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# MULTI-CELL ACCELERATING STRUCTURE DRIVEN BY A LENS-FOCUSED PICOSECOND THz PULSE

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## *Abstract*

Recently, gradients on the order of 1 GV/m level have been obtained in a form of a single cycle (~1 ps) THz pulses produced by conversion of a high peak power laser radiation in nonlinear crystals (~1 mJ, 1 ps, up to 3% conversion efficiency) [1]. Such high intensity radiation can be utilized for charged particle acceleration. However, these pulses are short in time (~1 ps) and broadband, therefore a new accelerating structure type is required. In this paper we propose a novel structure based on focusing of THz radiation in accelerating cell and stacking such cells to achieve a long-range interaction required for an efficient acceleration process. We present an example in which a 100 microJoule THz pulse produces a 600 keV energy gain in 5 mm long 10 cell accelerating structure for an ultra-relativistic electron. This design can be readily extended to non-relativistic particles. Such structure had been laser microfabricated and appropriate dimensions were achieved.

## INTRODUCTION

The progress in high gradient acceleration in normal conducting structures had been limited due to breakdown and thermal fatigue effects associated with pulsed heating [2-8]. Experimental statistics [4, 7, 9] yield the following scaling law for surface electric $E$ field as a function of exposure time $\tau$ (microwave pulse length): $E^p \cdot \tau$, where $p \approx 5\text{-}6$. It was also discovered that a breakdown threshold correlates with pulsed heating of accelerating structure $\Delta T$, which is defined by the surface magnetic field $H$, $\Delta T \sim H^2\sqrt{\tau}$ [7]. A few theoretical models had been developed to explain this behavior [10, 11]. These findings suggest that a further push towards high gradient can be done if pulse length is minimized. In this sense picosecond single-cycle THz pulses fit the picture.

Such pulses can be produced by high power lasers in non-linear crystals via optical rectification. The energy per pulse had been demonstrated to be as high as 1 milliJoule resulting in few gigavolt per meter fields [1, 12, 13]. In this paper we will present several ideas of how to establish efficient acceleration with such pulses. This work builds on existing effort of various groups [14, 15].

## MANIPULATION OF THE THz PULSE

Single cycle picosecond pulses are broadband, with spectrum covering the range from 0.1 to few THz. For this reason, such pulses are commonly referred to as THz pulses. In simulations we use a shorter bandwidth pulse (Fig. 1) because of computational resources limitation, but the behavior of a broader bandwidth pulse is very similar. In the case of short pulse accelerating structure must be extremely broadband, completely different from standard arrays of coupled resonators.

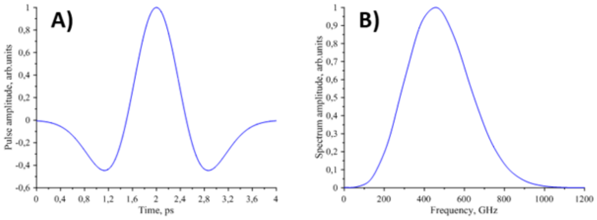

Figure 1: Picosecond THz pulse (A) and it spectrum (B) used for simulations.

A new approach is required for accelerating structure design to facilitate efficient energy transfer from a broadband picosecond pulse to a charged particle. For high accelerating gradients electric fields must be concentrated. For a broadband pulse this can be done via parabolic mirror (Fig. 2) or a dielectric lens (Fig. 3).

Both of these approaches are broad band, parabolic mirror in particular. Focussing with a lens requires that lens material does not have dispersion in the bandwidth of a pulse. High resistivity silicon and fused silica are good candidates.

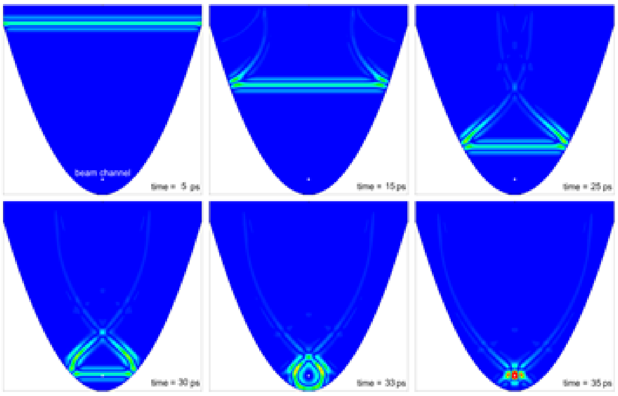

Figure 2: Simulations of 1-ps pulse propagation in a parabolic mirror, snapshots in time. A broadband RF pulse is focused by the mirror.

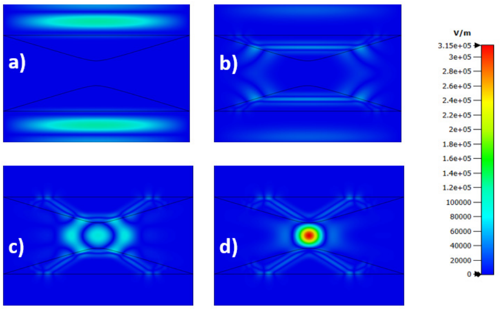

Figure 3: E-field distributions at the silicon lens while focusing the short THz pulse, for the time correspondent to THz pulse arrives to lens at t = 2.9 ps (a), for time when focusing begins t = 5.9 ps (b), for time when focusing is close to maximum at t = 7.9 ps (c), and in maximum of focusing at t = 8.9 ps (d).

Due to a short time scale of a pulse (~1 ps) acceleration length is limited to about 300 micrometres. Even for gradient of 1 GV/m this yields only 300 keV energy gain. A stack of cells has to be produced to achieve larger energy gain. To address this issue, multiple cells will be required. While the gradient per cell will be lower, since the same laser energy is divided between multiple cells, the total energy gain will be larger, according to the square root of the number of cells.

## MULTI-CELL ACCELERATION

One can stack back-to-back a large number of paraboloids like the ones shown in Fig. 2. But to make a large number of cells work together, one must provide a proper time shift, so that the electrons being accelerated arrive at the focus of the next paraboloid at the same time as the THz pulse is focused there. This timing can be provided by the use of difference of path lengths (Fig. 4, A and B) or by appropriate phase shifts (Fig. 4C). Figure 5 shows a simulation of the use of phase shifts for timing control. Dielectric plates loaded in the pre-paraboloid waveguides will provide the necessary time delays.

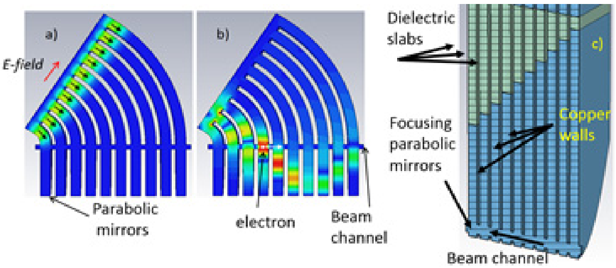

Figure 4: Timing for a multi-cell accelerating structure. A) and B) timing by path length – different time snapshots from simulation. C) Geometry of timing by phase delay, using the dielectric approach.

It is particularly attractive to join dielectric delay lines with focusing by a lens (Fig. 3). In this way a monolithic unit: delay line and lens provides both timing and focusing.

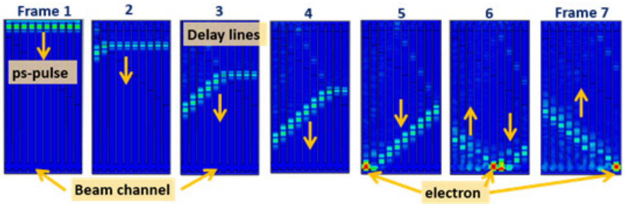

Figure 5: Simulation of timing by phase delay, snapshots in time. Focusing in the beam channel location occurs at different time in parabolic cells, due to the phase delay in the dielectric inserts.

## FABRICATION EXAMPLES

We laser ablated 10 parabolic mirror cells with appropriate path length shifts and stack them together (Fig. 6).

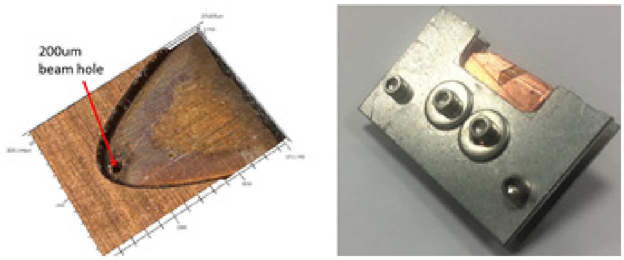

Figure 6: Left: Optical metrology of laser micro-ablated parabolic cell. Right: stack of parabolic cells with timing by path length.

The accuracy of such fabrication method is on the order of 1 µm for linear dimensions. This is fully acceptable for such THz structure. Copper walls with beam holes can also be produced by laser ablation along with fiducial features for the multi-layer structure assembly. Figure 7 shows lenses and delay lines laser cut from high resistivity silicon. The required accuracy and lens curvature is achieved.

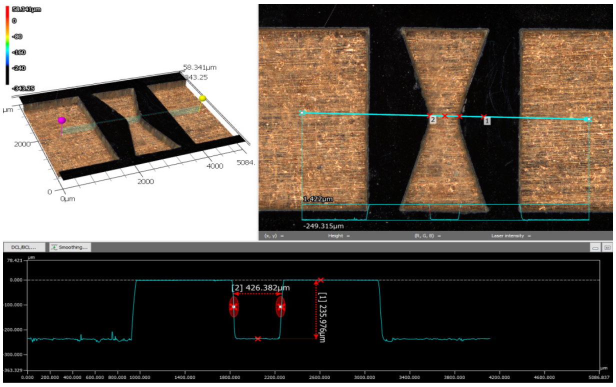

Figure 7: 3D scanning microscope metrology of the unit cell fabricated out of silicon.

Laser – based single cycle THz pulses can be used for efficient high gradient acceleration. Broadband accelerating structures are required.

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