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Powerful terahertz emission from laser wakefields in plasmas for diagnostics

Z.-M. SHENG[1], J. ZHENG[1], H.-C. WU[1], J. ZHANG[1] and K. MIMA[2]

[1]Laboratory of Optical Physics, Institute of Physics, CAS, Beijing 100080, People's Republic of China
(zmsheng@aphy.iphy.ac.cn)

[2]Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan

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Abstract. Broadband coherent emission around the electron plasma frequency can be produced from a laser wakefield by linear mode conversion in inhomogeneous plasmas. In addition to its potential use as a powerful terahertz source, it can be used as diagnostics of the wakefield produced for particle acceleration. In this paper, some simulation results are presented on the wake emission when the wakefield is driven in the wavebreaking regime and driven inside a plasma channel.

1. Introduction

The interactions of ultrashort intense laser pulses with plasma can provide a variety of novel radiation sources, such as short pulse X-rays, coherent high harmonics, attosecond pulses, as well as coherent far-infrared radiation in terahertz frequencies [1]. Recently, we suggested a new mechanism for powerful coherent emission of broadband, few terahertz radiation from laser wakefields in inhomogeneous plasmas by linear mode conversion [2, 3]. Since the laser wakefield can be excited at amplitudes as high as $100\,\mathrm{GV\,m^{-1}}$ even at the plasma density $10^{18}\,\mathrm{cm^{-3}}$ (at which the plasma frequency $\omega_p/2\pi = 9\,\mathrm{THz}$) [4], the field strength of the mode-converted emission can reach a few gigavolts per metre.

In addition to its potential use as a novel radiation source, the wake emission provides the possibility to diagnose the wakefield itself. In the proposed laser wakefield accelerators, wakefields are driven by highly relativistic laser pulses, where plasma wavebreaking [5, 6] and/or bubble formation [7] can occur. Particle acceleration by laser wakefields driven inside a plasma channel is also proposed for gigaelectronvolt electron energy gains [8, 9]. The plasma channel allows for the laser pulse to propagate over many times of the Rayleigh length without significant diffraction and can thus increase the acceleration length. In laser wakefield acceleration experiments, so far attention has been paid mainly to the diagnostic of energetic electron beams, but little attention has been devoted to the diagnostics of the wakefield itself. In order to understand the relation between the electron acceleration and the wakefield structure, however, it is preferable to have both diagnosed. Direct diagnostics of regular wakefields have been developed by a few groups [10–13]. A limitation with these diagnostics is that one obtains only some local information about the wakefield amplitude at particular positions. The diagnostics of bubble structures, wavebreaking, as well as wakefields excited

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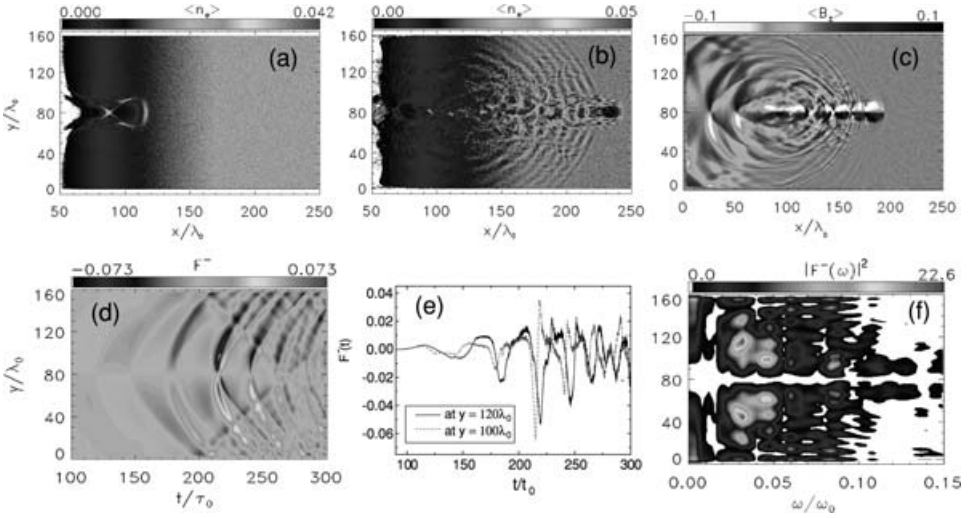


Figure 1. (Color online) Snapshots of the electron density in the wakefield driven at time $120\tau_0$ (a) and $250\tau_0$ (b). (c) The magnetic component in the z-direction associated with the wakefield at $t = 200\tau_0$; (d) Temporal profiles of the emitted pulse through the left boundary; (e) Temporal profiles of the emitted pulse through the left boundary at transverse coordinates $y = 100\lambda_0$ and $120\lambda_0$; (f) Spectra of the emitted pulse through the left boundary.

inside a channel as mentioned above would be even more challenging. The wake emission can provide information about the global structure such as wakefield amplitudes, plasma densities and even wavebreaking, etc. In this work, results by two-dimensional (2D) particle-in-cell (PIC) simulations are presented for the wake emission when there is plasma wavebreaking and when the wakefield is excited in a plasma channel.

2. Emissions from wakefields in the wavebreaking regime

In our 2D PIC simulations, a laser pulse is incident from the left boundary into the simulation box. It is s-polarized to distinguish it easily from the p-polarized wake emission [2]. The incident pulse is with $a_0 = 10.0$, $d_{\rm L} = 20\lambda_0$ and $W = 10\lambda_0$, where a_0 is the peak amplitude of the vector potential normalized by mc^2/e, $d_{\rm L}$ and W are the longitudinal and transverse sizes of the laser pulse, respectively. The plasma density increases linearly along the x-direction from 0 at $x = 50\lambda_0$ to $0.02n_{\rm c}$ at $170\lambda_0$, and then remains at this density.

At the given high laser intensity, the laser wakefield is highly broken and a bubble structure is formed. Owing to the inhomogeneity, the wakefield is not broken immediately in the relatively low-density region (see Fig. 1(a)), where a swallowtail-type structure is formed [6]. When the pulse propagates to a region with a relatively high density, a single bubble is formed behind the laser pulse, as shown in Fig. 1(b). The magnetic component inside and outside the plasma is plotted in Fig. 1(c). The emission fields shown in Figs 1(d) and 1(e) obviously exhibit a feature of being partially unipolar both in the upper and lower sides of the simulation box. In the upper side, the negative field amplitude is much larger than the positive field

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amplitude and *vice versa* in the lower side. Later the emission becomes irregular due to the occurrence of plasma wavebreaking.

As compared with simulations for the same incident pulse duration but lower laser intensities, the main emission frequency is reduced for the present case (see Fig. 1(f)). Physically, when the laser intensity becomes higher, the driven wakefield amplitude also becomes higher. Owing to the relativistic effect, the local plasma frequency is reduced for a given plasma density, i.e. the emitted frequency is approximately $\omega_{\rm p}(x)/\gamma$. The existence of the spectrum around $\omega = 0$ is concerned with the unipolar feature of the field mentioned above. The spectrum is peaked around the frequency $\omega/\omega_0 = 0.03 \approx 0.05$, which is slightly smaller than that for the case with a relatively lower light intensity $a_0 = 3$, for example. The emission spectrum is much broader in the present case than in the low light intensities. In another example, we reduce the pulse duration to $d_{\rm L} = 10\lambda_0$ and pulse diameter to $W = 5\lambda_0$. The amplitude of the emission fields is reduced obviously from the previous case, but the frequency of the emission peak does not change significantly from the previous case.

3. Emissions from a wakefield driven inside a plasma channel

In the simulation, we assume that the plasma density changes like $n = n_0 + \Delta n(y - y_{\rm c})^2/y_0^2$, where n_0 is the density in the center of the channel, Δn is the density change. The plasma region with such a channel is located in the middle of the simulation box along the laser propagation x-direction. We take $n_0 = 0.005n_{\rm c}$, $\Delta n = 0.04n_{\rm c}$, and $y_0 = 40\lambda_0$ in the following. The incident laser pulse is s-polarized with $a_0 = 0.5$, $d_{\rm L} = 10\lambda_0$, and $W = 10\lambda_0$. Figures 2(a)–(c) and 2(d)–(f) show different fields near the left and right boundaries of the simulation box. It is seen clearly that there is emission towards vacuum regions from the channel at both sides. The emission appears in conical structures, similar to the case in longitudinally inhomogeneous plasma found before [2]. The magnitudes of the emission from both sides of the channel are comparable.

Figure 2(g) shows the emission through the right boundary of the simulation box. It is strong at the beginning, reaching an amplitude about $10^{-3}(m\omega_0 c/e)$ at the given incident laser intensity. It then decays slowly with time. The emission is peaked at around the frequency $\omega \sim \omega_{\rm p0} = (4\pi n_0 e^2/m)^{1/2} = 0.071$. The emission to the left boundary is similar. In experiments, by detecting the amplitudes and frequencies of the wake emission in both sides of the plasma channel, one obtains a measure of the wakefield amplitudes and the plasma densities near two ends of the plasma channel.

4. Summary

When the incident pulse is at extremely high intensities, the wakefield can break and form a bubble-like structure. In this case, the emitted pulse is found to be regular only for a few cycles at the beginning, which also becomes partially unipolar. The frequency of the emission peak is shifted to a lower value due to the relativistic effect. When the wakefield is excited inside a plasma channel which is longitudinally homogeneous and transversely inhomogeneous, conical wake emission is also found from both sides of the channel. The emission from both sides offers measurements of the wakefield amplitudes and plasma densities near the two ends of the channel.

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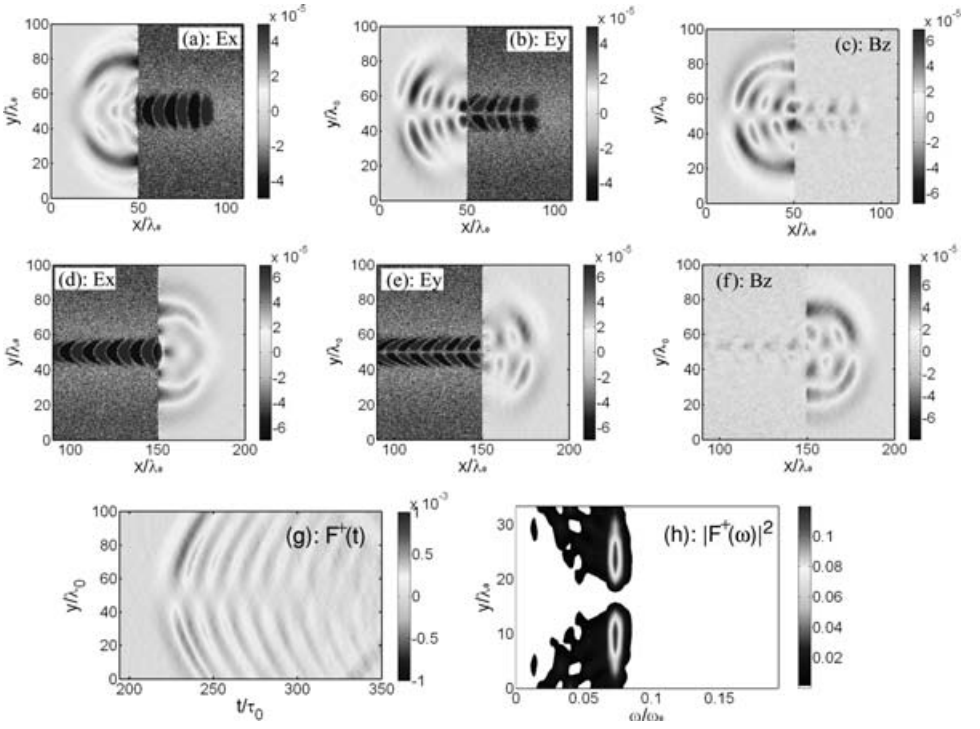


Figure 2. Snapshots of the electric and magnetic components associated with the wakefield excited inside a plasma channel. The plasma channel has a length of $100\lambda_0$ along the laser axis and $80\lambda_0$ in diameter. (a)–(c) show the fields close to the left boundary at $t = 100\tau_0$; (d)–(f) show fields close to the right boundary at $t = 200\tau_0$; (g) and (h) show the temporal profile and corresponding spectra (in arbitrary unit) of the emitted pulse through the right boundary.

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