UNIVERSITY OF PÉCS

Doctoral School of Physics

Nonlinear optics and spectroscopy program

Simulations of particle acceleration by terahertz pulses

PhD Theses

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PÉCS, 2022

1. Introduction

In the last two decades, the science of THz has undergone significant development, providing many new opportunities for efficient acceleration and manipulation of charged particles. The widespread applicability of THz based techniques and devices was made possible by the advent of THz sources based on femtosecond ($1 \text{ fs} = 10^{-15}$ s) lasers. Over the last decade, the energy of THz pulses generated by different techniques has increased by about 7 orders of magnitude, reaching 1 mJ of energy as well as a peak electric field strength of 100 $\frac{\text{MV}}{\text{cm}}$ [1].

In the study of the electromagnetic spectrum, the area between the radio wave and the infrared range has not been researched for a long time in terms of applications. This is the so-called terahertz range, which still has many advantages in the field of particle acceleration. Its advantages include the relatively long wavelength relative to lasers operating in the near-infrared range, which play a major role in time synchronization. In addition, the use of terahertz radiation allows waveguides and dielectric structures designed to increase acceleration efficiency to be machined by conventional techniques. Other advantages of a particle accelerator powered by terahertz radiation include a charge that can be varied in the range of a few fC to a few nC. In parallel with the development of THz sources, significant advances in particle manipulation with THz pulses [2-8], laser-driven particle accelerators [9, 10], dielectric particle acceleration [11-13], and X-ray generating techniques and devices was observed [14, 15]. The continuous development is well illustrated by the recent simulation and practical applications obtained by experimental equipment in the fields of electron emission [16, 17], electron acceleration [18-21], electron bunch compression [22, 23] and so-called streaking [24, 25].

Over the past few decades, many new ideas and practical implementations have emerged to increase the acceleration efficiency of particle accelerators powered by THz radiation. In my doctoral dissertation, in addition to the models we propose [2, 3], I present some of these, which predict final kinetic energies of MeV for electrons using a few mJ ─ a few tens of mJ THz pulses available in the near future.

2. Aims and Objectives

The design and optimization of a compact tabletop size particle accelerator is possible by determining the optimal values for several parameters. My task is primarily to determine these parameters using numerical software. My tasks also include optimizing the models and preparing for the experimental implementation of the parameterized compact electron accelerator.

To achieve adequate efficiency acceleration, it is essential to generate a high-energy THz pulse with a peak field strength of a few ─ a few 10 MV/cm and a near-single-cycle pulse shape. Increasing the peak electric field strength is possible by strong focusing. In this dissertation, I aim to study in detail the focusing of THz radiation and its effect on both the THz beam as well as the electron acceleration efficiency.

An additional condition for achieving the appropriate acceleration efficiency is the adjustment of the wavelength of the THz radiation to the size of the initial electron bunch. In my numerical simulations this typically means the applicability of a few 10-100 micrometer bunch sizes, i.e., a maximum central frequency radiation of about 0.1 ─ 1 THz. In my work, I aim to observe the effects of changing the initial bunch size and the initial bunch charge and to determine the optimal parameters in regard to the final spatial distribution and energy spectra of the accelerated electron bunch for THz pulses of different frequencies.

In addition, I aim to investigate the effects of changing the carrier-envelope phase of single-cycle pulses and to determine the optimal parameter to maximize the final kinetic energy of the electrons. I further aim to study the effects of changing the number of THz pulses and their propagation direction with respect to the acceleration gradient.

Another main goal of my research is to investigate the optimization of the post-acceleration of an electron and an electron bunch. After studying the techniques applicable to transverse bunch compression, I aim to investigate the focusing effect of a multilayer magnetic coil. After studying the longitudinal bunch compression techniques using THz radiation, I focus to explore the limits of longitudinal compression of the electron bunches with different initial energies and different initial sizes. My another goal is to optimize the parameters required to focus the electron bunch predicted by the particle accelerator I designed.

3. New Scientific Results

I. Via my computer simulations I have shown that using two counterpropagating THz pulses by synchronizing both the arriving time of the THz pulses to the interaction region and the birth time of the electrons, the resting (<10 eV kinetic energy) electrons can be accelerated to a few tens and a few hundreds of keV energies. I determined the effect of the size of the beam waist on the final kinetic energy of the electrons. Using my numerical simulations, I have shown that after the acceleration, the kinetic energy of the electrons is proportional to the inverse of the square of the beam waist. I performed my simulations with pulses with a central frequency of 0,14 THz, 0,3 THz, 0,7 THz and 3,0 THz, with a nearly single-cycle pulse shape and a mJ energy. I have shown that the kinetic energies of the electrons are 28 keV, 41 keV, 75 keV and 133 keV for the studied pulses. [S2].

II. With the help of my numerical simulations, I have shown that the acceleration efficiency of the initially rest electron can be increased by tilting the propagation direction of the initially counterpropagating terahertz pulses (to the opposed direction with the propagation direction of the electrons). In case of the pulses with a central frequency of 0,14 THz, 0,3 THz, 0,7 THz and 3,0 THz, with a nearly single-cycle pulse shape and the energy of 1 mJ, I determined the optimal tilt angle and the final kinetic energies that can be generated for a single electron. The optimal tilt angles for the pulses with a center frequency of 0,14 THz, 0,3 THz, 0,7 THz and 3,0 THz are as follows: 8 °, 10 °, 15 °, 20 °, while the relative energy growths are 1,0 keV, 2,4 keV, 6,4 keV and 20,5 keV, respectively. In the case of the pulse with 3,0 THz center frequency, I obtained the largest relative energy increase, which is 15 % compared to the case determined by the pulses propagating perpendicular to the preferred direction of the electrons [S2].

III. I have investigated the effects of the carrier-envelope phase value changing of the pulses on the final kinetic energy of the electrons in case of the electron acceleration achieved by THz pulses with a central frequency of 0,14 THz, 0,3 THz, and 0,7 THz. Based on my numerical simulations, I determined the optimal value of the carrier-envelope phases and the maximum electron energies thus obtained. Assuming a pulse energy of 1 mJ, the optimal tilt angles (8°, 10°, 15°) and focusing on a wavelength for the pulses with a central frequency of 0,14 THz, 0,3 THz and 0,7 THz, the optimum values for the initial phases are -29 °, 36 ° and -49 °, while the achieved relative energy gains are 10 %, 35 % and 20%, respectively [S2].

IV. I have shown with my numerical simulations that our proposed arrangement is also suitable for post-acceleration of the electrons, which have initial kinetic energies in the case where by covering the corresponding part of the focused THz pulse spot ─ which can be achieved by a fabricated flans from material of lithium niobate, poly (methyl methacrylate), polymethyl pentene or metal ─ we can reduce the effect of the electric field strength components that have a negative effect on the acceleration. During my optimization process, I determined both the optimal THz pulse tilt angles for the initial electron energies of 30 keV, 100 keV, 500 keV, 1000 keV and 2000 keV and the resulting electron energy increases in case of the post-acceleration achieved by two pairs of THz pulses with a central frequency of 0,3 THz. I assumed 0,5 mJ pulse energy and focusing to the wavelength. The optimal tilt angles are 35 °, 45 °, 68 °, 75 °, and 79 °, and the relative energy increases are 44 keV, 106 keV, 430 keV, 771 keV, and 1205 keV, respectively [S1, S2].

V. Using numerical simulations, I have investigated the dependence of the energy spread of the electron bunches (accelerated by our proposed arrangement) on the initial charge of a bunch at a constant initial bunch size. In the case of the arrangement, two pairs of THz pulses propagate opposite each other and accelerate electron bunches with different charge densities and a constant size of 33 µm (FWHM). After the electron gun, the average kinetic energy of the electron bunch with a charge density of 64,3 $\frac{nC}{cm^3}$ is 80 keV and its energy spread is 1.0 %. With the help of my simulation results I showed that by increasing the charge density initially determined at 64,3 $\frac{nC}{cm^3}$ by 2,5, 5, 10 and 25 times, the width of the final energy spectrum is 2, 4, 5 and 9 times greater. By reducing the charge density to fourth there is not significant difference between the width of the energy spectrum, it is about 1% [S1].

VI. My numerical investigations show that the arrangement we proposed is also suitable for longitudinal compression of the electron bunches. I have shown that using terahertz pulse the longitudinal compression of electron beams, propagating at around half the speed of light (80 keV) and at an average speed corresponding to 80 % of the speed of light (346 keV), is possible. I assumed two pairs of THz pulses with a central frequency of 0,3 THz propagating opposite each other and they propagate perpendicular to the propagation direction of the electron beams. In case of the electron bunch with the average energy of 80 keV, the initially measured 1233 fs bunch duration was nearly halved to 667 fs, while the beam duration of the electron bunch with average energy of 346 keV was reduced from 667 fs to 200 fs, so it becomes less than a third. Longitudinal compression of the electron beams is important in increasing the post-acceleration efficiency and achieving the ultra-short beam duration predicted by our proposed particle accelerator [S1].

List of Publications

Own publications

During my four years of research work, my results have been presented 27 times at international and domestic conferences.

i. Own publications related to the dissertation

a) Publications in peer-reviewed journals

[S1] **Sz. Turnár**, J. Hebling, J.A. Fülöp, Gy. Tóth, G. Almási, Z. Tibai, „Design of a THz-driven compact relativistic electron source", Applied Physics B, **127**, 38 (2021).

[S2] Z. Tibai, M. Unferdorben, **Sz. Turnár**, A. Sharma, J.A. Fülöp, G. Almási, J. Hebling, „Relativistic electron acceleration by focused THz pulses", Journal Physics B: At. Mol. Opt. Phys. **51** 134004 (8pp) (2018).

b) Presentations

[E1] L. Pálfalvi, Z. Tibai, J. A. Fülöp, Gy. Tóth, G. Krizsán, **Sz. Turnár**, G. Almási, J. Hebling,

„Application Possibilities of High Energy Terahertz Pulses in Particle Acceleration”, In: [s.n.] (szerk.) Kvantumelektronika 2018: VIII. Szimpózium a hazai kvantumelektronikai kutatások eredményeiről Budapest, Magyarország, 2018.06.15 Pécs: Pécsi Tudományegyetem Természettudományi Kar (PTE TTK), 2018. Paper E-7. 2p. (ISBN:978-963-429-250-0).

[E2] Z. Tibai, M. Unferdorben, **Sz. Turnár**, A. Sharma, B. Kovács, J. A. Fülöp, G. Almási, J. Hebling, „THz-pulse-driven electron post-accelerators” In: The Optical Society (szerk.) High Intensity Lasers and High Field Phenomena (HILAS): Proceedings High-Brightness Sources and Light-driven Interactions Strasbourg, Franciaország, 2018.03.26 -2018.03.28. Washington: The Optical Society, 2018. Paper HM3A.4. (Optics InfoBase Conference Papers), (ISBN:978-1-943580-40-8).

[E3] **Turnár Szabolcs**, Tibai Zoltán, Ashutosh Sharma, Almási Gábor, Fülöp József, Hebling János, „THz-driven electron acceleration setup in vacuum”, (dof)φ -A Fizikus Doktoranduszok Konferenciája (DOFFI 2018), június 14. - június 18. (2018), Balatonfenyves.

[E4] **Turnár Szabolcs**, Ashutosh Sharma, Fülöp József, Almási Gábor, Hebling János, Tibai Zoltán, „Compact THz-driven electron accelerators”, Hamburg, 8th Topical Workshop on Longitudinal Diagnostics for FELs, Június 25 - Június 28 (2018).

[E5] Tibai Zoltán, **Turnár Szabolcs**, Ashutosh Sharma, Almási Gábor, Fülöp József, Kovács Bálint, Hebling János, „Compact Setup for Electron Acceleration by Intense THz Pulses”, Bécs, EMN Meeting on Vacuum Electronics, (EMN 2018), Június 18 - Június 22 (2018).

[E6] **Turnár Szabolcs**, Kovács Bálint, Fülöp József, Almási Gábor, Hebling János, Tibai Zoltán, „Electron acceleration based on THz pulses”, Pécs, XVI. János Szentágothai Multidisciplinary Conference and Student Competition, Február 14 – Február 15. (2019), Pécs, Magyarország.

[E7] **Turnár Szabolcs**, Kovács Bálint, Fülöp József, Almási Gábor, Hebling János, Tibai Zoltán, „Possibilities of electron acceleration based on THz pulses”, 5th International Cholnoky Symposium, Április 25 – 26. (2019), Pécs, Magyarország.

ii. Other publications

a) Publications in peer-reviewed journals

[S3] **Turnár Szabolcs**, Krizsán Gergő, Hebling János, Tibai Zoltán, „Waveguide structure based electron acceleration usin THz pulses”, Optics Express, accepted (2022)

[S4] Zoltán Tibai, **Szabolcs Turnár**, György Tóth, János Hebling, Spencer W. Jolly, „Spatiotemporal modeling of direct acceleration with high-field terahertz pulses”, Optics Express, accepted (2022)

[S5] Gy. Tóth, L. Pálfalvi**, Sz. Turnár**, Z. Tibai, G. Almási and J. Hebling, “Performance comparison of lithium-niobate-based extremely high-field single-cycle terahertz sources,” Chinese Opt. Lett. 19, 111902 (2021).

[S6] Tibai Zoltán, **Turnár Szabolcs**, Kovács Bálint, Pálfalvi László, Almási, Gábor, Hebling, János, Részecskegyorsítás extrém nagy térerősségű terahertzes impulzusokkal, FIZIKAI SZEMLE 71: 2 pp. 47-52., 6 p. (2021).

Bibliography

[1] Gyula, P., *Extrém nagy hatásfokú félvezető anyagú terahertzes források.* 2018.

[2] Tibai, Z., et al., Relativistic electron acceleration by focused THz pulses. Journal of Physics B: Atomic, Molecular and Optical Physics, 2018. **51**(13): p. 134004.

[3] Turnár, S., et al., *Design of a THz-driven compact relativistic electron source.* Applied Physics B, 2021. **127**(3): p. 1-7.

[4] Fallahi, A., et al., Short electron bunch generation using single-cycle ultrafast electron guns. Physical Review Accelerators and Beams, 2016. **19**(8): p. 081302.

[5] Nanni, E.A., et al., *Terahertz-driven linear electron acceleration.* Nature communications, 2015. **6**(1): p. 1-8.

[6] Hebling, J., et al., *Optical manipulation of relativistic electron beams using THz pulses.* arXiv preprint arXiv:1109.6852, 2011.

[7] Huang, W.R., et al., *Toward a terahertz-driven electron gun.* Scientific reports, 2015. **5**(1): p. 1-8.

[8] Huang, W.R., et al., *Terahertz-driven, all-optical electron gun.* Optica, 2016. **3**(11): p. 1209-1212.

[9] Wong, L.J., et al., *Laser-induced linear-field particle acceleration in free space.* Scientific reports, 2017. **7**(1): p. 1-9.

[10] Carbajo, S., et al., *Direct longitudinal laser acceleration of electrons in free space.* Physical Review Accelerators and Beams, 2016. **19**(2): p. 021303.

[11] Tibai, Z., et al. *THz-pulse-driven particle accelerators*. in *4th EOS Topical Meeting on Terahertz Science & Technology*. 2014.

[12] Wei, Y., et al., *Investigations into dual-grating THz-driven accelerators.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2018. **877**: p. 173-177.

[13] Plettner, T., P. Lu, and R. Byer, *Proposed few-optical cycle laser-driven particle accelerator structure.* Physical Review Special Topics-Accelerators and Beams, 2006. **9**(11): p. 111301.

[14] Kaertner, F.X., et al., *AXSIS: Exploring the frontiers in attosecond X-ray science, imaging and spectroscopy.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2016. **829**: p. 24-29.

[15] Vinatier, T., et al. *Beam dynamics in THz dielectric-loaded waveguides for the AXSIS project*. in *Journal of Physics: Conference series*. 2017. IOP Publishing.

[16] Li, S. and R. Jones, *High-energy electron emission from metallic nano-tips driven by intense single-cycle terahertz pulses.* Nature communications, 2016. **7**(1): p. 1-7.

[17] Wimmer, L., et al., *Terahertz control of nanotip photoemission.* Nature Physics, 2014. **10**(6): p. 432-436.

[18] Curry, E., et al., *THz-driven zero-slippage IFEL scheme for phase space manipulation.* New Journal of Physics, 2016. **18**(11): p. 113045.

[19] Wong, L.J., et al., *Laser-induced linear-field particle acceleration in free space.* Scientific reports, 2017. **7**(1): p. 1-9.

[20] Fakhari, M., A. Fallahi, and F.X. Kärtner, *THz cavities and injectors for compact electron acceleration using laser-driven THz sources.* Physical Review Accelerators and Beams, 2017. **20**(4): p. 041302.

[21] Hibberd, M.T., et al., *Acceleration of relativistic beams using laser-generated terahertz pulses.* Nature Photonics, 2020. **14**(12): p. 755-759.

[22] Zhao, L., et al., *Femtosecond relativistic electron beam with reduced timing jitter from THz driven beam compression.* Physical review letters, 2020. **124**(5): p. 054802.

[23] Othman, M.A., et al., *Parallel-plate waveguides for terahertz-driven MeV electron bunch compression.* Optics express, 2019. **27**(17): p. 23791-23800.

[24] Zhang, D., et al., *Segmented terahertz electron accelerator and manipulator (STEAM).* Nature photonics, 2018. **12**(6): p. 336-342.

[25] Fabiańska, J., G. Kassier, and T. Feurer, *Split ring resonator based THz-driven electron streak camera featuring femtosecond resolution.* Scientific reports, 2014. **4**(1): p. 1-6.