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M.M. Škorić, T. Sato, A. Maluckov and M.S. Jovanović

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Micro- and Macro-scale Self-organization in a Dissipative Plasma

M. M. Škorić[a,b], T. Sato[a], A. Maluckov[c], M. S. Jovanović[c]

[a] *Theory and Computer Simulation Center*
National Institute for Fusion Science
Toki-shi, 509-5292, Japan
[b] *Vinča Institute of Nuclear Sciences*
P.O.B. 522, 11001 Belgrade, Yugoslavia
[c] *Department of Physics, University of Niš*
P.O.B. 91, 18001 Niš, Yugoslavia

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. An evidence that entropy rate extrema correspond to structural transitions is found.

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Keywords: Nonlinear Waves, Self-Organization, Raman Complexity, Plasma Simulation

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. An open system was found to exhibit different features in *SO*, depending on whether the energy pumping is instantaneous—final state of minimum energy, or continuous—the dynamical state of intermittency [1].

In this paper, an attempt is made to study kinetic self-organization 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 [3], are input energy loss, plasma heating and generation of suprathermal (hot) electrons. However, to account for these effects, kinetic treatment of highly nonlinear electron interaction with *epw* is required. To emulate these effects we apply a hybrid three–wave phenomenological kinetic model of *SRBS*, recently proposed by Škorić et al. [4]. We focus at dissipative structures that evolve at plasma micro- and macro scales and attempt to relate entropy rate extrema to structural transitions between different states of SO. The basic theoretical facts about hybrid model are shown in the second section. Characteristic numerical results in the context of *SO* are exposed in the third and fourth part of this paper.

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 [4]:

$$\frac{\partial a_0}{\partial t} + V_0 \frac{\partial a_0}{\partial x} = -a_1 a_2 \,,$$
$$\frac{\partial a_1}{\partial t} - V_1 \frac{\partial a_1}{\partial x} = a_0 a_2^* \,, \quad (1)$$
$$\frac{\partial a_2}{\partial t} + V_2 \frac{\partial a_2}{\partial x} + \Gamma a_2 + i\sigma |a_2|^2 a_2 = \beta_0^2 a_0 a_1^* \,.$$

The wave–particle interaction [3] is modeled by a damping term in the *epw* equation of (1), Γa_2 which includes a phenomenological anomalous kinetic dissipation and entropy balance related to a kinetic self-organization. Parameter Γ consists of: collisional damping (Γ_{coll}), 'linear' (Landau) damping by hot — resonant electrons ($\gamma_l \sim n_h$), where $n_h(t)$ stands for spatially averaged hot electron density:

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

(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):

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

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

Open boundaries and reemittance 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 equation (effect of plasma heating; E_b, E_h and $S_{tot} \to S_b + S_h + S_q$ are the average bulk and hot electron energy or corresponding energy flux of the bulk, hot and return ambient electrons, respectively) takes a form:

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

3. SIMULATION

The simulation is made via central-difference numerical code [2], which is complemented by equations for generation of resonant electrons (2) and heat balance equation (4) in the wave–particle system.

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. The effect of self-organization at large (wave-fluid) macro-scales is illustrated in Figure 1. Depending on k the system shows characteristic features of different dynamical regimes: steady–state ($k = 0.007$), quasi-periodic ($k = 0.05$), periodic ($k = 0.5$) and intermittent regime ($k > 0.9$).

Figure 2 illustrates the micro-scale, kinetic level of self-organization via temporal evolution of the electron distribution function. In the treatment bi-Maxwellian (bulk–hot) electron distribution, as suggested by kinetic and particle–in–cell (*PIC*) simulations [3,6], was assumed. One can readily observe an essential connection and interplay between two levels of *SO* in a dissipative plasma.

4. DISSIPATIVE STRUCTURES AND ENTROPY RATE

Self-organization in a strongly nonlinear far-from-equilibrium system leads to a creation of ordered states that reflect an interaction of this 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. A large amount of effort has been spent in attempts to relate the entropy rate extrema to structural bifurcations and transitions between different ordered states [1-2].

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. 3), 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. 4 we plot the entropy rate $dS(t)/dt$ in time together with a spatio-temporal profile of the scattered wave energy. We calculate the entropy S related to distributions $F_i = n_i f_i$, as: $S(t) = S_b(t) + S_h(t)$, where

$$S_i(t) = -\int_0^L dx \int_{-\infty}^{\infty} dv\, F_i(x,v,t) \ln F_i(x,v,t) \qquad (i = b, h)$$

For an intermittent regime, 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. An intermittent nature of this regime is shown through a repetitive pattern of behavior. We note that complex dissipative wave structures are mapped onto a more simple entropy rate time series. Intervals of near zero entropy rate during a laminar phase, mean a net balance between the entropy production and its expulsion. This serves as a possible example of a stationary nonequilibrium state realized in a strongly nonlinear open system [1].

Moreover, a hybrid nature of our model also allows us to recover kinetic properties of self-organization. By using an analytical dependence of the electron distribution on varying hot (bulk) temperature and density we expose a genuine picture of kinetic self-organization at plasma micro-scales. To show the self-organization featuring micro-levels, we plot the electron velocity distribution function. In Fig. 2 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. In Fig. 5, we further plot the electron distribution in time versus the entropy rate related to an intermittent regime. Once again, an evidence of micro-scale structural transitions that correspond to entropy rate extrema, is found. Indeed, one is able to observe a complex connection and interplay between macro and micro levels of self-organization in an open dissipative plasma.

5. 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. Although phenomenological, rather than rigorous, our open dissipative 3WI-hybrid model self-consistently accounted for the plasma entropy production and its removal, for both thermal and suprathermal electrons In that way, rich transient Raman complexity gradually gets self-organized and attracted to definite saturated dynamical states, such as: steady-state, quasi-periodic and an intermittent one. 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. 6, 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. 6) show an evident support of above Raman reflectivity pattern (Fig. 1, right top), obtained for a closed ($k = 0.007$) system.

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FIGURE CAPTIONS

Figure 1 Density of hot electrons and reflectivity versus time $[\omega_p^{-1}]$ for $k = 0.007, 0.05, 0.5, 0.9$ (top to bottom) respectively.

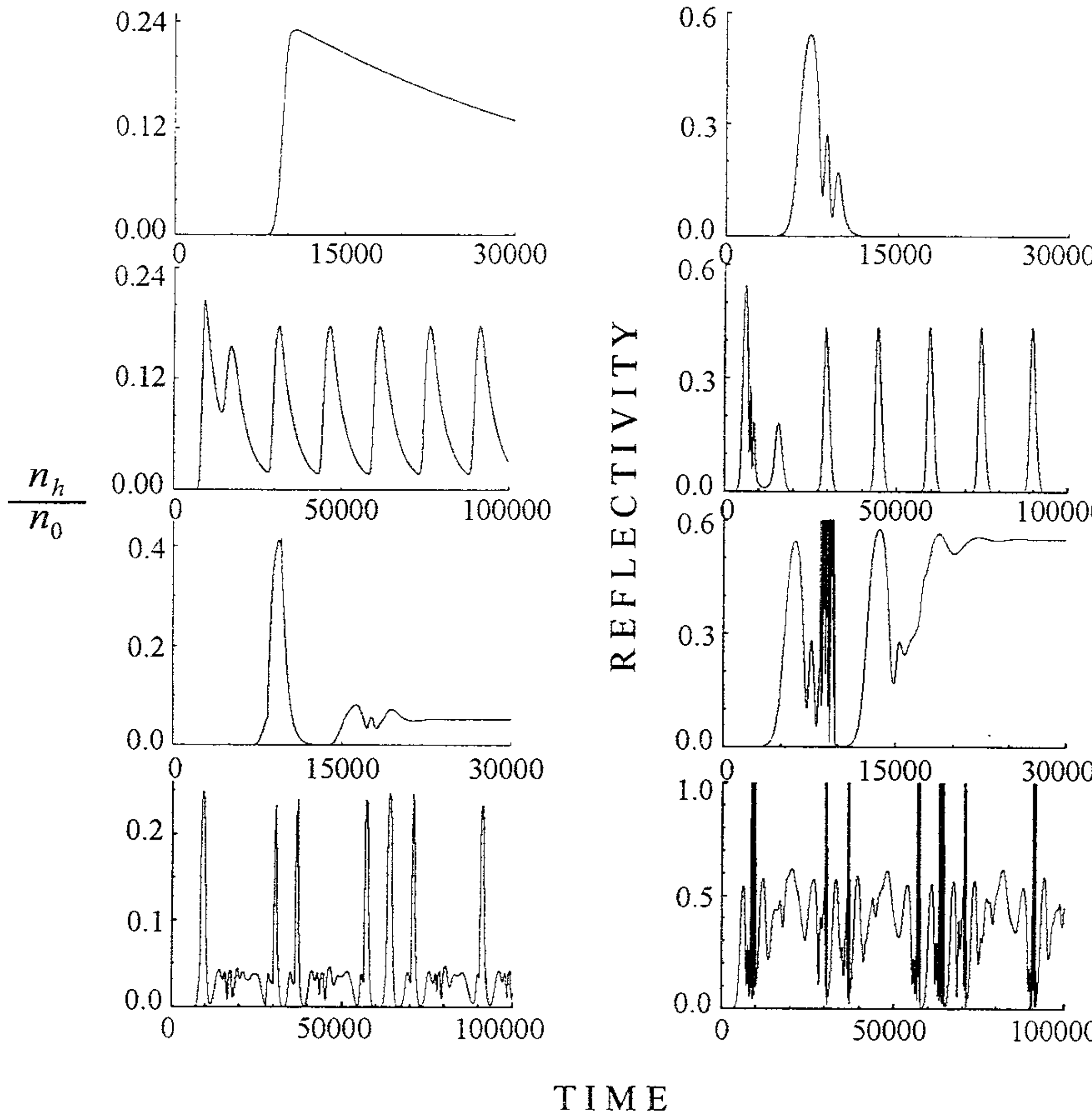
Figure 2 Three-dimensional view of the electron velocity distrubution in time for different saturated Raman regimes, as indicated by values of parameter k. Micro-kinetic scale self-organization of varying complexity is revealed in both thermal and suprathermal (hot) regions of the electron distribution.

Figure 3 Spatio-temporal profile of the electron plasma wave for varying k values. Different dissipative structures are seen on the route to complexity from the steady-state via quasi-periodic to intermittent regimes.

Figure 4 Intermittent dissipative backscatter-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.

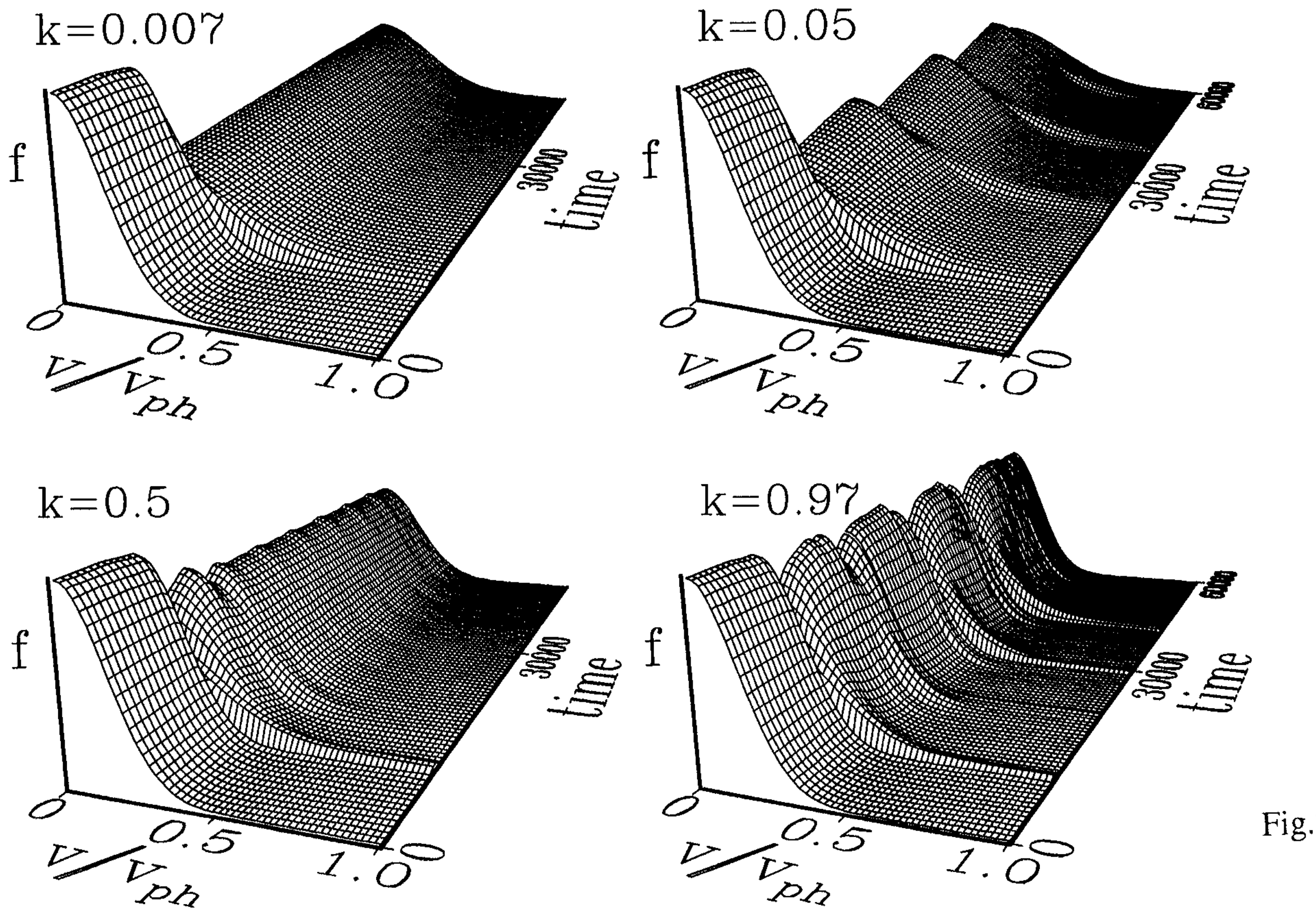
Figure 5 Intermittent electron distribution versus the entropy rate in time. Similar to fig 4, structural bifurcations at micro-scales, correspond to entropy rate extrema.

Figure 6 Simulation data for Raman reflectivity in time, obtained by a one-and-two-halves electromagnetic, relativistic, particle-in-cell code. (after Miyamoto et al. [6]). Initial plasma parameters were the same as above, with a pump equal to 0.02.



0.24
0.12
0.00
0
15000
30000
0.6
0.3
0.0
0.24
0.12
0.00
50000
100000
$\frac{n_h}{n_0}$
REFLECTIVITY
0.4
0.2
0.0
1.0
0.5
0.2
0.1
TIME

Fig.1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f
0
0.5
1.0
0
30000
time
V/V_ph
k=0.05
f
0
0.5
1.0
0
30000
60000
time
V/V_ph
k=0.5
f
0
0.5
1.0
0
30000
time
V/V_ph
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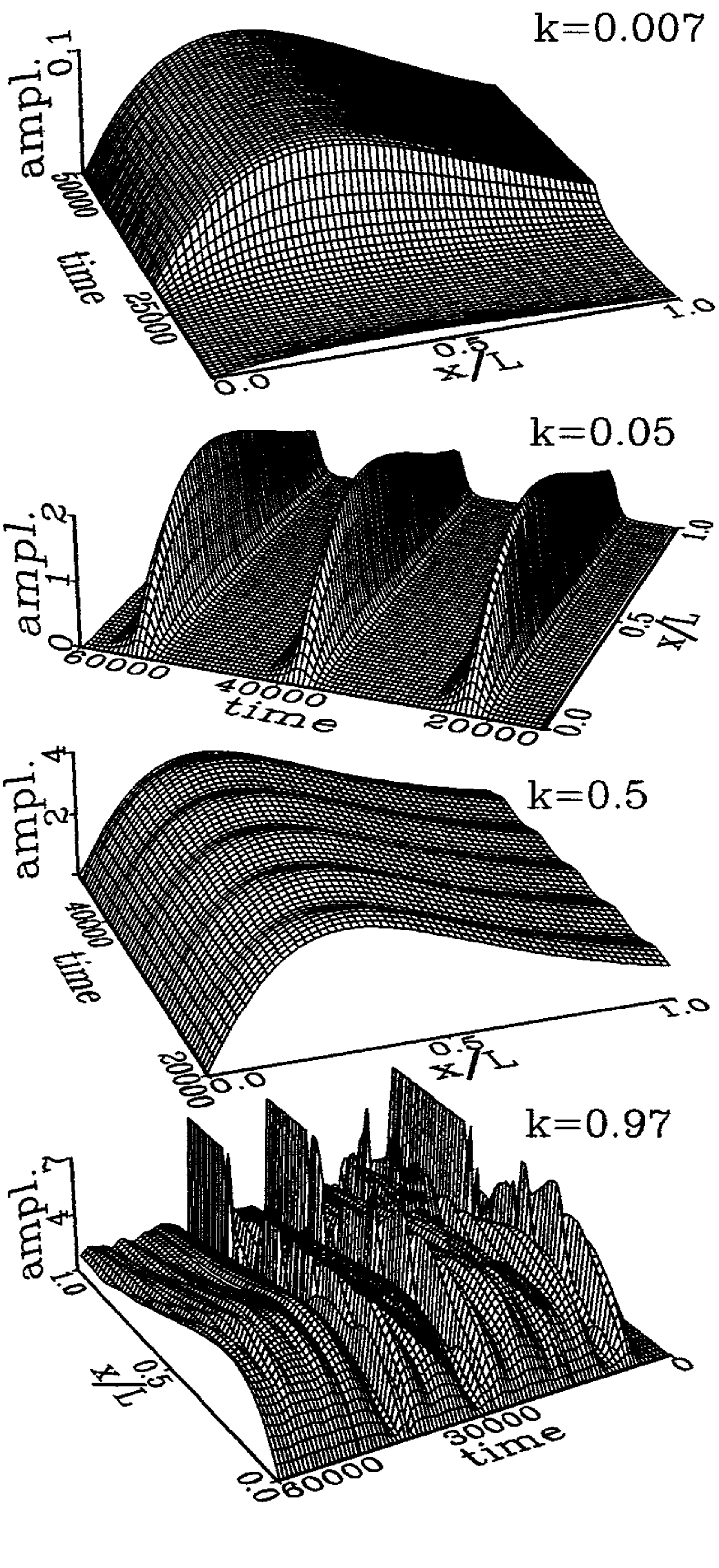
f
0
0.5
1.0
0
30000
60000
time
V/V_ph

Fig.2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0.1
50000
time
25000
0.0
0.5
x/L
1.0
k=0.05
ampl.
0
1
2
60000
40000
time
20000
0.0
0.5
x/L
1.0
k=0.5
ampl.
2
4
40000
time
20000
0.0
0.5
x/L
1.0
k=0.97
ampl.
1
4
7
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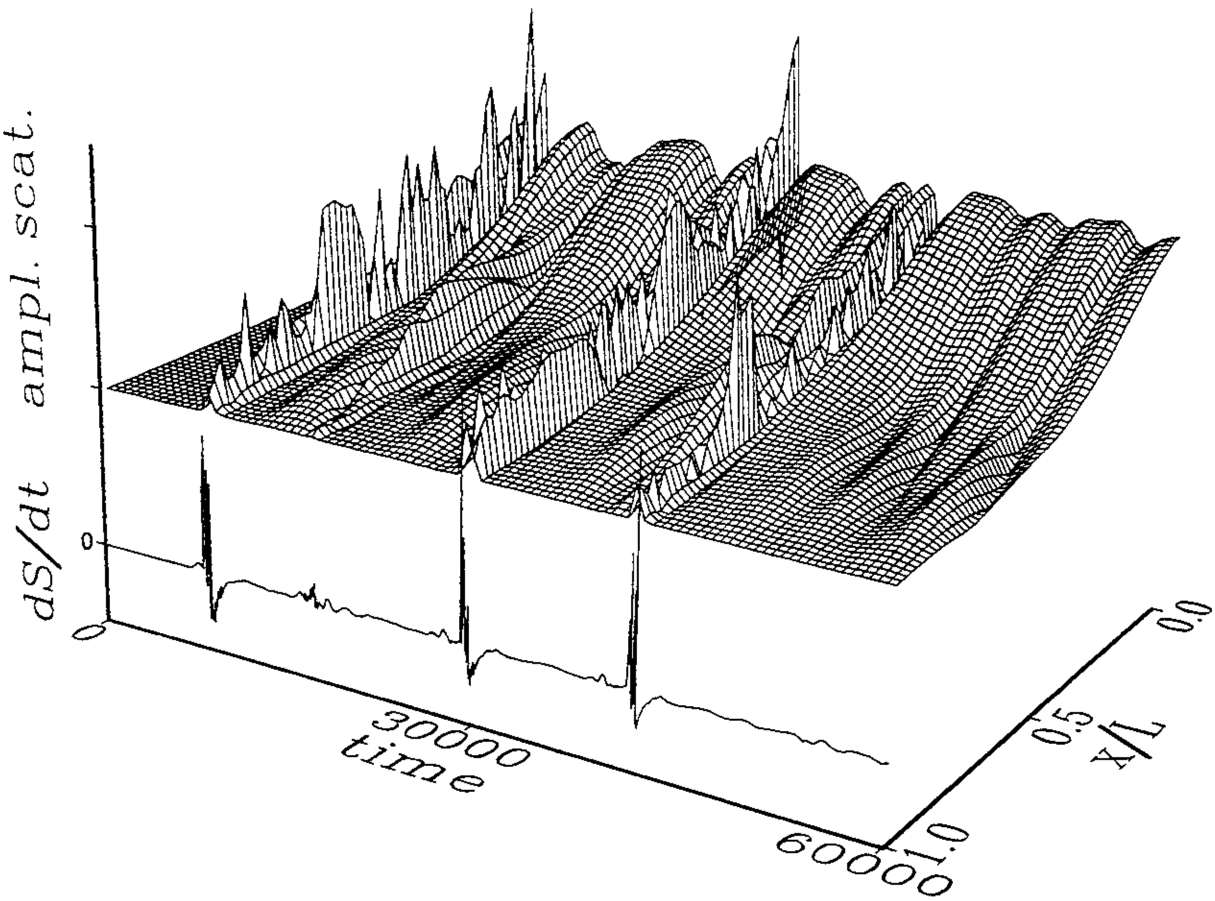
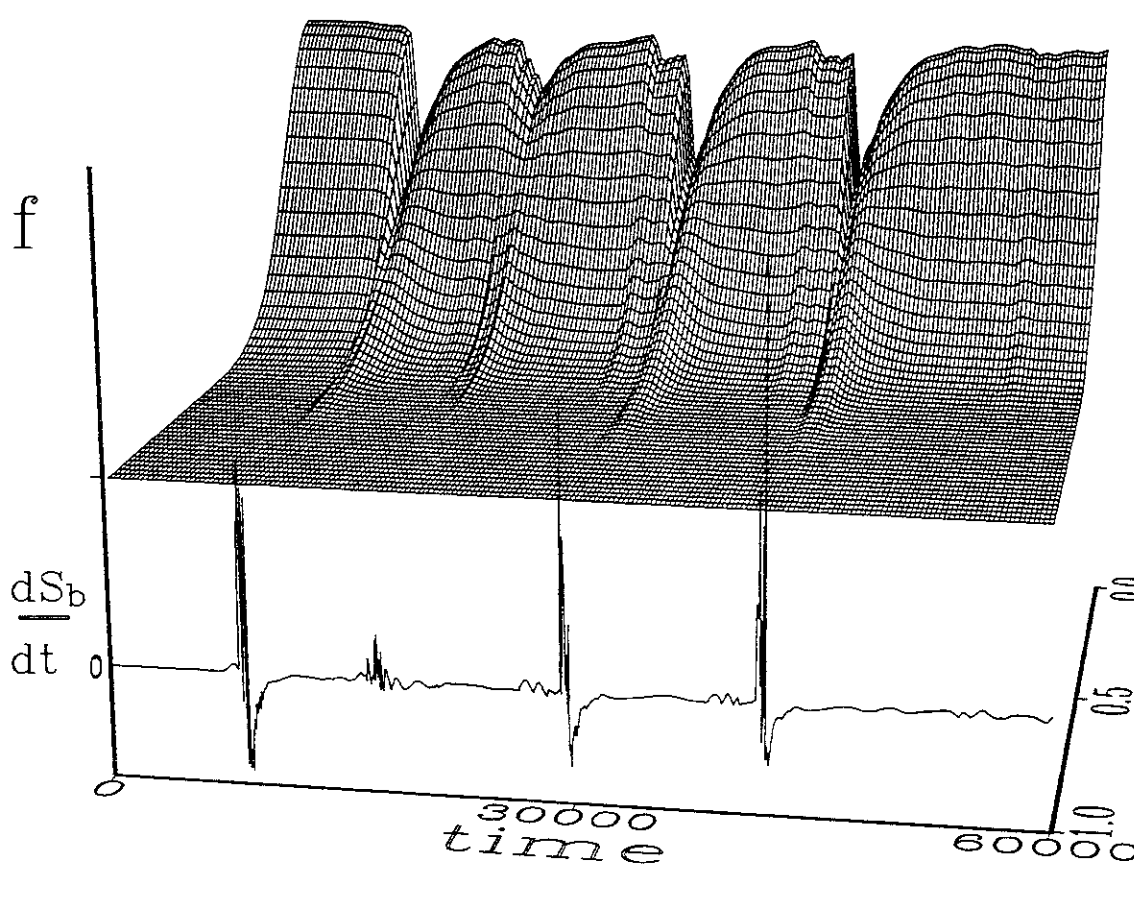
0.5
x/L
1.0
60000
30000
time
0

Fig.3



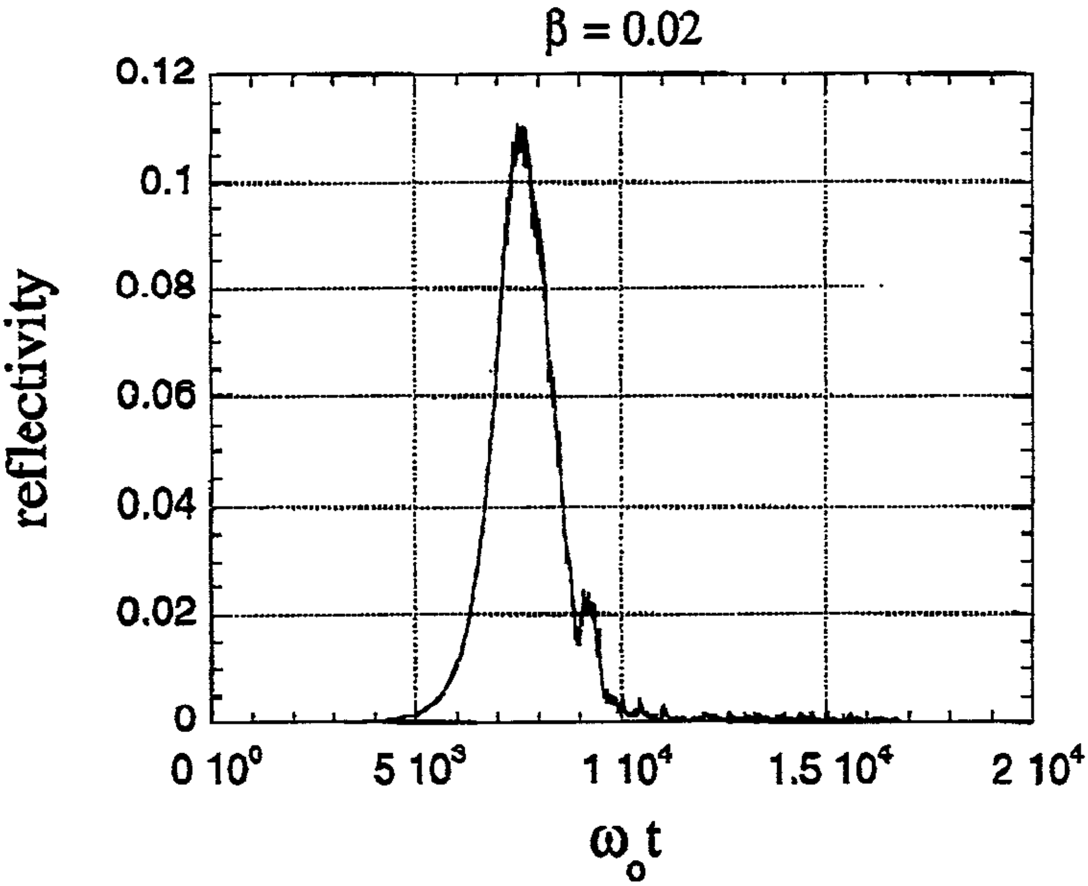
ampl. scat.
dS/dt
0
0
30000
time
60000
0.0
0.5
X/L
1.0

Fig.4



f
dSb
dt
0
0
30000
time
60000
0.0
0.5
V/Vph
1.0

Fig.5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0.12
0.1
0.08
0.06
0.04
0.02
0
reflectivity
0 10⁰
5 10³
1 10⁴
1.5 10⁴
2 10⁴
ω_o t

Fig.6

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