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ENERGY GAIN MEASUREMENT FOR ELECTRONS ACCELERATED IN A SINGLE-CYCLE THz STRUCTURE*

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Abstract

Gradients on the order of 1 GV/m have been obtained via 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). For electron beam acceleration with such broadband (0.1-5 THz) pulses, we propose arrays of parabolic focusing micro-mirrors with common central. To measure energy gain of electrons in the THz structure we propose applying a voltage (up to 400 kV) to the structure respecting the cathode and anode. Electrons become preliminary accelerated at the entrance that makes design of the structure simpler, because velocity of particles is near to be constant and almost equals the speed of light. On the other hand, the anode can be reached only by the electrons accelerated in the THz field so that one can directly measure the resulting energy gain at the anode.

SINGLE-CYCLE THz STRUCTURES

High-field single cycle THz pulses are now produced by means of laser light rectification in a nonlinear crystal [1-2]. Such pulses can potentially provide ~1 GV/m acceleration of sub-picosecond bunches. In [3-8], a new accelerating structure design was proposed, which introduces a set of waveguides with different adjusted lengths.

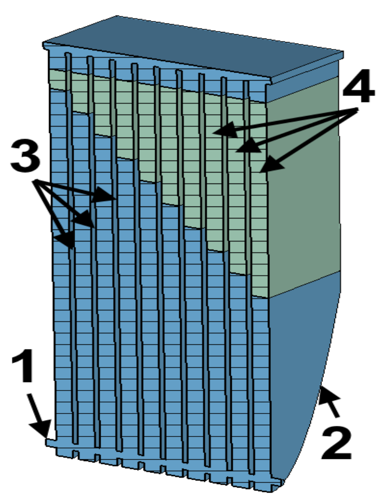

Figure 1: Sketch of broad band THz structure based on dielectric delay waveguides: 1 – beam channel, 2 – mirrors of the parabolic shape, 3 – oversized vacuum waveguides, 4 – delay waveguides filled with dielectrics.

Accelerating structure design is based on waveguide array with different adjusted delays, in which the synchronism of accelerated particles with transversely propagating picosecond THz pulse is to be sustained (Figure 1). Inserted dielectric slabs of the different lengths provide the synchronism of the accelerated particles with transversely propagating single-cycle THz pulse (Figure 2). In the transverse direction, the accelerating structure introduces focusing parabolic mirrors. These mirrors enhance the accelerating field seen by electrons by several 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 oversized waveguide. The THz pulse is focused in at the very end of the structure.

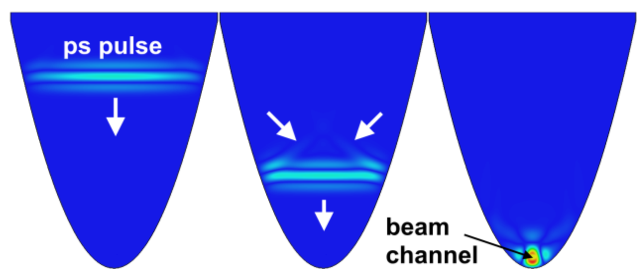

Figure 2: E-field distributions at the parabolic mirror while focusing the short THz pulse, for the time correspondent to beginning of focusing at t=3.6 ps (left), for time when focusing is close to maximum at t=7.6 ps (center), and in maximum of focusing (right) at t=11.6 ps.

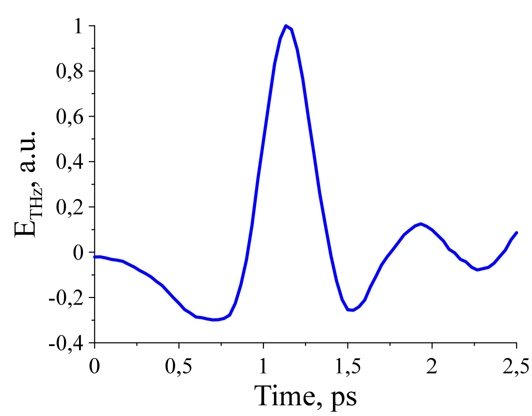

Figure 3: Experimental oscillogram of the single cycle THz pulse shape.

The structure in Figure 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.

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The experimental oscillogram of the single cycle THz pulse obtained in Institute of Applied Physics is shown in Figure 3.

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, neighboring dielectric plates have incrementally decreasing lengths counting from the left side to the right side. The mentioned increment is given by:

$$\Delta = \frac{P}{\sqrt{\varepsilon - 1}}. \quad (1)$$

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

Fields and a bunch in the accelerating structure are shown in Figure 4 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: 0.01 pC charge, initial energy 50 keV, bunch length 0.25 ps, bunch diameter 10 μm (at cathode). The structure design was performed so that all cells have equal lengths. The mentioned dielectric delays compensated grows of particle velocity from cell to cell.

In this simulation, for the full THz pulse energy about 2 μJ the maximum of the electric field in each cell was as high as 220 kV/cm. As one can see in the Figure 5, the electron bunch was accelerated up to energy more than 55.7 keV, in accordance with our expectations.

Fabrication

The accelerating structure will be fabricated from the copper foil of 50 μm thickness with 20 μm partitions by means of laser ablation technique. Dielectric delay inserts will be produced from Teflon. The parts will be assembled all together being tightened between flanges and lined up with stainless steel pins.

The described THz structure could also 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 [8].

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

Parameters	Value
Number of cells	10
Dielectric permittivity	2.1
Cell length	0.05 mm
Beam pipe diameter	0.1 mm
Focal length	0.13 mm
Iris thickness	0.05 mm
Width	3.0 mm
Length	1.0 mm

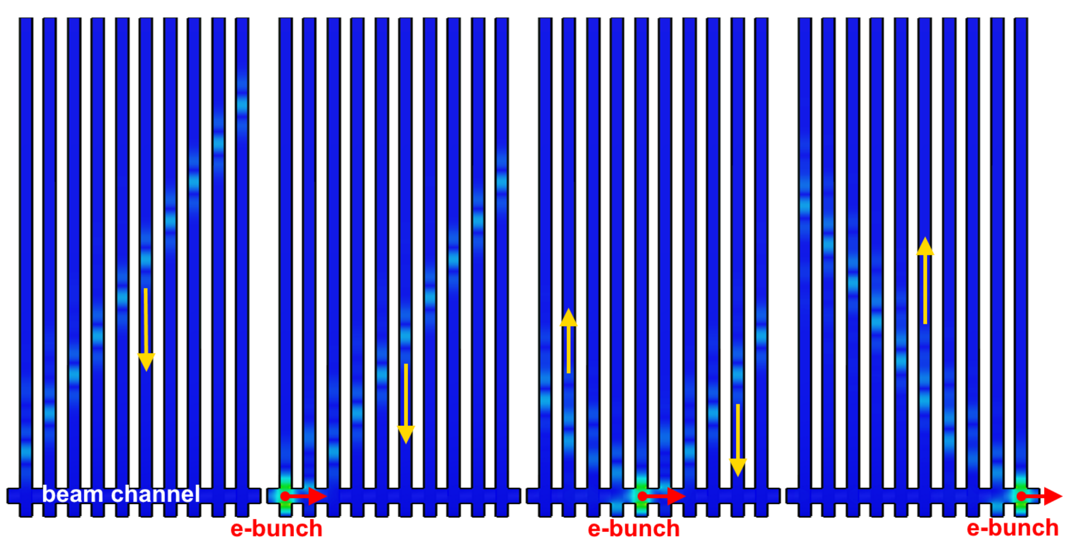

Figure 4: Front view of dielectric delay line THz accelerating structure (time proceeds from left to right).

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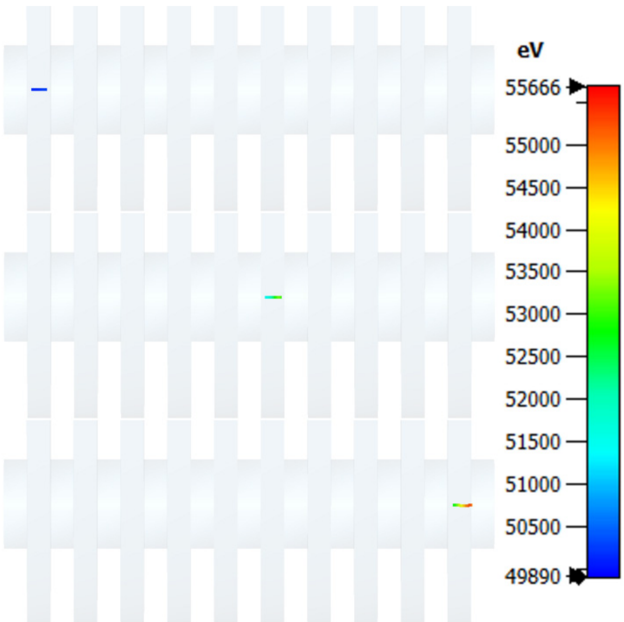

Figure 5: Bunch acceleration for three sequent time frames: top – bunch enters the first cell (t=11.6 ps), center – bunch crosses middle line (t=15.6 ps), bottom – bunch arrives the end (t=18.8 ps).

EXPERIMENTAL SETUP

Experiments with THz Pulse Generation in $LiNbO_3$ Crystal

In preliminary experiments we converted laser pulses into THz radiation using ~100 fs, 7 mJ laser with 10 Hz repetition rate [9]. Laser pulses with tilted front of the intensity were formed with a diffraction grating (1700 lines per mm). We investigated how conversion efficiency depends on optical beam size and duration (Figure 6).

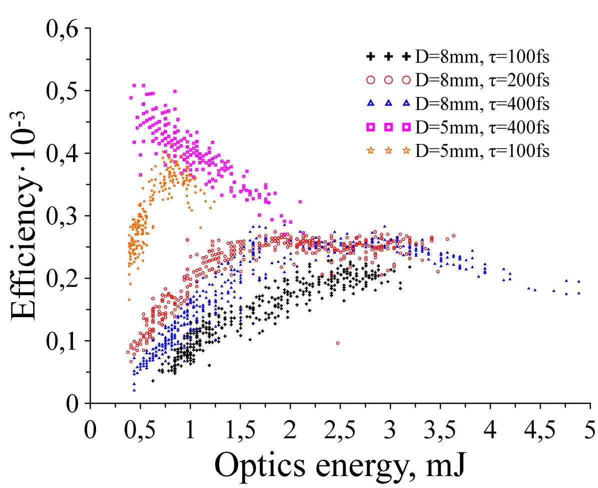

Figure 6: Efficiency of optical to THz radiation conversion in $LiNbO_3$ vs optical pulse energy for different pulse lengths and laser beam sizes.

It was found out that the efficiency for 100 fs laser pulses of 8 mm diameter linearly grows up with laser energy until 2 mJ and saturates at 3 mJ. For longer laser pulses (200-400 fs) the efficiency saturates at as low energy as 1.5 mJ and becomes 20 % more than in case of the short pulses. It was also shown that decreasing of laser beam diameter by 1,5 times enhanced the efficiency at low beam energies. However, the saturations came faster in comparison with wider beams, at 0.5-1 mJ. Maximum of the efficiency, 0.05%, was observed at 0.7 mJ and 400 fs pulse duration.

Electron Gun

We plan to study acceleration of electrons to be accelerated up to 50 keV prior the THz structure. For that purpose, we elaborated an electron gun based on a needle cathode irradiated by 800 nm TiSa laser (Figure 7). The use of the same laser for electron emission and THz generation allows to simplify synchronization issues substantially. Preliminary experiments with a needle (~1 µm) cathode showed that the emission current grows up with energy of laser pulse and then saturates. Maximum emitted charge in our experiments was as high as 10 pC.

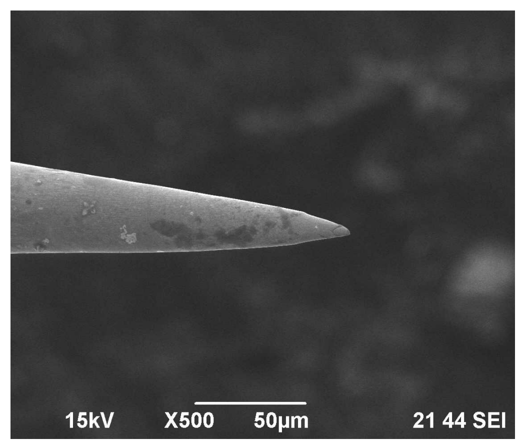

Figure 7: Tungsten cathode needle as shown in electronic microscope.

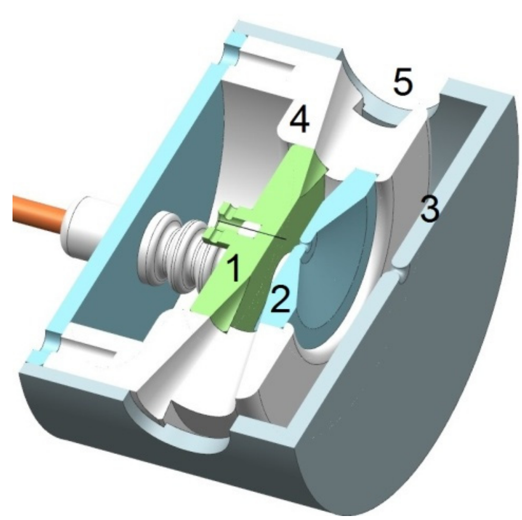

Figure 8: Electron DC acceleration gun: 1 – needle cathode, 2 – intermediate anode, 3 – main anode, 4 – insulator, 5 – gate for laser beam.

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In the proposed electron gun the needle cathode will be set under 100 V negative potential with respect to the first intermediate anode (Figure 8). The intermediate cathode is aimed to collect electrons with high transverse velocities. A section between anodes will be designed as a quasi-Pierce gun to provide beam focusing. We anticipate getting at the gun exit about 1 mm diameter bunches with 50 keV energy of the electrons. Before the THz structure we are going to put 70 μm iris to mitigate velocity and position spreads.

Energy Gain Measurement

We consider two experimental methods to measure energy gain. The first method is a classical measurement method by means of spectrometer based on DC deflecting magnet (Figure 9).

The second method exploits another idea. To measure energy gain of electrons we propose applying a voltage (50-100 kV) to the structure respecting the cathode and anode. Electrons arrive to the structure being accelerated up to 50 keV. Behind the THz structure electrons lose their energy being experienced the deceleration equals to the prior DC acceleration so that only energy accumulated in the THz structure would be remained. The anode can be reached only by the electrons accelerated in the THz field so that one can directly measure the resulting energy gain by means of the YAG screen.

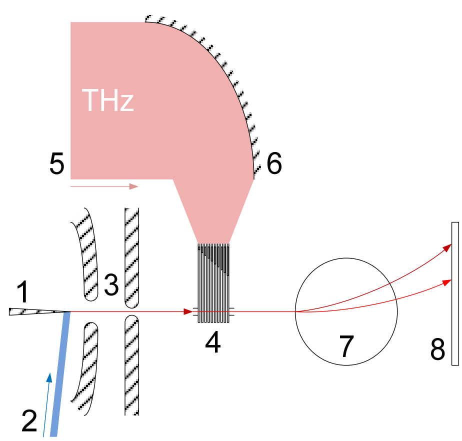

Figure 9: Sketch of experimental setup based on spectrometer measurements: 1 – needle cathode, 2 – laser beam, 3 – accelerating DC gun, 4 – THz accelerating structure, 5 – THz beam, 6 – parabolic focusing mirror, 7 – spectrometer, 8 – YAG screen.

CONCLUSION

Acceleration gradients at level GV/m could be reached in a multi-cell structure using picosecond single-cycle THz pulses produced by the conversion of laser radiation in nonlinear crystals. Energy gain measurements include needle cathode irradiated by femtosecond laser, DC acceleration section, multi-cell THz structure, and spectrometer or DC deceleration section before YAG screen.

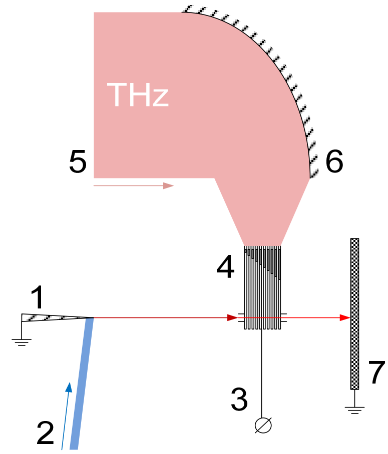

Figure 10: Sketch of experimental setup based on deceleration section measurements: 1 – needle cathode, 2 – laser beam, 3 –accelerating section, 4 – THz accelerating structure, 5 – THz beam, 6 – parabolic focusing mirror, 7 – deceleration section, 8 – YAG screen.

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