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Intense Reflection of a Relativistic Laser Pulse in Subcritical Plasmas

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Abstract

Interaction of relativistic electromagnetic (EM) (laser) pulse with plasmas has been investigated by means of electromagnetic particle-in-cell simulations. When a relativistic laser pulse, stronger than a critical intensity, is injected into a uniform plasma of sub-critical density ($n_c/4 < n_0/\gamma < n_c$), strong reflection is observed. The frequency of the back-scattered wave is near the effective electron plasma frequency which is well below its unperturbed value. This novel stimulated scattering instability is recognized as a three-wave parametric resonance decay of the incident wave into an electron-acoustic wave (EAW) ($\omega \ll \omega_p$) and a scattered EM Stokes sideband. The slow Stokes lightwave gradually builds up to eventually propagate through the plasma-vacuum interface in a form of short superintense reflectivity bursts of coherent low-frequency EM radiation.

Keywords:

laser plasma interaction, particle simulation, electron acoustic wave, stimulated scattering

1. Introduction

Interaction of strong electromagnetic (EM) waves with an underdense plasma now casts challenging issues in a variety of fields of plasma science [1]. In particular, stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) have been intensively investigated, since these instabilities can reflect laser energy and preheat a target in inertial fusion experiments. Recently, by means of particle simulations, it was found that the strong scattering of laser light from a plasma layer of subcritical density ($n_c/4 < n/\gamma < n_c$); where γ is the relativistic factor [2,3]. Intense coherent reflectivity pulsations at frequencies below the electron plasma frequency were observed in regions which were overdense for standard SRS. The spectrum has been explained by a resonant three-wave parametric decay of the relativistic laser pump into the slowed Stokes light sideband and the trapped electron-acoustic wave. The electron-acoustic-wave scattering had been proposed by Montgomery *et al.* [4,5] to reinterpret underdense plasma data from the Trident laser facility. It was shown that stimulated scattering associated with the trapped electron-acoustic wave (SEAS) [4,6] can possibly explain anomalous backscatter data which was previously attributed to stimulated Raman back-scattering from unrealistically low plasma density. At large amplitudes, electron trapping can support undamped traveling modes (BGK-alike) or with a small dissipation, weakly damped traveling solutions, while, in Maxwellian plasmas, slow linear electron-acoustic mode is strongly Landau damped. The SEAS to SRS signal ratio was smaller than 10^{-3} in the experiment. On the contrary, the simulation reported strong SEAS which dominates over stimulated Raman backward scattering (B-SRS). A SEAS model as a resonant parametric coupling of three waves [2] has been proposed under a weakly varying envelope approximation [7,8]. The backscattered wave is driven near critical region, i.e., $\omega_s \approx \omega_p$, which implies $k_s \approx 0$ and $V_s \approx 0$. Here k_s and V_s are the wave number and the group velocity of the scattered wave, respectively. The backscattered wave, therefore, is a slowly propagating electromagnetic wave such that the frequency and wave number of EAW match a three-wave resonance, as $\omega_a = \omega_0 - \omega_s \approx \omega_0 - \omega_p$ and $k_a = k_0 - k_s \approx k_0$.

In this paper, we show detailed temporal evolutions of interaction of laser with a subcritical plasma in order to clarify the SEA scattering.

2. Stimulated electron acoustic scattering

In this section, we describe one spatial dimension and three velocity dimension relativistic electromagnetic particle-in-cell simulation. Initially uniform plasma layer with length

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l is placed in the center of the simulation system. The plasma layer is surrounded by vacuum region. The linearly polarized laser with electric field along y-axis propagates along x-axis from the left hand side of the plasma layer. Damping region for EM wave and electrons is placed in each boundary. Ions are immobile and are initially placed so as to satisfy charge neutrality condition everywhere. The number of grids is 25 per c/ω_0 and more than 50 particles per one grid cell are used, where c and ω_0 are the speed of light and the laser frequency, respectively.

In Fig. 1, the temporal evolution of reflectivity is shown. Here, the plasma length $l = 50\ c/\omega_0$, the plasma density $n = 0.7\ n_{cr}$, the electron temperature $T_e = 500$ eV, the laser strength $\beta_0 = (eE_0)/(mc\omega_0) = 0.5$, where $n_{cr} = n(\omega_0/\omega_p)^2$ is the critical density. We can observe strong reflection around $\omega_0 t = 350$. The reflectivity reaches 0.8. In order to see the physical feature of this process, we show the temporal evolution of EM and ES fields in Fig. 2 and electron x vs. v_x phase space distribution in Fig. 3. The electrostatic wave is growing in the whole of the plasma layer at $\omega_0 t = 125$. This is accompanied by strong acceleration of electrons up to $\approx 0.3\ c$. Further growth of this ES wave brings even the bulk electrons into resonance with its phase velocity ($\omega_0 t = 125$). At $\omega_0 t = 161$, numerous electrons are trapped in the potential well of the ES wave. At the same time, a strong EM wave is superimposed to the incident laser. As a result, the total EM field strength exceeds $\beta \approx 1.45$. It is interestingly observed that the wave number k_a of the ES wave is nearly equal to the wave number k_0 of the laser wave. This is consistent with the above mentioned three wave scattering model. From $\omega_0 t = 125$ to 286 the slow EM wave gradually builds up, approaching the left-hand side of the plasma layer. This developed EM wave propagates out through the plasma-vacuum interface from $\omega_0 t = 313$ to $\omega_0 t = 403$. In this process, the plasma electrons are strongly accelerated and are heated to relativistic energies.

Figure 4 shows reflected EM spectrum in the left hand side and passing EM spectrum in the right hand side of the plasma layer for the two time intervals, $\omega_0 t = 89$–677 and $\omega_0 t = 527$–1125. The spectra are taken in the vacuum regions at distance 25 c/ω_0 from the plasma-vacuum interfaces. It is seen that the main contribution to the scattered waves is the backscattered Stokes wave near $\omega/\omega_0 \approx 0.7$. In the forward direction, a broad spectrum of the Stokes and anti-Stokes waves is seen. During the later time period ($\omega_0 t = 527$–1125) these Stokes and anti-Stokes waves become well defined

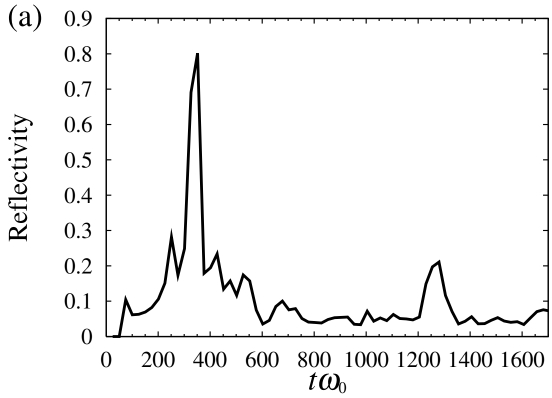

Fig. 1 Reflectivity in time for the case with $n = 0.7\ n_{cr}$, $l = 50\ c/\omega_0$, $T = 500$ eV and $\beta = 0.5$. Reflectivity and transmissivity are averaged over four periods of the incident wave.

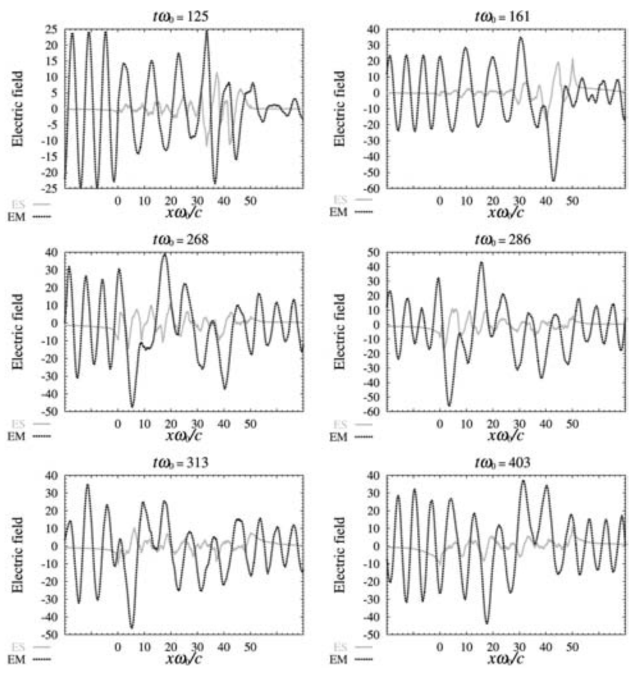

Fig. 2 Profiles of EM and ES fields from $\omega_0 t = 27$ to 403 for the case with $n = 0.7\ n_{cr}$, $l = 50\ c/\omega_0$, $T = 500$ eV and $\beta = 0.5$.

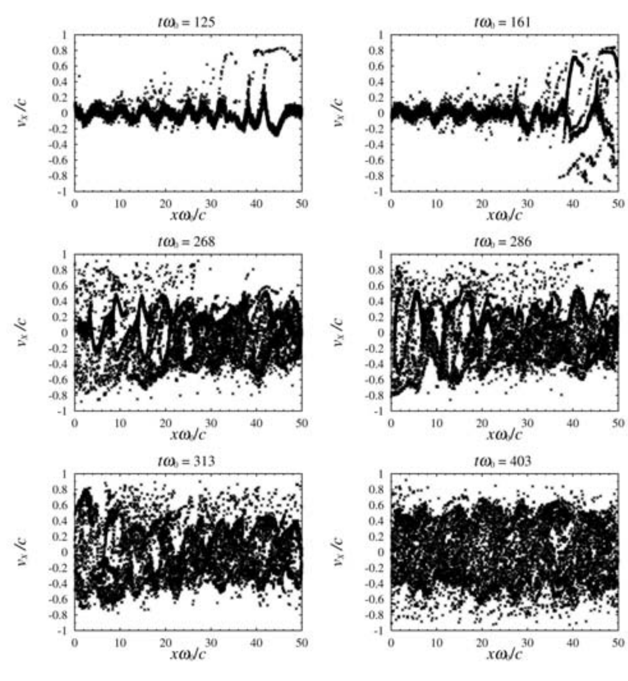

Fig. 3 Phase space plot from $\omega_0 t = 27$ to 403 for the case with $n = 0.7\ n_{cr}$, $l = 50\ c/\omega_0$, $T = 500$ eV and $\beta = 0.5$.

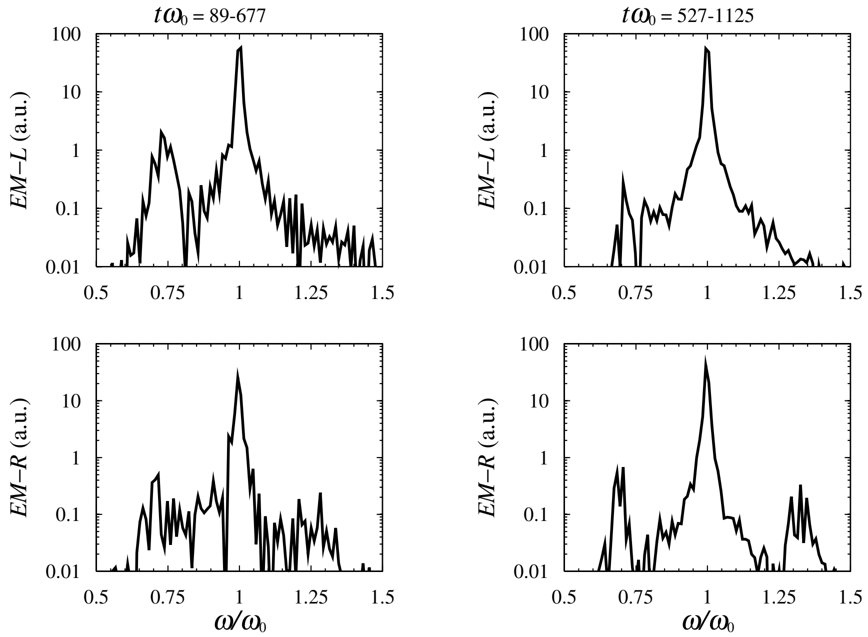

Fig. 4 Spectra of electromagnetic wave in front (EM-L) and behind (EM-R) the plasma layer for the two time intervals, $\omega_0 t$ = 89 – 677 and $\omega_0 t$ = 527 – 1125 for the case with n = 0.7 n_{cr}, l = 50 c/ω_0, T = 500 eV and β = 0.5.

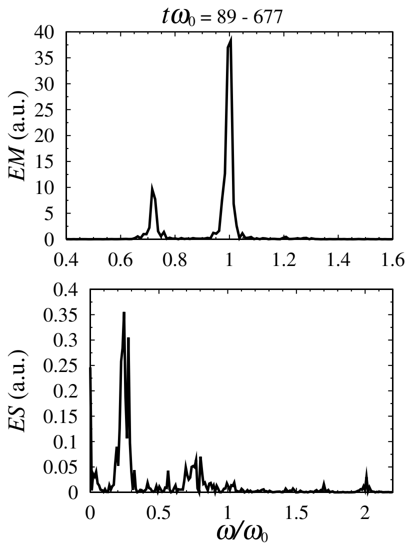

Fig. 5 Spectra of electromagnetic and electrostatic fields in the plasma layer for the time interval $\omega_0 t$ = 89 – 677 for the case with n = 0.7 n_{cr}, l = 50 c/ω_0, T = 500 eV and β = 0.5. The spectra are taken at 25 c/ω_0 from the front end of the plasma layer.

around frequency which is previously determined by the frequency of the backscattered Stokes wave, i.e. $\omega/\omega_0 \approx$ 0.7. The contribution of the backscattered waves in this time domain is lower, which is consistent with evolutions of the reflectivity.

Figure 5 shows the spectra of EM and ES waves in the plasma layer for the time interval $\omega_0 t$ = 89 – 677. The spectra are taken at 25 c/ω_0 from the left hand side boundary of the plasma layer. Here, the plasma frequency of the plasma layer is $\omega_p/\omega_0 \approx 0.84$. As is known, the presence of large amplitude waves in a plasma shifts the plasma frequency to the lower one. One can see that there are three main waves associated with SEAS instability: the laser wave ($\omega/\omega_0 \approx 1$), a Stokes EM wave at the (effective) plasma frequency $\omega_s/\omega_0 \approx 0.7$ and an ES wave with a frequency below the plasma frequency $\omega_a/\omega_0 \approx 0.3$ (electron acoustic wave). It should be noted that the electron plasma (Langmuir) wave does not play a significant role in the instability as well as 2nd ES harmonic ($\omega/\omega_0 = 2$). We also note that the anti-Stokes wave is much lower than the Stokes wave. Further, we note that the laser, scattered and electron acoustic waves well satisfy the frequency matching condition, $\omega_0 = \omega_s + \omega_a$. These results clearly show that in the process of the instability, a fraction of the laser light is converted to a scattered light and an electron acoustic wave.

Similar EM and ES spectra accompanied by the SEAS instability in plasmas that are overdense for the SRS instability are observed in a large number of simulations.

3. Summary

We have investigated the stimulated scattering of laser light in subcritical plasmas by means of 1D3V electromagnetic relativistic PIC simulation code. When a relativistic laser wave is injected into a uniform plasma, strong reflection is observed. The frequency of the back-scattered wave is near the effective electron frequency. This stimulated scattering instability is recognized as a three wave parametric resonant decay of the incident wave into an electron acoustic wave and a scattered EM Stokes sideband. It is clearly shown that the Stokes lightwave gradually builds up to eventually propagate through the plasma-vacuum interface in a form of short superintense reflectivity bursts of coherent low-frequency EM radiation. The spectrum observed in the simulation and the feature of time development of EM wave are quite consistent with the explanation based on the three wave interaction model ([2,3]).

Acknowledgments

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References

[1] W.L. Kruer, Phys. Plasmas **7**, 2270 (2000).
[2] Lj. Nikolić, M.M. Škorić, S. Ishiguro and T. Sato, Phys. Rev. E **66**, 036404-1, (2002).
[3] Lj. Nikolić, M.M. Škorić, S. Ishiguro and T. Sato, Fusion Sci. Tech. **43**, 359 (2003).
[4] D.S. Montgomery *et al.*, Phys. Rev. Lett. **87**, 155001 (2001).
[5] D.S. Montgomery *et al.*, Phys. Plasmas **9**, 2311 (2002).
[6] H.A. Rose and D.A. Russell, Phys. Plasmas **8**, 4784 (2001).
[7] R.W. Harvey and G. Schmidt, Phys. Fluids **18**, 1395 (1975).
[8] D.W. Forslund *et al.*, Phys. Fluids **18**, 1002 (1975).