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ABSTRACT

Terahertz radiation (THz)-based electron acceleration has the potential as a technology for driving the next-generation, compact ultrafast and ultrabright electron and x-ray sources. Dephasing is one of the key problems that prevent long THz–electron interaction lengths in the sub- to few-MeV range, where electron velocities vary significantly during high-field acceleration. Here, we present a phase-shifter design with double vacuum channels to alternate the phase velocity that effectively extends the THz–electron interaction length in THz-powered dielectrically loaded waveguides. The electrons are swept multiple-times back and forth through the accelerating phase of the THz wave to undergo continuous acceleration along the entire interaction. In addition, the double vacuum channel design enables increases in both the phase and group velocities of the THz wave, which leads to an adaptive synchronous acceleration with extended interaction length. This method paves the way for the practical implementation of THz-powered devices for high-energy ultrafast electron sources.

Terahertz radiation (THz)-driven electron acceleration has recently emerged as a promising approach for overcoming certain technological limitations of conventional particle accelerators. In particular, laser-based THz sources[1–4] show great potential to enable order-of-magnitude higher sustainable field strength[5,6] up to the GV/m range,[7] with increased timing precision compared to the conventional radio frequency (RF) sources.[8] The millimeter wavelength supports sub-picosecond electron beam manipulation with a moderate charge at the picocoulomb (pC) level.[9] Proof-of-principle demonstrations have shown tens of keV acceleration,[10–18] high-field beam manipulations,[13,15,19–22] as well as application in ultrafast electron diffraction[23] confirming the high potential of THz-accelerator technology for future compact ultrafast electron sources.

For efficient electron acceleration, the electron bunch should remain in the accelerating phase of the THz wave over the entire THz–electron interaction length. However, in the non-relativistic regime, high THz fields can lead to a rapid change in the electron speed. As a result, even over very short interaction lengths, the electrons can slip from the accelerating to the decelerating phase due to the mismatch between the electron velocity and the THz phase velocity. This "dephasing" is a general problem in accelerators, which becomes more severe for shorter driving wavelengths. Dephasing is one of the key challenges in electron acceleration driven by shortwave THz radiation, and a variety of approaches have, therefore, been proposed to address it. In structures employing transversely injected, single-cycle THz pulses, a segmented structure was demonstrated that enabled phase matching of low-energy (55 keV) electrons over millimeter-scale interaction lengths.[13] In the relativistic regime, a THz-driven, inverse free-electron laser (IFEL) scheme was demonstrated that enabled phased propagation of 4–9 MeV beams with single-cycle THz pulses over tens-of-centimeter distances.[12,24] Dielectrically loaded waveguides (DLWs) have also been proposed to increase interaction lengths in the case of multi-cycle THz drivers,[15–18,25,26] where the waveguide and dielectric dimensions are used to tune the THz phase velocity. This solution works well for relativistic electrons with velocities that do not change much during acceleration but can suffer severe dephasing for lower energy electrons. In principle, the dephasing can be addressed by tapering the dielectric properties to locally adjust the phase velocity,[26] mirroring the approach used in conventional accelerators. However, the small dimensions lead to tight tolerances on fabrication, which are very challenging to achieve in practice. An alternate approach is to cascade DLW stages,[15] allowing re-timing and rephasing the interaction in between by taking advantage of the velocity difference of the THz wave in vacuum vs inside the DLW, thereby extending the overall interaction length. This scheme, however, only works in the strongly non-relativistic regime where the difference in velocity between the electrons and the THz wave in vacuum is appreciable. In addition, the necessity of coupling the THz out and back into the DLW between stages leads to a complex setup, especially in the case of multiple stages.

Here, we introduce a scheme based on double vacuum channels to locally modulate the THz phase velocity in the DLWs and thereby periodically introduce phase shifts that allow the electrons to remain in the accelerating phase of the THz wave for extended interaction lengths. The phase-shifter design is simple, relatively easy to fabricate, and minimizes reflective losses. Our simulations show that by employing a DLW with two phase shifters, a 50 keV electron beam driven by a 100 μJ, 25 cycle THz pulse experiences an energy gain of 170 keV, which is a more than twofold increase over the case without the shifter. This double vacuum channel simultaneously increases the group and phase velocities of the THz wave, addressing not only dephasing but also the walk-off between the electron bunch and temporal envelope of the THz pulse, which limits the interaction length. This concept is applicable over a range of electron energies, paving the way for practical implementation of THz-powered ultrafast electron sources in demanding applications such as compact light sources[27,28] and ultrafast electron diffraction.[29,30]

Figure 1 shows the schematic of the collinear electron acceleration. Both the electron beam and multi-cycle THz with the TM_{01} mode are injected into the DLW. The TM_{01} mode multi-cycle THz can be generated with a segmented half wave plate from a linearly polarized beam. In the inset of Fig. 1, we mark the negative half-cycle of the THz pulse as the section between zero crossing points A and B. The negative and positive parts of the THz wave represent the accelerating and decelerating phases, respectively. To optimize the electron-energy gain, the interaction length while in the accelerating phase must be maximized, and the decelerating phase must be avoided. This optimization can be done by injecting the electrons at the zero-crossing point B, which is the leading part of the accelerating half cycle, and tuning the initial phase velocity of the THz wave to be slightly larger than the injected electron speed. With proper tuning, the electrons slip backward through the half cycle but gain sufficient energy during acceleration to overtake the THz wave before reaching point A and dephasing. As a result, the electron beam sweeps two times through the accelerating phase of the THz wave to get the maximum energy gain [full simulation is presented in the multimedia view of Fig. 2(a)]. As the group velocity of the THz wave is low ($\sim$0.25c) compared with the electron speed ($\sim$0.41c), the injection point should be at the trailing end of the THz pulse so that the electrons remain within the pulse envelope as long as possible. For short enough THz pulses, the electrons can outrun the pulse envelope before dephasing.

On the other hand, if the accelerating field is sufficiently high or the THz pulse is sufficiently long, the electron beam can outrun the accelerating half cycle and begin decelerating before it outruns the THz pulse envelope. This scenario results in inefficient use of the THz energy, as part of the pulse does not participate in the interaction. By introducing a phase shifter (Fig. 1) to re-position the electrons relative to the THz wave, the interaction can be extended, and a greater portion of the THz energy is engaged. The phase shifter is based on a double-vacuum-channel design in which the center channel on the inside of the dielectric contains the electrons and the majority of the THz energy (Fig. 1). A second channel, in the shape of an annular ring surrounding the dielectric capillary, is used to lower the effective dielectric constant that leads to an increase in both the THz phase and group velocity [Fig. 3(a)] allowing the THz–electron interaction to sweep from point B to point A [Fig. 2(b)]. Despite the changes in velocity, a TM_{01} mode is maintained within the phase-shifter section of the

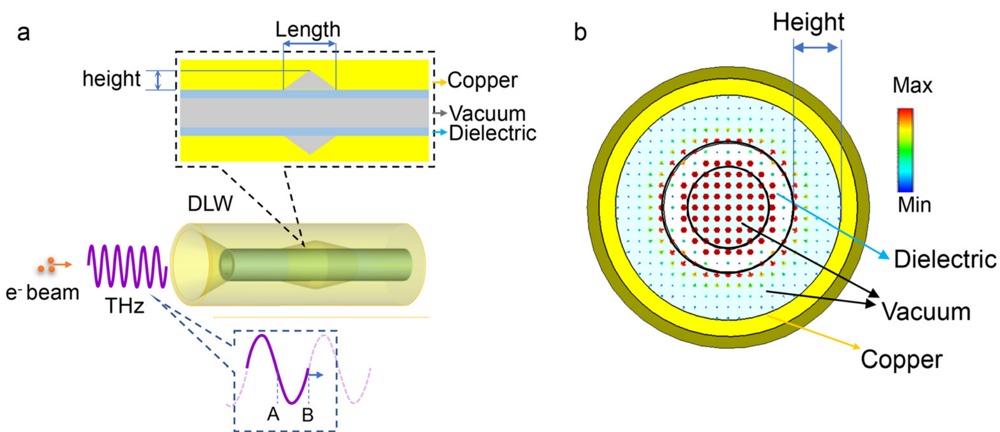

FIG. 1. Schematic of the phase shifter. (a) The electron beam is injected collinearly with the THz wave into the DLW. Inset top: longitudinal cross section of the DLW structure. Inset bottom: definition of the zero-crossing points A and B. (b) Lateral cross section of the electric field distribution in the center of the phase shifter. For a practical design case in the simulation, we assumed that the injected electron beam has an energy of 50 keV (0.41c).

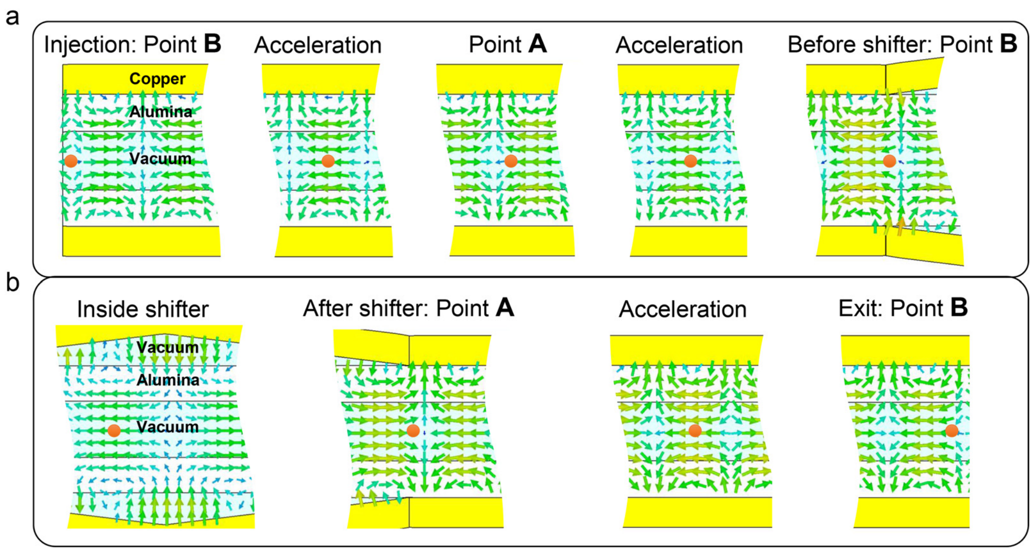

FIG. 2. Particle-in-cell simulations of electron acceleration. (a) Simulated electron acceleration before the phase shifter. The electrons sweep two times through the negative half cycle of the accelerating phase. (b) Simulated electron acceleration inside and after the phase shifter. The electrons sweep from point B to A and A to B, respectively. The simulation is performed with CST Microwave Studio software.[31] Multimedia views: https://doi.org/10.1063/5.0096685.1; https://doi.org/10.1063/5.0096685.2

waveguide [Fig. 1(b)]. After the phase shifter, the electrons are once again traveling faster than the THz wave and can continue their acceleration as they sweep again from point A to point B [full simulation results are presented in the multimedia view of Fig. 2(b)]. This process can be repeated as needed using successive phase shifters to allow the electrons to sweep through the accelerating half cycle multiple times.

Several practical issues should be considered in the design of the phase-shifter device. First, the phase shifter region influences the transmission of the THz pulse [Fig. 3(b)]. The benefits of re-phasing the electron bunch must, therefore, be weighed against the losses in THz energy. Second, due to the small scale of the structures, deviations in the dimensions of the fabricated device compared to the design can cause the phase-shifter to be improperly positioned relative to the dephasing point. Fortunately, these deviations can be compensated by adjusting the injection time of the electron beam and taking advantage of the large velocity difference between the THz wave and the electron beam inside the DLW to shift the dephasing point to the phase-shifter location. This degree of freedom, thus, provides a higher tolerance against deviations in the DLW length and phase shifter position. In quantitative terms, micron-level errors in the DLW and horn coupler dimensions can result in a few tens-of-degree phase changes between electron bunch and THz wave [Fig. 3(c)], which will result in a reduced energy gain. This influence is also enhanced with the increase in THz field amplitude as the change in velocity is increased.

A concrete case is considered next, assuming an injection energy of 50 keV, a 100 μJ THz with 25 cycles at 300 GHz, and two-phase

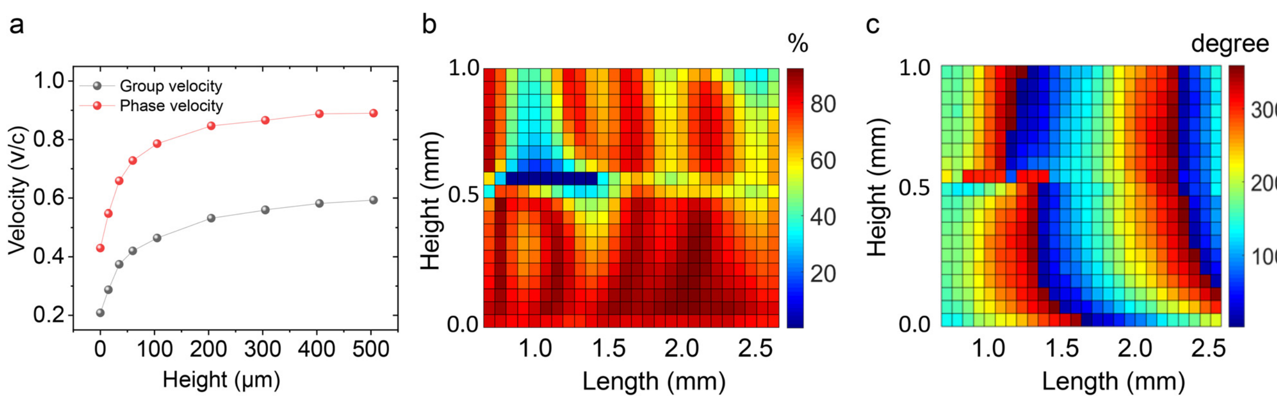

FIG. 3. (a) Simulated THz phase and group velocity as a function of outer vacuum height of the phase shifter. (b) Relative THz coupling efficiency after the phase shifter as a function of height and length. (c) Relative THz phase shift after the phase shifter as a function of the height and length of the shifter. The amount of coupling efficiency and the phase shift is compared with the case without the shifter. The dielectric tube has an inner vacuum radius of 0.25 mm and a dielectric thickness of 0.14 mm. Alumina (Al_2O_3) with a dielectric constant of 9.9 is used in the simulations.

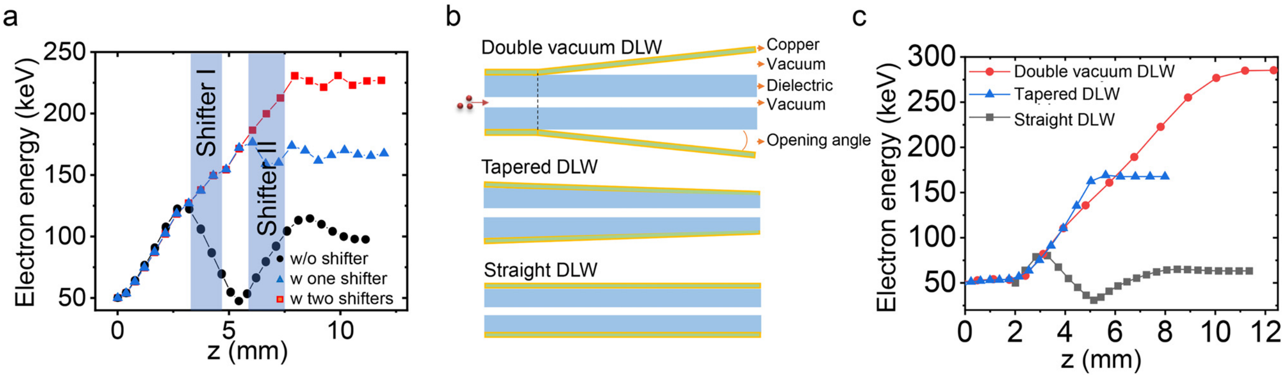

FIG. 4. Electron acceleration. (a) Simulation for electron acceleration with two phase shifters (red), one phase shifter (blue), and without phase shifter (black) for THz pulses with higher field and longer pulse duration. The simulation has used 100 μJ THz energy with 25 cycles at 300 GHz. Phase shifter I has a width of 1.8 mm and a height of 0.33 mm. Phase shifter II has a width of 2 mm and a height of 0.36 mm. (b) Schematic design for the double vacuum channel DLW (top), tapered DLW (middle), and straight DLW (bottom). (c) The corresponding simulation of electron acceleration for different cases in (b). The simulation for (c) has used ~90 μJ THz energy with 15 cycles at 300 GHz. The opening angle of the vacuum region outside the dielectric is 0.44°. Multimedia view: https://doi.org/10.1063/5.0096685.3

shifters. The DLW is designed to have an initial phase velocity of 0.53c which exceeds the initial velocity of the injected electrons (0.41c). With a single phase shifter, the energy gain increased by roughly 70% to 125 keV, compared to 75 keV without phase shifter [Fig. 4(a)]. By adding a second phase shifter, a total improvement of 130% is achieved, resulting in an energy gain of over 175 keV. The distance to the second shifter is less than the distance to the first because as the electrons gain energy and speed, the rate of dephasing also increases. A design which increases the THz phase velocity after each phase shifter can, therefore, help to extend the interaction length, and thus, energy gain.

Two schemes are considered for longitudinally modifying the phase velocity to achieve synchronous acceleration: varying the height of the second channel and varying the thickness of the dielectric [Fig. 4(b)]. In the first concept, by adjusting the space between the dielectric and the copper waveguide continuously, the THz phase velocity can be matched to the electron speed and the speed of the THz pulse envelope also increases, both of which contribute to a greater than 3× improvement in energy gain compared to the straight DLW [Fig. 4(c)]. By contrast, tapering of the dielectric part maintains continuous phase matching but with reduced interaction length, leading to a more moderate 1.5× improvement compared to the straight DLW. It can be seen from the multimedia view of Fig. 4(b) that with the double-vacuum-channel DLW, the group velocity is increasing along the tube, and the THz wave is traveling much faster than for the tapered or straight DLWs, leading to ~3× and ~10× larger interaction lengths, respectively [Fig. 4(c)]. The double-vacuum-channel approach, therefore, appears to be the more favorable one than the other two solutions. Such a scheme is also potentially more efficient than single cycle THz acceleration, where the THz–electron interaction length is limited due to the transversely injected THz pulses.[14] However, it should be noted that the THz phase velocity is very sensitive to the vacuum height outside the dielectric. To get synchronous acceleration, the height should, therefore, be controlled very carefully. For example, changing the opening angle of the vacuum region from 0.44° to 0.40° (around 10%) will lead to about 20% less energy gain. Hence, even though it is more efficient than the shifter design, the small opening angle requires higher fabrication precision than the shifter design, where a much larger angle can be used. The electron energy spread and bunch length, which are not discussed here, may become larger during acceleration. If so, they can be compensated by injecting a shorter electron bunch which can be achieved with a THz-powered buncher.[14]

In summary, we have presented a scheme for mitigating dephasing and extending interaction lengths in THz-driven accelerators by modulating the phase velocity of the THz wave inside a DLW Linac. Using phase shifters, the electron beam can be made to continuously sweep back and forth across the accelerating phase of the THz wave. Multiple shifters can be added as long as the electron beam is still within the envelope of the THz wave. This is an efficient solution and is especially important for using high-field, temporally long THz pulses to power electron acceleration in the non-relativistic regime, where the electron speed is changing dramatically. The scheme can be extended to adaptive synchronous acceleration and out performs both a straight DLW and an alternative approach using tapering of the dielectric in both interaction length and energy gain. Such a shifter can also be used to correct the dispersion-induced velocity mismatch during the THz-powered electron compression. The phase shifter proposed in this work is, of course, not the only solution for modulating the THz phase velocity. Our results clearly show that, however, significant gains can be made by engineering the longitudinal phase-velocity profile using approaches that are practically feasible. The work addresses the difficult problem of transitioning from non-relativistic to relativistic beams, which is an as-yet unsolved challenge for the field of THz-driven electron acceleration which holds great promise for future ultrafast electron sources.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Dongfang Zhang: Funding acquisition (equal); Methodology (equal); Project administration (lead); Supervision (lead); Writing – original draft (lead); Writing – review and editing (equal). **Yushan Zeng:** Formal analysis (equal); Investigation (equal); Software (equal). **Moein Fakhari:** Investigation (equal); Methodology (equal). **Xie He:** Investigation (equal); Methodology (equal). **Nicholas Hill Matlis:** Supervision (equal); Writing – review & editing (equal). **Franz X. Kärtner:** Funding acquisition (lead); Methodology (lead); Project administration (lead); Resources (lead); Supervision (lead); Writing – review and editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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[31]See CST–Computer Simulation Technology, https://www.cst.com for information about the software used.