§8. Simulation of Terahertz Radiation Generation from Laser Created Plasma

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In the past decade, several radiation generation schemes and frequency upshifts based on laser plasma interaction experiments have been studied for plasma applications of a short and a tunable radiation source. Yoshii *et al.* have proposed a new mechanism by which a short electromagnetic pulse is radiated by the interaction between a laser wake field or a short electron bunch and a static magnetic field [1]. In the magnetized plasma, the wake field has both electrostatic and electromagnetic components. This enables the wake to propagate through the plasma and couples radiation into the vacuum. This phenomenon is called the Cerenkov wake and the emitted frequency of the radiation is expected to be close to the plasma frequency when the laser is irradiated in the underdense plasma. The first proof-of-principle experiment of this theory has been carried out by Yugami *et al.* and the maximum observed frequency of the emitted radiation was 0.2 THz with a pulse duration of 200 ps [2]. The direction of the radiation was the same as that of laser propagation. Moreover, terahertz radiation has been recently observed using the laser wakefield accelerated electron bunch by coherent transient radiation at the vacuum-plasma boundary.

On the other hand, we have observed radiation that is generated by the interaction between a laser and unmagnetized plasma [3]. The maximum radiation frequency is 325 GHz with a broad frequency spectrum much lower than the plasma frequency ω_p. The polarization of the radiation is in the radial direction, i.e. the TM_{01} mode.

Theoretical study for this generation electromagnetic waves from the laser created plasma is carried out by using 1D and 2D particle in cell (PIC) codes, in collaboration with Prof. Y. Sentoku in Nevada University, Reno. These PIC codes used for the research are also developed by Prof. Sentoku. In this year, we developed the explanation of the experimental results of the THz radiation from the laser created filament. This radiation is emitted with conical structure and sub-THz region in the frequency which is much smaller than the plasma frequency. To explain this radiation, we consider the wave equation taking the plasma current around the laser pulse into account,

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \frac{\omega_p^2}{c^2}\right)\boldsymbol{B}_r = \mu_0 e \nabla n \times \boldsymbol{v},$$

where ω_p, n, and $\boldsymbol{v}$ represent the plasma frequency, the plasma density and the electron velocity, respectively. The right hand side is considered as the source of the radiation and apparently $e\nabla n \times \boldsymbol{v}$ is nonzero and responsible for THz generation in the filament. In the 2D calculation, the source term $\nabla n \times \boldsymbol{v} = (v_y \partial n/\partial x - v_x \partial n/\partial y)\hat{z}$ is the responsible for THz magnetic field $\boldsymbol{B}_r$(Fig. 2). According to the contour plot of the product of the density gradient and the electron velocity, $\nabla n \times \boldsymbol{v}$, we can see the strong radiation source along the laser propagation, where the plasma density is much lower than the plasma density at the laser center. Therefore the electrons there oscillate at local plasma frequency which is much smaller than the maximam plasma frequency at the center of the laser. The strong product region is the function of the distance of the laser propagation, the emitted frequency is not monochromatic and wide in the frequency spectrum. The radiation frequency is much lower than plasma frequency, as expected.

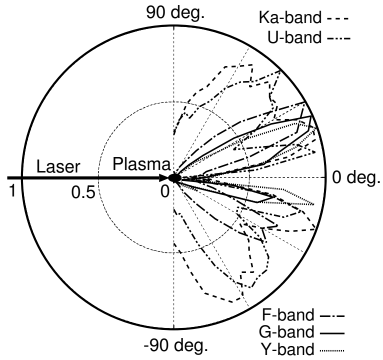

Fig. 1: Angular distribution of emitted radiation. The emitted radiation has a broad spectrum, higher-frequency component and a smaller angle with respect to the laser direction.

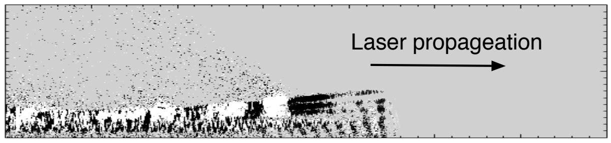

Fig. 2: Snapshot of the contour plot of $|\nabla n \times \boldsymbol{v}|$. The laser propagates from left to right. After the laser propagation, the laser ionizes the gas and we can see the density fluctuation(plasma wake field). Strong $|\nabla n \times \boldsymbol{v}|$ can be seen along the plasma density cliff.

1) J. Yoshii, C. H. Lai, T. Katsouleas, C. Joshi and W. B. Mori : Phys. Rev. Lett. **79** (1997) 4194.

2) N. Yugami, T. Higashiguchi, H. Gao, S. Sakai, K. Takahashi, H. Ito, Y. Nishida and T. Katsouleas : Phys. Rev. Lett. **89** (2002) 065003.

3) N. Yugami, K. Ninomiya, K. Kobayashi, and H. Noda : Jpn. J. Appl. Phys. **45** (2006) L1051.