Self-Generated Loss of Coherency in Brillouin Scattering and Reduction of Reflectivity

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Low reflectivity of stimulated Brillouin scattering is shown to result from wave-interaction incoherency caused by the ion sound-wave nonlinearity. The Brillouin reflectivity is numerically found to display a chaotic time evolution at laser fluxes below those at which ion sound-wave harmonic generation takes place. At these fluxes, the scattered light exhibits a spiky frequency spectrum. Scaling laws for the reflectivity are given.

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We investigate the reflectivity caused by stimulated Brillouin backscattering (SBS) in long–scale-length plasmas, a problem which is now of concern for laser-fusion experiments. Nonlinear theories that treat pump depletion as the unique saturation mechanism predict a negligible amount of laser light reaching the critical surface, provided that the characteristic length of the plasma exceeds a critical length[1] L_c. However, it has been pointed out by Kruer[2] that high reflectivity may give rise to a level of ion sound-wave (ISW) fluctuations $(\delta n/n)$ for which the following nonlinear kinetic effects on the ion population provide a natural mechanism for reduction of the reflectivity: Namely, there exists a substantial ion heating caused by ion trapping and ISW breaking, and the latter ion heating, in turn, reduces the reflectivity due to SBS occurring on heavily damped ion sound waves. Such nonlinear kinetic effects take place only if $\delta n/n$ exceeds the critical value $(\delta n/n)_K$ at which ISW breaking occurs because of the trapping of a large part of the cold background ions. Denoting by $(\delta n/n)_R$, the level of ISW fluctuations corresponding to a reflectivity R, one may estimate the critical flux ϕ_K above which these nonlinear kinetic effects take place by writing $(\delta n/n)_R = (\delta n/n)_K$, and, by using the conservation of fluxes, one obtains

$$\Phi_K = 55R^{-1}T_e(n/n_c)\lambda^{-2}(\delta n/n)_K^2,$$

where λ and T_e denote the laser wavelength and the electron temperature in units of micrometers and kiloelectronvolts, respectively; the subscript K stands for "kinetic," Φ_K is expressed in units of 10^{14} watts per square centimeter, and n/n_c denotes the ratio of the plasma density to the critical density. For $ZT_e/T_i \simeq 10$, $(\delta n/n)_K$ has been estimated[3] to be of the order of 0.2, so that one has $\Phi_K \simeq 2.2R^{-1}T_e(n/n_c)\lambda^{-2}$; T_i and Ze are the ion temperature and charge, respectively. We define as "strongly nonlinear" the regime $\Phi > \Phi_K$ for which the above nonlinear kinetic effects may be invoked to reduce the reflectivity.

In this Letter, we address the question of SBS in the opposite regime $\Phi < \Phi_K$, which we define as the regime of "moderate flux," where the nonlinear saturation mechanisms are necessarily of the fluid type. In this regime, the relevant experiments[4] exhibit one or several of the following characteristic behaviors: (i) a reflectivity lower than predicted by standard theory, (ii) a chaotic or burstlike SBS emission, and (iii) a large variability of the backscattered light spectrum. Fluid-type ion nonlinearity coupled with ISW harmonic generation is usually invoked[5] to explain the low reflectivity and the spectrum; the ion nonlinearity is then thought of as a mechanism for energy transfer into the dissipative domain of short wavelengths. By contrast, we show numerically that a significant reflectivity reduction follows from a loss of coherency of the SBS interaction, which in turn results from the ion nonlinearity. The central point is that the reflectivity reduction is numerically found to exist even in the absence of any wave damping and occurs at a critical threshold Φ_{inc} for the laser flux Φ corresponding to a very weak ion nonlinearity for which ISW harmonic emission is negligible; hence the reduction of the reflectivity cannot be attributed in this regime to any linear or nonlinear damping. We conclude that it is simply a direct consequence of the loss of coherency for SBS interaction and that it should be therefore decoupled from the mechanism of ISW harmonic generation.

In order to investigate the role of the ISW nonlinearity, we have studied SBS in a homogeneous plasma at rest. Our system may be described by the following set of mode-coupling equations:

$$(\partial_t + c\,\partial_x)a_0 = -\gamma_0 a_1 a_s, \tag{1a}$$

$$(\partial_t - c\,\partial_x)a_1 = \gamma_0 a_0 a_s^*, \tag{1b}$$

$$(\partial_t + C_s\,\partial_x + i\alpha|a_s|^2)a_s = \gamma_0 a_0 a_1^*, \tag{1c}$$

where a_0, a_1, and a_s respectively denote the slowly varying envelope, in dimensionless units, of the pump wave, scattered wave, and ISW. The boundary conditions are $a_0(0,t)=1$ and $a_1(L,t)=a_s(0,t)=0$, where L is the length of the plasma slab, γ_0 is the usual convective growth rate for SBS, and c and C_s are the light and sound-wave group velocities, respectively. The standard coherent mode-coupling equations are recovered with $\alpha=0$; the nonlinear frequency shift $\Delta\omega_{\rm nl}=\alpha|a_s|^2$, which accounts for the fluid-type ion nonlinearity, may be derived by using the so-called reductive method[6] applied to the Korteweg–de Vries equation for the ion sound wave. The validity domain for reducing the Korteweg–de Vries nonlinearity to a nonlinear frequency shift is given by the condition $(\delta n/n)_R << (\delta n/n)_H \equiv 3k_s^2\lambda_{\rm De}^2$, where k_s is the wave number of the ISW, $\lambda_{\rm De}$ is the Debye length, and the subscript H stands for "harmonic." If one remembers that ISW steepening and strong harmonic generation occur in the opposite case $\delta n/n >> 3k_s^2\lambda_{\rm De}^2$, one sees that the validity domain for Eqs. (1) corresponds to the regime in which harmonic generation is negligible. More precisely, in this regime, the amplitude of the first harmonic goes like the square of the fundamental so that it is small enough to be treated perturbatively and to give rise to a nonlinear frequency shift. The regime of moderate flux $(\delta n/n)_R < (\delta n/n)_K$ can therefore be subdivided into two subregimes: (i) The subregime that we define as "weakly nonlinear," where the inequality $(\delta n/n)_R < (\delta n/n)_H$ is satisfied; in this subregime, the ion nonlinearity is weak enough to be reduced to a nonlinear frequency shift, the ISW harmonic generation is negligible, and SBS is correctly described by Eqs. (1). (ii) The subregime of "intermediate nonlinearity," $(\delta n/n)_H < (\delta n/n)_R < (\delta n/n)_K$; the inequality $(\delta n/n)_H < (\delta n/n)_R$ corresponds to the existence of a strong ISW harmonic generation, i.e., the harmonic amplitudes are of the same order of magnitude as the fundamental; the second inequality $(\delta n/n)_R < (\delta n/n)_K$ is the condition for the ion nonlinearity to be of the fluid type, i.e., for the absence of strong nonlinear kinetic effects. Writing $(\delta n/n)_R = (\delta n/n)_H$, one obtains the critical flux Φ_H below which SBS can be described by Eqs. (1):

$$\Phi_H = 3.2\times 10^{-2} R^{-1}(n_c/n)\,T_e^3\lambda^{-2}.$$

We now concentrate on the weakly nonlinear regime $\Phi < \Phi_H$. Equations (1) may be written in a dimensionless form so that SBS is entirely characterized in the weakly nonlinear regime by only three parameters: $\epsilon \equiv C_s/c$, $L/L_c \equiv (2/\pi)\gamma_0 L/(cC_s)^{1/2}$, and $\Gamma = \alpha/\alpha_{\rm inc} \equiv \alpha/4\gamma_0(C_s/c)^{3/2}$. The latter quantity Γ will appear further on to be the significant parameter regarding the effect of the ISW nonlinearity upon SBS. Equations (1) have been solved numerically for various values of the parameter Γ; the solutions essentially have two kinds of behavior depending upon the magnitude of Γ. For $\Gamma < 1$, the ISW nonlinearity modifies the case $\Gamma=0$ in an adiabatic manner, and no significant change is observed regarding the reflectivity. This result may be understood on physical grounds by observing that the inequality $\Gamma < 1$ corresponds to the condition that the nonlinear frequency shift remains smaller than the mode growth rate $2\gamma_0(C_s/c)^{1/2}$ and is therefore negligible. In the opposite case $\Gamma > 1$ and for $L > L_c$, the nonlinear frequency shift becomes large enough to destabilize the steady-state solution, and the system is numerically observed to enter into an incoherent regime. The parameter Γ may easily be related to the incident flux Φ according to $\Gamma = (\Phi/\Phi_{\rm inc})^{1/2}$, where $\Phi_{\rm inc}$ is thus the critical flux above which the ISW nonlinearity gives rise to an incoherent SBS interaction. One obtains

$$\Phi_{\rm inc} = 3.2\times 10^{-2}(n/n_c)\,T_e^3\lambda^{-2} \qquad (2)$$

with the same units as before.

Figure 1 shows the time history of the reflectivity $R(L,t) \equiv |a_1(x=0,t)|^2$ and the frequency spectrum of the backscattered light a_1 corresponding to the following set of parameters: $\epsilon = 7\times 10^{-4}$, $\Gamma=4$, and $L/L_c = 6$. The abscissa variables of Figs. 1(a) and 1(b) are $\gamma_0(t)$ and $(\omega-\omega_1)/\gamma_0$, respectively; ω_1 denotes the natural frequency of the backscattered light, namely, $\omega_1 = \omega_0 - \omega_s$, where ω_0 and $\omega_s = k_sC_s$ are the frequencies of the laser and of the ISW, respectively. One may first observe that in such an incoherent regime the reflectivity R displays a burstlike behavior in time. Concerning now the spectrum, the nonlinear frequency shift gives rise to an additional red shift $\delta\omega_1$, which is found to be typically of the same order of magnitude as the total width of the spectrum $\Delta\omega_1$. Another characteristic feature of the spectrum is the presence of peaks that are also observed in some experiments.[4] For completeness, we must say that reflective boundaries have already been proposed[7,8] as a possible origin of SBS incoherent interaction; in particular, spiky spectra have been obtained by Randall and Albritton[8] from numerical computations with reflective boundaries and $\alpha=0$. Clearly, the ISW nonlinearity also gives rise to a spiky spectrum whose peak separation is smaller than ω_s in the regime $\Phi_{\rm inc} < \Phi < \Phi_H$. We are thus led to the same conclusions as those formulated by the latter authors; i.e., a diagnosis of the temperature based upon ISW harmonic generation to explain the spectrum would lead erroneously to an electron temperature well below the actual one. For a quantitative comparison of our results with experimental data, it is convenient to convert the dimensionless frequency $(\omega-\omega_1)/\gamma_0$ of Fig. 1(b) into the ratio $(\omega-\omega_1)/\omega_s$ according to the formula

$$\frac{\omega-\omega_1}{\omega_s} = \left(\frac{A}{Z}\right)^{1/4}\left(\frac{n}{n_c}\right)^{1/2} T_e^{-3/4}\Phi^{1/2}\lambda\left(\frac{\omega-\omega_1}{\gamma_0}\right);$$

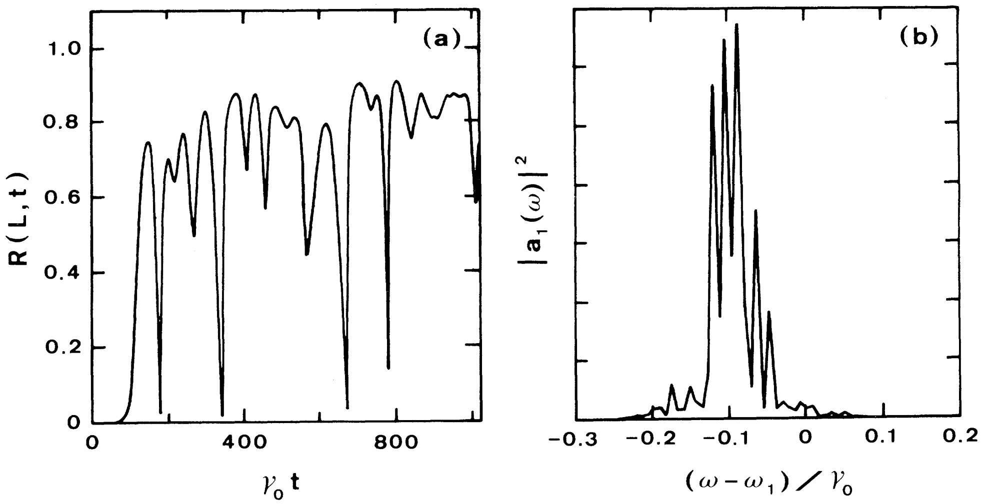

FIG. 1. (a) Time history of the backscattered light showing chaoticlike behavior. (b) Calculated frequency spectrum of the backscattered light exhibiting characteristic peaks. The parameters are $\epsilon=7\times10^{-4}$, $\Gamma=4$, and $L/L_c=6$.

Ze and $M_i=Am_p$ denote the ionic charge and mass, respectively. For $n/n_c=0.18$ and $A/Z=2$, the parameters that we have chosen for Fig. 1 correspond to $T_e=1$ keV and $\Phi\lambda^2=10^{13}$ W μm^2/cm^2.

We now consider the scaling laws of the time-averaged reflectivity $\overline{R}(L)$ and transmissivity $\overline{T}(L)$ in the regime of weak nonlinearity and of incoherent SBS interaction as defined by the inequalities $\Phi_{\text{inc}}<\Phi\le\Phi_H$. We have numerically found that the quantities $\overline{R}(L)$ and $\overline{T}(L)$ can be fitted in the unstable regimes $L>L_c$ by the following law:

$$\overline{R}(L)=1-\overline{T}(L)=1-\Gamma^{1/3}(L_c/L). \quad (3)$$

The agreement is fairly good provided that L exceeds a few L_c, as can be seen in Fig. 2: The full curve represents $\overline{R}(L)$ as given by Eq. (3), and the dots stand for the numerical results. The characteristic $1/L$ dependence of $\overline{R}(L)$ has to be compared with the standard case $\alpha=\Gamma=0$ (the dashed curve) for which $R(L)$ increases exponentially from zero to unity for $L>L_c$. The parameters for the numerical results of Fig. 2 are $\epsilon=7\times10^{-4}$ and $\Gamma=4$. The $\Gamma^{1/3}$ dependence of $\overline{R}(L)$ has been numerically tested on several decades of variation of ϵ. In physical units, we obtain the expression $\overline{R}(L)=1-6.5\Phi^{-1/3}(n/n_c)^{-2/3}\lambda^{1/3}\times L^{-1}$ with the same units as before.

Let us now discuss the limitation of our results and the connection with related works: (i) First concerning the effect of wave damping, we have numerically checked that the previous results are not modified as long as SBS remains in the regime of absolute instability. In the opposite case, we still observe a reduction of the reflectivity caused by the ISW nonlinearity whenever the nonlinear frequency shift $\Delta\omega_{\text{nl}}$ exceeds the linear damping ν_s of the ISW. (ii) Second, our results strictly apply to the weakly nonlinear regime $\Phi<\Phi_H$. However, we have observed that the more Φ exceeds the incoherent threshold Φ_{inc}, the more the system behaves in a chaotic way. For this reason, it seems justified to conjecture that incoherency effects are still responsible for the reflectivity reduction in the intermediate regime $\Phi_H<\Phi<\Phi_K$, where there exists a strong ISW harmonic generation. This conjecture seems to be well supported by the simulations of Heikkinen, Karttunen, and Salomaa,[9] which display, in the

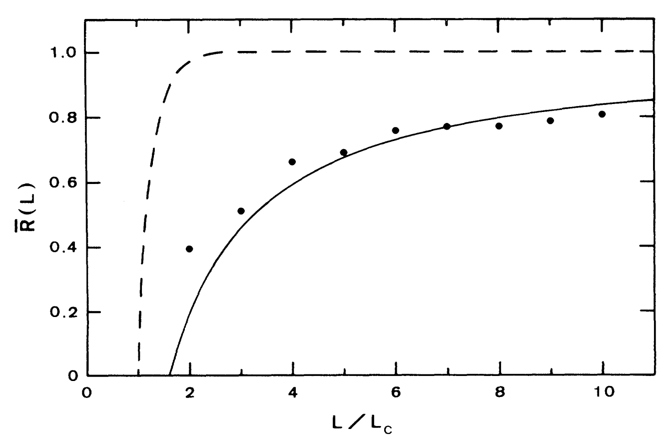

FIG. 2. Averaged reflectivity $\overline{R}$ as a function of the normalized length of the plasma L/L_c. The solid curve represents the scaling law given by Eq. (3); the dots stand for the numerical results; the dashed curve corresponds to the case $\alpha=0$ and is given for comparison with the standard steady-state solution.

regime of harmonic generation, a chaoticlike behavior for SBS and a lowered average reflectivity. (iii) Lastly, in the strongly nonlinear regime $\Phi > \Phi_K$, nonlinear kinetic effects take place and give rise to additional effects such as a nonlinear ISW damping; again experiments done by Clayton and co-workers,[10] as well as numerical simulations done by Forslund, Kindel, and Lindman,[11] still exhibit a burstlike behavior for SBS. Therefore, in this regime the reflectivity reduction cannot be solely attributed to the increase of the ISW damping, but must also in part result from the intrinsically incoherent nature of SBS interaction caused by the nonlinearity of the ion sound wave.

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