J. Plasma Physics (2013), vol. 79, part 6, pp. 1003–1006. © Cambridge University Press 2013
doi:10.1017/S0022377813001189


# Self-organization and control in stimulated Raman backscattering

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(Received 6 September 2013; revised 13 September 2013; accepted 16 September 2013; first published online 12 November 2013)

**Abstract.** A stimulated Raman scattering (SRS) on electron plasma waves in underdense plasmas is of a big concern in laser fusion due to an energy loss and target preheating. Complex features of large Backward-SRS (BRS) in experiments and simulations with laser fusion targets are found. Recently, to reach ultra-high intensities at multi-exawatts and beyond, relevant to high-energy physics, Raman amplification based on BRS was proposed; still, with high sensitivity and a narrow operational window. Firstly, we revisit a standard three-coupled mode model of BRS to show that the condition for an absolute instability is readily satisfied in uniform plasmas which excites large Raman signals from a background noise. It sets in for interaction length $L_0$ shorter than, both, the plasma length $L$ and absorption length $L_a$. Further, we point out a generic BRS feature, which due to a nonlinear frequency shift in large electron plasma wave (relativistic/trapping effects ), instead to a steady state, saturates via intermittent pulsations with incoherent spectral broadening. A 'break up' of Manley–Rowe invariants is shown to predict non-stationary BRS. Finally, an intermediate intensity regime is originally proposed for coherent femto-second pulse generation in a thin exploding foil plasma, with scalings investigated by theory and particle simulations.

## 1. Introduction

Nonlinear laser plasma instabilities are a useful test bed for exploring a rich variety of nonlinear and complex plasma phenomena. In laser fusion, big concern is related to a backward stimulated Raman scattering (BRS) on electron plasma waves (EPW) in underdense plasmas that results in a reduced coupling of laser energy to the target (Forslund et al. 1975; Kono and Škorić 2010; Hinkell et al. 2011). Difficulties with a long pulse and long plasma-scale modeling and *pF3D* code simulations of nonlinear BRS for NIF (National Ignition Facility, Livermore) fusion targets have been recognized (Hinkell et al. 2011). Recently, efforts to reach ultra-high laser intensity at multi-exawatts and beyond, for high-energy physics, are underway. At extreme laser power, where standard chirped-pulse amplification CPA fails, a new scheme, based on BRS amplification (Mourou et al. 2012), with a counter-propagating pico-second laser pump and a femto-second resonant seed, was proposed. Still, simulations and some experiments have revealed a BRS sensitivity and a narrow parameter window to avoid parasitic instabilities (forward-SRS, relativistic modulational instability, etc.) and nonlinear pulse destruction as laser pump propagates in a uniform plasma (Trines et al. 2011). Firstly, we revisit the standard three-coupled mode model of BRS to show that the condition for an absolute instability (Škorić et al. 1996; Kono and Škorić 2010) is readily satisfied in a uniform plasma, driving large Raman signals from a background noise. For example, for a moderate pump, $I \sim 10^{14}$ W cm$^{-2}$, in 10 microns long underdense plasma, the absolute BRS could dominate. It sets in for $L/L_0 > \pi/2$ and $L_0/L_a < 2$; where $L_0 = (V_e V_s)^{1/2}/\gamma_0$ is the interaction length, the plasma length is $L$ and $L_a$ is the absorption length; $\gamma_0$ is linear parametric BRS growth rate, $V_e$ and $V_s$ are plasma wave and BRS group velocity, respectively. We point out a generic feature of the nonlinear BRS saturation which, due to a nonlinear frequency shift (EPW) (Kruer 1990; Škorić et al. 1997; Yin et al. 2013), instead to a steady state through pump depletion, evolves via a quasi-periodic route to intermittent chaos, with large bursts and incoherent spectral broadening of Raman light (Škorić et al. 1996; Kono and Škorić 2010). Still, a fact that both interaction and absorption length are dynamical parameters which depend on plasma evolution contributes to an overall Raman complexity. Further, we investigate effective parameter control of the self-organized Raman states, including the Raman suppression, as well as, intermittent pulsations regime (Škorić et al. 1996, 1997). Finally, large coherent pulsation regime is proposed for femtosecond optical pulse generation by BRS in thin foil plasmas (Škorić et al. 1997), with scalings investigated by analytics and particle simulations.

## 2. Model of nonlinear stimulated Raman backscattering

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 EPW and 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 (Škorić et al. 1996; Kono and Škorić 2010)

$$\frac{\partial a_0}{\partial t} + V_0\frac{\partial a_0}{\partial x} = -M_0 a_e a_a, \tag{2.1}$$

$$\frac{\partial a_s}{\partial t} - V_s\frac{\partial a_s}{\partial x} = M_s a_0^* a_e, \tag{2.2}$$

$$\frac{\partial a_e}{\partial t} + V_e\frac{\partial a_e}{\partial x} + \Gamma_e a_e + i\delta\, |a_e|^2\, a_e = M_e a_0^* a_s, \tag{2.3}$$

where $V_i > 0$ are the group velocities, $\Gamma_e$ is 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 (2.3) is a generic nonlinear phase detuning (shift) due to relativistic/trapped electrons effect, $\sim \delta\, |a_2|^2$ (Kruer 1990; Škorić et al. 1997; Yin et al. 2013). With standard boundary conditions $a_0(0,t) = E_0$, $a_s(L,t) = a_e(0,t) = 0$, backscattering is an absolute instability (Forslund et al. 1975; Kono and Škorić 2010) for

$$L/L_0 > \pi/2, \tag{2.4}$$

where $L_0 = (V_s V_e)^{1/2}/\gamma_0$ is the interaction length and $\gamma_0 = E_0(M_e M_a)^{1/2}$ is the uniform growth rate. Since damping $\Gamma_a \neq 0$, for EPW, it defines the absorption length $L_a = V_e/\Gamma_e$, Raman backscattering becomes absolute under an extra condition (Forslund et al. 1975; Kono and Škorić 2010),

$$L_0/L_a < 2. \tag{2.5}$$

## 3. 'Break-up' of Manley–Rowe invariants and non-stationary BRS

By introducing the nonlinear phase shift term in the above system of equations, and assuming the steady state $\left(\partial/\partial t \to 0\right)$, conserved quantities (well-known Manley–Rowe invariants, (Forslund et al. 1975)) are readily calculated as (Škorić et al. 1997; Kono and Škorić 2010)

$$m_0 = V_0 n_0\,(x) - V_1 n_1\,(x) = const., \tag{3.1}$$

$$m_1 = V_0 n_0\,(x) + V_2 n_2\,(x) = const., \tag{3.2}$$

$$K(x) = A_0 A_1 A_2 \sin\phi - \frac{\delta}{4}A_2^4 = const. \tag{3.3}$$

with $n_i(x) = A_i(x)^2$, $i = 0, 1, 2$, and

$$a_i\,(x,t) = A_i\,(x,t)\, e^{i\phi_i(x,t)}, \tag{3.4}$$

where $A_i$ and $\phi_i$ 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

$$n_0\,(0) = 1, n_1\,(L) = 0, n_2\,(0) = 0, \tag{3.5}$$

the third invariant gives $K(0) = 0$. However, as at the rear boundary $x = L$, generally, $A_2(L) \neq 0$ results in $K(L) \neq 0$, which breaks up the invariance condition, as, $K(x) \neq const.$; hence, contradicting basic assumption of the steady state. This simple argument, due to Škorić (Škorić et al. 1997; Kono and Škorić 2010) explains an onset of BRS complexity due to nonlinear phase detuning, as readily observed in simulations and experiments on nonlinear BRS in laser-plasmas (Hinkell et al. 2011; Yin et al. 2013). At this point, we also note the relevance to Raman compression and amplification schemes found to be restricted to a weakly nonlinear regime (Trines et al. 2011; Mourou et al. 2012).

## 4. Self-organization of nonlinear BRS saturated states

The most useful information on the BRS is contained in the reflectivity $R$, which designates a fraction of incident laser intensity reflected backward (Škorić et al. 1996)

$$R = \frac{V_0\,|a_1\,(0)|^2}{V_1\,|a_0\,(0)|^2}; \tag{4.1}$$

with its maximum normalized to unity in the stationary case. To solve, appropriate initial and boundary conditions are required. We choose physically realistic boundary conditions, while the choice of the plasma slab length satisfies the criterion for the occurrence of the absolute instability. The wave amplitudes obey the corresponding initial and non-zero source fixed boundary conditions, where the main control parameter is the laser pump strength $\beta_0$ – a ratio of the electron quiver velocity to a speed of light. A series of numerical simulations of the above model in space-time, by means of a central difference method, has been performed for different system (laser and plasma) parameters within physically realistic values. The following parameters are chosen: $V_0 = 9.5 \times 10^{-3}$, $V_1 = 8.8 \times 10^{-3}$, $V_2 = 2.9 \times 10^{-4}$, $\Gamma = 1.6 \times 10^{-6}$, $\delta = 3.5$ and $\varepsilon_1 = 10^{-2}$, related to laser hohlraum fusion plasma conditions $n_0 = 0.1 n_{cr}$, $T_e = 1$ keV, $L = 100c/\omega_0$ and $v_e/\omega_{pe} = 10^{-5}$. As the pump strength $\beta_0$ increases over the absolute instability threshold, starting from the value 0.01, the

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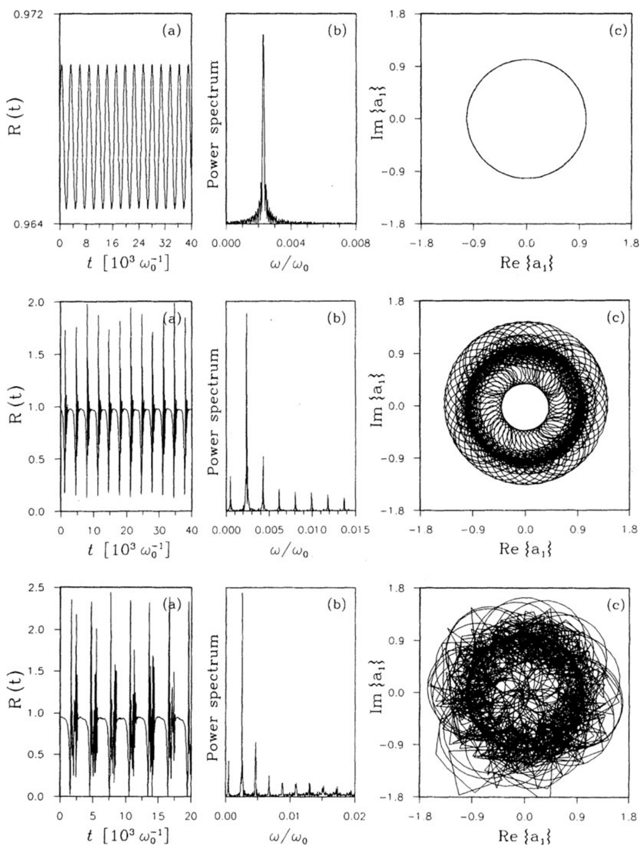


**Figure 1.** (a) Reflectivity, (b) power spectrum and (c) phase diagram for $\beta_0 = 0.02534$ (limit cycle), $\beta_0 = 0.027$ (2-torus), $\beta_0 = 0.03$ (intermittency), top to bottom.

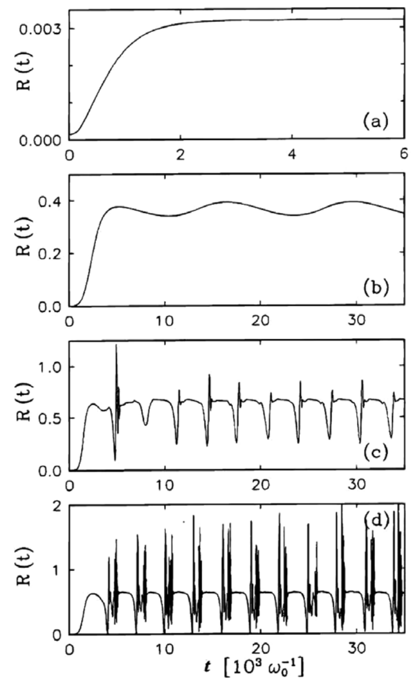


**Figure 2.** Control of reflectivity evolution by varying EPW damping rate $\Gamma/\omega_{pe}$: (a) $10^{-2}$, (b) $10^{-3}$, (c) $10^{-4}$, (d) $10^{-5}$.

self-organized saturated states follow a quasi-periodic route to intermittency

$$FP \rightarrow P \rightarrow QP \rightarrow I \rightarrow C, \tag{4.2}$$

where $FP$ stands for unimodal fixed point, $P$ for periodic, $QP$ for quasi-periodic, $I$ for intermittent, and $C$ for chaos, as shown in Fig. 1, (Škorić et al. 1996; Kono and Škorić 2010). Intensity-dependent intermittent pulsations and spectral broadening are inherent in above BRS complexity and consistent with recent laser fusion experiments and simulations (Hinkell et al. 2011; Yin et al. 2013). We stress a generic role of nonlinear detuning term in (2.3), as in its absence ($\delta = 0$) the BRS goes to a steady state, failing to recover complex Raman features. Still, in realistic physical situations with strong BRS, plasma parameters change in time, due to hot electrons in kinetic EPW and bulk plasma heating. Accordingly, the interaction length $L_0$ and effective absorption length $L_a$ become dynamical parameters. Generally taken, growth of both, the bulk temperature and effective damping (collisional, Landau), will increase the absolute threshold and suppress the BRS instability. To illustrate, in Fig. 2, we present an absorption length effect on BRS dynamics for an increasing EPW damping rate. Raman suppression and transition from non-stationary to stationary state follows a dissipation increase. Further, for self-consistent picture, we present kinetic particle simulations results in Fig. 3

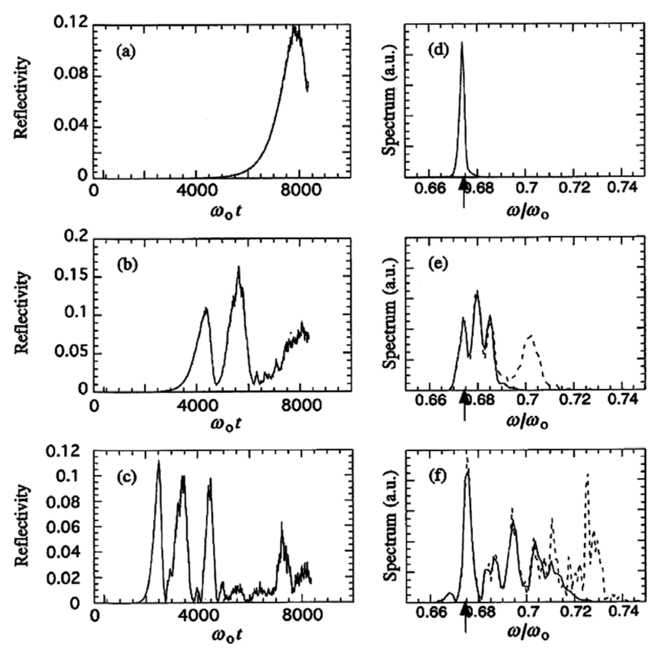


**Figure 3.** Particle simulation results for reflectivity in time and frequency spectra for $\beta_0$: (a), (d) 0.02, (b), (e) 0.03, (c), (f) 0.05 confirm a quasi-periodic route to intermittency, with blue shifted broadened spectra.

which show general agreement with the above Raman complexity scenario, with extra features of dynamical suppression due to kinetic effects. Pulsations and self-organized bursts are the common features of nonlinear kinetic BRS.

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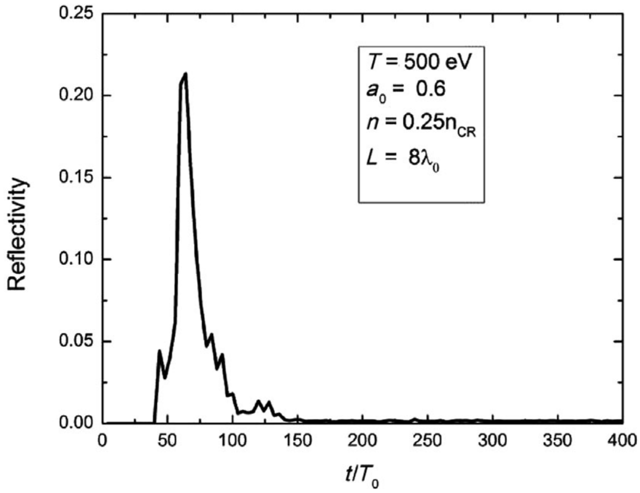


**Figure 4.** Particle simulation of compression into femto-second pulses by BRS in foil plasma ($T < 50$ femto-second).

## 5. Femto-second optical pulse generation by BRS in a thin foil plasma

Here, we propose an alternative method for the generation of ultra-short, femto-second-range optical pulses. The scheme exploits a self-organized quasi-periodic regime of BRS, as shown above, in the strong laser interaction with a thin foil plasma. In an underdense exploding foil plasma, beyond the threshold for absolute BRS, reflectivity can saturate via strong coherent pulsations (Škorić et al. 1997; Yin et al. 2013). With laser intensity in $10^{17}$ W cm$^{-2}$ range, exploding foil plasma is rapidly heated to halt the Raman instability and producing a single coherent pulse. By a proper choice of laser/plasma parameters, an ultra-short Raman backscatter pulse of few laser periods, i.e. in 10 femto-second range, can be produced, as illustrated by relativistic particle simulation results, shown in Fig. 4. In such a way, one can possibly obtain an inexpensive and flexible scheme for proliferation of energetic optical femto-second pulses by using the pico-second-scale laser systems, commonly available.

## 6. Conclusion

We discussed condition for absolute instability in stimulated Raman backscattering and reveal a generic role of nonlinear phase detuning in self-organization scenario. Quasi-periodic intermittent pulsations are found as common nonlinear saturation state, determined by the ratio between three dynamical parameters, given as: interaction, plasma and absorption length, respectively. Accordingly, effective control of self-organized regimes, including BRS suppression and coherent pulse generation appears to be feasible.

## Acknowledgements

The study was supported in parts by the Ministry of Education and Science of Serbia, project no. III 45010.

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