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High Power Laser Plasma Interactions in the Presence of Strong Magnetic Field

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The high power laser plasma interactions in the presence of strong magnetic field are studied by both analytic theory and particle in cell (PIC) simulation. Orders of kilo-tesla magnetic field is applied along laser propagation direction and plasma inhomogeneity. Simulation shows different laser absorption rates and electron temperature with different magnetic field. Solitons are observed at some particular amplitudes of magnetic field which corresponds to the maximum absorption rate. A set of fluid equations is proposed to describe the soliton and density envelop including ion's motion and finite temperature effects.

1. Introduction

One of the recent highlights in fast ignition is the effects of strong magnetic field on laser plasma interactions. Simulation [1,2] has shown different electron transportation and coupling efficiency between the hot electrons and plasma target. However, most of the work is focus on the beam plasma system or laser plasma interactions with sharp boundaries. In the existence of strong magnetic field, the nonlinear interactions between intense laser and underdense pre-plasma should be reconsidered. It is known to all that, linearly polarized laser will split into left branch, right branch, whistler mode or so, if the magnetic field is along the propagation direction. The laser can penetrate into the overdense plasma as whistler mode as long as the magnetic field is high enough. On the other hand, early simulations [3] have shown that up to 30-40% of the laser energy can be trapped in the quasi-stationary density cavities during the interaction with the underdense plasma. Esikrkepov [4] first gave the analytical soliton solutions for unmagnetized plasma in the framework of one-dimensional relativistic cold collisionless fluid approximation. The ion's effect and inhomogeneous case were later considered by Daniela and Bulanov [5,6], where they found the soliton type depends on the propagation velocity. In magnetized plasma, the presence of magnetic field is proved to have non-negligible effects on the properties of solitons [7]. In this study, we present the analytic and PIC simulation results of high power laser plasma interactions in the presence of strong magnetic field.

2. Results

The simulation setup is as follows, linearly polarized Gaussian laser comes in y direction with normalized intensity a_0=0.5, wavelength 0.82μm and duration 40fs. The fully ionized carbon plasma is distributed between y=500 and y=2500 with total length equals to 10μm. There is an exponential pre-plasma ranging from y=500 to y=1500. The uniform plasma density n_0 is $0.64n_c$, where n_c is the cut off density. The electron and ion temperature is 0.5kev. The external magnetic field B_0 is also applied in y direction.

2.1 *Polarization and propagation*

We first study the laser polarization and propagation under different amplitudes of magnetic field. Figure 1 shows the time evolution of laser field at three different places with B_0=2kT and 10kT. The disappearance of fast time oscillations in the uniform plasma (y=2000) and vacuum (y=2750) in the 10kT case clearly shows the laser changes its polarization. This is because of the different cut off position for the right and left branch which is determined by the magnetic field and plasma density.

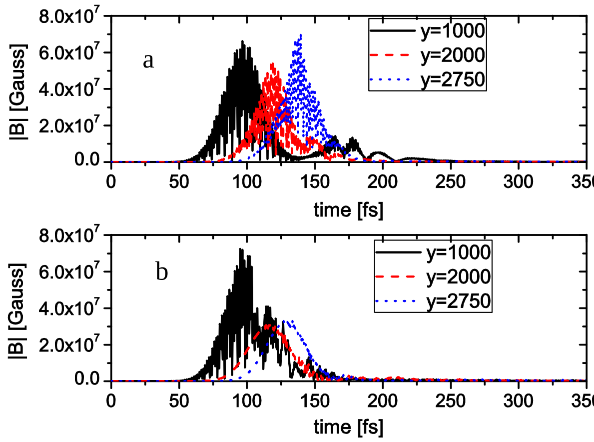

Fig. 1. The time evolution of laser magnetic field at 3 different places, y=1000, 2000, and 2750 with external magnetic field a) B_0=2kT, b) B_0=10kT.

2.2 *Absorption rate and velocity distribution*

The dependence of plasma absorption rate (both electrons and ions) on amplitudes of magnetic field is plotted in Fig. 2a. As we can see, the direction of magnetic field does not affect the absorption rate and nearly 37% of the laser energy is absorbed by the plasma when the magnetic field is around 4kT or 10kT. However, if we look into the electron velocity distribution, we find laser energy is mainly deposited in y direction in 4kT case; while in 10kT case, the transverse component contributes a great portion. This result implies that if we want to use the magnetic field to guide the fast electrons, the field should not be too large.

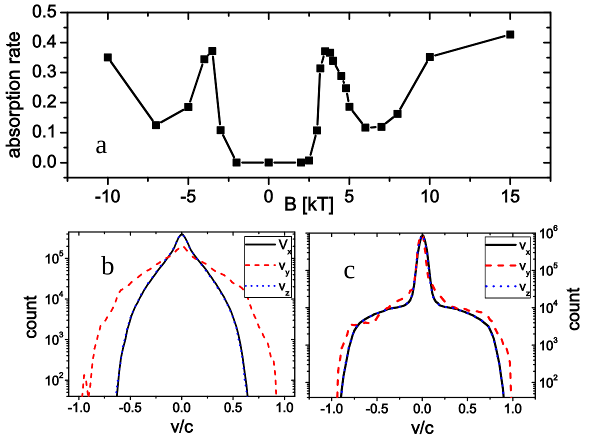

Fig. 2. a) The absorption rate with different amplitudes of magnetic field. Minus means the magnetic field is in the opposite direction of y axis. The electron velocity distribution for b) B_0=3.8kT, c) B_0=10kT.

2.3 *Solitons*

If we check the wave envelop and density behavior around B_0=4kT, we find there is a density cavity inside the uniform plasma and the laser is trapped as solitons inside the cavity. The soliton is generated because of the density redistribution due to the ponderomotive force as well as the relativistic modification of local refractive index. Figure 3a shows the density and spatial distribution of laser magnetic field at time t=184fs when the incident laser has already gone in the case where B_0=3.8kT. On the soliton edges, the density reaches almost 2 times of the local density. Figure 3b is the spectrum of B_z at different places. Since the main frequency of soliton is smaller the laser frequency as well as the local plasma frequency, the laser can be well trapped for a long time in the density cavity and converts its energy to plasma eventually. Note that, besides the main frequency and laser frequency, the solitons have also the harmonics.

The soliton amplitude a and scalar potential φ can be described by the following normalized equations,

$$a'' + \omega^2 a = a\left[\frac{\varphi + R_e}{v_{the}^2(\gamma_e - \Omega/\omega)} + \frac{-\rho\varphi + R_i}{v_{thi}^2(\gamma_i + \rho\,\Omega/\omega)}\right] \quad (1)$$

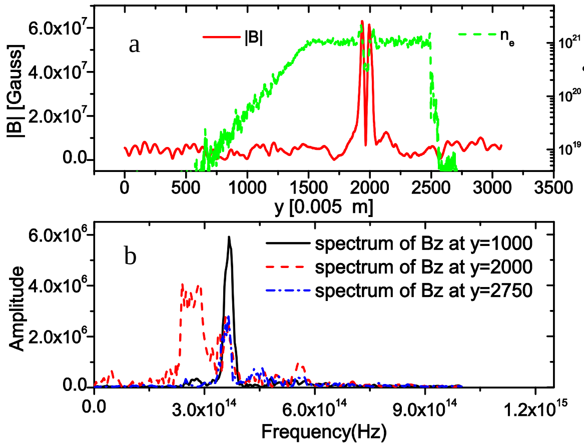

Fig. 3. a) The density (right) and spatial distribution of laser magnetic field (left) at time t=184fs. b) The spectrum of B_z at three different coordinates y=1000, 2000 and 2750. The magnetic field is B_0=3.8kT.

$$v_{the}^2 v_{thi}^2 \varphi'' - c_s^2 \varphi = v_{thi}^2 R_e - v_{the}^2 R_i \quad (2)$$

where $R_e = -\gamma_e - \Omega/2\omega\gamma_e^2 + c_{e0}$, $R_i = -\gamma_i + \rho\Omega/2\omega\gamma_i^2 + c_{i0}$, $p_e - a = (\Omega/\omega)(p_e/\gamma_e)$, $p_i + \rho a = -\rho(\Omega/\omega)(p_i/\gamma_i)$, $v_{th\alpha}$, p_α, γ_α are the thermal velocities, momentum and energy for α^{th} particle, c_s is the sound speed, ρ is the mass ratio between electrons and ions, ω and Ω are the soliton frequency and electron cyclotron frequency and $c_{\alpha 0}$ is numerical constant determined by the boundary condition. The normalizations are as follows, length, time, density, velocity, momentum, vector and scalar potential are normalized by c/ω_{pe}, ω_{pe}, n_0, c, $m_\alpha c$, $m_e c^2/e$, with $\omega^2_{pe}=4\pi n_0 e^2/m_e$ the plasma frequency.

3. Conclusions

We have investigated the laser polarization, absorption rates and soliton formation in the existence of strong magnetic field. A set of fluid equations is used to describe the soliton envelop including the ion and finite temperature effects.

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