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Development of Electromagnetic Instabilities in the Interaction of Ultraintense Laser Pulses with Overdense Plasmas

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Abstract

Self-generated magnetic fields are obserbed in laser-irradiated targets plasmas. Numerical simulations are carried out using a three-dimensional Particle-in-Cell method. The growth rates and the saturation points of the self-generated magnetic field in our simulation are in good agreement with the results of our theoretical calculations.

1. Introduction

It is known that the interaction of ultraintense laser pulses with overdense plasmas leads to the generation of magnetic field, and then the electron trajectories are bent backwards by the self-generated magnetic fields. Therefore the fast electrons are prevented from transporting the energy into the center of the compressed core. The self-generated magnetic fields are a serious obstacle to realization of the fast ignitor. There have been many reports about Weibel-type instability [1,2,3] of self-generated magnetic fields. In this paper, we will show that the growth rate of the Weibel-type instability [7] of 3-D Particle-in-Cell (PIC) simulation is consistent with that of our theoretical results, and we will similarly discuss the saturation of magnetic energy.

2. Weibel-type magnetic field generation

2.1 Simulations and theory

We apply a PIC method to simulate the interaction of overdense plasmas with intense ultrashort laser pulses. The method is based on the electromagnetic PIC and is appropriate for the analysis of the dynamics of overdense plasmas generated by arbitrarily polarized, obliquely incident laser pulses. Our PIC code is fully three-dimensional in both space (x, y, z) and velocity space (v_x, v_y, v_z) in the rectangular Cartesian coordinate system. It also takes into consideration the relativistic correction. In this code, the particle and the field quantities are derived from the time evolution of a closed differential equation set which consists of equations of motion and Maxwell equations, and are solved self-consistently in the given plasma systems.

Simulations were performed for laser wave length of 1.06 μm, laser pulse width 20 fs, laser beam diameter 1.0 μm and laser intensities 10^{19} W/cm^2. The time step is chosen to be 0.1/ω_L where ω_L is the laser frequency, spatial step 0.2c/ω_L cells 1000×30×30, electrons 2×10^6 and ions 2×10^6. The maximum electron density is n_c, where n_c is the critical density. Fig. 3 shows the temporal profile of the magnetic energy. The fields show exponential growth versus time. We can calculate the growth rate of the spontaneous magnetic field in our simulation and also compare the results to our theoretical ones.

The Maxwellian for the electrons is

$$f(v_x, v_y, v_z) = \frac{n}{(2\pi)^{3/2} u_x u_y u_z} \exp\left[-\left(\frac{v_x^2}{2u_x^2} + \frac{v_y^2}{2u_y^2} + \frac{v_z^2}{2u_z^2}\right)\right], \tag{1}$$

and also

$$\frac{1}{2} m u^2 = \frac{1}{2} k_B T \, , \tag{2}$$

where x-axis is the laser-irradiated one, n the number density, v the velocity, u the thermal velocity, m the mass, k_B the Boltzmann constant and T the temperature.

For the bi-Maxwellian electron distribution, the maximum growth rate of the Weibel-type instability is given by [3]

$$\gamma^T = \sqrt{\frac{8}{27\pi}} \omega_L \sqrt{\frac{k_B T_z}{mc^2}} \frac{A^{3/2}}{A+1}, \tag{3}$$

where A is an anisotropic factor and defined by

$$A \equiv \frac{T_x}{T_z} - 1 \, , \tag{4}$$

and $T_x > T_y = T_z$.

We can calculate the growth rate of the spontaneous magnetic field in our simulation and also compare the results to our theoretical ones. Figs. 1, 2, 3 and 4 show target density profile, anisotropy parameter, magnetic field, magnetic field at log scale and thermal velocity (v_z / c) respectively. From Figs.1, 2, 3 and 4, we can estimate the growth rates of the self-generated magnetic fields about $\gamma^S = 8.9\times10^{-2}\omega_L$ by PIC simulation. This growth rate is consistent with $\gamma^T = 8.4\times10^{-2}\omega_L$.

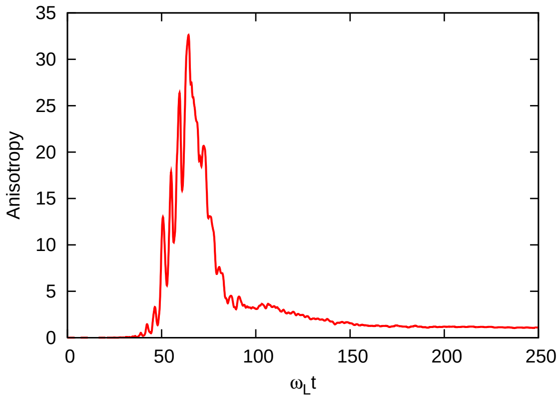

Figure1. Temporal profile of the anisotropic factor A .

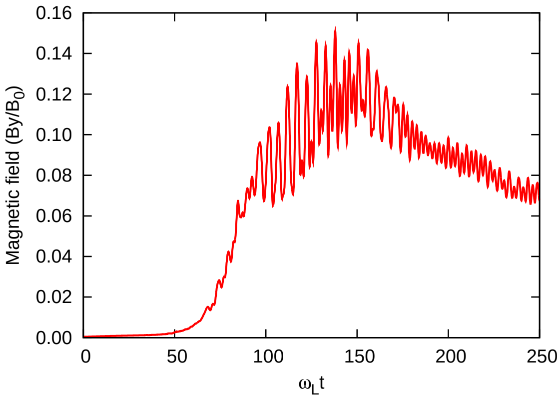

Figure 2. Temporal profile of the self-generated magnetic fiel B_y / B_0

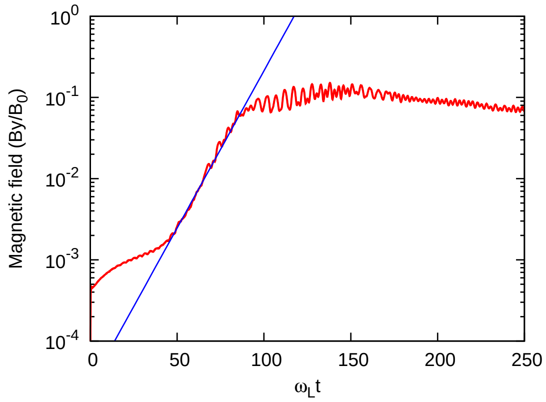

Figure 3. Temporal profile of the self-generated magnetic field B_y / B_0 at logscale.

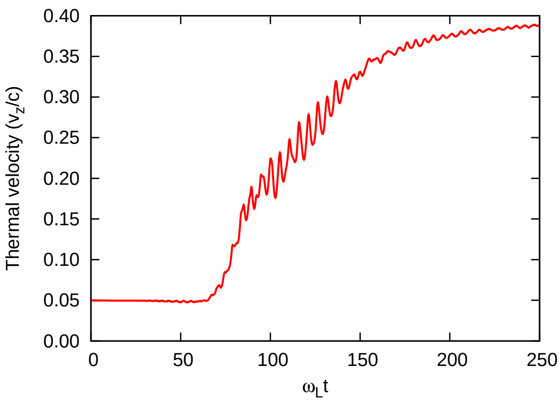

Figure 4. Temporal profile of the thermal velocity v_z / c .

2.2 The saturation of the self-generated magnetic fields

At first the self-generated magnetic fields grow exponentially, but shortly afterwards saturate. It is found that the magnetic field energy saturates once the magnetic bounce frequency has increased to a value comparable to the linear growth rate prior to saturation [6].The system of the saturation is considered that particles are trapped near the bottom of the wave potential when $\omega_B \cong \gamma^T$,where ω_B is magnetic bounce frequency and is defined by next expression.

$$\omega_B = \sqrt{\left(\frac{ek}{m}\right)\left(v_z B_y\right)} \quad , \qquad (5)$$

where e is the charge of an electron, k the largest wave number, m the mass of an electron, and v_z the largest thermal velocity in the z direction, and B_y the largest magnetic field. The magnetic field saturates at a value B_y [6] where

$$\frac{B_y}{B_0} = \left(\gamma^T\right)^2 \frac{1}{k v_z \omega_L} \ , \qquad (6)$$

$$B_0 = \frac{m\omega_L}{e} \, . \qquad (7)$$

From Figs. 3 and 4, we can estimate the largest magnetic field $B_y / B_0 = 6 \times 10^{-2}$ by PIC simulation. This largest magnetic field by the simulation is consistent with $B_y / B_0 = 2.5 \times 10^{-2}$ from Eq. (6).

3. Results

The maximum growth rate γ^s obtained from PIC simulation is consistent with the maximum growth rate γ^T obtained from Eq. (3) as indicated in section 2.1. In these situations, Weibel-type instability is also of interest because it is thought to be one of the basic mechanisms for magnetic field generation and temperature anisotropy is necessarily formed in laser-plasma interactions.

Recent laser-plasma experiments with an ultraintense laser have revealed many kinds of phenomena and have given rise to interesting new problems as well, and the existence of self-generating magnetic fields is one of the most important problems. Anisotropic electron velocity distribution can induce various instabilities in plasmas.

We have performed three-dimensional particle simulation on the plasmas that have anisotropic temperatures. As a result, intense self-generated magnetic fields were observed.

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