RELATIVISTIC ELECTROMAGNETIC SOLITON AND ION VORTICES IN INTENSE LASER INTERACTION WITH SUBCRITICAL PLASMAS

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In the past years, much work has been put into the studies of stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), because they can produce energetic particles that preheat the core of a fusion pellet. Recently, the stimulated electron acoustic wave scattering (SEAWS) was reported in experiments [1] and was also exposed by particle-in-cell (PIC) simulations in subcritical plasmas [2,3]. In addition to the high-frequency electron plasma wave (EPW), the low-frequency electron acoustic wave (EAW) whose frequency and phase velocity are between an ion acoustic wave (IAW) and an EPW, were noted by previous authors [4]. Recently, the excitation of EAW and its stability against decay have investigated by PIC simulation, and it is found that an EAW is a nonlinear wave and its excitation process must create the trapped particle population [5]. In this paper, we study the stimulated trapped EAW scattering (T-SEAWS) instability at a subcritical density range which are overdense for SRS by PIC simulation, it is found that the T-SEAWS instability appears and its early physical behavior is almost the same whether the ion dynamics is taken into account or not. However, when the ion dynamics are considered, the generation of the IAW, the electromagnetic (EM) soliton and the ion vortices in ion phase-space are studied.

Simulation model

One-dimensional relativistic EM PIC simulation code was used. The $100\, c/\omega_0$ long plasma layer put at region of $x=0-100\, c/\omega_0$, two vacuum and damping regions are used at both sides, where c and ω_0 are the light speed and frequency of laser. Electron and ion temperature are $T_e = 5T_i = 1keV$ with mass ratio $m_i/m_e = 1836$. Laser pulse which linearly polarized in y-direction is launched at $x = -50c/\omega_0$. The time, electric and magnetic field are normalized to $2\pi/\omega_0$, $m_e\omega_0 c/e$ and $m_e\omega_0/e$, respectively; when laser pulse arrives at the vacuum–plasma boundary, $\omega_0 t = 0.0$. The ES field E_x is averaged over the electron plasma wavelength, while the EM field E_y, B_z and $E_y^2 + B_z^2$ are averaged over the laser wavelength. In all our simulations,

plasma density is taken at the subcritical density range ($0.25n_c < n/\gamma < n_c$, γ is relativistic factor, n_c is critical density), in the case the standard SRS is excluded.

Simulation results

When intense laser enters the subcritical density plasma, with time goes on, an EAW is excited. As shown in figure 1, a large number of electrons are trapped in the tough of EAW, so we put a word 'trapped' before EAW, i.e.,'T-EAW'. Because of the strong electron trapping, the initial Maxwellian distribution then deforms into "water-bag" like distribution and generates highly energetic

Figure 1. snapshots for phasespace and velocicy distribution in the case of $n = 0.6n_c$ and $a = 0.6$, respectively.

electrons with the main contribution near the phase velocity of the EAW, the Landau damping of EAW therefore stops, so the excited EAW then grows and saturates with time. Like the SRS, we found when the normalized laser amplitude $a > 0.4$ the T-SEAWS instability takes place. In a linear stage, as shown in Figure 2, its spectrum is well explained by a resonant three-wave parametric decay of an intense laser pump into the slow backscattered Stokes EM sideband and the T-EAW. The frequency of the backscattered Stokes EM wave in the vacuum region is $\omega_s = 0.62\omega_0 \approx \omega_{pe}/\gamma^{1/2}$, which nearly equals the relativistic electron plasma frequency, while the corresponding EAW is $\omega_{eaw} = 0.40\omega_0 < \omega_{pe}$. The corresponding wave numbers all measured inside plasma are $k_s^p = 0.12k_0$, $k_0^p = 0.80k_0$ and $k_{eaw} = 0.92k_0$, respectively, here $k_0 = \omega_0/c$ is the wave number of laser in vacuum. In the early T-SEAWS instability, the matching conditions for

both the frequency $\omega_0 = \omega_s + \omega_{eaw}$ and the wave number $k_0^p = -k_s^p + k_{eaw}$ appear to be satisfied perfectly. It is easy to obtain the phase velocity of EAW, $v_{eaw}^{ph} = \omega_{eaw}/k_{eaw} = 0.43c$, which just locates in the platform of water-bag distribution.

Figure 2. Frequency spectrum of backscttered EM wave and ES field E_x, and wavenumbers of E_x and E_y inside plasma, respectively.

We found the T-SEAWS instability appears and its early physical behavior is almost the same whether the ion dynamics is taken into account or not. However, if the ion dynamics is considered, an IAW mode with frequency $\omega_{IAW} = 0.023\omega_0 \approx \omega_{pi}$, which approximately equals the natural ion plasma frequency,
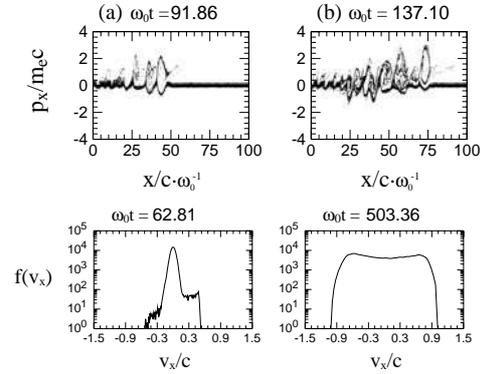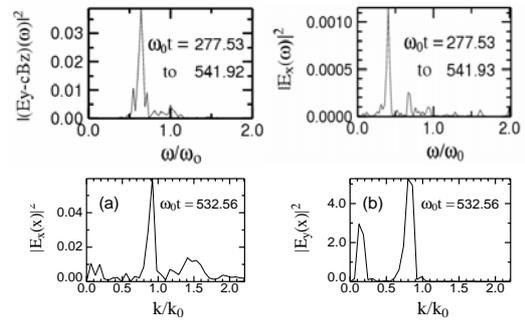
can be excited at an early stage and persist with a time. The excited IAW propagates forward, as time goes on, at later time $\omega_0 t = 137.10$, ion orbits begin to overturn, close to $x \approx 40\omega_0 / c$ point, while the steep IAW density shock-like wave front breaks. After that, by EM energy localization in the density cavity, one EM soliton is nucleated at the same position and continues to grow in time to saturate at $\omega_0 t \approx 1589.27$ with its maximum EM energy $E_y^2 + B_z^2 \approx 2.5$. During its growth, first, a large number of electrons are expelled from the high EM field region by the relativistic ponderomotive force. At about $\omega_0 t \approx 1345.73$, because of large inertia, slow ions pile up at the front of the soliton $x \approx 40\omega_0 / c$, one sharp ion density peak is formed. Simultaneously, electrons do not accumulate at the front and rear sides, because of their small inertia. Then, as in the figure 3 shows, at the narrow region around the soliton front edge $x \approx 40\omega_0 / c$, a net positive charge forms. Behind the ion density peak, namely inside the soliton region, to preserve the charge neutrality, more electrons will be pushed away to balance the ion density peak by the charge separation ES field. Thus, a net negative charge region forms. This charge distribution results in a double layer structure, as the ES field E_x plot shows. Both the EM soliton field and the local large E_x sheath field via interplay can strongly accelerate or decelerate ions. Ions with initial negative velocity inside the soliton or reflected by a sharp ion density peak, they will first experience a deceleration process and then accelerate again. While ions with positive velocity experience just the reverse processes. As a result, at $\omega_0 t \approx 1345.73$, as the ion phase-space plot shows in figure 3, eventually a trapped ion-vortex (ion-hole) structure is formed.
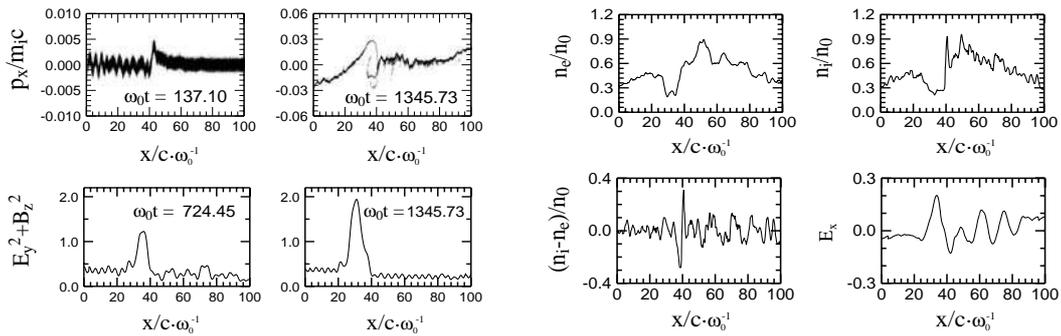

Figure 3. Snapshots for ion phase space, energy density of the EM field $E_y^2 + B_z^2$, plasma density and ES field E_x in the case of $n = 0.6 n_c$ and $a = 0.6$, respectively.

In figure 4, we plotted the time-integrated reflectivity and transmissivity of laser pulse for two simulation models. In the case of $n = 0.6 n_{cr}$ and $a = 0.6$, there is only about 55% of laser pulse energy transmitted within 500 laser periods while propagating through the 100 c / ω_0 thick uniform plasma layer, while, in the case of $n = 0.7 n_{cr}$ and $a = 0.8$, the corresponding

transmissivity is about 60%. It should be noted that a large part of laser pulse energy is reflected and absorbed by the plasma layer.

The detailed physical mechanism of the ion vortex formation is a beautiful paradigm of a complex interplay among nonlinear interactions at micro (kinetic) and macro (EM-fluid) scales of both electron and ion plasma components resulting in self-organization into large ordered localized coherent structures. From the topological viewpoint, discontinuities of two types: shock

Figure 4. Refectivity and transmissivity of the EM wave measured in vacuum region.

waves and tangential discontinuities are often found in dynamical systems. In the Kelvin-Helmholtz (K-H) instability pattern, if the wave scroll curve exhibits double tangency, the pattern is named after Ying-Yang pattern [6]. It appears that ion-vortex can be classified as the K-H patterns, likely formed due to a topological defect, i.e., density cavity in the soliton, while the early ion-vortex structure nicely reminds of the well-known Ying-Yang pattern.

In conclusion, the T-SEAWS instability at a subcritical density range which are overdense for SRS is studied by 1D-PIC particle simulation, it is found that it takes place whether the ion dynamics is taken into account or not. However, when the ion dynamics is considered, the generation of the IAW, the EM soliton and the ion-vortex were observed; such behaviors were also found in inhomogeneous subcritical plasma. From topological viewpoint, ion-vortex should belong to the well-known Ying-Yang pattern in the generic K-H instability pattern.

References

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[6] R. M. Kiehn, *Instabilty Patterns, Wakes and Topological Limit Sets*, IUTAM Conference Proceedings, Poitier, France, October 1992, published in J. P. Bonnet and M. N. Glauser, (eds) *Eddy Structure Identification in Free Turbulent Sh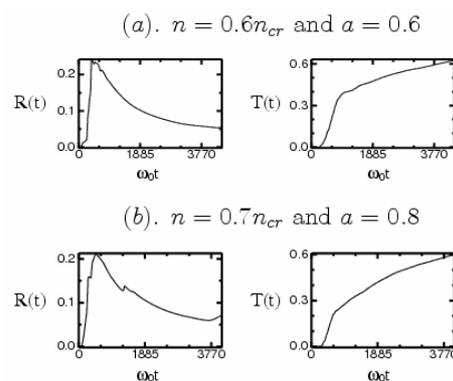ear Flows* (Kluwer Academic Publishers, 1993), p. 363.