*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-2.027 (2009)*

Terahertz Radiation from a Laser Plasma Filament

Hui-Chun Wu[*], J. Meyer-ter-Vehn

Max-Planck-Institut für Quantenoptik, Garching, Germany

The experiment [1] by Hamster found that terahertz (THz) radiations can be generated when an intense laser pulse is focused in gas or on solid targets. When the laser pulse is focused into gas, due to the balance among natural diffraction, plasma defocusing and Kerr self-focusing, laser pulse carries out periodic defocusing and self-focusing, and can propagate a very long distance. After the laser pulse, a narrow and long plasma column is left. This is called as a laser filament. There is a long controversy [2] around THz radiation mechanism from a laser filament.

As a simple and remote-distance THz source, recently, THz radiation from the laser filament regains elaborate investigations [3,4]. THz emissions are found to be directed on the laser direction and radially polarized. It can be enhanced by an external electrostatic field. The transition-Cherenkov model [3,4] is proposed to explain this kind of THz generation. Authors consider a dipole-like current generated by the laser ponderomotive force propagating in a limited distance, and calculate THz radiation in a Cherenkov radiation formulary [5]. The current decays by the plasma collision process. The transition-Cherenkov model can explain THz radiation pattern well.

In the present work, we clarify the reason why there is THz radiation in a laser filament and provide a physical basis for the transition-Cherenkov model. We find the transversely nonuniform plasma density in the filament makes THz radiation possible. The laser ponderomotive force pushes electron and separate the space charge. Electron current oscillates forward and backward in the electrostatic wakefield. When the electron passes by the transverse boundary of the filament, the coupling between electron motion and nonuniform density profile induce a net radiating current, which is a fraction of the total electron current. The radiating current is mainly located within laser pulse and the first cycle of the wakefield. It is just like a dipole propagating with the laser pulse and build up THz pulse in the forward direction. Two-dimensional (2D) particle-in-cell (PIC) simulation shows THz radiation are radially polarized and double-lobe pattern.

---

[*] email : hcwu@mpq.mpg.de

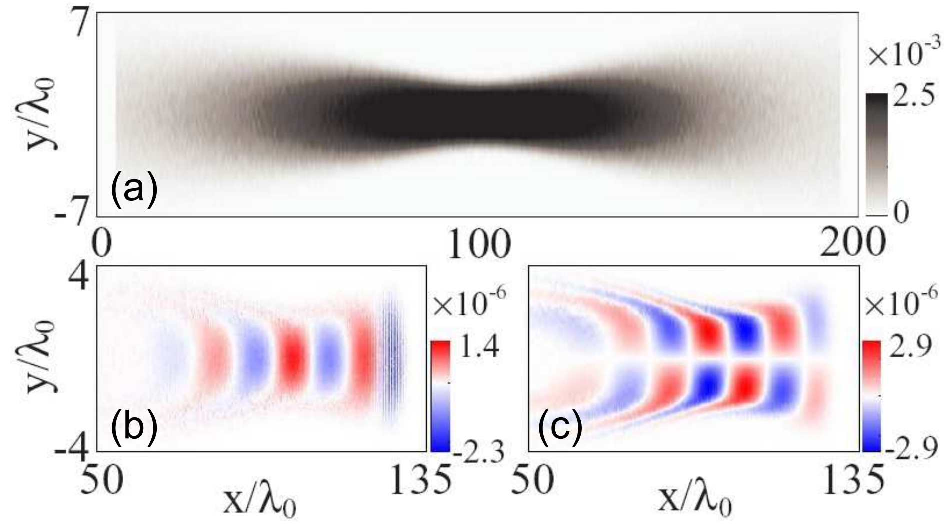

Fig. 1. (a) Plasma density of the filament after the laser pulse; (b) longitudinal electron current J_x and (c) transverse current J_y at $t=140\tau_0$.

We consider a short filament in the tenuous gas, where the laser pulse is focused just one time and the filament length is limited and on the order of laser Rayleigh length. In Ref. [2], THz radiation from a long filament is analysed and simulated. They introduce the periodic plasma density along the filament to simulate radial-direction THz radiation. We also consider a high laser intensity of above 10^{15} W/cm² and tunnelling ionisation is dominant for plasma formation. During the short rising time of the pulse, atoms are ionised, and then the main pulse interacts with ionised plasma. In our case, the laser filament is mainly determinated by the initial focusing and plasma defocusing. Kerr effect can be negligible and pulse breakup does not occur.

From the 2D PIC simulation [6], a short filament after the laser pulse is shown in Fig. 1(a). The laser pulse (s-polarized) propagates from left to right along y=0 and its geometric focus is at $x=100\lambda_0$, $\lambda_0=800$ nm. The pulse has the shape $\sin^2(\pi t/T)$ with $T=20\tau_0$ and the waist width $W=2.5\lambda_0$. The peak intensity is about $I=5.35\times10^{15}$ W/cm². We choose He gas with density $0.0025n_c$ within $x \in [5\lambda_0,195\lambda_0]$, n_c is critical plasma density for the laser. Around the laser focus, all He atoms is ionised and loss only one electron. So, the peak plasma density in filament is $n_0=0.0025n_c$, which corresponds to a plasma wavelength $\lambda_p=20\lambda_0$. With the increase of the laser intensity around the focus, the plasma density reaches maximum on the center of the filament. The filament length with the density above $0.5n_0$ is about $120n_0$. The density linearly increases from $0.16n_0$ to n_0 within $x \in [5\lambda_0,70\lambda_0]$. The slowly varying plasma density ensures that the electromagnetic emissions come from the filament body, instead of from plasma surfaces [2]. The filament diameter at $x=100\lambda_0$ is about $4\lambda_0$.

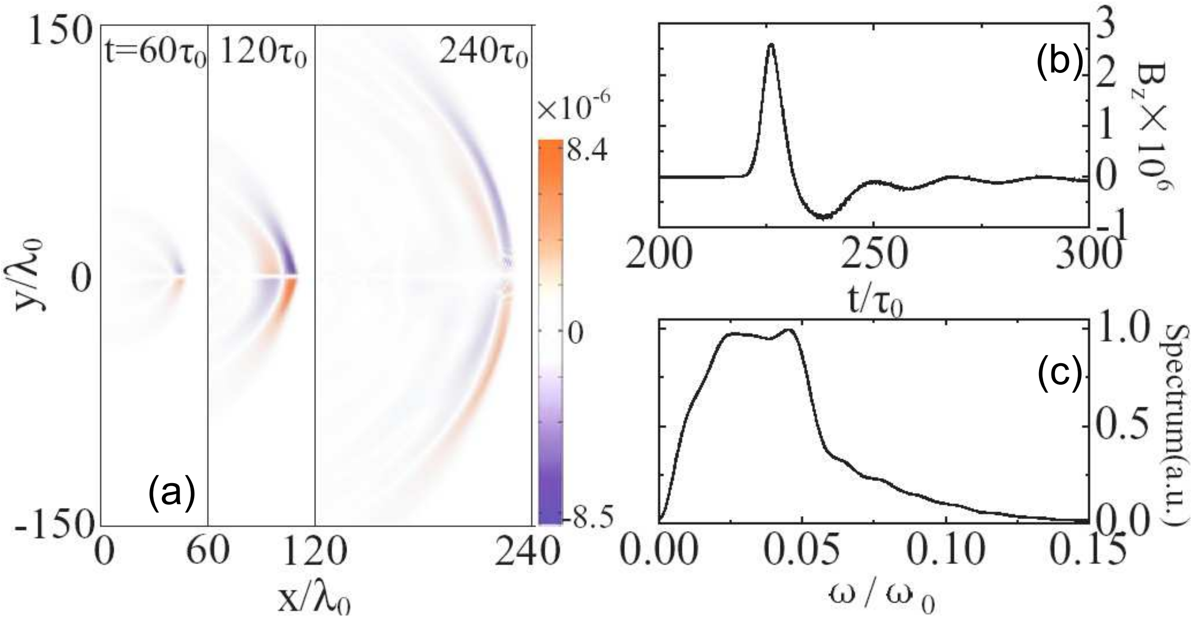

Fig. 2. (a) Radiating magnetic field B_z at $t=60\tau_0$, $120\tau_0$ and $240\tau_0$; the temporal shape (b) and the spectrum (c) of B_z pulses traced at $[x,y]=[200\lambda_0,-60\lambda_0]$.

The laser pulse pushes the electrons by the ponderomotive force and induces both longitudinal current J_x [Fig. 1(b)] and transverse current J_y [Fig. 1(c)]. The currents oscillates with the plasma frequency. These currents may generate p-polarized electromagnetic wave radiations. The magnetic component B_z is plotted in Fig. 2(a). A single-cycle THz pulse is emitted from the plasma filament and co-propagates with the laser pulse. In the 3D space, the THz radiation should be radially polarized in the far field and null along the laser axis. This agrees with the experiments [3,4]. The pulse shape and the corresponding spectrum are illustrated in Fig. 2(b) and 2(c). The THz frequency is broad and around plasma frequency.

In the following, we will clarify the reason why there is the THz radiation from the filament. For a general electromagnetic system, in the Coulomb gauge, the electromagnetic radiation equation is

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})A_r = -\mu_0 J_r, \qquad (1)$$

where $J_r = J - \frac{1}{c^2}\frac{\partial}{\partial t}\nabla\varphi_w$ is radiating current i.e. rotational part of total current J , and $J_r = J - \frac{1}{c^2}\frac{\partial}{\partial t}\nabla\varphi_w$ is the electrostatic potential of the wakefield. The electric field is $E=E_r+E_w$, here the radiating field $E_r=-(\partial/\partial t)A_r$ and the wakefield $E_r = -\nabla\varphi_w$. The existent electromagnetic radiation implies the nonzero J_r, which demands $\nabla \times J \neq 0$. The curl of the total current reads

$$\nabla \times J = -e\nabla n_e \times v - en_e \nabla \times v \tag{2}$$

In fact, the observed THz radiation in the near field region in Fig. 2 is comparable with the wakefield. The filament is a narrow plasma column. Because the tunnelling ionisation rate is exponentially dependent on the light field, the filament has a sharp transverse boundary. Within the laser pulse, plasma density increases from zero on the pulse head to the maximum. Apparently, $\nabla n_e \times v$ is nonzero in the filament and responsible for THz radiation. Making the curl of Eq. (1) and using Eq. (2) , one has

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \frac{\omega_p^2}{c^2})B_r = -e\nabla n_e \times v, \tag{3}$$

where ∇n_e is nonzero due to the initially nonuniform density. In the 2D case, the source term is $\nabla n_e \times v = (v_y \partial n_e / \partial x - v_x \partial n_e / \partial y)\hat{z}$. We can see that the coupling between the electron velocity and perpendicular density gradient is responsible for THz magnetic vector B_z in Fig. 2.

References

[1] H. Hamster, A. Sullivan, S. Gordon, W. White, and R. W. Falcone, Phys. Rev. Lett. 71, 2725 (1993).

[2] P. Sprangle, J. R. Penano, B. Hafizi, and C. A. Kapetanakos, Phys. Rev. E 69, 066415 (2004).

[3] C. D'Amico, A. Houard, M. Franco, B. Prade, A. Mysyrowicz, A. Couairon, V. T. Tikhonchuk, Phys. Rev. Lett., 98, 235002 (2007).

[4] C. D. Amico, A. Houard, S. Akturk, Y. Liu, J. Le Bloas, M. Franco, B. Prade, A. Couairon, V. T. Tikhonchuk, and A. Mysyrowicz, New J. Phys. 10, 013015 (2008).

[5] J. Zheng, C. X. Yu, Z. J. Zheng, and K. A. Tanaka, Phys. Plasmas 12, 093105 (2005).

[6] H.-C. Wu, J. Meyer-ter-Vehn, and Z.-M. Sheng, New J. Phys. 10, 043001 (2008).