TERAHERTZ TECHNIQUES IN THE ADVANCED ACCELERATOR LANDSCAPE

M.T. Hibberd* [1,2], R. Appleby[1,2], J. Bradbury[1,2], G. Burt[1,3], D.M. Graham[1,2], B. Higuera Gonzalez[1,2], S. Jamison[1,3], J. Jones[1,4], D. Lake[1,3], C. Mosley[1,3], L. Nix[1,3], T. Pacey[1,4], C. Shaw[1,3], S. Siaber[1,3], D. Walsh[1,4]
[1]Cockcroft Institute, Daresbury, UK; [2]The University of Manchester, Manchester, UK; [3]Lancaster University, Lancaster, UK; [4]Accelerator Science and Technology Centre, Daresbury, UK.

Abstract

Terahertz (THz)-frequency particle acceleration provides a natural "bridge" between conventional electronic-based (radio-frequency RF) and novel photonic-based (laser plasma wakefields LWFA) drivers, offering stable, high-frequency, high-gradient fields for compact interactions, coupled with direct femtosecond-scale synchronization to the THz drive laser. These unique properties ideally position THz technologies to enhance the capabilities of existing RF infrastructure, while also solving key challenges to help drive the transition towards compact high-gradient laser-based accelerator applications.

As a key example, we present our latest experimental results and simulations demonstrating efficient THz-driven chirping and energy modulation of relativistic electron bunches, enabling the compression of ultrashort bunches and picosecond-spaced bunch trains with femtosecond-scale "temporal-locking" to the THz drive laser. These results unlock a potential array of advanced electron-laser applications requiring precise synchronization at the shortest timescales, of which includes solving the external injection challenge that has long-hindered LWFA progress. We will discuss our work towards achieving this goal, in addition to highlighting the other unique roles THz technologies can play in the future advanced accelerator landscape.

INTRODUCTION

The delivery of high-energy, high-charge electron bunches (and bunch trains) with femtosecond-scale bunch length and arrival timing directly synchronized to an external laser promises to open up an array of novel laser-based accelerator applications. These include direct probing of strong-field quantum electrodynamics through relativistic electron-laser collisions [1], free-electron laser (FEL) pump-probe experiments [2], single-shot ultrafast electron diffraction [3], and controlled external electron injection to enable high-quality laser-plasma wakefield acceleration [4]. Amongst others, these examples highlight an exciting transition towards a new accelerator landscape operating at the boundaries of photon science and accelerator physics.

Simultaneously achieving these critical bunch parameters remains out of reach for existing radio-frequency (RF) infrastructure alone, which is ultimately limited by unavoidable sources of jitter stemming from the use of multiple RF systems (e.g. electron gun, linear accelerating cavities) required for high-energy beams and the complex interplay between the inherent energy and timing fluctuations. Laser-generated terahertz (THz) pulses provide a route to overcome these limitations, underpinned by the significant progress in THz-driven acceleration and manipulation of electron beams achieved within the last decade. Proof-of-principle demonstrations with relativistic beams include the first scalable THz linac [5], staged acceleration [6, 7] and novel self-injection schemes [8]. Furthermore, for electron beams with MeV-scale energy and fC-level charge, THz streaking for femtosecond longitudinal diagnostics [9] and THz-driven compression with arrival-time jitter suppression [10, 11] have both been achieved.

Despite these breakthroughs, to facilitate the next-generation of advanced electron-laser applications, femtosecond-scale control of electron bunches at higher energies and charge is critical and has remained a major hurdle to overcome. Here we present a concept and experimental groundwork to achieve this [12], exploiting the phase-velocity matched interaction of laser-generated multi-cycle THz pulses with 35.5 MeV, 30 pC electron bunches in a dielectric-lined waveguide structure. We experimentally demonstrate THz-frequency energy modulation capable of compression into ultrashort picosecond-spaced bunch trains or single bunches as short as 15 fs. Crucially, we also show that the THz interaction simultaneously induces "temporal locking" of the compressed electron bunch (or bunch trains) to the THz drive laser with electron-to-laser arrival-time jitter suppressed down to 25 fs, independent of the as-measured 200 fs laser timing jitter. With optimized THz and electron bunch parameters, our results demonstrate that bunch compression and temporal-locking at the femtosecond level is within reach, entering a new regime exploiting hybrid THz-RF techniques.

CONCEPT AND EXPERIMENT

Standard RF compression techniques utilize off-crest or zero-crossing phase to imprint an energy chirp on the electron bunch, with higher energy at the bunch tail compared to the head, resulting in longitudinal bunch compression after subsequent drift (velocity-bunching) or dispersion (magnetic chicane). We adapt this technique for THz fields with 2-3 orders-of-magnitude higher frequency, enabling efficient chirping of short sub-picosecond input bunches for ultra-short single-bunch compression. Furthermore, injection of

* morgan.hibberd@manchester.ac.uk

longer few-picosecond bunches enables interaction across multiple cycles of the THz field, providing unique capability for energy modulation and subsequent generation of picosecond-spaced trains of ultrashort bunches. In each case, the THz-induced chirp/modulation is synchronized to the laser-generated THz fields, providing active ”temporal locking” of the compressed bunches to the drive laser system. The combination of a high-gradient, high-frequency THz-driven interaction downstream of RF infrastructure enables the suppression of bunch timing jitter inherent to RF and laser systems, unlocking the potential for femtosecond control of relativistic electron beams.

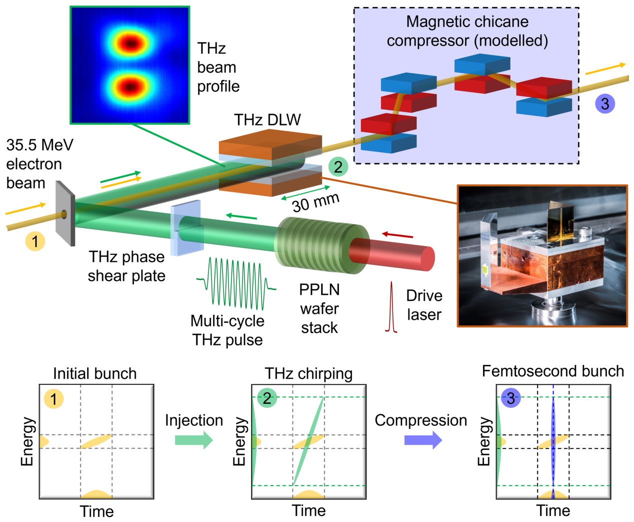

Figure 1: Schematic diagram of the experimental concept showing the laser-generated THz source converted into a TEM_{01} mode (THz camera image in inset) to drive the accelerating mode of the dielectric-lined waveguide (DLW, photo in inset). The (1) injected electron bunch experienced (2) THz chirping and subsequent (3) compression was modelled through dispersion-matching in a magnetic chicane, as indicated by the illustrative diagrams of the bunch longitudinal phase-space at each stage in the lower inset panels.

Our experiment (depicted in Fig. 1) exploited the Compact Linear Accelerator for Applications (CLARA) facility at Daresbury Laboratory, which provided 35.5 MeV electron bunches in short, low-energy spread (400 fs rms, 2 pC, 50 keV FWHM) and long, chirped (2.5 ps rms, 30 pC, 450 keV FWHM) bunch configurations. The THz source (0.39 THz center frequency, > 100 μJ pulse energy) was provided by a custom stack of 20 periodically-poled lithium niobate (PPLN) wafers (135 μm thick, 50.8 mm diameter) [13] driven by laser pulses with up to 350 mJ energy from a 10 Hz, 800 nm, 50 fs (transform-limited) Ti:sapphire multi-pass amplifier system. The emitted THz free-space TEM_{00} mode was converted to a quasi-TEM_{01} mode using a phase-shear plate that provided a π phase-shift between the top and bottom halves of the THz beam, enabling coupling to the accelerating mode in a rectangular dielectric-lined waveguide (DLW). The DLW was lined at the top and bottom with 70 μm-thick fused quartz, creating a 460 μm aperture of 30 mm length and 1.2 mm width to mediate a phase-velocity matched THz-electron interaction, with the resulting electron beam imaged in an energy spectrometer.

RESULTS AND DISCUSSION

For the short-bunch configuration, THz-driven acceleration, deceleration, chirping and de-chirping (not shown) were experimentally observed as a function of the THz-electron injection phase, enabling the longitudinal phase-space (LPS) to be modelled for each interaction (see Fig. 2). For subsequent compression, the bunch with a maximum THz-induced chirp of 345 keV/ps (see Fig. 2b and f) was propagated through a modelled chicane with matched dispersion. As shown in Fig. 3, a final bunch length of 15 fs rms was attained, corresponding to a compression factor of 27 from the initial injected 400 fs rms bunch.

For the long-bunch configuration, a THz-driven energy modulation over approximately 4 field cycles was observed, changing from a sinusoidal variation at low THz field strengths to sharp peaks when the initial bunch chirp was exactly cancelled out by the THz-induced chirp (see Fig. 4). At this point, the THz interaction acted as a unique diagnostic tool, with the modulation period providing time-energy correlation and the peak widths enabling direct measurement of the time-slice uncorrelated energy spread, which could be precisely mapped along the whole bunch through femtosecond optical time-delay scanning.

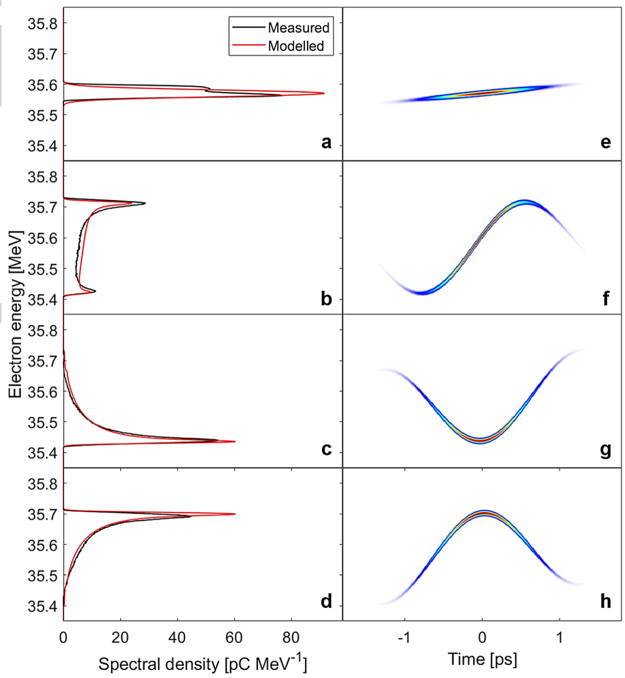

Figure 2: Measured and modelled energy spectra for 400 fs rms electron bunches at various THz-electron injection phases for (a) no interaction, (b) chirping, (c) deceleration and (d) acceleration. The corresponding longitudinal phase-space profiles for each phase are given in (e)-(h) extracted from fitting to the measured spectral profiles.

At higher THz field strengths, peak-splitting due to over-modulation was observed, with the periodic chirping enabling compression through a modelled chicane into a train of ultrashort bunches with duration down to 37 fs rms and spacing of 2 ps. These bunch trains are shown alongside the single bunch scheme for 50 shots (see Fig. 5), accounting for measured (and estimated) sources of jitter in the RF and laser systems, including RF linac phase and amplitude jitter, laser arrival-time jitter and fluctuations in THz amplitude. Our results demonstrate the capability for significant suppression (down to 25 fs rms) of the bunch (or bunch train) arrival time relative to the THz drive laser, which with further improvement to the THz source, waveguide interaction and bunch parameters, will open a route towards electron-laser synchronization at the femtosecond level.

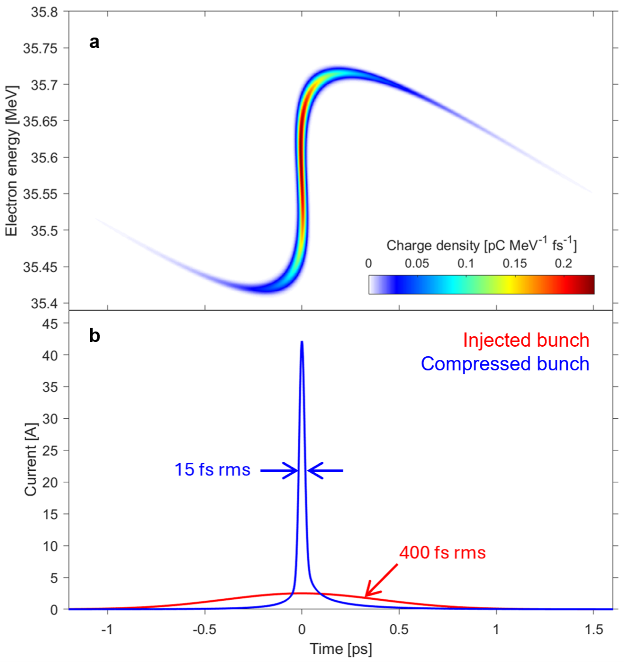

Figure 3: (a) Modelled longitudinal phase-space of the THz-chirped bunch following compression in a matched magnetic chicane and the (b) corresponding temporal profile compared to the initial injected bunch.

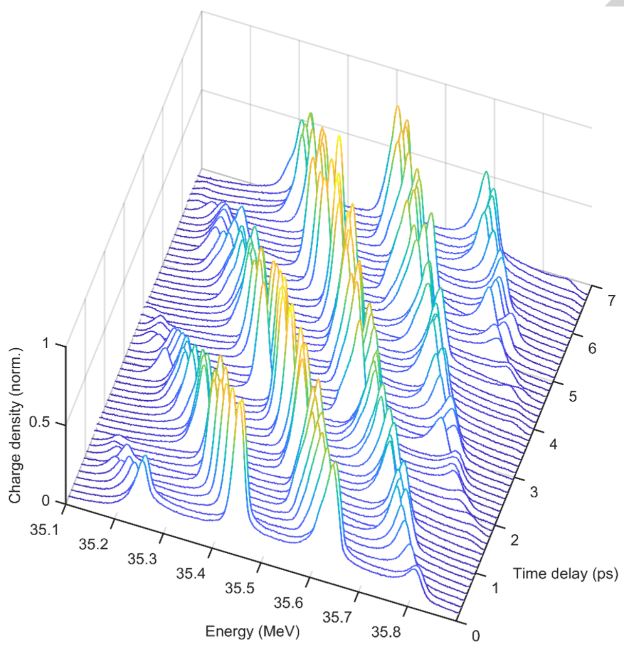

Figure 4: Measured electron energy spectra showing multi-cycle THz-driven energy modulation with optimized periodic chirp cancellation resulting in sharp energy peaks. The modulated spectrum is shown as a function of THz-electron time delay, allowing direct probing of the longitudinal time-slice properties of the injected bunch.

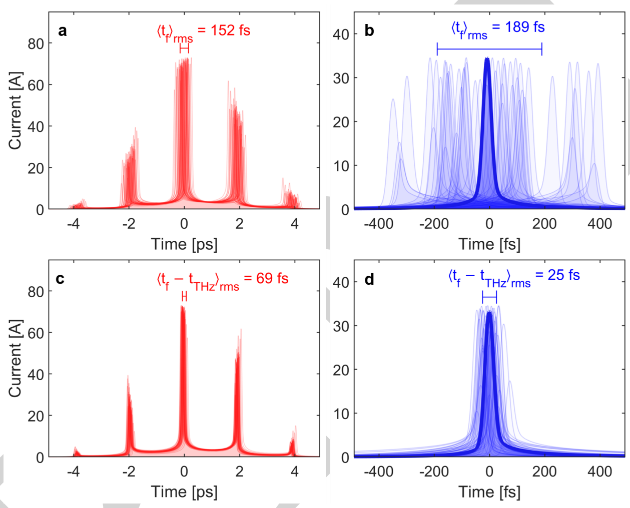

Figure 5: Modelled temporal projections of 50 shots in the presence of RF and laser jitter sources for THz-driven (a) bunch trains and (b) single-bunch compression relative to an independent reference clock. The corresponding projections relative to the THz drive laser are given in (c) and (d), highlighting THz-driven electron-laser "temporal-locking".

CONCLUSION

We have demonstrated that laser-generated THz pulses can be used with conventional RF accelerator technology for femtosecond temporal control of relativistic electron beams, taking advantage of the high-frequency THz interaction and direct laser synchronization to complement the unmatched spatial and spectral beam quality delivered by RF machines. From our experimental achievement of THz-driven energy modulation and chirping, we have demonstrated the capability to generate THz-frequency bunch trains with tunable micro-bunch spacing and shown a route to compression of single electron bunches down to 15 fs and below. Through further optimization it will be possible to exceed kA peak currents and push towards the femtosecond regime. We highlight the inherent "temporal-locking" of the compressed bunches to the THz drive laser, providing a pathway to solve the extreme femtosecond synchronization demands of future laser-based applications, including external injection into laser plasma wakefield accelerators [14].

REFERENCES

[1] M. Mirzaie *et al.*, "All-Optical Nonlinear Compton Scattering Performed With a Multi-Petawatt Laser", *Nature Photon.*, vol. 18, pp. 1212-1217, 2024. doi:10.1038/s41566-024-01550-8

[2] Z. Guo *et al.*, "Experimental Demonstration of Attosecond Pump–Probe Spectroscopy With an X-Ray Free-Electron Laser", *Nature Photon.*, vol. 18, pp. 691-697, 2024. doi:10.1038/s41566-024-01419-w

[3] P. Salen *et al.*, "State-of-the-Art Electron Beams for Compact Tools of Ultrafast Science", *Ultramicroscopy* vol. 268, pp. 114080 2025. doi:10.1016/j.ultramic.2024.114080

[4] Y. Wu *et al.*, "High-Throughput Injection–Acceleration of Electron Bunches From a Linear Accelerator to a Laser Wakefield Accelerator", *Nat. Phys.*, vol. 17, pp. 801–806, 2021. doi:10.1038/s41567-021-01202-6

[5] M.T. Hibberd *et al.*, "Acceleration of Relativistic Beams Using Laser-Generated Terahertz Pulses", *Nature Photon.*, vol. 14, pp. 755-759, 2020. doi:10.1038/s41566-020-0674-1

[6] H. Xu *et al.*, "Cascaded High-Gradient Terahertz-Driven Acceleration of Relativistic Electron Beams", *Nature Photon.* vol. 15, pp. 426-430, 2021. doi:10.1038/s41566-021-00779-x

[7] H. Tang *et al.*, "Stable and Scalable Multistage Terahertz-Driven Particle Accelerator", *Phys. Rev. Lett.*, vol. 127, pp. 074801, 2021. doi:10.1103/PhysRevLett.127.074801

[8] X.-Q. Yu *et al.*, "Megaelectronvolt Electron Acceleration Driven by Terahertz Surface Waves", *Nat. Photon.*, vol. 17, pp. 957-963, 2023. doi:10.1038/s41566-023-01251-8

[9] L. Zhao *et al.*, "Terahertz Streaking of Few-Femtosecond Relativistic Electron Beams", *Phys. Rev. X*, vol. 8, pp. 021061, 2018. doi:10.1103/PhysRevX.8.021061

[10] E.C. Snively *et al.*, "Femtosecond Compression Dynamics and Timing Jitter Suppression in a THz-Driven Electron Bunch Compressor", *Phys. Rev. Lett.*, vol. 124, pp. 054801, 2020. doi:10.1103/PhysRevLett.124.054801

[11] L. Zhao *et al.*, "Femtosecond Relativistic Electron Beam With Reduced Timing Jitter From THz Driven Beam Compression", *Phys. Rev. Lett.*, vol. 124, pp. 054802, 2020. doi:10.1103/PhysRevLett.124.054802

[12] M.T. Hibberd *et al.*, "Terahertz Control of Relativistic Electron Beams for Femtosecond Bunching and Laser-Synchronized Temporal Locking", preprint available at arXiv:2508.20685 doi:10.48550/arXiv.2508.20685

[13] C.D.W. Mosley, *et al.*, "Large-Area Periodically-Poled Lithium Niobate Wafer Stacks Optimized for High-Energy Narrowband Terahertz Generation", *Opt. Express*, vol. 31, pp. 4041, 2023. doi:10.1364/OE.475604

[14] A. Amini *et al.*, "Controlling External Injection in Laser-Plasma Accelerators With Terahertz Frequency Bunch Manipulation", preprint available at arXiv:2604.16059 doi:10.48550/arXiv.2604.16059