Coherent terahertz radiation emitted by wide-angle electron beams from a laser-wakefield accelerator

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ABSTRACT

Laser-wakefield accelerators generate femtosecond-duration electron bunches with energies from 10s of MeV to several GeV in millimetre distances by exploiting the large accelerating gradients created when a high-intensity laser pulse propagates in an underdense plasma. The process governing the formation of the accelerating structure ("bubble") also causes the generation of sub-picosecond duration, 1-2 MeV nanocoulomb electron beams emitted obliquely into a hollow cone around the laser propagation axis. We present simulations showing that these wide-angle beams can be used to produce coherent transition radiation in the 0.1-5 THz frequency range with 10s μJ to mJ-level energy if passed through an inserted metal foil, or directly at the plasma-vacuum interface. We investigate how the properties of terahertz radiation change with foil size, position and orientation. The bunch length and size of wide-angle beams increase quickly as the electrons leave the accelerator, causing a shift of the radiation frequency peak from about 1 THz at a distance of 0.1 mm from the accelerator exit to 0.2 THz at 1 mm. If the foil size is reduced, for example to match the typical diameter of the plasma channel formed in a laser-wakefield accelerator, simulating the emission from the plasma-vacuum boundary, the low-frequency side of the spectrum is suppressed. The charge of wide-angle electron beams is expected to increase linearly with the laser intensity, with a corresponding quadratic increase of the terahertz radiation energy, potentially paving the way for mJ-level sources of coherent terahertz radiation.

Keywords: Terahertz generation, laser-wakefield acceleration

1. INTRODUCTION

Terahertz (THz) radiation, which lies between 0.1 and 10 THz (30–3000 µm) in the electromagnetic spectrum, is of interest for many applications, such as chemical and biological imaging, communication and quality control.[1–4] There are many sources of THz radiation, but few of them produce high-intensity pulses suitable for driving non-linear optical effects in materials.[5] One source of intense THz pulses is coherent transition radiation (CTR) emitted by an electron beam passing through a thin metallic foil.[6] If the bunch length is shorter than the radiation wavelength, the contribution from all the electrons add coherently and the total radiated power scales as the square of the beam charge. Assuming a longitudinally and transversally Gaussian bunch, the spectrum of CTR can be calculated analytically in the far-field approximation.[7] As shown in Figure 1, efficient generation of CTR with frequency up to 10 THz is possible for bunch durations shorter than about 100 fs, which are achievable using conventional accelerators equipped with bunch compressors or other beam manipulation devices.[8] Laser-driven electron accelerators,[9] on the other hand, directly produce bunches with duration as short as 1–5 fs.[10,11] Recent experiments have shown, for example, that electron beams with energy of 250 MeV, charge of 250 pC, divergence of 7 mrad and an estimated bunch length of 5 fs can be produced reliably using self-truncated ionisation injection.[12] If focused down onto a metallic foil to a radius of 50 µm, this beam would produce broadband CTR with 1 mJ energy in the 0.1–20 THz spectral range.

Laser-wakefield accelerators have been shown not only to produce high-energy, short electron bunches, but also to emit a low-energy, high-charge electron beam on a cone centred along the laser propagation axis.[13,14]

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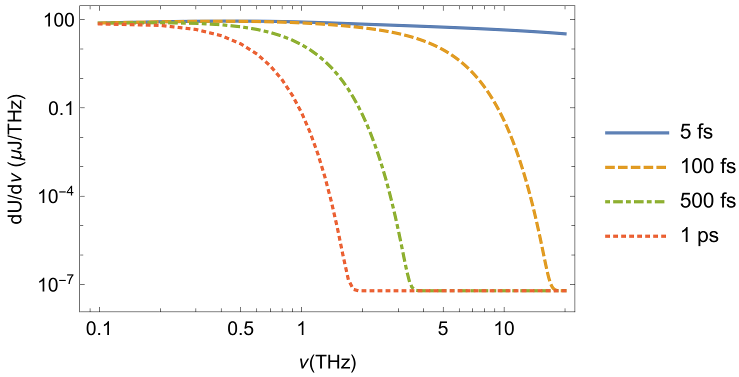

Figure 1. Spectrum of CTR generated by a 250 MeV Gaussian electron bunch with charge of 250 pC, transverse radius (σ) of 50 µm and duration (FWHM) of 5 fs, 100 fs, 500 fs and 1 ps.

Theoretical studies indicate that these wide-angle beams can also produce mJ-level THz radiation.[15] Here we present numerical simulations to investigate the properties of this THz source. We show that the bunch duration of wide-angle beams is predicted to be longer than what is obtained from measurements and simulations of high-energy forward electron beams, resulting in the suppression of CTR at frequencies above 1–3 THz, depending on the geometry. The large beam charge, however, still enables to reach mJ-level energies in the 0.1–3 THz spectral range.

2. RESULTS

A schematic diagram of a possible setup to produce THz radiation using wide-angle electron beams is presented in Figure 2. A laser beam is focused onto a gas or plasma target to an intensity in excess of 1×10^{18} W/cm^2, generating a high-energy forward electron beam along the laser propagation axis and a low-energy electron beam in a cone around the laser axis. A foil intercepts the wide-angle beam at an offset d and angle α from the laser axis. Transition radiation is emitted in the backward and forward direction and observed on a detector at a distance R from the centre of the foil. Here we have chosen $R = 500$ mm, which corresponds to a realistic value for an experiment. The laser-plasma interaction has been modelled with the particle-in-cell (PIC) code OSIRIS.[16] The properties of wide-angle electron beams have been found to vary little with laser and plasma parameters for a large range of values.[13] Here, as a representative example, we present the results of a three-dimensional simulation of a horizontally polarised laser with 0.8 μm wavelength, normalised vector potential $a_0 = 3$, spot radius $w_0 = 7$ μm and 20 fs pulse duration interacting with a pre-ionised plasma with density 2×10^{19} cm^{-3} and 500 μm length. These parameters reproduce experiments presented in Ref. 13. A sample of 20,000 electrons has been selected from the phase-space distribution produced by OSIRIS and used to calculate numerically transition radiation from the foil using a vector model described in Ref. 15 and 17.

Figure 3 shows the spatial profile and the energy spectrum of wide-angle electrons as they hit a 1 mm $\times$ 1 mm foil at an offset $d = 100$ µm from the laser axis and orientation $\alpha = 60°$. The mean electron energy is 1.8 MeV with an exponential distribution. The beam size (FWHM) is 144 µm in the horizontal direction (x) and 65 µm in the vertical direction (y). The bunch duration (FWHM) in the direction perpendicular to the foil surface is 160 fs. As the beam propagates further away from the accelerator, the transverse and longitudinal size grow quickly, as shown in Figure 4, which corresponds to the electron distribution on a 3 mm $\times$ 3 mm foil placed at offsets $d = 100$ µm, $d = 500$ µm and $d = 1$ mm, and orientations $\alpha = 60°$ and $\alpha = 0$ (parallel to the laser axis). For $d = 1$ mm and $\alpha = 60°$ the beam size is 630 µm in the horizontal direction and 310 µm in the vertical direction with a bunch duration of 410 fs. If the foil is parallel to the laser axis the beam size is 910 µm in the horizontal direction and 555 µm in the vertical direction with a bunch duration of 2.3 ps.

The modelling of CTR emitted by wide-angle electrons passing through the foil requires a numerical approach to account for the complex electron bunch shape. Here we use a vector model that is valid for arbitrary incidence angles and directly uses the phase-space electron distribution obtained from PIC simulations. Figure 5 shows the spectrum of CTR generated on a 3 mm $\times$ 3 mm foil with orientation $\alpha = 0$ and $\alpha = 60°$ for different offsets d from

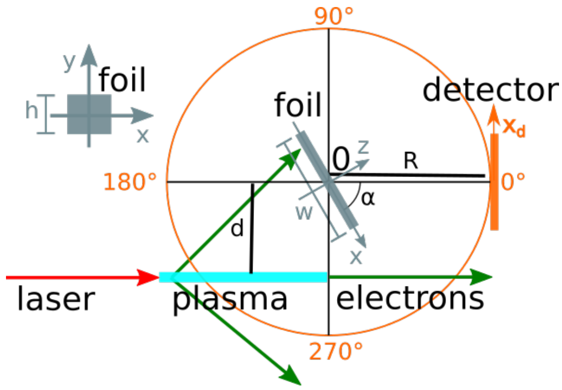

Figure 2. Schematic diagram of a THz source based on laser-driven wide-angle electron beams passed through a thin metallic foil.

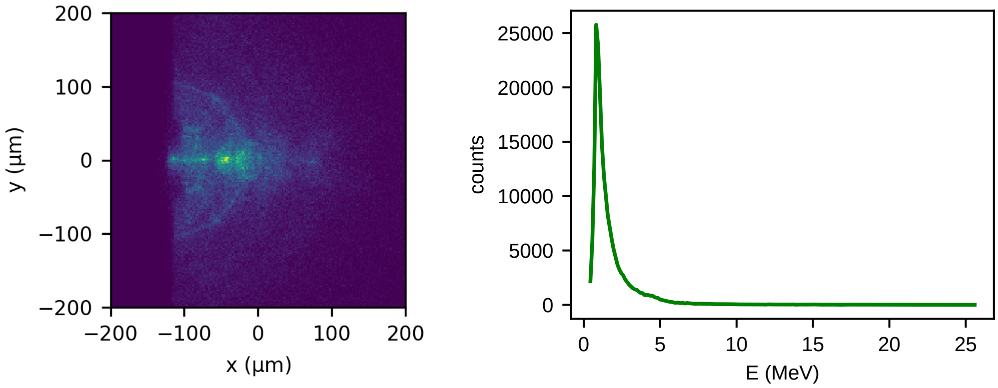

Figure 3. Spatial profile (left) and spectrum (right) of wide-angle electrons on a 1 mm × 1 mm foil with 60° orientation and 100 μm offset from the laser axis. Plots represent a sample of 200,000 particles obtained from OSIRIS simulations.

the laser axis, assuming an electron beam charge of 1 nC and observation angle of 0°. The integrated radiation energy for $d = 100\,\mu\mathrm{m}$ in a 45° cone is 295 µJ for $\alpha = 0$ and 56 µJ for $\alpha = 60°$. Simulations indicate that the charge of wide-angle electron beams scales linearly with laser intensity and can exceed 10 nC using commercially available lasers.[13] The CTR energy scales with good approximation as the square of the charge,[13] allowing to reach mJ-level energies.

3. DISCUSSION

Laser-wakefield accelerators produce 100s MeV electron bunches with femtosecond duration, mrad divergence and up to 100s pC charge that can drive mJ-level THz sources based on CTR from a thin metallic foil. Intense THz radiation can also be produced using the low-energy, high-charge electrons that laser-wakefield accelerators emit over a wide-angle cone around the laser propagation axis. The divergence of transition radiation is approximately $1/\gamma$, with γ the relativistic factor of the electrons. For low energy, as in wide-angle beams, radiation is emitted over a large angle, of the order of 40° (FWHM), which may require re-focusing and may not be desirable for some applications. An advantage of low electron energies, on the other hand, is that the formation length of forward transition radiation is about 1 mm at 1 THz, in contrast to a formation length longer than 10 m for a 250 MeV electron beam.[18] For both forward and oblique electron beams, the THz source can be realised in practice by inserting a thin metallic foil very close to the accelerator exit. However, in this region the laser intensity is still very high and the foil is likely to be quickly damaged. High-energy electron beams could be transported and focused further downstream at a distance where laser damage is no longer an issue using high-gradient permanent quadrupoles[19] or plasma lenses.[20,21] Wide-angle electrons, on the other hand, are not co-propagating with the

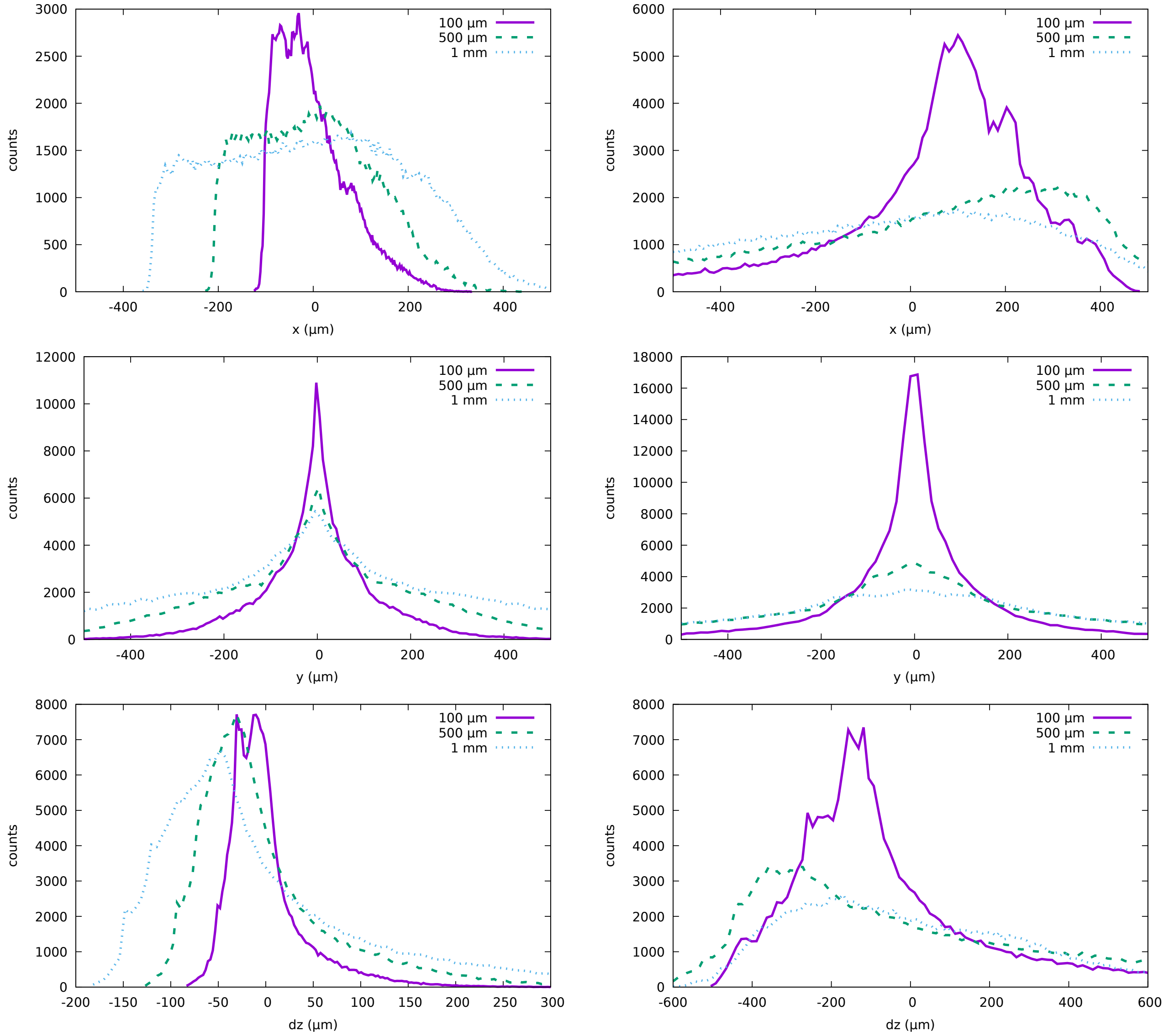

Figure 4. Horizontal (top), vertical (middle) and longitudinal (bottom) profile of a wide angle electron beam intercepting a 3 mm × 3 mm foil with 60° (left) and parallel (right) orientation with respect to the laser propagation axis at an offset of 100 µm, 500 µm and 1 mm. Plots represent a sample of 200,000 particles obtained from OSIRIS simulations.

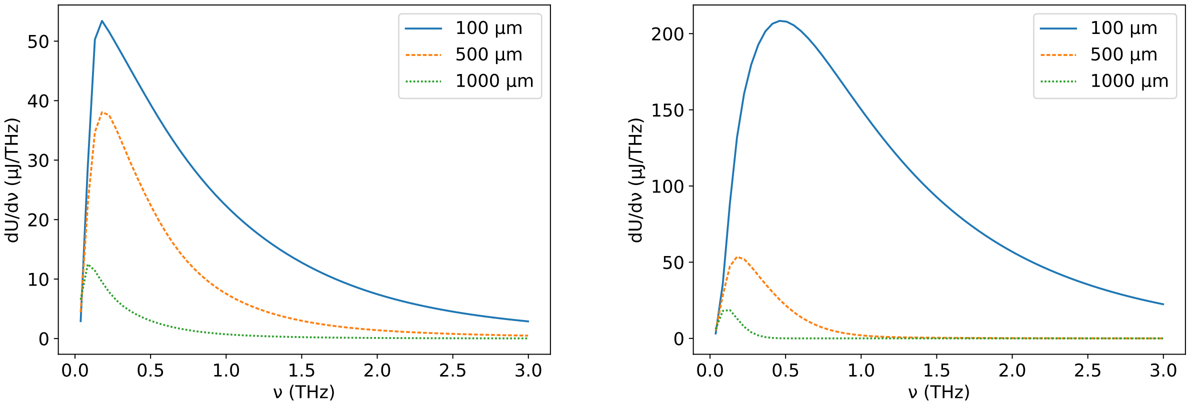

Figure 5. Spectrum of CTR emitted by a 1 nC wide-angle electron beam passing through a 3 mm × 3 mm foil with 60° (left) and parallel (right) orientation for varying offset. Plots are calculated from a sample of 20,000 particles obtained from OSIRIS simulations.

laser beam, and could be passed through a foil placed off-axis, avoiding the intense part of the laser beam. The quick beam expansion, however, will lead to the suppression of the high frequency part of the emitted CTR. Wide-angle electron beams can also produce radiation directly at the plasma-vacuum boundary, which can act as a metallic interface.[22] In this case a suppression of the low frequency part of the spectrum is expected because the transverse size of the plasma (100s μm) can be smaller than the radiation wavelength.

In conclusion, we have shown that wide-angle electrons emitted by laser-wakefield accelerators can produce THz radiation with 10s μJ to mJ-level energy in the 0.1–5 THz spectral range, depending on the laser parameters and experimental geometry. Radiation can be produced by inserting a metallic foil close to the accelerator exit or directly at the plasma-vacuum boundary. In the latter case THz radiation could be an unwanted background noise in experiments, requiring proper shielding.

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