Terahertz Radiation from Laser Created Plasma by Applying a Transverse Static Electric Field

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ABSTRACT

We have been experimentally observed a terahertz (THz) radiation from laser created plasma by applying a transverse static electric field. Some theoritical models have been proposed, however, they are not enough to explain the phenomena of the plasma with the external electric field. We have developed new model to explain this phenomena and confirmed its validity by using 2D-PIC simulation.

Keywords

terahertz, radiation, external electric field, plasma, laser

1. Introduction

Terahertz (THz) radiation with narrow cone structure in the forward direction from high intense femtosecond laser pulse created plasma has been observed [1-3]. This THz radiation is produced by the longitudinal oscillation currents induced by the laser ponderomotive force after the laser propagation.

Additionally, the significantly increased THz emission intensity in the forward direction has been observed when the transverse static electric field is applied to the plasma [4,5]. Aurélien Houard *et al.* have proposed that the radiation source is the transverse oscillation electron current due to shielding of the external electric field. This oscillation frequency is equal to the plasma frequency with decaying in a few electron collision time. However, we have been experimentary measured the sub-THz radiation, whose frequency is much lower than the plasma frequency. This paper destribes the derivation of the mechanism of the THz radiation from laser created plasma by applying the transverse static electric field.

The organization of the present paper is as follows. In Sec.2, the theory which we proposed is described or presented. To verify our theory, we conducted both experiments and 2D-PIC simulation. In Sec.3, we show, present or state experimental results. The simulation results are reported in Sec.4. A summary and discussion are given in Sec.5

2. Theory

In the following, we will clarify the electro magnetic field in the plasma when applied external electric field. We take the coordinates (x,y,z) in this article, where x is in the longitudinal direction of the laser propagation axis, and (y,z) plane is the transverse dimension of the laser propagation axis. The static electric field to laser created plasma is applied in the y direction. The wave equation with external static electric filed is written as

$$\left(\frac{\partial^2}{\partial t^2} + \omega_{\rm p}^2 - c^2\nabla\right) E_y(x,t) = -\omega_{\rm p}^2 E_{\rm ex}, \quad (1)$$

where c, ω_p and $E_{\rm ex}$ are the speed of light, plasma frequency and external static electric field in the y derection, respectively. Plasma frequency is defined as $\omega_p = \sqrt{e^2 n_e/m_e\varepsilon_0}$, where e, n_e, m_e and ε_0 are electron charge, electron density, mass of electron and permittivity of vacuum, respectively. By the use of the new coordinates ($\xi = x - v_{\rm g}t$) moving with the laser group velocity $v_{\rm g}$, we obtain

$$\left\{(v_{\rm g}^2 - c^2)\frac{\partial^2}{\partial \xi^2} + \omega_{\rm p}^2\right\} E_y(\xi) = -\omega_{\rm p}^2 E_{\rm ex}. \quad (2)$$

By applying the Laplace transformation to Eq. (2), we obtain

$$E_y(s) = -\frac{\omega_p}{\sqrt{v_{\rm g}^2 - c^2}} \frac{\frac{\omega_p}{\sqrt{v_{\rm g}^2-c^2}}}{s^2 + \frac{\omega_{\rm p}^2}{v_{\rm g}^2-c^2}} E_{\rm ex}(s), \quad (3)$$

where s is a complex number frequency parameter. Inverse-Laplace transform of Eq. (3) becomes

$$E_y(\xi) = -\frac{\gamma\omega_{\rm p}}{c}\int_0^{\xi'} \exp\left\{\frac{\gamma\omega_{\rm p}}{c}(\xi-\xi')\right\} E_{\rm ex}(\xi')d\xi',$$

where γ is the lorentz factor which is defined as $\gamma = \frac{1}{\sqrt{1-v_{\rm g}^2/c^2}}$. Then we have

$$E_y(\xi) = E_{ex}\exp\left(\gamma\frac{\omega_{\rm p}}{c}\xi\right). \quad (4)$$

We use coordinates (x,t) rather than the coordinate ξ, electric field in the plasma with the external electric field is

$$E_y(x,t) = E_{ex}\exp\left(\gamma\frac{\omega_{\rm p}}{c}x - \gamma\frac{v_{\rm g}}{c}\omega_{\rm p}t\right). \quad (5)$$

We calculate magnetic field and current density in the plasma with external electric field in the same way as electric field, we obtain

$$B_z(x,t) = -\frac{E_{ex}}{v_g}\left\{1-\exp\left(\gamma\frac{\omega_p}{c}x - \gamma\frac{v_g}{c}\omega_p t\right)\right\} \quad (6)$$

$$J_y(x,t) = \frac{\varepsilon_0 c}{\gamma v_g}E_{ex}\left\{1-\exp\left(\gamma\frac{\omega_p}{c}x - \gamma\frac{v_g}{c}\omega_p t\right)\right\} \quad (7)$$

From eq.(5), the electric field at the plasma-gas boundary $x = 0$ is decayed with $\gamma v_{\rm g}\omega_{\rm p}/c \approx \gamma\omega_{\rm p} \gg \omega_{\rm p}$ in time. This means the electric field decays very quickly. From eq.(7), the electron current is induced, however, it is also quickly decayed and does not oscillate, therefore it is differnet from the previous theoy[5].

3. Experimental results

Ti:sapphire chirped pulse amplified laser, delivering 120 fs duration (FWHM) pulses at 800 nm, with a maximum energy of 30 mJ per pulse operating at a repetition rate of 10 Hz was used. As illustrated in Fig. 1, laser pulse is focused in air by lens whose focal length is 1000 mm to create plasma. Laser created plasma is applied the transverse static electric field which induced by the two electrodes that located along the laser propagation axis. THz radiation intensity from laser created plasma by applied external electric field is detected by the use of crystal detector which is calibrated and has response at the F band (90 - 140 GHz). Fig. 2 shows the angular distribution of the THz emission generation. The conical forward radiation with no radiation on the propagation axis without the transverse static electric field was observed. As the external electric field is bigger, the radiation intensity is bigger on the propagation axis. Fig. 3 shows intensity of the radiated THz wave as a function of the external electric field. THz radiation intensity was proportional to square of the external electric field.

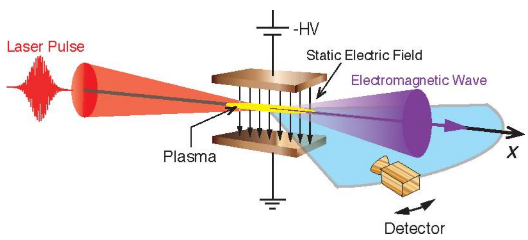

Fig.1 Experimental method for THz generation

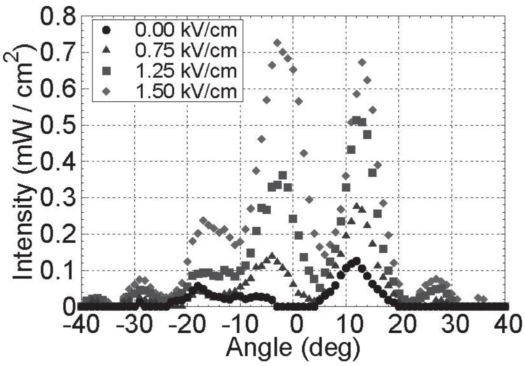

Fig.2 Measurement of the angular distribution of the THz radiation based on the wake current (without external electric field) and based on an applied external electric field (with ecternal electric field)

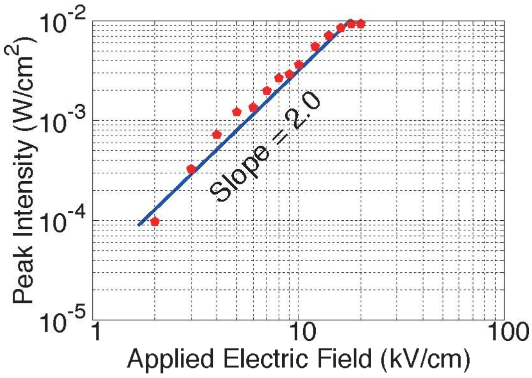

Fig.3 Intensity of the radiated THz wave as a function of the external electric field. THz radiation intensity is proportional to square of the external electric field.

4. Simulation results

We used two-dimensional particle-in-cell (2D-PIC) simulation code. The laser pulse whose parameters is same as experiment propagates in the x direction from left to right and is polarized along the z axis. We choose N_2 gas with 10^3 Pa within $x \in [0\ \mu\mathrm{m}, 300\ \mu\mathrm{m}]$. After the laser propagates, N_2 molecules are ionized, then the plasma whose electron density is $10^{18}\mathrm{cm}^{-3}$ which corresponds to the plasma frequency $\omega_\mathrm{p} = 9.0$ THz is generated; see Fig. 4. We apply the electric static field in the y direction to the plasma.

Figure 5 shows the temporal evolution of the laser electric field, electron density, electric field and magnetic field in the laser created plasma (x = 100 μm, y = 0 μm) with the external electric field. As it is shown in Fig. 5, electric field in the plasma is shielded rapidly, and goes to zero. On the other hand, static magnetic field which corresponding to $B_z = E_\mathrm{ex}/v_\mathrm{g}$ is induced. The oscillation currents which is proposed by previous study dose not appear due to the shielding of electric field in the plasma. These results are agreement with our theory.

Intense half cycle THz pulse centered at 1.3 THz whose frequency is much lower than the plasma frequency is radiated from plasma by applied the static electric field. Fig. 6(a) shows intensity of the radiated THz wave as a function of the external electric field. THz radiation intensity was proportional to square of the external electric field. Fig. 6(b) shows angular distribution of the THz radiation. In the absence of static field, we observe the typical conical shape of the THz emission from the longitudinal current. With electric field, intensity of the THz wave increases and is radiated along laser propagation axis. These results is good agreement with experimental results.

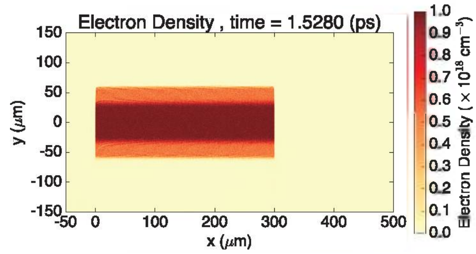

Fig.4 Spatial distribution of the electron density.

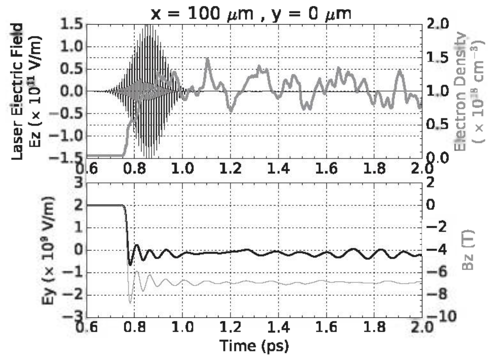

Fig.5 2D-PIC simulation result. Temporal evolution of the laser electric field, electron density, electric field and magnetic field in the laser created plasma ($x = 100\ \mu$m, $y = 0\ \mu$m).

(a) (b)

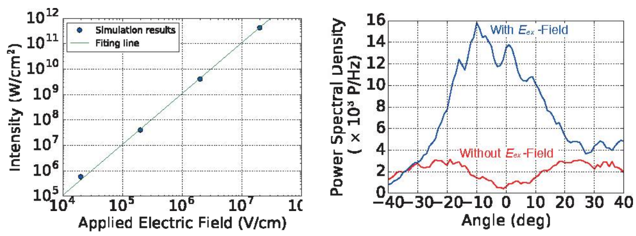

Fig.6 (a) Intensity of the radiated THz wave as a function of the external electric field. THz radiation intensity is proportional to square of the external electric field. (b) Simulation results of the angular distribution of the THz radiation based on the wake current (Without external electric field) and based on an applied external electric field.

5. Summary

We have constracted the model of the THz radiation from laser created plasma by applying the transverse static electric field. We confirmed a new theory by the comparison the experimental results and 2DPIC simulation. In the simulation, electric field in the plasma is shielded rapidly, and static magnetic field is induced of the plasma. These results are good agreement with our theory.

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