Optimization of THz Radiation Generation from a Laser Wakefield Accelerator

G. R. Plateau[*,†], N. H. Matlis[*], O. Albert[**,†], C. Tóth[*], C. G. R. Geddes[*], C. B. Schroeder[*], J. van Tilborg[*], E. Esarey[*,‡] and W. P. Leemans[*,‡]

[*]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, U.S.A.*
[†]*École Polytechnique, Palaiseau 91128, France*
[**]*Laboratoire d'Optique Appliquée, Palaiseau 91761, France*
[‡]*University of Nevada, Reno, Nevada 89557, U.S.A.*

Abstract. Ultrashort terahertz pulses with energies in the μJ range can be generated with 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 create accelerated electrons which upon exiting the plasma emit terahertz pulses via transition radiation. Because these electron bunches are ultrashort ($<$ 50 fs), they can radiate coherently (coherent transition radiation – CTR) in a wide bandwidth ($\sim$ 1 - 10 THz) yielding high intensity terahertz pulses [2]. In addition to providing a non-invasive bunch-length diagnostic [3] and thus feedback for the LWFA, these high peak power THz pulses are suitable for high field (MV/cm) pump-probe experiments. Here we present energy-based measurements using a Golay cell and an electro-optic technique which were used to characterize these THz pulses.

Keywords: T-rays generation, CTR, LWFA, Beam diagnostics
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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 ($n_e \sim 4\times10^{19}$ 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 reveals 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 interferes constructively 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.

Alternatively, maximizing the radiated energy can be done by controlling the THz mode quality and by optimizing the energy and the charge of the electron bunch via

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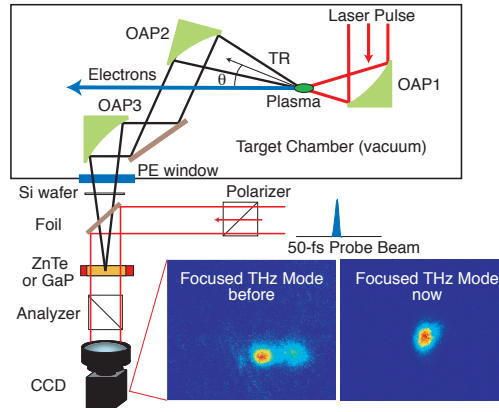

FIGURE 1. Setup for THz spatial profile measurement through E-O sampling in a GaP or ZnTe crystal, using a 50 fs optical probe beam.

pre-pulse control for the driver beam. Pressure, gas jet longitudinal position and driver beam compression can be scanned to optimize the LWFA performance. We next present results on optical mode measurements (THz peak electric field optimization) and on the study of three different techniques for pre-pulse control and their impact on the THz pulse energy.

Control of the THz mode profile

CTR produced by a LWFA is characterized through measurement of its spatial beam profile, temporal waveform and spectrum, and its total energy.

A two-dimensional (2D) electro-optic (E-O) diagnostic [5] was used to measure the THz spatial profile (Fig. 1). A collimated, linearly polarized probe beam overlapped 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 acted as an electrical bias on the crystal, inducing a localized birefringence. Also incident on the crystal was a collimated laser probe beam ($\lambda_0 = 800$ nm) that overfilled the THz spot at the crystal plane. The probe polarization was rotated by the THz-induced birefringence and a camera read out the THz spatial mode by looking at the light passing through a second crossed polarizer. The THz imaging optics were motorized to allow *ex-situ* optimization of the focused THz modes [6], and hence of the THz peak electric fields. THz mode profiles produced were round and Gaussian with $1/e^2$ radius $\simeq 0.52$ mm, and had little or no observable aberration.

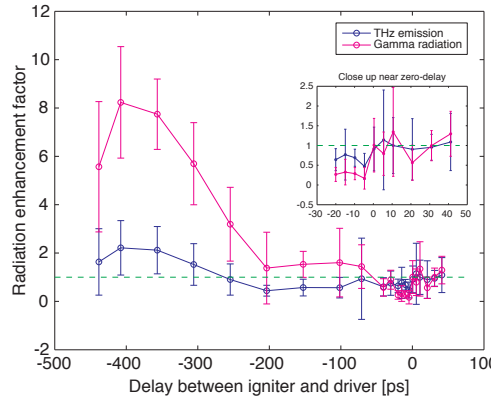

FIGURE 2. THz and gamma radiation enhancement (defined as the ratio of signals with and without the presence of igniter pulse) as a function of the arrival time of the igniter beam. Negative delay corresponds to earlier arrival of the igniter pulse.

OPTIMIZING THE ELECTRON BUNCH PERFORMANCE VIA PRE-PULSE CONTROL

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 adjusted 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 [7]. Enhancement factors > 5 have been achieved for the THz pulse energy by implementing the XPW.

Controllable pre-pulse: igniter beam

By introducing a precursor (igniter) pulse with controllable timing, the plasma is pre-ionized and a guiding structure is created. This effect enhances the operation of the accelerator, producing greater charge, more energetic and shorter electron bunches [8, 9]. A bolometer was used to characterize effects of this technique on THz generation.

At small negative delays (igniter arriving just before driver), the igniter has a deleterious effect, diminishing THz radiation by $\sim 50\%$. One explanation is the diffraction of the driver beam by the pre-plasma formed by the igniter [10]. For longer delays, more than 200 ps before the driver beam, an enhancement appeared (Fig. 2) and peaking at ~ 400 ps. This timescale is correct for hydrodynamic effects to play a role [11, 8], making it reasonable to attribute the enhancement to guiding of the driver beam, resulting in higher electron beam energy (confirmed by the increased level of gamma radiation) and possibly shorter electron bunches (reducing space charge effects).

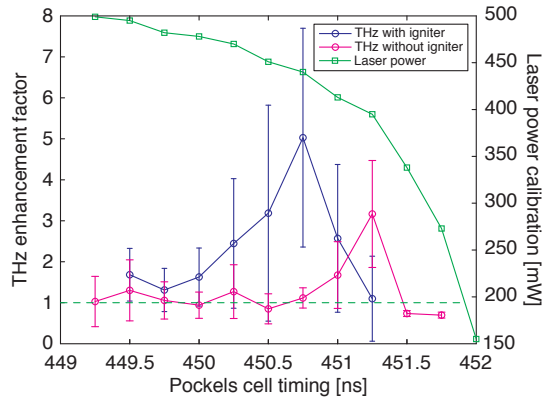

FIGURE 3. Control of the THz signal by controlling the laser front end ejection (Pockels cell timing), with and without additional igniter pulse. The top curve shows the decrease in laser energy as the Pockels cell cuts into the main pulse.

Pre-pulse filtering: Pockels cell

An alternative approach is to filter out ASE (amplified spontaneous emission) and 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 therefore 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 energy by a factor 5.

The results above show that 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} [12]. Before and after the implementation, contrast measurement using a third-order cross-correlator device ("Sequoia" from Amplitude Technologies) was performed. A contrast enhancement Fig. 4(a) of 3 orders of magnitude was achieved on the -0.75 ps pre-pulse and up to 4 orders on the other pre-pulses.

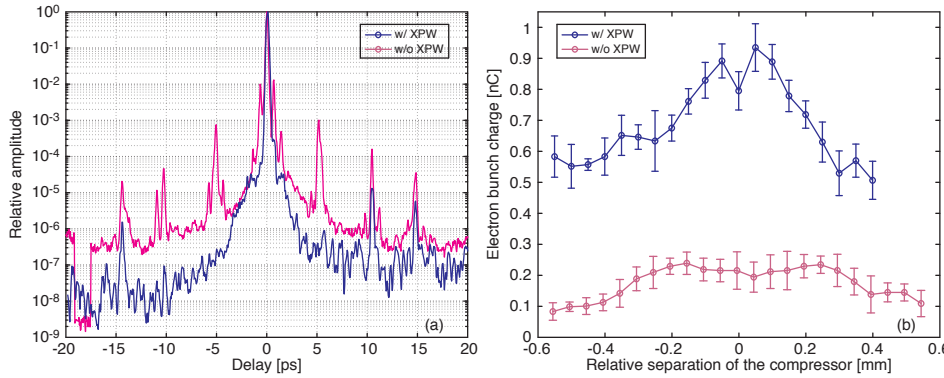

FIGURE 4. Comparisons of (a) laser contrasts at interaction and (b) scans of electron bunch charge vs. laser pulse compression done before the XPW upgrade and after the XPW implementation. On the left side (a), the remaining pre-pulse and post-pulses are instrument artifacts. On the right side (b), the pulse compression is expressed in terms of the relative separation of the compressor gratings. Optimum compression is obtained at zero.

Effect of contrast enhancement on THz emission

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

For the THz energy 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 [13]. Because saturation occurs at 1.44 V, its full-scale detection limit is only 0.85 μJ.

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 was then integrated to yield the energy in the whole beam, which was 5.1 μJ, close to the value deduced from 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 $> 5\mu$J of energy and to focus them with good mode quality, resulting in $\simeq 0.3$ MV/cm peak electric field. 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.

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