Observation of Terahertz Emission from a Laser-Plasma Accelerated Electron Bunch Crossing a Plasma-Vacuum Boundary


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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.

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Terahertz radiation (or T rays) is nonionizing electromagnetic radiation with submillimeter wavelength, which can be used to noninvasively measure optical properties of materials with hundred micron resolution. T rays have applications [1,2] in biological imaging, material screening, semiconductor imaging, surface chemistry, and high-field condensed matter studies. High peak power radiation is required for rapid two-dimensional imaging [3] and for nonequilibrium and nonlinear 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 a 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/γ, where γ = 1/√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 compact 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 10¹⁰ background electrons to relativistic energies [13,14], albeit with 100% energy spread. LWFAs can produce ultrashort (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 the 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 accelerated 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 setup is shown in Fig. 1), relativistic $e^-$ beams were generated by focusing laser pulses from a Ti:Al$_2$O$_3$ laser operating at 800 nm to a waist $w = 6 \mu$m 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 $\tau_{\text{FWHM}} \simeq 50$ fs and a peak power level $P \simeq 8$ 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 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 $100 \mu$m $\pm 15 \mu$m. Radiation in the 0.3–3 THz range was reflected out of the vacuum chamber through a window using a 5 $\mu$m 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 (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 fluctuations.

Modeling of the radiation process can be done by assuming that the plasma (with dielectric constant

![FIG. 1 (color online). Schematic of the experimental setup. 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.](image1)

![FIG. 2. Bolometer voltage versus 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 $S = 2.73 \times 10^4 \text{ V/W}$ and thermal conductivity $G = 17.01 \mu\text{W/K}$. Since the radiation bursts are much shorter than the bolometer time constant, $\tau_{\text{bolo}} = 0.33 \text{ ms}$, the detector operates as a calorimeter. The absorbed energy is then given by $E_{\text{absorbed}} = G\tau_{\text{bolo}}\Delta V_{\text{bolo}}/(R\eta_{\text{bolo}}) = 4.0\Delta V_{\text{bolo}}$ (in pJ), where $R = SG = 4.64$ is the induced voltage per K of temperature rise (in V/K), $\Delta V_{\text{bolo}}$ is the height of the voltage pulse (in V), and $\eta_{\text{bolo}} \sim 0.3$ is the bolometer efficiency. The radiated energy is $E_{\text{radiated}} = E_{\text{absorbed}}/\eta_{\text{coll}}$, where $\eta_{\text{coll}}$ is the overall collection efficiency of the system.](image2)
transverse extent of the self-fields of the relativistic elec-
(i.e., the ratio of the transverse size of the plasma

describes the relative influence of the transverse boundary
curves), \( \epsilon \) is the correction due to diffraction radiation from the
e-beam propagation direction, \( u = \gamma v/c \) is the normal-
ized electron momentum, and \( g(u) \) is the normalized
e-beam momentum distribution. Here

\[
F = \int d\zeta d\tilde{\gamma}_z e^{-i\hat{k}\cdot \tilde{\gamma}_z} e^{-i\omega_\parallel z/u} f(\tilde{\gamma}_z, z)
\]

is the Fourier transform of the e-beam spatial distribution
\( f(\tilde{\gamma}_z, z) \), or spatial form factor, where \( \hat{k} \) is the radiation
wave vector, and

\[
D = 1 - J_0(bu \sin \theta)[bK_1(b) + b^2K_0(b)/2] - b^2K_0(b)J_2(bu \sin \theta)/2
\]

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

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 \( F = F_1 F_\parallel \), where \( F_1 = \exp[-(k\sigma_k \sin \theta)^2/2] \) and \( F_\parallel = \exp[-(\omega \sigma_\parallel u)^2/2] \), with \( \sigma_k \) the rms transverse bunch radius and \( \sigma_\parallel \) the
rms longitudinal bunch length. Fully coherent emission in both the transverse and longitudinal directions requires
\( F \approx 1 \). This condition is satisfied when \( \sigma_k \sin \theta \) 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 \( g(u) = u^{-1} \exp[-u/\gamma T] \), where \( \gamma T \) is the tempera-
ture 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 \( \theta_{coll} \ll 1/\gamma T \ll 1 \) and frequency bandwidth \( \Delta \omega/\omega \) is given by
\( \Delta W_e \approx 4m_e c^2(r_e/\lambda)N_e^2(\gamma T \theta_{coll})^4(\Delta \omega/\omega) \). For example,
\( \Delta W_e = 30 \mu J \) within \( \theta_{coll} = 50 \) mrad for a 1.5 nC bunch with
temperature \( \gamma T = 9 \) 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 \( \theta_{peak} \sim 1/\gamma T \), 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 ef-
tective divergence angle of the source.

In the experiments, \( \theta_{coll} \) was limited to about 30 mrad,
and the e beams contained up to 1.5 nC. The measured
radiated energy per pulse between 0.3 and 3 THz was
between 3 and 5 nJ/pulse. Figure 4 shows the energy
\( \Delta W_e \) within the bandwidth 0.3–3 THz versus \( \rho \) for
(a) \( \theta_{coll} = 30 \) mrad, (b) \( \theta_{coll} = 100 \) mrad, and (c) \( \theta_{coll} = 200 \) mrad calculated using Eq. (1) with corrections due to
finite temperature and finite transverse plasma size \( \rho \). 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 \( \rho = 100 \mu m, \theta_{coll} = 30 \) mrad,
higher than present sources. These intense rays will provide access to nonlinear regimes and highly nonequilibrium processes using MV/cm field strengths and may also benefit two-dimensional $T$-ray imaging.

1.5 nC charge, and $\nu_{\text{eff}} = 4.6$ 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 $\theta_{\text{col}}$ to 100 mrad increases the radiated energy per pulse to $>0.3 \mu$J. Furthermore, as shown in Fig. 4, 100 $\mu$J/pulse could be achieved by increasing $\rho$ to the mm scale. This could be done by focusing a laser beam with cylindrical optics to produce a vertical mm-scale sheetlike 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 $\mu$J level in a 0.1 rad cone.

In summary, a compact 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 cutoff 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 $\mu$J/pulse, which is more than 2 orders of magnitude higher than present sources. These intense $T$ rays will provide access to nonlinear regimes and highly nonequilibrium processes using MV/cm field strengths and may also benefit two-dimensional $T$-ray imaging.

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