J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 333–336

# Spontaneous Magnetic Field and High Harmonics in Laser-Dense Plasma Interaction

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(Received: 9 December 2003 / Accepted: 7 April 2004)

**Abstract**

The high harmonics in the reflection spectra from short intense laser pulse interaction with overdense plasmas were observed by the particle-in-cell (PIC) simulations. The simulation reveal that the quasistatic magnetic field and transverse density modulation can influence the electron dynamics, which is in responsible of high harmonic generation.

**Keywords:**

high harmonics, particle-in-cell, quasistatic magnetic field, electron dynamics

## 1. Introduction

The generation of high harmonics in the process of solid target irradiated by short intense laser has been successfully observed in experimentally and in simulations [1-2]. A mechanism for high harmonics emission was proposed by Bulanov et al. [3], based on phase modulation by the laser light upon reflection from an oscillating plasma-vacuum interface, viz. oscillating mirror model, agreed with particle-in-cell (PIC) results [4].

Recent experiments also report the effect of initial scale length of plasma to the high harmonic emission [5-6]. The experiments of harmonics have also been used to estimate the magnitude of self-generated magnetic field.

The generation and features of high harmonics involves a number of laser and plasma parameters. In the existence of pre-plasma on the front of solid target, transverse density modulation occurs and can be enhanced substantially due to laser filamentation instability [7]. This type of instability was found to be stronger in the direction perpendicular to the laser polarization direction. So for p-polarization laser in our simulations, the transverse density is not evident comparing to s-polarization laser. The generation of dipole magnetic field near the critical density can be attributed to the joint interaction of filamentation instability and Weibel instability. So, the forward relativistic electron streams can acquire perpendicular velocity component due to the action of the Lorentz force. In this paper, we present our PIC simulation results, which demonstrate that the density modulation and magnetic field play important role to high harmonic emission.

## 2. PIC simulation results of the high harmonic emission

We first introduce the basic physics model and picture. Properties of the plasma response are strongly dependent on the polarization of the laser in relativistic regime. Let $\vec{A}(\vec{r}, t)$ and $\varphi$ be the vector and scalar potential, $\vec{E} = -\partial\vec{A}/\partial t - \nabla\varphi$, with Coulomb gauge $\nabla\cdot\vec{A} = 0$, and from Ampere's and Poisson's equation, the equations for $\vec{A}(\vec{r}, t)$ and $\varphi$ are written as

$$\begin{aligned} &\nabla^2\vec{A} - \frac{1}{c^2}\frac{\partial^2\vec{A}}{\partial t^2} = -\frac{4\pi}{c}\vec{J}_\perp, \\ &\nabla^2\varphi = -4\pi\rho, \end{aligned} \tag{1}$$

where $\vec{J}_\perp$ is the electric current perpendicular to the z direction (light propagates along the z direction), $\rho$ the charge density and c the light velocity.

Define $\vec{A}(\vec{r}, t) = R[\vec{e}_p A_0 \exp \mathrm{i}(kz - \omega t)]$, $\vec{e}_p = \vec{e}_y \pm \alpha \mathrm{i}\vec{e}_x$. The laser pulse is linearly polarized when $\alpha = 0$. The momentum equation is as follow

$$\frac{\mathrm{d}}{\mathrm{d}t}(\vec{P} - e\vec{A}) = e[\nabla\varphi - (\nabla\vec{A})\cdot\vec{v}], \tag{2}$$

where $\vec{v}$ is electron velocity, and $-e$ the charge of an electron. In the perpendicular direction

$$\vec{P}_\perp = e\vec{A}. \tag{3}$$

In the parallel direction

$$\frac{\mathrm{d}}{\mathrm{d}t}P_z = e\frac{\partial\varphi}{\partial z} - \frac{e}{2\gamma}\frac{\partial}{\partial z}A^2. \tag{4}$$

Relativistic factor for electron is $\gamma$, $\gamma = (1 + P_z^2 + A^2)^{1/2} = \sqrt{1 + A^2}/\sqrt{1 - v_z^2}$.

Source term for the electromagnetic field is $J_\perp \propto \delta n\ \cdot$

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$\sqrt{1-v_z^2}\Big/\sqrt{1+A^2}\vec{P}_\perp$, and the high order terms are responsible for high harmonic generation. If the laser pulse is linearly polarized, $A^2$ contains a term oscillating at twice the laser frequency. It is well known that when the laser is normal incidence, only “odd” laser harmonics are generated, and p-polarized “even” laser harmonics can be generated when the laser is incident under an angle to the surface. This picture can be explained by “oscillating mirror model” [4]. For circular polarized laser, $A^2$ is not dependent on fast time variance, and the ponderomotive force is determined by the shape of pulse. High harmonics cannot be generated through oscillating mirror mechanism.

Two dimensional (2D) configuration corresponding to eqs. (1)–(4) is considered. A 2D fully relativistic and electromagnetic PIC code is used to study the nonlinear behavior. That $\lambda_0 = 1$ μm is the laser wavelength in vacuum,

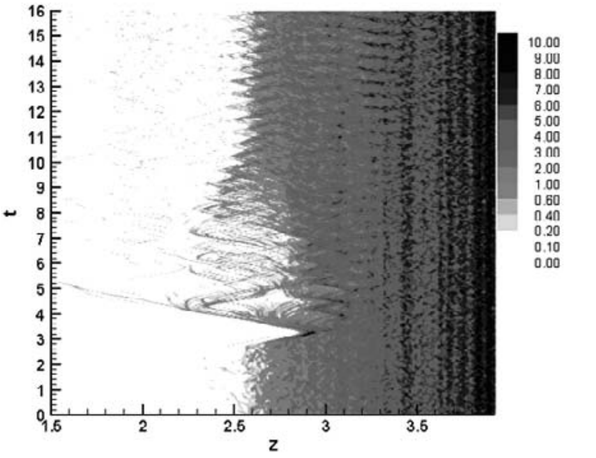


Fig. 1 Spatial-tme profile of $n_e$ at $x = 0$. Time is in laser cycle unit and length is in laser wavelength unit.

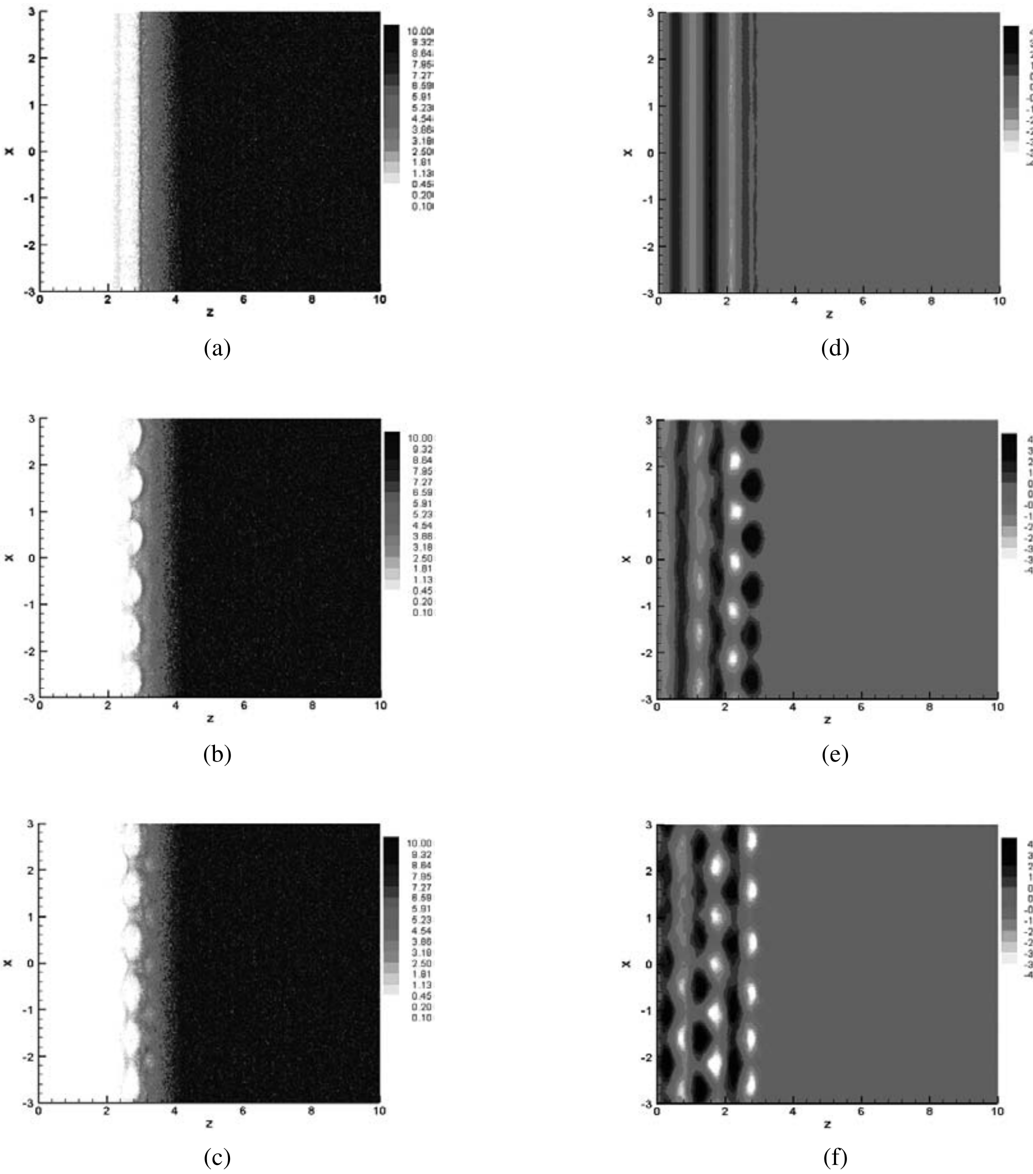


Fig. 2 Contours of plasma density (a-c) and laser field $E_y$ (d-f) at $t = 4$, 10, 14 laser cycle.

$\omega_0 = 2\pi c/\lambda_0$ and $n_c$ is the critical density. The simulation size is $12\lambda_0$ long in the z-direction with $2.4\lambda_0$ of vacuum been preceded, and the plasma density is ramped from $0.45n_c$ to $9n_c$ over a distance of $1.6\lambda_0$, then a plasma plateau with $7\lambda_0$ length and $9n_c$ density exists. The plasma density in the x-direction is uniform with $6\lambda_0$ wide. One cell has each 30 electrons and ions, and ions are immobile as a neutralized background. The grid size and time step are chosen as $dx = dz = 0.01\lambda_0$, $dt = 0.005\tau(\tau = 2\pi/\omega_0)$ in order to ensure that the first several order harmonics can be detected.

The laser pulse with intensity $I = 10^{19}$ W/cm$^2$ linearly polarized in the $y$-direction is incident normally with transversely uniform and longitudinally semi-infinite, which rises up in about three laser cycles with a Gaussian profile.

From Fig. 1, when the pre-plasma exists, the dominate motion of density oscillation by the linearly polarized laser pulse is in longitudinally direction with the frequency $2\omega_0$, density modulation in transverse occurs later with the order of one laser wave length due to the laser filamentation as can be clearly seen in Fig. 2.

The profile of current density vector and self-generated magnetic field is given in Fig. 3 at two time intervals, 7 and 11 laser cycle. The Weibel instability of plasma with hot and cold electron streams develope in the same time as the laser filamentation instability. The Weibel instability cause the break up of relativistic electron beams into filaments guided by quasistatic magnetic fields with transverse scale length on the order of the local plasma skin depth $\sim\lambda_0$ near the critical density [8-9]. The peak magnitude of the ring-like magnetic field $\langle B_y \rangle$ is about 20 MG. Electron trajectories can be affected through the "$v_z$ cross $\langle B_y \rangle$" force to induce a transverse oscillation. For relativistic electron, the gyro-radius is about micron order. In Fig. 3, the electron current density vector is given. The relativistic electrons move in different direction in transverse at different position because sign of the magnetic field $\langle B_y \rangle$ is by turns in negative or positive, so change the sign of "$v_z$ cross $\langle B_y \rangle$" force. The electrons in the longitudinal direction mainly oscillate in "$2\omega_0$" frequency, so the static magnetic field generates harmonic current at "$2\omega_0$" along x-direction. For s-polarized light, the "$\omega_0$" term of density variation vanishes. High harmonics in "even mode" can be generated through this transverse oscillating mechanism. The "$v_y$ cross $B_x$" term (here, $v_y$ is the electron quiver velocity, and $B_x$ is the laser magnetic field) force also induces a transverse "$2\omega_0$" oscillation when the s-polarized laser oblique incident on the vacuum-plasma interface explained by "oscillating mirror model" [4]. Normal incidence laser is under an angle to the transverse modulation surface (see Fig. 2(b-c)), even harmonic can also be generated through this mechanism. It is difficult to distinguish mechanisms of even harmonic generation due to density modulation or magnetic field mechanisms.

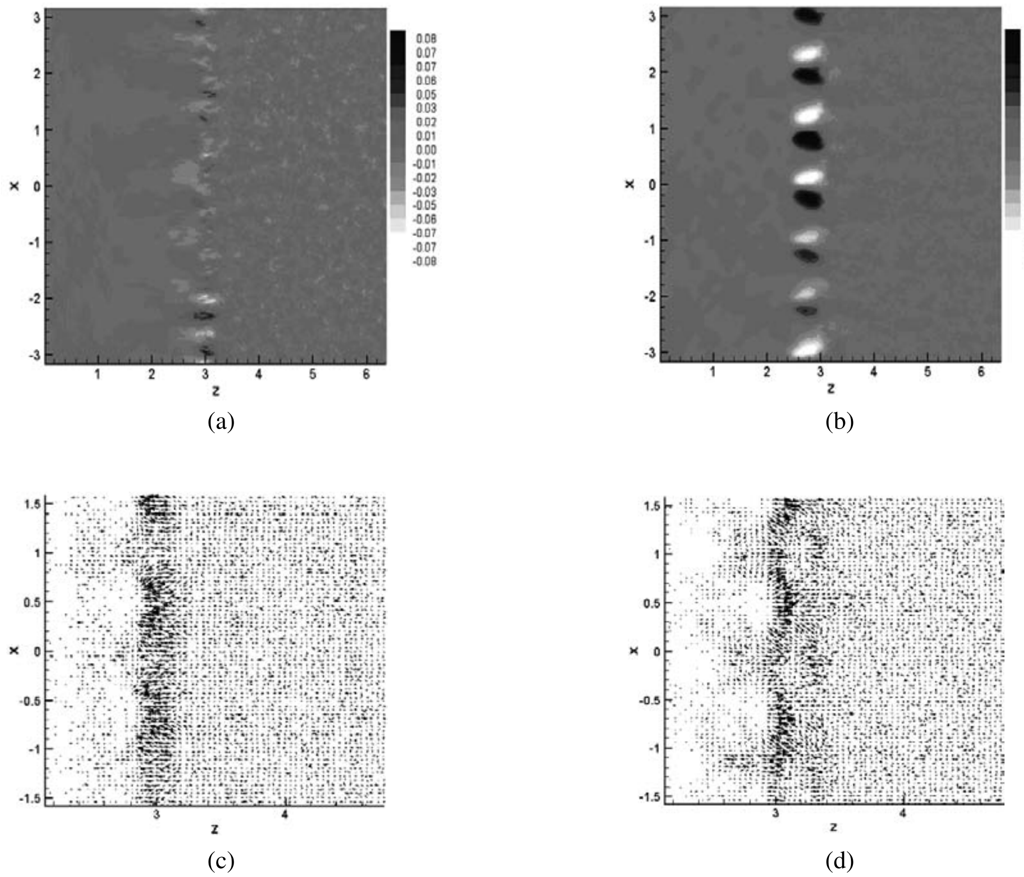


Fig. 3 Contours of magnetic field (a-b) and current density vector (c-d) at $t$ = 7, 11 laser cycle.

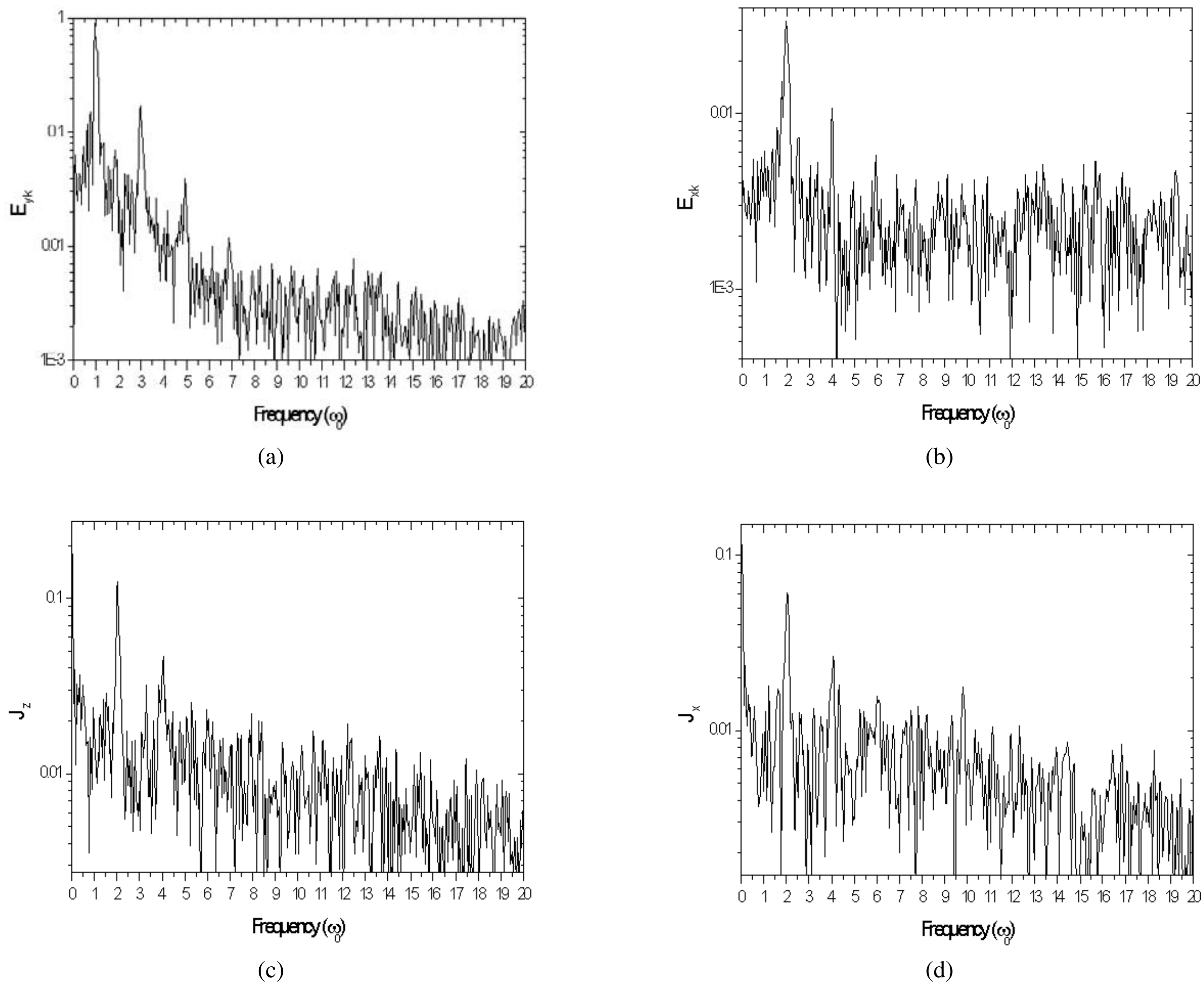


Fig. 4 Reflected light spectra (a-b) and electron current spectra (at $z = 3\lambda$, $x = 0.25\lambda$) (c)(d).

The reflected light was Fourier analyzed to obtain the harmonic components, which can be seen in Fig. 4. The fields $E_x$, $E_y$ and the electron current density are recorded in ($z = 3\lambda_0$, $x = 0.25\lambda_0$). The even modes of reflected light in the perpendicular direction of incident laser were given. Even harmonics were generated by transverse $2\omega_0$ oscillating current.

For the p-polarized laser pulse, the incident fields were ($E_x$, $B_y$). Although the same laser and plasma parameters were used, the transverse modulation of density and field is not evident, so weak high harmonics are detected.

## 3. Conclusion

The high harmonics in the reflection spectra from short intense laser pulse interaction with overdense plasmas are observed by the PIC simulations. The simulation reveal the quasistatic magnetic field generated by the longitudinal current can strongly influence the transverse electron dynamics, which, in addition to the transverse density modulation, is in responsible of high harmonic generation.

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