6 mm such that the convergence angle matched that of the tapered horn coupler (Fig. 3a) of the photogun.

C. *THz coupling*

The position and pointing of the beam focus were then scanned to optimize coupling of the THz energy into the gun interaction volume. The coupling efficiency was evaluated by pumping from one side and measuring the energy emitted from the other. A maximum transmission of 1.4% was achieved, which is close to predicted values by simulations. To evaluate the coupled spectrum, we scanned the relative delay of the two THz pulses and monitored the charge generated by field emission via a channeltron detector (Fig. 3b). Comparing the Fourier transform of this signal with the transported spectrum of the THz measured by interferometry (Fig. 3c) shows evidence of the low-frequency cut-off expected near 220 GHz for this design.

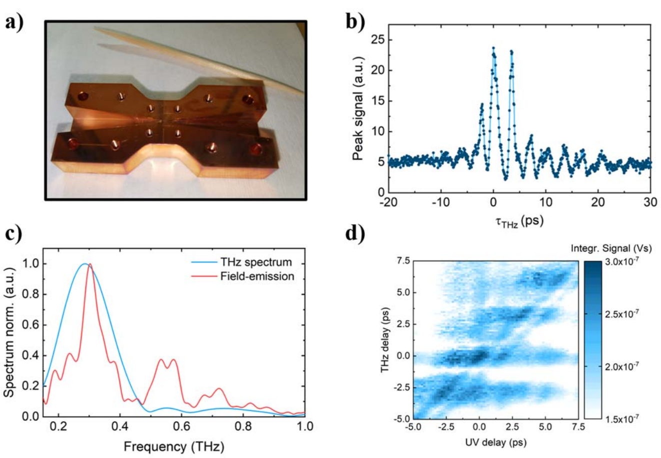

Fig. 3. (a) Prototype of a THz photogun transversely pumped by single-cycle pulses from both sides. (b) Field emission signal vs THz relative delay. (c) Comparison of the THz spectrum with the Fourier transform of the field emission delay scan data. (d) Channeltron signal vs the THz and UV delay.

D. *Relative delay of the pulses*

To power the THz photogun, the relative timing between the two THz pulses and the UV pulse for the photoinduced injection of the electrons into the accelerating field must be set correctly. The relevance of the relative timing between the pulses was investigated via measuring the integrated channeltron signal dependent on the two relative time coordinates (Fig. 3d). The number of electrons detected is very sensitive to the relative delay between the THz pulses which determine the degree of interference between the fields and thus the maximum peak electric field for acceleration. In addition, the background signal due to field-emitted electrons sensitively depends on this delay. The timing for the injection of photo-generated electrons is set via the UV pulse. For maximal signal, the UV pulse is required to inject the electrons into the half-cycle with highest field amplitude of the THz waveform in the accelerator. As the UV pulse used in this experiment had a duration of > 1 ps, the contrast along the UV delay is washed out accordingly. The experimental results of this measurement were qualitatively reproduced via a simple 1D numerical model, indicating the photogun works as expected. Initial measurements via retarding DC fields as well as using a magnetic steerer and multi-channel-plate detector indicate extracted electron energies up to ~ 3 keV.

E. *Discussion of the results*

As some characteristics of the setup were slightly off from the original design values, there remains room for improvement of the optical setup and the accelerator device. For example, the photogun was designed for THz pulses centered around 300 GHz, while the transported THz spectra centered at slightly lower frequency of ~ 290 GHz. This leads to lower coupling efficiency into the acceleration volume, but also to a slightly detuned length of the interaction between accelerating field and electrons. However, the underlying modular design of the photogun allows adjustment of the interaction volume via variable spacer foils to match the accelerating field. Future work will focus on improving the amount of THz coupled into the accelerator and to optimize the ratio between field-emitted and photo-injected electrons as well as beam quality.

III. Summary

We present results of a study of generation, transport and coupling of THz radiation to a novel THz photogun prototype yielding electron bunches with energies reaching multiple keV. Additionally, the importance of the relative timing of the individual optical pulses in the accelerator is investigated. Initial results are promising, and predictions show that performance can be expected to increase significantly with further optimization. Higher transported THz fields will enable multi-layered THz driven photoguns aiming for electron energies towards 1 MeV. Such compact devices are not only interesting as injectors for subsequent LINACS but would also enable interesting experiments based on ultrafast electron diffraction.

References

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