Invited Paper

Terahertz accelerator based electron and x-ray sources

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Abstract: The generation and use of THz radiation for electron acceleration and manipulation of electron bunches has progressed over the last decade to a level where practical devices for THz guns, acceleration and a wide range of beam manipulations have become possible. Here, we present our progress on generation of single-cycle THz pulses at the two-hundred micro-Joule level to drive advanced acceleration and beam manipulation devices. Specifically, we use pulses centered at 0.3 *THz* to power a segmented terahertz electron accelerator and manipulator (STEAM) capable of performing multiple high-field operations on the 6D-phase-space of ultrashort electron bunches. Using this STEAM device, we demonstrate record THz-acceleration of >60 *keV*, streaking with <10 *fs* resolution, focusing with >2 *kT/m* strength, compression to ~100 *fs* as well as real-time switching between these modes of operation. The STEAM device demonstrates the feasibility of THz-based electron accelerators, manipulators and diagnostic tools enabling science beyond current resolution frontiers with transformative impact.

Keywords: Single-Cycle THz generation, THz guns, THz acceleration, THz beam manipulation

1. Introduction

Over the last years, substantial THz acceleration of electrons from a DC-gun [1] or from rest [2] using relatively low energy THz pulses, in the few tens of μJ range, was demonstrated showing the feasibility of THz acceleration. Since then, quasi-monoenergetic electron bunches with a few percent energy spread and 400 eV mean energy have been demonstrated from a parallel plate THz gun [3]. Based on these early results, we envisioned construction of a FEL like X-ray source [4] within the European Synergy Grant AXSIS: Frontiers in Attosecond X-ray Science Imaging and Spectroscopy. The source utilizes a pre-bunched electron beam from a nano-structured cathode accelerated by a THz gun to relativistic energies driven with single-cycle THz pulses. Those electron pulses are then injected into a THz accelerator composed of a dielectrically loaded metal waveguide excited with a mutli-mJ, multi-cycle pulse with a carrier frequency of 0.3 *THz*. The resulting highly-relativistic, longitudinally-modulated electron bunch is then injected into an optical undulator, i.e., a counter propagating, optical, high energy pulse with a normalized vector potential close to 1 for efficient coherent X-ray generation. Here, we discuss the first experimental steps towards such a source by reporting experimental results on the single-cycle THz generation and the accelerating structure of the electron gun, which is a segmented THz waveguide [5]. The segmented architecture of the gun, which ensures proper phasing between the electrons and the electromagnetic field, is excellent, not only for acceleration of the electron bunches, but also for beam manipulation. This device, which we call a segmented terahertz electron accelerator and manipulator (STEAM), is capable of performing multiple high-field operations on the 6D-phase-space of ultrashort electron bunches. Using single-cycle, 0.3 *THz* pulses, we demonstrate record THz-acceleration of >60 *keV*, streaking with <10 *fs* resolution, focusing with >2 *kT/m* strength, compression to ~100 *fs* as well as real-time switching between these modes of operation [6].

In section 2, we present our progress in single-cycle terahertz pulse generation using the tilted-pulse front technique in cryogenically cooled Lithium Niobate. Terahertz pulse with > 100 micro-Joule energy at 280 *GHz* center frequency are generated with 40-*mJ*, 1-micron pulses of picosecond duration from a cryogenically cooled Yb:YLF laser. In section 3, we discuss the STEAM device and its various modes of operation. In section 4, we summarize the results achieved and give an outlook to future work.

2. Single-Cycle THz pulse generation

The electron gun in the AXSIS accelerator requires single-cycle THz pulses with energies beyond what has previously been demonstrated. In the current design, two single-cycle THz pulses of about 0.5 *mJ* and a center frequency of 0.3 *THz* are required to power the photo-gun. The choice of center frequency is based on the balancing of several factors including THz generation efficiency, THz absorption in lithium niobate, optical bandwidth and accelerator structure manufacturing tolerances. In general, the generation efficiency increases with THz frequency, $\boldsymbol{\Omega}$, due to the $\boldsymbol{\Omega}^2$ dependence of the DFG process. This dependence, however, is counteracted by the THz absorption in lithium niobate which also increases with $\boldsymbol{\Omega}^2$ below the first phonon resonance. Higher THz frequencies generally require larger laser bandwidths, which for high-average-power lasers can become a severe limitation. For higher frequencies, the size of the accelerator structures also becomes smaller, making them more difficult to fabricate, allowing less charge to be supported, but requiring less THz energy to reach the same field. Ultimately, changing the THz frequency effectively trades one technical difficulty for another, and the design frequency of about 0.3 *THz*, with its 1 *mm* wavelength, is optimized for our current capabilities. For single-cycle THz generation, phase matching is best accomplished via the tilted pulse front method, which has been used to demonstrate the highest efficiencies (0.8%) and the highest energies of up to 0.4 *mJ* to date [7], for frequencies below 1 *THz*. In this record-setting work it was found that the THz center frequency reduced significantly with increasing energy so that at 0.16 *mJ*, the frequency was well below 0.2 *THz*. Here we report generation of single-cycle THz pulses with a center frequency of 0.28 *THz*, an energy of 0.2 *mJ* and a conversion efficiency of 0.5% using a 40-*mJ*, 1020-*nm*, 1-*ps* laser (Fig. 1). This result demonstrates that by scaling to 100 *mJ* laser pulses, the required 0.5 *mJ* THz pulses are achievable. To have a margin for error, however, to account for losses in propagation and coupling, it will be necessary to improve efficiency to the 1% level or double the driver pulse energy, correspondingly. This improvement is expected to be possible by upgrading the imaging optics and output coupling in the tilted pulse-front setup.

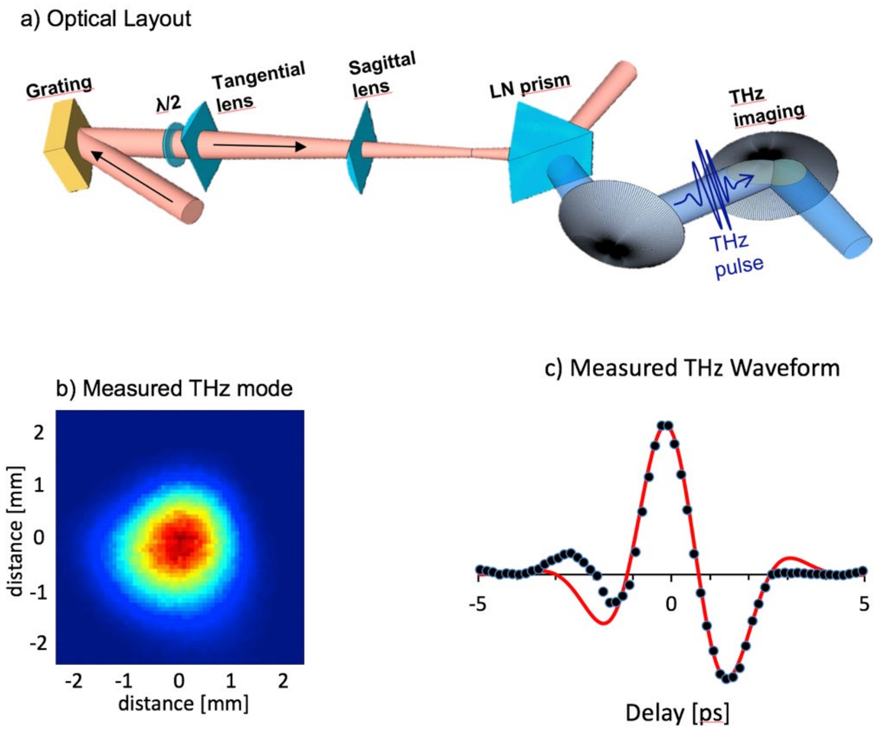

Fig. 1 (a) Tilted pulse front layout. (b) Measured THz beam profile at source. (c) THz waveform measured by electro-optic sampling [8].

3. STEAM device

Using the single-cycle pulses described in the last section, we made pioneering progress in the demonstration of THz-based acceleration of electrons. Initial work concentrated on proof of principle demonstrations of the two key ingredients of a THz-based linear accelerator: a THz-driven photogun [3] and a THz-driven LINAC [1]. In the early THz-gun work, 34 μJ of single-cycle THz pulses was used to accelerate electrons from rest to peak energies of 0.8 keV in a transversely-pumped structure that concentrated the THz field in one dimension. In the THz-LINAC work, 10 μJ were used to modulate the energies of electrons from a 57 keV DC gun by 7 keV using a longitudinally-pumped waveguide structure. This early work has now been significantly extended by development of a new device designed to optimize the interaction of electrons with a transversely propagating THz field [5]. In this concept, two counterpropagating, single-cycle THz pulses interact with electrons traveling at 90° such that the electric-field vector is parallel to the electron motion. The interaction region is sub-divided using thin metal sheets into multiple individual plane-parallel waveguides into which the THz pulse energy is distributed. Each waveguide layer is embedded with a dielectric slab whose length is precisely tuned to delay the time of arrival of the THz waves at the interaction point so that the electrons experience the same THz phase at each layer. Simulations have been performed [5] showing that with a total of 2 *mJ* of THz energy, electrons can be accelerated from rest to 2 *MeV* using this device (Fig. 2).

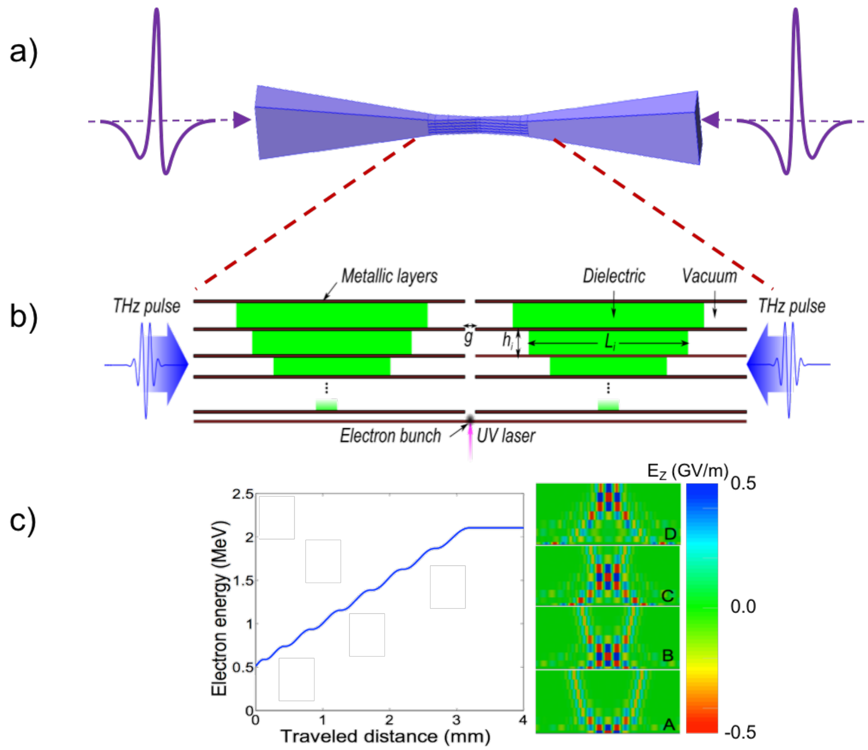

Fig. 2 a) Concept of segmented structure showing two input horns to concentrate the THz energy into the interaction region b) Diagram displaying the organization of the waveguide layers. c) Simulation showing acceleration of electrons from rest to 2 *MeV* using 2 mJ of THz energy [5, 8].

Figure 3 shows the operation of the STEAM-device. According to the Lorentz force law, the electrons experience both the electric and magnetic fields of the THz pulses during interaction inside the STEAM device. The electric field is responsible for acceleration and deceleration, while the magnetic field induces deflections. Two modes of operation are therefore possible. The electric-field mode, or “E-mode”, occurs when the two counterpropagating THz pulse interfere constructively in the electric field at the interaction point and the magnetic field cancels. The magnetic field mode, or “B-mode”, occurs when one of the fields is delayed by half a period, such that the magnetic fields interfere constructively at the interaction point and the electric field cancels. Selection of the operating mode is done by adjusting the delay of the THz drive pulses and the UV photoemission pulse. The E-mode is used for acceleration, compression & focusing, while the B-mode is used for deflection and streaking. Due to the transverse pumping geometry, the electrons slip through the THz waveform as they propagate. The thickness of the layers and the length of the dielectric inserts are designed so that the electrons experience approximately the same half cycle of the THz waveform in each layer.

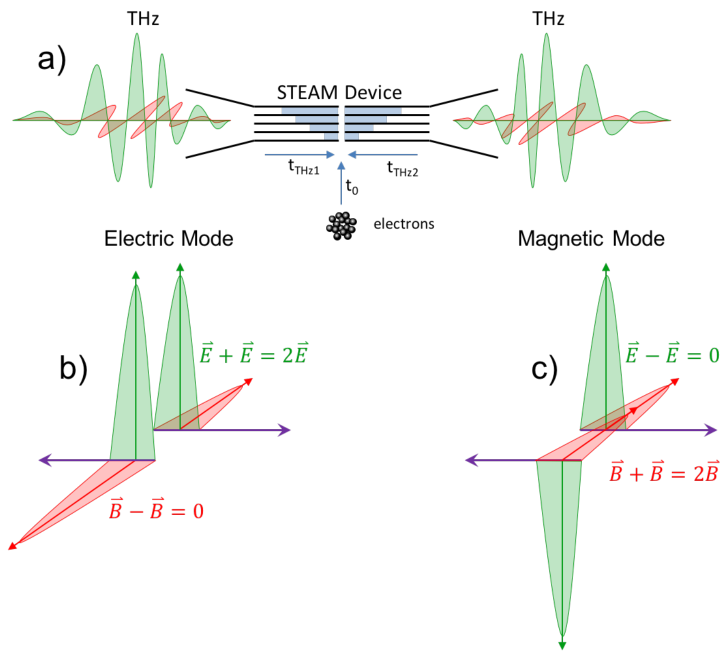

Fig. 3 a) Orientation of electric and magnetic fields relative to STEAM device b) Field orientations in the electric mode. c) Field orientations in the magnetic mode.

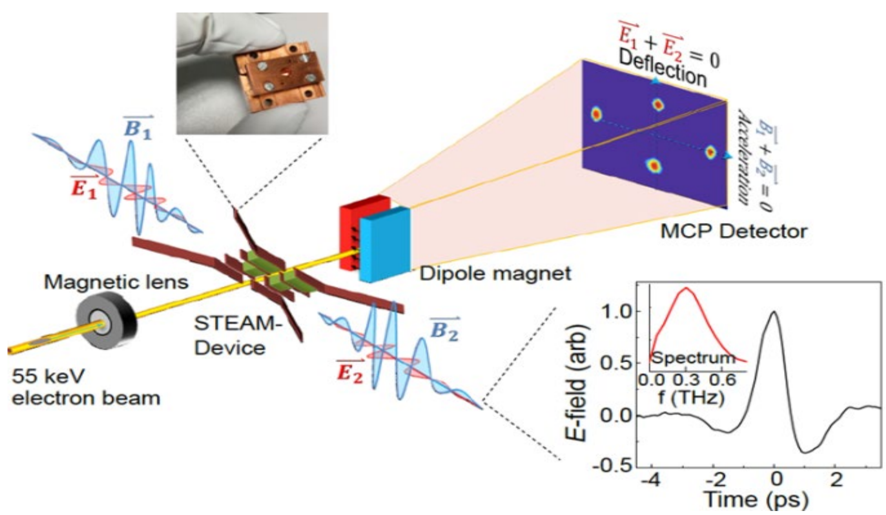

Fig. 4 Acceleration and manipulation of an electron bunch from a 55 *keV* DC-gun using a STEAM device. The two counter-propagating THz beams interact with the 55 *keV* electron beam inside the STEAM device. Subsequently, the electron beam is detected by the camera [6].

A first demonstration of this device was performed recently [7] with the experimental setup shown in Fig.4, consisting of a 55 *keV* photo-triggered DC gun, a three-layer implementation of the THz-powered STEAM device and a diagnostic section. Ultraviolet pulses for photoemission were generated by two successive stages of second harmonic generation (SHG), while single-cycle THz pulses were generated by optical rectification as discussed in section 1.

4. Experimental results

In the electric mode, maximum acceleration and deceleration occurred when the injection phase was chosen so that the electrons experience the half cycle of the THz waveform centered about the negative and positive crests of the field, respectively. The peak fields reached ~70 *MV/m*, resulting in a maximum energy gain of more than 40 *keV* and a shift of the peak of the energy spectrum by more than 30 *keV* (Fig. 5(a)) using the available ~2×6 *μJ* of coupled THz energy. In this configuration, the deflection was minimized due to the cancellation of the magnetic fields. When the electrons are timed to interact with a section of the waveform centered at the zero-crossing of the electric field, the temporal field gradient is maximized resulting in a time-varying longitudinal acceleration and thus a velocity gradient that induces either compression or stretching of the electron bunch as it propagates (Fig. 5b). A minimum duration of ~100 *fs* FWHM was achieved (Fig. 5(b)). The temporal electric-field gradient at the zero crossing is intrinsically coupled to a transverse spatial gradient in the magnetic fields which results in focusing or defocusing of the electron beam (Fig. 5c). Peak focusing gradients reached over 2 *kT/m*, approaching those found in an active plasma lens.

In the magnetic mode, the relative timing of the THz fields is different from that of the electric mode by a half period resulting in reinforcement of the magnetic and cancellation of the electric fields. When the electron interaction window is centered on the crest of the magnetic field, the deflection is maximized and the acceleration (or deceleration) is minimized. Electrons centered at the zero-crossing of the THz magnetic field experience a deflection that is a steep function of time, effectively streaking the bunch and projecting the temporal electron charge profile onto the spatial dimension of the MCP detector with sub-10 *fs* temporal resolution (Fig. 2d).

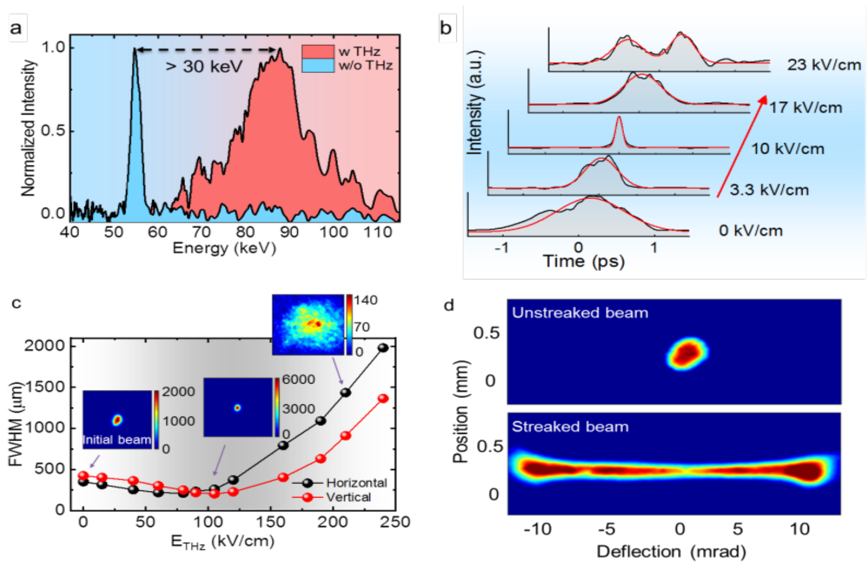

Fig. 5 Functions of the STEAM device. (a) Acceleration of electron beam with electron energy spectra for input beam (blue curve) and accelerated beam (red curve). (b) Temporal compression of the electron pulses as a function of the THz field in the rebunching mode. (c) Transverse electron beam focusing as a function of the THz field in the focusing mode. (d) Images of the electron beam on the detector with and without the THz deflection field in the streaking mode [6].

5. Femtosecond control of multi-stage THz acceleration and bunch manipulation.

The initial demonstrations shown above only start to explore the essential capabilities of this technology and thus leave room for further improvement of basic beam parameters as well as development of THz-based methods to control them. Key steps along this development plan include increasing THz pulse energies to enable electron energies in the MeV range, tuning of the injected electron bunch length and control over energy spread and emittance.

The setup shown in Figure 6 uses multiple functionalities of the STEAM device [6] to provide both compression and high-field THz-driven acceleration in a staged geometry. The UV pulses driving the photo cathode are produced, via two SHG stages, from a small fraction of the picosecond pulses from a cryogenic Yb:YLF laser, and are then directed onto a gold photocathode of a 55 *keV* DC gun. This Yb:YLF laser also drives four synchronized optical-rectification stages, each generating single-cycle terahertz pulses. The STEAM compression device is used to reduce the bunch length to sub-picosecond lengths, thereby providing femtosecond control over the accelerating phase. In this way, the effects of the bunch duration on the THz acceleration process are explored. We achieve a peak acceleration field of 200 *MV/m,* resulting in a record >70 *keV* THz acceleration from an injected 55 *keV* electron beam resulting in up to ~125 *keV* accelerated electrons, see Fig. 7.

The transverse emittance is determined by scanning the current of a focusing solenoid and measuring the size of the electron beam profile on the MCP. In the case of an uncompressed injection beam, parabolic fits to beam size versus current reveal a transverse emittance in the horizontal and vertical directions of $\varepsilon_{x,n}$=1.703 *mm* mrad and $\varepsilon_{y,n}$=1.491 *mm* mrad, respectively. Implementing compression of the injected electron bunch improves the measured transverse emittance by a factor of 6, to $\varepsilon_{x,n}$ = 0.285 *mm* mrad, $\varepsilon_{y,n}$ = 0.246 *mm* mrad, respectively. Note, that the emittance reduction factor is roughly twice that of the bunch duration. This result is an indication of the nonlinearity of the interaction dynamics with time: the electrons interact with the linear part of the electric field but with the nonlinear part of the magnetic field. The emittance reduction is due in part to the reduction in energy spread, caused by the reduction in the range of accelerating and decelerating forces experienced as well as to a reduction in the transverse momentum spread, caused by the reduction in the range of focusing and defocusing fields experienced.

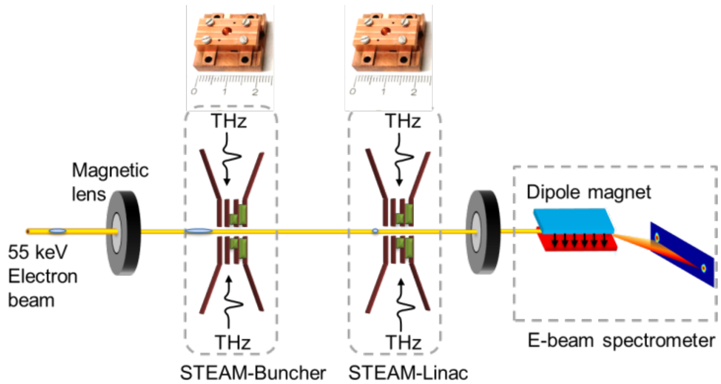

Fig. 6 Schematic illustration of the experimental setup. 55 *keV* electron bunches are generated by a DC electron gun. The STEAM-buncher is driven by two counter-propagating terahertz beams with energy ~2×50 *nJ* for electron compression. The STEAM-linac is driven by ~2×15 *μJ* THz radiation for electron acceleration. [9]

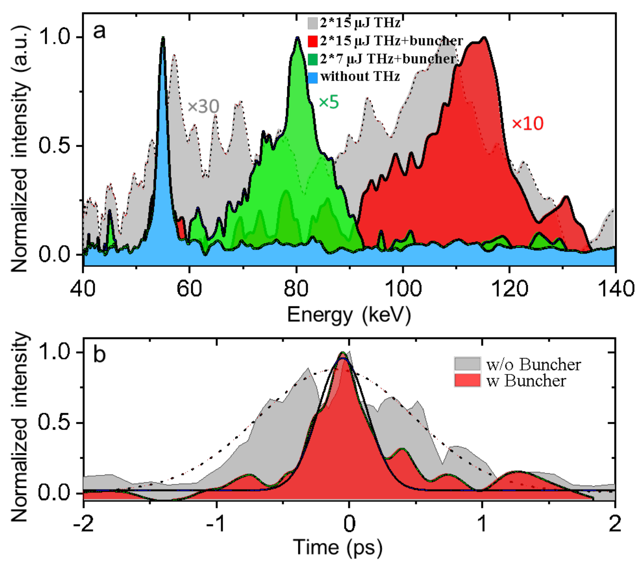

Fig. 7 Energy spread compensation. a, Measured electron energy spectra for input beam (Blue shaded curve), accelerated beam without buncher (gray shaded curve) and with buncher (2×7 *μJ* THz: green shaded curve and 2×15 *μJ* THz: red shaded curve). The energy distribution is normalized to the 55 *keV* input electron beam with around 1 fC bunch charge. **b,** Measured input electron pulse duration with (red shaded curve) and without buncher (gray shaded curve). [9]

6. Conclusions

The results of our work over the last years has encompassed THz generation and THz acceleration of electrons. Recently, we have been also able to extend multi-cycle THz generation close to the mJ-level generation by using Joule-level chirped laser pulses from a Ti:Sapphire laser system and the chirp and delay technique together with large aperture periodically poled lithium niobite crystals [10, 11]. This combination of technical methods constitutes a new THz-driven accelerator technology which holds great promise for future accelerators and light sources. The intermediate wavelength scale of millimeters enables frequencies to be increased by two orders of magnitude over conventional RF-driven technologies, enabling higher fields and field gradients to be sustained with powerful and beneficial effects on electron beam properties. At the same time, the scale is still sufficiently large to allow traditional fabrication and control methods, resulting in devices which are fine-tunable, which sustain high repetition rates and which are stable over long periods of time. Specifically, we have demonstrated a novel segmented THz electron accelerator and manipulator which has set new records in THz acceleration, streaking and focusing with a very compact device. The segmented structure makes it possible to phase match the electron-THz interaction for non-relativistic beams, making it ideal for use in a high-gradient photogun. The independent control over the counter-propagating THz pulse timing gives the STEAM device the ability to switch dynamically between different modes. Recently, the inclusion of a STEAM buncher in the setup shown in Fig. 6 before the STEAM accelerator section lead to a more narrowband acceleration of electrons by more than 60 keV. The results presented here are an important step in demonstrating a practical, compact THz-driven electron and later light source capable of probing material structure and function well beyond current limits of temporal resolution.

Acknowledgement

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References

[1] E. A. Nanni, W. R. Huang, K. Ravi, et al. “Terahertz-driven Linear Electron Acceleration”. *Nat. Com*. 6, 8486 (2015).

[2] S. Li and R. R. Jones. “High-energy electron emission from metallic nano-tips driven by intense single-cycle terahertz pulses”. *Nat. Com*. **7**, 13405 (2016).

[3] W. R. Huang, et al. “Terahertz-driven, all-optica l electron gun”. *Optica* 3, 1209 (2016).

[4] F. X. Kärtner et al. AXSIS: Exploring the frontiers in attosecond X-ray science, imaging and spectroscopy, Nucl. Instrum. *Methods Phys. Res*. A 829, 24–29 (2016).

[5] A. Fallahi, M. Fakhari, A. Yahaghi, et al. *Phys. Rev. Accelerators and Beams* 19, 081302 (2016).

[6] D. Zhang, A. Fallahi, M. Hemmer, et al. "Segmented THz electron accelerator and manipulator (STEAM)". *Nat. Photonics* 12: (6) 336 (2018).

[7] J.A. Fülop, Z. Ollmann, C. Lombosi, et al. "Efficient generation of THz pulses with 0.4 mJ energy". *Opt. Exp*. 22, 20155–20163 (2014).

[8] N. Matlis, F. Ahr, A.-L. Calendron, et al. "Acceleration of electrons in THz driven structures for AXSIS". *NIMA* A 909, 27–32 (2018).

[9] D. Zhang, A. Fallahi, M. Hemmer, et al. "Femtosecond phase control in high-field terahertz-driven ultrafast electron sources". *Optica* 6, 872-877 (2019).

[10] H. Ishizuki and T. Taira. "Half-joule output optical-parametric oscillation by using 10-mm-thick periodically poled Mg-doped congruent LiNbO3". *Opt. Exp*. 20, 20002–20010 (2012).

[11] S.W. Jolly, N.H. Matlis, F. Ahr, et al. "Spectral phase control of interfering chirped pulses for high-energy narrowband terahertz generation ". *Nature Communications* 10, 872-877 (2019).