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Characteristics of THz Emission from Plasma Generated by a Femtosecond Pulse Laser
フェムト秒パルスレーザー生成プラズマからのテラヘルツ放射特性

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Conical forward THz emission from a plasma filament generated by an intense femtosecond laser pulse has been observed. The emitted radiation frequency is much lower than the plasma frequency estimated by both the gas density and the laser intensity. The electromagnetic wave is generated by the time variation of the electron velocity at a point of a large density gradient from simulation results.

1. Introduction

THz radiation, which is the electromagnetic radiation between visible and long wavelength spectral region, have been considered as a powerful and an important research tool for atoms, molecules, and so on. The THz region had remained as the last unexplored spectral region, due to not existing of efficient emitters and detectors. Recently, the THz radiation can be produced by free-electron lasers (FEL), semiconductor antenna, and plasmas generated by intense laser pulse. For the case of plasma based sources, table-top laser-driven sources can provide THz radiation easily.

Conical forward THz emission from plasmas generated by intense femtosecond laser pulse in air have been observed and studied [1-2]. C. D'Amico *et al.* concluded this radiation is due to the plasma space charge with dipole-like structure moving at the speed of light in the wake of the laser pulse. However, sufficient laser wake generation is not expected. Furthermore, the radiation frequency is much lower than the plasma frequency estimated by both the gas density and the laser intensity. In this research, we have characterized the electromagnetic radiation from the plasma generated by the femtosecond laser pulse by using a 2D-PIC (particle in cell) simulation code.

2. Experiment

The experimental setup is shown in Fig. 1 (a). In this research, we have characterized electromagnetic radiation from plasma generated by a Ti:Sapphire laser pulse, which is operated at the wavelength of 800 nm produced the maximum energy of 40 mJ with a pulse duration of 120 fs (FWHM). The laser pulse was focused into N_2 (nitrogen) gas (10^2 - 10^5 Pa) with a focal length lens (300 - 1000 mm). Signals of emitted radiation from plasma ware detected by crystal detectors, which can detect the electromagnetic radiation between 26.5 and 320 GHz.

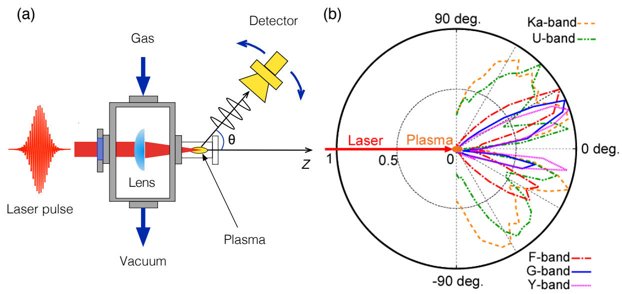

Fig.1. (a) Schematic of the experimental setup. (b) Angular distribution of radiation from plasma.

Typical angular distribution of the radiation is shown in Fig. 1 (b). The signal intensity of the emitted radiation depended on the radiation angle, the gas pressure and the focal length. The maximum intensity was observed at the gas pressure of approximately 10^3 Pa. The radiation angle with short focal length under the condition of same gas pressure was larger than that of long focal length. To investigate this radiation, we conducted the calculation by the 2D-PIC simulation.

3. Simulation

We conducted the 2D-PIC simulation using the experimental parameters. The laser pulse (p-polarized) propagates from left to right and its geometric focus is at $x = 0$ with in area $\{(x, y) \mid -320 < x < 1280, -480 < y < 480\}$; these units are in μm.

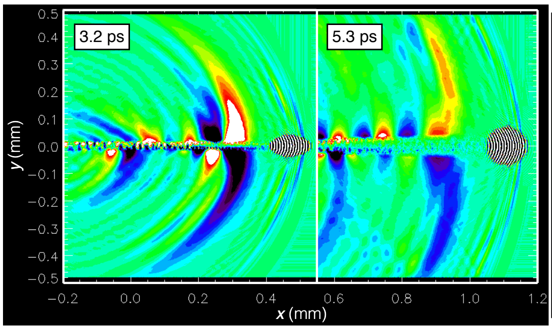

Fig.2. The typical magnetic field B_z at t = 3.2,5.3 ps.

The pulse has the Gaussian profile with d = 20 micron in diameter and the pulse duration of τ = 120 fs (FWHM). The laser intensity is $I = 1\times10^{17}$ W/cm^2 and the wavelength is 800 nm. We choose N_2 gas with the density $n = 2.6\times10^{17}$ cm^{-3} as working gas, which is initially distributed in the region of $\{(x, y) \mid -320 < x < 1280, -480 < y < 480\}$.

Typical contour plot the magnetic field of the electromagnetic wave, which is generated by the laser pulse is shown in Fig. 2. The calculation starts at t = 0. Here, the magnetic component B_z is perpendicular to the paper surface. The electromagnetic waves were observed behind the laser pulse propagation. To describe the mechanism of the radiation, H.-C. Wu *et al.* have pointed out the generation of the emission from the cliff in the plasma density which is created by the intense laser pulse and presented the radiation by using following the wave equation,

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \frac{\omega_p^2}{c^2}\right)\mathbf{B}_r = \mu_0 e \nabla n_e \times \mathbf{v}. \qquad (1)$$

The right-hand side of this equation indicates the source of the radiation. The equation predicts that the electromagnetic wave can be generated the region at which the product of density gradient and

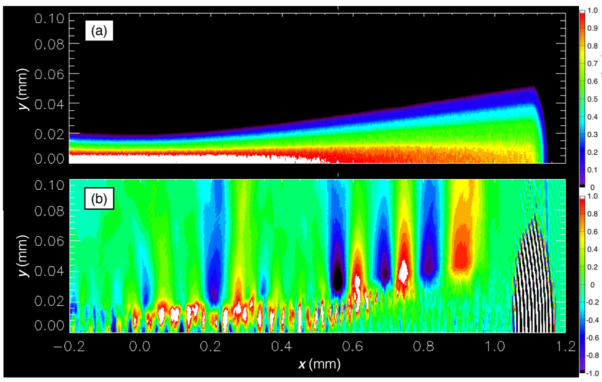

Fig.3 The calculated electron plasma density (a) and the magnetic field (b) near the plasma filament.

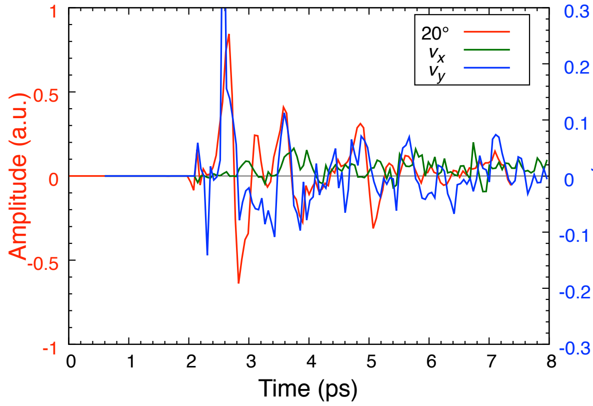

Fig.4. The electromagnetic wave shape traced at (x, y) = (150, 54.7), and time variation of the electron velocity +0.6 ps at (x, y) = (0, 20).

the electron current exists [3]. The calculated electron plasma density and the magnetic field near the plasma filament are shown in Fig. 3 (a) and (b). The strong magnetic field is observed at the boundary between the plasma and the neutral gas., that is, the cliff in the plasma density. The electromagnetic wave and x and y component of the electron velocity at (x, y) = (150, 54.7) is illustrated in Fig. 4. These are measured at the points away 160 micron from the focal point and 20 degree with respect to the laser propagation axis. One cycle oscillation of the magnetic field with the period of about 0.4 – 1.2 ps corresponding to the frequency 0.8 – 2.4 THz, is observed. This frequency is lower than the plasma frequency of 6 - 9 THz, which is estimated by the simulation. At the density cliff, because the gradient of the density is considered to be constant, the product of the right-hand side of the wave equation strongly influenced by the electron velocity and the waveform of the magnetic field is similar to the electron velocity.

4. Conclusion

We experimentally observed the conical forward THz emission that depends on the radiation angle, the gas pressure and the focal length from the plasma filament generated by the intense femtosecond laser pulse. The electromagnetic wave is generated at the plasma density cliff. The electron oscillation caused by v_y at the points of a large density gradient is the radiation source.

References

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