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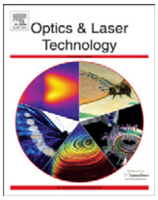

Numerical simulations of THz emission from the laser wakefields through linear mode conversion

Bai Xu [a,*], Yongda Li [a], Hongliang Wang [b]

[a] Department of Physics, Changchun University of Science and Technology, Changchun 130022, PR China
[b] Military Representative Office of PLA 2nd Artillery in Beijing, Beijing 100143, PR China

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ABSTRACT

A nonlinear one-dimensional particle-in-cell (PIC) program is used to simulate the generation of high power terahertz (THz) emission from the interaction of an ultrashort intense laser pulse with underdense plasma under magnetized and unmagnetized cases. The magnetic field in laser-irradiated plasma has an important effect on the resonant absorption, and makes the results different. The spectra of THz radiation are compared under different cases (with or without external magnetic field), and the optimized parameters including plasma density scale length, incident angle and external magnetic field are calculated. High-amplitude electron plasma wave driven by a laser wakefield can produce powerful THz emission through linear mode conversion under certain conditions. With incident laser intensity of 10^{18} W/cm^2, the generated emission is computed to be of the order of several MV/cm field and tens of MW level power. It is suitable for the studies of high-field and nonlinear physics in the THz regime.

1. Introduction

Recent progress in making ultrashort (10–100 fs) laser pulses has opened new possibilities for investigating relativistic laser–plasma interaction and corresponding generation of THz radiation. Currently the THz radiation from laser irradiated plasma is attracting increasing interest. A laser wakefield is an electron plasma wave driven by the ponderomotive force of a laser pulse [1], which can be converted into an electromagnetic wave under certain condition. In the past 10 years, Hamster et al. found that the interaction between ultrashort laser pulses and plasmas leads to the emission of coherent, short-pulse radiation at THz frequencies [2], Loffler and Roskos introduced that THz radiations can be generated by photoionization of electrically biased gases with amplified laser pulses, and studied the efficiency of generation process [3]. Sheng et al. proposed that THz radiation can be generated from a laser wakefield through linear mode conversion, which is confirmed by particle-in-cell (PIC) simulations [4]. More recently, this method has been used under inhomogeneous magnetized plasmas [5].

It is well known that an electromagnetic wave can convert into an electrostatic wave near the point where the dielectric function for electrostatic waves vanishes, and anomalous absorption of the electromagnetic wave energy takes place with the generation of large-amplitude electrostatic waves. This absorption progress is named as linear mode conversion. Means et al. studied the inverse problem and found that there is a reversal symmetry in the electromagnetic–electrostatic mode conversion [6], which was confirmed later by Hinkel-Lipsker et al. [7]. One can get an electromagnetic emission generated through mode conversion from a wakefield excited with a laser pulse incidence into a plasma.

In this paper, we compile one-dimensional particle-in-cell (PIC) program to simulate the generation of high power THz emission from the laser driven wakefield in both magnetized and unmagnetized plasma. Relatively simple as it is, 1D PIC code is effective enough to reveal some physics. In the unmagnetized case, THz emission is produced from electrostatic wave conversion into electromagnetic wave, which is the inverse process of resonance absorption in laser–plasma interactions. In the magnetized case, the mode conversion is based on the upper-hybrid resonance absorption, which makes the conversion condition and emission spectra different. We compare the different progress with PIC simulation and analyse the spectra of THz emissions with and without external magnetic field, calculate the optimized parameters such as density scale length, pulse width, incident angle (in the unmagnetized case), external magnetic field (in the magnetized case).

2. Cold relativistic plasma equations

As shown in Fig. 1, we consider a laser pulse irradiates at an angle θ into the magnetized inhomogeneous plasma, the plasma

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[*] Corresponding author.
E-mail address: xubai001@126.com (B. Xu).

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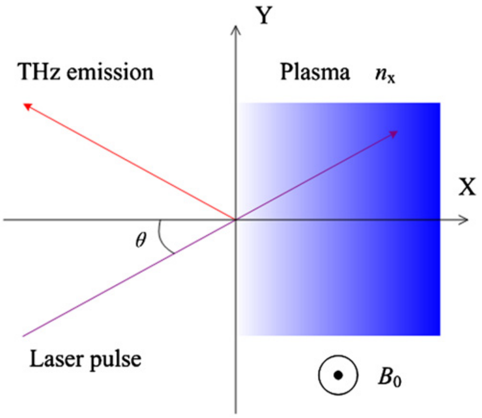

Fig. 1. THz emission from a wakefield generated by a laser pulse incidence obliquely to the magenetized plasma with inhomogeneous density.

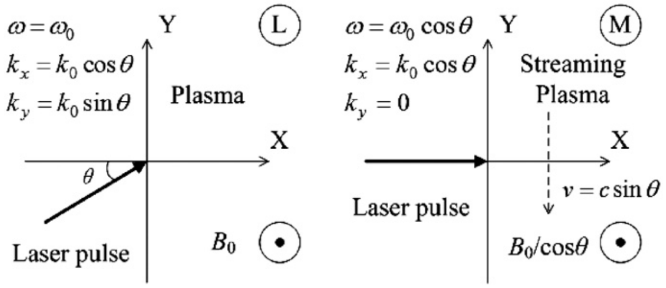

Fig. 2. Lorentz transformation from laboratory frame L to moving frame M.

density increases linearly along the x direction and the external magnetic field B_0 is along the z direction. The plasma is underdense, i.e. $\lambda^2/\lambda_P^2 \ll 1$, where λ is laser wavelength and λ_P is plasma wavelength, $\lambda_P = 2\pi c/\omega_P$ and $\omega_P = \sqrt{ne^2/\varepsilon_0 m_e}$ is plasma frequency. The plasma density increases linearly with distance, i.e. $n(x) = n_0 x/L$, where $L = n_c/n'$ is plasma density scale length, n_c is the critical density and $n' = \partial n/\partial x$ is the density gradient. The external magnetic field B_0 is along the z-direction perpendicular to the incident plane.

The present investigation is restricted to one-dimensional geometry. We make a Lorentz transformation from the laboratory frame L to a frame M [8], moving in y-direction parallel to the surface such that the pulse is normally incident in frame M. The 1-D model is valid as long as the laser spot size is very large compared to the plasma wavelength, i.e., $r_s \gg \lambda_p = 2\pi/k_p$, where $k_p = \omega_p/c$. As shown in Fig. 2, for the angle of incidence θ, the frame velocity $v_f = c\sin\hat{e}_y$, $\hat{e}_y$ is a unit vector along the y direction. While the plasma is at rest in L, and streams in M with $-v_f$.

In changing from L to M, and describing the problem with vector potentials $\mathbf{A}$, Maxwell's equations then read

$$\left(\partial_x^2 - \frac{1}{c^2}\partial_t^2\right)\mathbf{A}(x,t) = -\frac{1}{\varepsilon_0 c^2}\mathbf{J}_\perp(x,t) \tag{1}$$

$$\mathbf{E}_\perp(x,t) = -\partial_t \mathbf{A}(x,t) \tag{2}$$

$$\mathbf{B}(x,t) = \nabla \times \mathbf{A}(x,t) \tag{3}$$

The motion equation is

$$d_t\mathbf{P} = d_t(m\gamma\mathbf{V}) = q(\mathbf{E} + \mathbf{V} \times \mathbf{B}) \tag{4}$$

The plasma is assumed to be a cold electron slab with a static background of ions, where m and q are electron mass and charge respectively. In the fluid picture, the total time derivatives d_t is interpreted as $d_t = \partial_t + v_x\partial_x$. The electron momentum $\mathbf{P} = m\gamma\mathbf{V} = \mathbf{P}_\perp + P_x$ and relativistic factor $\gamma = \sqrt{1 + (\mathbf{P}/mc)^2}$. The transverse momentum $\mathbf{P}_\perp$ is written in the form

$$d_t(\mathbf{P}_\perp + q\mathbf{A}) = -qV_x B_{M0}\hat{e}_y \tag{5}$$

where $B_{M0} = B_0/\cos\theta$ is the magnetic field in the moving frame. It is convenient to get $d_t(P_y + qA_y) = -qV_x B_{M0}\hat{e}_y$ and $d_t(P_z + qA_z) = 0$ from Eq. (5). The transverse momentum can be written as

$$\mathbf{P}_\perp = m\gamma\mathbf{V}_\perp = \mathbf{P}_{\perp 0} - q\mathbf{A} \tag{6}$$

where $\mathbf{P}_{\perp 0} = -mc\tan\theta\hat{e}_y$ denotes the initial transverse momentum, corresponding to the plasma streaming in negative y direction. The initial distribution of ions is given by $n_i(x) = n_{cM}\Theta(x)$, where $n_{cM} = n_c/\cos\theta$, $\Theta(x) = x/L$ is the linearly density description for our case.

The transverse current $\mathbf{J}_\perp$ in Eq. (1) contains electron and ion contributions, $\mathbf{J}_\perp = -e(n_e\mathbf{V}_{\perp e} - n_i\mathbf{V}_{\perp i})$, where $\mathbf{V}_{\perp e} = \mathbf{P}_\perp/m\gamma$ and $\mathbf{V}_{\perp i} = -c\sin\theta\hat{e}_y$. After these substitutions, the final result can be expressed in terms of the scaled dimensionless quantities $\mathbf{a} = e\mathbf{A}/mc$, $\mathbf{p} = \mathbf{P}/mc$, $\mathbf{v} = \mathbf{V}/c$, $B = B_0 e/m$, $n = n_e/n_{cM} = n_e\cos\theta/n_c$. Which satisfy the following equations:

$$\left(\partial_x^2 - \frac{1}{c}\partial_t^2\right)\mathbf{a} = \left(\frac{\omega_p}{c}\right)^2\left[\frac{n}{\gamma\cos\theta}(a_z\hat{e}_z + p_y\hat{e}_y) + \Theta(x)\tan\theta\hat{e}_y\right] \tag{7}$$

$$d_t(p_y - a_y) = v_x B\hat{e}_y \tag{8}$$

$$d_t(p_z - a_z) = 0 \tag{9}$$

Eq. (7) determines whether the THz radiation from the laser wakefield occurs. For unmagnetized case, i.e. $B=0$. According to Eq. (8), one can get $p_y = a_y + c_0$, where $c_0 = \mathbf{P}_{\perp 0}/mc = -\tan\theta\hat{e}_y$. Substituting p_y into Eq. (1) leads

$$\left(\partial_x^2 - \frac{1}{c}\partial_t^2 - \frac{\omega_p^2 n}{c^2\gamma\cos\theta}\right)\mathbf{a} = \left(\frac{\omega_p}{c}\right)^2\left[\Theta(x) - \frac{n}{\gamma\cos\theta}\right]\tan\theta\hat{e}_y \tag{10}$$

It is clear that there exists THz emission from the wakefield around the plasma frequency if the incident angle $\theta \neq 0$, and the emission is always p polarized.

For magnetized case, two new features are introduced into the process of resonant absorption. First, the resonant frequency is now the upper hybrid frequency $\omega_{uh} = (\omega_p^2 + \omega_c^2)^{1/2}$, instead of the plasma frequency ω_p and $\omega_c = eB/m$ is the electron cyclotron frequency. Second, the Lorentz force provides coupling between the electromagnetic and electrostatic waves so that, even for normal incidence, mode conversion into the THz emission takes place and significant absorption of the incident laser energy occurs. According to Eq. (8), for normal incidence of laser pulse, i.e. $\theta = 0$, there is still a nonzero source in the right-hand side of Eq. (7) and leads to the THz emission occurs. The THz emission is also p polarized as in unmagnetized case.

3. PIC simulation results

In order to simulate the process of THz emission generated from plasma wakefield excited by laser pulse, one-dimensional PIC program is compiled. According to the derivation above, we set incident laser pulse with s polarization in order to distinguish it from the p polarized THz emission. The laser wavelength $\lambda_0 = 1\ \mu\text{m}$, the corresponding critical density of the plasma $n_c = m\omega_{p0}^2\varepsilon_0/e^2 = 1.1 \times 10^{21}\ \text{cm}^{-3}$ and the plasma frequency is $\omega_{p0}/2\pi = 293$ THz. The simulation range is $25\lambda_0$, the left part is vacuum (between $x=0$ and $5\lambda_0$) and the right part is the plasma (between $x = 5\lambda_0$ and $25\lambda_0$). The plasma density increases linearly with distance from left boundary $n(x = 5\lambda_0) = 0.03n_c$ to right boundary $n(x = 25\lambda_0) = 0.09n_c$. We select an incident laser pulse