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Acceleration of electrons in THz driven structures for AXSIS

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A R T I C L E I N F O

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A B S T R A C T

We describe initial steps in the development of the technology for a THz-driven accelerator that will drive a compact attosecond X-ray light source. THz-driven structures represent a promising emerging technology for compact acceleration of sub-femtosecond electron bunches. The millimeter scale of the driving field offers a favorable compromise between conventional accelerators which are proven and reliable but large and costly, and other advanced accelerators like plasma-based or laser-driven devices where the microscopic accelerator structures make device control difficult and limit the charge payload. By contrast the THz-driven structures are large enough to be fabricated by conventional means leading to a high degree of repeatability and control, can support field gradients that are significantly higher than in conventional accelerators, promising capabilities to produce sub-femtosecond electron bunches. In addition, the strong fields in THz based devices offer potential for compact, strong-field manipulation and diagnosis of electron bunches. Our results pave the way for development of a THz-based light source for sub-femtosecond investigation of material structure.

1. Introduction

Over the past century, X-ray light sources based on linear accelerators of electrons have been the work horses for studying the inner structure of materials on atomic scales. Synchrotrons in particular have been responsible for providing over 90% of the structures of proteins via X-ray crystallography [1]. Many proteins, however, can be difficult or impossible to grow into large enough crystals to provide sufficient signal for reconstruction of the structures. With the advent of free-electron lasers (FELs), a new measurement technique known as "serial femtosecond crystallography" was made possible [2] in which the protein structure could be reconstructed by using a series of nano-sized crystals of random orientation. In order to get diffraction patterns of sufficient quality, the full dose of X-rays must be concentrated onto the tiny area of the nanocrystals, resulting in total destruction of the samples. Synchrotrons, which produce X-ray pulses that are typically tens of picoseconds long, cannot be used for this method because the structure being measured disappears long before the X-ray pulse is over. FELs, however, can provide pulses with durations in the femtosecond range that are short enough to interact with the crystals before significant atomic rearrangement in the sample, enabling characterization of the structures of many biologically important molecules that were previously inaccessible [2].

The success of the first such machine, i.e., the Linac Coherent Light Source (LCLS), has lead to a scientific demand that far exceeds its capabilities. In spite of the construction of other FELs around the world, access to this specialized source of photons remains extremely limited. An additional problem is that while atomic rearrangement in these experiments occurs on a tens-of-femtosecond scale [3], it is known that electronic rearrangement, through processes such as Auger decay, can occur on timescales below one femtosecond [4]. Obtaining accurate spectroscopic data from these nano-crystals thus requires X-ray pulses that can reach the attosecond regime.

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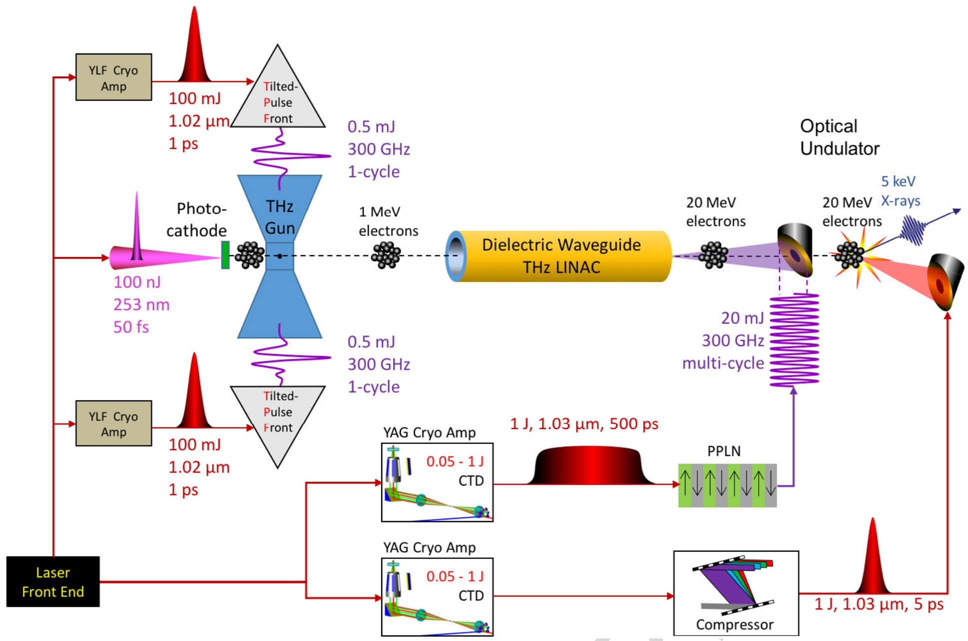

Fig. 1. Architecture of the AXSIS attosecond X-ray source.

Alternate "compact" technologies being developed for electron acceleration, including laser–plasma accelerators (LPAs) [5] and dielectric laser accelerators (DLAs) [6], have the potential for solving both of these problems by employing short-period, high-gradient acceleration fields that not only reduce the size of the device but also favor generation of short electron bunches (translating to short X-ray pulses). For reference, conventional accelerators, which are powered by microwaves, are typically limited by field-emission at metal surfaces to peak acceleration gradients in the range of 10–100 MeV/m [7]. LPAs, however, which generate acceleration structures dynamically in a plasma, can produce extremely high acceleration gradients in the range of 1×10^5 MeV/m, but suffer from difficulties in tuning and control due to strong nonlinearities in the interaction which cause instabilities. DLAs, on the other hand, use optical frequency fields to accelerate particles directly, which enables generation of high gradients but requires extreme tolerances in timing of injected electrons and are limited to bunch charges in the femtocoulomb range due to the micron-scale of the wavelength.

Very recently, a new technology driven by pulsed THz radiation [8] has emerged that combines many of the advantages of conventional accelerators, whose large scale brings control and ease of fabrication, with the advantages of novel, compact accelerators employing high fields. THz accelerators employ millimeter scale structures that can support moderate charge and can still be fabricated by traditional methods but can also support fields in the range of several hundred MV/m due to the favorable scaling of field-emission-threshold with frequency [9–11]. Stronger fields and shorter drive wavelengths both contribute to higher field gradients which allow bunches to be accelerated to relativistic energies more quickly and thus reduce the deleterious effects of space charges. Using pulsed drivers and scaling to higher drive frequencies also lowers the energy required to reach a given field strength as well as the amount of heat deposited in the structure, which can help compensate for reductions in supported charge by allowing higher repetition rates. THz based acceleration has previously been limited by the lack of sufficiently energetic THz sources. Recent developments in lasers and laser-based THz generation methods, however, have enabled demonstration of millijoule-level single-cycle [12] as well as multi-cycle [13] THz sources opening up the possibilities for practical THz-driven accelerators.

2. The AXSIS project

In the context of this wave of THz development, the AXSIS (Attosecond X-ray Science: Imaging & Spectroscopy) project [14] has been initiated with the goal of demonstrating a compact attosecond X-ray light source based on a fully THz-driven accelerator. The accelerator will be composed of a relativistic photogun driven by single-cycle THz pulses and a multi-cycle-driven THz LINAC which produces electrons of energy up to 20 MeV. The electrons will collide with a counter-propagating Joule-class laser beam which acts as an optical undulator to produce X-rays in the biologically relevant 4–12 keV range. All components will be driven by beams originating from a single laser system, ensuring intrinsic synchronization as well as the possibility of sub-femtosecond resolution in pump–probe studies. The AXSIS project involves the development of four key and very challenging technologies: (1) Joule-class lasers operating at kilohertz repetition rates; (2) single- and multicycle THz sources in the millijoule to tens-of-millijoule range based on nonlinear difference frequency generation (DFG); (3) THz-driven accelerator modules, including MeV-class photo-guns and tens-of-MeV-class LINACs; and (4) efficient X-ray generation via optical undulation of MeV class electron beams. The architecture of the AXSIS system is shown in Fig. 1.

3. Laser system

To ensure proper synchronization of the electrons, the THz pulses and the optical undulator, the machine will be based on a single laser system operating at a final repetition rate of 1 kHz. This system will provide the following laser pulses: (1) 50 fs, 100 nJ pulses at 253 nm for generation of electrons at the photocathode; (2) 2×1 ps, 100 mJ pulses at 1.02 µm for generating single-cycle pulses via the tilted pulse-front scheme in lithium niobate [15]; (3) 500 ps, 1 J pulses at 1.03 µm for generating multi-cycle THz pulses in periodically-poled lithium niobate; and (4) 5 ps, 1 J pulses at 1.03 µm to act as the optical undulator. The energy requirements of pulses (2) and (3) are determined by the efficiency of the DFG process and the THz pulse energies required for acceleration. For the gun, 2×0.5 mJ single-cycle pulses will be needed to reach 1 MeV. Given the state of the art for single-cycle THz generation of near 1% [12], 2×100 mJ of laser energy is expected to suffice and provide a little spare. For multi-cycle THz generation,

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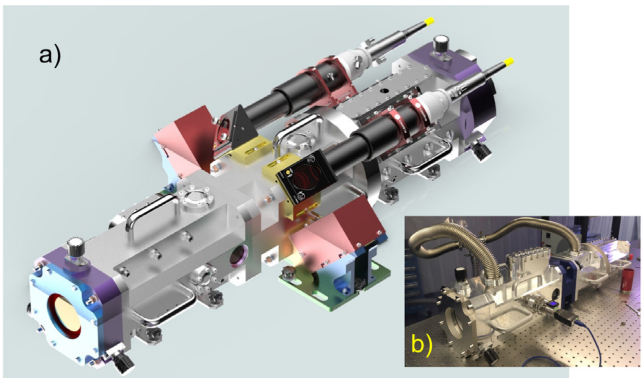

Fig. 2. (a) Schematic of the amplifier. (b) Photo of assembled device.

efficiencies of several percent are expected, based on simulation [16]. As approximately 20 mJ of THz will be required to reach 20 MeV final energy, 1 J of laser energy is anticipated to suffice, again with a little extra to account for losses in THz transportation and coupling.

Of these laser pulses, the first two have been proven by multiple groups, but pulses Joule-class lasers at a kilohertz have yet to be demonstrated. The research program for the AXSIS project thus includes a substantial component for development of a Joule, kilowatt amplifier (Fig. 2) which is based on a Yb:YAG cryogenic thin disk. Design and fabrication work for this system has been completed and assembly and testing are now underway.

4. THz generation

The AXSIS accelerator will require generation of single-cycle as well as multi-cycle THz pulses with energy beyond what has previously been demonstrated. In the current design, two single-cycle THz pulses of energy 0.5 mJ and center frequency of 0.3 THz are required to power the photogun, and a 500 ps long, 0.3 THz narrow-band pulse of energy 20 mJ is required to power the LINAC. The choice of center frequency is based on the balance of several factors including THz generation efficiency, THz absorption, optical bandwidth and accelerator structure manufacturing tolerances. In general, the generation efficiency increases with THz frequency, Ω, due to the Ω^2 dependence of the DFG process. This dependence is somewhat counteracted, however, by the THz absorption in lithium niobate which also increases with Ω below the first phonon resonance. Higher THz frequencies generally require larger laser bandwidths, which for high-average-power lasers can become a severe limitation. The size of the accelerator structures also becomes smaller, making then more difficult to fabricate, but less THz energy is required to reach the same field in these smaller structures. Ultimately, changing the THz frequency effectively trades one technical difficulty for another and the design frequency of 0.3 THz, with its 1 mm wavelength, is optimized for our current capabilities.

To achieve sufficiently high THz generation efficiencies via DFG to make the design THz pulse energies feasible requires precise control of the phase-matching conditions. For single-cycle THz generation, phase matching is accomplished via the tilted pulse front method [15] which has been used to demonstrate the highest efficiencies (0.8%) and energies (0.4 mJ) to date [12] for frequencies below 1 THz. In this record-setting work it was found that the THz center frequency reduced significantly with increasing energy so that at 0.16 mJ, the frequency was well below 0.2 THz. Here we report generation of single-cycle THz pulses with a center frequency of 0.28 THz, an energy of 0.2 mJ and a conversion efficiency of 0.5% using a 40 mJ, 1020 nm, 1 ps laser (Fig. 3). This result demonstrates that by scaling to 100 mJ laser pulses, the required 0.5 mJ THz pulses are achievable. To have a margin for error, however, to account for losses in propagation and coupling, it will be necessary to improve efficiency to roughly the 1% level. This improvement is expected to be possible by upgrading the imaging optics and output coupling in the tilted pulse-front setup.

For multi-cycle THz generation, quasi phase matching using periodically-poled lithium niobate (PPLN) crystals is currently the preferred method since simulation has shown that it allows scaling to long interaction lengths with efficiencies reaching multiple percent [16]. In early work, we reported generation of microjoule-level multi-cycle pulses, two orders of magnitude higher than previously reported by cryogenic cooling of the PPLN and by using compressed pulses at 800 nm with a tailored bandwidth, resulting in efficiencies of about 0.1% [17]. This work, however, was limited both by the aperture of the available crystals (3×3 mm) and by the damage threshold of the material which limits the incident intensity. In more recent work it was demonstrated that energy could be scaled up by another order of magnitude (to ~40 μJ) by using two pulses linearly chirped in time to reduce the intensity for a given fluence, with a delay chosen so that the instantaneous frequency difference between the two pulses satisfied the narrow quasi-phase matching condition of the PPLN [18]. Another order of magnitude (and record energy of 604 μJ) has very recently been achieved by tuning the phase structure of the chirped pulses and by increasing the aperture of the crystal to 10×15 mm in order to allow an increase in the incident energy at the same fluence [13]. These large aperture crystals, provided by Prof. Taira from the Laser Research Center at the Institute for Molecular Science in Japan, represent the state of the art in what is currently possible for PPLN. Fig. 4 shows the spectral characterization of the multi-cycle THz pulses generated in collaboration with the LUX group at DESY on a Ti:Sapphire laser at 5 Hz with up to 1 J of available energy. While these results represent a significant step forward in optical generation of multi-cycle THz pulses, another similar step forward will be required to reach the 20+ mJ of multi-cycle THz energy anticipated for the LINAC. Research into this next step is on-going. However, it is expected that it will require, among other things, optimization of the spectral content and spatio-temporal profiles of the laser pulses, optimization of the output coupling of the THz from the crystals and recycling of the laser pulse energy in multiple crystals. Early results from simulations under development indicate that with these improvements, tens of millijoules of energy are possible from a 1 J laser pulse.

5. Electron acceleration

In parallel with the efforts on pushing the boundaries of laser-based THz generation, our group has also made pioneering progress in demonstration of THz-based acceleration of electrons. Initial work concentrated on proof of principle demonstrations of the two key ingredients of a THz-based linear accelerator: a THz-driven photogun [19] and a THz-driven LINAC [8] (Fig. 5). In the THz-gun work, 34 μJ of single-cycle THz was used to accelerate electrons from rest to peak energies of 0.8 keV in a transversely-pumped structure that concentrated the THz field in one dimension. In the THz-LINAC work, 10 μJ were used to modulate the energies of electrons from a 57 keV DC gun by 7 keV using a longitudinally pumped waveguide structure.

This early work has now been significantly extended by development of a new device designed to optimize the interaction of electrons with a transversely propagating THz field [20]. In this concept, two counter-propagating single-cycle THz pulses interact with electrons traveling at 90° such that the electric-field vector is parallel to the electron motion. The interaction region is sub-divided into sub-mm layers by thin metal sheets, effectively creating multiple waveguides into which the THz pulse energy is distributed. Each waveguide layer is embedded with a dielectric slab whose length is precisely tuned to delay the time of arrival of the THz waves at the interaction point so that the electrons experience the same THz phase at each layer. Simulations have been performed [20] showing that with 2 mJ of THz energy, electrons can be accelerated from rest to 2 MeV using this device (Fig. 6). Implementation of this new device is currently underway and is revealing very promising performance. These new results will be reported elsewhere [21].

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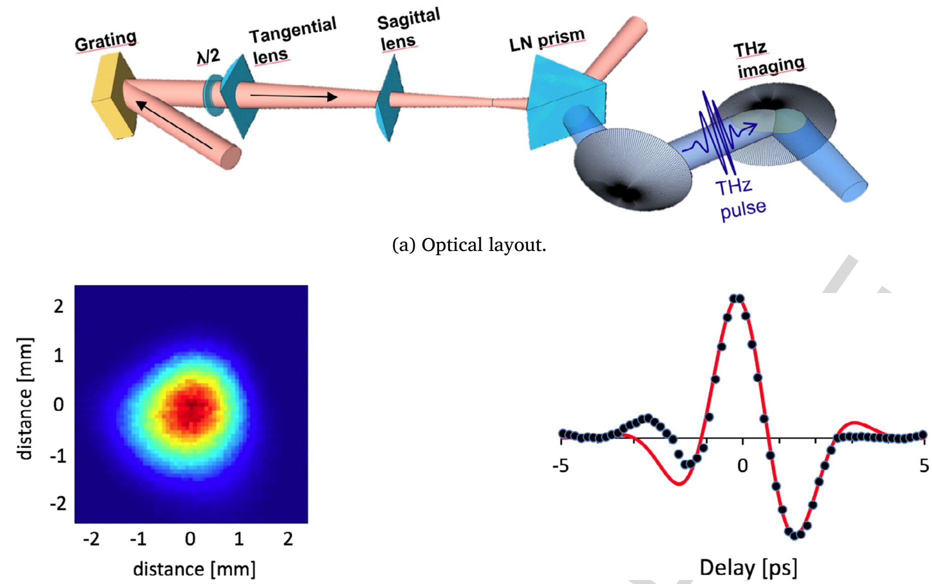

(a) Optical layout.

(b) Measured THz mode.

(c) Measured THz waveform.

Fig. 3. (a) Tilted pulse front layout. (b) Measured THz beam profile at source. (c) THz waveform measured by electro-optic sampling.

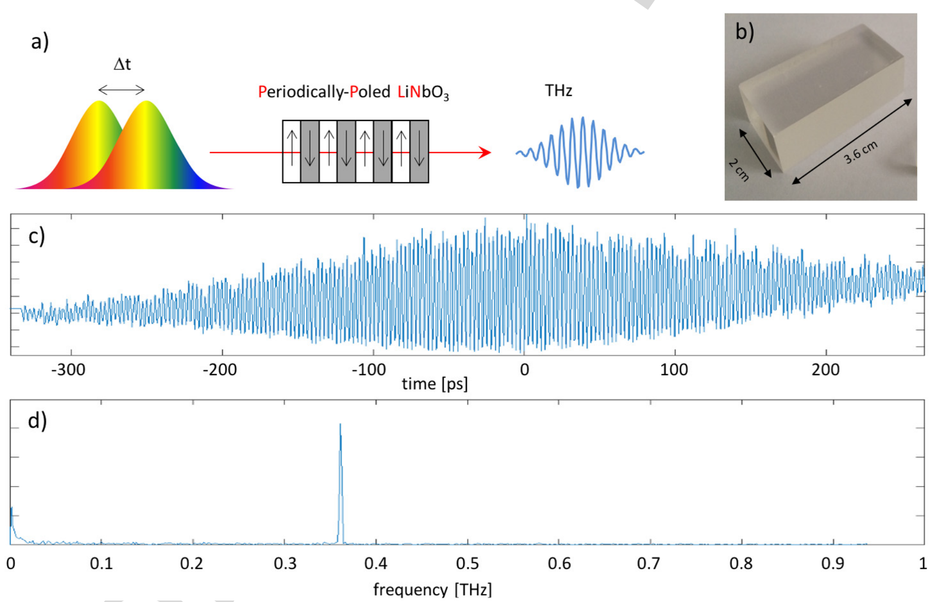

Fig. 4. (a) Chirp & delay concept (b) Large aperture PPLN donated by Prof. Taira from the Institute for Molecular Science in Japan. (c) Interferometric autocorrelation of the THz pulse. (d) Power spectrum of THz pulse obtained from Fourier Transform of (c), centered at 0.36 THz.

6. Conclusions

The results of our work over the last five years has encompassed laser development, THz generation and THz acceleration of electrons. This combination of technical methods constitutes a new THz-driven accelerator technology which holds tremendous promise for future accelerators and light sources. The intermediate wavelength scale of millimeters enables frequencies to be increased by two orders of magnitude over conventional RF-driven technologies, enabling higher fields and field gradients to be sustained with powerful and beneficial effects on electron beam properties. At the same time, the scale is sufficiently large to allow traditional fabrication and control methods, resulting in devices which are fine-tunable, sustain high repetition rates and are stable over long periods of time. This combination of advanced capability and conventional practicality makes THz-acceleration technology an attractive option for the future of accelerators both for fully THz-driven devices and for hybrid conventional/THz devices which employ THz modules to enhance specific capabilities. This new technology, however, requires big steps forward in the development of technical knowhow to support it, including methods for generation of single-cycle and multi-cycle THz pulses with high energy as well as laser sources with spectral and temporal structures, pulse energies and repetition rates optimized to power these THz generation methods. The development of these techniques with capabilities to provide the parameters specified by the AXSIS project itself represents a major advancements that will have large impacts on science and technology well outside of the accelerator and light-source community. The results and progress summarized here show the viability of the AXSIS concept.

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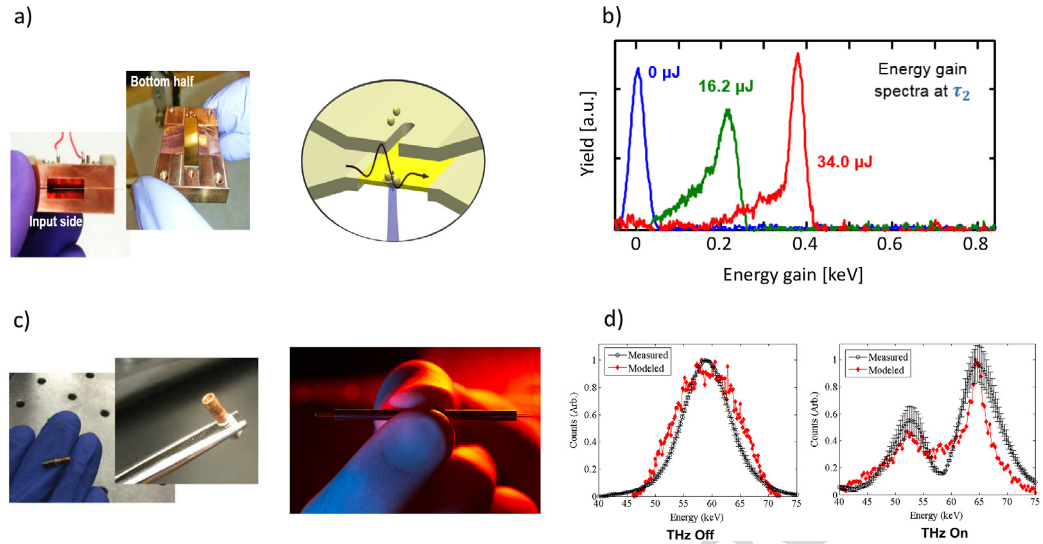

Fig. 5. (a) Setup of the parallel plate THz gun with a 75 μm interaction distance yielding a maximum of 0.8 keV electrons (b) Electron energy spectra optimized for monochromaticity showing a peak energy of just under 0.4 keV and a peak acceleration gradient of $E_z \approx 0.3$ GeV/m. (c) Pictures of the THz LINAC. (d) Energy modulation of ±7 keV on a 57 keV electron beam injected from a DC-gun.

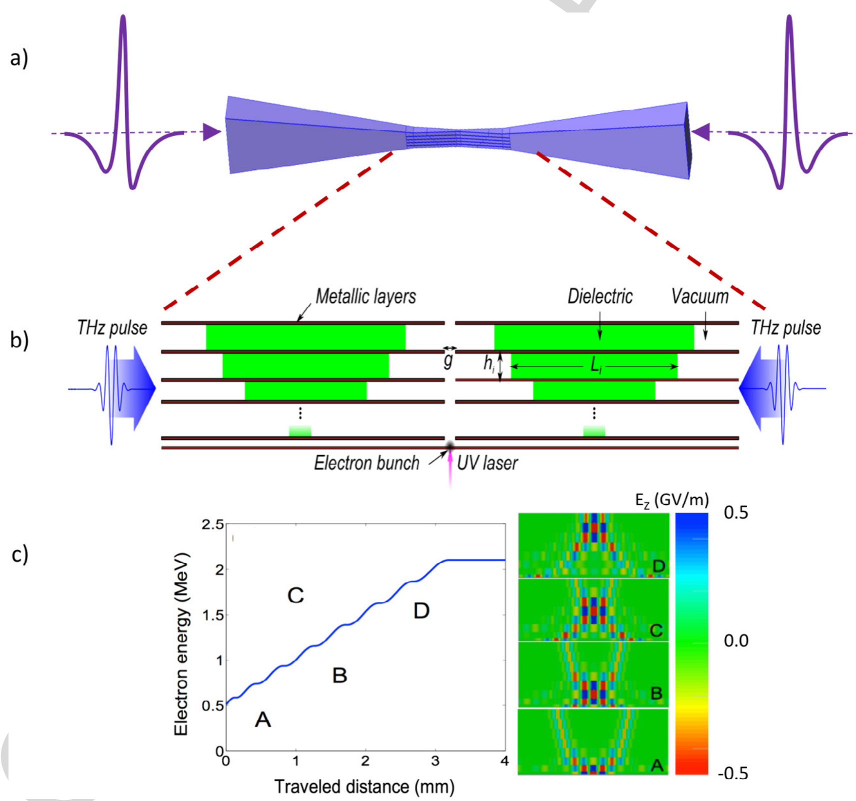

Fig. 6. (a) Concept of segmented structure showing two input horns to concentrate the THz energy into the interaction region (b) Diagram displaying the organization of the waveguide layers. (c) Simulation showing acceleration of electrons from rest to 2 MeV using 2 mJ of THz energy [20].

Acknowledgments

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