Observation of THz emission from a laser-plasma accelerated electron bunch crossing a plasma-vacuum boundary

W.P. Leemans, C.G.R. Geddes,* J. Faure, Cs. Tóth, J. van Tilborg,† C.B. Schroeder, E. Esarey, G. Fubiani,‡ D. Auerbach, B. Marcelis, M.A. Carnahan, R.A. Kaindl, J. Byrd, and M.C. Martin
Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720
(Dated: April 14, 2003)

Coherent radiation in the 0.3–3 THz range has been generated from femtosecond electron bunches at a plasma-vacuum boundary via transition radiation. The bunches produced by a laser-plasma accelerator contained 1.5 nC of charge. The THz energy per pulse within a limited 30 mrad collection angle was 3–5 nJ and scaled quadratically with bunch charge, consistent with coherent emission. Modeling indicates that this broadband source produces about 0.3 μJ per pulse within a 100 mrad angle, and that increasing the transverse plasma size and electron beam energy could provide more than 100 μJ/pulse.

PACS numbers: 07.57.Hm,41.75.Ht, 41.75.Jv

Terahertz radiation (or T-rays) is non-ionizing electromagnetic radiation with sub-millimeter wavelength, which can be used to non-invasively measure optical properties of materials with hundred micron resolution. T-rays have applications [1, 2] in biological imaging, material screening, semi-conductor imaging, surface chemistry, and high-field condensed matter studies. High peak power radiation is required for rapid two-dimensional imaging [3] and for non-equilibrium and non-linear studies that require MV/cm fields [2]. Laser-triggered solid-state based sources of THz radiation have been developed that rely on switched photoconducting antennas (e.g., [4] and references therein) or optical rectification of femtosecond pulse trains [5]. Large aperture biased GaAs structures, operated at 1 kHz repetition rate, have produced on the order of 0.5 μJ/pulse [6]. Most other sources using either laser switched structures or optical rectification have operated at high frequency (10's of MHz) with μW–mW level average power.

Alternatively, THz radiation can be generated from electron beams (e-beams) through various methods, including bending in a magnetic field (synchrotron radiation) [7] and by traversing a medium with a discontinuity in dielectric properties (transition radiation) [8, 9]. The radiation is coherent when electrons in a bunch emit in phase, which requires that the bunch structure be shorter than the radiation wavelength λ. The coherent radiation intensity scales quadratically with the total charge, rather than linearly as in the case of incoherent emission. Conventional accelerators can produce sub-ps bunches containing pC's of charge [10, 11], operating at high repetition rate and hence generating high average T-ray power [12]. They also provide a solution for producing T-rays with a narrow divergence angle, given by $1/\gamma$, where $\gamma = 1/\sqrt{1-(v/c)^2}$ is the relativistic Lorentz factor, v the electron velocity, and c the speed of light. However, bunch lengthening and emittance growth due to space charge effects limit the charge per bunch in these short bunches to pC's and, hence, limit the radiated peak power. The 0.5 μJ/pulse produced by the linac-based source [12], and present solid state T-ray sources [6] (limited by material damage), is insufficient for high field applications that require multi-MeV/cm. Achieving high pulse energy is therefore an important challenge that will enable numerous applications requiring intense T-rays.

In this Letter we present first experimental results and supporting calculations of an electron beam based THz source that has the potential to achieve unprecedented levels of energy per pulse by relying on two novel components: (1) extremely dense, sub-ps electron bunches produced with a table-top laser-plasma-based accelerator and (2) the production of coherent transition radiation at the boundary between a plasma and vacuum. Laser wakefield accelerators (LWFA) rely on the excitation of large amplitude longitudinal plasma waves with an intense laser and can operate with 1–100 GV/m accelerating gradients. These large fields can accelerate more than 10^{10} background electrons to relativistic energies [13, 14], albeit with 100% energy spread. LWFA's can produce ultra-short (femtosecond) bunches containing nC's of charge because space charge effects are mitigated inside the accelerator structure through shielding provided by the background ions in the plasma. This is not the case in a conventional accelerator and limits the achievable peak current in those accelerators. To produce high peak power coherent radiation, emission must occur before space charge and energy spread effects cause bunch density reduction during propagation in vacuum. This requirement is naturally satisfied by generation of transition radiation at the plasma-vacuum boundary of the LWFA, provided certain criteria regarding transverse size and longitudinal gradient are satisfied.

THz-emission from laser excited plasmas had been reported earlier [15] and was attributed to the excitation of radial plasma density oscillations at a plasma density resonant with the laser pulse duration. This mechanism predicts very low emission at densities used in our experiments and does not rely on production of acceler-

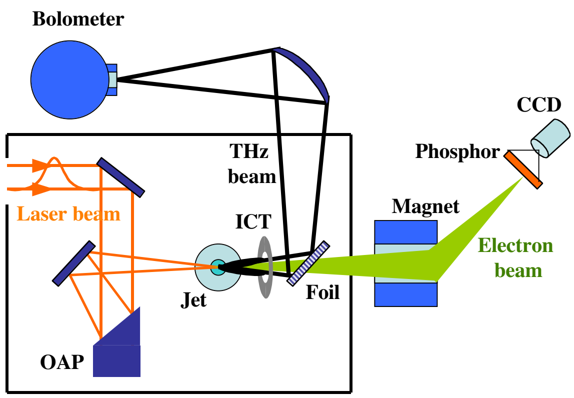

FIG. 1: Schematic of the experimental set-up. High peak power laser pulses entered the vacuum chamber and were focused onto a high pressure pulsed He gas jet using an off-axis parabola (OAP). An integrating current transformer (ICT) measured the amount of accelerated electrons (charge). A metal-coated foil directed the THz radiation outside the vacuum chamber onto a spherical mirror that focused the radiation onto a Helium cooled bolometer. The electron energy distribution was measured using an imaging magnetic spectrometer to momentum disperse the e-beam onto a phosphor screen that was imaged by a CCD camera.

ated electrons. In addition, the far-field radiation pattern shows no emission in the forward (laser) direction. Evidence for incoherent transition radiation has been observed in the optical regime from fast electron generation in laser interactions with solid targets [16]. Coherent transition radiation at longer wavelengths could potentially be generated in laser-solid target experiments from the interaction of the fast electrons with the rear-side of the solid target.

In our proof-of-principle experiments (a schematic of the set-up is shown in Fig. 1), relativistic e-beams were generated by focusing laser pulses from a Ti:Al_2O_3 laser operating at 800 nm to a waist $w = 6$ μm onto a 2 mm long supersonic Helium gas jet inside a vacuum chamber [17]. The laser pulses had a full-width-half-maximum (FWHM) duration $\tau_{\rm FWHM} \geq 50$ fs and a peak power level $P \leq 8$ TW. The charge per bunch and e-beam spatial profile were measured using an integrating current transformer (ICT) and a phosphor screen, respectively. The energy distribution was obtained using an imaging magnetic spectrometer and a a phosphor screen with CCD camera and can be well-fitted by a power law distribution $\propto \gamma^{-1.6}$. The plasma density profile, measured with a folded-wave interferometer using 400 nm wavelength, 50 fs duration laser pulses, had a typical transverse size of 100 μm$\pm$15 μm. Radiation in the 0.3–3 THz range was reflected out of the vacuum chamber through a window using a 5 μm thick metal coated nitrocellulose foil 30 cm from the gas jet. (Although transition radiation will be generated when the beam propagates through this foil, the emission is incoherent due to bunch lengthening [18] and transverse beam size increase at that location, measured with a phosphor screen.) The radiation then propagated in air and through laser beam attenuators, and was focused with an f/30 metal coated spherical mirror onto a cooled (4.2 K) Si-based bolometer, equipped with an internal 3 THz low-pass filter, to measure the radiated energy. The spectral transmission properties of all solid materials used in the T-ray path were measured using a ZnTe based optical rectification system [19].

The bunch charge was varied by changing either the laser pulse duration or the position of the gas jet with respect to the laser beam focal position [14, 17]. The quadratic dependence of the peak amplitude of the bolometer signal versus bunch charge is shown in Fig. 2 and is consistent with coherent emission of radiation. The large vertical error bars on the signal are believed to be due to pointing fluctuations of the e-beam on the order of 10 mrad, which is comparable to the 30 mrad collection half-angle of the bolometer. The angular distribution of the coherent radiation (See Fig. 3) has a minimum in the direction of the e-beam, and therefore is sensitive to fluctuations in e-beam pointing. Increasing the collection angle will hence significantly reduce the fluctuations.

Modelling of the radiation process can be done by assuming that the plasma (with dielectric constant $\epsilon = 1 - \omega_p^2/\omega^2$, where ω_p and ω are the plasma and radiation frequencies, respectively) is equivalent to a conductor with a sharp conductor-vacuum boundary. The transition radiation will be generated by e-beam induced polarization currents at plasma densities below critical for the radiation wavelength. The plasma density profile used in the LWFA experiments had a sufficiently large gradient such that the dielectric constant satisfied $|\epsilon| \gg 1$ within a distance of order a skin depth, and therefore the plasma can be well-modeled as a conductor for frequencies $\omega < \omega_p$. In addition, provided the plasma scale length is short compared to the formation length, we expect the dielectric interface to radiate as if it were a sharp dielectric-vacuum boundary. The radiated energy W_e per unit solid angle $d\Omega$ and frequency range $d\omega$ by a bunch consisting of N_e electrons travelling normal to the plasma-vacuum boundary is [20]

$$\frac{d^2W_e}{d\omega d\Omega} = \frac{r_e}{\pi^2 c}(m_e c^2) N_e (N_e - 1) \sin^2\theta \times \left| \int du g(u) F(\omega, \theta, u) \frac{u(1+u^2)^{1/2}}{(1+u^2\sin^2\theta)} D(\omega, \rho, \theta, u) \right|^2 , \quad (1)$$

where r_e is the classical electron radius, m_e is the electron rest mass, θ is the angle of observation with respect to the e-beam propagation direction, $u = \gamma v/c$ is the normalized electron momentum, and $g(u)$ is the normalized

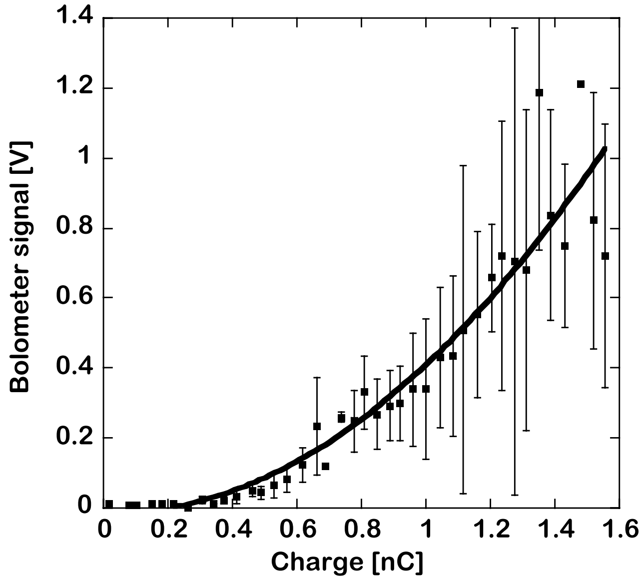

FIG. 2: Bolometer voltage vs. charge per bunch for a 30 mrad collection half-angle. Each square represents an average of 50 experimental shots, with rms variation as error bar. The solid line is a quadratic fit to the data, indicating coherence of the radiated signal. The bolometer (Infrared Laboratories) had a voltage responsivity $S = 2.73\times10^8$ V/W and thermal conductivity $G = 17.01$ μW/K. Since the radiation bursts are much shorter than the bolometer time constant, $\tau_{\rm bolo} = 0.33$ ms, the detector operates as a calorimeter. The absorbed energy is then given by: $E_{\rm absorbed} = G\tau_{\rm bolo}\Delta V_{\rm bolo}/(R\eta_{\rm bolo}) = 4.0 \times \Delta V_{\rm bolo}$ (in pJ), where $R = S \times G = 4.64$ is the induced voltage per K of temperature rise (in V/K), $\Delta V_{\rm bolo}$ is the height of the voltage pulse (in V), and $\eta_{\rm bolo} \sim 0.3$ is the bolometer efficiency. The radiated energy is $E_{\rm radiated} = E_{\rm absorbed}/\eta_{\rm coll}$, where $\eta_{\rm coll}$ is the overall collection efficiency of the system.

e-beam momentum distribution. Here

$$F = \int dz d^2\vec{r}_\perp e^{-i\vec{k}_\perp\cdot\vec{r}_\perp} e^{-i\omega z/v} f(\vec{r}_\perp, z) \tag{2}$$

is the Fourier transform of the e-beam spatial distribution $f(\vec{r}_\perp, z)$, or spatial form factor, where $\vec{k}$ is the radiation wave vector, and

$$D = 1 - J_0(bu\sin\theta)\left[bK_1(b) + b^2K_0(b)/2\right] - b^2K_0(b)J_2(bu\sin\theta)/2 \tag{3}$$

is the correction due to diffraction radiation from the transverse edge of the plasma. The parameter $b \equiv k\rho/u$ describes the relative influence of the transverse boundary (i.e., the ratio of the transverse size of the plasma ρ to the transverse extent of the self-fields of the relativistic electrons $\sim \gamma\lambda$), and K_0, K_1, J_0, and J_2 are Bessel functions. For large transverse size (i.e., $b \gg 1$), $D \simeq 1$, and the coherent radiation is well-described by transition radiation. For $b \sim 1$, diffraction radiation will strongly modify the radiated energy spectrum.

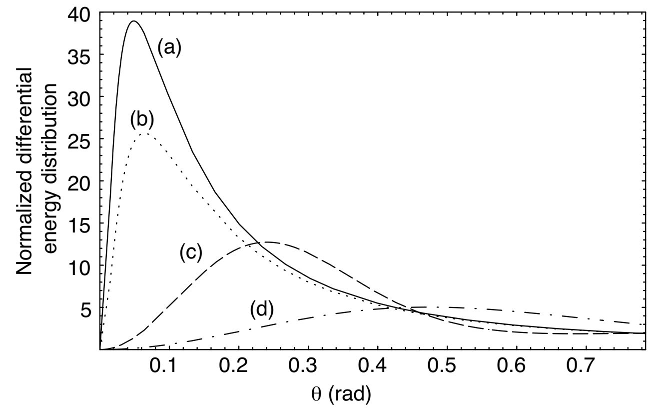

FIG. 3: Normalized energy per unit solid angle and frequency of the coherent radiation $(d^2W_e/d\omega d\Omega)\pi^2c/e^2N_e^2$ versus observation angle θ for the normalized transverse plasma size ρ/λ and e-beam temperature $u_{\rm T}$: (a) ρ/λ=100 and $u_{\rm T} = 12$ (solid curve), (b) ρ/λ=100 and $u_{\rm T} = 9$ (dotted curve), (c) ρ/λ=2 and $u_{\rm T} = 9$ (dashed curve), and (d) ρ/λ=1 and $u_{\rm T}$ = 9 (dotted-dashed curve). Curve (d) is near experimental parameters.

The degree of coherence in the bunch will be determined by the form factor Eq. (2). For a bunch with an uncorrelated Gaussian spatial distribution, the spatial form factor is $F = F_\perp F_\parallel$, where $F_\perp = \exp[-(k\sigma_\perp\sin\theta)^2/2]$ and $F_\parallel = \exp[-(\omega\sigma_\parallel/v)^2/2]$, with $\sigma_\perp$ the rms transverse bunch radius and $\sigma_\parallel$ the rms longitudinal bunch length. Fully-coherent emission in both the transverse and longitudinal directions requires $F \simeq 1$. This condition is satisfied when $\sigma_\perp\sin\theta$ and $\sigma_\parallel$ are much less than the radiation wavelength.

Laser-plasma generated e-beams in the self-modulated regime can be characterized by a Boltzmann momentum distribution $g(u) = u_{\rm T}^{-1}\exp[-u/u_{\rm T}]$, where $u_{\rm T}$ is the temperature of the distribution. In the limit $b \gg 1$ (i.e., in the limit of large transverse plasma size), the amount of radiated energy in the collection cone half-angle $\theta_{\rm coll} < 1/u_{\rm T} < 1$ and frequency bandwidth $\Delta\omega/\omega$ is given by $\Delta W_e \simeq 4m_ec^2(r_e/\lambda)N_e^2(u_{\rm T}\theta_{\rm coll})^4(\Delta\omega/\omega)$. For example, $\Delta W_e = 30$ μJ within $\theta_{\rm coll} = 50$ mrad for a 1.5 nC bunch with temperature $u_{\rm T} = 9$ in a bandwidth 0.3–3 THz.

The radiated energy $d^2W_e/d\omega d\Omega$ obtained from Eq. (1), for a Boltzmann momentum distribution, versus observation angle, is plotted in Fig. 3. Figure 3 shows that for $b \gg 1$ the angular distribution of the radiation is peaked at approximately $\theta_{\rm peak} \sim 1/u$, and that the effect of the finite transverse plasma size (for $b \sim 1$) is to shift the peak of the angular distribution to larger angle. This clearly indicates the importance of having a sufficiently large transverse size of the plasma to minimize the effective divergence angle of the source.

In the experiments, $\theta_{\rm coll}$ was limited to about 30 mrad, and the e-beams contained up to 1.5 nC. The measured

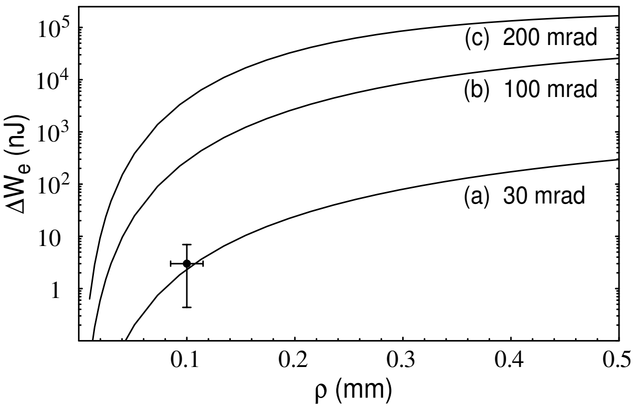

FIG. 4: Calculated total energy ΔW_e(nJ) (curves) radiated by a 1.5 nC e-beam with 4.6 MeV temperature for frequencies 0.3–3 THz versus transverse plasma size ρ(mm) within (a) 30 mrad, (b) 100 mrad and (c) 200 mrad. Point is bolometer measurement. Horizontal and vertical error bars are due to uncertainty in interferometrically-measured transverse plasma size $\rho = 100\ \mu\text{m} \pm 15\ \mu\text{m}$ and the collection cone 30 mrad $\pm$ 10 mrad, respectively.

radiated energy per pulse between 0.3–3 THz was between 3–5 nJ/pulse. Figure 4 shows the energy ΔW_e within the bandwidth 0.3–3 THz versus ρ for (a) $\theta_{\text{coll}} =$ 30 mrad, (b) $\theta_{\text{coll}} = 100$ mrad, and (c) $\theta_{\text{coll}} = 200$ mrad calculated using Eq. (1) with corrections due to finite temperature and finite transverse plasma size ρ. We approximated the electron momentum distribution at the plasma-vacuum boundary as a Boltzmann distribution with a single effective temperature of 4.6 MeV. For the experimental parameters ($\rho = 100\ \mu$m, $\theta_{\text{coll}} = 30$ mrad, 1.5 nC charge, and $u_{\text{T}} = 4.6$ MeV) the calculated energy per pulse is 2.3 nJ, which agrees within error bars with the 3–5 nJ measured experimentally (cf. Fig. 4).

The measured THz pulse energy can be dramatically increased by a number of straightforward methods. For the experimental parameters, increasing θ_{coll} to 100 mrad increases the radiated energy per pulse to $> 0.3\ \mu$J. Furthermore, as shown in Fig. (4), 100 μJ/pulse could be achieved by increasing ρ to the mm-scale. This could be done by focusing a laser beam with cylindrical optics to produce a vertical mm-scale sheet-like plasma through which the e-beam propagates. Increasing the mean energy of the e-beam to the few 10's of MeV with, e.g., a channel guided laser wakefield [21], could further increase the pulse energy to the few 100 μJ level in a 0.1 rad cone.

In summary, a table-top source of coherent THz radiation based on transition radiation at a vacuum-plasma boundary from laser wakefield generated electron beams has been demonstrated. An LWFA enabled the production of fs duration electron bunches containing several nC of charge. Transition radiation at the plasma boundary provided a radiation mechanism when the beam was at its most dense. The radiation is directed and intrinsically synchronized to the laser beam. The long and short wavelength spectral cut-off can be tuned using the transverse plasma profile and bunch length. In the present experiment 3–5 nJ-level pulses were collected within a limited 30 mrad collection angle, in good agreement with predictions from our model. Our model furthermore indicates that an optimized source, with a millimeter transverse scale plasma sheet at the exit of the accelerator, could produce, in a 100 mrad angle, in excess of 100 μJ/pulse, which is more than two orders of magnitude higher than present sources. These intense T-rays will provide access to non-linear regimes and highly non-equilibrium processes using MV/cm field strengths and may also benefit two-dimensional T-ray imaging.

We acknowledge contributions of D. Bruhwiler, G. Dugan, L. Archambault, J. Corlett, D. Li, M. Dickinson, S. DiMaggio, D. Syversrud, N. Ybarrolaza, J. Wallig, D. Calais, P. Catravas, F. Sannibale, J. Singley and D. Chemla. This work was supported by DOE under contract DE-AC03-76SF00098. C.G.R. Geddes acknowledges the Hertz Foundation for support.

---

* Also at University of California at Berkeley
† Also at Technische Universiteit Eindhoven, the Netherlands
‡ Also at Université de Paris XI, Orsay, France

[1] D. M. Mittleman *et al.*, Appl. Phys. B **68**, 1085 (1999).
[2] J. Orenstein and A. J. Millis, Science **288**, 468 (2000).
[3] B. Ferguson *et al.*, Opt. Lett. **27**, 1312 (2002).
[4] A. S. Weling *et al.*, Appl. Phys. Lett. **64**, 137 (1994).
[5] X.-C. Zhang *et al.*, Appl. Phys. Lett. **56**, 1011 (1990).
[6] E. Budiarto *et al.*, IEEE J. Quantum Electron. **32**, 1839 (1996).
[7] T. Nakazato *et al.*, Phys. Rev. Lett. **63**, 1245 (1989).
[8] U. Happek, A. J. Sievers, and E. B. Blum, Phys. Rev. Lett. **67**, 2962 (1991).
[9] M. L. Ter-Mikaelian, *High-energy electromagnetic processes in condensed media* (Wiley-Interscience, New York, 1972).
[10] P. Kung *et al.*, Phys. Rev. Lett. **73**, 967 (1994).
[11] W. D. Kimura *et al.*, Phys, Rev, Lett. **86**, 4041 (2001).
[12] G. L. Carr *et al.*, Nature **420**, 153 (2002).
[13] V. Malka *et al.*, Science **298**, 1596 (2002).
[14] W. P. Leemans *et al.*, Phys. Rev. Lett. **89**, 4802 (2002).
[15] H. Hamster *et al.*, Phys. Rev. Lett. **71**, 2725 (1993).
[16] J. J. Santos *et al.*, Phys. Rev. Lett. **89**, 025001 (2002).
[17] W. P. Leemans *et al.*, Phys. Plasmas **8**, 2510 (2001).
[18] G. Fubiani *et al.*, in *Proc. of the 2002 Advanced Accelerator Concepts Workshop*, edited by C. E. Clayton and P. Muggli (AIP, NY, 2002), Vol. 647, pp. 203–212.
[19] D. Grischkowsky *et al.*, J. Opt. Soc. Am. B **7**, 2006 (1990).
[20] C. B. Schroeder *et al.*, Technical Report No. LBNL-, Lawrence Berkeley National Laboratory (unpublished).
[21] A. J. W. Reitsma *et al.*, Phys. Rev. ST Accel. Beams **5**, 051301 (2002).