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Generation of Quasistatic Magnetic Field in the Relativistic Laser-Plasma Interactions

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Abstract

The magnetic field generation by a relativistic laser light irradiated on a thin target at the oblique incidence is investigated using a two dimensional particle-in-cell simulation. Three kinds of quasistatic magnetic fields, which are located at the front surface, inner plasma, and rear surface, are found. First magnetic field which is located on a front surface arises very quickly, of which raising time is almost the same of the laser raising time. Second magnetic field is gradually growth in a inner plasma by the Weibel instability, which occurs between the fast electrons generated by the vacuum heating and their return currents. Final magnetic field that is located on the rear surface of the thin target arises also very quickly when electrons pass through the surface and return into the plasma.

Keywords:

relativistic laser, magnetic field generation, surface magnetic field, relativistic laser-plasma, Weibel instability, vacuum heating

1. Introduction

Laser plasma interaction in the relativistic regime where the normalized vector potential $a_L \simeq (I_L\lambda_\mu^2/1.37 \times 10^{18})^{1/2} \geq 1$, where I_L and λ_μ are the laser intensity in W/cm^2 and the wavelength in μm, respectively, is crucial for inertial fusion energy with the fast ignitor scheme [1], multi-MeV proton, and electron generation. In particular, the generation of magnetic fields during high intensity laser-solid target interactions have attracted much interest for the past 30 years [2-4]. The magnetic fields are generated by various mechanisms, which are the currents produced from perpendicular density and temperature gradients in the ablated plasma [2], the radiation pressure associated with the laser pulse itself [3], the current of fast electrons generated during the interaction, and the Weibel instability [4]. Recently, self-generated magnetic fields whose amplitudes are of the order of a few hundred mega gauss have been observed in the overdense region of an irradiated solid target by a relativistic laser irradiation [5]. The maximum amplitude of self-generated quasistatic magnetic field is roughly one third of the laser electromagnetic field [6]. The magnetic field associated with a intense laser with intensity I_L is extremely large, $B_L = 290 \times (I_L/10^{19})$ Mgauss.

The self-generated magnetic fields can play a significant role in laser absorption [7] and transport of high energy particles in dense plasmas [8]. In addition, at the oblique incidence, the magnetic fields is localized on the plasma surface, which depth is less than a laser wavelength and amplitude is about one third of the laser electromagnetic field [9-11].

In this paper the magnetic field generation by a relativistic laser light irradiated on a thin target at the oblique incidence is investigated by a two-dimensional (2D) electromagnetic particle-in-cell (PIC) simulation. Recently, an irradiation on thin films with a thickness of a few micron has been of interest for ion acceleration by compact intense short pulse lasers [12].

2. PIC simulation

We use the 2D PIC simulation with immobile ions. The schematic is shown in Fig 1. The plasma density $n_e = 1.12 \times 10^{22}$ cm^{-3}, which corresponds to $n_e/n_c = 10$, where n_c is the critical density for $\lambda = 1$ μm, and the initial temperature is 9.4 keV. The laser intensity rises in 5 fs and remains constant after that. The peak irradiated intensity $I = 1 \times 10^{19}$ W/cm^2, which corresponds to $a \simeq 2.7$. The magnetic field associated with a intense laser B_L =290 Mgauss. In order to study the

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difference between oblique and normal incidence, we simulate two angles of incidence $\theta = 0°$ (normal incidence) and 60° (oblique incidence), respectively. Both p- and s-polarized laser irradiation are studied for the oblique incidence.The number of spatial grids and particles are 1024×512 and 4×10^6, respectively.

The quasistatic magnetic field $\tilde{B}_z$ at the normal incidence after t = 75 fs is shown in Fig. 2. The quasistatic magnetic field is obtained by averaging over a laser period and normalized by 46 Mgauss. The feature of the quasistatic magnetic field at the normal incidence has been well investigeted [4]. The magnetic field is growth into a inner plasma by the Weibel instability, which occurs between the fast electrons generated by the $\boldsymbol{J} \times \boldsymbol{B}$ heating [13] and their return currents. Since there is no current parallel to the surface unlike the case of oblique incidence shown later, the magnetic field along the surface does not appear both the front and rear side. A periodic structure near the front surface may be made by three mechanisms which are the kinetic effects, convection loss, and mode coupling. The details of the mechanisms are described in Ref. 4. Similar structures appear at the oblique incidence.The quasistatic magnetic fields $\tilde{B}_z$ at the oblique incidence with p-polarized laser after t = 10, 25, and 75 fs are shown in Figs. 3(a), 3(b), and 3(c), respectively. We found three kinds of quasistatic magnetic fields, which are located at the front surface, inner plasma, and rear surface. The magnetic field on the front surface arises very quickly,

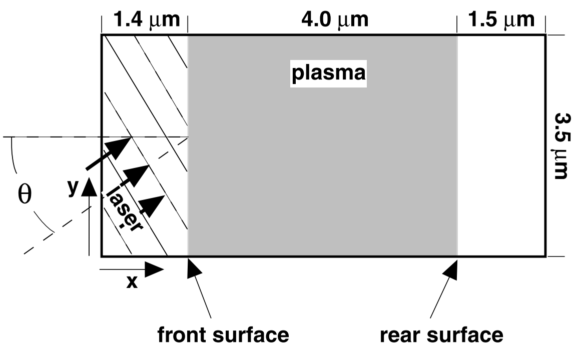

Fig. 1 A schematic of two dimensional PIC simulation. The density profile is initially homogeneous with a sharp plasma-vacuum interface. The incident laser light is periodic in y direction and two period in the simulation box. θ is an angle of incidence.

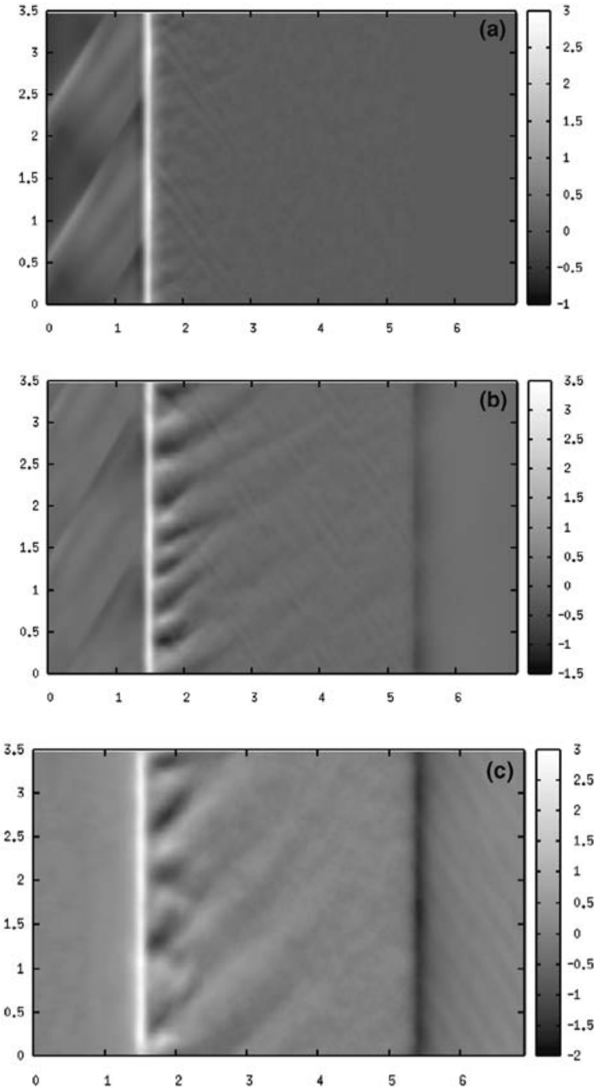

Fig. 3 The time evolution of the quasistatic magnetic fields $\tilde{B}_z$ at the oblique incidence (θ = 60 deg) with p-polarized laser. Figures (a), (b), and (c) are shown after t = 10, 50, and 75 fs, respectively.

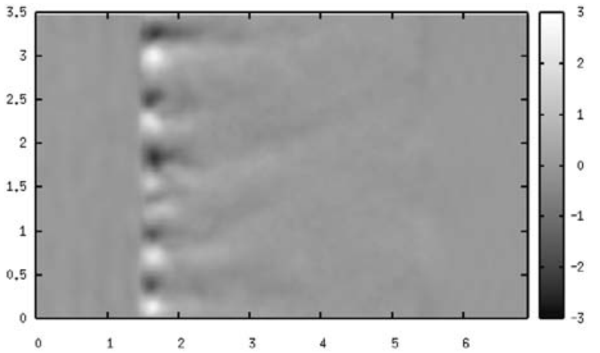

Fig. 2 Quasistatic magnetic field $\tilde{B}_z$ at the normal incidence after t = 75 fs. Spatial size is normalized by 1 μm.

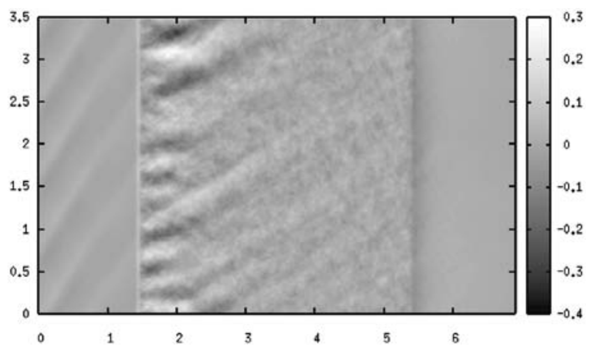

Fig. 4 Quasistatic magnetic field $\tilde{B}_z$ at the oblique incidence (θ = 60 deg) with s-polarized laser after t = 75 fs.

of which raising time is almost the same of the laser raising time is seen in Fig. 3(a). The amplitude of the quasistatic magnetic field, $|\tilde{B}_z| \simeq 0.4\ B_L$, hardly changes after the laser intensity reaches maximum in all Fig. 3. The magnetic field in a inner plasma is also generated by the fast electrons like the $\boldsymbol{J} \times \boldsymbol{B}$ heating of the normal incidence. The growth direction is the fast electron propagation direction that is determined by the combination of $\boldsymbol{J} \times \boldsymbol{B}$ heating and the vacuum heating [14], namely the direction is not the laser incidence one. After fast electrons arrive at the rear surface, a quasistatic magnetic field along the rear surface instantaneously occurs like the front surface. The amplitude is about a half of the front field one.

We also simulate at the oblique incidence with s-polarized laser to compare the difference between the polarization direction. The quasistatic magnetic fields $\tilde{B}_z$ after t =25 fs is shown in Fig. 4. The structures of the magnetic field are the same as the case of the p-polarized laser appears. The amplitude is less than 1/10 of the p-polarized laser. There are two main reasons of the difference of the amplitude. The first reason is a laser absorption in which the rate of the p-polarized laser is larger than one of the s-polarized laser. The second reason may be because contribution of the laser electric field along the surface and the current according to it is large in the case of the p-polarized laser. However, the amplitude along the rear surface is one third of the fornt one. This shows that the magnetic field of both the front surface and inner plasma strongly affects the electron transport. A refraction of the magnetic field near the front surface are found in Figs. 3 and 4. The refraction occurs by two generation mechanisms of a magnetic field. One is from the first electron generated by the laser field directly as discussed above. The other is from the hot electron heated by the laser field at the surface. The direction is parallel to the gradient of the electron temperature, namely perpendicular to the surface.

3. Conclusion

The interaction of the relativistic laser light irradiated on a thin target at the oblique incidence is investigated using a two dimensional particle-in-cell simulation. We found three kinds of quasistatic magnetic fields in the both p- and s-polarized laser. The front surface magnetic field arises very quickly due to the laser raising. The magnetic field in a inner plasma is gradually growth by the Weibel instability. The magnetic field on the rear surface of the thin target arises also very quickly when electrons pass through the surface and return into the plasma.

One of the mechanism of the surface magnetic field generation is explained as follows (see Fig. 5). When an intense laser pulse is irradiated obliquely on a solid surface with a steep density gradient, fast electrons are injected into the plasma due to the vacuum heating and $\boldsymbol{J} \times \boldsymbol{B}$ heating. The accelerated electrons form a high energy jet which induces a magnetic field. When a sufficiently intense magnetic field is generated along the surface, a significant fraction of high and low energy electrons are reflected back to the vacuum by the magnetic field. These electron motions account for the surface current, and enhances the surface magnetic field. Since the magnetic field enhances the surface current, this becomes a positive feedback process and sustains the surface current and magnetic field. Another mechanism which is due to the contribution of the laser electric field along the surface and the current according to it is especially important in the case of the p-polarized laser.

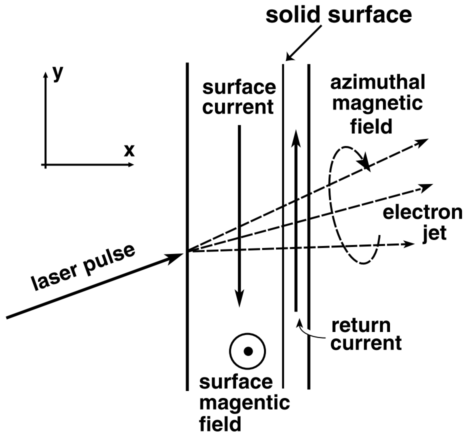

Fig. 5 A schematic of the generation mechanism of a surface magnetic field.

It is noted that, since periodic boundary conditions in y direction were applied, this results become appropriate when a spot size of the laser is sufficiently large compared with the pulse length. Therefore, when the spot size is small, a different result may appears.

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