

Kinetic waves induced by electron trapping in Stimulated Raman Scattering in laser-plasma interaction

Alain Ghizzo¹, D. Del Sarto, M. Sarrat, P. Bertrand

Institut Jean Lamour- UMR 7198- Université de Lorraine, Nancy, France

alain.ghizzo@univ-lorraine.fr

Topics

1. Vlasov plasmas
2. Electrostatic case: KEEN waves driven by an external ponderomotive force
3. Electromagnetic case: SRS-B in the kinetic regime
4. Conclusions

Vlasov-Maxwell system (1)

Numerical resolution of the Liouville's equation (also called Vlasov or Boltzmann's equation with collision term)

Its numerical integration is a real challenge in plasma physics.

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \frac{d\mathbf{x}}{dt} \cdot \nabla_x f + \frac{d\mathbf{p}}{dt} \cdot \nabla_p f = 0$$

Vlasov-Maxwell system (2)

Vlasov equation

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m\gamma} \cdot \nabla_x f + \left(\mathbf{E} + \frac{\mathbf{p}}{m\gamma} \times \mathbf{B} \right) \cdot \nabla_p f = 0$$

$$\gamma = \sqrt{1 + \frac{\mathbf{p}^2}{m^2 c^2}}$$

Maxwell equations

$$\text{rot E} = - \frac{\partial \mathbf{B}}{\partial t}$$

$$\text{rot B} = \mu_0 \mathbf{J} + \frac{\partial \mathbf{E}}{c^2 \partial t}$$

$$\text{div E} = \frac{\rho}{\epsilon_0}$$

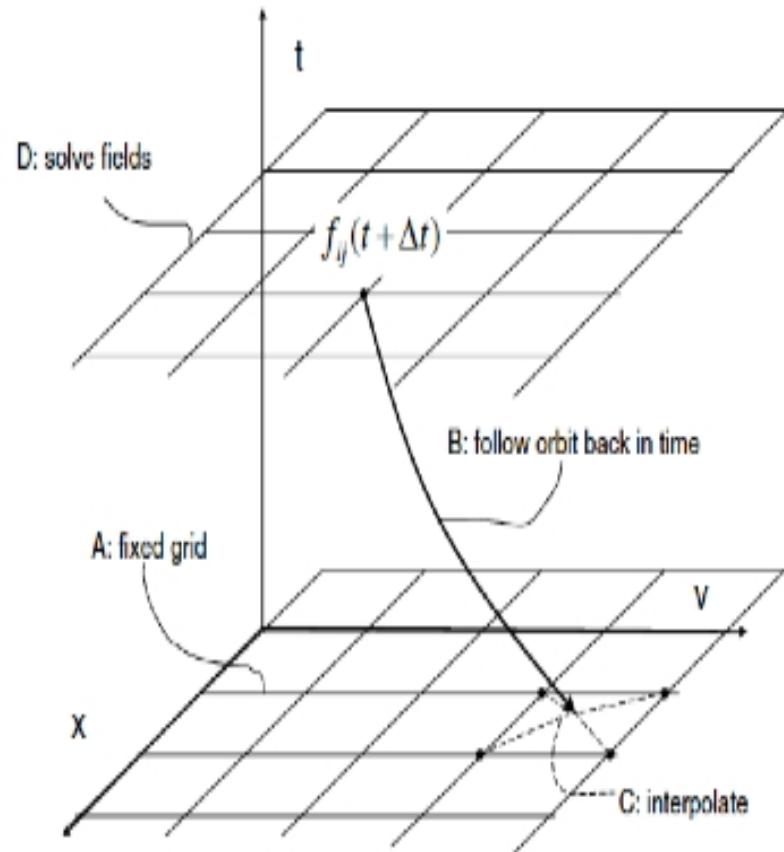
$$\text{div B} = 0$$

Source terms:

$$\mathbf{J} = \iiint \frac{\mathbf{p}}{m\gamma} f d^3 p$$

$$\rho = \iiint f d^3 p$$

Direct attack: Semi-Lagrangian Solvers



Vlasov codes: based on
the resolution of f along
the characteristics
(Newton's laws)

the interpolation of f on
grid points by cubic
splines

E. Sonnendrucker, J. Roche, P. Bertrand, **A. Ghizzo**, JCP. 149, 201 (1999).

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Montgomery et al.'s PRL :

Experimental observation of Trapped Electron Acoustic Waves (TEAW), a class of Kinetic Electrostatic Electron Nonlinear (KEEN) waves

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Observation of Stimulated Electron-Acoustic-Wave Scattering

D. S. Montgomery,¹ R. J. Focia,² H. A. Rose,¹ D. A. Russell,³ J. A. Cobble,¹ J. C. Fernández,¹ and R. P. Johnson¹

¹*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*

²*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

³*Lodestar Research Corporation, Boulder, Colorado 80301*
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A diffraction-limited laser interacts with a plasma whose conditions are uniform on the scale of the focused laser spot. Two distinct, narrow waves are observed in the backscattered spectrum with phase velocities of $v_\phi/v_e = 1.4 \pm 0.08$ and 4.2 ± 0.1 , where v_e is the electron thermal speed. The high-velocity wave is ordinary stimulated Raman scattering (SRS) from a Langmuir wave. The low-velocity wave corresponds to stimulated scattering from an electron-acoustic wave (SEAS), and implies strong electron trapping. Previous SRS data from low-density plasmas are reinterpreted in terms of SEAS.

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PACS numbers: 52.35.Fp, 52.35.Mw, 52.35.Sb, 52.38.-r

BIBLIO: DGK-style waves: EPW & (T)EAW

- [6] I. B. Bernstein, J. M. Greene, and M. D. Kruskal, Phys. Rev. **108**, 546 (1957).
- [7] H. Schamel, J. Plasma Phys. **13**, 139 (1975); Phys. Scr. **20**, 336 (1979); Phys. Plasmas **7**, 4831 (2000), and references therein.
- [8] J. P. Holloway and J. J. Domínguez, Phys. Lett. A **138**, 279 (1989); Phys. Rev. A **44**, 3856 (1991).

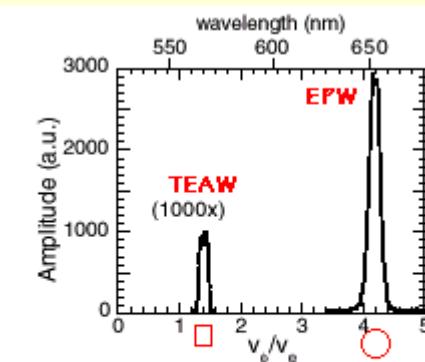
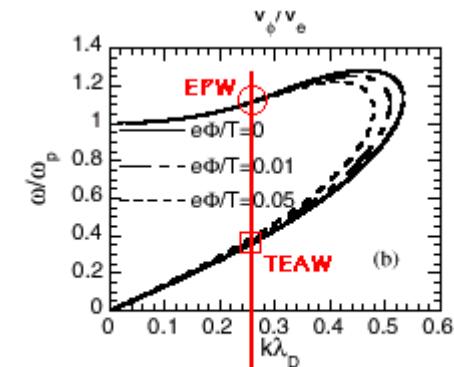


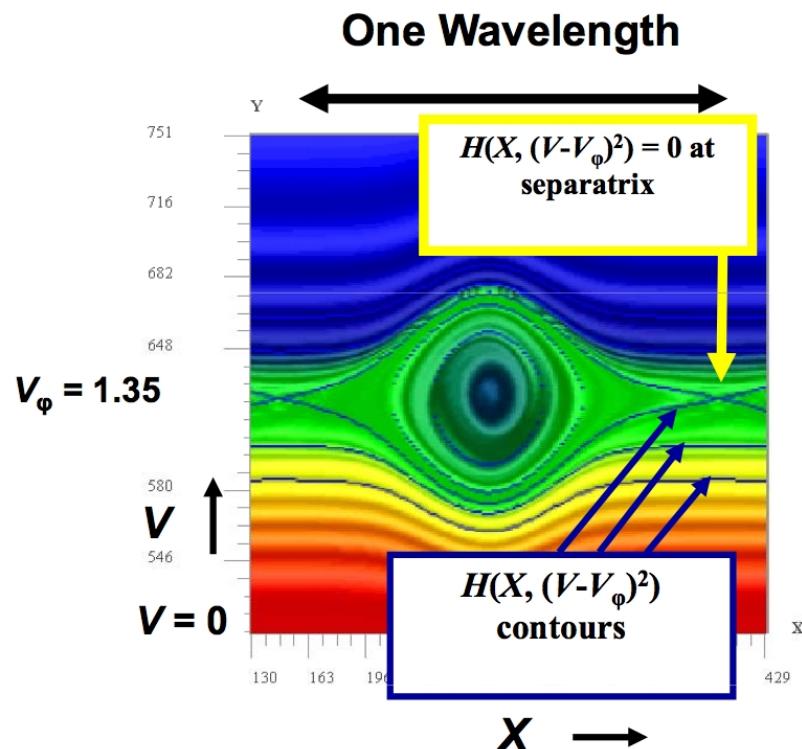
FIG. 1. Plot of SEAS and SRS backscatter spectrum versus electrostatic wave v_ϕ/v_e for the single hot spot experiment. SEAS mode is shown 1000× larger. Upper axis corresponds to the scattered light wavelength.



selected by laser scatter geometry

Kinetic Electrostatic Electron Nonlinear (KEEN) waves (3)

Stable Non-sinusoidal KEEN $f(X, V)$ $\lambda = 3.84$
 $I_D (= 256 \Delta x \text{ cells})$



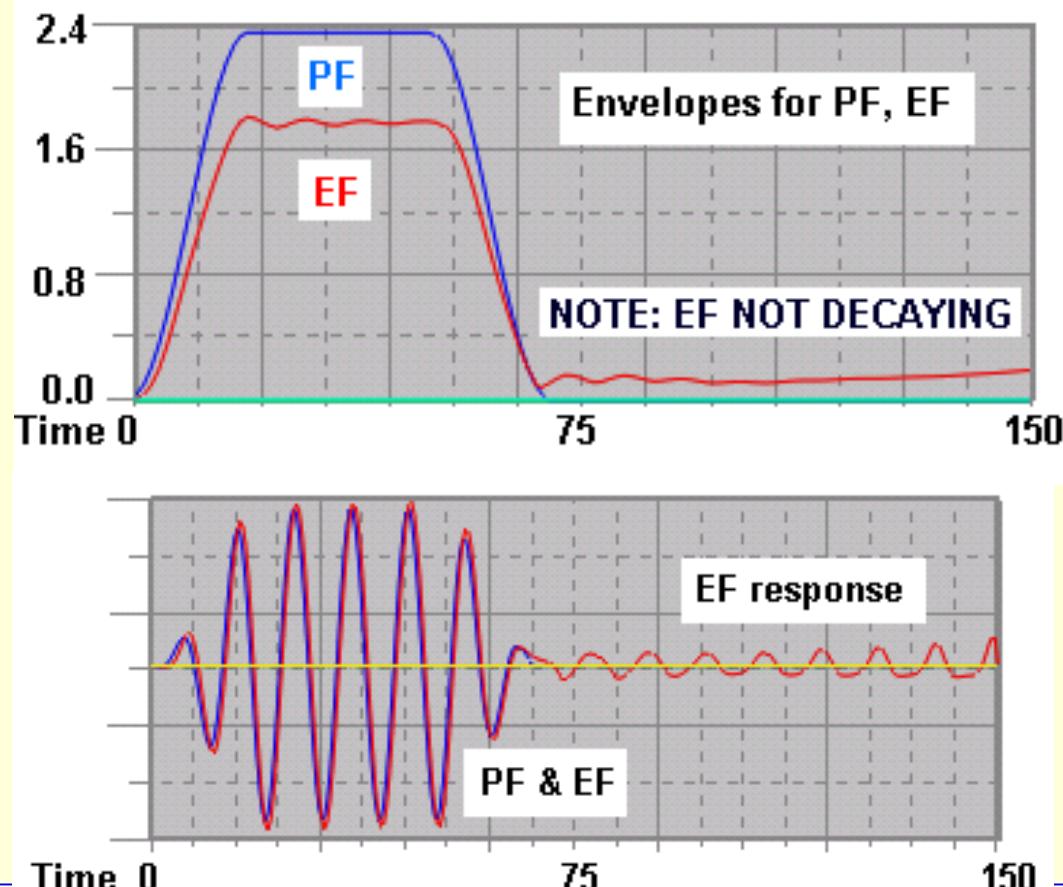
Bernstein- Greene-Kruskal (BGK) waves are solution of the stationary Vlasov-Poisson system

BGK are self-sustained solutions characterized by hole in the phase space. Phase space holes behave as quasi-particles

BGK are ideal nonlinear solutions, not always accessible to real situations, their emergence from a homogeneous plasma is not explained

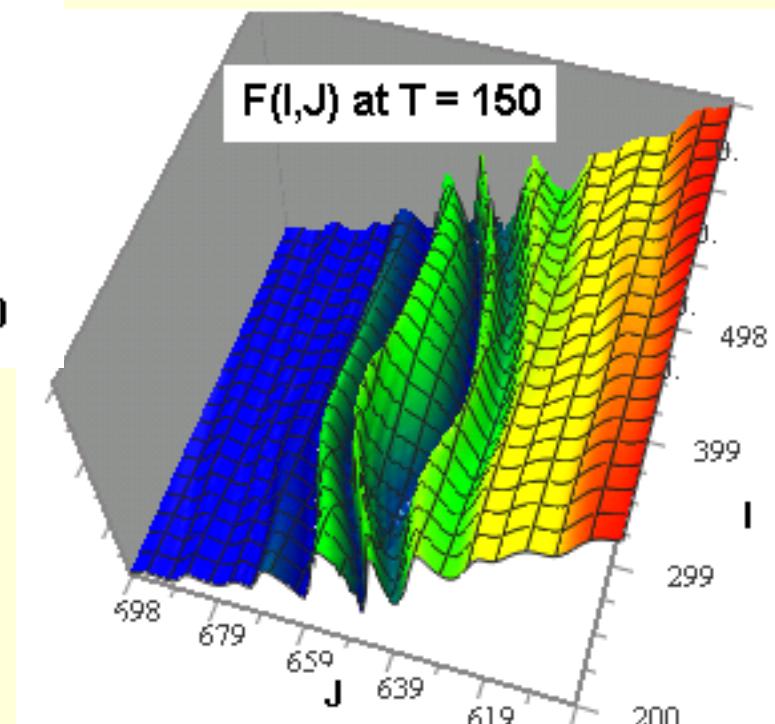
**KEEN waves driven near the "Soft" Threshold.
Dilemma: To Decay or to Form Phase Space
Vortices?**

Max PF = 0.017

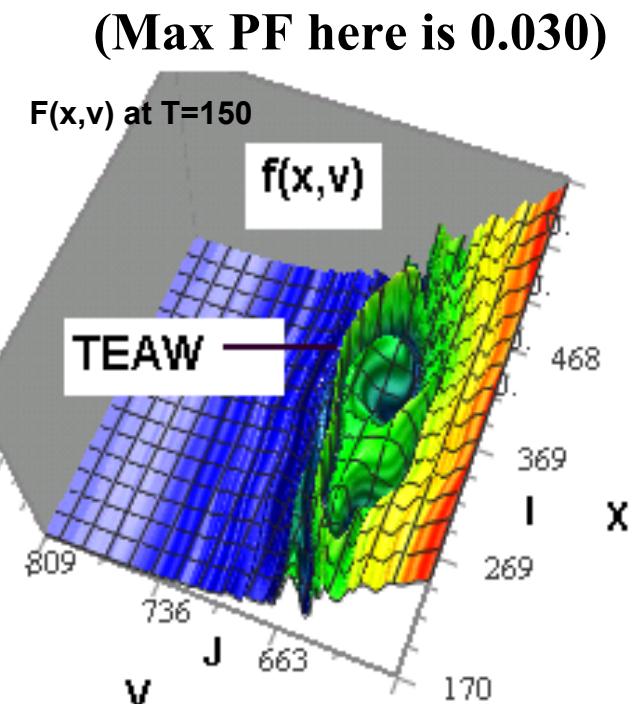
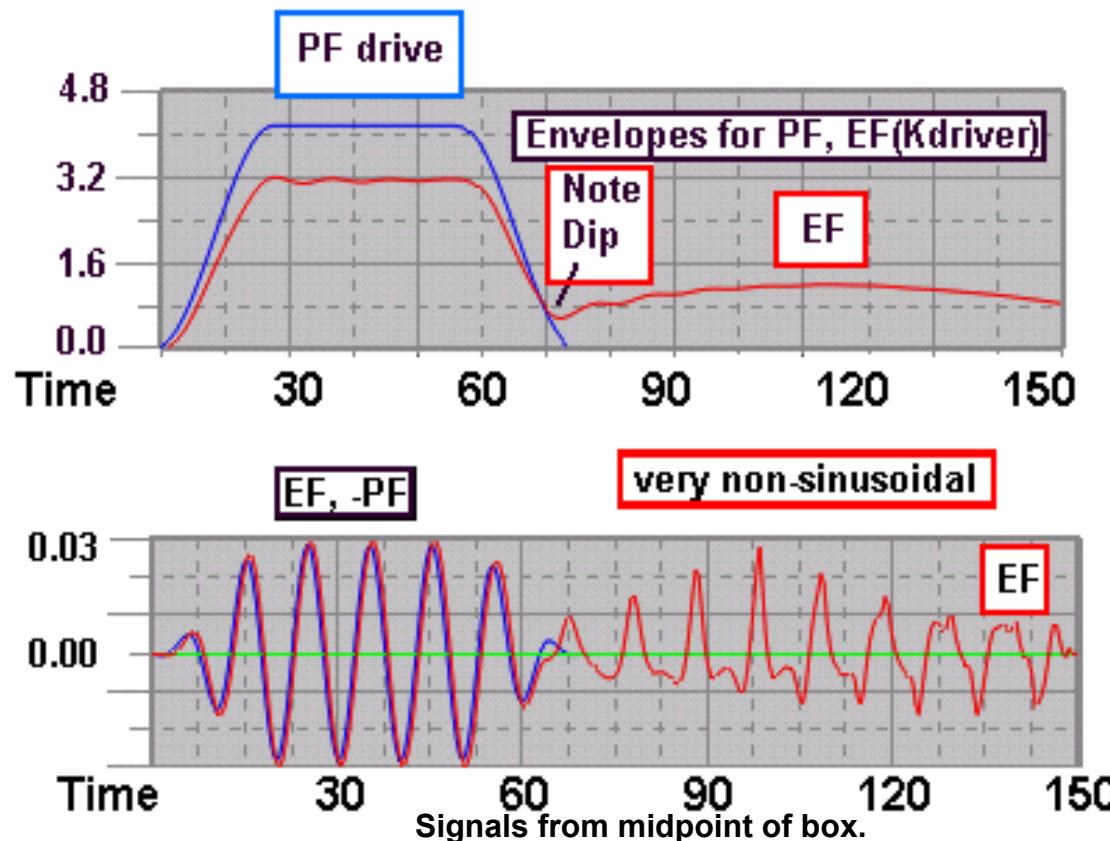


TEAW, K=0.39...

PF(max) = 0.017 gives a marginal TEAW, surviving well after PF => 0

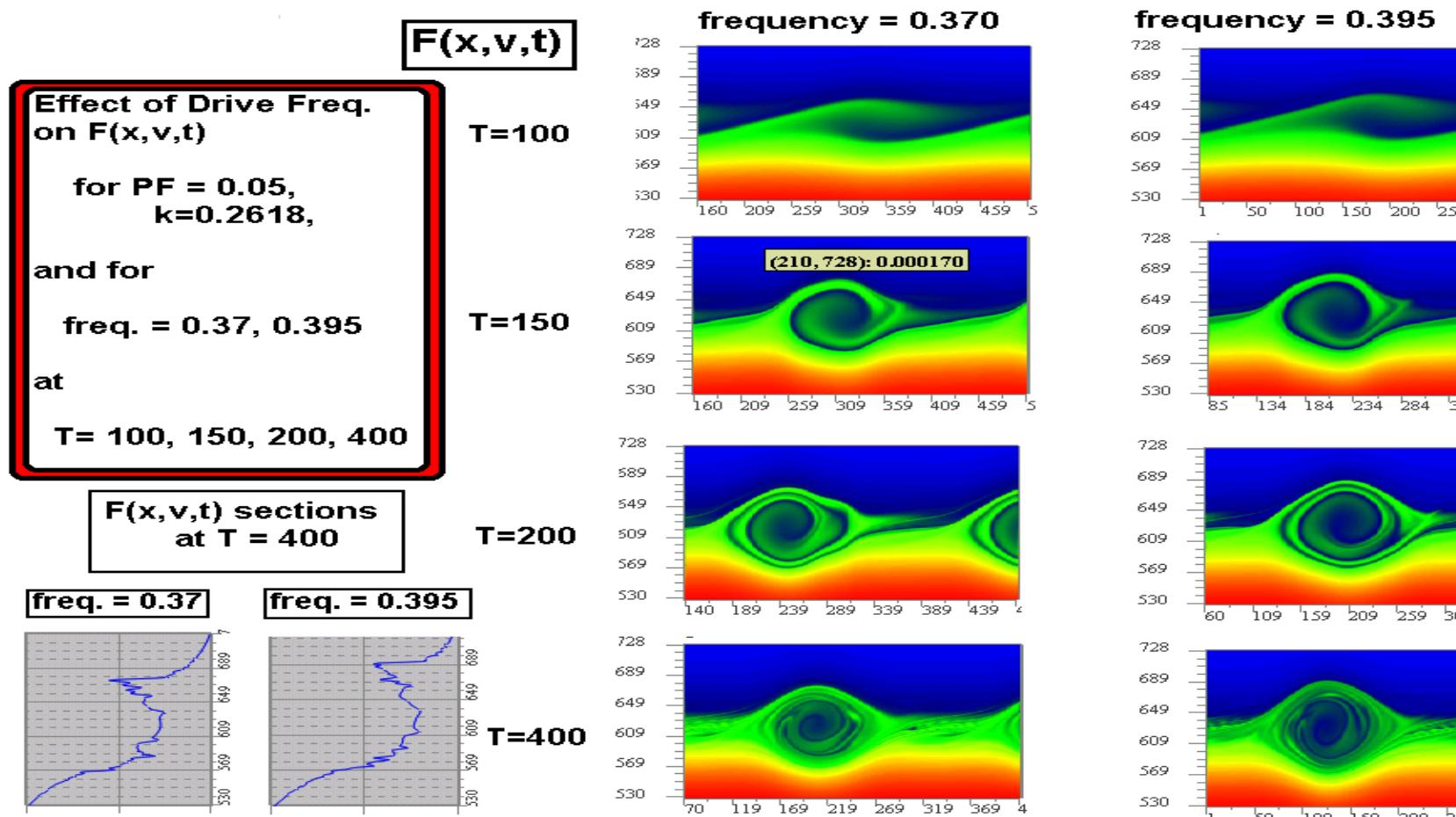


**KEEN wavess, Driven somewhat
Over their "Soft" Threshold, (e.g. 2x)
Show Resurgence, but then Hobble & Barely Survive**



T.W. Johnston, Y. Tyshetskly, A. Ghizzo, P. Bertrand, Physics of Plasmas 16 (4) 042105 (2009).

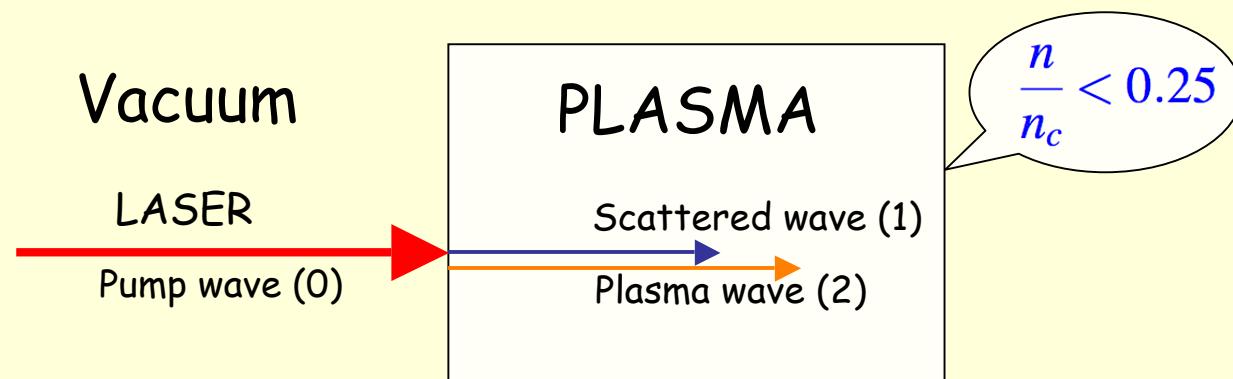
KEEN waves: emergence of self-sustained holes



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SRS- B : 3 mode coupling



Electron plasma in a fixed ion homogeneous background

Quasi particles (photons, plasmons)
Energy conservation

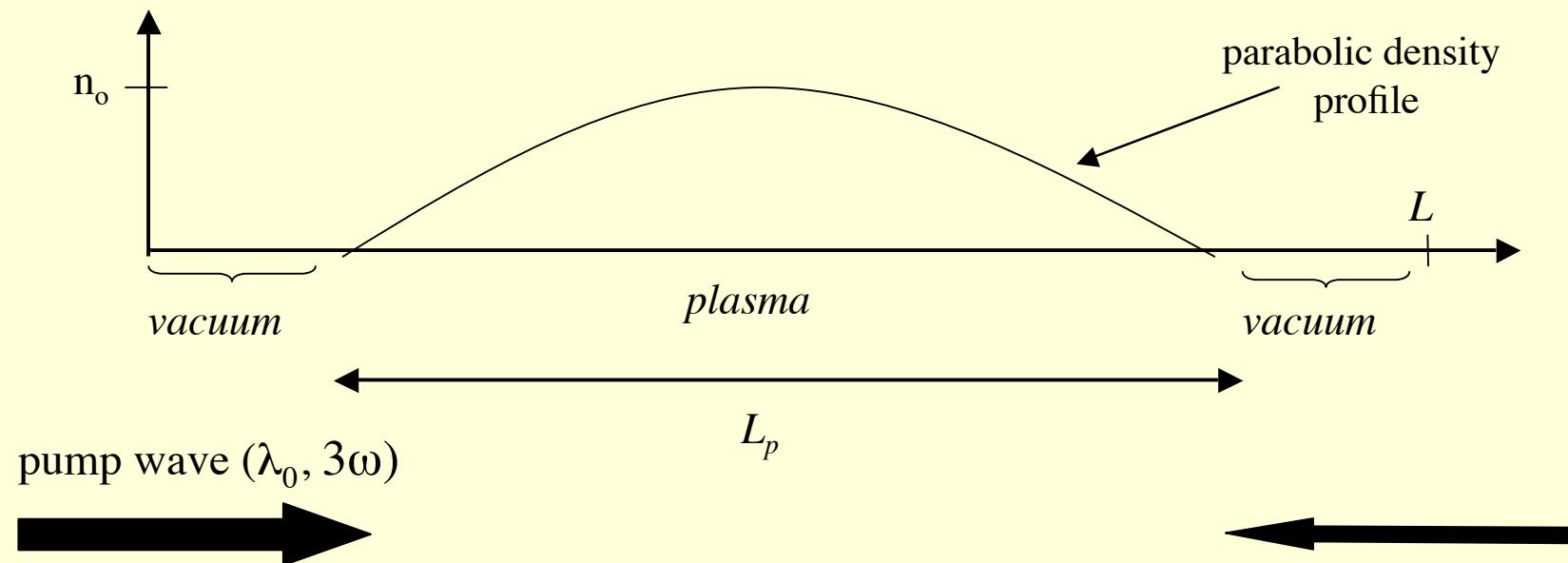
$$\omega_0(k_0) = \omega_1(k_1) + \omega_2(k_2)$$

Momentum conservation

$$k_0 = k_1 + k_2$$

SRS-B in the « kinetic » regime (2)

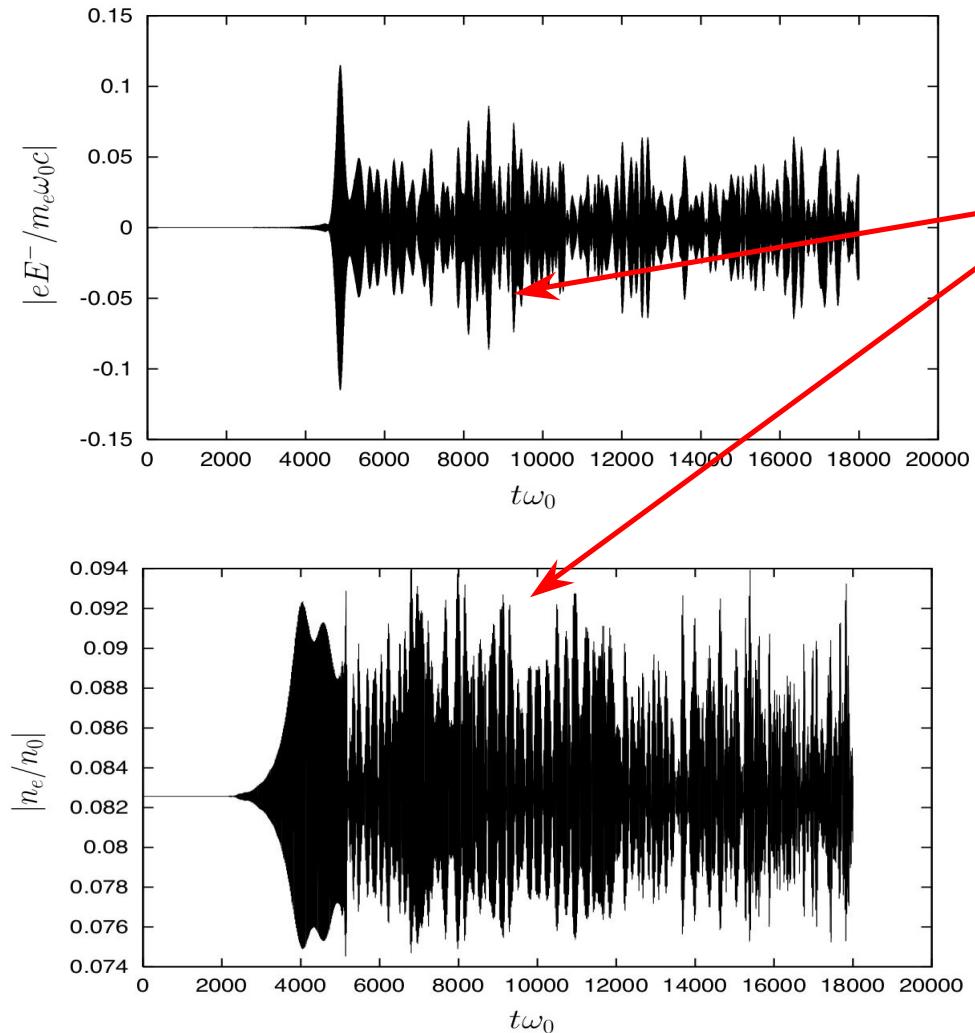
Initial conditions



Numerical parameters :

- $\lambda_0 = 1/3 (1.06)\mu\text{m} \approx 0.353\mu\text{m}$ / $\lambda_s = 1/2 (1.06)\mu\text{m} = 0.53\mu\text{m}$
- $\omega_0^{-1} \approx 2.10^{-16}\text{s} = 0.2\text{fs}$
- Plasma length : $640 \lambda_0 \approx 230\mu\text{m}$

SRS-B in the « kinetic » regime (3)



- SRS-B reflectivity presents a bursting behavior

$$\omega_0 = \omega_s + \omega_{epw}$$

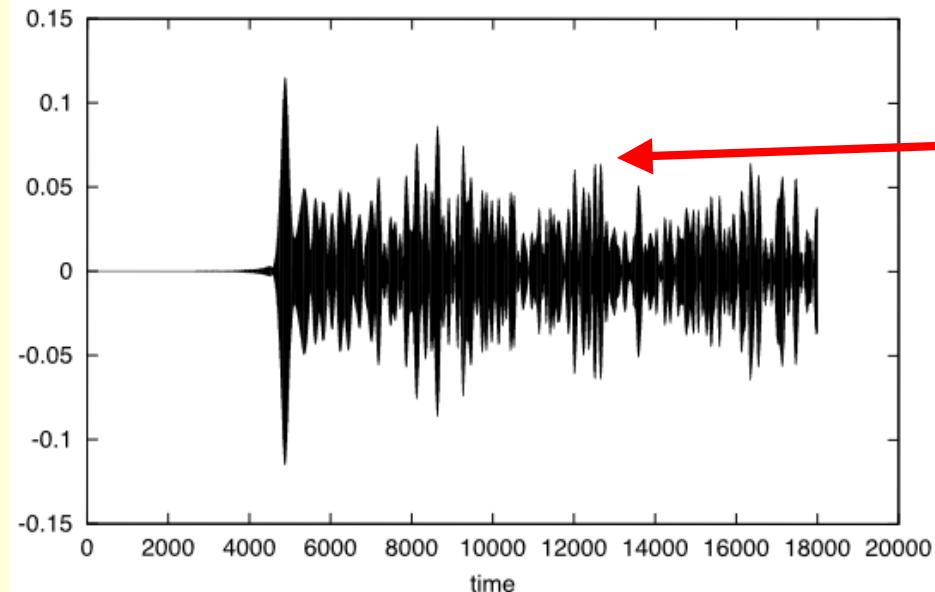
$$1 = 2/3 + 1/3$$

$$k_0 = -k_s + k_{epw}$$

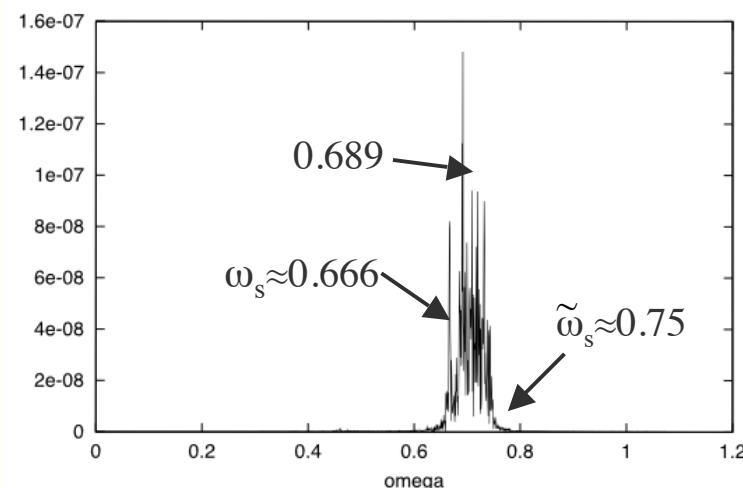
$$0.957 = -0.60 + 1.559$$

- Nonlinear frequency shift - G.J. Morales and T.M. O'Neil, PRL 28, 417 (1972) -

SRS-B in the kinetic regime (4)



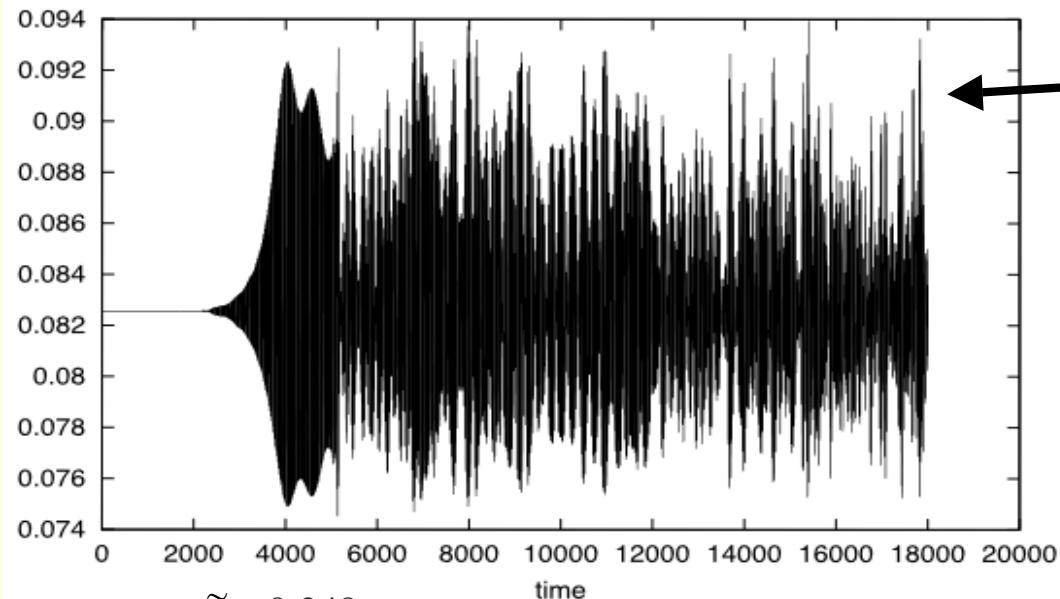
After a fluid-like phase, kinetic effects induce a bursting behaviour in both scattered and plasma modes



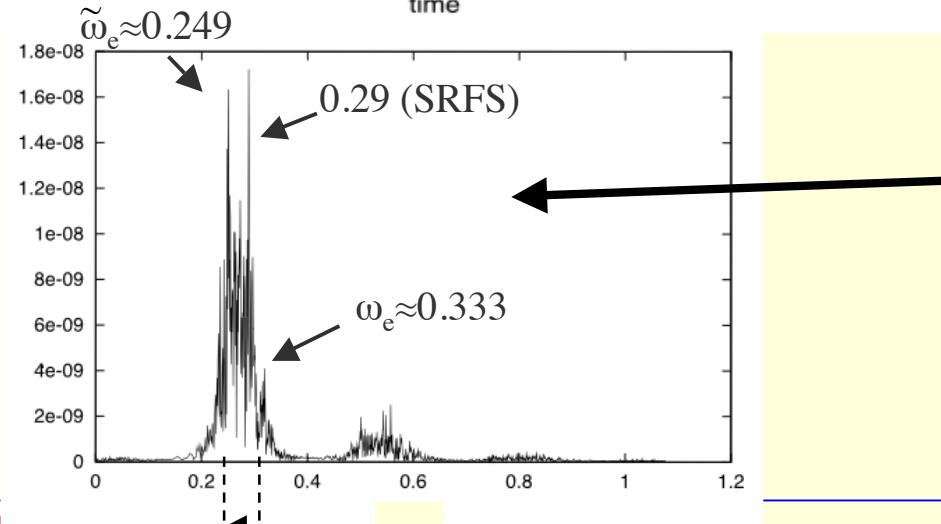
E- reflected ω -spectrum

M. Albrecht-marc, A. Ghizzo et al,
Phys Plasmas 14, 072704 (2007).

SRS-B in the kinetic regime (5)

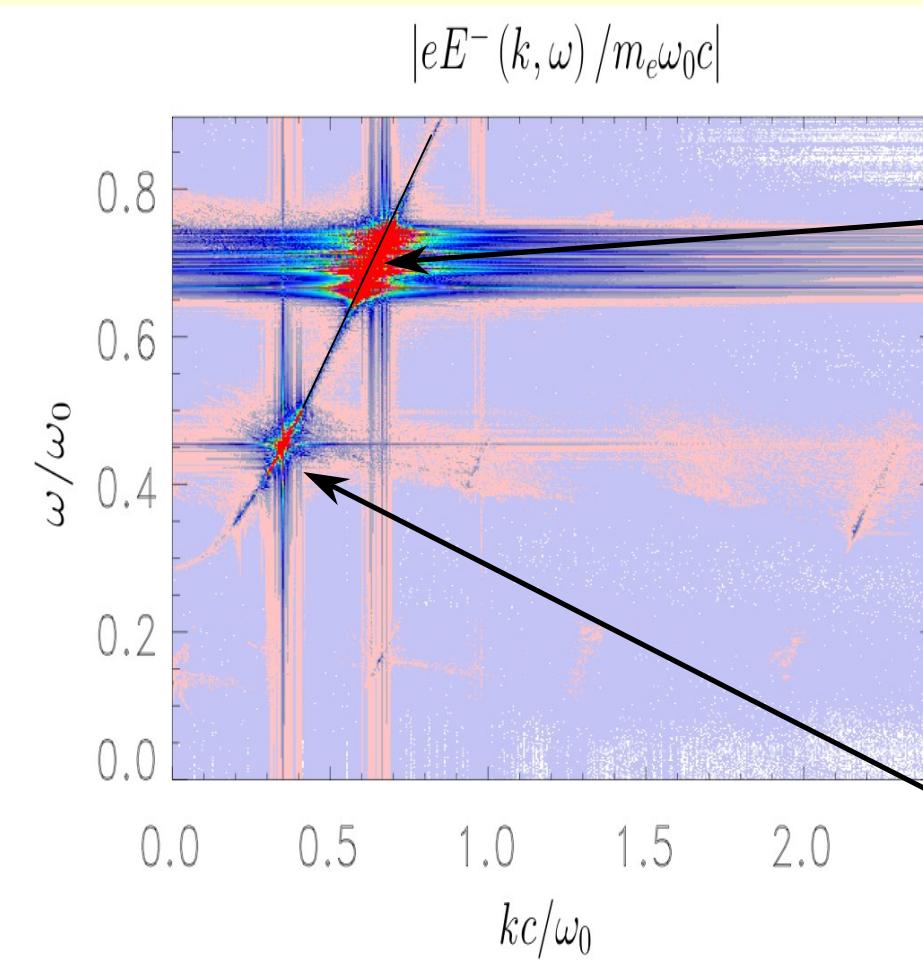


- Bursting behavior in the time evolution of the electron density



$n_e \omega$ -spectrum

SRS-B in the « kinetic » regime (6)



- Maintain of SRS-B resonance

$$\omega_0 = \omega_s(\tilde{k}_s) + \omega_{epw} - \delta\omega$$

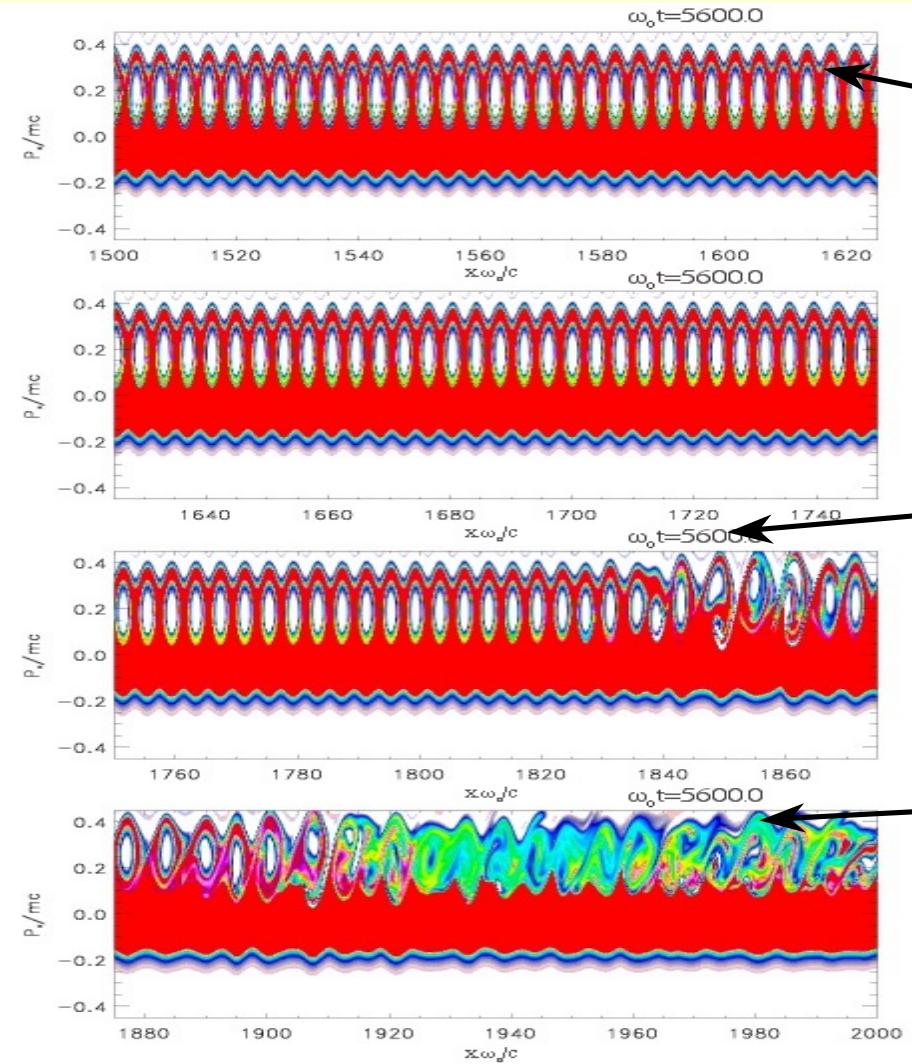
$$k_0 = -\tilde{k}_s + k_{epw} + \delta k$$

$$\tilde{\omega}_s = \omega_s(k_s) - \delta k \left(\frac{\partial \omega}{\partial k} \right)_{k_s}$$

$$\tilde{\omega}_s = \omega_s - \delta k v_{gs}$$

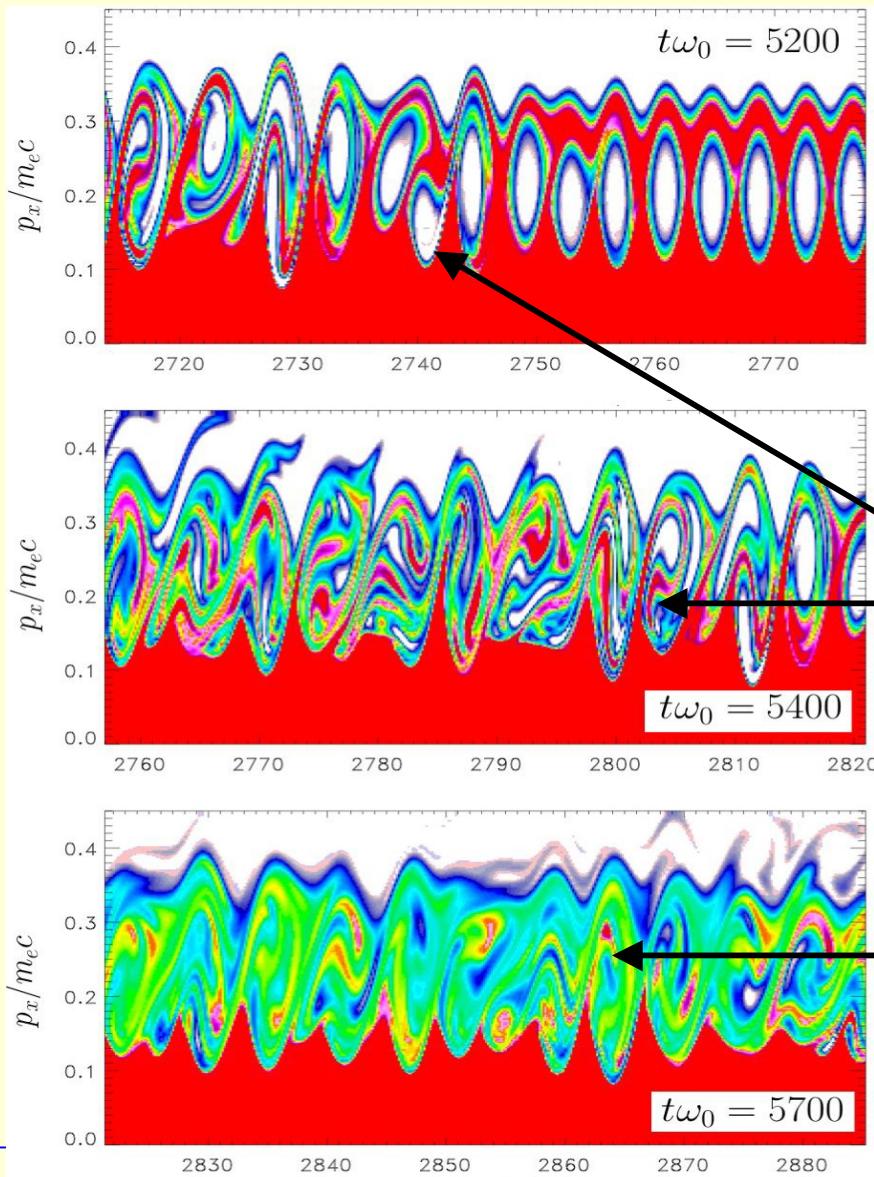
- Raman rescattering instability involving KEEN waves and SRS-F scattered light

SRS-B in the « kinetic » regime (7)



- Langmuir wave induced by SRS-B process
- Vortex-merging leading to weak turbulence
- BGK-like self-sustained structures (persisting over a long time)

SRS-B : Diagnostics of moving windows



We follow the same
particle population (the
window moves at the
linear phase velocity)

Vortex-merging leading to
weak turbulence

BGK-like self-sustained
structures (persisting
over a long time)

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Conclusions

Kinetic effects are dominated by trapped particles leading to phase space holes which suppress the Landau damping

Kinetic effects in plasmas allow more phenomena than are found using only fluid theory with « ad hoc » kinetic damping.

Vlasov code are adapted to study parametric instabilities (SRS, SBS) in the new « kinetic » regime in laser-plasma interaction