Bursting behaviours in cascaded stimulated Brillouin scattering*

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Stimulated Brillouin scattering is studied by numerically solving the Vlasov–Maxwell system. A cascade of stimulated Brillouin scattering can occur when a linearly polarized laser pulse propagates in a plasma. It is found that a stimulated Brillouin scattering cascade can reduce the scattering and increase the transmission of light, as well as introduce a bursting behaviour in the evolution of the laser-plasma interaction. The bursting time in the reflectivity is found to be less than half the ion acoustic period. The ion temperature can affect the stimulated Brillouin scattering cascade, which can repeat several times at low ion temperatures and can be completely eliminated at high ion temperatures. For stimulated Brillouin scattering saturation, higher-harmonic generation and wave–wave interaction of the excited ion acoustic waves can restrict the amplitude of the latter. In addition, stimulated Brillouin scattering cascade can restrict the amplitude of the scattered light.

Keywords: bursting behaviour, stimulated Brillouin scattering, cascade

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1. Introduction

Many instabilities, such as stimulated Brillouin scattering (SBS), can be excited when an intense laser propagates in a plasma. In SBS, the incident light wave decays into a scattered light wave and an ion acoustic wave (IAW).[1] Since SBS can be detrimental to inertial confinement fusion, it has been intensively studied.[2−7] In addition, many methods of reducing or eliminating SBS have been proposed, including smoothing the laser and increasing the Landau damping of the ion acoustic waves. Doping a low-Z material into the high-Z plasma can increase the Landau damping, because the thermal velocity of the low-Z plasma is near the IAW phase velocity of the high-Z plasma. Two-ion species plasmas are also useful for plasma diagnostics.[3] Therefore, IAWs in multi-ion plasmas have been widely investigated.[8−11] When the ion temperature is much lower than the electron temperature, strong SBS can take place since the IAW Landau damping is small. However, if the scattered light is sufficiently intense, it can also induce SBS, so that SBS cascade can emerge. Using one-dimensional Vlasov–Maxwell simulation,[12−14] in this study, we will consider SBS in a mixed carbon–hydrogen plasma. We find that SBS cascade can reduce the scattering level. The evolution of the reflectivity also exhibits a bursting behaviour, and the burst period can be much shorter than the IAW period. The SBS cascade appears only when the ion-to-electron temperature ratio is low. When the ratio approaches unity, the cascade is suppressed, and the fast and the slow IAW scatterings can be clearly distinguished. The SBS cascade causes the bursting behaviour in the reflectivity and also saturates the SBS. That is, SBS cascade can restrict the amplitude of scattered light and further cascade. In addition, higher-harmonic generation and three-IAW wave decay can restrict the amplitude of the SBS excited IAW.

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2. Physical model and simulation parameters

A Vlasov–Maxwell numerical simulation code is used. The physical model of the laser-plasma interaction is the same as that in Refs. [12] and [14]. The laser is incident on the plasma from the left. The electron density of underdense plasma is $0.3n_{\rm c}$, where $n_{\rm c} = m_{\rm e}\omega_{\rm L}^2/4\pi e^2$ is the critical density, with e and $m_{\rm e}$ being the electron charge and rest mass, respectively, and $\omega_{\rm L}$ and $\lambda_{\rm L} = 0.351$ μm being the frequency and the wavelength of the laser light respectively. The length of the simulation box is $935\lambda_{\rm L}$, and the plasma is $571\lambda_{\rm L}$ long and it is located in the centre of the box. The electron temperature is 5 keV, and the carbon and the hydrogen ion temperatures are both 0.5 keV. The carbon-to-hydrogen ion number density ratio is 1 : 6. Krook collisions are introduced at the plasma boundaries in order to absorb the fast IAWs there and suppress other boundary effects. The laser intensity is 10^{16} W/cm^2, corresponding to the laser parameter $a = eE/m_{\rm e}\omega_{\rm L}c = 0.03$, where E is the electric field and c is the light speed in vacuum.

3. Simulation results and discussion

The time dependence of the reflectivity is shown in Fig. 1. The averaged reflectivity is about 82%, as shown in the top panel of Fig. 1(a). The high reflectivity is caused mainly by the low ion temperature. The reflectivity shows a bursting behaviour. The bursting time is about $700T_{\rm L}$, for $t < 11000T_{\rm L}$, where $T_{\rm L}$ is the laser period. While it is less than $100T_{\rm L}$ for $t > 11000T_{\rm L}$, the two stages are quite different. For $t < 11000T_{\rm L}$, the bursting behaviour can be explained as the reduction of Landau damping and the frequency shift of ion acoustic wave.[15] The reduction of Landau damping increases the reflectivity of SBS, while the frequency shift reduces the reflectivity, so the reflectivity is oscillatory with the descending amplitude during $1500T_{\rm L} < t < 8000T_{\rm L}$. Increasing the ion temperature to 0.75 keV, the reflectivity tends to a steady state during $3000T_{\rm L} < t < 8000T_{\rm L}$ as shown in the bottom panel of Fig. 1(a).

The growth rates obtained from analysing the slopes of the reflectivity are shown in Fig. 1(b). From the corresponding theory of three-wave interaction, the nonlinear dispersion relation for SBS is[16,17]

$$\frac{1}{\chi_{\rm e}(\omega,k)} + \frac{1}{1+\sum\chi_{\rm i}(\omega,k)} = \frac{k^2 v_{\rm os}^2}{4}\left[\frac{1}{D\left(\omega-\omega_{\rm L},k-k_{\rm L}\right)} + \frac{1}{D\left(\omega+\omega_{\rm L},k+k_{\rm L}\right)}\right], \quad (1)$$

where the growth rate γ is the imaginary part of the frequency ω, $k_{\rm L}$ is the wavenumber of the incident light, $v_{\rm os}$ is the quiver velocity of an electron in the pump field, $D(\omega,k) = -\omega^2+k^2c^2+\omega_{\rm pe}^2$, $\omega_{\rm pe}$ is the electron plasma frequency, and $\chi_{\rm e}$ and $\chi_{\rm i}$ are the electron and the ion susceptibilities, respectively. The growth rate from Eq. (1) is smaller than the simulation result. A discrepancy between the result from numerical simulation and that from the SBS theory based on three-wave parametric coupling has also been noted in earlier investigations.[18–20] In Fig. 1(a), one can also see that at large time ($t > 11000T_{\rm L}$), the reflectivity exhibits a burst behaviour, which can be attributed to the SBS cascade.[21]

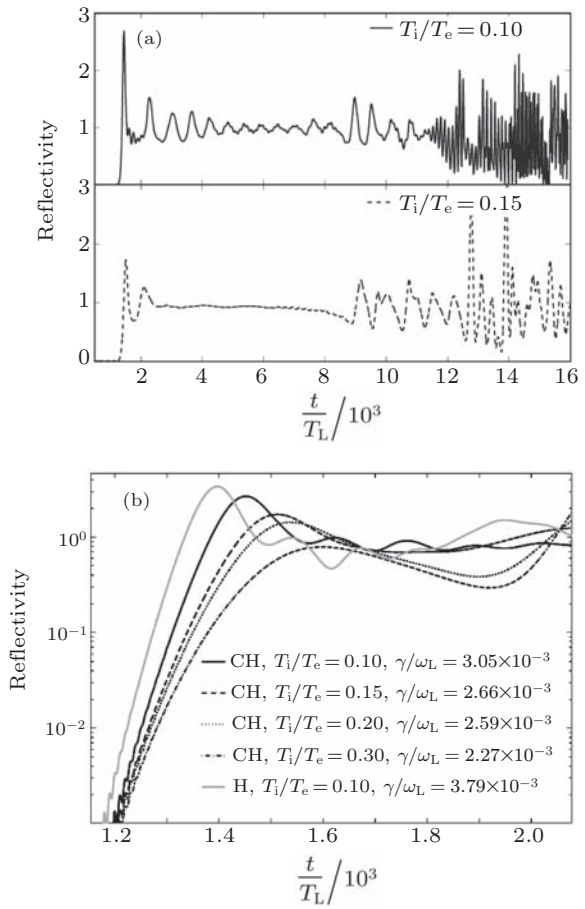


Fig. 1. (a) Time dependences of reflectivity for different ion temperatures in carbon–hydrogen plasma, (b) the linear growth rates for different cases. Here, $T_{\rm L}$ is the laser period, $T_{\rm i}$ and $T_{\rm e}$ are the ion and the electron temperatures, γ is the linear growth rate, and $\omega_{\rm L}$ is the incident laser angular frequency.

The spatiotemporal evolution of the electrostatic field is shown in Fig. 2, from which we can obtain the phase velocity of the IAW. The slopes of the iso-phase curves for $x > 220\lambda_{\rm L}$ and $t < 6000T_{\rm L}$ are all $2.3\times10^{-3}c$, which corresponds to the phase velocity of the fast IAW. For the Maxwellian distribution, the fast and the slow IAW frequencies are $3.87\times10^{-3}\omega_{\rm L}$ and $1.10\times10^{-3}\omega_{\rm L}$, and the damping rates are $0.2\times10^{-3}\omega_{\rm L}$ and $0.36\times10^{-3}\omega_{\rm L}$, respectively. For $t > 11000T_{\rm L}$, one can see a backward propagating IAW (leading to cross-hatching of the iso-phase curves in the figure). This IAW, which propagates in a direction opposite to that of the primary IAW, can be attributed to the fact that when the SBS backscattered light is sufficiently strong, the latter can also encounter SBS and excite an IAW. The IAW phase velocity changes, and the structure of electrostatic fields splits at $x = 215\lambda_{\rm L}$ and $t = 7000T_{\rm L}$, as can be seen in Fig. 2. However, if the IAW is of large amplitude before that occurs, higher harmonics can be generated. Higher harmonic generation is also a saturation mechanism of the SBS.[11] The density perturbation associated with the second harmonic is[22]

$$\frac{\delta n(2k_{\rm a})}{n_{\rm i}} = \frac{1}{2}\frac{[\delta n(k_{\rm a})/n_{\rm i}]^2}{1/(1+k_{\rm a}^2\lambda_{\rm d}^2) - 1/(1+4k_{\rm a}^2\lambda_{\rm d}^2)}, \quad (2)$$

where $n_{\rm i}$ is the hydrogen ion density, $k_{\rm a}$ is the IAW wavenumber, and $\lambda_{\rm d}$ is the Debye length. Fourier analysis of the hydrogen density from the simulation results yields the ratio $\delta n(k_{\rm a}) : \delta n(2k_{\rm a}) : \delta n(3k_{\rm a}) = 10 : 2 : 1$ for the density perturbations of the harmonics. Fourier analysis of the electrostatic field fluctuations at the location of maximum intensity yields the IAW frequency $3.83\times10^{-3}\omega_{\rm L}$, which accords well with that of the theory.

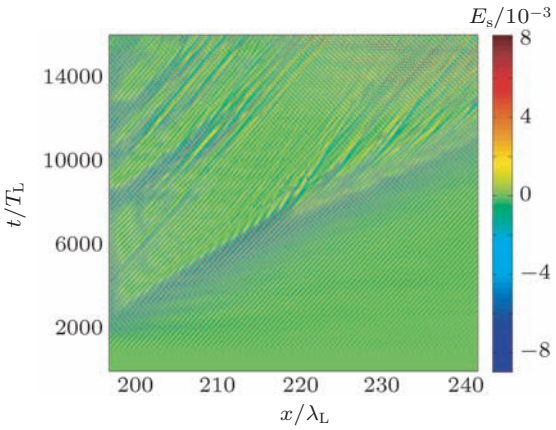


Fig. 2. (colour online) Evolution of the electrostatic field $E_{\rm s}$, where $\lambda_{\rm L}$ is the laser wavelength in vacuum. The backward propagating IAW perturbations can be seen at larger time, especially in the upper right-hand quadrant of the figure.

Figure 3 is for the spectra of the reflected and the transmitted light, showing the emergence of SBS cascade. For $t < 11000T_{\rm L}$, the reflected light is due mainly to SBS by the fast IAW (the slow-IAW scattered light is not evident). For $t > 11000T_{\rm L}$, the scattered-light spectrum exhibits several peaks. The two neighbouring peaks have a $2\omega_{\rm a}$ frequency difference, where the fast-IAW frequency is $\omega_{\rm a} \sim 3.87\times10^{-3}\omega_{\rm L}$. The transmitted-light spectrum also exhibits the SBS cascade, so that both Stokes and anti-Stokes waves exist.

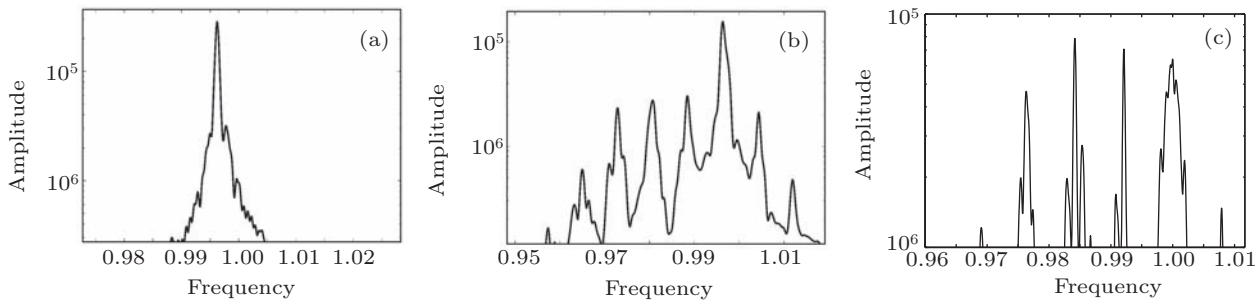


Fig. 3. Time integrated spectra of the (a) reflected light for $t < 11000T_{\rm L}$, (b) reflected-light for $t > 11000T_{\rm L}$, and (c) transmitted light. The frequency is normalized by $\omega_{\rm L}$.

The hydrogen ions can be trapped by both the forward and the backward propagating SBS-excited IAWs if the latter has a sufficiently large amplitude as shown in Fig. 4. Ion trapping can reduce Landau damping of the IAW.[23] Because of weaker Landau damping of the backward IAW, the cascade behaviour becomes clearly observable for $t > 11000T_{\rm L}$, when trapping of hydrogen ions in the latter occurs.

On the other hand, the heavy carbon ions are not trapped since their thermal speeds are much less than the IAW phase speed.

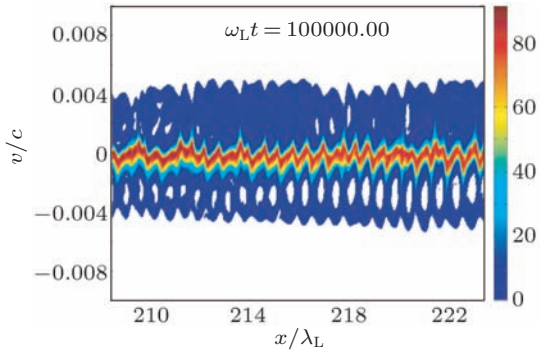


Fig. 4. (colour online) Distribution function of the hydrogen ions, x is in units of λ_L and v is in units of light speed c.

Since Landau damping can suppress the SBS cascade, we also carry out simulations for different ion temperatures, ion-species contents, and laser intensities. It is found (not shown) that cascade behaviour can appear in a pure hydrogen plasma with $T_i/T_e = 0.1$, carbon and hydrogen plasma with $T_i/T_e = 0.2$, helium and hydrogen plasma with $T_i/T_e = 0.2$, and at lower laser intensities ($a = 0.02$) for $t > 54000T_L$, etc. In all these cases the bursting period is less than the IAW period. However, the cascade can be completely suppressed at sufficiently high ion temperatures by strong Landau damping.

4. Conclusion

The SBS in a mixed carbon–hydrogen plasma is investigated using one-dimensional Vlasov–Maxwell simulation. It is found that the cascade of SBS appears if the hydrogen-ion temperature is much lower than the electron temperature. The cascade reduces the SBS scattering level, increases the maximum of the instantaneous SBS reflectivity, and shortens the bursting time to less than the IAW period. IAW harmonics are also observed. Large amplitude forward and backward propagating SBS-excited IAWs can trap hydrogen ions. Excitation of higher harmonics and three-wave decay of the excited IAWs can saturate the SBS and restrict the IAW amplitude, and SBS cascade can restrict the amplitude of the scattered light. The cascade is also responsible for the bursting behaviour in the SBS reflectivity.

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