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Terahertz radiation emission from plasma beat-wave interactions with a relativistic electron beam

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ABSTRACT

We present a mechanism to generate terahertz radiation from laser-driven plasma beat-wave interacting with an electron beam. The theory of the energy transfer between the plasma beat-wave and terahertz radiation is elaborated through nonlinear coupling in the presence of a negative-energy relativistic electron beam. An expression of terahertz radiation field is obtained to find out the efficiency of the process. Our results show that the efficiency of terahertz radiation emission is strongly sensitive to the electron beam energy. Emitted field strength of the terahertz radiation is calculated as a function of electron beam velocity.

1. Introduction

Terahertz (THz) radiation is the portion of the electromagnetic spectrum at the boundary between the microwaves and the infrared. There are several well-known sources for coherent THz radiation generation such as solid state oscillators, quantum cascade lasers, optically pumped solid state devices and novel free electron devices, which have n turn stimulate a wide range of applications from material science to telecommunications, from biology to biomedicine [1]. Today most widely used sources of pulsed THz radiation are laser driven THz emitters based on frequency down conversion from the optical region [2,3]. In free-electron based sources, to overcome the necessity of reducing the size of the components, several methods have been proposed to let the electrons exchange momentum and allow photon emission. The most familiar method is the use of magnetic wiggler to generate the electromagnetic radiation by the electron beam [4]. In this scheme, an electron beam within a distance comparable to the wavelength of the radiation can emits the coherent radiation. Moreover, a radio-frequency modulated electron beam at wavelengths comparable to the electron bunch length can generates the short pulses of coherent THz radiation.

There also exits laser based THz sources, which can fit on or scale of the size of a table-top. A terahertz field greater than 400 kV/cm generated using short 25 fs pulses has been reported by Bartel et al. [5]. Karpowicz et al. [6] reported the generation and detection of broadband terahertz pulse in air covering the spectral range of 0.3 to 10 THz with 10% or larger of the maximum electric field. Terahertz wave generation mechanism in air was originally attributed to the four-wave rectification process through the third-order optical nonlinearity of air [7]. However, it has been suggested that the plasma formation plays an important role in the terahertz wave generation process [8]. The four-wave rectification mechanism was tested by Xie et al. [9] by controlling the relative phase, amplitude and polarization of the fundamental and second harmonic pulses. Kim et al. [10] proposed a transient photo current model based on the rapid ionization by femtosecond laser pulses by following the driven motions of electrons by an asymmetric electric field.

Laser-plasma based accelerators [11] such as the laser wakefield accelerators [12–14] and the laser beat-wave accelerators [15–17] are widely being researched as possible alternate sources for high energy electron beam. These systems could be used to generate THz radiation. There are several theoretical mechanisms to generate THz from laser-plasma interactions [18–20]. Bystrov et al. [18] have proposed the Terahertz radiation of plasma oscillations excited upon the optical breakdown of a gas. Chen [19] has studied the THz radiation using a tailored laser pulse in a plasmas. Such radiation source has a broad tunability range in frequency spectra. Antonsen et al. [20] have a theoretical model for THz radiation generation in a nonuniform plasma. Miniature corrugated channels has been proposed for THz radiation generation by bunched electron beams in plasmas.

In our work, we utilize the plasma beat-wave generated in laser beat-wave accelerator for THz radiation generation process. In a beat-wave

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accelerator, two co-propagating lasers, having frequency difference equal to the plasma electron frequency, can excite a large amplitude plasma wave. We use this plasma beat-wave to generate THz radiation while interacting with a negative energy relativistic electron beam. The negative energy of the beam means that the electron beam propagates opposite to the plasma wave in this scheme. An electron beam propagating through a plasma causes the onset of plasma instability due to the free energy available in the relativistic motion between the beam and the plasma [21]. The plasma beat-waves at moderate laser intensities acquire levels large enough to causes the onset of parametric instabilities. Beam space charge mode can be existed if an electron beam is present. The plasma beat-wave nonlinearly couples with the THz electromagnetic mode to drive the negative-energy beam space-charge mode. Both decayed waves grow in the expense of the beam and the plasma beat-wave. The oscillatory velocity combines with an existing negative-energy beam mode to produce ponderomotive force that drives the electromagnetic sideband. The sidebands couple to the pump wave to produce a nonlinear current that drives the instability. In a result, the plasma beat-wave and the electron beam both lose their energy during the nonlinear interactions and generate THz radiation. In Section 2, we present the theoretical model used to find out the THz radiation field strength. In Section 3, we explain the numerical results and discuss the physics behind the suggested mechanism and we make final remark in the last section.

2. Theoretical model

We consider a plasma of the density n_0 and the electron temperature T_e. Two collinear laser beams of large amplitude propagate in a plasma with electric fields

$$\mathbf{E_{01}} = \mathrm{Re}\,\hat{x} A_{01} \exp[-i(\omega_{01} t - k_{01} z)], \tag{1}$$

$$\mathbf{E_{02}} = \mathrm{Re}\,\hat{x} A_{02} \exp[-i(\omega_{02} t - k_{02} z)], \tag{2}$$

where $|A_{01}|^2_{x=0} = A^0_{01}\exp(-x^2/r^2_{01})$, $|A_{02}|^2_{x=0} = A^0_{02}\exp(-x^2/r^2_{02})$, $\omega_{01} - \omega_{02} \approx \omega_p$, $\omega_{01} \geq \omega_p$, $\omega_{02} \geq \omega_p$, ω_{01} and ω_{02} are the laser frequencies, $\mathbf{k_{01}}$ and $\mathbf{k_{02}}$ are the wave vectors of the laser beams, and r_{01} and r_{02} are the laser spot sizes. They produce oscillatory velocities $\upsilon_{0j} = e\mathbf{E_{0j}}/mi\omega_{0j}$ $(j = 1, 2)$ and exert a ponderomotive force $\mathbf{F_p} = -(e/2c)(\upsilon_{01}\times\mathbf{B}^*_{02} + \upsilon_{02}\times\mathbf{B}^*_{01}) = \hat{z} iek_0\phi_{p0}\exp[-i(\omega_0 t - k_0 z)]$ on them, where $\phi_{p0} = eA_{01}A_{02}/2m\omega_{01}\omega_{02}$, $\omega_0 = \omega_{01} - \omega_{02}$, $\mathbf{k_0} = \mathbf{k_{01}} - \mathbf{k_{02}}$, $\mathbf{B_{0j}} = c\mathbf{k_{0j}} \times \mathbf{E_{0j}}/\omega_{0j}$, and $-e$ and m are the electron charge and mass, respectively. Because of the large mass and the slow response of the ions, we consider them immobile. The ponderomotive force drives a large amplitude beat-wave in a plasma. We write the Eulerian equation for the plasma-wave electric field driven by the ponderomotive force of the beating laser pumps as [22]

$$\ddot{E}_p + \omega_p^2 E_p + \upsilon_{th}^2 E_p'' = \frac{1}{2} A_{01} A_{02} \omega_0^2 \sin(\Delta kz - \Delta\omega t), \tag{3}$$

where $\omega_p = (4\pi n_0 e^2/m)^{1/2}$ is the unperturbed plasma frequency, $\upsilon^2_{th} = 3T_e/m$, T_e is the electron temperature, $\Delta k = k_0$ and $\Delta\omega = \omega_0 \approx \omega_p$ are the frequency and wave number differences of the two laser pumps. Under cold plasma approximation, we take $\upsilon_{th} \approx 0$ and the solution of Eq. (3) can be in the form

$$\mathbf{E}_p = \mathrm{Re}\,\hat{z} E_{p0} \exp\left[-i\left(\omega_0 t - k_0 z\right)\right]. \tag{4}$$

The plasma beat-wave acquires a large amplitude to onset of the parametric instabilities. We also consider a relativistic electron beam of density n_{0b} passes through it in opposite direction with initial velocity of $-\upsilon_{ob}\hat{z}$. Thus the plasma beat wave is traveling in opposite direction to the electron beam. The fundamental beat-wave $(\omega_0,\ \mathbf{k}_0)$ parametrically couples to the electron beam and excites a negative energy beam mode $(\omega_b,\ \mathbf{k_b})$ and a THz electromagnetic wave $(\omega_1,\ \mathbf{k}_1)$, where $\omega_1 = \omega_b + \omega_0$, and $\mathbf{k_1} = \mathbf{k_b} + \mathbf{k_0}$. The slow-beam space charge mode has negative energy $(\omega_b = -\mathbf{k}_b \cdot \upsilon_{0b})$. The plasma beat-wave imparts oscillatory velocity to the plasma and beam electrons. Solving the equation of motion and continuity, the velocity and density perturbation of the beam electrons can be written as

$$\upsilon_{\mathbf{0}b} = \frac{e\mathbf{E_p}}{mi\gamma^3_{0b}(\omega_0 - k_0\upsilon_{0b})}, \tag{5}$$

$$n^1_{0b} = \frac{ek_p\mathbf{E_p}}{mi\gamma^3_{0b}(\omega_0 - k_0\upsilon_{0b})^2}. \tag{6}$$

Here, we perturb the plasma equilibrium as $\boldsymbol{\upsilon}_b = \boldsymbol{\upsilon}_{0b} + \boldsymbol{\upsilon}^1_{0b}$, $n_b = n_{0b} + n^1_{0b}$, $\gamma_b = \gamma_{0b} + \gamma^1_{0b}$, where $\gamma_{0b} = (1 - \upsilon^2_{0b}/c^2)^{-1/2}$ and $\gamma^1_{0b} = \gamma^3_{0b}(\upsilon^2_{0b}/c^2)$. Corresponding quantities for plasma electrons, $\boldsymbol{\upsilon}_{0e}$ and n_{0e}, can be deduced from Eqs. (5) and (6) by dropping the subscript b and taking $\boldsymbol{\upsilon}_{0b} = 0$. The plasma beat-wave decays into the negative energy beam mode with potential of $\phi = \Phi\exp[-i(\omega_b t + k_b z)]$ and a THz electromagnetic wave with electric field of $\mathbf{E_1} = A_1\exp[-i(\omega_1 t + k_1 z)]$. The linear response of the beam electrons at $(\omega_1,\ \mathbf{k}_1)$ is

$$\upsilon^1_{1b} = \frac{e\mathbf{E}_1}{mi\gamma^3_{0b}(\omega_1 - k_1\upsilon_{0b})}. \tag{7}$$

The THz radiation $(\omega_1,\ \mathbf{k}_1)$ couples with the pump wave $(\omega_0,\ \mathbf{k_0})$ to produce a ponderomotive force $(\mathbf{F_p} = m\gamma\upsilon\cdot\nabla\upsilon)$ at frequency of $(\omega_b,\ \mathbf{k}_b)$. The longitudinal ponderomotive force on the beam electrons can be explicitly written as $\mathbf{F_{p}}_b = \hat{z} eik_b\phi_{pb}$, where $\phi_{pb} = -e\mathbf{E^*_p}\mathbf{E_1}/2m\gamma^5_{0b}(\omega_1 - k_1\upsilon_{0b})(\omega_0 - k_0\upsilon_{0b})$. Ponderomotive potential ϕ_p for plasma electrons can be deduced by taking $\upsilon_{0b} = 0$ in the same expression. ϕ_p and ϕ at $(\omega_b,\ \mathbf{k}_b)$ produce electron beam density perturbation

$$n_b = \frac{k_b^2}{4\pi e}\chi_b(\phi + \phi_p), \tag{8}$$

where $\chi_b = -\omega^2_{pb}/\gamma^3_0(\omega_b - k_b\upsilon_{0b})^2$ and $\omega_{pb} = (4\pi n_{0b}e^2/m)^{1/2}$. Similarly, the plasma electron density perturbation is

$$n = \frac{k_b^2}{4\pi e}\chi_e(\phi + \phi_p), \tag{9}$$

where $\chi_e = -\omega^2_p/\omega^2_b$. Using the density perturbation in Poisson's equation, we obtain $\varepsilon\phi = -\chi_b\phi_{pb} - \chi_e\phi_p$, where $\varepsilon = 1 + \chi_e + \chi_b$. The nonlinear current density and density perturbation at the THz electromagnetic wave can be written as $\mathbf{J}^{\mathbf{NL}}_1 = -n_b e\upsilon^{\mathbf{1}}_{0b}/2$. The wave equation governing the terahertz field can be written as

$$-\nabla^2\mathbf{E}_1 + \nabla(\nabla\cdot\mathbf{E_1}) = -\frac{4\pi i\omega_1}{c^2}\mathbf{J}^{\mathbf{NL}}_1 + \frac{\omega^2_1}{c^2}\varepsilon_1\mathbf{E}_1, \tag{10}$$

where $\varepsilon_1 = 1 - \omega^2_p/\omega^2_1$. Assuming the radial variation of the electrostatic pump mode to be small over the width of the beam and taking the divergence of Eq. (10), we obtain $\mathbf{E}_1 = -4\pi i\omega_1\mathbf{J}^{\mathbf{NL}}_{\mathbf{1}}/(\omega^2_1 - \omega^2_p)$, which gives

$$|\mathbf{E_1}| = -\frac{ek^2_b\omega^2_{pb}|\mathbf{E_p}|\phi_p}{2m\gamma^6_0\omega_1(1 - \omega^2_p/\omega^2_1)(\omega_0 - k_0\upsilon_{0b})(\omega_b - k_b\upsilon_{0b})^2}, \tag{11}$$

where we have considered that, in the case of when beam density (or the beam current) is small, $\chi_b \ll 1$, the self-consistent potential of the beam can be neglected as compared to the ponderomotive potential $(\phi \ll \phi_{pb})$.

3. Numerical results and discussion

Using Eq. (11), we depict the THz field strength with respect to the THz frequency. The used numerical parameter are as follows: $a_{01} = eA_{01}/m\omega_{01}c = 1$ and $a_{02} = eA_{02}/m\omega_{02}c = 1$ (corresponding to peak laser intensity $I_{01} \approx I_{02} \approx 1.37\times10^{18}$ W/cm^2), the considered wavelength of first laser is $\lambda_{01} \sim 1$ μm and the wavelength of second laser has been chosen according to the resonant condition for beat-wave excitation, and the initial waist size is $r_{01} \approx r_{02} \sim 10$ μm. The plasma electron density considered for this calculation is $n_0 \approx 10^{16}$ cm^{-3}. We consider that an