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Studies of Stimulated Raman Scattering in Laser Plasma Interactions

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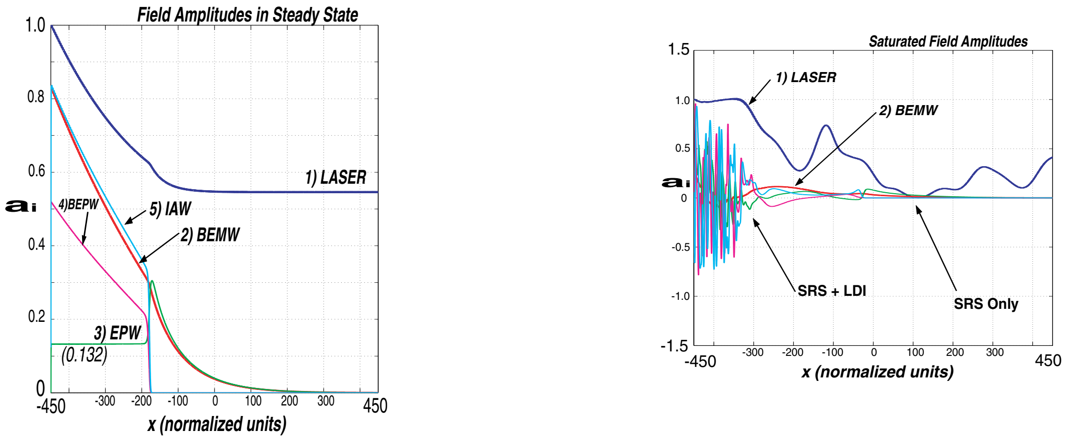
Abstract. Coupled theoretical and computational work is presented aimed at understanding and modeling stimulated Raman backscattering (SRBS) relevant to laser-plasma interactions (LPIs) in large-scale, nearly homogeneous plasmas. We address the following five observed, nonlinear phenomena associated with SRBS: coupling of SRBS to Langmuir decay interactions (LDIs); cascading of LDI; SRS cascades; and stimulated electron acoustic wave scattering (SEAS).

1. Introduction

In the past few years, experiments on the TRIDENT facility at the Los Alamos National Laboratory (LANL) have undertaken to study LPIs in (independently) preformed plasmas with a diffraction limited laser beam, thus approximately simulating LPIs in a single hot spot (SHS) [1], relevant to indirect drive inertial confinement fusion. We present results from recent analytical and computational studies [2,3] of LPIs with particular reference to SRBS in SHS [3]–[5].



(a)

(b)

Figure 1: *(a)* $k\lambda_{De} = 0.32$ *(*$n_e/n_{cr} = 0.04$*); (b)* $k\lambda_{De} = 0.28$ *(*$n_e/n_{cr} = 0.05$*).*

2. Coupled Mode Model Equations (CMME) for SRBS–LDI and Cascades

We considered the following model LPI in their simplest description of nonlinearly coupled modes [6]: (a) SRBS; (b) SRBS coupled to LDI; (c) SRBS + LDI coupled to

LDI-cascade (LDIc); and (d) SRBS coupled to SRS-cascade (SRSc). In the most complex case considered, (c), this entailed solving the following seven nonlinearly coupled mode equations:

$$\begin{aligned}
\text{LASER} &: \quad L_1 a_1 = -K_1 a_2 a_3 && (1)\\
\text{BEMW(EPW)} &: \quad L_2 a_2 = K_1 a_1 a_3 && (2)\\
\text{EPW(BEMW)} &: \quad L_3 a_3 = K_1 a_1 a_2 - K_2 a_4 a_5 && (3)\\
\text{BEPW(FEMW)} &: \quad L_4 a_4 = K_2 a_3 a_5 - K_3 a_6 a_7 && (4)\\
\text{IAW(EPWc)} &: \quad L_5 a_5 = K_2 a_3 a_4 && (5)\\
\text{CEPW} &: \quad L_6 a_6 = K_3 a_4 a_7 && (6)\\
\text{CIAW} &: \quad L_7 a_7 = K_3 a_4 a_6 && (7)
\end{aligned}$$

In these equations $L_j = (\partial/\partial t) + v_{gj}(\partial/\partial x) + \nu_j$ is the linear wavepacket operator on the slowly-varying action density amplitudes in space and time (see first reference in [6]). The above equations can be reduced to apply to (d) by labeling (2) as EPW, (3) as BEMW, (4) as FEMW, (5) as EPWc [as shown in parentheses along (2)–(5)], and setting K_3, a_6, and a_7 to zero.

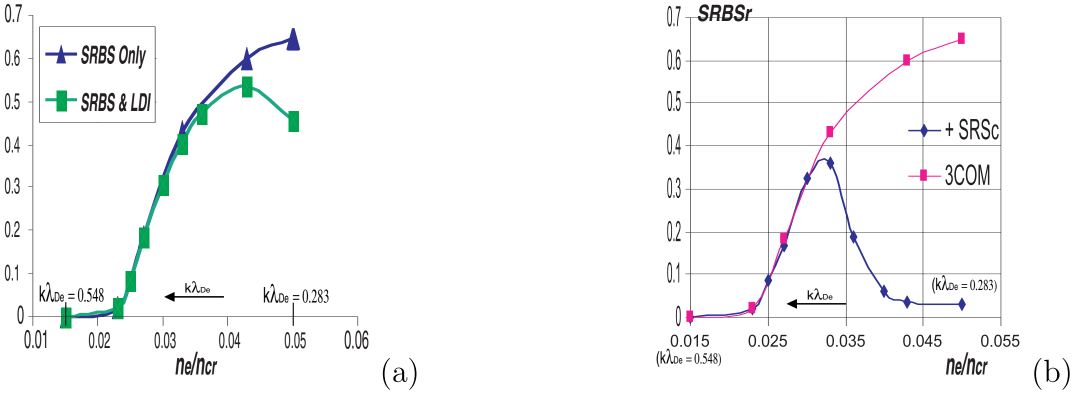


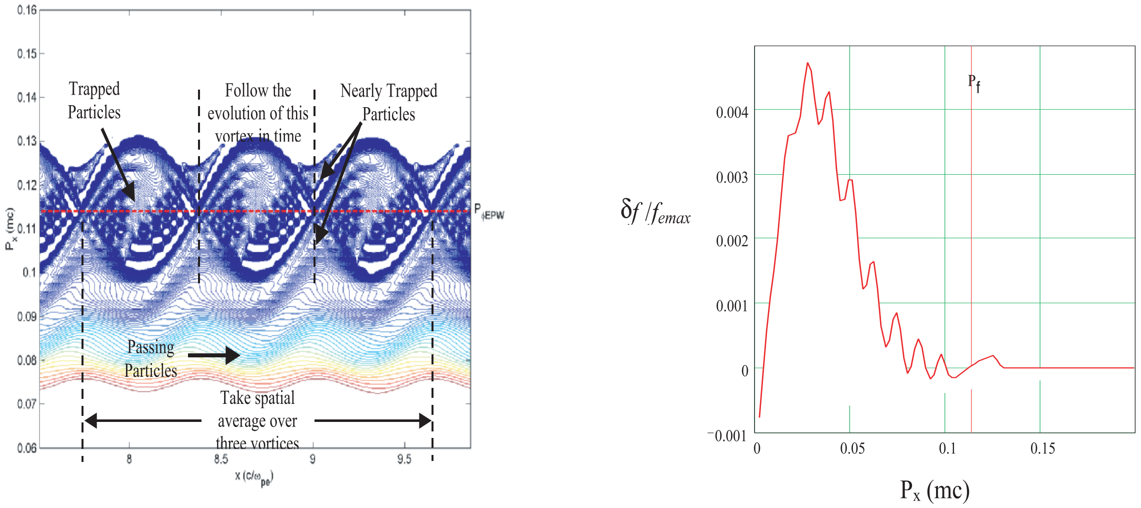
Figure 2: *(a) SRBS reflectivity with and without coupling to LDI; (b) SRBS reflectivity with and without the SRS cascade.*

2.1 Bounded Length Interaction Computations From CMME Studies

We modeled the SHS-LPI as occuring in a bounded homogeneous plasma of length L, with an incident laser field at $x = 0$. Parameters chosen to represent typical SHS-LPI experiments [1,5] were: $L = 250\ \mu m$; a Maxwellian plasma with 70% hydrogen and 30% carbon ions; $T_e \approx 700\ eV$; $T_i \approx 100$–$500\ eV$ (depending on electron density n_e where the interaction was made to occur); $\lambda_o = 527\ nm$; and a laser intensity $P_o \approx 10^{15}$ Watts/cm^2; (n_e/n_{cr}) was varied, as in the experiments to obtain LPIs as a function of the EPW $k\lambda_{De}$. The results shown in the following figures are presented in terms of normalized quantities used in the computations: action densities normalized to laser a_0, and distances normalized to $v_{g3}/(|K_{LDI}|a_0)$. Thus for the given laser and plasma parameters, the interactions length of 250 μm is 900 normalized x-units, and the SRBS energy flow reflectivity is

$$SRBS_r \equiv \left. \frac{|v_{g2}| \mathrm{w}_2}{|v_{g1}| \mathrm{w}_1} \right|_{x=0} \approx \frac{\omega_2}{\omega_1} |a_2(x=0,t)|^2 \ . \tag{8}$$

(Note, $x = 0$ is shown as -450 normalized x units.) The following is a summary of results.



(a) (b)

Figure 3: *(a) Electron distribution at* 51.7 (ω_{pe}^{-1})*; (b) Its deviation from the initial Maxwellian.*

1. *Coupling of SRBS to LDI* — Dramatic changes in space-time occur as the ELD of the EPWs is changed. For strong ELD ($k\lambda_{De} \gtrsim 0.4$), although SRBS may be present, LDI is not excited anywhere in the SHS plasma. For intermediate ELD ($k\lambda_{De} \sim 0.32$), LDI is excited but spatially localized near the boundary where the laser enters the SHS plasma; the EPW is saturated just above the LDI threshold [see Figure 1(a)]. Notably, for weak ELD ($k\lambda_{De} \lesssim 0.28$), LDI is intense in the plasma region near the laser entrance boundary, and exhibits incoherent space-time fluctuations [Fig. 1(b)] akin to spatiotemporal chaos (STC) [7]; the consequence is an appreciable reduction in SRBS reflectivity due to the ensuing dephasing. However, the low reflectivities observed in the SHS-LPI experiments are not predicted by SRBS coupling to LDI [Figure 2(a)].

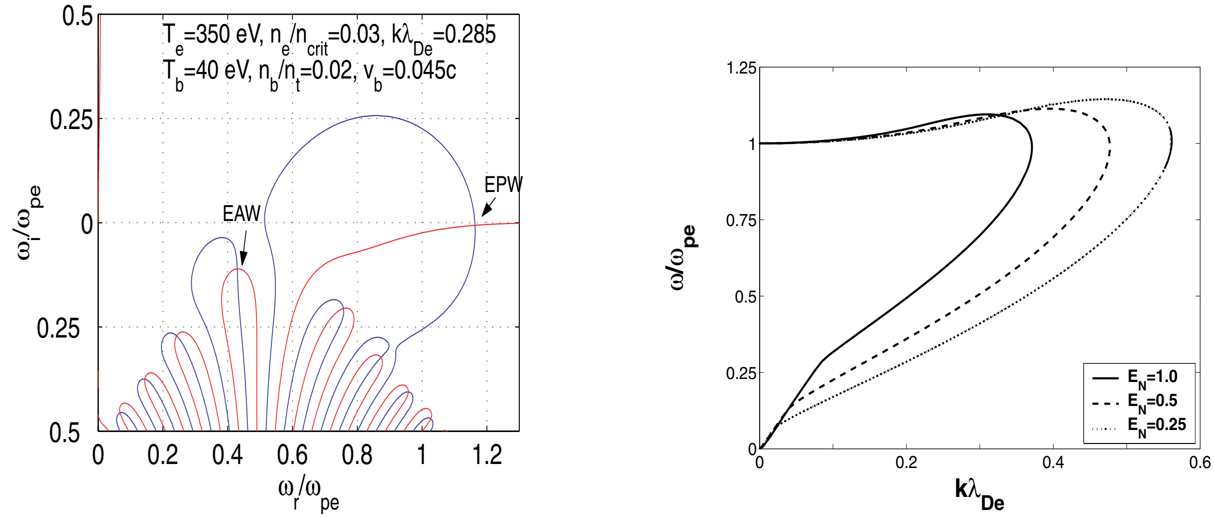
2. *Cascading of LDI* — The SHS-LPI experiments [3] have shown the existence of LDI cascades associated with SRBS. From our coupled mode simulations of (1)–(7), that include the first LDI cascade, we find that its effect is to slightly increase the SRBS reflectivity. This can be understood from the fact that the cascade drains energy from the LDI, thus enhancing SRBS which was reduced by LDI in the absence of the cascade. We thus explain the observation of cascades and their effect on the SRBS reflectivity, but we find that these cascades do not contribute significantly to predict the observed saturated values of reflectivity in the particular SHS-LPI.

3. *SRS Cascades* — We find that an SRS cascade gives a more significant decrease in the SRBS reflectivity than LDI [Fig. 2(b)]. This is readily understood from the Manley-Rowe relations. SHS-LPI experiments have so far not looked for this type of cascade.

Our results, although different in some respects, are complementary to [8,9].

3. Fluid Vlasov-Maxwell Simulations and Models for SRBS–SEAS

We have studied and modeled SEAS, analytically and numerically, with a model that differs from the one proposed in [4], considering that SRBS evolves its EPW to amplitudes that trap electrons. With a nonlinear, one-dimensional, Eulerian, Vlasov-Maxwell code [10], we launched a laser propagating field on a trapped electron distribution function due to an independently generated EPW in a plasma with parameters of the recent SEAS experiment [3,4], thus simulating a saturated state of SRBS. The evolution of this setup shows indeed that SRBS is essentially saturated, and in addition exhibits the generation of low-density, thermally spread beamlets below the phase velocity of the EPW (Figure 3) [11]. Estimating from Fig. 3(b) the presence of a beamlet ($v_b \approx 0.045\ c$, $T_b \approx 40\ eV$, $n_b \approx 0.02\ n_e$), the linear natural modes of the plasma with beamlet show a relatively weakly damped EAW [see Figure 4(a)]. Parametric growth rates for this system, driven by the laser, are given by the kinetic dispersion relation (see e.g., [12]):



(a) (b)

Figure 4: *(a) EPW and EAW modes; (b) Nonlinear electrostatic modes [13].*

$$(1+\chi_e)\, D_+ D_- = (kv_0/2)^2\, \chi_e (D_+ + D_-) \tag{9}$$

where $\chi_e = [-Z'(\zeta_p)/2k^2\lambda_{Dp} - Z'(\zeta_b)/2k^2\lambda_{Db}]$, with $\zeta_p = (\omega/|k|\sqrt{2}v_{Tp})$, and $\zeta_b = (\omega - kv_b/|k|\sqrt{2}v_{Tb})$; $D_\pm = c^2(k\pm k_0)^2 + \omega_{pe} - (\omega \pm \omega_0)^2$, and $v_0 = (e|E_0|/m_e\omega_0)$. For laser intensities of 10^{16} Watts/cm^2, calculations from (9) show that for a range of beamlet parameters (from $T_b \overset{\sim}{<} 50\ eV$ for $n_b \overset{\sim}{>} 0.02\ n_e$, and $T_b \overset{\sim}{<} 20\ eV$ for $n_b \overset{\sim}{>} 0.01\ n_e$), consistent with Fig.

3(b), one obtains a (quasimode) parametric growth rate $\approx 1.6 \times 10^{-4}\ \omega_o$ in a narrow frequency range at $\omega_r \approx 0.45\ \omega_{pe}$ ($k\lambda_{De} \approx 0.285$), similar to the observed SEAS, and an SRBS growth rate of $\approx 9.4 \times 10^{-3}\ \omega_o$ (essentially unaffected by the above beamlet parameters) in a narrow range at $\omega_r \approx 1.15\ \omega_{pe}$ ($k\lambda_{De} \approx 0.267$), as expected. Preliminary results from the (k, ω) spectra of the Vlasov code simulations confirm the results of this model. Finally, we find that a fully nonlinear, *steady state* solution of the one-dimensional Vlasov equation in an electrostatic wave electric field [13] exhibits *nonlinear* EAW-type modes below the plasma frequency [see Fig. 4(b), $E_N = eE_o/(m_e\omega_p\sqrt{2}v_{Te})$]; their excitation in SRBS also remains to be studied.

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