Cascaded high-gradient terahertz-driven acceleration of relativistic electron beams

Hanjun Xue, Lixin Yan, Yingchao Du, Wenhui Huang, Qili Tian, Renkai Li, Yifan Liang, Shaohong Gu, Jiarui Shi and Chuanxiang Tang

Terahertz-driven acceleration has recently emerged as a route for delivering ultrashort bright electron beams efficiently, reliably and in a compact set-up. Many working schemes and key technologies related to terahertz-driven acceleration have been successfully demonstrated and are being developed. However, the achieved acceleration gradient and energy gain remain low, and the potential physics and technical challenges in the high-energy regime are still underexplored. Here we report whole-bunch acceleration of relativistic beams with an effective acceleration gradient of up to 85 MV m⁻¹ in a single-stage configuration and demonstrate a cascaded terahertz-driven acceleration scheme of relativistic beams with an energy gain of 204 keV. These proof-of-principle results represent a critical advance towards high-energy terahertz-driven acceleration of relativistic beams, which are scalable and have great potential to provide high-quality beams, with implications for future terahertz-driven electron sources and related scientific discoveries.

Acceleration and control of high-quality electron beams using electromagnetic waves ranging from radio-frequency to optical lasers has been a major goal in the development of modern science and technology. Limited by radio-frequency-induced plasma breakdown, conventional accelerators will require costly facilities with large size and power demands to meet the request for future extreme high-energy accelerators. Novel acceleration concepts driven by laser fields, wakefields and terahertz fields have demonstrated their effectiveness at generating stronger fields (greater than gigavolts per metre) for beam acceleration and manipulation, which can be scaled to smaller and more economical facilities for providing high-energy bright beams. These concepts include plasma wakefield accelerations, laser-driven dielectric accelerations and terahertz-driven accelerations, each with different advantages. Great progress has been made in delivering high-charge bright beams through the tremendous efforts of the plasma wakefield acceleration community in recent decades. Laser-driven dielectric accelerators face challenges in structure fabrication and are suitable for low bunch charge owing to the submicrometre optical wavelength.

Great interest has recently been focused on terahertz-driven acceleration given that it shares certain advantages with radio-frequency acceleration and laser-driven dielectric acceleration. The scaling $E_{\text{max}} \propto f^{1/4} \tau^{-1/4}$ was observed for the copper surface from 2.856 GHz to 11.424 GHz, where $E_{\text{max}}$ is the maximum field strength, $f$ is the field frequency and $\tau$ is the pulse duration. For higher radio and terahertz frequencies, more systematic exploration is underway to reveal the precise scaling, that is, the dependence of $E_{\text{max}}$ on $f$, $\tau$, the materials of the accelerating structures (such as copper) and so on. It has been demonstrated that a dielectric structure can sustain fields greater than gigavolts per metre in the terahertz regime. The millimetre-scale terahertz wavelength also simplifies the structure fabrication and supports considerable charge per bunch. The past decades have witnessed tremendous progress in terahertz-driven electron guns, terahertz-driven acceleration, and manipulation of low-energy beams and relativistic beams. Previous works have achieved a multimegavolt-per-metre acceleration gradient and dozens of kiloelectronvolt energy gains while leaving room for further improvements in the high-energy regime. Whole-bunch acceleration of relativistic beams has not been demonstrated, and the energy gain and the acceleration gradient still need to be improved. The next key step for this technology is cascaded terahertz-driven acceleration in the relativistic regime, which is now a major obstacle that limits scaling up of the current technology to a higher-energy regime.

Here we experimentally demonstrate whole-bunch acceleration and cascaded terahertz-driven acceleration of relativistic beams with an energy gain of 204 keV. We employ dielectric-loaded waveguides (DLWs) to slow down the travelling TM01 field excited by single-cycle coherent transition radiation (CTR) terahertz pulses. Energy spectrum manipulation is exploited over the full cycle of the terahertz wave with an estimated peak field on the DLW axis of 1.1 GV m⁻¹ and a calculated acceleration gradient of 85 MV m⁻¹. Simulation results show great potential for transverse emittance preservation. These proof-of-principle results are now scalable and hold great potential for preserving beam qualities, representing a critical step forwards in the development of compact high-energy terahertz-driven accelerators.

Figure 1 shows a schematic of the single-stage terahertz-driven accelerator. The Tsinghua Thomson scattering X-ray source (TTX) is configured to provide two electron bunches (see Methods): an 850 pC, 30.4 MeV drive bunch for generating the CTR pulse and a 1.5 pC, 34.3 MeV witness bunch following the drive bunch for a terahertz–electron interaction. The drive bunch perpendicularly strikes an aluminium film coated on a quartz substrate, generating a 132 µC CTR terahertz pulse centred at 0.6 THz (Fig. 1d,e). The radially polarized terahertz pulse (Fig. 1f) is coupled to the DLW via a tapered horn coupler, exciting a travelling TM01 field whose longitudinal component can be used to accelerate the following witness bunch. The length of the witness bunch is estimated to be 460 fs full-width at half-maximum (FWHM), which is shorter than the half-cycle of the terahertz field, enabling whole-bunch acceleration. The inner diameter of the DLW is 436 μm with a dielectric wall thickness of 52 μm and the linear accelerator (linac) is
10 mm in length, including a 5 mm tapered horn for wave coupling (Fig. 1b,c). The inner diameter of the CTR target is 0.5 mm, which is sufficiently large for the witness bunch to transmit while intercepting most of the drive bunch, generating a significant CTR pulse (Fig. 1). The witness bunch penetrates through apertures along the beamline while the terahertz pulse is delayed by a motorized stage. The energy spectrum of the witness bunch is determined via a dipole spectrometer located at the end of the beamline. Insets: a, The aluminium target. b, The horn coupler and quartz capillary. c, A schematic of the terahertz linac. d, e, Temporal (d) and spectral (e) profiles of the CTR terahertz pulse determined by electro-optical sampling measurements. f, The focal spot profile of the CTR pulse.

Figure 2a compares the mean energy (100 shots) of the witness bunch as a function of the terahertz delay with the CST (http://www.cst.com) simulation result. The maximum mean energy gain is 170 ± 84 keV and at this time delay the highest energy gain of an individual shot has reached 330 keV. By contrast to previous results that show simultaneous acceleration and deceleration, the energy spectrum clearly moves to the high-energy side, establishing whole-bunch acceleration of the witness bunch at the π/2 injection phase (Fig. 2c). The DLW is designed to match the velocity of the witness bunch (0.9999c) at 0.6 THz with a group velocity of 0.48c, where c is the speed of light. A temporal walk-off arises when the electron bunch loses overlap with the wave envelope, resulting in a limited terahertz–electron interaction length. The simulation in Fig. 2b indicates that the energy gain remains constant at ~170 keV after interacting with the terahertz wave from 0 mm to 2 mm (interaction length); the effective acceleration gradient is calculated to be 85 ± 42 MV m⁻¹. It is worth noting that 90% of the total energy gain takes place between 0.5 mm and 1.6 mm, which would amount to a higher effective acceleration gradient of 155 ± 76 MV m⁻¹. The peak electric field inside the DLW is estimated to reach 1.1 GV m⁻¹. The discrepancy between the acceleration gradient and the peak field comes from the waveguide dispersion, the broad bandwidth of the terahertz pulse and the relatively long bunch length (see Supplementary Information); it can be optimized in future terahertz-driven accelerators (see Methods). Figure 2c,d presents four optimal individual energy spectrums selected from each time delay, showing distinct energy spectrum manipulation. The witness bunch is generated with a negative energy chirp (see Methods), that is, the electron energy at the bunch head is higher than that at the bunch tail. The energy spectrum splits into two peaks at the π-injection phase because the bunch head experiences acceleration while the bunch tail experiences deceleration. The measured energy spread increases from 167 keV to 210 keV. At the 2π-injection phase, an energy dechirp arises when the bunch head is decelerated while the bunch tail is accelerated, resulting in strongly energy spectrum compression with energy spread decreasing from 167 keV to 141 keV.

By cascading two DLWs driven by the backwards and forwards CTR pulses generated from a tantalum film coated on a TPX (poly(4-methyl-1-pentene)) substrate, we construct a cascaded terahertz-driven acceleration configuration as shown in Fig. 3. Both the backwards and forwards CTR pulses are centred at approximately 0.6 THz (see Fig. 3b,c), with pulse energies of 66 μJ and 35 μJ, respectively. Figure 4a shows the individual energy variation compared with the simulation results, indicating that each single-stage terahertz linac can work effectively. The energy spectrum in Fig. 4b,d clearly moves to the high-energy side in sequence when linacs I and II begin to operate, verifying successfully cascaded terahertz-driven acceleration of the witness bunch. A total energy gain of 204 ± 64 keV is observed with a 115 ± 2 keV energy gain in the first stage and an 89 ± 63 keV energy gain in the second stage, which agrees well with the simulation result shown in Fig. 4b. The measured bunch charge decreases from 1.9 pC initially to 350 fC due to the collimation tolerance and beam mismatching, which could
**Fig. 2 | Single-stage terahertz-driven acceleration and energy modulation.**

**a.** The mean energy of the witness bunch as a function of terahertz–electron delay. The red dots are measured values with error bars of one standard deviation over 100 shots, whereas the black line is the simulation result.

**b.** A simulation of the experimental set-up when the injection phase is \( \pi/2 \). \( z \) is the longitudinal distance from the entrance of the dielectric waveguide. The dashed lines indicate the locations that correspond to 5% and 95% energy gains.

**c.** Snapshots of the energy spectrometer at different injection phases. The colour scale refers to the grey of the figure pixels, which corresponds to the charge density.

**d.** A normalized projected energy spectrum that corresponds to c.

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**Fig. 3 | Cascaded terahertz-driven linacs.**

Two terahertz linacs are separately powered by backwards and forwards CTR terahertz pulses. The second stage is a copy of the first stage (as depicted in Fig. 1). The main difference is the newly designed CTR target, which enables considerable terahertz radiation in both the backwards and forwards directions.

Insets: **a.** The tantalum target. **b,c.** Temporal (b) and spectral (c) profiles of the CTR terahertz pulse in the backwards (red) and forwards (blue) directions determined by electro-optical sampling measurements.
be mitigated by precisely collimating and employing additional beam focusing components (see Supplementary Information). The total terahertz pulse energy applied in the cascaded experiment is smaller than that in the single-stage experiment, whereas the obtained energy gain is higher than that in the single-stage experiment, indicating that the demonstrated cascaded working scheme can lower the required terahertz energy for future higher-energy terahertz-driven accelerators.

In summary, we have successfully demonstrated whole-bunch acceleration and cascaded terahertz-driven linear acceleration of relativistic beams. The energy gain is an order of magnitude higher than previous results, and can be further improved to the megaelectronvolt level with negligible transverse emittance growth (0.2%) with millijoule-level terahertz sources (see Methods). Submillijoule narrowband terahertz sources\textsuperscript{24,25} and millijoule-level single-cycle terahertz sources\textsuperscript{26,27} have been reported so far. The demonstrated cascaded acceleration scheme offers the opportunity to further improve the energy gain, making terahertz-driven acceleration attractive for related high-energy accelerator applications. The demonstrated cascaded concept and whole-bunch acceleration take a critical step forwards in the high-energy regime, revealing the full capability of terahertz-driven acceleration. These proof-of-principle results establish a route for achieving tabletop all-optical high-energy terahertz-driven accelerators, which can be scaled up with great potential for providing high-quality beams, marking a key milestone in the development of terahertz-driven acceleration technology in the relativistic regime.

**Online content**
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Methods

Double bunch generation. The drive bunch and the witness bunch used in this experiment are produced by the TTX beamline at Tsinghua University (see Extended Data Fig. 1a). A 266 nm ultraviolet laser (~700 fs FWHM) is split into two pulses while one pulse is stacked by four e-BBO crystals, forming a 9 ps flattop laser pulse, and the other pulse is delayed by a motorized stage (see Extended Data Fig. 1b). These two laser pulses illuminate the S-band radio-frequency gun, generating the drive bunch and the witness bunch with a preset 1.41 ns time delay (approximately four radio-frequency cycles). The drive bunch is accelerated at the ~45° radio-frequency phase and then imprinted a positive energy chirp for subsequent bunch compression in the magnetic chicane. The measured bunch energies are 30.4 MeV (drive bunch) and 34.3 MeV (witness bunch) as determined via a dipole spectrometer located at the end of the TTX beamline. Dynamic simulations based on ASTRA28 show that the bunch length is compressed to ~700 fs FWHM (drive bunch) and ~460 fs FWHM (witness bunch) after the magnetic chicane. To maximize the CTR pulse energy, the magnetic chicane is configured to minimize the bunch length of the drive bunch; thus, the witness bunch is over compressed, resulting in a negative energy chirp (that is, the electron energy at the bunch head is higher than that at the bunch tail). The bunch length of the witness bunch is approximately 1/4 cycle of the CTR pulse, enabling whole-bunch acceleration.

Double terahertz pulse generation and characterization. Transition radiation is emitted when a relativistic beam crosses the boundary between vacuum and metal. If the radiation wavelength exceeds the electron bunch length, all of the electrons emit coherently. In these experiments: an aluminium film on a quartz substrate for single-stage terahertz-driven acceleration, and a tantalum film on a TPX substrate for cascaded terahertz-driven acceleration. The drive bunch would generate considerable CTR waves in both the backwards and forwards directions for either film. The main difference comes from the different substrates, as quartz/TPX has a low/high transmittance in the frequency range 0.2 THz to ~1 THz. The quartz absorbs the most forward CTR terahertz wave, whereas the TPX allows most forward CTR transmittance in the frequency range 0.2 THz to ~1 THz. The quartz absorbs the most forward CTR terahertz wave, whereas the TPX allows most forward CTR THz wave to transmit, as a result, the tantalum target with a TPX substrate can deliver considerable CTR pulses simultaneously on both sides. The pulse energy is measured by a Collay cell detector and the focal spot is observed via a terahertz camera. A single-shot electro-optical sampling method29 is employed to determine the temporal profile of the CTR pulse. Coherent transition radiation can generate a radially polarized single-cycle terahertz pulse with considerable pulse energy, which couples well to the TM01 mode of the DLW in the far field. These beam-based frequency-tunable terahertz sources benefit intrinsic synchronization as the terahertz pulses and the witness bunch are produced by the same seeding laser.

Terahertz linac. The terahertz linac consists of a quartz capillary inserted into a hollow cylindrical copper waveguide with a tapered horn coupler. The permittivity of quartz is approximately 3.85. The DLW is designed to match the velocity of the witness bunch at 0.6 THz. For a given vacuum radius and a given dielectric thickness, there is only one working frequency at which the phase velocity equals the electron speed (0.9999c) according to the dispersion relation. Extended Data Fig. 2a shows the calculated frequency map for different dimensions when $v_e = 0.9999$ c. A larger vacuum radius is desirable for a larger group velocity, which will contribute to a longer terahertz–electron interaction length; however, the peak field along the DLW axis decreases as the vacuum radius increases, which results in lower accelerating gradients. There exists a compromise between increasing the interaction length and strengthening the accelerating field. Extended Data Fig. 2b shows the calculated energy gain for different dimensions when $v_e = 0.9999$ c and $f_0 = 0.6$ THz. The inner diameter of the quartz capillary is 436 μm with a dielectric wall thickness of 52 μm. The corresponding group velocity is 0.48c, as shown in the dispersion curve in Extended Data Fig. 2c. The longitudinal electric field is optimized to be fairly homogenous in the vacuum regime with only a 3% reduction from the vacuum axis to the dielectric wall (see Extended Data Fig. 2d). The horn coupler is 5 mm in length and the hole at the horn cone has a diameter that corresponds to a bandwidth of more than 300 GHz at approximately 0.6 THz. The terahertz linac can effectively work with optically generated terahertz sources after converting the linearly polarized terahertz waves to radially polarized ones.

Megaelectrovolt-level terahertz-driven acceleration. The transverse force generated by the TM01 mode electromagnetic field of a DLW on an electron moving with velocity $v_e$ in the $z$ direction scales as $F_z = (1 - v_e/c) A$, where $A$ is an amplitude coefficient, $v_e$ is the phase velocity of the wave inside the DLW, and $c$ is the velocity of light and the subscript $r$ stands for the radial direction (see Supplementary Information). The net transverse force tends to vanish in our configuration where $v_e = v_r = c$, and the longitudinal electric field is optimized to be fairly homogeneous along the radial direction (see Extended Data Fig. 2d), indicating that our approach holds great potential for preserving transverse beam qualities in the relativistic regime.

Extended Data Fig. 2f shows the simulation results of a megaelectrovolt-level terahertz-driven accelerator using the designed DLWs and the demonstrated cascaded concept, assuming a 20 μC, 300 MV, 206 fs FWHM electron bunch and a ten-cycle, 0.6 THz flattop terahertz wave with one cycle rise/fall time. The simulation predicts a 2.07 MeV energy gain using 1 μl terahertz pulse energy in a single-stage configuration. The interaction length is estimated to be ~6 mm and the effective acceleration gradient is calculated to be 345 MV m⁻¹, and the corresponding peak field in the DLW axis is 570 MV m⁻¹ according to the field analysis. The estimated transverse emittance with/without the terahertz field is 0.516/0.517 mm mrad (negligible 0.2% growth), verifying the capability of transverse emittance preservation of this approach. A cascaded configuration where each DLW is powered by a 250 μl terahertz pulse also achieves an energy gain of approximately 1.96 MeV, showing that the demonstrated cascaded acceleration concept can greatly lower the required terahertz energy for high-energy beam acceleration with a factor of approximately 1/N, where N is the number of stages. The energy gain can be further improved with additional terahertz sources for more acceleration stages.

Submillijoule narrowband terahertz sources26,27 and millijoule-level single-cycle terahertz sources24,25 have recently been exhibited and are continuously being improved. Megaelectrovolt-level terahertz-driven acceleration with negligible emittance growth is achievable with these demonstrated concepts. Shorter electron bunches (approximately tens of femtoseconds) and higher power terahertz sources with narrower bandwidth (comparable to the effective frequency bandwidth of the DLW) are foreseeable in the future. The energy gain can be further improved with perfect transverse emittance preservation, indicating that this work establishes a feasible route to achieve future compact high-energy terahertz-driven accelerators.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author on reasonable request.

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Author contributions

H.X., W.H., L.Y. and Y.D. conceived and designed the experiment. H.X. built and developed and performed the simulations for data evaluation and interpretation of results. H.X., W.H., L.Y. and Y.D. performed the simulations for data evaluation and interpretation of results. H.X. wrote the manuscript with contributions from W.H., L.Y., R.L., Y.D. and C.T. H.X. designed the DLW and the tapered horn coupler with the help of J.S. H.X. developed and performed the simulations for data evaluation and interpretation of results. H.X. wrote the manuscript with contributions from W.H., L.Y., R.L., Y.D. and C.T. W.H. provided management and oversight to the project.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to W.H.

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Extended Data Fig. 1 | TTX beamline and the laser splitting setup. The TTX beamline (a) and the laser splitting setup (b).
Extended Data Fig. 2 | THz linac. a, Frequency map for different DLW dimensions when \(v_p = 0.9999c\). b, Calculated normalized energy gain for different DLW dimensions when \(v_p = 0.9999c\) and \(f_0 = 0.6\) THz. c, Dispersion curve of the designed DLW. d, Normalized magnitude of the longitudinal electric field along the radial axis. e, Calculated coupling of the horn coupler. f, Simulation results of megaelectronvolt-level THz-driven acceleration using the designed DLW for single-stage and cascaded configurations.