ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLO11

SINGLE CYCLE THz ACCELERATION STRUCTURES*

S.V. Kuzikov†, S.P. Antipov, E. Gomez, Euclid Techlabs LLC, Bolingbrook, IL, USA
A.A. Vikharev
Institute of Applied Physics of Russian Academy of Sciences, Nizhny Novgorod, Russia

Abstract

Recently, gradients on the order of 1 GV/m have been obtained in the form of single cycle (~1 ps) THz pulses produced by the conversion of a high peak power laser radiation in nonlinear crystals (~1 mJ, 1 ps, up to 3% conversion efficiency). These pulses however are broadband (0.1-5 THz) and therefore a new accelerating structure type is required. For electron beam acceleration with such pulses, we propose arrays of parabolic focusing micro-mirrors with common central. These novel structures could be produced by a femtosecond laser ablation system developed at Euclid Techlabs. This technology had already been tested for production of several millimetres long, multi-cell structures which has been tested with electron beams. We also propose use of these structures where necessary GV/m E-fields are excited by a drive bunch travelling in a corrugated waveguide. The radiated by drive bunch sequence of short-range delayed wakes are guided in this case by metallic disks and reflected back being focused exactly at the time when the witness bunch arrives.

BROAD BAND THz ACCELERATING STRUCTURES

High-field single cycle THz pulses are now produced by means of laser light rectification in a nonlinear crystal [1]. Such pulses can potentially provide ~1 GV/m acceleration of sub-picosecond bunches. In [2-6], a new accelerating structure design was proposed, which introduces a set of waveguides with different adjusted lengths.

Concept of Delay Waveguides

Accelerating structure design is based on empty waveguides with different adjusted lengths, in which the synchronism of accelerated particles with transversely propagating picosecond THz pulse is to be sustained (Fig. 1).

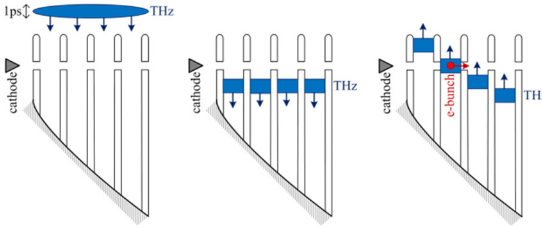

Figure 1: Sketch of particle acceleration in a structure by picosecond THz pulse for three sequent time frames.

Dielectric Delay Concept

This concept exploits inserted dielectric slabs of different lengths, in which the synchronism of accelerated particles with transversely propagating single-cycle THz pulse is sustained (Fig. 2). In the transverse direction, the accelerating structure introduces focusing parabolic mirrors (Fig. 3). These mirrors enhance the accelerating field seen by electrons by a factor of 3-10 times. Such design allows for an overall reduction of losses and mitigation of the negative action of frequency dispersion in the waveguide, because most pathway of THz pulse propagation lies in a wide waveguide. The THz pulse is focused in at the very end of the structure.

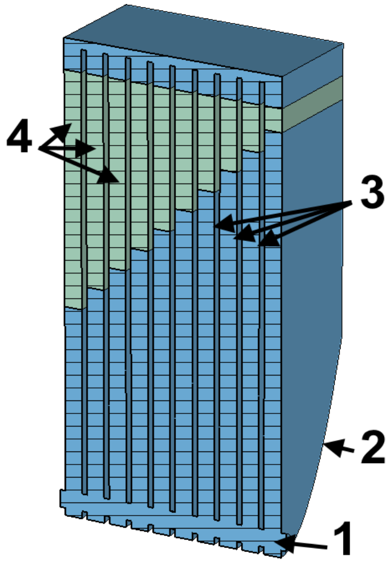

Figure 2: Sketch of broad band THz structure based on dielectric delay waveguides: 1 – beam channel, 2 – mirrors of the parabolic shape, 3 – oversized vacuum waveguides, 4 – delay waveguides filled with dielectrics.

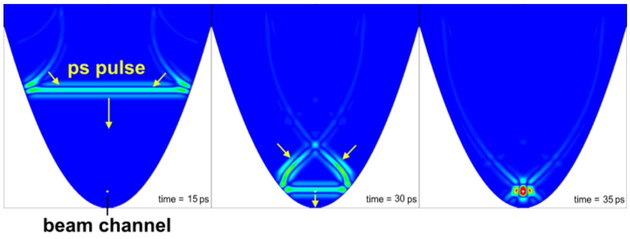

Figure 3: E-field distributions at the parabolic mirror while focusing the short THz pulse, for the time correspondent to beginning of focusing at t=15 ps (left), for time when focusing is close to maximum at t=30 ps (center), and in maximum of focusing (right) at t=35 ps.

---

* This work was supported by the Russian Science Foundation under Grant 19-42-04133 in the part of beam dynamics simulations for THz structures.

† s.kuzikov@euclidtechlabs.com

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLO11

The structure in Fig. 2 consists of the identical parabolic mirrors described above. The structure is fed by a single-cycle THz pulse propagating in parallel to metallic blades where the E-field is perpendicular to these blades (Fig. 4).

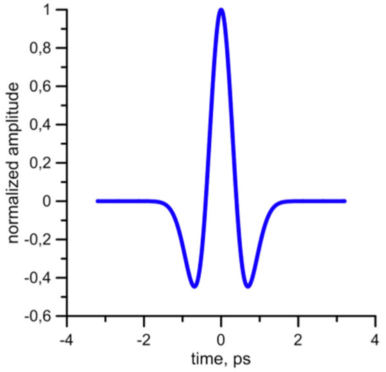

Figure 4: Single cycle THz pulse shape.

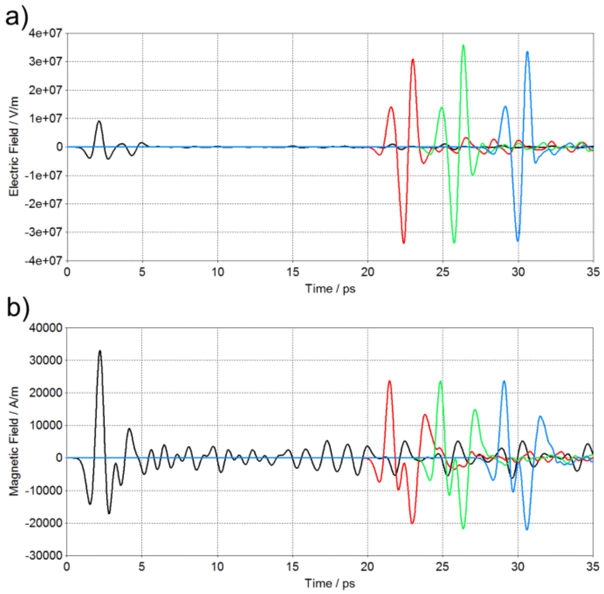

Figure 6: Electric (a) and magnetic (b) fields at axis of beam pipe: field of incident pulse (black curve), field in 1st cell (red), in 5th cell (green), in 10th cell (blue).

Leading into the parabolic mirrors there are dielectric plate delay lines that provide necessary synchronism of a short electron bunch flying through the structure. That is why, neighbouring dielectric plates have incrementally decreasing lengths counting from the left side to the right side. The mentioned increment is given by:

$$\Delta = \frac{P}{\sqrt{\varepsilon - 1}}, \tag{1}$$

where ε - is dielectric permittivity, P – is a period of the structure.

Fields and a bunch in the accelerating structure are shown in Fig. 5 for sequent time points. Here the bunch flies from left to right, and time proceeds from left to right as well. Beam pipe diameter was chosen as much less than cell length, in order to not perturb the THz pulse focusing and to prevent a considerable power leakage along the whole structure.

Figure 6 shows the incident pulse field distribution before parabolic mirrors and the fields in the 1st, 5th, and 10th cells, correspondingly. Note that the maximum accelerating electric fields in the cells are almost 3.5 times higher than the incident pulse field. The magnetic field in each cell is closer to zero than the corresponding electric fields maxima so that deflection forces at structure's axis are remarkably low.

Beam Dynamics Simulations

Beam dynamics were simulated using CST Microwave Studio. For simulations, we used the structure parameters shown in the Table 1, and the bunch parameters: 1pC charge, initial energy 10 MeV, bunch length 0.15 mm, bunch diameter 50µm.

In this simulation, the maximum of the electric field in a cell was as high as 500 MV/m. As one can see in the Fig. 7, the electron bunch was accelerated up to energy more than 10.4 MeV, in accordance with our expectations.

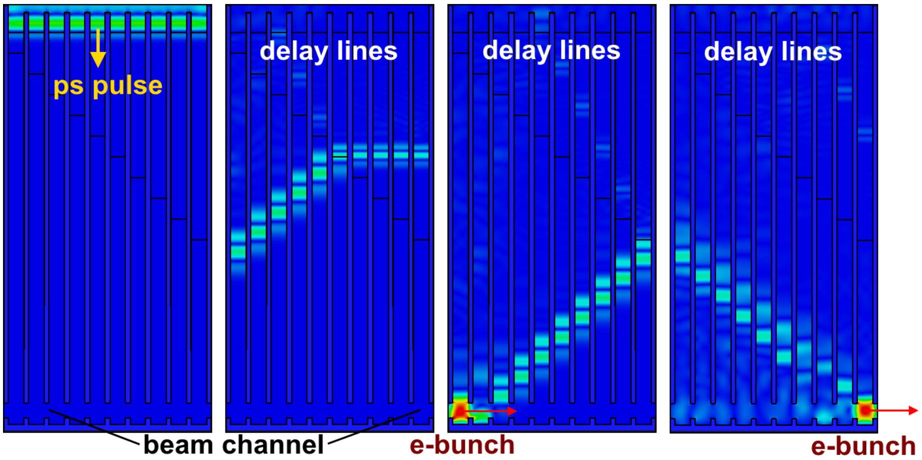

Figure 5: Front view of dielectric delay line THz accelerating structure (time proceeds from left to right).

Table 1: Parameters of THz Accelerating Structure Fed by 1 ps THz Pulses:

Parameters	Value
Number of cells	10
Dielectric permitivity	3.75
Cell length	0.26 mm
Beam pipe diameter	0.1 mm
Focal length	0.16 mm
Iris thickness	0.06 mm
Width	2.5 mm
Length	2.6 mm

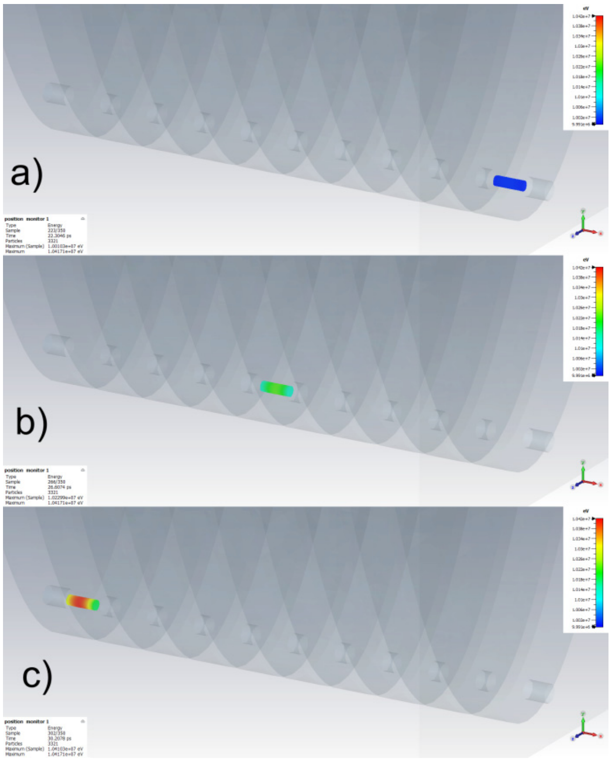

Figure 7: Bunch acceleration for three sequent time frames: a – bunch enters the first cell (t=22 ps), b – bunch crosses middle line (t=26 ps), c – bunch arrives the end (t=30 ps).

Production Technology

The described broad band THz structure could be produced by a femtosecond laser ablation system developed at Euclid Techlabs. This technology has already been tested for production of a 270 GHz Photonic Band Gap (PBG) structure made of high resistivity silicon. The prototype structure of 2.5 mm length was produced using this fs laser ablation technology (Fig. 8).

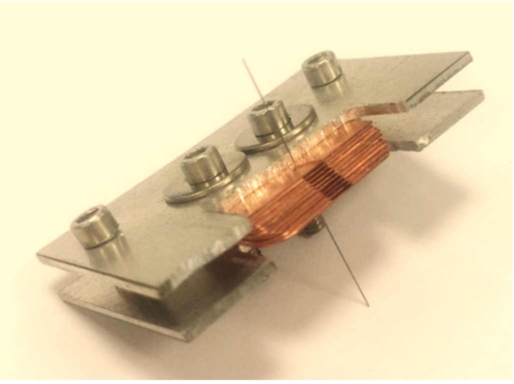

Figure 8: First prototype produced from stack of copper parabolic waveguides.

This structure was compiled from 10 copper plates. On each plate we ablated the parabolic mirror and the hole for electrons. Then all the plates were joined together so that the holes aligned for the common channel for the e-beam. In Fig. 8, one can see the ∅0.2 mm rod which demonstrates that all holes were well lined up.

CONCLUSION

The highest acceleration gradients (~GV/m level) could be reached using picosecond single-cycle THz pulses produced by the conversion of laser radiation in nonlinear organic crystals. The proposed structures have a strong ability to provide a high absolute value of accelerated electrons.

REFERENCES

[1] C. Vicario, A. V. Ovchinnikov, S. I. Ashitkov, M. B. Agranat, V. E. Fortov, and C. P. Hauri, “Generation of 0.9-mJ THz pulses in DSTMS pumped by a Cr:Mg2SiO4 laser,” Opt. Lett., vol. 39, No. 23, pp. 6632–6635, 2014. `https://doi.org/10.1364/OL.39.006632`

[2] S. V. Kuzikov, A. E. Fedotov, N. Yu. Peskov, A. N. Stepanov, A. A. Vikharev, “Millimeter and submillimeter-wave, high-gradient accelerating structures”, *AIP Conf. Proc.*, vol. 1812, p. 060002, 2017. `https://doi.org/10.1063/1.4975869`

[3] S. V. Kuzikov, S. Shchelkunov, A. A. Vikharev, “Concepts for a Short Wavelength rf Gun”, *AIP Conf. Proc.*, vol. 1812, p. 080005, 2017. `https://doi.org/10.1063/1.4975891`

[4] Yu. A. Sergeev *et al*,“Strong terahertz fields: interaction with condensed matter and electron acceleration” *EPJ Web Conf.*, vol. 149, p. 05009, 2017. `https://doi.org/10.1051/epjconf/201714905009`

[5] S. V. Kuzikov, S. P. Antipov, O. A. Ivanov, A. A. Vikharev, and A. L. Vikharev, “Novel Concepts of a High-Brightness Photoinjector RF Gun”, in *Proc. 38th Int. Free Electron Laser Conf. (FEL'17)*, Santa Fe, NM, USA, Aug. 2017, pp. 397-400. `https://doi.org/10.18429/JACoW-FEL2017-WEA04`.

[6] S. Kuzikov, S. Antipov, A. Vikharev, Y. Danilov and E. Gomez, "Quasi-Optical THz Accelerating Structures," *2018 IEEE Advanced Accelerator Concepts Workshop (AAC)*, Breckenridge, CO, USA, 2018, pp. 1-5. `https://doi.org/10.1109/AAC.2018.865943`