A THz DRIVEN TRANSVERSE DEFLECTOR FOR FEMTOSECOND LONGITUDINAL PROFILE DIAGNOSTICS

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Abstract

Progress towards a THz-driven transverse deflecting longitudinal profile diagnostic is presented. The deflector is driven with sub-picosecond quasi-single cycle THz fields generated by non-linear optical rectification. To utilize the large deflection field strength of the source for longitudinal diagnostics it is necessary to maintain the single-cycle field profile of the THz pulse throughout the interaction with the relativistic beam. Our scheme allows for the octave spanning bandwidth of the single-cycle pulses to propagate without dispersion at subluminal velocities matched to co-propagating relativistic electrons, by passing the pulse distortion and group-carrier walk-off limitations of dielectric loaded waveguide structure. The phase velocity is readily tuneable, both above and below the speed of light in a vacuum, and single-cycle propagation of deflecting fields at velocities down to 0.77c have been demonstrated.

INTRODUCTION

Measurement of coherent diffraction or transition radiation (CDR and CTR), together with methods of phase retrieval promise the ability to characterise bunch longitudinal charge density profile at the few-femtosecond level, although issues of ambiguity in phase retrieval remain. A range of electro-optic techniques have been demonstrated that provide unambiguous temporal profile, but they have yet to achieve capability in the few femtosecond regime. Transverse defecting structures are currently the only diagnostic devices that are capable of unambiguous femtosecond resolution longitudinal profile, and in addition they are capable of characterising electron-bunch 'slice' parameters which are inaccessible to the CDR/CTR and electro-optic techniques. Transverse deflecting structures however come with significant demands on location and space within an electron transport system, along with large RF infrastructure costs. Here we describe progress towards developing a THz driven transverse deflection diagnostic that offers significantly smaller footprint and flexibility in location, reduced infrastructure costs, and potential for sub-femtosecond temporal resolution.

In a transverse deflecting structure the measurement of temporal properties is driven by a time varying transverse kick and drift space and electron beam optics converting the temporally dependant kick into a transverse displacement. The achievable time resolution of the transverse streak is underpinned by the longitudinal gradient of the deflection force, $\frac{\partial F_\perp}{\partial z} \sim \omega \int dz\, E_\perp^{peak}\,(z - tc\beta_s)$, where $c\beta_s$is the phase velocity of the deflection field and the synchronised particle beam, and ω the frequency of the deflection field. For deflection fields at THz frequencies, with a 2-orders of magnitude increase in the longitudinal gradient compared to an RF driven structure with the same peak deflection fields, high time-resolution can be obtained with either significantly reduced peak field strengths, or reduction in physical interaction space (or a combination of both). Laser generated single-cycle sources are well established within the ultrafast laser and THz spectroscopy communities, and sources with 10-100MV/m field strengths in single-cycle sub-picosecond pulses have been widely demonstrated in conventional THz non-linear materials [1,2], while sources of GV/m field strengths have been demonstrated in more exotic organic materials [3]. While much of the historic development of THz sources has been driven by demand in materials science, within the accelerator community there has been significant interest in generating high-field sources for atto-second photon diagnostics. For such an application the electric field of a THz pulse provides a time dependent acceleration of soft-xray liberated photoelectrons, and from analysis of the photo-electron energy spectra the arrival time and temporal duration of the xray pulse can be inferred.

The application of THz pulses for particle acceleration has been previously proposed by several groups [4,5,6], and more recently acceleration of low energy electron beams has been demonstrated [7,8]. Deflection of relativistic beams with THz pulses has been considered recently by Fabianiska et al. [9], where it was proposed to use split ring resonators to enhance the field strength and provide a significant deflection force within the gap of the resonator. To further enhance the time resolution or provide deflection on higher energy beams it is natural to consider an extended interaction length, which introduces the necessity to match the THz carrier-wave velocity with the electron bunch velocity. Waveguide or resonant structures offer a route to slow the phase velocity to less than the velocity of light in vacuum for a 'phase-matched' interaction, but such an approach inherently comes with unavoidable dispersion and distortion of the single-cycle pulse. The dispersion gives rise to a decaying field

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strength with propagation distance, and group velocity walk-off between the THz envelope and the electron bunch. Here we demonstrate a concept that produces sub-picoseond single cycle pulses with deflecting electric and magnetic fields that propagate at velocities less than the vacuum speed of light without distortion or dispersion. The ability to match the velocity of the single-cycle deflecting fields with a particle beam makes the concept scalable to higher integrated deflection impulse through scaling of the interaction length.

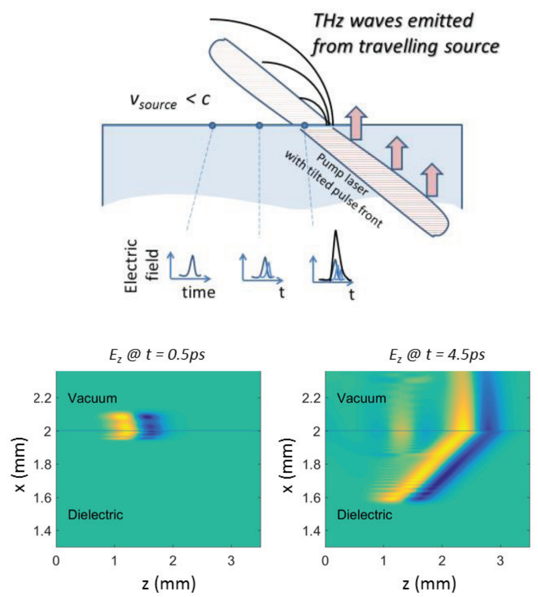

Figure 1: (Top) Conceptual schematic for the generation of a subluminal single-cycle THz pulse near the surface of a non-linear medium. The laser is propagating in a normal-incidence direction with respect to the material surface, with an effective travelling source produced by the local arrival time-delay of the tilted pulse front. The optical carrier wave-fronts are themselves travelling normal to the surface and cannot be used directly for the electron-beam interaction. (Bottom) FDTD calculation of the THz field generated by a bipolar THz source near a dielectric surface, with source velocity β_s=0.995.

THz TRAVELLING WAVE DEFLECTOR

Our scheme uses optical rectification to generate single-cycle THz pulses with transverse magnetic and electric fields co-propagating with an electron beam. To overcome the challenges of maintaining a sub-luminal velocity matching with the electron beam, and to eliminate the dispersion of the single cycle pulse, we transfer the task of propagation from the THz regime to the optical regime with a propagating travelling-wave pump laser for the THz generation; the interaction between the THz and electron beam is through 'locally' produce single-cycle electric and magnetic fields. For optical rectification sources, the temporal profile or carrier-wave of the THz pulse at the generation location follows the time derivate of the optical pulse envelope. To achieve a sub-luminal carrier wave we exploit this group-to-phase conversion together with optical pulse front tilts giving a controllable arrival-time delay at different generation locations with the non-linear generation material, as shown schematically in Figure 1. While a travelling source can also be produced simply with an optical beam incident at an oblique angle to the non-linear material, for a planar medium such an arrangement is restricted to effective velocities greater than the vacuum speed of light by the laws of refraction. The excitation of the THz sources through tilted optical pulse fronts allows coupling of the optical energy into the non-linear material at sub-luminal velocities.

The out-coupling of the THz fields from inside the source material to the vacuum region is subject to conditions of boundary continuity and refraction, and for conventional many-cycle electromagnetic waves the transition from super-luminal to sub-luminal source propagation is equivalent to meeting conditions for the critical-angle of total internal reflection and post-boundary evanescent wave propagation [10]. For the single cycle pulses generated by optical rectification the classification of the post-boundary fields as non-propagating and exponentially decaying in amplitude is no longer appropriate. To provide a detailed and quantitative picture of the single-cycle propagation from a sub-luminal source, finite difference time domain (FDTD) simulations have been undertaken.

An example calculation of emission from (and into) the surface under sub-luminal conditions is presented in Fig 1. For the calculation a travelling bipolar THz source matching that expected for optical rectification of an ultrashort laser pulse is imposed within the dielectric material. The source is given an effective velocity $c\beta_s$ which can be chosen to match the velocity of the electron bunch. In line with the optical rectification generation process there is no magnetic field source and the electric field of the source term is polarized purely in the z-direction, which also corresponds to our chosen source propagation direction. As apparent in the results of Fig. 1, after an initial stage of propagation where the field is established in the region above the source plane, a stable pulse is obtained, travelling with a wavefront normal to the surface and with a velocity set by the effective source velocity.

In Fig. 2 we present the results of a simulated interaction of a 10 MV/m travelling wave deflector with a 200 MeV electron beam. The bunch transverse distribution is for a 0.3 mm.mrad normalised emittance, typical of a RF injector. The transverse beam size at injection is Δx_{rms} = 30 μm. The particle phase space evolution was obtained through numerical solution of the relativistic equation of motion. A fourth-order Runge-Kutta algorithm was embedded within the FDTD field evaluation algorithm, with particle velocities and positions updated at each time step of the FDTD code. The position and momentum of 5000 electrons were tracked as they propagated through the

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field structure. As shown in Fig. 2, after 10mm interaction a significant transverse kick is achieved, and even with a pure drift space following the interaction a time resolution of <10 fs is predicted. A higher time resolution could be obtained through optimisation of electron beam transport or through longer interaction length.

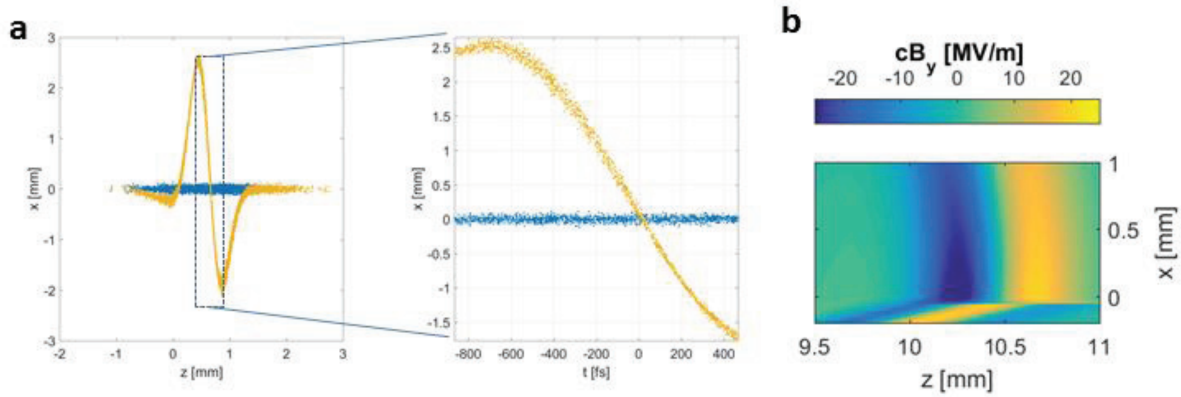

Figure 2: (a) simulated deflection imposed on a 200 MeV, ε = 0.3 mm.mrad beam with a 1 cm interaction region and a 1 metre drift. Blue: without THz pulse. Orange: with a 10 MV/m THz source driving the interaction. (b) FDTD simulations of the magnetic field produced in the vacuum region by a travelling wave THz source.

EXPERIMENTAL DEMONSTRATION

We have experimentally demonstrated a sub-luminal travelling-wave THz source meeting the criteria described above. The non-linear medium for the optical rectification THz generation was a 10mm x 10mm ZnTe single crystal, and a separate ZnTe crystal was used for electro-optic detection of the THz near the emitter surface. The probe laser for the electro-optic detection was scanned across the source, enabling a spatial and temporal mapping of the THz fields as they propagate across the surface. The experimental arrangement is shown schematically in Fig. 3a. The pulse front tilt on the optical pump beam was obtained by a diffraction grating, and the tilt was able to be tuned to give effective source velocities above and below the speed of light in vacuum. The electro-optic detection used a retro-reflection geometry, with the probe incident normally onto the generation surface and retro-reflected by the dielectric-air boundary in the detection ZnTe crystal. After interaction of the probe with the THz, the probe polarisation was analysed through a standard 'balanced detection' arrangement.

The spatial-temporal mapping of the THz evolution shown in Fig3b is for a pulse travelling at v=1.02c; As will be reported elsewhere [11], we have experimentally characterised single-cycle pulses traveling with velocities from 0.77c to 1.75c. The ZnTe non-linear media used in the demonstration reported here is not amenable to generation of very high field strengths. An alternative material, LiNbO3, is widely used material for generating >10MV/m THz pulses. While the significant disparities in optical and THz refractive indices in this material lead to it acting as a 'chenkov' non-collinear THz source, we have also devised an arrangement and demonstrated single-cycle travelling source in LiNbO3 [11].

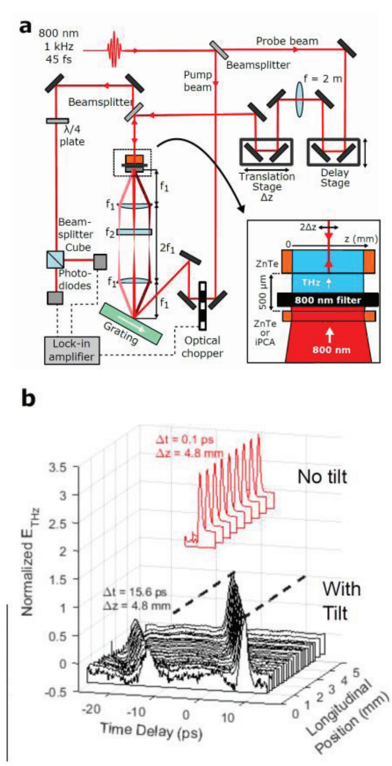

Fig. 3. (a) Schematic of the experimental system for measuring the THz travelling wave emitted from a ZnTe optical rectification source optically excited with a tilted pulse-front, and (b) plots showing the spatio-temporal mapping of the THz pulse measured 500µm above the ZnTe surface.

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