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Experimental Observation of Radiation from the Interaction of Ultra-High Intense Laser Pulse with Weakly Magnetized Plasma

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Abstract

From the interaction between an ultra-short-high intensity laser pulse and weakly magnetized plasma, the radiation in the range of microwave frequency have been observed. A wakefield is generated by a mode locked Ti:sapphire laser beam at 800 nm wavelength and 100 fs (FWHM)pulse width and a maximum energy of 100 mJ per pulse, with repetition rate of 10 Hz. The pulse duration of this radiation is about 200 ps (detection limit) with a frequency around 55 GHz. The frequency of the radiation was measured by time of flight method. The radiation emission could be explained by the electron motion along the applied dc magnetic field under the electric field which is created by the ion column.

Keywords:

ultra-short-high intense laser, wakefield, weakly magnetized plasma, microwave frequency

1. Introduction

In the last decade the interaction between plasma and the electromagnetic wave have been studied both theoretically [1-3] and experimentally [4] in the field of plasma based accelerators and new types of radiation sources. Acceleration as the $\boldsymbol{V}_p \times \boldsymbol{B}$ scheme, was originally presented as the plasma based high energy acceleration at the present wakefield scheme [5-8]. The origin of the radiation source is proposed to be attributed to some mechanisms which convert the large amplitude plasma wakes in to tunable radiation emission such as harmonic radiation, Raman scattering or photon acceleration [9-11].

The mechanism of the emission of terahertz (THz) radiation from laser excited plasma has been reported by Hamster *et al.* [12], and the creation of radiation is explained on the basis of creation of nonlinear currents.

Yoshii *et al.* [13] have suggested that the production of high-power tunable radiation is due to the interaction between the intense laser pulse, or short electron bunch, and the static magnetic field. In the plasma, the large amplitude plasma wakefield can be produced by the intense laser pulse according to some mechanisms such as laser wakefield (LWF) [1], laser beat-wave (LBW) or self-resonant laser wakefield (SRLWF) [14]. By applying the static magnetic field, perpendicular to the plasma wakefield propagation direction, the electromagnetic wake propagates through plasma with nonzero group velocity and can coupled into vacuum as the radiation via the plasma boundary. The first proof-of-principle experiment of this theory has been carried out by Yugami *et al.* [15].

In this paper, the generation of radiation in the range of microwave is reported and explained by using the model of the electron oscillation in the vicinity of a ultra-narrow plasma column, produced by a Ti:sapphire laser beam when it is highly focused in the region of weak dc magnetic field. The radiation emission frequency is measured by the time of flight (TOF) method. The frequency of emitted radiation can be explained by the electron oscillation under the electric field created by the ion column.

2. Experimental setup

In Fig. 1 the experimental setup is shown. The plasma wakefield is excited by the Ti:sapphire laser beam which operates at a wavelength of 800 nm, and a maximum energy of 100 mJ with a duration of 100 fs [full width at half maximum (FWHM)]. The laser beam is propagated through a 5 mm thickness CaF_2 window and is focused by an $f/5$ lens (f is the focal length) of 8 mm diameter on the region where the static magnetic field is applied. The focal spot diamter is less than 20 μm and its maximum intensity is estimated to be nearly 10^{17} W/cm^2. We used a horn antenna and the waveguide with cutoff of 31.4 GHz combination for the

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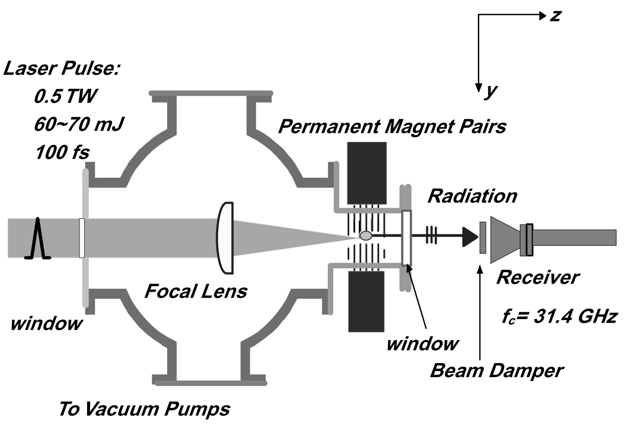

Fig. 1 Experimental setup for observation and the detected of the emitted radiation from wakefield product due to interact of laser beam and weakly magnetized plasma.

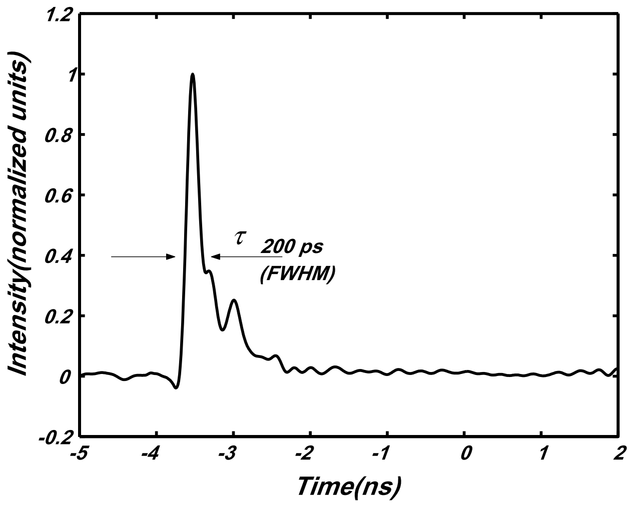

Fig. 2 A typical spectrum of emission radiation waveform.

radiation diagnostics. The radiation is detected by a crystal detector. The oscilloscope (Tektronix; TDS-694c) with an analog frequency bandwidth of 3 GHz was used. The maximum strength of the applied dc magnetic field could be varied from 0 to 7 kG.

3. Results and discussion

Figure 2 shows a typical spectrum of emitted radiation waveform with a duration of 200 ps (FWHM) in the presence of 7 kG applied magnetic field. Nitrogen was used as a working gas. The pulse width of the radiation, τ, calculated from the following relation

$$\tau = \frac{L_p}{V_g}, \quad (1)$$

where L_p is the plasma length, (of the order of Rayleigh length) and $V_g = (\omega_c/\omega_p)^2 c$ is the group velocity of the wakes in the plasma, where ω_c is cyclotron frequency and c is velocity of light. In this experiment L_p is estimated about 1.6 mm with laser spot size of 20 µm. The plasma electron density is estimated to be about 1.45×10^{17} (cm^{-3}) corresponding to working gas of pressure equal to 4.5 Torr, leading to plasma frequency around $\omega_p \cong 4.7 \times 10^{13}$ rad/s. So theoretically the pulse duration of radiation (τ) can be evaluated about 880 ns at $B_0 = 6.7$ kG, where B_0 is magnetic field which corresponds to $\omega_c = 1.2 \times 10^{11}$ rad/s. This time (τ) is evidently longer than the experimental results of pulse duration of the radiation. Up to now, this discrepancy between theoretical and experimental results of the pulse duration of radiation can not be explained.

Figure 3 shows the frequency of the emitted radiation at the presence of perpendicular dc magnetic field. The frequency of the radiation is measured by the 'time of flight' (TOF) method. The frequency of the emitted radiation is given by

$$f = f_{cf} \ \frac{ct}{(c^2 t^2 - L^2)^{1/2}}, \quad (2)$$

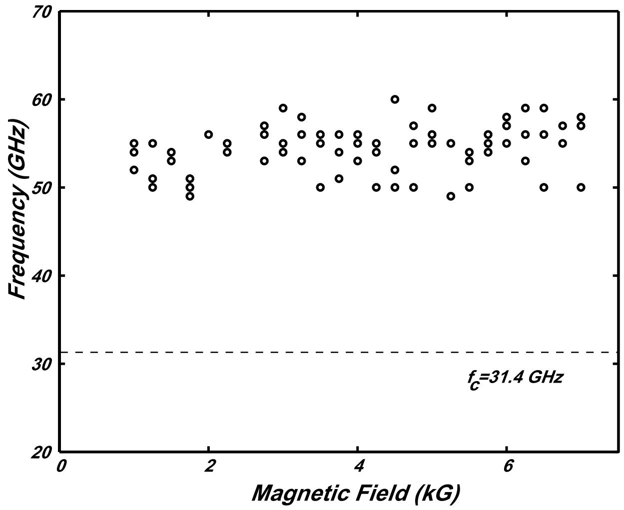

Fig. 3 Fluctuation of radiation frequency in a variable magnetic field strength (0–7 kG) is around 55 GHz.

where L, t and f_{cf} are the waveguide length, the flight time of the radiation pulse through a waveguide and waveguide cutoff frequency, respectively. The estimated frequency of the detected pulse is about 55 GHz.

The radiation frequency is approximately equal to plasma frequency in the theory. In our experiment the radiation frequency is much lower than the expected value. By considering the radial electron oscillation, we could explain this discrepancy. When a laser beam is tightly focused ($c/\omega_p \gg w$), where w is focal radius of the laser beam, the electrons are expelled by ponderomotive force of the laser beam in the radial direction, with respect to the laser pulse propagation. As a result the positive space charge is created. These electrons make the plasma wake to oscillate in the radial direction, due to remain ion column beyond the boundary of ionized plasma. The plasma oscillation can radiate the electromagnetic wave in presence of external dc magnetic field, with a radiation frequency several times smaller than the plasma frequency. The equation of radial motion of electrons in tightly focused laser is given by [16]

$$m\,\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -4\pi n_0 e^2 w \ , \tag{3}$$

where w, m, n_0, and e are the plasma ions column diameter, or focal radius of the laser beam, electron mass, plasma density and elementary charge, respectively. The maximum radial electron oscillation amplitude (r_0) can be obtained by the integration of the above equation which is initially accelerated by the laser ponderomotive force, as follows

$$r_0 = \frac{v_{OSC}^2}{2\omega_p^2 w} \ , \tag{4}$$

where $v_{OSC} \simeq a_0 c$ is the initial velocity of electron oscillation and $\omega_p = 2\pi f_p$. The laser strength parameter (a_0) was taken equal to 0.27. In our experiment the focal radius of laser beam is equal 20 μm, and the maximum amplitude of electron oscillation is in the range of micrometer. These electrons oscillation amplitude depends to the value of spot size diameter.

The frequency of the emitted radiation is in the range of microwave too. The ratio of the frequency of the electron oscillations to the plasma frequency can be estimated as follows

$$\frac{f}{f_p} = \frac{\pi}{2}\sqrt{\frac{w}{2r_0}} \ . \tag{5}$$

This equation shows the discrepancy between the expected value of plasma frequency and radiation frequency.

Figure 4 shows the polarization of the emitted radiation. The polarization of the emitted radiation is measured by rotating the receiver horn antenna around the z axis. The emitted radiation is expected to be polarized in the x direction, perpendicular to the direction of the applied external dc magnetic field. Radiation intensity at $\theta = 0°$ was normalized to the maximum value. In our experiment the gas pressure of the nitrogen is 4.5 torr and static magnetic field is 7 kG. The intensity of the data is depended to the rotate angle of the horn antenna. The polarization of the radiations results in the electron motion along the magnetic field.

Figure 5 shows the effect of dc magnetic field on the intensity of radiation emission. The magnetic field is varied by changing dc electric current on poles which are controlled from out side of the vacuum tube. The stare mark on Fig. 5 represent the average of data taken up to five order of magnitude and the error bars indicate the standard deviation of the experimental data at each magnitude of magnetic field strength. In our experiment, according to $\omega_c \ll \omega_p$ condition, the magnetic field strength had very small effect on the output power of radiation.

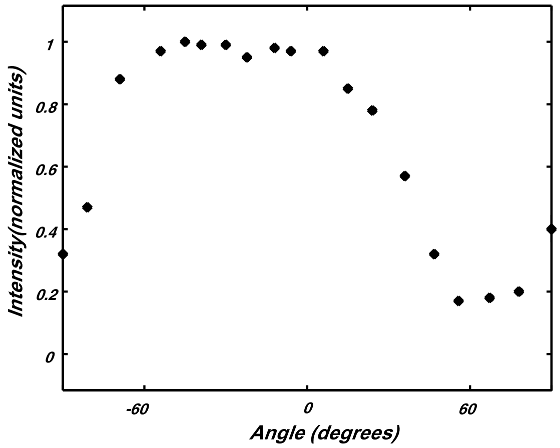

Fig. 4 Variation of the radiation intensity versus rotation of angle of the horn antenna around z direction.

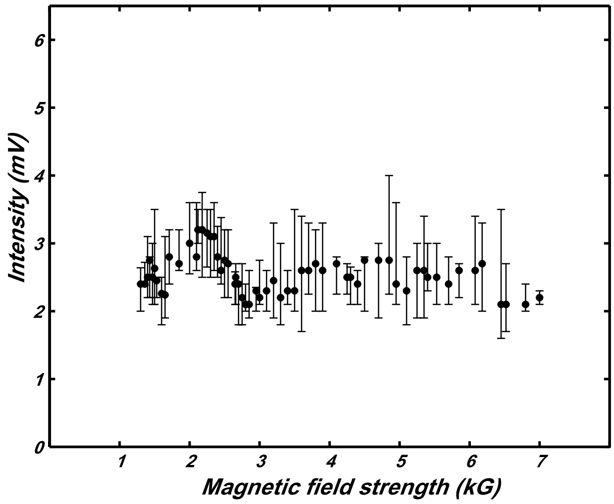

Fig. 5 The effect of variable magnetic field strength on the intensity of emission radiation.

4. Conclusions

We have studied the interaction between the ultra short intense laser pulse and the weakly magnetize plasma, leading to generation of microwave radiation. This microwave radiation emission could be explained by the oscillation of the electrons under the electric field, which is created by the ion column along the applied dc magnetic field. We have observed that the radiation intensity has a weak dependence on the magnetic strength field.

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