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Ion vortices in ion phase space in intense laser interaction with subcritical plasma

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Abstract. A novel stimulated trapped electron-acoustic wave scattering instability by a linearly polarized laser interacting with a subcritical density plasma layer is observed by particle simulation. Its spectrum in the early stage is well-explained by a resonant three-wave parametric decay process and it takes place whether the ion dynamics are taken into account or not. When ion dynamics are considered, the excitation of the ion electrostatic wave, the generation of the electromagnetic (EM) soliton and the formation of ion vortices due to the large EM soliton, etc., are studied.

1. Introduction

Relativistic laser–plasma interaction is a source of various electronic instabilities. In resent years, much work has been put into studies of stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), concerning their ability to produce energetic particles that can preheat the core of a fusion pellet. Early authors (Fried and Gould 1961; Stix 1962; Montgomery 1971) examining the linearized Vlasov electrostatic (ES) dispersion relation by ignoring the particle trapping effect, also noted solutions which they termed electron-acoustic waves (EAWs). Recently, a new type of stimulated scattering, the so-called stimulated EAW scattering (SEAWS) was proposed in experiment (Montgomery et al. 2001) and was also studied by particle simulation (Nikolić 2002).

In this paper, the novel trapped SEAWS (T-SEAWS) instability induced by a linearly polarized laser interacting with a plasma layer at subcritical density range ($n_{\mathrm{cr}}/4 < n/\gamma < n_{\mathrm{c}}$, γ is relativistic factor) is studied by particle simulation. Its spectrum in the early stage is well-explained by a resonant three-wave parametric decay of the laser pump into the slowed Stokes light sideband with $\omega_{\mathrm{s}} \sim \omega_{\mathrm{pe}}/\gamma^{1/2}$ and the trapped EAW with $\omega_{\mathrm{eaw}} < \omega_{\mathrm{pe}}$, the T-SEAWS instability takes place whether the ion dynamics are taken into account or not. When ion dynamics are considered, the excitation of the ion ES wave, the generation of the electromagnetic (EM) soliton after ion ES wave breaking, and the formation of ion vortices due to

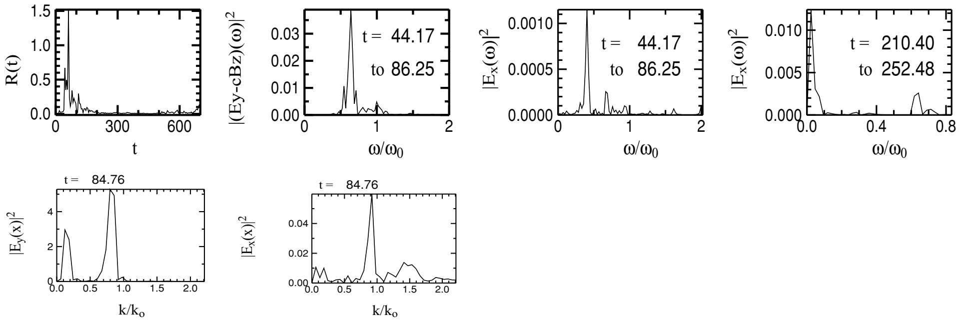

Figure 1. The reflectivity and frequency spectrum of reflected EM wave, frequency spectra of ES field E_x inside plasma, and wavenumbers of E_x and E_y inside the plasma.

the ions are accelerated and trapped by the regular EM and ES fields inside soliton, etc., are studied.

2. Simulation model

Fully relativistic EM *one-dimensional and three-velocity* particle-in-cell (PIC) code is used. Plasma length and density are $L = 100c/\omega_0$ and $n = 0.6n_{\rm cr}$, it begins at $x = 0$ and ends at $100c/\omega_0$, in the front and back sides, there are two $200c/\omega_0$ vacuum regions, where c , ω_0 and $n_{\rm cr}$ are the speed of light, frequency and critical density of the laser pulse, respectively. Electron and ion temperature are $T_{\rm e} = 5T_{\rm i} = 1\,{\rm keV}$ with mass ratio $m_{\rm i}/m_{\rm e} = 1836$. The number of cells is 20 per 1 c/ω_0, 100 electrons and 100 ions per cell. A linearly polarized laser with its electric field E_0 along the y direction and normalized laser amplitude $a = eE_0/m_{\rm e}\omega_0 c = 0.6$ is initialized at $x = -50c/\omega_0$ position, where e and $m_{\rm e}$ are the electron mass and charge. The electrons which enter the vacuum build a potential barrier that prevents other electrons from leaving the plasma. Two additional damping regions were used for these electrons and the EM waves. The time, electric field and magnetic field are normalized to $2\pi/\omega_0$, $m\omega_0 c/e$ and $m\omega_0/e$, respectively; time is taken as zero, $t = 0.0$, when the laser pulse arrives at the vacuum–plasma boundary. In this paper, the field E_x is averaged over the electron plasma wavelength $\lambda_{\rm p}$; the EM field E_y, B_z and $E_y^2 + B_z^2$ are averaged over the laser wavelength λ_0.

3. Simulation results

For a plasma density $n > 0.25n_{\rm cr}$, standard SRS instability was forbidden. We found that when the laser amplitude $a > 0.4$, T-SEAWS begins to take place. Its spectrum in early stage is well-explained by a resonant three-wave parametric decay of an intense laser pump into the slowed Stokes light sideband and the trapped EAW (see Fig. 1). The backscattered EM wave in the vacuum region is found to be driven near the perturbed electron plasma wave frequency $\omega_{\rm s} = 0.62\omega_0 \approx \omega_{\rm pe}/\gamma^{1/2}$, while the corresponding EAW with frequency $\omega_{\rm eaw} \approx 0.40\omega_0$ is excited. The wavenumber of the EM waves inside the plasma has two peaks, i.e. $k_{\rm s}^{\rm p} \approx 0.12k_0$ and $k_0^{\rm p} \approx 0.80k_0$, which correspond to backscattered and laser EM waves, respectively; for the EAW $k_{\rm eaw} \approx 0.92k_0$, where $k_0 = \omega_0/c$ is the wavenumber of the laser EM wave in vacuum. The matching conditions for frequency $\omega_0 = \omega_{\rm s} + \omega_{\rm eaw}$ and for wavenumber

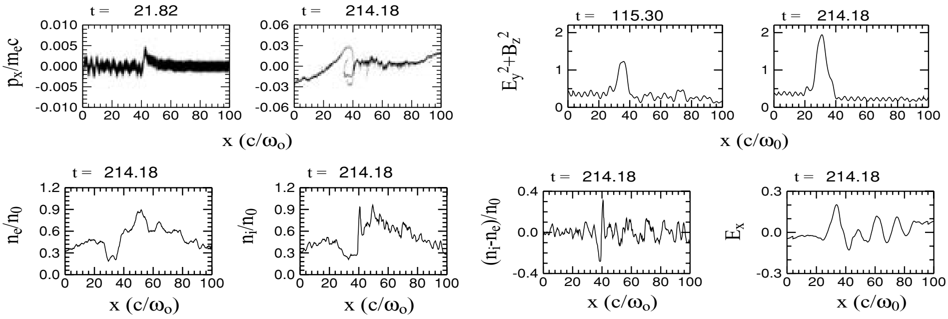

Figure 2. Snapshots for ion phase space, energy density of the EM field $E_y^2 + B_z^2$, plasma density and ES field E_x.

$k_0^{\mathrm{p}} = -k_{\mathrm{s}}^p + k_{\mathrm{eaw}}$ are well-satisfied. Here, the EM waves for both pump and backscattered modes satisfy the standard dispersion relation $\omega_{0,\mathrm{s}}^2 = \omega_{\mathrm{pe}}^2/\gamma + c^2(k_{0,\mathrm{s}}^{\mathrm{p}})^2$, respectively.

During SEAWS instability, large parts of electrons are trapped by the potential of the EAW, and this is the reason why we put a 'T-' before 'SEAWS'. The T-SEAWS instability and its early physics behaviors are almost the same whether the ion dynamics are taken into account or not. When ion dynamics are considered, an ion ES wave is excited at the early stage; however, its peak in the spectrum is hard to discern because it is suppressed by strong EAWs. When the T-SEAWS finished, an ion ES wave peak with frequency $\omega_{\mathrm{pi}} \approx 0.023\omega_0$, approximately equal to the natural ion plasma frequency $0.021\omega_0$, can be observed clearly (see Fig. 1). The excited ion ES wave propagates forward, as shown in the ion phase-space plots in Fig. 2, and it breaks from $t \approx 21.82$ at nearly $x = 40c/\omega_0$. After that, one EM soliton begins to form at the breaking position, and grows with time and saturates at $t \approx 252.94$ with maximum EM energy density $E_y^2 + B_z^2 \approx 2.5$ without changing its position. While the soliton is growing, a large part of the electrons and ions inside are pushed away from the high EM field region by ponderomotive force. At the right edge of soliton $x \approx 40c/\omega_0$, because of large ion inertia, ions pile up and one sharp ion density peak is formed. Electrons do not pile up to form an electron density peak at the right and left edge of the soliton, because of small electron inertia. Therefore, at a narrow region around the soliton right edge $x \approx 40c/\omega_0$, a net positive charge region then forms such as the $(n_{\mathrm{i}} - n_{\mathrm{e}})/n_0$ plot shown in Fig. 2. Behind the ion density peak, namely inside the soliton, to keep the electrical neutralitzation, more electrons are accelerated to close the ion density peak by the electric field of charge separation (Coulomb force), and a net negative charge region is then formed. This charge distribution can result in an ES field structure such as the ES field E_x plot shown in Fig. 2. Both the large amplitude EM soliton and the formed E_x interplay and they together accelerate or decelerate ions: ions with a negative velocity inside the soliton or those which are reflected by a sharp ion density peak will first experience a deceleration process and are then accelerated again by the EM soliton and ES field; ions with positive velocity, experience the reverse processes. As a result, as shown in Fig. 2, at $t = 214.18$, a trapped ion-vortex structure in phase space, which is like a two-stream instability, can be formed.

The sheath ES fields will form at both boundaries when the laser pulse is propagating in plasma. Near the sheath ES fields, ions will leave from the boundaries,

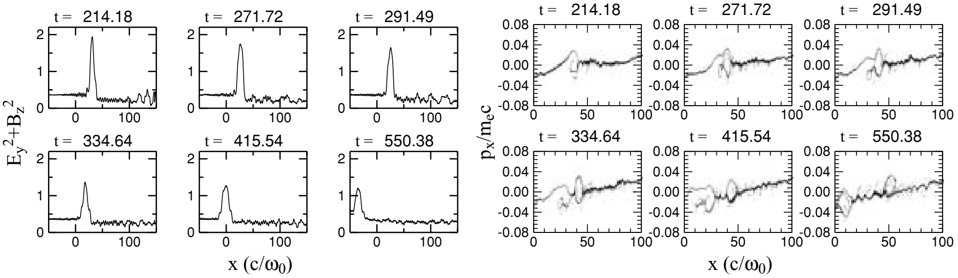

Figure 3. Energy density of EM field and ion phase-space snapshots.

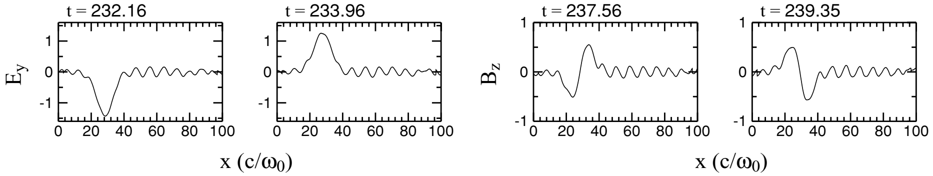

Figure 4. The plots for electric field E_y and magnetic field B_z.

and electrons then follow in order to keep electrical neutralization. As a result, the plasma density decreases from the middle part to the front and rear boundaries gradually with time. The formed soliton will be accelerated with an acceleration proportional to the gradient of plasma density towards the low-density side (Sentoku et al. 1999). The large-amplitude soliton is formed in the front region of the plasma on the side which the laser enters, therefore it is accelerated backwards to the boundary. As it is propagating backwards, by large EM field and large charge separation ES field inside soliton, the continuous energy exchange between ions and soliton will take place. A large part of the ions are accelerated and trapped inside the soliton, in the path of soliton acceleration, and several trapped ion vortices then form and persist with time (see Fig. 3). The EM soliton loses its energy due to its continuous energy exchange with ions, and its amplitude become weaker and weaker. When the soliton arrives at the plasma boundary or disappears in the plasma, the corresponding ion acceleration and trapping will finish; after that, the formation of new ion vortices stops, are these formed ion vortices will blur and become hard to see with time, and they will eventually disappear inside the plasma due to ion vortices losing their energy to the bulk plasma.

The size of vortices is approximately equal to the size of the soliton, i.e. $\Delta x_{\text{vortex}} \approx \Delta x_{\text{soliton}} \approx 1 \sim 2\lambda_{\text{pe}}$. Its transverse electric field E_y has half-cycle structure, while the corresponding magnetic field B_z has one-cycle structure (Fig. 4). The spatial EM structure is oscillatory in time.

4. Conclusions

The novel T-SEAWS instability induced by a linearly polarized intense laser interacting with a plasma layer at a subcritical density range has been studied by particle simulation. It takes place whether the ion dynamics are taken into account or not and its spectrum in the early stage is well-explained by a resonant three-wave parametric decay process. When the ion dynamics are considered, the excitation of the ion ES wave and the generation of solitons and ion vortices, etc., are observed. This occurs not only in homogeneous plasmas, but also in inhomogeneous plasmas, and all of the same physics behaviors can be observed; we will report our results in future publications.

We predict that the same story will be taken place in two-dimensional simulations, however, this needs to be proved by future simulations.

Acknowledgements

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