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Electromagnetic radiation at the electron plasma wave frequency by an intense laser pulse interacting with low-density plasmas

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Abstract. The generation of low-frequency radiation at around the terahertz frequency, caused by a linearly polarized intense laser pulse passing through a low-density homogeneous plasma, is studied by one-dimensional particle simulations. The excited transverse current component with its frequency at the electron plasma frequency serves as a radiation source to generate electromagnetic waves both in the front and the rear side vacuum regions of the plasma layer. It is found that the electromagnetic radiation fields increase with both increasing plasma density and increasing laser amplitude.

1. Introduction

Radiation in the terahertz frequency regime has wide applications (Mittleman et al. 1999; Orenstein and Millis 2000). Several ways to obtain terahertz radiation, such as coherent radiation at a plasma–vacuum boundary via transition radiation (Leemans et al. 2003; Sheng et al. 2004), narrow-band terahertz radiation produced by free-electron lasers (Weling 1994; Ramian et al. 1992); broadband terahertz radiation produced by thermal sources and by table-top laser-driven sources (Auston et al. 1984; Bonvalet et al. 1995) and by short electron bunches in accelerators (Nakazato et al. 1989), etc., have been studied, but so far only with low power. Achieving high pulse energy is an important challenge that will enable numerous applications. The production of high-power broadband terahertz radiation from subpicosecond electron bunches in an accelerator has been reported (Carr et al. 2002). Terahertz radiation from a femtosecond laser-induced plasma channel which oscillates at the plasma frequency has been suggested (Cheng et al. 2001).

In this paper, we present simulation results on the electromagnetic (EM) radiation at around the terahertz frequency, caused by a linearly polarized intense laser passing through low-density homogeneous plasma, $n \leqslant 0.001 n_{\mathrm{cr}}$, where n_{cr} is the critical density of the laser pulse. The simulation results for the existence of the radiation current are given. We found that the EM radiation fields increase with both increasing plasma density and laser amplitude.

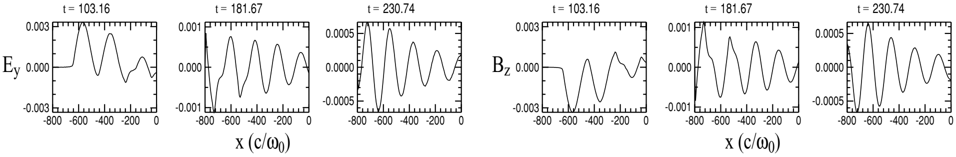

Figure 1. The EM field E_y and B_z radiated from the front side of plasma layer in the case of plasma density $n = 0.001n_{\rm cr}$ and laser amplitude $a = 0.3$.

2. Simulation model

Fully relativistic EM one-dimensional particle-in-cell code is used in simulations. Plasma length, density and temperature are $L = 200c/\omega_0$, $n = 0.001n_{\rm cr}$ and $T_{\rm e} = 1\,{\rm keV}$, where c and ω_0 are the vacuum light speed and frequency of laser pulse, respectively. The plasma layer is located in the center of the simulation box, which begins at $x = 0$ and ends at $x = 200c/\omega_0$. In the front and rear sides, there are two $900c/\omega_0$ long vacuum regions. Ions are typically kept immobile as a neutralizing background. The cell size is $1/20\ c/\omega_0$, and 100 particles per cell. A linearly polarized laser pulse, which with the electric field E_0 along the y-direction and normalized amplitude $a = eE_0/m_{\rm e}\omega_0 c$, is launched in the $-400c/\omega_0$ position before the plasma layer, where e and $m_{\rm e}$ are electron charge and mass, respectively. In order to excite a large electron plasma wave, a finite pulse length that is nearly equal to the wavelength of the electron plasma wave $\lambda_{\rm p}$ is used. The electrons which enter the vacuum build a potential barrier that prevents more electrons from leaving the plasma. For these electrons, as well as for outgoing EM waves, two additional damping regions are used. In this paper, time t, electric field $\mathbf{E}$, magnetic field $\mathbf{B}$ and current density $\mathbf{J}$ are normalized to $2\pi/\omega_0$, $m_{\rm e}\omega_0 c/e$, $m_{\rm e}\omega_0/e$ and $m_{\rm e}\omega_0^2 c/e$, respectively; the time is taken at $t = 0$ when the laser pulse arrives at the vacuum–plasma boundary. The electrostatic (ES) field E_x is averaged over electron plasma wavelength λ_p, the EM field E_y, B_z and current density J_y are averaged over one laser wavelength λ_0.

3. Simulation results and analysis

The first simulation is performed in the case of laser amplitude $a = 0.3$. The head of the laser pulse enters the plasma at $t = 0.0$. After the ($t \approx 63.5$) laser pulse leaves the plasma layer, as shown in Fig. 1, a low-frequency EM wave is radiated from the front side of plasma layer, it lasts for several hundred laser periods; the amplitudes both for electric field E_y and magnetic field B_z decrease with time. As time goes on, the regular monochromatic property of EM radiation will be destroyed by the noise. In addition to the front side, the low-frequency EM radiation can also be observed from the rear side of plasma layer. Figure 2 shows frequency spectra for reflected and transmitted EM waves, and one can see that they have the same frequency $\omega_{\rm r} \approx 0.033\omega_0$, which is nearly equal to the electron plasma frequency $\omega_{\rm p} = 0.032\omega_0$.

In order to understand the physics details, the snapshots for ES field E_x and transverse current density J_y inside the plasma and their frequency spectra are plotted in Fig. 3. As we know, in such a low-density plasma, there is almost no instability to take place. After an intense laser pulse enters and propagates inside the plasma, by a large ponderomotive force of the laser EM field, the longitudinal electron plasma oscillation with frequency $\omega_{\rm p}$ can be excited behind the front of

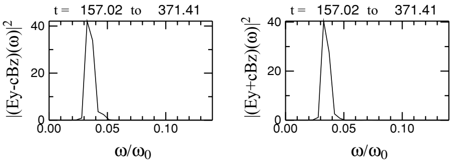

Figure 2. Frequency spectra for reflected and transmitted EM waves both measured in the place of $50c/\omega_0$ long distance from the front and rear side of plasma layer in the case of plasma density $n = 0.001n_{\mathrm{cr}}$ and laser amplitude $a = 0.3$.

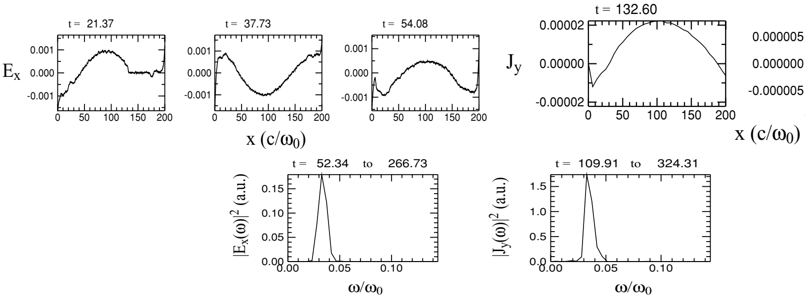

Figure 3. ES field E_x and transverse current density J_y and their frequency spectra excited by laser pulse passing through plasma layer in the case of plasma density $n = 0.001n_{\mathrm{cr}}$ and laser amplitude $a = 0.3$.

laser pulse. In the intense laser condition, by the force of $-e\mathbf{v} \times \mathbf{B}$ component, one dominant transverse current component J_y oscillating at about ω_{p} is also generated. The current density J_y takes the form of a standing wave. After the laser pulse leaves the plasma layer, both E_x and J_y decrease with time. This transverse current density component J_y can serve as a radiation source to radiate EM waves both in the front and the rear side vacuum regions of the plasma layer. The E_y and B_z components have the same frequency ω_{p} as that of the J_y component. Due to the continuous EM radiations, the current density J_y and therefore the EM radiation field (E_y and B_z) become weaker and weaker with time. As time goes on, compared with the weak current density J_y, the noise component plays an important role: it then destroys the monochromatic property of EM radiation. When J_y decreases to the noise level, eventually the monochromatic EM radiation will be finished.

The temporal EM radiation fields increase with increasing laser amplitude on condition that $a < 1.2$, i.e. $E_y^r(t) \propto a$, $B_z^r(t) \propto a$. However, there exists a saturation amplitude $a = 1.2$, i.e. in the cases of laser amplitude $a \geqslant 1.2$, although one can still detect clear EM radiation with frequency at ω_{p}, but it does not have fine spatial wave structures. In the higher intense laser amplitude case, apart from the electron plasma wave, some other ES modes might also be excited at the same time, and they can perhaps influence the transverse current density J_y component and therefore the monochromatic property of EM radiation.

Another series of simulations have also been performed by using low plasma density $n = 0.0001n_{\mathrm{cr}}$ and laser amplitude $a = 0.3$. As shown in Fig. 4, EM radiation with a lower frequency $\omega_{\mathrm{r}} \approx 0.011\omega_0$, which is nearly equal to the electron plasma wave frequency $\omega_{\mathrm{p}} = 0.01\omega_0$, is also observed. As in the case of plasma density

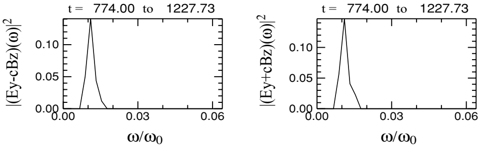

Figure 4. Frequency spectra for reflected and transmitted EM waves both measured in the place of $100c/\omega_0$ long distance from the front and rear side of plasma layer in the case of plasma density $n = 0.0001n_{\mathrm{cr}}$ and laser amplitude $a = 0.3$.

$n = 0.001n_{\mathrm{cr}}$, under the same simulation parameters, the temporal EM radiation fields both from the front and rear sides increase with increasing laser amplitude on condition that $a < 1.5$. Similarly, a saturation amplitude $a = 1.5$ exists, i.e. in the higher laser amplitude $a \geqslant 1.5$ cases, the observed EM radiation does not have fine spatial wave structures.

We also found that, for the same laser amplitude cases, the temporal EM radiation fields increase with increasing plasma density. For example, in our simulations, for the same laser amplitude $a = 0.3$ cases, the EM radiation fields for the plasma density $n = 0.0001n_{\mathrm{cr}}$ case are smaller than those of the $n = 0.001n_{\mathrm{cr}}$ case.

It is not difficult decrease the plasma density to obtain EM radiation with a lower frequency.

For a wavelength $\lambda_0 = 1.0\,\mu$m laser pulse, we can get the EM radiation frequencies $f_{\mathrm{r}} = \omega_{\mathrm{r}}/2\pi \approx 9.6$ THz in the case of $n = 0.001n_{\mathrm{cr}}$, and $f_{\mathrm{r}} = \omega_r/2\pi \approx 3.3$ THz in the case of $n = 0.0001n_{\mathrm{cr}}$. From our simulation results, perhaps, this can open up a new way to get terahertz EM radiation.

4. Conclusions

In conclusion, we present simulation results on the generation of EM radiation at around the terahertz frequency, caused by linearly polarized intense laser passing through the low-density homogeneous plasma. Intense laser propagates inside the plasma, longitudinal electron plasma oscillation excited, by the force of $-e\mathbf{v} \times \mathbf{B}$ component, one transverse current component J_y with its frequency at ω_{p} is also generated, transverse current J_y serves as radiation source to generate EM waves both in the front and the rear sides of the plasma layer. The EM radiation fields increase with both increasing plasma density and laser amplitude.

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