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Three-dimensional particle-in-cell simulations of energetic electron generation and self-generated magnetic field with high-intensity laser pulses in overdense plasmas

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Abstract. The interaction of high-intensity laser pulses with overdense plasmas is studied by three-dimensional particle-in-cell (PIC) simulations. Self-generated magnetic fields are observed in the plasma target owing to Weibel-type instability. The growth rates of the self-generated magnetic field in our simulation are in good agreement with the results of our theoretical calculations.

1. Introduction

The recent progress in the development of ultraintense, short pulse lasers has allowed for the exploration of many new regimes in the field of laser–plasma interactions. A fast ignitor (FI) concept [1, 2] was proposed as the approach to efficiently ignite the high-density fusion fuel plasmas with an ultraintense short pulse laser. In the FI scheme, the intense laser pulse propagates through a coronal plasma up to several times the critical density and delivers energy to fast electrons; these highly energetic particles then transport the energy through the overdense plasma to the center of the compressed core and ignite the fuel there. It is known that the fast electrons are prevented by the self-generated magnetic field. There have been many reports about Weibel-type instability [3–5] of self-generated magnetic field. The Weibel-type instability breaks up the fast electron current into filaments. Particle-in-cell (PIC) simulations have shown the break up of fast electron beams into filaments guided by magnetic fields [6–8]. This paper is devoted to three-dimensional (3D) PIC simulations of the Weibel-type instability in an overdense plasma [9, 10].

2. 3D PIC simulation of Weibel-type instability in the intense laser–plasma interaction

In order to simulate the time evolution of a plasma system, we performed an electromagnetic PIC simulation. Our PIC code is fully 3D in both space (x, y, z)

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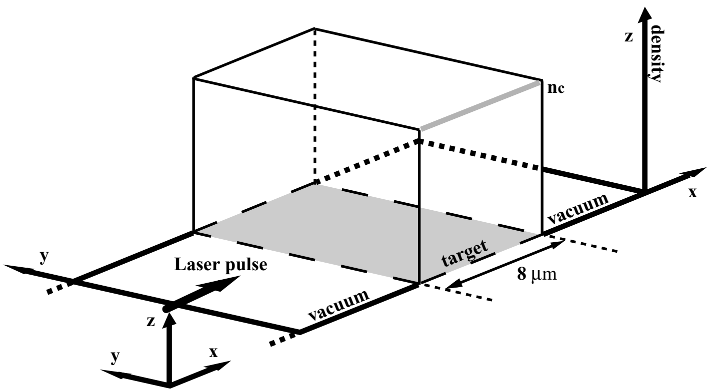

Figure 1. Target density profile.

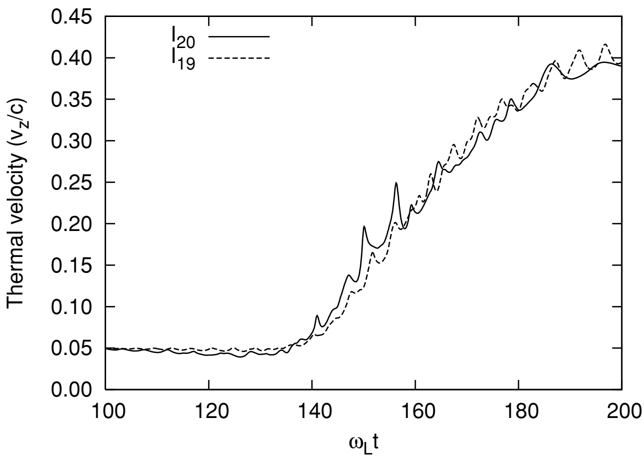

Figure 2. Themal velocity v_z/c versus time.

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 system. Simulations were performed for a p-polarized laser (E_y, B_z), laser wavelength of $1.06\,\mu$m, laser pulse width 20 fs, laser beam diameter $1.0\,\mu$m and laser intensities 10^{19} and 10^{20} W cm^{-2}. The initial temperature of electrons and ions are 1 keV, 40 eV, respectively, and the electron–ion mass ratio is 1/1837. The time step is chosen to be $0.1/\omega_{\rm L}$ where $\omega_{\rm L}$ is the laser frequency, spatial step $0.2c/\omega_{\rm L}$, cells $1000 \times 30 \times 30$, electrons 2×10^6 and ions 2×10^6. The maximum electron density is $n_{\rm c}$, where $n_{\rm c}$ is the critical density. Figures 1, 2, 3 and 4 show target density profile, temporal profiles of thermal velocity (v_z/c), anisotropy parameter A and magnetic field energy, respectively. The laser pulse interacts with the target at a time of $\omega_{\rm L} t = 100$. From the linearlized Vlosov equation and linearized Maxwell's equations, we obtain the maximum growth rate $\gamma^{\rm T}$

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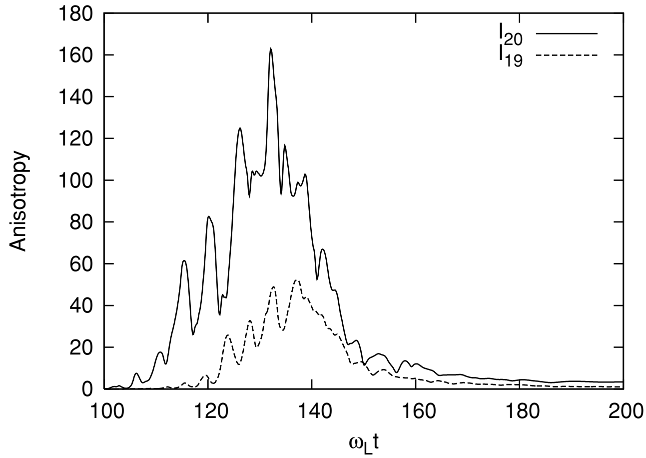

Figure 3. Anisotropy parameter A versus time.

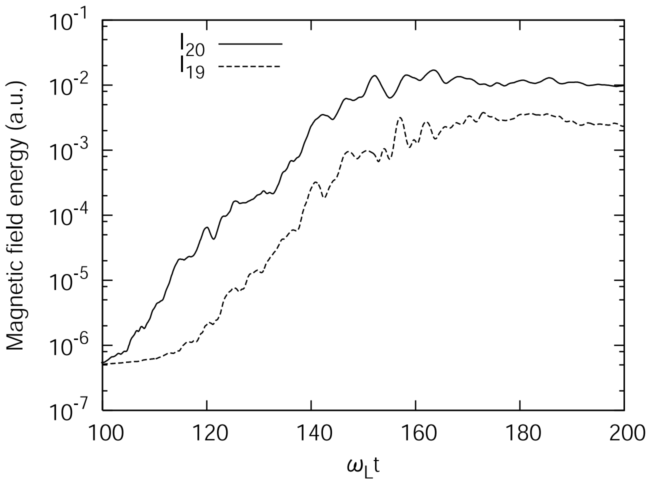

Figure 4. Self-generated magnetic field energy versus time.

of the Weibel-type instability [3]

$$\gamma^{\mathrm{T}} = \sqrt{\frac{8}{27\pi}\frac{v_z^{\mathrm{th}}}{c}\frac{A^{3/2}}{A+1}}\omega_{\mathrm{L}} \tag{2.1}$$

where v_z^{th} is the z component of the electron thermal velocity v^{th}, c the velocity of light, ω_{L} the laser frequency and A the anisotropy parameter

$$A = \frac{{v_x^{\mathrm{th}}}^2 + {v_{\mathrm{D}x}^{\mathrm{th}}}^2}{{v_z^{\mathrm{th}}}^2 + {v_{\mathrm{D}z}^{\mathrm{th}}}^2} - 1 \tag{2.2}$$

where $v_{\mathrm{D}x}^{\mathrm{th}}$, $v_{\mathrm{D}z}^{\mathrm{th}}$ are the x component and z component of the drift velocity, respectively. Self-generated magnetic fields are plotted in Fig. 4, from which we can estimate that the maximum growth rates γ^{S} are about $1.14 \times 10^{-1}\omega_{\mathrm{L}}$ for

10^{19} W cm^{-2} and $1.27 \times 10^{-1}\omega_{\mathrm{L}}$ for 10^{20} W cm^{-2} at maximum anisotropy parameter. These growth rates are consistent with $\gamma^{\mathrm{T}} \approx 1.16 \times 10^{-1}\omega_{\mathrm{L}}$ for 10^{19} W cm^{-2} and $1.63 \times 10^{-1}\omega_{\mathrm{L}}$ for 10^{20} W cm^{-2}.

3. Conclusions

We have investigated the mechanism of self-generated magnetic fields in the interaction of high-intensity laser pulses with overdense plasmas. The self-generated magnetic fields have been obtained by 3D PIC simulation. The growth rates of the magnetic fields in the simulation are in good agreement with the results of the Weibel-type instability.

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