EXPERIMENTAL DEMONSTRATION OF ULTRASHORT μJ-CLASS PULSES IN THE TERAHERTZ REGIME FROM A LASER WAKEFIELD ACCELERATOR*

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Abstract

We demonstrate generation of ultrashort high peak electric field THz pulses of few μJ using laser wakefield accelerators (LWFA), which are novel, compact accelerators that produce ultrashort electron bunches with energies up to 1 GeV [1] and energy spreads of a few percent. Laser pulses interacting with a plasma accelerate electrons which upon exiting the plasma emit terahertz pulses via coherent transition radiation (CTR) in a wide bandwidth ($\sim 1-10$ THz) yielding terahertz pulses of high intensity [2]. In addition to providing a non-invasive bunch-length diagnostic [3] of the LWFA, these high peak power THz pulses are suitable for high field (MV/cm) pump-probe experiments. Here we present work on maximizing the peak field of the THz pulses by optimizing the optical mode and the energy produced by CTR for which we demonstrate the importance of pre-pulse control on the main drive laser beam.

THZ RADIATION FROM A LWFA

Experiments were conducted using a 10 TW Ti:sapphire laser system at the LOASIS facility, LBNL. An 800-nm laser pulse ($\geqslant 40$ fs, up to 0.5 J) is focused ($w_0 \simeq 6\mu$m) onto Helium gas ($n_e \sim 4 \times 10^{19}$ cm^{-3}) from a supersonic nozzle [4]. A $\sim$ 1 nC electron bunch, generated by the laser-plasma interaction, propagates through the plasma-vacuum interface, producing CTR (THz) pulses. A portion of the THz radiation (0.178 steradian) is collected and collimated (Fig. 1) by an off-axis parabola (OAP2) and refocused by another OAP (OAP3).

Theoretical analysis [2] of the generation of CTR by the electron bunch reveal a strong dependence of the THz peak power on the bunch charge, plasma size, bunch length and electron energy. Since each electron in the bunch emits independently, the radiation only constructively interferes if the bunch is shorter than the emitted wavelength. The bunch length (< 50 fs) thus sets the cut-off frequency of the THz spectrum (typically $5-10$ THz). Sensitivity to plasma size is caused by diffraction. If the source is smaller than the diffraction limit, the THz energy will not couple efficiently to the propagating mode, setting the cut-on frequency of the spectrum ($0.1-0.2$ THz).

However, bunch duration and plasma size are difficult to vary. Therefore, we concentrated on optimizing electron bunch energy and charge by employing pre-pulse control of the driver beam and maximizing the peak electric field by controlling the THz mode quality. Pressure, gas jet longitudinal position and driver beam compression were also scanned to optimize the LWFA performance. A full analysis of the complex dependence of the THz on these parameters is currently in progress.

Control of THz mode profile

The amount of CTR produced by a LWFA is characterized by its spatial beam profile, temporal waveform and spectrum, and its total energy. The THz imaging optics were motorized to allow *ex-situ* optimization of the focused THz modes [5], and hence of the THz peak electric fields.

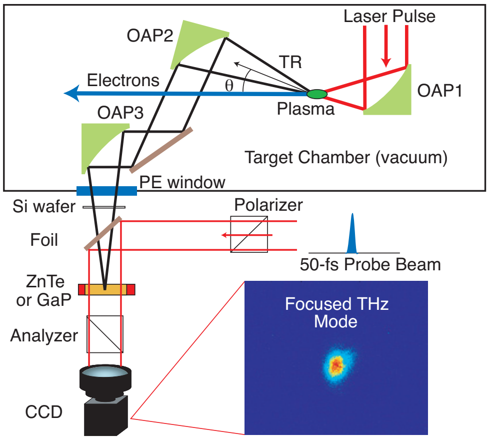

Figure 1: Setup for THz spatial profile measurement through E-O sampling in a GaP or ZnTe crystal, using a 50 fs probe beam.

The two-dimensional (2D) electro-optic (E-O) diagnostic of the THz spatial profile (Fig. 1) overlaps a collimated, linearly polarized probe beam with the focused THz pulse in an E-O active crystal (*e.g.* GaP or ZnTe $\langle 110 \rangle$). The high amplitude, low frequency field of the THz acts as an electrical bias on the crystal, inducing a localized birefringence. Also incident on the crystal is a collimated laser probe beam ($\lambda_0 = 800$ nm) that overfills the THz spot at the crystal plane. The probe polarization is rotated by the

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THz-induced birefringence and a camera reads out the THz spatial mode by looking at the light making it through a second crossed polarizer. THz mode profiles produced are round and Gaussian with $1/e^2$ radius $\simeq 0.52$ mm, and have little or no observable aberration.

CONTROL OF THE LASER PRE-PULSE

We evaluated three different methods of pre-pulse control. In the first, we introduced a second colinearly propagating laser pulse (“igniter” beam) to act as a controllable pre-pulse with adjustable timing. In the second method, we adjust the timing of a Pockels cell to selectively attenuate laser energy arriving prior to the main pulse. In the last method, we implemented a contrast improvement system based on the cross-polarized wave (XPW) technique [6].

Controllable pre-pulse: igniter beam

By introducing a precursor (igniter) pulse with controllable timing, the plasma is pre-ionized mitigating the effects of any pre-existing pre-pulses on the main drive beam. In addition, a guiding structure is created. Both of these effects enhance the operation of the accelerator, producing greater charge, more energetic and shorter electron bunches [7]. A bolometer was used to characterize effects of this beam.

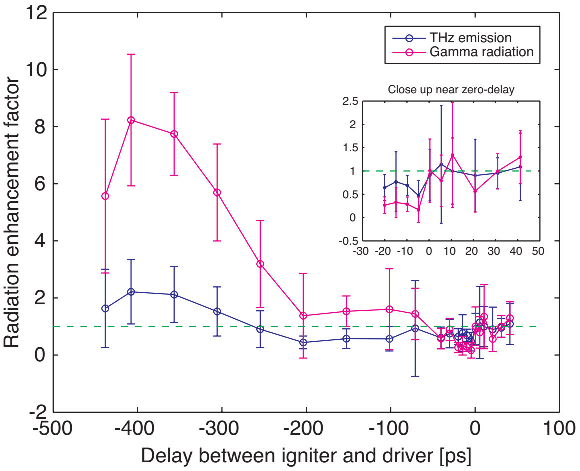

Figure 2: THz and gamma radiation enhancement as a function of the arrival time of the igniter beam.

At small negative delays (igniter arriving just before driver), the igniter has a deleterious effect, similar to the pre-existing pre-pulses, creating a partially ionized volume which disrupts the propagation of the driver beam and diminishes THz radiation by $\sim 50\%$. However, when the igniter comes more than 200 ps before the drive beam, an enhancement appears (Fig. 2). This timescale is correct for hydrodynamic effects to play a role [8], making it reasonable to attribute the enhancement to guiding of the main drive beam, resulting in higher electron beam energy (confirmed by the gamma radiation) and possibly shorter electron bunches (less space charge effects).

Pre-pulse filtering: Pockels cell

An alternative approach is to filter out pre-existing pre-pulses by using a Pockels cell to attenuate laser energy arriving prior to the main pulse. The Pockels cell switching happens on a nanosecond time-scale and the procedure represents a compromise between eliminating pre-pulses and cutting into the main pulse (Fig. 3). The Pockels cell timing was scanned with and without an igniter beam to find the optimum. With the igniter, we managed to enhance the THz radiation energy by a factor 5.

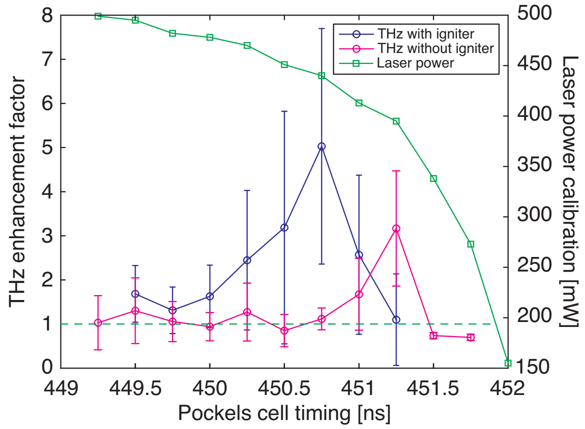

Figure 3: Control of the THz signal by controlling the laser front end ejection (Pockels cell timing), with and without additional igniter pulse. The top curve shows the decrease in laser energy as the Pockels cell cuts into the main pulse.

The results above show that a laser pre-pulse control on a sub-nanosecond time scale is critical to improve the performance of both LWFA and THz source. We therefore implemented a laser contrast improvement system which is described in the next section.

Pre-pulse filtering: XPW

The cross-polarized wave (XPW) technique is based on cubic anisotropy induced by intense laser pulses in nonlinear crystals with high third-order non-diagonal coefficients, such as BaF_2. The nonlinear crystal is placed in between two crossed polarizers. The polarization rotation is intensity dependent. Therefore, the main pulse is transmitted with high efficiency through the analyzer. The smaller pre-pulses and pedestal do not create enough induced anisotropy and hence are suppressed. This technique can achieve laser pulse contrast up to 10^{-11} [9]. Before and after the implementation, a contrast measurement using a third-order cross-correlator device (“Sequoia” from Amplitude Technologies, Fig. 4) was performed. A gain of 3 orders of magnitude was achieved on the -0.75 ps pre-pulse and up to 4 orders on the other pre-pulses.

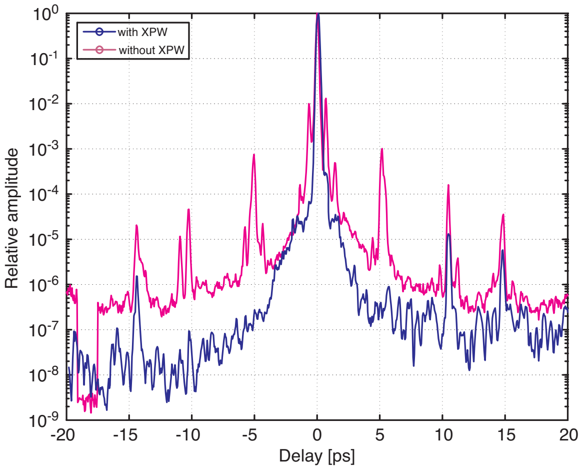

Figure 4: Optical contrast at the interaction point before (upper curve) and after (lower curve) installation of the XPW contrast filter.

Effect of contrast enhancement on THz

A new set of experiments done with the contrast-enhanced laser show not only a dramatic increase in the production of charge, THz (a factor ~ 4), gammas and neutrons, but also a dramatic decrease in shot-to-shot fluctuations, from 100% to 10%.

Preliminary optimization has already allowed us to reach several μJ of THz. For these measurements we used a Golay cell which is much smaller than a conventional bolometer, but $3-4$ orders less sensitive. Its calibration (0.59 μJ/V) in the THz band was done at the FELIX facility in the Netherlands [10]. Because saturation occurs at 1.44 V, its full-scale detection limit is only 0.85 μJ.

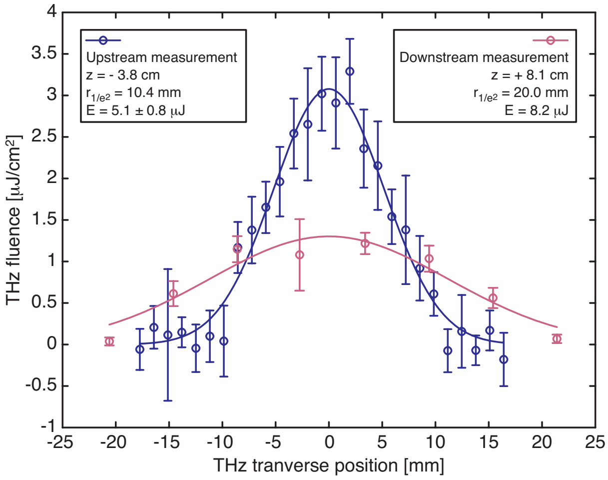

Figure 5: THz spatial energy distribution at an upstream position from the focus (scanning a slit), and a downstream position position (scanning the Golay cell).

THz energy was sufficient to strongly saturate the Golay cell. Thus, to recover the energy the detector was moved 8.1 cm downstream of the THz focus until the signal was reduced below saturation. The detector was then scanned transversely to recover the radial distribution of the THz energy, and hence the total energy (assuming cylindrical symmetry of the THz beam) which was calculated to be 8.2 μJ.

In a second technique, the Golay cell was placed at the THz focus, and a narrow (0.9 mm) slit aperture was scanned across the THz beam at a plane 3.8 cm upstream of focus. The resulting distribution of energy density (Fig. 5) was then integrated to yield a full energy of the beam of 5.1 μJ, in reasonable agreement with the first technique. It should be noted that the second technique employs no assumptions about the shape of the beam profile, making it theoretically more accurate. In fact, theory predicts that there will be strong chirping (*i.e.* variation in frequency) of the beam in the direction perpendicular to that scanned; it is possible that the mode profile is not perfectly axis-symmetric, accounting for some of the discrepancy in the two measurements.

CONCLUSION

We have demonstrated the ability to generate THz pulses with several μJ of energy and to focus them with good mode quality . We have also examined the relevance of the pre-pulse dynamics on the performance of the LWFA and on the generation of THz radiation. We find that the effect of the pre-pulse is significant and that the use of laser contrast enhancement is crucial for achieving both high energy and good stability.

REFERENCES

[1] W. P. Leemans *et al.*, Nature Phys. 2, 696 (2006)

[2] C. B. Scroeder, E. Esarey, J. van Tilborg and W. P. Leemans, Phys. Rev. E 69, 016501 (2004)

[3] J. van Tilborg *et al.*, Phys. Rev. Lett. 96, 014801 (2006)

[4] C. G. R. Geddes *et al.*, Phys. Rev. Lett. 100, 215004 (2008)

[5] G. R. Plateau, E. Esarey, C. G. R. Geddes, W. P. Leemans, N. Matlis, C. B. Schroeder, J. van Tilborg, C. Tóth, Proc. Particle Accel. Conf. THPMN114 (2007)

[6] A. Jullien, O. Albert, F. Burgy, G. Hamoniaux, J.-P. Rousseau, J.-P. Chambaret, F. Augé-Rochereau, G. Chriaux and J. Etchepare, Opt. Lett. 30, 920 (2005)

[7] C. G. R. Geddes *et al.*, Nature 431, 538 (2004)

[8] T. R. Clark and H. M. Milchberg, Phys. Rev. Lett. 78, 12, 2373 (1997)

[9] V. Chvykov, P. Rousseau, S. Reed, G. Kalinchenko and V. Yanovsky, Opt. Lett. 31, 1456 (2006)

[10] E. Chiadroni, H. Delsim-Hashemi, L. Fröhlich and O. Grimm, Report on the visit at FELIX, FOM Rijnhuizen, Technical report (2005)