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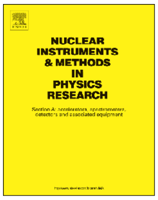

Emission of strong Terahertz pulses from laser wakefields in weakly coupled plasma

Divya Singh [a,b,*], Hitendra K. Malik [a]

[a] PWAPA Laboratory, Department of Physics, Indian Institute of Technology Delhi, New Delhi 110 016, India
[b] Department of Physics & Electronics, Rajdhani College, University of Delhi, Raja Garden, Ring Road, New Delhi 110015, India

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ABSTRACT

The present paper discusses the laser plasma interaction for the wakefield excitation and the role of external magnetic field for the emission of Terahertz radiation in a collisional plasma. Flat top lasers are shown to be more appropriate than the conventional Gaussian lasers for the effective excitation of wakefields and hence, the generation of strong Terahertz radiation through the transverse component of wakefield.

1. Introduction

Interaction of intense lasers with plasma is a very enriched field of research, giving rise to very interesting physical phenomena like laser induced fusion, higher harmonic generation, laser-plasma channeling, laser plasma acceleration and plasma based radiation sources. These radiation sources range from X-ray to THz frequency domain. Now a days Terahertz radiation sources have several applications and are being used extensively for imaging, material characterization, topography, tomography, communication, etc. [1]. THz radiation can be produced from plasma and electron beam based THz emitters, such as coherent radiation from plasma oscillations driven by ultrashort laser pulses [2], transition radiation of electron beams [3], synchrotron radiation from accelerator electrons [4], Cherenkov wake radiation in magnetized plasmas [5] and emission from laser plasma channels in air. Plasma is found to be more suitable than the solid targets due to longer sustainability at higher powers of the laser. Theoretical and simulation studies of extremely powerful Terahertz emission by the interaction of chirped [6] and few cycle laser pulses [7] with tenuous plasma have been reported by Wang et al. Ostermayr et al. have used super-Gaussian pulse for the laser plasma acceleration [8].

A wakefield is an electrostatic wave driven by a laser pulse in plasmas. There have been a number of studies on the excitation of the large amplitude wakefield because of its extensive application prospects, such as in high-gradient electron acceleration [9], proton acceleration [10] and X-ray radiation [11]. Sheng et al. have proposed that high efficiency THz emissions can be produced from a laser driven wakefield in an inhomogeneous plasma through linear mode conversion [12]. Wu et al. [13] have studied the effect of the transverse magnetic field on this process and have found significant enhancement in the efficiency of THz generation. Since the typical plasma oscillation frequency for these applications is in the Gigahertz to Terahertz range, the wakefield can potentially serve as a powerful THz emitter. Above mentioned, all schemes talk about the wakefield excitation but none of them have discussed collisional plasma.

In theories as well as in experiments, collisional effects are generally ignored but our calculations and results show that the even small fraction of collisions in the range ($\nu = 0.05\omega_p$ to $0.5\omega_p$) reduce the longitudinal wakefield and therefore amplitude of emitted THz field is also reduced greatly. The collision frequency depends on the electron temperature as per the relation

$$\nu_e = \nu_0 \left(T_e / T_0 \right)^{s/2}.$$

where, s is a parameter characterizing the type of collision in plasma, where T_0 is the equilibrium temperature [14]. For experimentation purpose it is promising to convert a considerable fraction of the energy of plasma oscillations exciting longitudinal wakefield in the plasma is reemitted with their frequencies controlled over a terahertz range radiation by varying the parameters

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* Corresponding author at: Department of Physics & Electronics, Rajdhani College, University of Delhi, Raja Garden, Ring Road, New Delhi 110015, India.
E-mail address: dsingh@rajdhani.du.ac.in (D. Singh).

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of the ionized gas, i.e. the pressure and temperature. In particular, Golubev et al. [15] have experimentally obtained THz radiation from the optical breakdown of a gas and investigated the effect of gas pressure and temperature on collisions. They found the collision frequency of the order of $1.5\times10^{13}\ \mathrm{s}^{-1}$ and plasma frequency $3.0\times10^{14}\ \mathrm{s}^{-1}$ at the atmospheric pressure and when the temperature $T_e = 15$ eV. Therefore, the inequality $\nu<\omega_p$ may be fulfilled at the normal pressure for better amplitude of the THz radiation. However, at the higher pressure of the order of 400 atm, both the frequencies become equal ($f_p\approx\nu\approx6\times10^{15}\ \mathrm{s}^{-1}$). Hence, the corresponding radiation frequency falls into the optical range, which, is of little interest. Hence, it is important to consider collisions for normal pressure and temperature in laser plasma interaction experimentally. On the other hand, Chen [16] has studied experimental behavior of Neon plasma with respect to electron collision frequency by varying plasma density for different temperatures and concluded that the electron collisions in uniform density plasma are sensitive to electron temperature at a given gas temperature and show weak dependence on the gas pressure. Thus it become imperative to control collisions in the laser plasma interaction mechanism. Therefore, we justify the discussion on emission of THz radiation pulses from wakefields in collisional plasma when Gaussian and flat top lasers are used and we also justify that the collision frequency that we have considered are experimentally viable.

In the present article, we present a theoretical analysis for Terahertz radiation generation based on the scheme of the excitation of wakefield produced by the propagation of highly intense ultra-short flat top laser through collisional magnetized plasma of uniform density, where ions are supposed to be immobile and electron neutral collisions prevail.

2. Excitation of plasma currents, wakefield and THz radiation

In the present work, we consider a flat top laser (FTL) of frequency ω and wave number k, propagating in the plasma of uniform density n_0 along the z-axis. The field of the laser is given as $\vec{E}=E_0 e^{\left[-\left(\frac{y}{b_w}\right)^6\right]} e^{[i(kz-\omega t)]}\hat{y}$, where E_0 is the field amplitude and b_w is the beamwidth of the laser. The laser electric field is taken to be polarized along the y-axis whereas an external magnetic field is taken to be applied along the x-axis. In the presence of the external magnetic field (B), the laser field impart oscillatory velocity to the electrons whereas plasma ions remain immobile. The plasma is weakly coupled, so the electron neutral collisions are taken to be present.

We make use of the perturbation approach. Hence, physical quantities like electron velocity, plasma density and plasma currents are expanded to their first order in orders of laser strength parameter ($a=\frac{eE_0}{mc\omega}$«1 approximated). The electron dynamics in the plasma is completely expressed by the force equation, where collisional force (frequency ν) acts as a damping cause. The plasma electron velocity is computed as,

$$\vec{v}=\vec{v}^{(0)}+a\vec{v}^{(1)}$$
$$=eE_0 e^{\left[-\left(\frac{y}{b_w}\right)^6\right]}\left[\frac{1}{im(\omega+i\nu)}\hat{y}+a\left\{\frac{(\omega+i\nu)}{im[(\omega+i\nu)^2-\omega_c^2]}\hat{y}+\frac{\omega_c}{m[(\omega+i\nu)^2-\omega_c^2]}\hat{z}\right\}\right]$$
$$e^{i(kz-\omega t)}.$$

No component of the velocity is found to arise in the direction of the external magnetic field. The cyclotron frequency is represented as $\omega_c=\frac{eB}{mc}\hat{x}$. Under the influence of collisional forces and external magnetic field, the electron oscillations become nonlinear. Therefore, nonlinear density perturbations are generated. Different order components of the nonlinear density are computed using equation of continuity where n_0 is taken to be the ambient density of the plasma. The components of the nonlinear plasma density are obtained as $n^{(1)}=\frac{kn_0\vec{v_y}^{(1)}}{(\omega-k\vec{v_y}^{(0)})}\hat{y}+\frac{kn_0\vec{v_z}^{(1)}}{\omega}\hat{z}$. Due to the density perturbations in the plasma, coupling of plasma oscillations with density fluctuations take place that drive nonlinear plasma currents. Thus magnitude of these nonlinear plasma currents are obtained as

$$\vec{J}=n_0e^2E_0 e^{\left[-\left(\frac{y}{b_w}\right)^6\right]}\left[\frac{1}{(\omega-k\vec{v_y}^{(0)})}\frac{i\omega(\omega+i\nu)}{m[(\omega+i\nu)^2-\omega_c^2]}\hat{y}+\frac{\omega_c}{m[(\omega+i\nu)^2-\omega_c^2]}\hat{z}\right]e^{i(kz-\omega t)}.$$

Now we will discuss how nonlinear plasma current densities cause the excitation of various components of the wakefield and thereby the emission of THz radiation in collisional plasma. The components of electric and magnetic wakefield are coupled with time dependent Maxwell's equations by using $\vec{E_w}$ and $\vec{B_w}$ as the components concerning the wakefield. In general, the magnetic wakefield is not considered further, the reason being that they have very low magnitudes as compared to the electric wakefields. Using quasistatic approximation, we consider that the laser pulse does not evolve significantly and therefore, the field variations are assumed to be time independent. Maxwell's equations are expressed in terms of the transformed coordinate $\xi=z-v_g t$ as laser propagates along z axes with group velocity v_g. Further, the plasma electron motion is analyzed under the excited plasma wakefield using force equation. On combining the Maxwell's equations with the force equation, we obtain differential equations for the wakefields as follows

$$\frac{\partial^2\vec{E_z}}{\partial\xi^2}+\frac{\partial^2\vec{E_y}}{\partial\xi^2}+k_p^2\left[\vec{E_z}+\left(\frac{\omega}{\omega-kv_y^{(0)}}\right)\vec{E_y}\right]$$
$$=-\frac{k_p^2 m}{e}\times eE_0 e^{\left[-\left(\frac{y}{b_w}\right)^6\right]}$$
$$\left[\left(\frac{\omega}{\omega-kv_y^{(0)}}\right)\frac{\nu(\omega+i\nu)}{im[(\omega+i\nu)^2-\omega_c^2]}\right.$$
$$\left.+\left[\frac{\omega_c}{im(\omega+i\nu)}-\frac{\nu\omega_c}{m[(\omega+i\nu)^2-\omega_c^2]}\right]\right], \tag{1}$$

where $k_p^2=\frac{4\pi n_0e^2}{mc^2}$ is the plasma wave number. Eq. (1) is solved numerically for the y-and z-components of the wakefield using Runge–Kutta method for collisional magnetized plasma with boundary condition that $\vec{E_z}=0$ at $\xi=0$ and $\xi=L/2$. Here L is the length of the laser pulse. Numerical solution of Eq. (1) and hence, the wakefields are plotted in the next section. It is observed that the magnitudes strictly depends on the relative amplitude of the laser field, electron neutral collision and cyclotron frequencies.

We further calculate the transverse component of the wakefield in terms of the horizontal wakefield analytically. This transverse component of the oscillating wakefield is emitted as THz pulses. The analytical expression of the transverse THz field amplitude is obtained as

$$\vec{E}_{THz}=\left[\frac{1}{k_p^2}\frac{6y^5}{b_w^6}\frac{\omega_c(\omega-kv_y^{(0)})(\omega^2-\omega_c^2+i\nu\omega)}{\omega(i\omega-\nu)\left[(\omega+i\nu)^2-\omega_c^2\right]}+\frac{i\nu(\omega+i\nu)}{[(\omega+i\nu)^2-\omega_c^2]}\right]$$
$$E_0 e^{-(y/b_w)^6}. \tag{2}$$

It is evident from the mathematical calculations that the plasma wakefields are excited in the plasma due to propagation of highly intense laser through it. These wakes are longitudinal and transverse in nature. It is well-known that the longitudinal wakefields are used for the acceleration purpose, whereas the transverse component is of less importance. Our calculations