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THZ-BASED FEMTOSECOND MEV ELECTRON BUNCH COMPRESSION*

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Abstract

We demonstrate a new design of a dispersion-free parallel-plate tapered waveguide that provides focusing of strong field terahertz (THz) pulses. The structure is used to imprint an energy chirp on MeV bunches and enables bunch compression. We further demonstrate some preliminary results of the THz-driven bunch compression at the SLAC UED facility.

INTRODUCTION

Ultrafast electron diffraction (UED) science allows for better understanding of energy matter interaction at the subatomic level [1–4]. Within this context, interest in laser-generated THz wave-matter interaction has recently surged as a new regime for controlling electrons with high temporal precision [5–9]. Previously, we have demonstrated sub-femtosecond electron diagnostics using laser-generated single-cycle THz radiation, which is intrinsically phase locked to the optical drive pulses, to manipulate multi-MeV relativistic electron beams [10]. Here we demonstrate further steps towards achieving ultrafast timing resolution that utilizes femtosecond electron bunches. The proposed setup allows for compressing electron beam bunches down to a 10s of femtosecond using interaction with high field single-cycle THz pulses. Several THz-based techniques for beam compression were recently proposed [7], [11, 12], however here we demonstrate for the first time an optimized structure excited by strong field THz fields dedicated to bunch compression.

CHARACTERIZATION OF PARALLEL-PLATE THZ WAVEGUIDE

Here we use an optimized tapered PPWG with application to electron bunch compression. We show in Figure 1(a) the tapered PPWG that is used to focus intense single-cycle THz pulses. The PPWG is made of copper and optimized to provide optimal focusing to an incident broadband THz Gaussian beam. Note that the tapered PPWG only focuses in one dimension (along y) without disturbing the pulse propagation along this direction. The THz is generated using an intense Ti:sapphire 800 nm laser to pump a $LiNbO_3$ crystal and produce single cycle high THz fields through the tilted-pulse-front scheme. The THz is then guided to the structure using parabolic mirrors. The electric fields are measured inside the tapered structure using electro-optic sampling. We clearly observe that the single-cycle characteristics of the THz signal are preserved with almost no dispersion. Moreover, we show that the PPWG produces ~ 40 MV/m peak electric field at the minimum gap, causing a twofold field enhancement compared to free space given 0.9 μJ of THz energy.

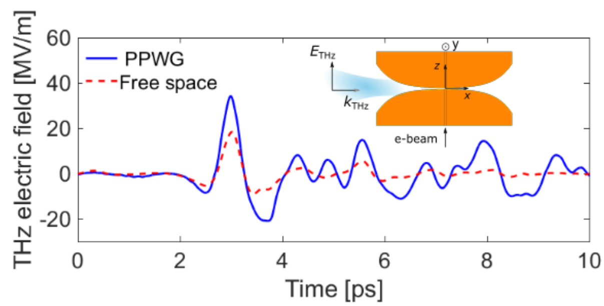

Figure 1: Measurement of the electric field inside a tapered parallel-plate waveguide using electro-optic sampling, compared to the one in free space. The PPWG minimum gap here is 180 μm.

For the beamline experiment, we used a modified version of the structure in Figure 1. The modification entails the use of a shorted structure [13] where the PPWG is terminated right after the beam tunnel to provide enhanced THz interaction, and the chirp provided by the shorted structure is estimated to be about 1 keV/(100 fs $\cdot \sqrt{\mu J}$). The shorted structure also reduces transverse dispersion as well as transverse deflection.

THZ-DRIVEN BUNCH COMPRESISON EXPERIEMENT

The experimental setup for the THz-driven bunch compression is depicted in Figure 2. An electron bunch with 2.5 MeV kinetic energy was used in the UED beamline, with < 6fC of beam charge and > 85 fs RMS bunch length. The beam was aligned from the S-band rf gun into the compressor structure using two solenoid lenses, steering magnets and pinhole collimator. Electron bunches enter the tapered PPWG compressor in Figure 2 and interact with the THz through the gap; providing enough energy chirp to compress the bunch after some drift distance.

Two separate THz sources were constructed to produce quasi-single-cycle THz pulses and drive the compression and transverse deflector setup. THz pulses with < 3 μJ pulses were transported into the vacuum chamber and focused into the shorted compressor structure using off-axis parabolic mirrors, while a vertically polarized <1 μJ pulse is transported into the streaking chamber, as shown in Figure 2. The time of arrival of the two THz pulses relative to the electron bunch is controlled using two delay stages.

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A diffraction detector, about 3 m downstream from the compressor is used to obtain shot images of the electron bunches.

As the THz propagates into the structure, the magnetic field (along the y-direction) at the interaction region produces a transverse deflection of the bunch (along the x-direction). This deflection was corrected with steering magnets downstream but is exploited to identify and optimize the spatiotemporal overlap of the interaction. A measurement of the beam centroid along x as a function of the THz delay is shown in Figure 2 and shows about 1.5 mrad peak deflection, which agrees well with the predicated values given the input THz pulse energy.

The bunch length was characterized by transverse deflection in the THz-driven streaking setup after a 1 m drift from the compressor. When the bunch is maximally streaked, i.e., when the time-of-arrival of the bunch coincides with zero crossing of the THz pulse with the near-linear streaking ramp at the streaking slit, the beam temporal/longitudinal profile is mapped onto the vertical axis of the detector. Integrated images of the streaked beam profile are shown also in Figure 3 for various time delays indicated in the top panel of Figure 3. These time delays correspond to various phases which the bunch undergoes: uncompressed (at t_1 and t_5), decompressed (at t_2 and t_4), and compressed (at t_3).

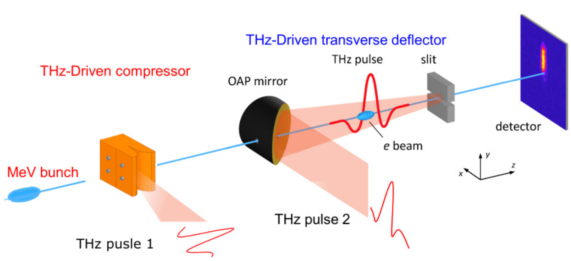

Figure 2: Schematic of the beamline setup for the THz-driven bunch compression experiment.

The streaked beam images indicate that the minimum compressed bunch length for this case is < 40 fs RMS and gives a lower bound of ~2.5 for the compression factor. The uncompressed bunch length was too long (longer than the assumed 85 fs RMS), especially for lower beam kinetic energy, to fit within the near-linear region of the streaking linear ramp. As such, a pileup of the projected beam distribution at either end of the streaked image occurs and making precise characterization of the initial bunch length a significant challenge. We have also produced compressed bunches at various beam kinetic energies with the smallest highest compression factor was achieved for about 2.5 MeV.

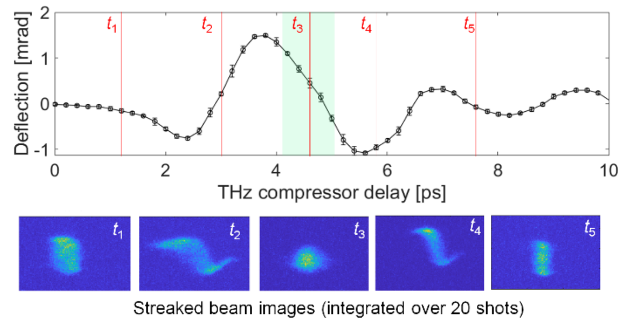

Figure 3: (Top) Deflection scan of the electron bunch varying as a function of the THz compressor delay. The green shaded area represents the optimal timing window for compression. (Bottom) Streaked images of the bunch at different THz delays.

CONCLUSION

We have shown a PPWG-based THz-driven bunch compressor for UED applications. We have presented the measurement of the THz fields inside the interaction region in the structure that demonstrated good coupling. We also have shown preliminary results of compression of a 2.5 MeV bunch and also potentially reduced jitter. This result is a promising step toward a better temporal resolution of UED using the proposed THz-based technique.

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