ULTRAFAST ELECTRON GUNS FOR THE EFFICIENT ACCELERATION USING SINGLE-CYCLE THz PULSES[*]

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Abstract

Over the past decades, advances in ultrafast technologies led to the generation of intense ultrashort THz to optical pulses with single-cycle pulse duration. Using such ultrashort pulses for electron acceleration offers advantages in terms of higher thresholds for material breakdown which opens up a promising path towards increased acceleration gradients. Conventional accelerator technology is based on either continuous wave or long pulse operation, where resonant or guiding structures are employed. In this contribution, we introduce novel structures for electron acceleration which operate with single-cycle pulses called single-cycle ultrafast guns. The operating frequencies considered here are at THz wavelengths inspired by the recent progress in the optical generation of intense single-cycle THz pulses. We begin with designing guns for low energy pulses and proceed with structures designed for high energy pulses. More importantly, it is shown that the already achieved THz pulse energies of 10 µJ are enough to realize relativistic fields for electron acceleration. These structures will underpin future devices for fabricating miniaturized electron guns and linear accelerators.

INTRODUCTION

The past century has witnessed enormous progress in acceleration technology for producing high energy particles to achieve breakthrough discoveries in fundamental research. Some prominent examples of these techniques are high-energy colliders, x-ray light sources, and electron diffraction. Particle accelerators are devices playing major roles in all these techniques, enabling dramatic advances in our understanding of the universe. The first and most critical stage of an accelerator is the gun, which accelerates particles initially at rest relativistic speeds [1]. Therefore, many of limits in accelerator operation and particle beam quality are set by the gun properties.

The need for high energy particles as well as the usually required large facilities to provide such particles have triggered world-wide efforts to design compact accelerators. Among the various candidate technologies, ultracompact electron gun technology driven by optically-generated THz pulses could drastically shrink the size and cost of such sources thereby easing the access to individual investigators [2, 3]. Absolute synchronization stability is a significant benefit of such systems, since the THz pulses are generated by the same laser as the photo trigger. With a breakdown gradient threshold of several GV/m (more than one order of magnitude above RF guns), THz guns also have the potential to reduce the emittance and energy spread of electron beams. The recent development of GV/m gradient THz sources pumped by compact, commonly-available few-mJ lasers shows great promise.

Generally, there is a conceptual gap between standard accelerator technology and ultrafast science. Microwave and millimeter-wave technology, used in conventional accelerators, are very well developed for producing continuous wave (CW) radiation. Therefore, accelerators are mostly designed with narrowband excitations. Examples are the widely used cascaded cavities which operate based on a resonance behavior and traveling wave accelerators, in which fields of a guided mode are employed for acceleration. Hence, direct usage of a standard accelerator geometry excited by a short pulse laser incurs wasting a large portion of input energy. The goal in this study is to introduce novel structures that aim to accelerate particles from rest using short pulse excitation, which we like to call *single-cycle ultrafast electron guns*. We start with presenting a structure which operates based on low-energy single cycle THz pulse, namely 10 µJ and simulate the bunch and dynamics within the proposed gun. Subsequently, a technique for using high energy single-cycle THz beams with 260 µJ energy to achieve relativistic electrons will be discussed.

LOW-ENERGY SINGLE-CYCLE ULTRAFAST ELECTRON GUN

The structure in Fig. 1 operates based on a low-energy pulse. A single cycle pulse enters the acceleration region through a large horn receiver antenna, is focused by the metallic walls, and accelerates an electron bunch injected into the pulse at the optimal time (phase). A reflector is devised with a distance equal to $\lambda_0/4$ (λ_0 is the central wavelength of the pulse) to further enhance the accelerating field at the injection region. The accelerated electron leaves the pulse before the decelerating cycle arrives in order to acquire an optimal acceleration efficiency.

To simulate the interaction of the proposed structure with the incoming THz beam, we use full-vector time domain simulation of field propagation using the discontinuous Galerkin Time Domain (DGTD) method. The method is combined with a Particle-In-Cell (PIC) algorithm to simultaneously update the electrons motion and simulate the electron beam propagation [4]. The input THz pulse is a Gaussian beam focused at the electron injection point in the middle of the

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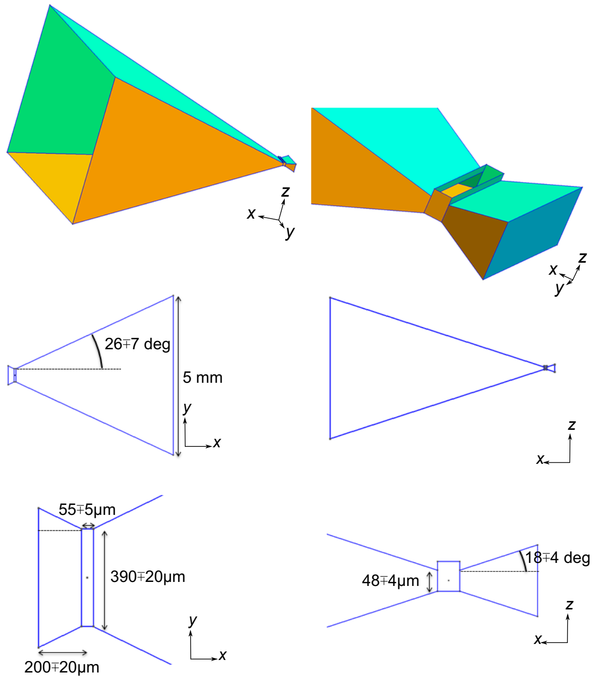

Figure 1: Schematic illustration of the considered geometry for the low-energy ultrafast electron gun

gun with linear polarization along the z-axis which is the acceleration path of electrons. The peak field is assumed to be $E_0 = 56.5$ MV/m which corresponds to a 10 µJ THz energy. The Rayleigh radius of the Gaussian beam is 1 mm and we assume temporal variations according to a Gaussian pulse with 2.5 ps variance, central frequency of 400 GHz and zero carrier envelope phase. The accelerating field at the electron injection point obtained from DGTD calculations is shown in Fig. 2a, which evidences an enhancement factor of 16 in the acceleration gradient. If an electron is released at the time instant when the accelerating field is 50 MV/m, then the electron energy increases with the travel distance according to Fig. 2b. The simulations show the feasibility of an ultracompact 25 keV electron gun using a 10 µJ THz energy.

To achieve an accurate assessment on the gun operation, we need to simulate the bunch evolution during the acceleration in such a THz gun. The properties of the considered UV laser incident on the cathode to produce the photoemitted electron bunch is: Pulse duration = 40 fs, laser spot size = 20 µm. We assume that the laser pulse is strong enough to produce 100 fC of bunch charge on the cathode surface. This bunch is modeled with 20’000 macro-particles. According to the simulation results, 80% of the electrons will travel through the narrow slit on the gun and are extracted from the photinjector. The output bunch size will be approximately (13.2 µm, 10.5 µm, 1.9 µm) with a relative energy spread of $(6.5, 6.5, 15) \times 10^{-4}$. The obtained emittance of the bunch is (0.01, 0.005, 0.005) mm mrad which shows the great promise of the single-cycle THz guns.

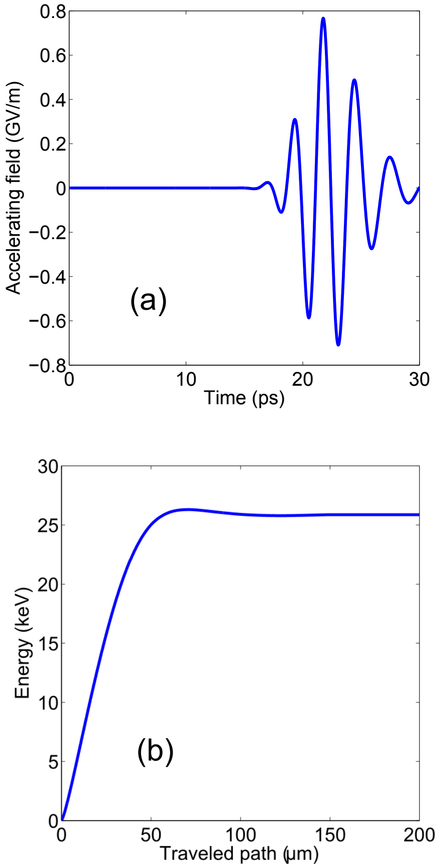

Figure 2: (a) Acceleration gradient at the electron injection point and (b) corresponding energy gain of an electron traveling in the low-energy THz gun.

If higher energy THz pulses are injected into this gun the strongly enhanced electric field damages the gun metallic boundaries and causes the failure of the device functioning. In addition, a high energy pulse is able to accelerate electrons to relativistic velocities. This causes the electrons to be pushed by the beam along the propagation direction and deflects the electrons from the acceleration path. Therefore, subtle designs need to be developed which are able to scale the injected power to achieve high energy particles without damaging the device.

HIGH-ENERGY SINGLE-CYCLE ULTRAFAST ELECTRON GUN

The configuration illustrated in Fig. 3 is designed to solve the above two problems. First, two linearly polarized beams are symmetrically coupled into the multilayer structure in order to cancel out the push due to the magnetic field. Second, the phase front of the THz beam is divided into several parts, which are isolated from each other using thin metallic plates. In each layer, dielectric inclusions are added to delay the arrival time of the pulse to the acceleration region. By properly designing the filling factor of dielectrics and the

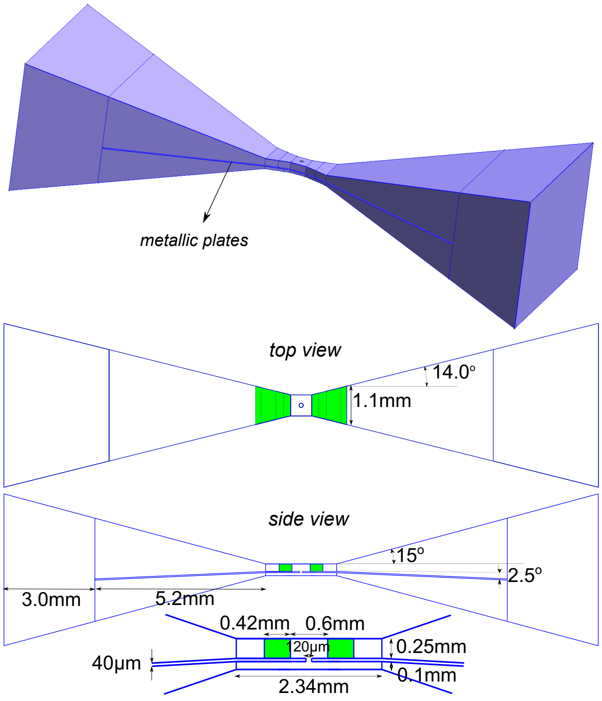

Figure 3: Schematic illustration of the considered geometry for the high-energy ultrafast electron gun

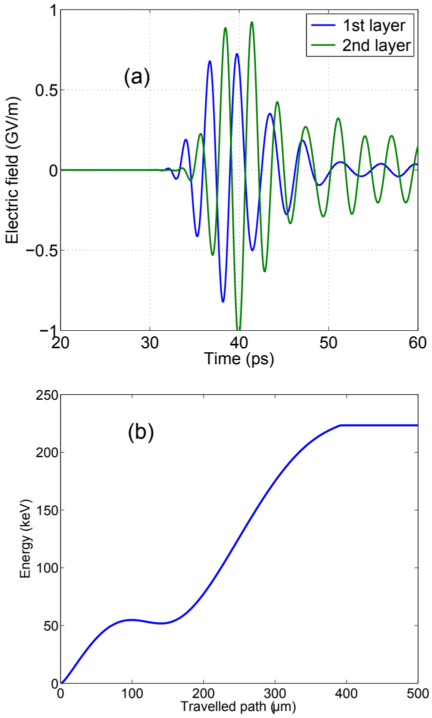

Figure 4: (a) Accelerating field in two layers along the electron injection point and (b) corresponding energy gain of an electron traveling in the high-energy THz gun.

thickness of each layer, continuous acceleration of electrons from rest throughout the whole phase front can be achieved.

We assume two Gaussian beams enter the structure from the two sides and are focused at the electron injection point in the middle of the gun. Both THz beams have linear polarization along the z-axis which is the acceleration path for electrons with a peak field of $E_0 = 196.5$ MV/m which corresponds to a 130 µJ THz energy. The Rayleigh radius of the Gaussian beam is 0.9 mm and we assume temporal variations according to a Gaussian pulse with 3.3 ps variance, central frequency of 300 GHz and zero carrier envelope phase. The temporal evolution of the electric field obtained from DGTD calculations is shown in Fig. 4a, which evidences achievement of 1 GV/m acceleration gradient in the proposed gun. If an electron is released at the time instant when the accelerating field is 50 MV/m, then the electron energy increases with the travel distance according to Fig. 4b. The simulation results demonstrate a compact 230 keV electron gun driven by two 130 µJ THz pulses.

To evaluate the electron bunch properties exiting the THz gun, we perform exactly the same bunch simulation as before for the high-energy case. According to the simulation results all of the 100 fC electrons emitted in the gun are accelerated and leave the gun. The ultimate bunch dimensions are (12.5 µm, 13.5 µm, 2.0 µm) with a relative energy spread of $(6.0, 6.0, 200) \times 10^{-5}$. The obtained emittance of the bunch is $(0.012, 0.012, 0.006)$ mm mrad).

CONCLUSION

We have introduced a theoretical solution for producing electron bunches with 100 fC charge with ultra-short bunch lengths ~6 fs using novel structures for electron acceleration which operate with single-cycle THz pulses. It is shown that the already achieved THz pulse energies of 20-200 µJ are enough to realize relativistic fields for electron acceleration. These structures enable efficient acceleration of particles in an ultracompact setup with the short pulse durations which lead to ultrahigh brightness electron beams.

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