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Control and ultra-short pulse generation in stimulated Raman backscattering

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Abstract. A stimulated Raman scattering (SRS) is a great concern for laser fusion, causing an energy and symmetry loss and target preheating. In particular, for dominating backward-SRS (BRS), a complexity of nonlinear saturation was revealed. Recently, to develop lasers at multi-exawatts and beyond, relevant to high-energy physics, a proposed Raman amplification based on BRS met a restrictive operation window. Here, we stress BRS generics that due to a nonlinear frequency shift (relativistic/trapping effect), it nonlinearly saturates with intermittent pulsations. A "break up" of Manley-Rowe invariants explains a non-steady saturation. Further, a coherent pulsation BRS regime is proposed for femto-sec pulse generation in a thin exploding foil plasma, with parameter scalings investigated by analytics and particle simulations.

1. Introduction

Nonlinear laser plasma instabilites are useful paradigms of complex phenomena. In laser fusion, backward stimulated Raman scattering (BRS) in an underdense plasma results in a reduced coupling of laser energy to the target [1-3]. Recently, novel ultra-intense lasers beyond multi-exawatts, when standard CPA fails, were discussed for high-energy physics. Raman amplification scheme [4], with a counter-propagating pico-second laser pump and a femto-second resonant seed, was proposed. Still, simulations and experiments found a narrow parameter window to avoid parasitic instabilities (Forward-SRS, relativistic MI, etc.) and pulse destruction already at moderate intensities [5]. Firstly, in a standard 3-coupled mode model of BRS we outline the condition for an absolute instability [2, 6], that is readily satisfied in a uniform plasma which amplifies large Raman signals from a background noise. Even at low intensity, $I \sim 10^{14}$ W/cm^2, ~10 microns long, 0.1 of a critical density (N_0), absolute BRS dominates. As a generic feature, due to a nonlinear frequency shift (in EPW) [7-9], instead to a steady-state via pump depletion, BRS saturates through intermittent pulsations with reflectivity bursts and spectral broadening [2, 6]. The absolute BRS sets in for the interaction length L_0 shorter than, both, the plasma length L and absorption length L_a. The fact that, both, interaction and absorption length depend on plasma dynamics, contributes to an overall Raman complexity. Finally, large coherent pulsation regime is proposed for efficient femto-sec optical pulse generation by BRS in thin foil plasmas [9], with scalings studied by analytics and particle simulations.

2. Model

Stimulated Raman backscattering in a plasma is a paradigm of a three-wave parametric instability (3WI) whereby a strong electromagnetic-laser light (pump) wave decays into an electron plasma wave (EPW) and a backscattered light wave downshifted in frequency. The coupled 3WI process obeys a resonant matching condition for frequencies and wavenumbers of three waves ($\omega_0 = \omega_1 + \omega_2$, $\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2$). We model BRS as a resonant parametric coupling of 3WI for $a_i(x,t)\exp[i(k_i x - \omega_i t)]$, in a weakly varying envelope approximation [1,2,6]

$$\frac{\partial a_0}{\partial t} + V_0 \frac{\partial a_0}{\partial x} = -M_0 a_e a_s, \tag{1}$$

$$\frac{\partial a_s}{\partial t} - V_s \frac{\partial a_s}{\partial x} = M_s a_0^* a_e, \tag{2}$$

$$\frac{\partial a_e}{\partial t} + V_e \frac{\partial a_e}{\partial x} + \Gamma_e a_e - i\delta \left|a_e\right|^2 a_e = M_e a_0^* a_s, \tag{3}$$

where $V_i > 0$ are the group velocities, Γ_e is a damping rate for EPW ($\Gamma_0 = \Gamma_s = 0$ for light waves is used), $M_i > 0$ are the coupling coefficients and a_i are the wave amplitudes, where $i = 0,\ s,\ e$, stand for the pump, backscattered wave and EPW, respectively. A self-modal cubic nonlinearity in (3) is a generic nonlinear phase detuning (shift) due to relativistic/trapped electrons effect, $\sim \delta \left|a_2\right|^2$; e.g. a relativistic shift as $\delta = 3\omega_{pe}^3/16c^2 n_0^2 k_2^2$, [7-9]. With standard boundary conditions, $a_0(0,t) = E_0$, $a_s(L,t) = a_e(0,t) = 0$, BRS is absolute instability for $L/L_0 > \pi/2$, where $L_0 = (V_s V_e)^{1/2}/\gamma_0$ is the interaction length and $\gamma_0 = E_0(M_e M_s)^{1/2}$ is the uniform growth rate. If EPW damping, $\Gamma_e \neq 0$, it defines the absorption length $L_a = V_e/\Gamma_e$ with Raman backscattering becoming absolute under an extra condition, $L_0/L_a < 2$, [1-2].

2.1. Nonstationarity and "Break-up" of Manley-Rowe invariants

Assuming the steady state $(\partial/\partial t \to 0)$, conserved quantities (well known Manley-Rowe invariants, [1]) are calculated from (1-3), as [2, 9], (subscripts 1, 2 replace s, e, respectively)

$$m_0 = V_0 n_0(x) - V_1 n_1(x) = const., \tag{4}$$

$$m_1 = V_0 n_0(x) + V_2 n_2(x) = const., \tag{5}$$

$$K(x) = A_0 A_1 A_2 \sin\phi - \frac{\delta}{4} A_2^4 = const. \tag{6}$$

with $n_i(x) = A_i(x)^2$, $i = 0, 1, 2$, and $a_i(x,t) = A_i(x,t)\, e^{i\phi_i(x,t)}$, where A_i and ϕ_i, are the amplitude and phase of the wave, with the total phase shift given as $\phi = \phi_0 - \phi_1 - \phi_2$.
For boundary conditions, $n_0(0) = 1, n_1(L) = 0, n_2(0) = 0$, the third invariant gives $K(0) = 0$. However, as at the rear boundary $x = L$, in general, $A_2(L) \neq 0$, implying $K(L) \neq 0$; which breaks the invariance condition, i.e, $K(x) \neq const.$; hence, contradicting a basic assumption of the steady state. This simple argument by Škorić et al., [2, 9], predicts an onset of BRS complexity due to nonlinear phase detuning; as presently readily found in simulations and experiments on nonlinear BRS in laser plasmas [3, 8]. We also note above relevance to proposed Raman compression and amplification schemes, found to be limited to a weakly nonlinear regime [4-5].

3. Self-organization and route to complexity

The reflectivity R, which designates a fraction of incident laser intensity reflected backward [1,6]

$$R = \frac{V_0 \left|a_1(0)\right|^2}{V_1 \left|a_0(0)\right|^2}; \tag{7}$$

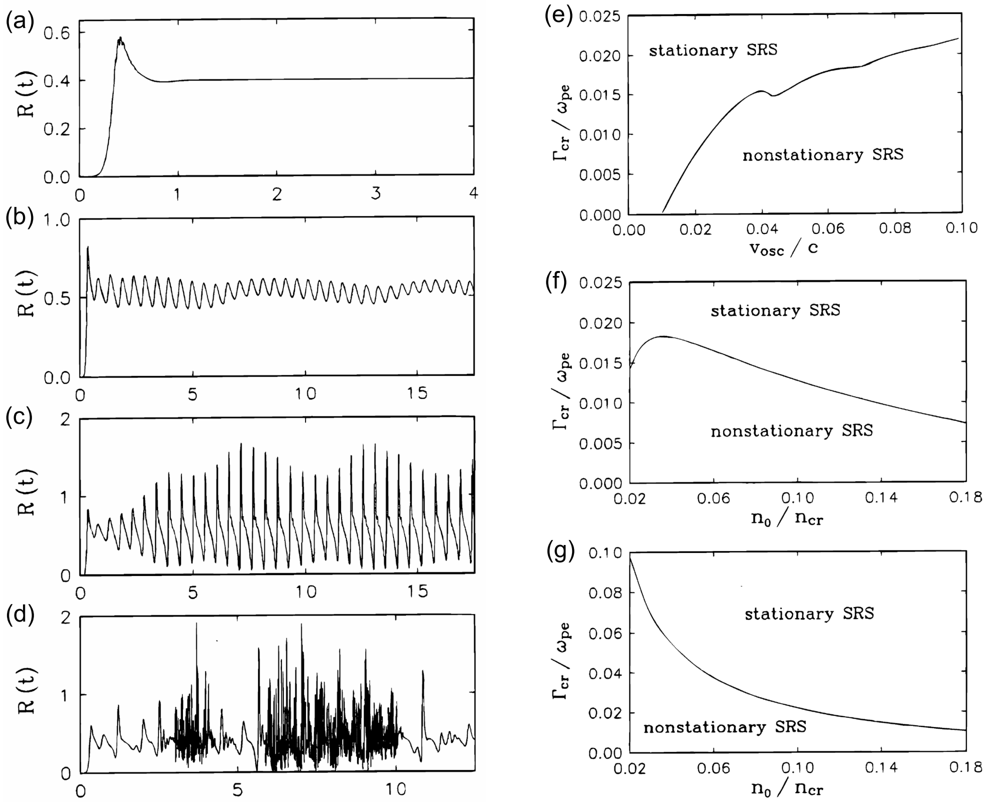

Figure 1. Raman complexity in time ($10^3/\omega_0$) versus EPW damping rate Γ/ω_{pe}: (a) 0.06, (b) 0.02, (c) 0.018, (d) 0.012, for $\beta_0 = 0.1$, $N_0 = 0.1n_{cr}$, $L = 100c/\omega_0$, $T_e = 1keV$ and Bifurcation diagrams for onset of complexity (e) $(\Gamma - \beta_0)$ and $(\Gamma - N_0)$ for (f) $\beta_0 = 0.03$, (g) $\beta_0 = 0.1$

has maximum normalized to unity in the stationary case. To solve the system (1-3), we choose realistic boundary conditions which satisfy the condition for absolute instability. A series of numerical simulations in space-time are run for system (laser and plasma) parameters related to hohlraum plasmas $N_0 = 0.1n_{cr}$, T_e =1 keV, $L = 100c/\omega_0$ and varying Γ_e/ω_{pe}. As laser pump β_0 (ratio of electron quiver velocity to speed of light) increases beyond absolute instability threshold, self-organized saturated states follow a quasi-periodic route to intermittency $FP \rightarrow P \rightarrow QP \rightarrow I \rightarrow C$, where FP stands for unimodal fixed point, P for periodic, QP for quasiperiodic, I for intermittent, and C for chaos, as shown in Fig. 1, [2, 6]. Intensity dependent intermittent pulsations and spectral broadening are inherent in BRS complexity as observed in recent experiments and simulations [3, 8]. Still, frequency broadenings measured are typically within a few percent of ω_0 and justify a weak-coupling model (e.g. Figs 2-6 [6]). We stress a generic role of nonlinear detuning term in (3), as if absent (δ=0), BRS goes to a steady-state failing to recover complex Raman features. Realistically, for large BRS, due to hot electrons from kinetic EPW and bulk plasma heating, interaction length L_0 and absorption length L_a change in time. Generally, a growth of both, the bulk temperature and effective damping (collisional, Landau) increase the absolute treshold and suppress the BRS instability. To illustrate, in Fig. 1 we show characteristic lengths effect on BRS dynamics and bifuraction diagrams for an onset of complexity. Raman supression and transition from nonstationary to steady-state (FP), indicated by a borderline (Fig. $1e - g$), follows a dissipation increase.

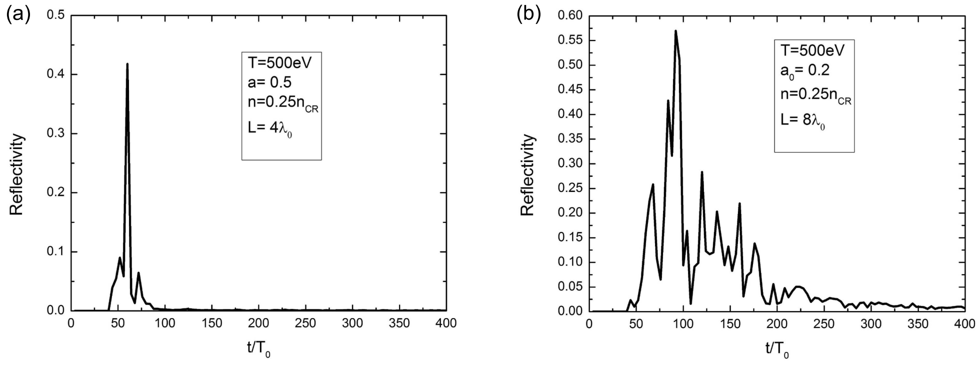

Figure 2. (a) Particle simulation of Raman compression into coherent fs-pulse in thin hydrogen foil plasma ($T \sim 10$ fs); (b) Unsuitable parameters choice results in incoherent Raman pulsations.

4. Femto-sec pulse generation by Raman backscattering in thin foil plasma

Here, we explore a new method for generation of ultra-short, fs-range optical pulses [9-10]. The scheme exploits a quasi-periodic coherent regime of BRS, as above, in laser interaction with a thin foil plasma. In an underdense exploding foil plasma, beyond the threshold for absolute BRS, reflectivity saturates with large pulsations [8-10]. For laser intensity in 10^{17} W/cm^2 range, hot electrons can rapidly halt the Raman instability and produce a single coherent pulse. By a proper choice of laser/ plasma parameters, an ultrashort Raman backscatter pulse of few laser periods, i.e. in 10 fs range is generated; as illustrated by relativistic particle simulatation results in Fig. 2. Therefore, one possibly finds a simple, robust and flexible scheme for proliferation of energetic optical fs-pulses by using the ps-scale laser driver system, now widely available.

5. Conclusion

We outlined a condition for absolute instability in stimulated Raman backscattering and crucial role of a nonlinear phase detuning in a route to complexity. Nonlinear saturation via intermittent pulsations is common, defined by the ratio between three parameters: interaction, plasma and absorption length, respectively. Accordingly, effective control of self-organized states, including kinetic BRS suppression and ultra-short coherent pulse generation appears to be feasible.

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References

[1] Forslund D W, Kindel J M and Lindman E L 1975 *Phys. Fluids* **18** 1002
[2] Kono M and Škorić M M 2010 *Nonlinear Physics of Plasmas* (Berlin: Springer) ch 12
[3] Hinkell D *et al* 2011 *Phys. Plasmas* **18** 056312
[4] Mourou G A *et al* 2012 *Optics Comm.* **285** 720
[5] Trines R M G M., Fiuza F, Bingham R *et al* 2011 *Nature Physics* **7** 87
[6] Škorić M M *et al* 1996 *Phys. Rev. E* **53** 4056; ibid. 1994 *AIP Conf. Proc.* **318** 380
[7] Kruer W L 1990 *Phys. Scr.* T**30** 5; Bingham R 1990 ibid. T**30** 24
[8] Yin L *et al* 2013 *Phys. Plasmas* **20** 012702; Berger R L *et al* 2013 *Phys. Plasmas* **20** 032107
[9] Škorić M M *et al* 1997 *AIP Conf. Proc.* **406** 381; ibid. 2009 **1188** 15
[10] Škorić M M, Nikolić Lj and Ishiguro S 2013 *J. Plasma Phys.* **79** 1003