PHASE SPACE MANIPULATION WITH LASER-GENERATED TERAHERTZ PULSES

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Abstract

Ultrafast lasers are able to generate THz pulses with >1MV/m field strengths, and with controllable electric field temporal profiles. We report progress on an experiment to demonstrate the use of laser generated THz pulses to manipulate the γ-z correlation of a $\sim$20 MeV electron bunch on a sub picosecond time scale. The manipulation is achieved in free space, without external magnetic fields or undulators, by the interaction of the bunch with the longitudinal electric field of a co-propagating THz pulse in a TEM_{10}^{*}-like mode. We discuss the potential for arbitrary phase space control, including the possibility of correcting temporal jitter and driving electron beams into synchronisation with the laser.

INTRODUCTION

Phase space manipulation with THz pulses has the potential to bridge the time-scale between manipulation with nanosecond period RF, and laser and harmonic manipulation on the femtosecond scale. Laser-driven sources have a demonstrated capability of $>\ 1\,\mathrm{MV.m}^{-1}$ in the THz frequency range, rising to $100\,\mathrm{MV.m}^{-1}$ for mid-infrared wavelengths[1, 2]; the temporal profile of the THz electric field can be modified or tuned by shaping of the drive laser temporal profile, using well established laser shaping techniques; allowing electric field profile ranging from octave spanning quasi-unipolar pulses through to wavelength tunable narrowband pulses[4].

Here we report progress on an experiment to demonstrate energy modulation on a low energy (10 MeV-25 MeV) electron beam through interaction with a co-propagating THz pulse. The THz pulse is generated with a TEM_{10}^{*} like polarisation, which has a longitudinal component to the electric field on axis. Such modes have been considered before for laser vacuum acceleration (for example [5, 9, 7, 8]). A common conclusion of these past studies is the limiting role played by the faster than c phase velocity of a laser beam near the focus. For THz pulses where the electric field oscillations are of approximately 0.5ps in duration, this constraint is partially relaxed, allowing for an extended interaction region even for relatively low energy beams where it cannot be assumed that $\beta \approx 1$.

EXPERIMENT DESCRIPTION

The experimental concept is shown schematically in Fig.1. Radially-polarised THz pulses are generated using a large area GaAs photo-conductive antenna, and then directed into the electron beam transport line of the ALICE (Accelerator and Lasers in Combined Experiments) accelerator at STFC Daresbury Laboratory [3]. The THz pulse and electron beam are combined by a mirror with a 5 mm radius central aperture, and are free to co-propagate over a region exceeding 2 m in length. The THz beam is focused to a central interaction point approximately 90 cm from the combining mirror. Downstream of the interaction point, imaging of the beam on a YAG:Ce screen in the central dispersive region of the ALICE magnetic compressor is used to characterise the bunch spectrum. The experiment aims to observe a THz induced modulation on this projected energy spread measurement, which requires the accelerator to be operated in a non-standard mode, without the energy chirp needed for magnetic compression.

A YAG:Ce screen for electron bunch transverse imaging, and an intra beamline ZnTe crystal/mirror assembly for in situ electro-optic transverse and temporal THz measurements, are located at the THz focal position. The THz measurements use a laser probe split from the main laser beam and co-propagating down the accelerator beamline with relative THz-probe time delay set by an optical delay line.

As discussed by by Huang et al. [8], the Guoy phase shift of the electromagnetic wave can give rise to cancellation of any energy gain or loss as the beam transits through the focal region. While simulations indicate that for our quasi-single cycle THz pulses a measurable net energy gain or loss can be maintained, we have installed an optional aperture at the focus, allowing the THz-electron beam interaction to be interrupted through scattering of the THz pulse.

THz Source

For our initial experiments we are using a large area photo-conductive antenna. Such antennae have a high conversion efficiency from laser to THz pulse energy, although do not have the electric-field profile shaping capability that is possible with non-linear frequency difference mixing or optical rectification [4] Our antenna consists of a 75 mm diameter, 500 μm thick, GaAs wafer with a radial bias field across the surface. The bias is applied through a hemispher-

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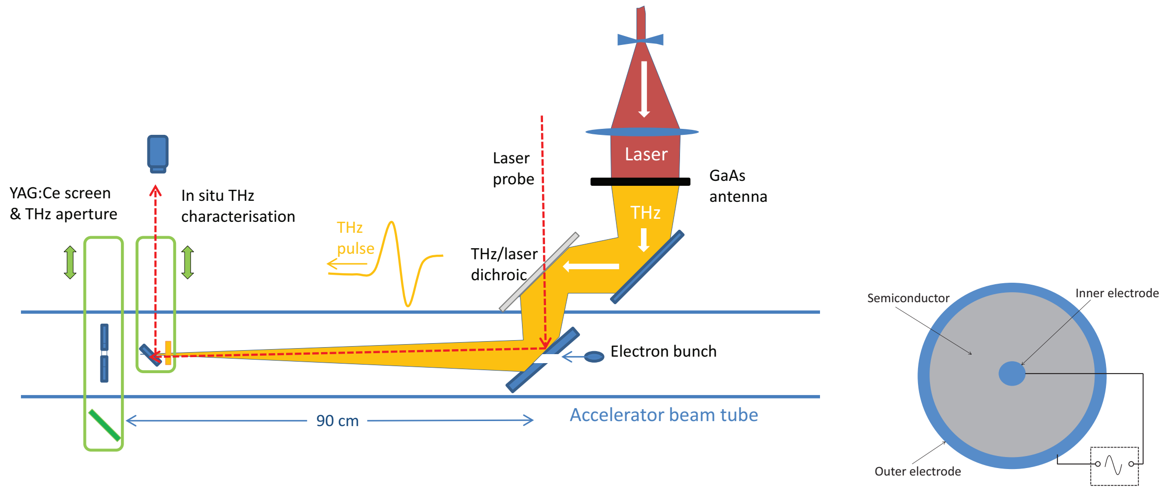

Figure 1: (Left) Schematic of the experimental arrangement. The laser is expanded to fill the large-area GaAs antenna, with a (virtual) focus of the laser beam used to establish THz focusing through a phased-antenna effect. Within the accelerator beam pipe the THz is reflected by a mirror with an aperture, and co-propagates with the electron beam. THz and electron beam diagnostics, and an optional THz beam-block are located near the THz focus. (Right) The antenna electrodes are arranged concentrically to give a radial bias field.

ical central electrode and a concentric annular outer electrode. A radial current surge is initiated by the laser excitation, and this gives rise to the transverse (radial) component of the radiated electric field pulse,

$$\mathbf{E}(\mathbf{x}, t) = \frac{1}{4\pi\epsilon_0} \int \mathrm{d}^3\mathbf{x}' \frac{1}{R} \left[\nabla' \rho - \frac{1}{c^2} \frac{\partial \mathbf{J}}{\partial t} \right]_{\mathrm{ret}} \tag{1}$$

where $\mathbf{J}$ is the surface current on the wafer. A longitudinal component to the electric field is required for it to satisfy $\nabla \cdot \mathbf{E} = 0$ in free space; a longitudinal field is produced by the net charge density ρ, which from continuity of charge $\partial\rho/\partial t = -\nabla \cdot \mathbf{J}$, will be non-zero in our situation of radially varying bias field and current. To focus the THz pulse we take advantage of the known ability of the radiated THz pulse to adopt the divergence characteristics of the excitation laser pulse; an effective 'phase array antenna' is produced by the laser pulse front so that a focusing excitation laser gives rise to a focusing THz pulse. Observed differences between the focussing of radial and linearly polarized antenna are under investigation.

To a first approximation (neglecting semiconducting saturation and field-dependent mobility), the radiated field strength is linearly dependent on the applied bias field. To maximise this applied bias, a pulsed high-voltage source is used, and can produce up to 120 kV across the electrodes without breakdown. The pulsed high voltage source is synchronised to the $\approx$2 mJ per pulse, $<$ 50 fs Ti:S laser that switches the antenna to the conducting state. While the laser is able to operate at 1 kHz, the voltage source limits us to approximately 250 Hz. The emitted field strength is also proportional to the laser pulse energy, although saturation is known to occur for laser energy densities $> 100\,\mu\mathrm{J.cm}^{-2}$. The measured dependence of the field strength on pulse energy confirms that our source is working below saturation. Using electro-optic detection as described below, the peak *transverse* field strength of the THz pulse has been measured at $\sim 0.4\,\mathrm{MV.m}^{-1}$. We expect significant improvements in THz field strength following recent improvements in the pulse energy delivered by laser system.

To allow for off-line development and characterisation of the THz source, a secondary THz generation and detection system has been constructed, closely matching the arrangement used in the accelerator but in a more accessible laser lab environment. The THz field is measured using the electro-optic effect, where the instantaneous electric field strength from the THz pulse creates an effective birefringence in a non-linear material, which in turn modifies the polarisation state of a synchronised sub-50 fs 800nm probe laser pulse. For transverse THz imaging, a large 10 mmx10 mm electro-optic ZnTe crystal is used, and the transmitted probe beam is passed through an analysing polariser, and detected by a camera that is imaging the EO crystal. The electro-optic effect is itself polarisation dependent, and for a given arrangement of crystal and incident probe polarisation, the camera imaging will be sensitive to only one linear (transverse) polarisation component of the THz pulse. An example of imaging the THz horizontal polarisation is shown in Fig. 2, where the background subtracted probe intensity is proportional to the THz electric field strength. A similar pattern, rotated by 90^0, is observed for a vertical polarisation sensitive measurement. Figure 2 also shows the temporal profile of a pulse, where the two traces refer to measurements on either side of beam center.

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The polarity reversal of the transverse field is as expected for a TEM^*_{10} mode, and is sufficient to infer the presence of a longitudinal field component on the beam axis. Future measurements using a alternative configuration of the EO detection will seek to measure longitudinal fields directly

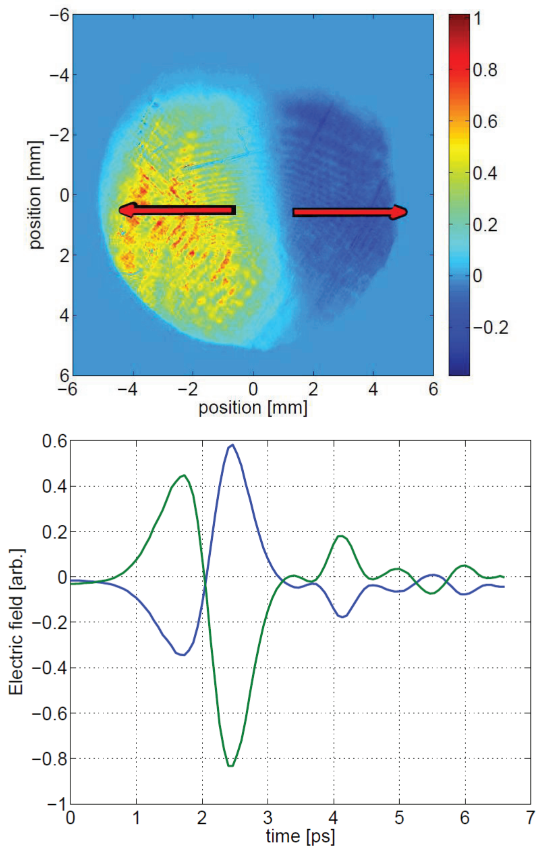

Figure 2: (Top) Imaging of the transverse electric field of a radially polarised pulse, field near the focus of the THz pulse. The electro-optic detection is polarisation dependent, and the image shows the horizontal THz field component, as indicated by the arrows. (Bottom) Measured temporal profiles, where each trace corresponds to a probe laser sampling the left or right lobes of the upper image.

Electron Beam and Diagnostics

The ALICE accelerator [3] is a superconducting energy recovery linac, with typical beam energy of $\leq$ 30 MeV, and bunch charge of 40-80pC. The bunch timing structure consists of macrobunch repetition rate of $<$ 20 Hz, with each macrobunch contains from 1 to 8000 individual electron bunches occurring at a repetition rate of 81.25/n MHz, n=1.64. The THz source is not capable of MHz repetition rates, and only interacts with a single bunch per macrobunch. To provide the best conditions for interaction with the THz pulse and observing an energy modulation, a new electron beam set-up has been implemented. First, the energy is reduced to 22.5 MeV, which is somewhat below the standard operating energy of 26 MeV. This results in a larger geometric emittance and relative energy spread, because of the reduced adiabatic damping, which results in a larger beam size at the beam observation point in the chicane. However, assuming that an interaction with a THz pulse gives a fixed absolute energy modulation, the relative energy modulation is larger at lower beam energy, which results in a larger beam size modulation. Overall, it is found that there is some modest benefit in reducing the beam energy; the improved stability in the beam at higher energy argues against reducing the beam energy significantly below 22.5 MeV. To minimise the energy spread on the electron beam, the relative phases in each of the booster and linac cavities need to be set precisely. The final step in the machine set-up involves implementing a new electron beam optics, that produces a waist in the beam size at the THz interaction point, and also minimizes the beam size at the observation point in the chicane. The latter is important, since any energy modulation will be most clearly observed if the beam size is dominated by the dispersion.

A small, but significant, macro-bunch to macro-bunch energy and energy-spread jitter has been observed in the post-interaction beam energy diagnostic. To mitigate for this jitter in forthcoming experiments, the energy spectra diagnostic has been modified to allow for the measurement of a pair of single bunch spectra, with only one bunch interacting with the THz, and the second bunch separated in time by $\approx$ 800 ns. This time separation is sufficient to suppress the overlap of the scintillation from sequential bunches on the YAG:Ce screen (the decay time was measured as $\sim$ 100 ns).

Simulations

We have carried out modelling the temporal and spatial profile of the THz pulse emitted from the antenna. This modelling includes the antenna semiconductor dynamics when excited by the laser, and the diffractive propagation of the pulse. The temporal profile of the pulse electric field changes dramatically as it propagates through the focus, a consequence of the Guoy phase shift together with the extremely broadband spectrum. For our propagation geometry, with no intermediate focus, diffraction gives rise to a frequency dependent waist, further complicating the pulse transverse profile.

In Figure 3 a simulation of the electron energy gain is shown for a simplified case of an ideal TEM^*_{10} mode transverse profile, and a quasi single-cycle pulse temporal profile. The peak transverse electric field is $\approx 1\,\mathrm{MV.m^{-1}}$, while the longitudinal electric field on axis reaches $\approx 0.3\,\mathrm{MV.m^{-1}}$ at the focus. Even for electron energies as low as 10MeV, the evolution of the interaction is dominated by the Guoy phase shift, with the slippage from $\beta < 1$ having only a minor role in the dynamics. The rapid change of polarity of the electric field near the focus switches particles from experiencing an energy loss to an energy gain. This energy gain (or loss) is maintained by both the quasi-single-cycle temporal profile of the pulse, and the reduction in field strength as the pulse propagates beyond the focus.

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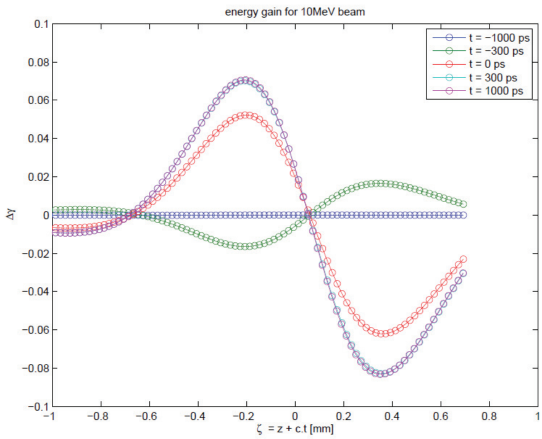

Figure 3: The energy modulation imposed on 10 MeV on-axis electrons by a quasi-single cycle TEM^*_{10} pulse. The various plots are snap-shots of the electron beam energy as it propagates towards and through the focus of the co-propagating THz pulse. Time $t = 0$ corresponds to the THz pulse at the focus, while $t > 0$ corresponds to when the pulse and electron beam have propagated beyond the focal region.

STATUS & OUTLOOK

The entire experimental system has been commissioned, and preliminary experiments aimed at observing the expected THz induced energy modulation have been undertaken. No THz modulation has yet been observed, although we believe improvements in the system which have been put in place will allow us to make a successful measurement during late 2012.

Laser-driven Terahertz sources have many characteristics that make them attractive for phase-space manipulation. The picosecond periods of Terahertz pulses match the time scale of bunch lengths in conventional accelerators, and allows for "bunch slicing" schemes without the few femtosecond oscillatory smearing of optical laser bunch slicing. Terahertz pulses generated through non-linear optical frequency mixing, optical rectification, and photoconductive antenna may have octave spanning spectral extent, and the electric field temporal profile of these broadband pulses can readily be tuned and controlled through established laser temporal shaping techniques.

FELs often strive for synchronisation with external lasers. If the THz profile is shaped to provide a chirp to the electron bunch, with the addition of a matched R_{56} after the interaction the timing errors of the bunch with respect to the Terahertz pulse can be corrected. Exploiting the intrinsic femtosecond level synchronization of the THz electric field phase to the drive laser, Terahertz bunch manipulation has the potential to actively drive the bunch into synchronisation with external lasers.

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REFERENCES

[1] F. Blanchard, L. Razzari, H.-C. Bandulet, G. Sharma, R. Morandotti, J.-C. Kieffer, T. Ozaki, M. Reid, H. F. Tiedje, H. K. Hauge and F. A. Hegmann. Opt Express **15** 13212 (2007).

[2] A. Sell, A. Leitenstorfer, R. Huber Opt. Lett. **33** 2767 (2008).

[3] http://www.stfc.ac.uk/ASTeC/Programmes/Alice/35997.aspx

[4] J. Ahn, A. V. Efimov, R. D. Averitt, A. J. Taylor. Opt. Express **11** 2486 (2003).

[5] E. Esarey, P. Sprangle, J. Krall, "Laser acceleration of electrons in vacuum" Phys. Rev. E **52** 5443 (1995).

[6] M.O. Scully and M.S. Zubairy, Phys. Rev. A **44** 2656 (1991).

[7] Y.I. Salamin, Opt. Lett. **32**, 90, (2007).

[8] Z. Huang and G. Stupakov, M. Zolotorev. Phys. Rev. ST **7** 011302 (2004).

[9] F. Caspers, E. Jensen, "Paricle accleration with the axial electrioc field of a TEM_{10} mode laser beam" CERN/PS 89-69 1989).

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