Design of a THz-driven compact relativistic electron source

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Abstract

A THz-pulse-driven compact, < 150 mm in total length, two-stage electron accelerator setup was designed. It uses 2×2 pairs of nearly counter-propagating focused THz pulses. The effects of the initial bunch charge and the propagation direction of the THz pulses on the energy of the accelerated electrons were investigated by numerical simulations. Generation of 8 fC electron bunches with up to 340 keV energy; only 2.0% energy spread and compressed on-target duration of 200 fs is predicted using single-cycle low-frequency THz pulses with less than 4.5 mJ total energy.

1 Introduction

Conventional particle accelerator technology is based on two types of electron guns: radio-frequency (RF) and DC guns. The most important practical features of electron guns are compactness, cost, accelerating gradient, and beam quality. RF accelerators are relatively large and costly devices. They suffer from field strength and timing jitter limitations, which are below 200 MV/m and around 100 fs, respectively [1–4]. Conventional DC guns have performance limitation even at 10 MV/m owing to field emission breakdown [5]. In the quest for cost-effective solutions, laser-driven compact acceleration schemes have been proposed and demonstrated. These can provide more precise synchronization and substantially stronger fields for particle acceleration and manipulation. Laser-plasma accelerators have been extensively studied over the last few decades [6–11]. Recently, dielectric laser accelerators [12, 13] and terahertz-driven accelerators [14–17] have been emerging.

Terahertz (THz) pulses have about two orders of magnitude longer wavelength than visible or near-infrared pulses. Utilizing such long driver wavelengths enables to extend the interaction length between the particles and the electric field, potentially resulting in ultrashort electron bunches with very

high brightness and quality. Strong-field THz pulse sources up to the GV/m range have been developed in recent years [18–21], opening a new route for efficient acceleration of charged particles. This development has triggered recent work on simulation of THz-driven electron manipulation [22, 23], electron gun [24], dielectric accelerator [25, 26], and X-ray generation [27, 28]. THz-driven experiments on electron emission [29–31], acceleration [32–34], compression and streaking [34–38] have also been reported.

In this paper, a numerical design study of a compact THz-driven electron accelerator (C-TEA) setup is presented. It is based on our earlier proposal of using counter-propagating focused THz pulses for electron acceleration [39]. Here, critical technical aspects have been addressed, and the detailed simulation of the electron dynamics of the complete setup has been carried out, containing an electron gun, bunch compressors, and a post-accelerator. The emphasis is on post-acceleration to application-relevant energies, and the prediction of electron bunch energy spectra and spatial distributions.

The paper is structured as follows. The compact electron accelerator is introduced in Sect. 2. Section 3 describes the results of the numerical simulations. The first acceleration stage (electron gun) is presented in Sect. 3.1, the transversal and longitudinal bunch manipulation in Sect. 3.2, and the post-acceleration in Sect. 3.3. Section 4 concludes.

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2 The THz-driven compact electron accelerator setup

The schematic view of the proposed C-TEA setup is shown in Fig. 1. It consists of four main parts. (i) The first part is the electron gun, where the injection of electrons is accomplished by ionizing atoms in a gas jet. Two pairs of counter-propagating focused THz pulses, with electric field vectors along the z -axis, accelerate the electrons from rest to about 80 keV. (ii) In the second part, a solenoid and two pairs of THz pulses are used to reduce both the transversal and the longitudinal sizes of the bunch. The THz pulses reduce the longitudinal extent of the electron bunch; the solenoid focuses the bunch to the center of the third part. (iii) The third part is the post-acceleration stage with two pairs of focused THz beams. A retarding dielectric structure (slabs, or a cylinder with a centered hole), inserted into the beams, provide particle-field synchronization [39]. (iv) The fourth part is another bunch compression stage with a solenoid and two pairs of THz pulses. The transversal and longitudinal foci are set to the detector position. The size of the complete C-TEA is shorter than 150 mm.

Recently, a new tilted-pulse-front pumped plane-parallel slab THz source has been investigated numerically [40] and demonstrated experimentally [41]. In the first proof-of-principle experiment, single-cycle pulses with 1 μJ energy and 0.3 THz central frequency have been generated [41]. Importantly, the numerical simulations [40] and experimental results [41] indicate the straightforward scalability of such a setup to high THz pulse energies of 0.5 mJ or more. This energy level is abundantly suitable for particle accelerators. Alternatively, with the new tilted-pulse-front pumped near plane-parallel slab THz source [42], using the same pump pulse length, it is possible to

tailor the pulse-front tilt and the echelon steps size to the generation of different low THz frequency pulses with high-level energy. In our simulation, both in the electron gun as well as in the post-acceleration stages, THz pulses each of 0.5 mJ energy, and 0.3 THz mean frequency have been used to accelerate and post-accelerate the electron bunch.

For compressor stages, much less energy (nJ– μJ) is sufficient (see Sect. 3.2). Although applying here THz pulses with longer wavelength (smaller frequency) could result in more effective compression, we supposed the same THz frequency as for the accelerator stages for letting the setup less complicated. In compressor stages (ii) and (iv), four THz pulses have been used, each of 70 nJ (ii) and 2.4 μJ (iv) energy, respectively. The values of the parameters assumed in the simulations for the THz pulses in the different sections (i–iv) of the setup are listed in Table 1. The assumed THz waveforms are shown in Fig. 1 inset.

Table 1 In-focus parameters of the accelerator and compressor THz pulses

Parameter	Acceleration (both (i) and (iii))	Compression (ii)	Compression (iv)
Mean frequency	0.30 THz	0.30 THz	0.30 THz
Pulse duration	1.66 ps	1.66 ps	1.66 ps
Beam waist	1.0 mm (λ_{THz})	1.0 mm ($1 \cdot \lambda_{\text{THz}}$)	1.0 mm ($1 \cdot \lambda_{\text{THz}}$)
Pulse energy	0.5 mJ	70 nJ	2.4 μJ
Peak electric field	3.68 MV/cm	44.2 kV/cm	258 kV/cm

λ_{THz} is the wavelength corresponding to the mean frequency of the THz pulses used for acceleration and compression

Fig. 1 Scheme of the compact THz-driven electron accelerator setup with the envelope of the electron trajectories. The blue spheres illustrate the size of the electron bunch at different places. Inset: waveforms of the accelerator (red curve) and compressor (orange curve) THz pulses as assumed in the simulations

3 Results

Numerical simulations were performed using the General Particle Tracer (GPT) software [43], which also accounts for the space charge effect in three dimensions. The relativistic equation of motion for a macroparticle reads as

$$\frac{d(\gamma m \vec{v})}{dt} = F_{\text{fields}} + \sum_j F_j, \quad (1)$$

where m is the rest mass of the microparticle, γ is the relativistic factor, $\vec{v}$ is the particle velocity, and F_j is the Coulomb force between two-point charges. F_{fields} is the Lorentz force, which acts on the macroparticles due to the electromagnetic fields:

$$F_{\text{field}} = q \cdot \left(\vec{E}(x, y, z, t) + \vec{v} \times \vec{B}(x, y, z, t) \right). \quad (2)$$

Here q is the macroparticle charge. When the THz pulses act on the electron bunch, Eq. (2) is the combination of the electric field strength and magnetic induction of the superposed THz pulses, respectively. In case of the solenoid, the macroparticles perceive only the effect of the magnetic force by the solenoid magnet. For each individual THz pulse, the electric field is given by

$$\vec{E}(r, z, t) = \begin{bmatrix} E_0 \frac{w_0}{w(z)} \exp \left(-\frac{r^2}{w(z)^2} + i \left\{ kz - \omega t + k \frac{r^2}{2R(z)} - \eta(z) + \varphi \right\} \right) \\ 0 \\ -\frac{2iE_0}{k} x \frac{w_0}{w(z)} \left(\frac{1}{w(z)^2} - \frac{k}{i2R(z)} \right) \exp \left(-\frac{r^2}{w(z)^2} + i \left\{ kz - \omega t + k \frac{r^2}{2R(z)} - \eta(z) + \varphi \right\} \right) \end{bmatrix} \cdot f(z, x, t), \quad (3)$$

where r is the radial distance from the propagation axis of the THz beams (in this case the z -axis), with the focus located at $z=0$. $k = 2\pi/\lambda_{\text{THz}}$ is the wave number, λ_{THz} is the wavelength of the THz pulse, $w(z)$ is the radius at which the field amplitude falls to $1/e$ of its on-axis value, w_0 is the waist radius, $R(z)$ is the radius of wavefront curvature, $\eta(z)$ is the Gouy phase, and φ is a constant phase. A Gaussian temporal envelope, $f(z, x, t) = \exp \left(-2 \ln 2 \left(z - k \frac{x^2}{2R(z)} \frac{c}{\omega} - ct \right)^2 / c^2 \tau^2 \right)$ is taken for the THz pulse, where τ is the FWHM pulse duration, and c is the speed of light in vacuum.

3.1 Electron gun

Our calculation is based on an electron gun arrangement, which is very similar to the one proposed earlier [39]. However, instead of supposing one–one pair of driving THz beam pairs, two–two pairs was supposed. The advantage of this modification is that for the same

total energy of all THz pulses, the field acting on the electrons is $\sqrt{2}$ higher for the modified setup comparing to the original one. Our calculations show that using 2×1 mJ THz pulses, the mean energy of the uncompressed bunch is around 41 keV, and the normalized emittances are $\epsilon_{n,x} = 26.4$ nm rad and $\epsilon_{n,y} = 12.4$ nm rad, respectively. By contrast, applying 4×0.5 mJ THz pulses, at the same moment, the mean energy of the uncompressed bunch is 79.6 keV, and the normalized emittances are $\epsilon_{n,x} = 17.3$ nm rad and $\epsilon_{n,y} = 17.2$ nm rad, respectively. In conclusion, another advantage of using more THz beam pairs is the better electron beam emittance resulted by the more symmetrical arrangement.

The electrons are generated in a Kr gas jet by three-photon ionization using the focused fourth harmonic of a 1- μm wavelength femtosecond pulse. A Kr density of $3 \cdot 10^{16} \frac{1}{\text{cm}^3}$ has been assumed [44]. A gas jet is an ideal choice for an electron gun, as it easily enables the controlling of both the charge and the initial electron bunch size. In our calculation, the FWHM of the ionized sphere region in the gas jet is 33 μm . The initial bunch charge is 20 fC, which is modeled by 125,000 macroparticles.

Two pairs of counter-propagating single-cycle THz pulses create a transient standing wave and accelerate the electrons. The magnetic fields of the counter-propagat-

ing THz pulses have opposite signs, which minimize the deflection effects on the electron bunch. The birth time of the free-electron bunch in the gas jet, determined by the arrival of the ionizing laser pulse, is synchronized to the zero-crossing of the THz field. In this way, only the second, negative half-cycle of the THz electric field accelerates the electrons [39].

Our calculations show that about 80 keV electron energy can be achieved from the gun with the initial parameters mentioned above. The energy spread of the electron bunch is 1.0% for 20 fC initial bunch charge. We also examined the energy spectra of the accelerated bunch for larger initial bunch charges, while keeping the same initial bunch size of 33 μm (FWHM). The corresponding energy spectra are shown in Fig. 2. Obviously, the higher the initial charge of the electron bunch is, the more significant the space charge effect is. The energy spread of the bunch is increased, which means broader energy distribution and larger sizes in all directions. For 50 fC, 100 fC, 200 fC, and 500 fC charges (being 2.5, 5, 10, and 25 times larger than the reference 20 fC case), the width

Fig. 2 Electron energy spectra after the first accelerator stage (at $z = 34.5$ mm) for different initial bunch charges

of the energy spectrum becomes 2, 4, 5 and 9 times larger, respectively.

3.2 Focusing elements

Transversal and longitudinal bunch compression is needed to maximize the number of efficiently post-accelerated electrons and to achieve ultrashort duration and small spot size at the target point. For transversal size reduction, multilayered solenoids have been used. The on-axis magnetic field has been calculated with finite-element analysis software (Comsol). By considering practical dimensions of the solenoid, a position at 17.5 mm behind the gun has been chosen for the center of the first solenoid (Fig. 1). The center of the second solenoid has been installed at 17.5 mm distance behind the

second acceleration stage. Assuming 8.0 A and 18.7 A currents, the field strengths of the first and the second solenoids are 0.15 T and 0.35 T, respectively. The number of coils is 300, the length of the solenoids is 15 mm, the internal radius is 4.25 mm, and the outer radius is 9.25 mm. A wire diameter of 0.5 mm was used.

The first longitudinal bunch compression is accomplished at a distance of 35.0 mm behind the gun by two pairs of counter-propagating focused THz pulses, each of 0.3 THz central frequency (Fig. 1). Their polarization directions are identical with those of the accelerator THz pulses, but the polarity is reversed (Fig. 1 inset). Electrons with higher kinetic energies (at the leading edge of the electron bunch) from the first acceleration stage are synchronized to the peak of the decelerating part of the THz pulses. Medium-energy electrons around the center of the bunch see the zero-crossing of the THz field, whereas the slowest electrons see the accelerating part of the THz pulses. In this case, faster electrons are going to slow down, and the slower ones are going to accelerate. A similar four-pulse THz compressor is used after the post-acceleration stage at a position of 110 mm behind the gun (Fig. 1).

The modification of the phase-space distribution significantly reduced the electron bunch durations (from 1233 to 667 fs) at the post-acceleration stage ($z = 75.0$ mm, Figs. 1 and 3a) and at the target ($z = 147$ mm, Figs. 1 and 3b).

3.3 Post-acceleration

Post-acceleration of the compressed electron bunch is possible in a similar geometry, by using two pairs of synchronized focused THz pulses and so a multistage acceleration structure can be realized. To eliminate the effect of the decelerating part of the THz pulses, a lithium niobate (LN) holey

Fig. 3 **a** Phase-space distribution of the bunch before longitudinal compression (red dots) and after compression at the post-acceleration stage (blue dots). **b** Phase-space distribution of the efficiently accelerated electrons at the target point

cylinder was used with 2 mm length in the z-direction and 1.5 mm and 0.5 mm outer and inner diameters, respectively (other materials should also be appropriate, for instance, small TPX and PMMA). The THz pulses were focused to the edge of the LN crystals, which delayed the positive (decelerator) half-cycle of the THz pulses, while the negative (accelerator) half-cycle was passing by in free space [39]. The propagation of the THz pulses through and around the LN cylinder was calculated by COMSOL Multiphysics (see Ref. [39]) which takes into account the diffraction effect. Consequently, the decelerating half cycles of the pulses are not able to interact with the electron bunch. On the other hand, the arrival time of the accelerating half-cycle of the THz pulses to the interaction region coincides with the arrival time of the electrons. The post-acceleration stage is placed at 75.0 mm behind the gun (Fig. 1).

The kinetic energy gain of the electrons can be increased by tilting the propagation direction of the THz beams (Fig. 4a). There is a trade-off between increasing the interaction length and reducing the z-component of the field (Fig. 4a inset) with increasing tilt angle θ . Based on our calculations, in the case of 80 keV initial electron energy, the optimal value of the tilt angle is $\theta = 40^\circ$. Using accordingly tilted THz beams, the energy gain of post-acceleration is increased by 38%, to 349 keV maximum kinetic energy, to be compared to about 253 keV at $\theta = 0^\circ$.

For the sake of completeness, it should be pointed out that the higher the initial kinetic energy is, the more significant the positive effect of THz beam tilting is. According to our calculations using 4×0.5 mJ THz pulse energy and optimal tilt angles, in case of 0, 30, 100, 500, 1000, 2000 keV initial electron energies, the energy gain is 86, 200, 306, 685, 1046

and 1465 keV, which exceeds the $\theta = 0^\circ$ case energy gains by 6, 44, 106, 425, 771 and 1180 keV, respectively (Fig. 4b).

After the second acceleration stage, 41% of the initial number of the electrons can achieve at least 340 keV energy with a relative energy spread ($\Delta E/E$) as small as 2.0% (Fig. 5a). These electrons have a mean energy of ~ 346 keV. Taking advantage of the second compression stage, the transversal size of the bunch of these efficiently accelerated electrons can be reduced at the target to 83 μm and the longitudinal size to about 48 μm (corresponding to ~ 200 fs bunch duration), both FWHM (Fig. 5b).

4 Conclusion

A numerical design study has been presented on the acceleration and temporal compression of electrons by counter-propagating pairs of focused THz pulses. The compact two-stage electron accelerator has a total length of less than 15 cm and is driven by single-cycle THz pulses with a total energy of less than 4.5 mJ. The required THz pulse parameters can be provided by presently available THz technology.

The dependence of the electron gun energy spectrum on the bunch charge has been investigated. The simulations predict the production of electron bunches with 20 fC charge, 80 keV energy, and 1.0% relative energy spread from the electron gun. The transverse emittance in the horizontal and vertical directions is $\varepsilon_{x,y,n} = 49$ nm rad.

In the post-acceleration stage, the optimization of the propagation direction of the accelerating THz pulses has been carried out for different input electron energies. Utilizing electron beam spatial and temporal focusing by magnet and bunch compression technique by THz pulses,

Fig. 4 **a** The final kinetic energies of the electron for different θ angles. Inset: electron energy as a function of the propagation distance for $\theta = 0^\circ$ (black curve) and $\theta = 40^\circ$ (red curve), showing an increased interaction length between the particle and the electric field

in the latter case. **b** Optimal tilt angles (black curve) and the corresponding electron energy gains (red curve) as a function of initial electron energy. Inset: dependence of the ratio of the energy gains for optimal θ and for the $\theta = 0^\circ$ case

Fig. 5 **a** The energy spectra after the first (black curve) and after the second (red curve) acceleration stage. **b** Longitudinal distribution of the electron bunch at the target point. Inset: transversal distribution at the same position

post-acceleration boosts the electron energy to 346 keV with 2.0% relative energy spread, 200 fs bunch duration, and 8 fC charge. The transverse emittance in the horizontal and vertical directions is around $\epsilon_{x,y,n} = 600$ nm rad. The predicted ultrashort electron bunches with narrow energy distribution are well suited for ultrafast time-resolved electron diffraction measurements and for further acceleration to still higher energies. Ultrafast electron microscopy and diffraction provide atomic-scale spatial and femtosecond temporal resolution [45–48]. Besides, ultrashort electron bunches make possible X-ray diffraction studies and experiments with a free-electron laser [49].

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