

CONSIDERATIONS FOR AN EFFICIENT TERAHERTZ-DRIVEN ELECTRON GUN *

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Abstract

We investigate a dispersion-controlled-acceleration scheme of low-energy electrons to mitigate phase slipping using a tapered dielectric lined waveguide (DLW). Our approach matches the velocity of an electron being accelerated in a slab-symmetric structure in a constant electric field. We also present first experimental results of a THz pulse propagating in a slab-symmetric DLW.

INTRODUCTION

Although conventional electron sources are often used to investigate the performance of advanced acceleration concepts [1], their adaptation to serve as an injector for an optimized advanced accelerator remains challenging. Instead several groups have developed short-pulse electron sources, e.g., based on dielectric grating [2], free-space THz streaking [3,4], or the proposed optically driven dielectric-waveguide sources [5]. Unfortunately, electron sources using an optical wave are typically limited in the charge they can produce since space charge is predominant at low energy and needs to be mitigated. For instance at $\lambda_{acc} = 800$ nm, a typical bunch length of a few nm would be required which would result in peak current, $Qc/(2\pi\lambda_{acc}) \geq 6$ kA for a 1 pC bunch charge (here c is the light velocity). Alternatively, using a THz pulse with $\lambda_{acc}=100$ μm would result in a peak current on the order of 50 A (taking $\sigma_z \approx 10^{-2}\lambda_{acc} \approx 1$ μm). The latter value is consistent with values typically achieved in conventional photoinjectors, see Ref. [6] for example. Likewise, the trade-off between electron bunch length and charge could enable the production of higher charge (up to 100 pC) in exchange for longer bunches.

Recently, the development of efficient (2%) laser-based THz sources (300 GHz) has opened the path to the development of THz-driven linacs [7–10]. In this scheme, a radially-polarized THz pulse is co-propagated with an electron bunch in a dielectric-lined waveguide (DLW) with optimized geometry; THz pulses with mJ energies can support accelerating fields on the order of GV/m. The THz-pulse is also matched to the structure thereby mitigating possible excitation of spurious modes (e.g. dipole modes often excited in beam-driven schemes dielectric-wakefield

acceleration [11]. This technique would work well at relativistic energies as the electron has a velocity close to the phase velocity of the THz pulse and the particle-wave slippage is negligible over the considered interaction lengths. In contrast, using a THz pulse to accelerate an electron bunch from rest, as recently demonstrated for the free-space case in Ref. [10], is prone to large phase-slippage effects that significantly alter the maximum energy achievable.

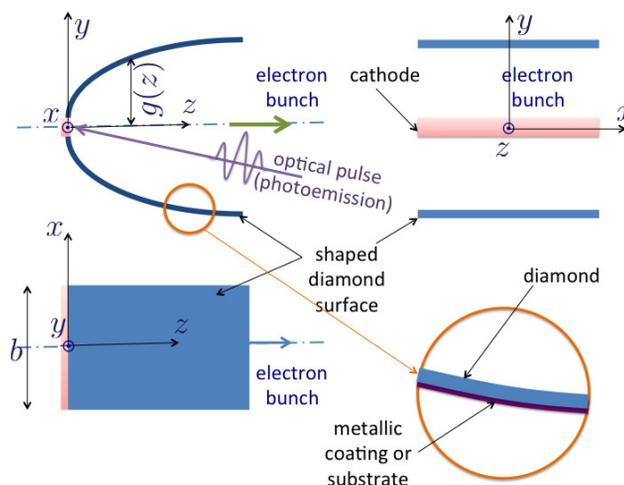


Figure 1: Section, top view and side view (respectively on top, bottom left and top right) of the proposed “THz gun” electron source.

This paper presents some preliminary considerations toward the development of a THz-driven electron source with some attempt to keep phase-slippage effects under control. A conceptual schematic of this low-energy electron source, henceforth dubbed “THz-gun”, appears in Fig. 1: two thin dielectric surfaces deposited on a metallic substrate (or free-standing with metalized outer surfaces) are faced to each other.

DISPERSION-CONTROLLED ACCELERATION

The rate of phase slippage between an electromagnetic travelling wave with axial field $E_z(z,t) = E_0 \sin(\omega t - kz + \psi_0)$ (where ω and k are respectively the wave’s frequency and wavenumber) and a particle with Lorentz factor γ is given by $d\psi/dz = \alpha k \sin(\psi)$ where $\psi = \psi(z,t) \equiv \omega t - kz + \psi_0$ (with ψ_0 being the injection phase), and $\alpha \equiv eE_0/(kmc^2)$ is

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normalized gradient. The slippage can be minimized by satisfying $\alpha \ll 1$ as done in RF guns where large accelerating gradients with relatively long electromagnetic wavelengths are employed. A similar problem occurs at THz frequencies and the phase slippage accumulated over the interaction length (which has to be many THz wavelength to achieve MeV-level energies) can be commensurate.

To control the phase slippage we shape the inner gap between the surfaces to follow a function $g(z)$ of the axial position z (coincident with the direction of propagation of the electron bunch). The function $g(z)$ is tailored to insure the phase velocity of the injected THz wave matches the electron beam's velocity thereby resulting in a quasi-monotonic energy transfer from the THz wave to the electron bunch. Ideally, the phase slippage between the wave and beam can be suppressed. In this paper we focus on a slab DLW as its tapering is practically easier to realize compared to a cylindrically-symmetric structure.

To give some insight into this possibility, we consider a dispersion relations for longitudinal section magnetic (LSM) modes in a slab-symmetric DLW described in Ref. [12]. In this geometry, a is the full width of the structure, b is the full width along the orthogonal direction, t is the thickness of the dielectric layers, and ϵ is the relative dielectric permittivity (illustrated in Fig. 2); additionally, we show the dispersion curve for a structure with dimensions $(f, t, a, \epsilon) = (300 \text{ GHz}, 30 \mu\text{m}, 1 \text{ mm}, 5.7)$ in Fig. 3.

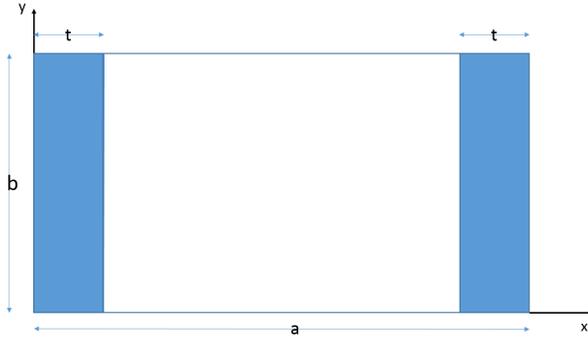


Figure 2: A transverse view of a slab-symmetric dielectric-lined waveguide (DLW). In this formulation the full outer size a is the sum of two identical dielectric layers with thickness t .

$$0 = \epsilon^2 k_{x_1}^2 \sin^2(k_{x_1} t) \sin(k_{x_2} (a - 2t)) - \epsilon^2 k_{x_2}^2 \cos^2(k_{x_1} t) \sin(k_{x_2} (a - 2t)) - 2\epsilon^2 k_{x_1} k_{x_2} \sin(k_{x_1} t) \cos(k_{x_1} t) \cos(k_{x_2} (a - 2t)), \quad (1)$$

where k_{x_1} and k_{x_2} represent the wavevectors inside and outside the dielectric material respectively and given by

$$k_{x_1}^2 = \frac{\omega^2}{c^2} \epsilon - k_z^2 - k_y^2, \text{ and } k_{x_2}^2 = \frac{\omega^2}{c^2} - k_z^2 - k_y^2. \quad (2)$$

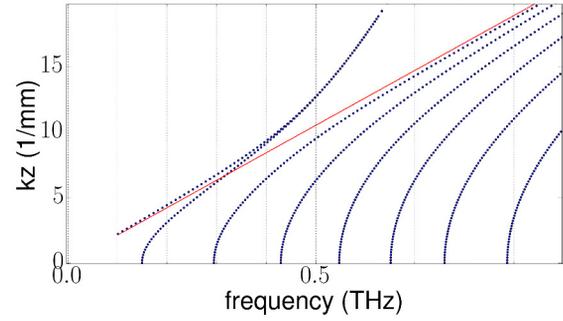


Figure 3: Dispersion curve for a DLW structure with parameters $(f, t, a, \epsilon) = (300 \text{ GHz}, 30 \mu\text{m}, 1 \text{ mm}, 5.7)$. The red line represents the light line and the different blue traces are associated to the LSM mode supported by the structure.

where k_x is the wavenumber in the dielectric plane, $k_y = \frac{n\pi}{b}$ is the wavenumber in the open plane, and k_z is the wavenumber in the longitudinal plane. Next we consider the non-relativistic equation of motion for a point charge accelerating from rest in a uniform DC electric field

$$z(t) = \frac{1}{qE_0} \sqrt{(cqE_0 t)^2 + (mc^2)^2} - \frac{mc^2}{qE_0}, \quad (3)$$

here q is the charge, E_0 is the electric field magnitude, $z = 0$ corresponds to the cathode surface, and mc^2 is the rest mass of the electron (assuming the electron is initially at rest at the cathode surface).

We then numerically explore the range of the fundamental accelerating mode (LSM₁₁) over the range where the wave velocity matches the particle velocity, i.e. for $k_z = \omega / (dz/dt)$ and retrieve from the solutions the required inner radius. To do this we need to hold constant several parameters as listed in Table 1. The corresponding inner gap variation along z appears in Fig. 4.

Table 1: Parameters Associated to the Numerical Solution of $k_z = \omega / (dz/dt)$.

parameter	symbol	value	units
electric field	E_0	100	MV/m
frequency	f	300	GHz
thickness	t	30	μm
open gap	b	1	cm
relative permittivity	ϵ	5.7	-

PRELIMINARY EXPERIMENTAL RESULTS

We developed a THz-source based on the tilted-wavefront technique (Ref. [7]) where a regeneratively amplified Ti:Saph (4 mJ/pulse) laser is used to generate single-cycle THz radiation (see Fig. 5); the THz radiation propagates through a 4-f system which allows for the placement of a

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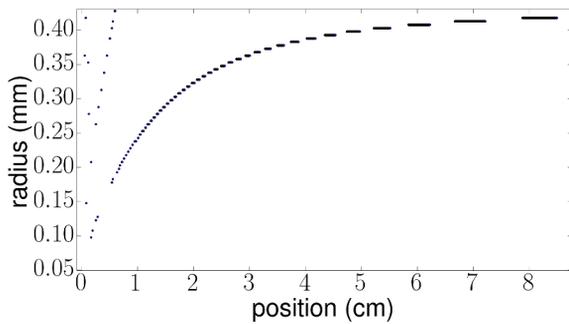


Figure 4: The inner gap profile as a function of longitudinal coordinate for the numerical solution with parameters listed in Tab. 1.

DLW at a focal point, before entering an electro-optic (EO) crystal with a probe beam whose delay is controllable via a translation stage. We present the autocorrelated THz pulse and spectrum in Fig. 6; note this data is taken without balanced detection and does therefore not exactly describe the true waveform; see Ref. [13].

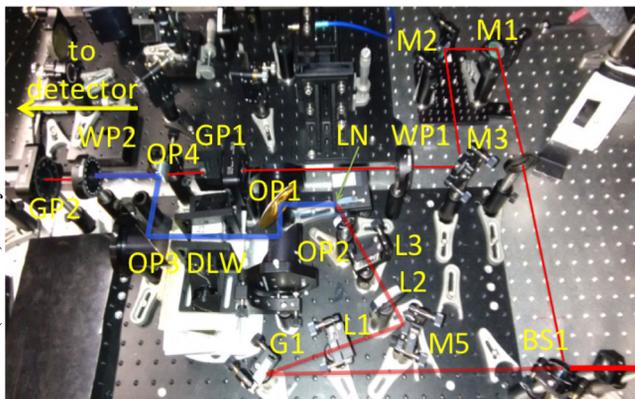


Figure 5: Experimental setup; an incoming 800 nm pulse (lower-right corner) is splitted (BS1); 95% is used for the tilted wavefront THz generation (blue trace); the rest of the beam passes through a delay stage (M1, M2, M3) before being recombined for EO detection.

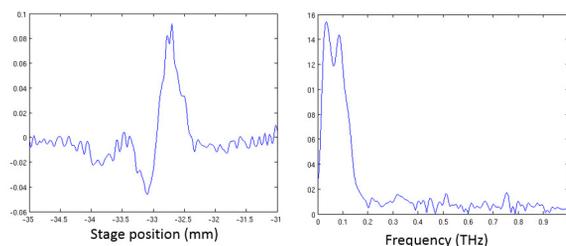


Figure 6: Data of the unbalanced electro-optical (EO) detection (left) and its corresponding spectrum (right) with no structure present. The spectrum is obtained from a fast-Fourier transform of the autocorrelation.

As a preliminary investigation into the possibility of this scheme, we investigated the dispersion in a slab-symmetric structure which was placed at the focal point shown in the experimental setup. We present experimental results for inner gaps of 1.5 mm and 2 mm in Fig. 7; the results indicate that the smaller aperture sizes lead to slower group velocities in the structure. A difficulty of this scheme is the difference of the THz-beam path with and without the DLW structure present; this ultimately leads to the smaller amplitude signal for EO detection. It should however be noted that no effort was made to match the THz pulse to the structure in this set of experiments.

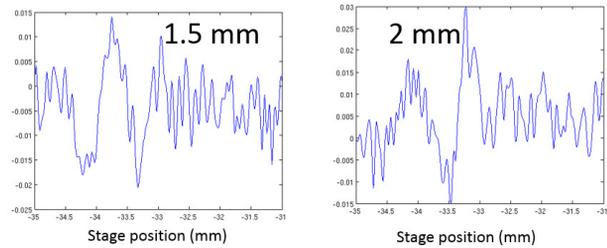


Figure 7: Unbalanced EO signal as a function of probe delay in mm. We show two inner gap results of 1.5 mm and 2 mm where there is noticeable slower group velocity in the smaller structure.

CONCLUSION

We investigated the possibility of a tapered DLW structure to “lock” the phase velocity of laser-generated THz pulse in a structure with an accelerating electron. Our preliminary theoretical results indicate it may be possible to generate such a structure by varying the gap and dielectric thickness size along the longitudinal axis of the structure. We also discuss our first experimental results of a laser-based THz generation scheme and our attempts toward measuring the dispersion in a slab-symmetric structure.

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