Transient Enhancement and Detuning of Laser-Driven Parametric Instabilities by Particle Trapping

H. X. Vu, D. F. DuBois, and B. Bezzerides
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
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Kinetic simulations of backward stimulated Raman scattering (BSRS), where the Langmuir wave coherence time is greater than the bounce time for trapped electrons, yield transient reflectivity levels far above those predicted by fluidlike models. Electron trapping reduces the Langmuir wave damping and lowers the Langmuir wave frequency, and leads to a secular phase shift between the Langmuir wave and the BSRS beat ponderomotive force. This phase shift detunes and saturates BSRS and a similar effect, due to ion trapping, is the saturation mechanism for backward stimulated Brillouin scattering. Competition with forward SRS is discussed.

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In this Letter, we present preliminary results on kinetic regimes of backward stimulated Raman scattering [1] (BSRS) dominated by electron trapping in the primary daughter Langmuir wave (LW). This study is motivated by the need to understand the unexpectedly high BSRS reflectivities observed in experiments emulating the conditions of the National Ignition Facility (NIF) [2,3]. In the case of BSRS, electron trapping can lead to much larger transient reflectivities than predicted by standard fluidlike Zakharov models in regimes with high Landau damping of the primary Langmuir wave (LW) with large values of $k_1 \lambda_D$ [4]. This study of the role of phase detuning by trapping also leads to a new understanding of previous work [5] on backward stimulated Brillouin scattering (BSBS) where ion trapping is the controlling nonlinearity.

In Figs. 1, we compare the BSRS reflectivities of the reduced-description particle-in-cell code (RPIC) ASPEN [6] and a hybrid version of the Zakharov model, called ODYSSEUS [7] which has fixed Landau damping for the LWs and includes ion kinetic effects. This comparison is made for a case in which the primary LW's Landau damping is $\nu_1/\omega_{pe0} = 3.8 \times 10^{-3}$, corresponding to $k_1 \lambda_D = 0.26$, where k_1 is the wave number of the primary LW. In terms of physical units, the simulation corresponds to a plasma with $T_e = 1.5$ keV, $T_i = 0.1$ keV, $n_{e0}/n_{cr} = 0.1$ for a 3ω laser with a vacuum wavelength of 0.351 μm (n_{cr} is the critical plasma density), and the laser intensity $I_0 = 5.6 \times 10^{14}$ W/cm^2. The size of the simulation domain $L = 100$ μm, and is represented by 8192 equally spaced mesh points. The electrons and ions are each represented by 128 particles/cell. To ensure that the only difference between the two calculations is the dynamical models employed, the initial noise for the hybrid calculation was set to agree with that of the corresponding RPIC calculation [6–9]. Notable differences between the RPIC and hybrid results are the significantly enhanced BSRS reflectivity for the RPIC calculation and its burstlike temporal behavior. In Figs. 1 we also show the time-averaged k-space LW spectrum. The very narrow width of the primary LW necessarily implies a large correlation time τ_c for the LW field. In particular, we find $\omega_b \tau_c > 1$, where $\omega_b = (eEk_1/m_e)^{1/2}$ is the bounce frequency and $\tau_c = (v_g \Delta k)^{-1}$, with v_g as the group velocity of the primary LW, Δk as a measure of the spectral width in k. In the higher $k_1 \lambda_D$ regimes considered here, the linear BSRS system is convectively saturated at low levels and the fastest growing mode k_1 predominates. This linear gain engages the trapping process which subsequently governs the nonlinear evolution. It is emphasized here that even though the RPIC model does not restrict the temporal evolution of BSRS to one k mode *ab initio,* a narrow LW spectrum has resulted.

From the spectrum, it is apparent that the Langmuir decay instability (LDI) [4] of the primary LW plays a very

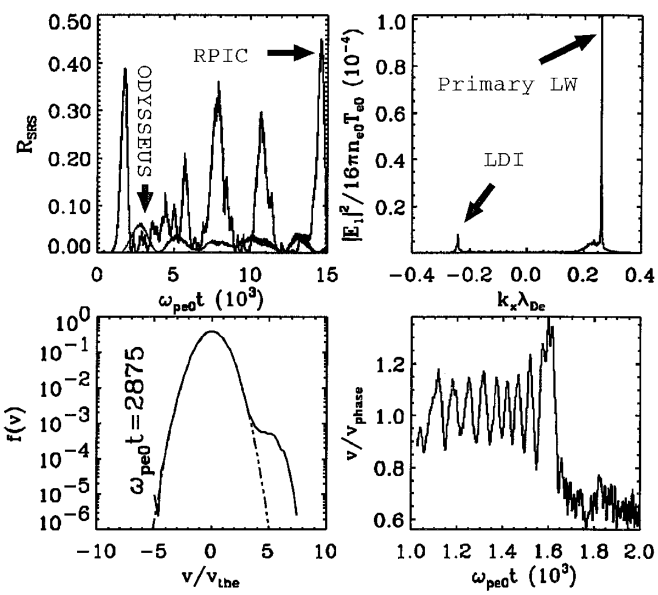

FIG. 1. BSRS reflectivity (top left), LW spectrum (top right), electron distribution function (bottom left), and particle orbit (bottom right). The BSBS reflectivity (not shown), is not significant for the times shown.

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small role in the saturation of BSRS in this regime. As the RPIC calculation develops in time, the spatially averaged electron distribution shows significant deviations from the initial Maxwellian distribution, with a characteristic flattening in the neighborhood of the phase velocity of the primary LW, indicating that electron trapping is prominent. To confirm that these deviations are consistent with the presence of electron trapping, we show in Figs. 1 a typical particle orbit in the neighborhood of the phase velocity, which clearly exhibits the bounded motion of a trapped particle. The seminal work of O'Neil [10] demonstrated that trapping dynamics reduces the LW damping from the Landau value for $\omega_b t > 2\pi$. Such a reduction of the LW damping is key to understanding the large reflectivity of the RPIC simulation shown in Figs. 1. This reduction has been conjectured to play a role in the nonlinear stage of BSRS [11].

Cohen and Kaufman [12] studied in detail the role of trapped electrons in the saturation Langmuir waves driven by a fixed, monochromatic, "ponderomotive-source" potential drive. A parallel study for driven ion acoustic waves was given by Cohen *et al.* [13]. Reduction in the wave damping, as in the work of O'Neil for undriven waves, and nonlinear frequency shifts, similar to the results of Morales and O'Neil [14], were found in the driven case. These results illustrated how trapped particles can detune the resonant response and determine the saturated wave amplitude for a driven wave.

Here, for the first time, is investigated the detuning due to trapping in the complete regenerative dynamics of the parametrically driven BSRS problem where the ponderomotive drive for the LW is varying in time in a self-consistent manner. The results in Figs. 1 inspire and justify a model of BSRS which involves only the laser pump, the scattered light wave, and a single, nonlinearly evolving, LW. Note that the pulselike behavior of the reflectivity in Fig. 1 implies a similar time-dependent behavior for the ponderomotive term driving the LW.

The equation for the slowly varying envelope, a_s, of the scattered light wave, driven by the SRS ponderomotive beat term between the incident light wave and the primary plasma wave a_p, is as follows:

$$(\partial_t + v_s \partial_x + \nu_s) a_s = \gamma_0 a_p^*, \quad (1)$$

where v_s is the group velocity of the scattered light wave, ν_s is the collisional damping of the light wave, and γ_0 is the linear growth rate proportional to the amplitude of the pump laser field. An energy equation can be derived from Eq. (1) in terms of the modulus and phase of the various field quantities ($a_s = |a_s| \exp^{i\phi_s}, a_p = |a_p| \exp^{i\phi_p}, \gamma_0 = |\gamma_0| \exp^{i\phi_0}$) as follows:

$$(\partial_t + v_s \partial_x) |a_s|^2 = -2\nu_s |a_s|^2 + |\gamma_0 a_s a_p| \cos\delta\phi(t), \quad (2)$$

where $\delta\phi(t) = \phi_0 - \phi_s - \phi_p$. The collisional damping, ν_s, of the scattered light wave is small, and is neglected in our simulations. Consequently, the scattered light wave modulus reaches a local extremum in time when the phase satisfies the following condition:

$$\cos\delta\phi = \frac{v_s \partial_x |a_s|^2}{|\gamma_0 a_s a_p|}. \quad (3)$$

We find that at local (temporal) minima, the right-hand side of Eq. (3) is approximately 0, and the above condition on the phase can be well approximated as $\delta\phi \approx (n + 1/2)\pi$. When the $\partial_x |a_s|^2$ and the $|\gamma_0 a_s a_p|$ terms are measured at a local (temporal) maximum (at the same location where the BSRS reflectivity is measured) from the actual simulation, Eq. (3) is found to be well satisfied. This is illustrated in Figs. 2, where $\delta\phi(t)$ is shown, for the case of the simulation in Figs. 1. As a reminder to the reader, we note that the simulation shown in Figs. 1 is a fully nonlinear, self-consistent RPIC simulation that does not make any assumption regarding the nature of the LW spectrum, e.g., the LW spectrum is not restricted or filtered in k space. Thus, in the full dynamics of the SRS problem, in a full RPIC simulation, there is a secular phase shift that detunes

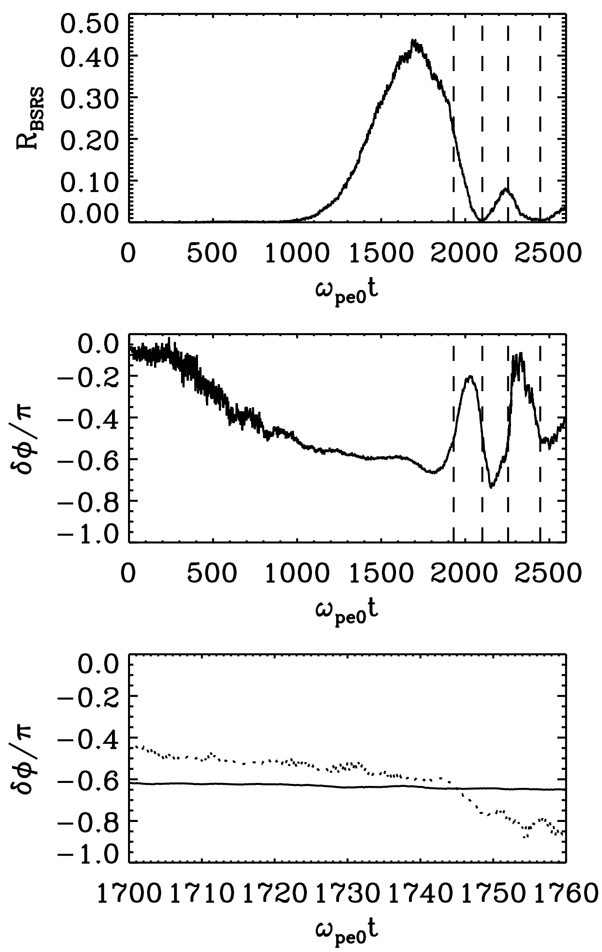

FIG. 2. Time history of the BSRS reflectivity (top), secular phase shift $\delta\phi$ (middle), left-hand-side and right-hand-side of Eq. (3) (bottom), for the case shown in Figs. 1. According to the bottom panel, Eq. (3) is satisfied at $\omega_{pe0}t \approx 1745$. This is indeed observed in the top panel as the first local maximum. At subsequent local extrema where $\partial_x |a_s|^2 \approx 0$, $\delta\phi \approx -\pi/2$, as indicated by the vertical dashed lines.

and saturates SRS. This secular phase shift depends intrinsically on the time-dependent nonlinear frequency shift and nonlinear damping of the Langmuir wave that traps electrons and also on the parametric coupling [15]. For the periodic driven LW case, also studied by Cohen and Kaufman [12], it is noted that a similar phase condition can be obtained, but was not identified in Ref. [12]. We find that because of the absence of spatial gradients in this particular situation, the secular phase shift $\delta\phi$ at local extrema is simply $\delta\phi = (n + 1/2)\pi$. Our simulation results for these cases (not shown) confirm this phase condition.

It is observed in Figs. 1 that the LW spectrum remains essentially monochromatic. The fastest growing mode at k_1 first grows, linearly and convectively, until trapping develops, resulting in further enhancement due to reduced damping associated with trapping, and is ultimately detuned by the secular phase shift. The nearby modes are linearly less resonant, and also see an initially strong linear Landau damping. These modes do not get excited to trapping levels, and remain strongly damped, and therefore do not grow comparably to the linearly resonant mode that has grown to the trapping level. Once the primary mode is excited to nonlinear levels, it is not valid to consider the stability of the neighboring modes as if the system were initially quiescent.

In summary, as the LW is driven up by BSRS, it develops a secular phase shift relative to the BSRS beat ponderomotive force resulting from a nonlinear frequency shift of the primary LW [14,16,17], thereby detuning BSRS. It is important to note that such a turnover in the reflectivity corresponds to LW levels well below wave breaking and is also too weak to excite appreciable LDI. It is noted that similar temporal burstlike behavior of the BSRS reflectivity was also observed in the work of Estabook *et al.* [18] in which it was conjectured that BSRS is saturated by increased nonlinear Landau damping (compared with linear Landau damping) due to hot electron generation. This mechanism for the saturation of BSRS is very different from that of this Letter.

It is important to confirm whether our model is robust in regimes with NIF parameters. For example, in Figs. 3, results are shown for a 1D RPIC simulation with $T_e = 4$ keV, $T_i = 2$ keV, $n_e/n_{cr} = 0.1$, $I_0 = 5.6 \times 10^{15}$ W/cm^2, and $L = 100$ μm, with $k_1\lambda_D \sim 0.40$. The BSRS reflectivity exhibits short bursts of 40%–50%, levels much higher than expected from fluid modeling given the large Landau damping. The time-averaged BSRS reflectivity is 3%. It is noted that while the physics of BSBS is included in our RPIC simulations shown in Figs. 1 and 3, BSBS did not develop to significant levels during the time intervals shown in these figures.

The electron distribution function (not shown) has the characteristic flattening at the phase velocity of the LW, indicating that trapping is occurring, consistent with the narrow LW spectrum for BSRS. In this case, time-averaged BSBS reflectivity is observed to be less than 0.5%. However, strong forward stimulated Raman scattering (FSRS) is excited, as evidenced in the LW spectrum at $k\lambda_D \sim 0.1$. FSRS is saturated by LDI-initiated collapse [4,8], giving rise to a broad spectrum at low $k\lambda_D$ ($|k\lambda_D| < 0.1$). This demonstrates that trapping-enhanced BSRS can coexist with significant FSRS. We have performed many 1D simulations in which BSRS is observed to be enhanced, compared to similar Zakharov simulations, for $k\lambda_{De}$ ranging from about 0.25 ($n_e/n_c = 0.1$, $T_{e0} = 1.5$ keV) to about 0.43 ($n_e/n_c = 0.1$, $T_e = 5$ keV). The LW spectrum was narrow, and electron trapping was observed in these simulations. Although the mechanism of trapping-enhanced BSRS obviously does not operate in all regimes, the domain of trapping-enhanced BSRS ranges over a fairly wide range of $k\lambda_{De}$, and includes both the NOVA and NIF regimes.

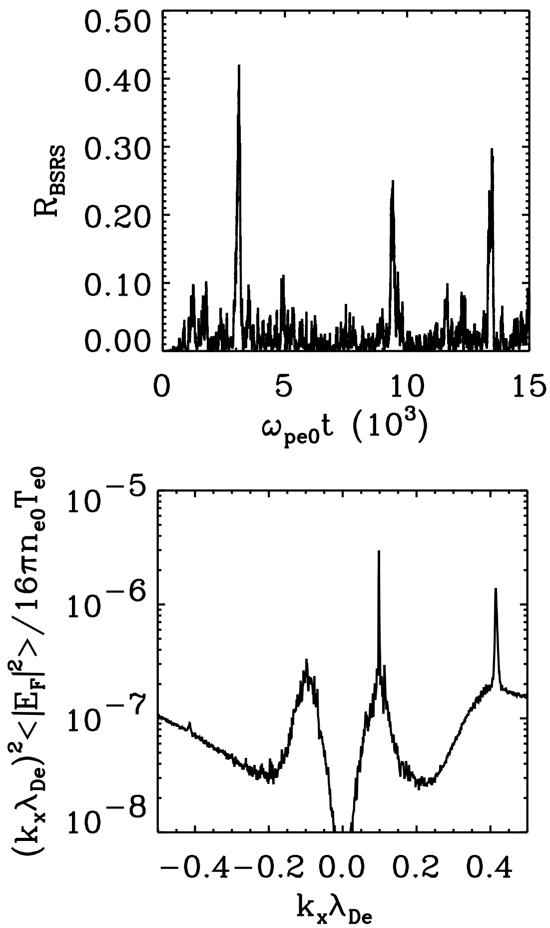

FIG. 3. Time history of the BSRS reflectivity (top) and time-averaged LW spectrum (bottom). The BSBS reflectivity (not shown), is not significant for the times shown.

It is noted that the flattening of the electron distribution, electron trapping, and the coexistence of BSRS and FSRS were observed in the work of Bertrand *et al.* [19]. However, this work failed to recognize that electron trapping can lead to enhanced BSRS. Furthermore, the Vlasov-Maxwell simulation model employed in this work did not allow ion motion. In our opinion, this restriction will lead to a serious overestimate of FSRS since the only saturation for FSRS other than pump depletion is LDI-initiated Langmuir collapse.

A similar saturation scenario is now understood to be present in particle-in-cell (PIC) simulations by Giacone and Vu for BSBS in the NIF parameter regime [5] where the BSBS reflectivity is only 10%, and pump depletion is not significant. Here the ion acoustic wave (IAW) was observed to trap ions, and lead to a measurable self-consistent nonlinear frequency shift of the IAW. Application of the same type of diagnostics discussed above shows that BSBS is again saturated by a secular phase shift between the IAW and the BSBS ponderomotive force at a level much lower than the wave breaking limit. No decay of this IAW into other IAWs was observed in 2D and 3D simulations of similar parameter regimes [6,20]. Cohen *et al.* [13] had performed hybrid simulations (particle ions, fluid electrons) of BSBS in a much more strongly driven regime with short simulation domains, and reported a reduction in the ion Landau damping and a IAW nonlinear frequency shift due to ion trapping. The saturation of BSBS in their simulations was attributed to the frequency shift of IAWs, but they did not discuss the related secular phase detuning discussed above. For cases where $k_1 \lambda_D < 0.17$, which also includes FSRS, we have a state of Langmuir turbulence where the LW spectrum is so broad that trapping is not important, and LDI and Langmuir collapse and quasilinear modification of the electron distribution function play important roles in the saturation of the instability.

In 2D and 3D, the time dependence of the BSRS reflectivity should be affected by the refreshment of the distribution function due to the transit of hot electrons out of the narrow transverse dimension of the hot spot. Since the 2D simulations show heating primarily in the direction of laser propagation, the transverse velocity is roughly thermal. The durations of the reflectivity bursts in Figs. 1 and 3 are short compared to the transit time of a thermal electron, so there is sufficient time for trapping enhancement and detuning.

In Vu *et al.* [6], a 2D simulation of BSRS is shown in Figs. 5, 6, and 8 where the plasma parameters are similar to those corresponding to Figs. 1. Again, the LW and IAW spectra are very narrow in this case, favoring electron and ion trapping. As shown in this reference, the RPIC method is capable of treating the competition of instabilities: BSRS, FSRS, BSBS, and LDI.

A more comprehensive study of the implications of trapping phenomena for even more realistic BSRS and BSBS configurations is underway. It is noted that collisional modification of the electron distribution function will be important if $Zv_{os}^2/v_e^2 > 1$ [21], where v_{os} is the electron quiver velocity in the laser field. For our simulations, $Zv_{os}^2/v_e^2 \ll 1$. In some NIF regimes with $Z > 1$ this may not be the case.

To our knowledge, ours is the first PIC simulation of BSRS in the trapping regime corresponding to NIF parameters such as laser intensity, speckle length, temperatures, and density. The simulations include the interaction with other instabilities and nonlinear effects such as LDI, driven collapse, FSRS, and BSBS. Our results support the suggestion that enhancement and detuning due to trapping may explain the high levels of BSRS observed in NIF emulation experiments on NOVA. We have made the first comparisons of RPIC results with those of the extended Zakharov models which, for $0.25 < k\lambda_{De} < 0.43$, predict levels of BSRS much lower than RPIC, too low to account for NOVA experiments. For lower values of $k\lambda_{De}$, the RPIC model [15] agrees with previous results.

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