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Relativistic soliton formation in laser magnetized plasma interactions

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Abstract. The laser plasma interactions in the presence of strong magnetic field are studied by employing particle-in-cell simulations. Simulations show that the energy absorption of strong laser pulse is mainly characterized by the electron cyclotron resonance heating (ECRH) when the magnetic field is large enough. However, it is found that for a weaker magnetic field, a standing or moving soliton can be generated in some moderate laser intensity regions, greatly enhancing the laser absorption. The laser intensity for the soliton heating decreases as the magnetic field increases. Furthermore, the soliton position moves towards the front boundary when the laser intensity or magnetic field strength increases.

1. Introduction

Recently, the study of laser plasma interactions in the presence of strong magnetic field has become a hot research topic in fast ignition. Kilo-tesla magnetic field has been proposed to guide the relativistic electron beams (REBs) and enhance the coupling efficiency of the REBs to the fuel core. However, due to the conversional laser pulse contrast, the under-dense pre-plasma formed by the pre-pulse is inevitable. Early particle-in-cell (PIC) simulations and experiments showed that a bright soliton can be generated during the interactions of a strong laser pulse with an under-dense plasma and up to 40% of the laser energy can be converted into the soliton structures, which makes the soliton formation an important energy conversion process in the laser plasma interactions [1, 2]. Hence, the formation and properties of the solitons should be reconsidered in the presence of strong magnetic field.

The dynamics of soliton formation in unmagnetized plasmas has been studied intensively. Kozlov et al first studied the relativistic solitons in a cold plasma by an envelope approximation [3]. Their work were extended by several authors to include the ion's motion and warm temperature effects [4-12]. Different types of solitons under different soliton velocities have been reviewed by D. Farina [12]. Compared with the systematic and abundant research results on the unmagnetized plasmas, the study of solitons in magnetized plasma is much less and insufficient [13,14]. In this paper, we present the numerical simulations of the effects of magnetic field on the soliton formation and properties. The analytical analysis of the soliton dynamics is left for another publication.

2. Simulation Results

One dimensional PIC simulations are carried out by employing the extended particle based integrated code (EPIC3D) [15,16]. The simulation is set up as follows. The system size is $15.36\mu m$, which corresponds to $L_y = 3072$ in normalized unit of $0.005\mu m$. A Gaussian shaped laser pulse is irradiated



from the left boundary with the wavelength $0.82\mu\text{m}$ and pulse duration 40fs. The peak intensity of the laser varies from $2.1 \times 10^{16}\text{W}/\text{cm}^2$ to $8.2 \times 10^{18}\text{W}/\text{cm}^2$ or $a_0 = 0.1$ to $a_0 = 2.0$ in normalized values. The laser is linearly polarized in the x direction. A fully ionized carbon plasma with electron and ion temperature 0.5keV is initially set between $y = 500$ to $y = 2500$ and a pre-plasma of density layer $n_e(y) = 0.63n_c \exp[(y - 1500)/164]$ is assumed from $y = 500$ to $y = 1500$. Here $n_c = 1.66 \times 10^{21}\text{cm}^{-3}$ is the cut off density for the laser wave. The uniform magnetic field is also applied in the y direction. In the simulations, periodic boundary conditions are employed for the particles while the laser waves are outgoing.

The laser absorption rate is used to evaluate the laser heating efficiency during the propagation of the laser pulse in different magnetized plasmas, as summarized in figure 1 [17]. The absorption rate is calculated by the ratio of energy increment of the electrons and ions to the laser energy. It shows that the dependence of heating efficiency on laser intensities are quite different for different magnetic field strength. Generally, larger amplitude laser can effectively heat the plasma, however, for not so strong magnetic field strength, there exists a moderate laser intensity region where enhanced heating occurs. The enhanced heating region moves to the lower laser intensity area as the magnetic field increases. When the magnetic field approaches the strength where electron cyclotron resonance happens, the enhanced heating disappears and the heating efficiency is almost independent of laser intensity, as shown by the line with upper triangles ($B_0 = 15.0\text{kT}$) in figure 1. Hence, the absorption is mainly characterized by the electron cyclotron resonance heating (ECRH) in the high magnetic field regime. The peak of the enhanced heating is about 37%, a little smaller than the ECRH heating efficiency.

The details on the laser pulse propagation in the enhanced heating region are depicted in figure 2, where a localized mode, namely, a bright soliton is observed, which co-exists with a plasma cavity. The bright soliton is the wave which the wave intensity is maximum at the center and vanishes at the infinity. The soliton formed in the magnetized plasma has the same properties as in the unmagnetized plasma [1], for example, long-lived and short width of about one laser wavelength. The mechanism of the soliton generation is as follows [12]. The density perturbation is generated after the laser pulse due to the ponderomotive force and the laser starts to lose energy. Meanwhile, the laser frequency decreases because this energy transfer is an adiabatic process and the ratio between the wave energy density and the frequency is conserved. Actually, if one checks the frequency spectra of the laser field at $y = 2000$, where the soliton is generated, a lower frequency spectrum appears besides the incident laser frequency. More importantly, it has a higher intensity than the laser frequency one. Once the laser frequency falls below the plasma frequency, the laser wave becomes trapped in the density cavity, forming a solitary wave. Since the group velocity of the laser pulse decays with the frequency in the weak magnetic field regime, the soliton wave propagates with almost zero velocity. As a result, the laser can be absorbed efficiently in the standing density well. In the case of weakly relativistic limit, the frequency downshift is approximately proportional to the density perturbation and the square of laser intensity. Meanwhile it has a positive correlation with the magnetic field strength [18]. Hence, as the magnetic field strength increases, the laser intensity region needed for the soliton formation reduces. If the density perturbation is not large enough to trap the laser wave, the soliton will collapse soon after its generation and moves away. Note that there is strong electrostatic field inside the soliton in the initial phase of the soliton

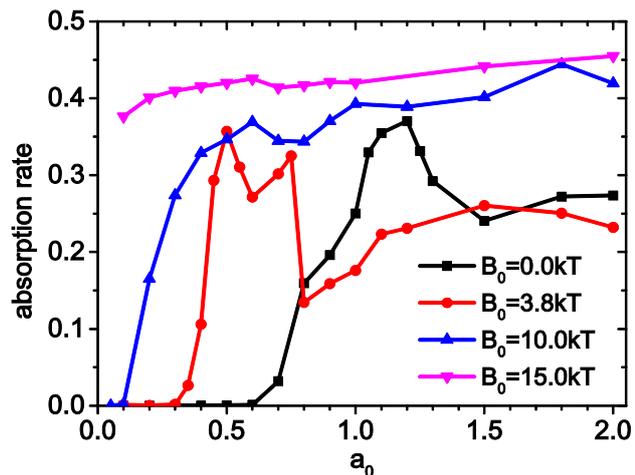


Figure 1. Energy absorption rate with laser intensity a_0 for different magnetic field strength. The magnetic field strength for ECRH is about 13kT.

formation. However, afterwards, the ponderomotive force starts to dig a hole in the ion density and the quasi-neutrality state can be achieved.

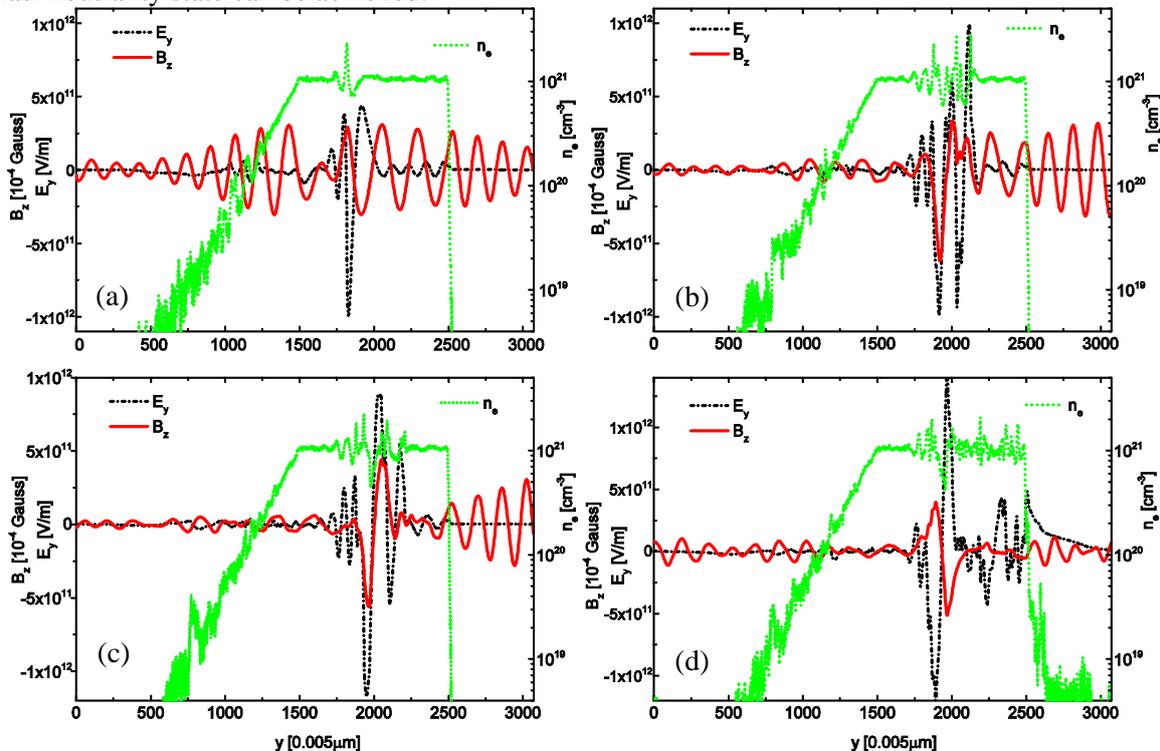


Figure 2. The time evolution of a standing soliton at $t = 119.6\text{fs}$ (a: upper-left), $t = 135.6\text{fs}$ (b: upper-right), $t = 139.1\text{fs}$ (c: bottom-left) and $t = 161.1\text{fs}$ (d: bottom-right) with $a_0 = 0.5$ and $B_0 = 3.8kT$.

The soliton position in the uniform density area is an interesting and meaningful issue, since we may potentially use the soliton generation to control the energy deposition position in the plasma. Some factors relevant to the soliton position are studied as shown in figures 3 and 4. Fig. 3 shows that, the soliton position shifts from the rear boundary to the front one when one increases the laser intensity or magnetic field strength. This may result from the dependence of the frequency downshift on the magnetic field strength and laser intensity, which may be characterized by a threshold for the soliton formation: one of the two factors increases, the other needed for soliton generation decreases. On the other hand, we have extended the system size to $L_y = 4096$ and changed the characteristic length of the pre-plasma, as shown in Figure 4. It is observed that the soliton position is independent of the system size, but shifts to the front boundary as the characteristic length of the pre-plasma increases. The detailed mechanism of the soliton position on the density profile still remains unknown and needs to be resolved in the future.

3. Summary

We have used the EPIC3D code to study the soliton formation and their properties in the strongly magnetized plasmas. It is found that, the absorption is dominated by the ECRH when the magnetic field strength is strong enough, e.g. comparable to the strength where ECRH occurs. In the case of weak magnetic field, standing or moving solitons can be generated in some moderate laser intensity regions, which can greatly enhance the absorption rate. 2D simulations also confirmed this enhancing effect [17]. The laser intensity for the soliton generation decreases as the magnetic field increases. The soliton is of long-living time with a very short width and a lower frequency compared to the incident laser wave. The relevant factors to soliton position are also studied. It is found that the soliton position depends on the characteristic length of the pre-plasma rather than the uniform plasma length. Furthermore, the soliton position moves from the rear boundary to the front one as the laser intensity or magnetic field

increases. Hence, considering the high efficiency of energy transfer by the solitons, the soliton generation in strongly magnetized plasmas may play an important role in fast ignition, laser-plasma based particle acceleration as well as other potential applications.

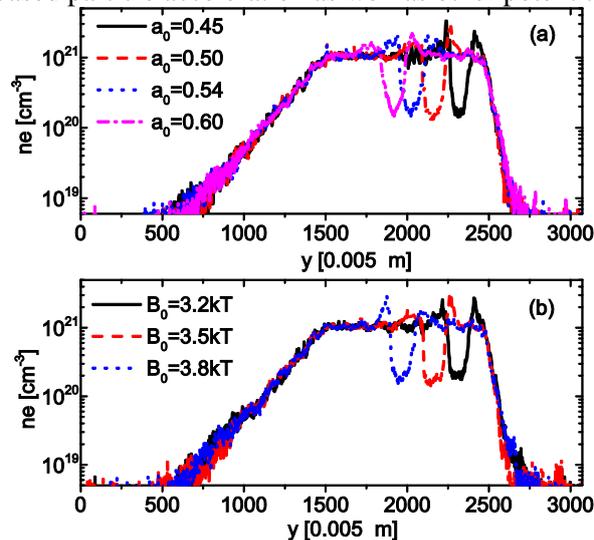


Figure 3. The soliton position dependence on laser intensities (a) and magnetic field strength (b). In (a) $B_0 = 3.5$ kT, and in (b) $a_0 = 0.5$.

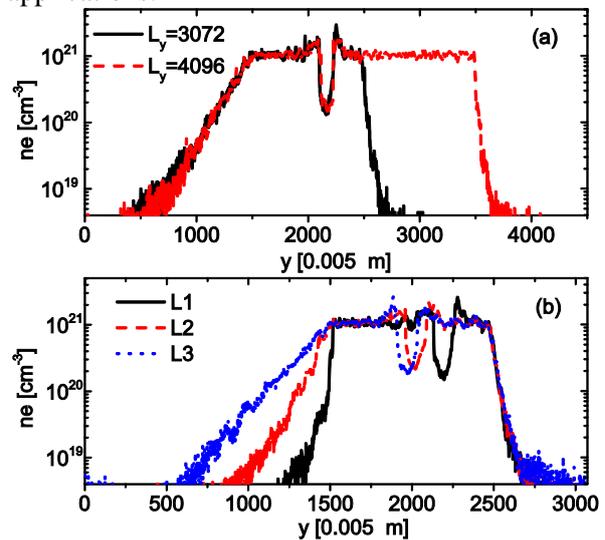


Figure 4. The soliton position dependence on system size (a) and characteristic length of the pre-plasma (b). The parameters are $a_0 = 0.5$, $B_0 = 3.5$ kT for (a) and $B_0 = 3.8$ kT for (b). “L1”, “L2” and “L3” in (b) represent the case without pre-plasma, with pre-plasma of characteristic length 82 and 164, respectively.

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