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# Micro- and Macro-Scale Self-Organization in a Dissipative Plasma

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## Abstract

We study a nonlinear three-wave interaction in an open dissipative model of stimulated Raman backscattering in a plasma. A hybrid kinetic-fluid scheme is proposed to include anomalous kinetic dissipation due to electron trapping and plasma wave breaking. We simulate a finite plasma with open boundaries and vary a transport parameter to examine a route to spatio-temporal complexity. An interplay between self-organization at micro (kinetic) and macro (wave/fluid) scales is revealed through quasi-periodic and intermittent evolution of dynamical variables, dissipative structures and related entropy rates. At this point, a consistency with a general scenario of self-organization is found.

## Keywords:

complexity, self-organization, stimulated Raman, scattering

## 1. Introduction

Self-organization (*SO*) is a generic process which describes a spontaneous formation of an ordered structure in a nonlinear far-from equilibrium system. Energy pumping, nonlinear instability, entropy production and expulsion are key governing processes. In this paper, an attempt is made to study kinetic self-organization [1] through a process of stimulated Raman backscattering (*SRBS*) in an underdense plasma [2]. Stimulated Raman scattering is a resonant three-wave (3WI) parametric instability which corresponds to the decay of an incident electromagnetic pump wave into a scattered wave plus an electron plasma wave (*epw*). Important effects, especially in the context of laser fusion schemes [3], are input energy loss, plasma heating and generation of suprathermal (hot) electrons. To emulate these effects we apply a hybrid three-wave phenomenological kinetic model of *SRBS*, proposed by Škorić *et al.* [4].

## 2. A Hybrid Model

The basic equations are coupled three-wave equations for slowly varying complex amplitudes of a pump ($a_0$), backscattered wave ($a_1$) and *epw* ($a_2$), respectively:

$$\frac{\partial a_0}{\partial t} + V_0 \frac{\partial a_0}{\partial x} = - a_1 a_2 \ ,$$

$$\frac{\partial a_1}{\partial t} - V_1 \frac{\partial a_1}{\partial x} = - a_0 a_2^* \ ,$$

$$\frac{\partial a_2}{\partial t} + V_2 \frac{\partial a_2}{\partial x} + \Gamma a_2 + i\sigma \left| a_2 \right|^2 a_2 = \beta_0^2 a_0 a_1^* \ . \quad (1)$$

Parameter $\Gamma$ is composed of collisional damping ($\Gamma_{\text{coll}}$), 'linear' (Landau) damping by hot – resonant electrons

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($\gamma_l \sim n_h$), where $n_h(t)$ stands for spatially averaged hot electron density:

$$\frac{dn_h(t)}{dt} = \frac{n_b(L,t)}{L} \int_{v_h - v_{tr}(L,t)}^{v_h + v_{tr}(L,t)} f_b \, dv - a \frac{v_h(t)\, n_h(t)}{L}, \quad (2)$$

($n_b$ is bulk electron density, $f_b$ is bulk distribution function, $v_h$ is velocity of hot electrons which equals the *epw* phase velocity, $v_{tr}$ is trapping velocity and $a$ is particle transport parameter) and nonlinear damping due to trapped resonant bulk electrons (in the thermal Maxwellian):

$$2\gamma_{nl} W(t) = \frac{mn_b(L,t)}{2L} \int_{v_h - v_{tr}(L,t)}^{v_h + v_{tr}(L,t)} v^3 f_b(v)\, dv, \quad (3)$$

where $W(t)$ is spatially averaged *epw* energy.

Open boundaries and re-emittance of fresh ambient electrons [5] is assumed. The particles (bulk and hot electrons) and energy (wave and particle) are being exchanged between a plasma and an environment through open boundaries with a conservation of particle number and total energy in the system. Accordingly, heat balance equatio (effect of plasma heating; $E_b$, $E_h$ and $\Phi_{tot} \rightarrow \Phi_b + \Phi_h + \Phi_q$ are the average bulk and hot electron energy or corresponding energy flux of the bulk, hot and return ambient electrons, respectively) takes form:

$$\frac{dW(t)}{dt} = \frac{d\,(E_b(t) + E_h(t))}{dt} + k \cdot \Phi_{tot}\Big|_0^L. \quad (4)$$

## 3. Dissipative Structures and Entropy Rate

The simulation is performed via the central-difference numerical code [2], where the simulation parameters are: $n_0 = 0.1\ n_{cr}$, $T_{b0} = 0.5$ keV and pump intensity, $\beta_0 = 0.0253$. Openness of a system, $k$ (0-1) was chosen as a bifurcation parameter. Self-organization in strongly nonlinear far-from-equilibrium systems leads to a creation of ordered states that reflect an interaction of a given system with its environment. These novel dynamical structures or patterns, named dissipative structures to stress the crucial role of dissipation in their creation, have become a central theme of the science of complexity [1,2,4]. On the other hand, there is a fundamental role of the entropy, in particular, the rate of entropy change in an open system. The rate of entropy production and its removal basically governs self-organization features of a system.

First, we focus at self-organized dissipative structures developed at the macro-scale. Indeed, in our model, basic wave and fluid density variables were assumed to vary slowly in space-time. Therefore, we expect that original spatio-temporal profiles, found in simulations, should correspond to large dissipative structures, self-organized at macro-scale levels. As an illustration, we plot the plasma wave profiles (Fig. 1), in particular, to reveal a genuine spatio-temporal nature of an intermittent regime as compared to regular dynamical regimes of the steady-state and quasi-periodic type [3,4]. Spatio-temporal complexity of quasi-steady and travelling wave patterns with regular and chaotic features is found in different states of self-organization.

Further, in Fig. 2 we plot the entropy rate $dS(t)/dt$ in time together with a spatio-temporal profile of the scattered wave energy. For an intermittent regime,

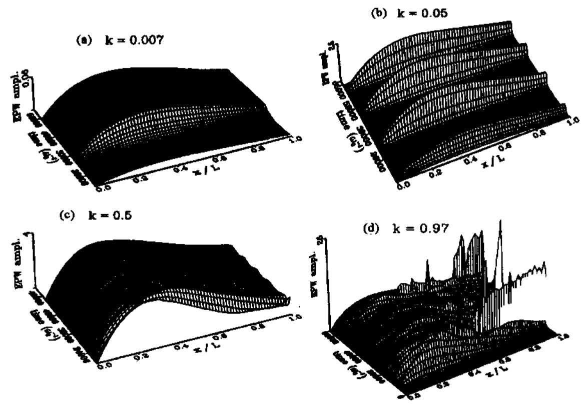


Fig. 1 Spatio-temporal profiles of the electron plasma wave for varying transport parameter $k$ values. Different dissipative structures are seen on the route to complexity, from the steady-state via quasi-periodic to intermittent regimes.

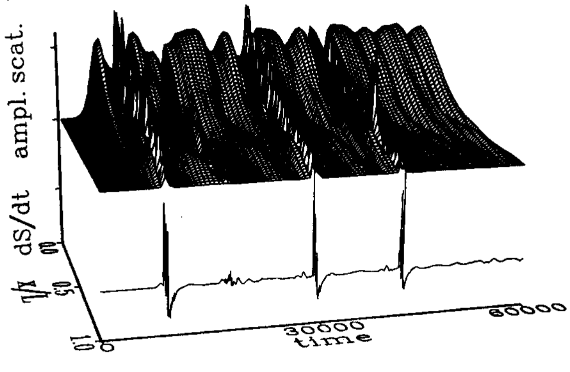


Fig. 2 Intermittent dissipative backscattered wave structures versus the corresponding entropy rate in time. Positive entropy jump coincides with an onset of chaos, while a negative burst indicates a transition from a chaotic to a laminar phase of SO at macro-scales.

featuring an interchange between chaotic and laminar phases, we find a clear evidence of structural transitions corresponding to the maximum (positive) and minimum (negative) entropy rate. As a striking example of self-organization in an open system we find a rapid entropy jump which coincides with an onset of a chaotic phase. Subsequent anomalous dissipation and entropy growth is halted by a sudden entropy expulsion into the environment. Negative burst in entropy rate indicates a bifurcation from a chaotic, back to a laminar quasi-periodic phase. Intervals of near zero entropy rate during a laminar phase, mean a net balance between the entropy production and its expulsion. This appears to be an example of a stationary nonequilibrium state possibly realized in a strongly nonlinear open system [1].

A hybrid nature of our model allows us to recover kinetic properties of self-organization. In Fig. 3 we see a three-dimensional view of the electron velocity distribution in time for different saturated Raman regimes, as indicated by values of parameter $k$. Kinetic self-organization of varying complexity is revealed in thermal and suprathermal (hot) regions of the electron distribution.

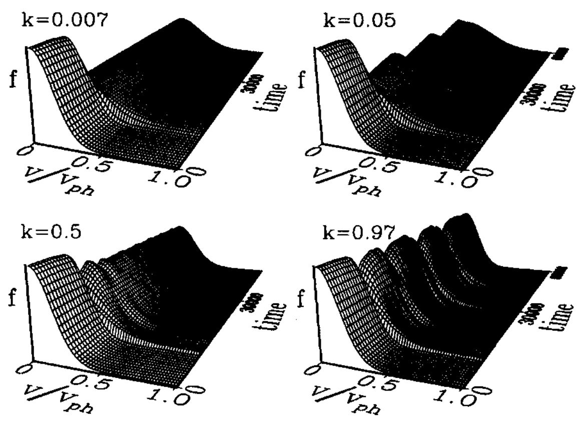


Fig. 3 Three-dimensional view of the electron velocity distribution in time for different saturated Raman regimes, as indicated by values of parameter $k$. Micro-kinetic scale self-organization of varying complexity is revealed in both thermal and suprathermal (hot) regions of the electron distribution.

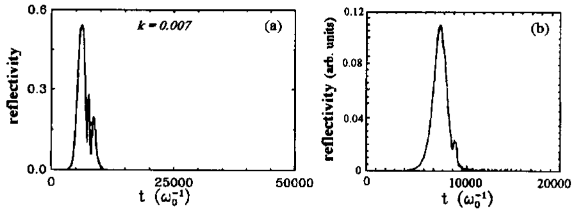


Fig. 4 Raman reflectivity versus time [$\omega_0^{-1}$] for $k = 0.007$ from the hybrid model simulation (a) and the corresponding data (b) obtained by a $1\frac{1}{2}$ relativistic particle-in-cell code (after Miyamoto *et al.* [6]). The pump strength was $\beta_0 = 0.0253$ and the plasma parameters: $n_0 = 0.1\, n_{cr}$, $T_e = 0.5$ keV, $L = 100\ c/\omega_0$.

## 4. Summary

In summary, we believe that our findings appear to be a first indication of a generic intermittent scenario in a kinetic self-organization of anomalous Raman instability. At this point we may note that one is able to claim a consistency with the working hypothesis and general scenario of self-organization in plasmas [1,4]. As a further step, we expect an important justification of our hybrid-modeling of saturated Raman complexity by the novel open boundary particle simulation code, currently under development [5]. As an early illustration, we show in Fig. 4b, recent particle-in-cell simulation data for a model of an isolated plasma slab in a vacuum [6]. For same plasma parameters, particle simulations (Fig. 4b) show an evident support of above Raman reflectivity pattern, obtained for a closed ($k$ = 0.007) system (Fig. 4a).

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