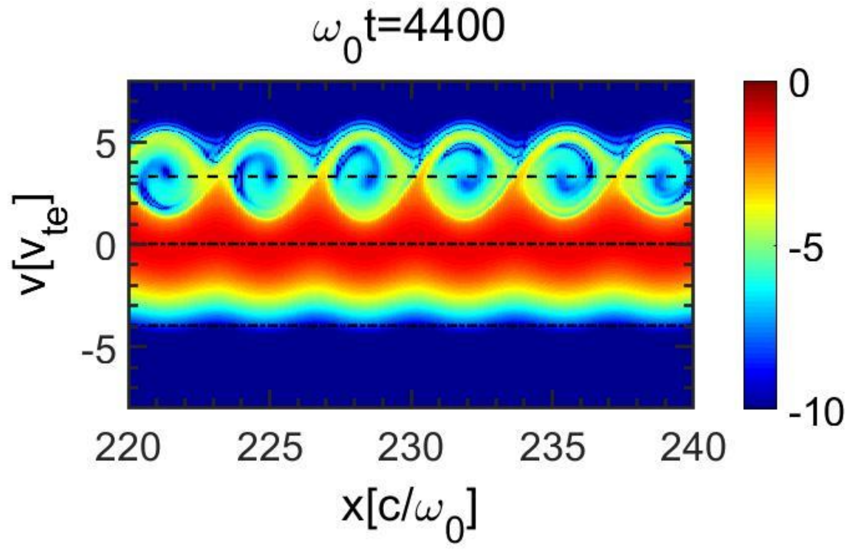
Phase space dynamics of trapped electrons in plasma waves

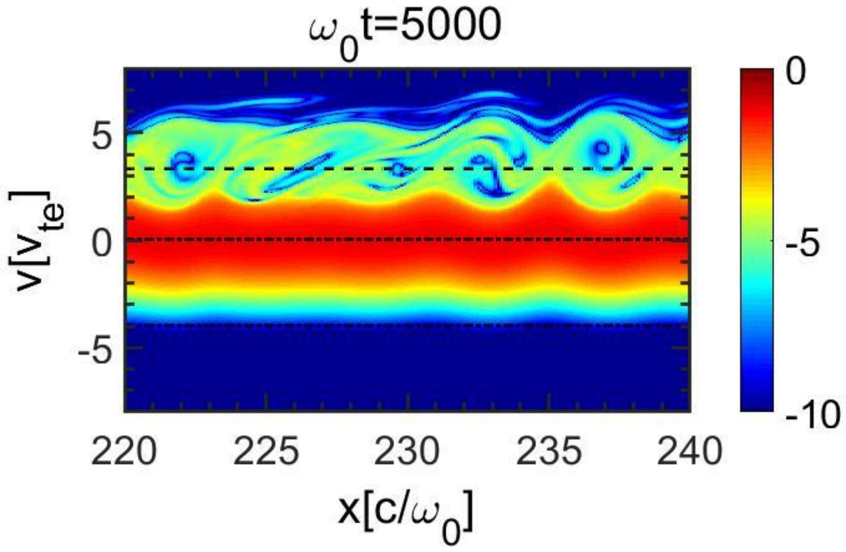
C.S. Liu

Presented at Theory Festival, France

July 2019

Phase space dynamics of trapped electrons in plasma wave in SRS





Phase space dynamics of trapped electrons in unstable plasma wave with a warm beam

Nonlinear Evolution and Saturation of an Unstable Electrostatic Wave

B. D. Fried, C. S. Liu
R. W. Means, and R. Z. Sagdeev

August, 1971 PPG-93

Abstract

The nonlinear development and saturation of a single Langmuir wave driven unstable by a gentle bump in the tail of the distribution function in a collisionless plasma is studied by treating the resonant particles numerically. Over a wide range of parameter values, the amplitude of the potential ϕ is found to saturate at such a level that the ratio $g \equiv \omega_b/\gamma_o \simeq 3.2$, where $\omega_b = (ek^2\phi/m)^{1/2}$ is the bounce frequency of the trapped particles in the wave trough and γ_o is the linear growth rate, approximately given by the classical Landau value. In view of the importance of inverse Landau damping for many instabilities, this work should have wide applicability and the results should be suitable for direct experimental tests.

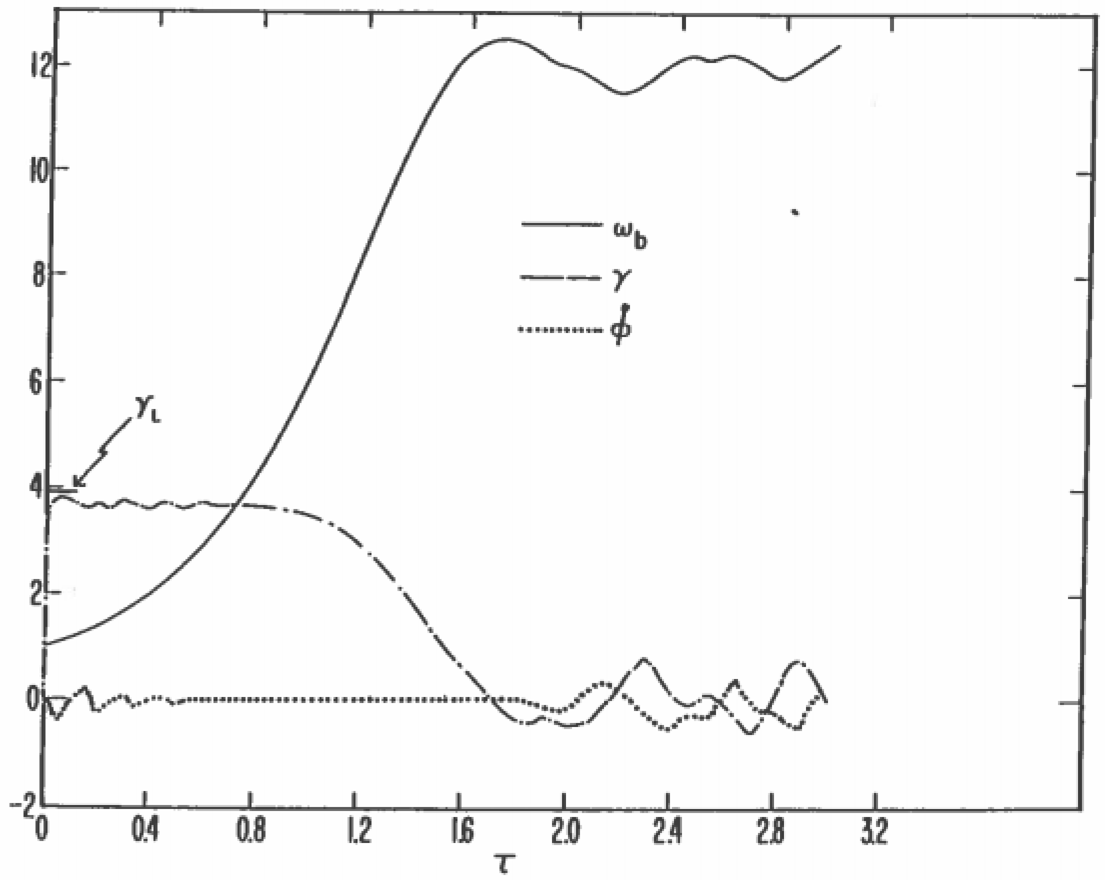


Fig. 2. Temporal evolution of the instantaneous frequency, $\omega_b(t) = [eE(t)k/m]^{1/2}$; growth rate γ_j; and frequency shift, ϕ ; for case A of Table I, with $N_v = 960$ and $N_z = 4$. The vertical scale is in the unit of initial bounce frequency, ω_{bo}; the horizontal scale is in the unit of ω_{bo}^{-1}. The Landau value, γ_L, given by (14), is also shown.

Parametric Instability in Laser Plasma Interaction and Nonlinear transition from convective to absolute instability of SRS

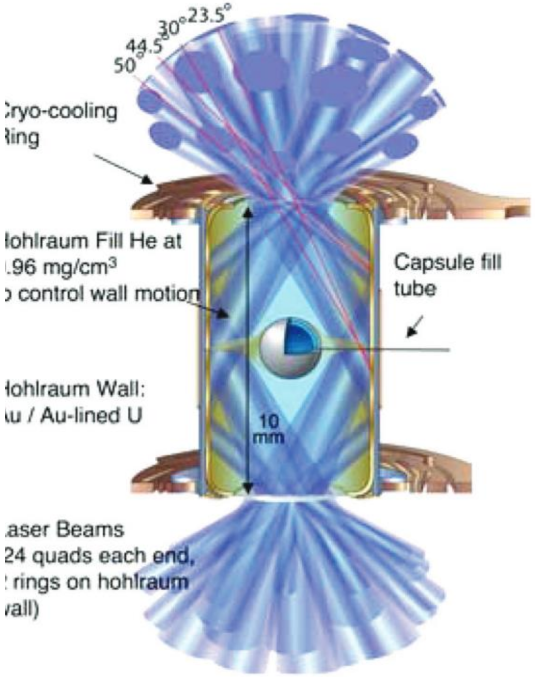
C. S. Liu

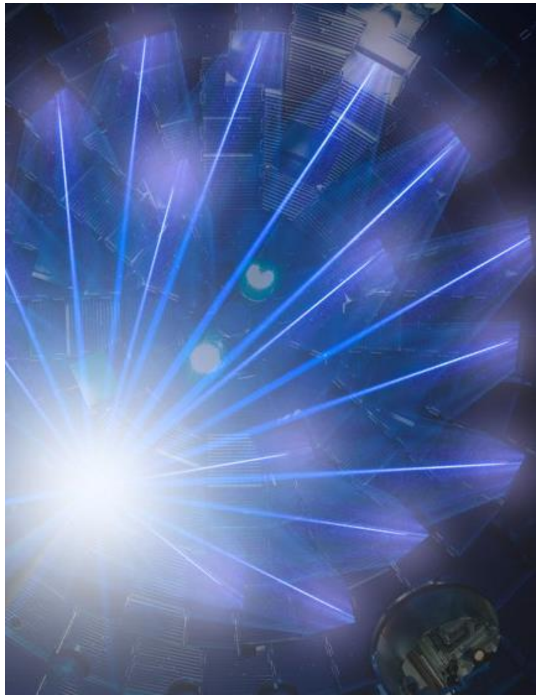
University of Maryland

In collaboration with Y. X. Wang, Q. Wang, C. Y. Zheng, Z. J. Liu and X. T. He

Drawing of Marshall Rosenbluth by Mike Campbell of LLE Rochester

Indirect Drive





National Ignition Facility (NIF)

1.85 MJ, 192 Lasers, 500 trillion watts, 3.5 billion dollar

Raman Scattering:
a reason for NIF failure to ignite, 2012

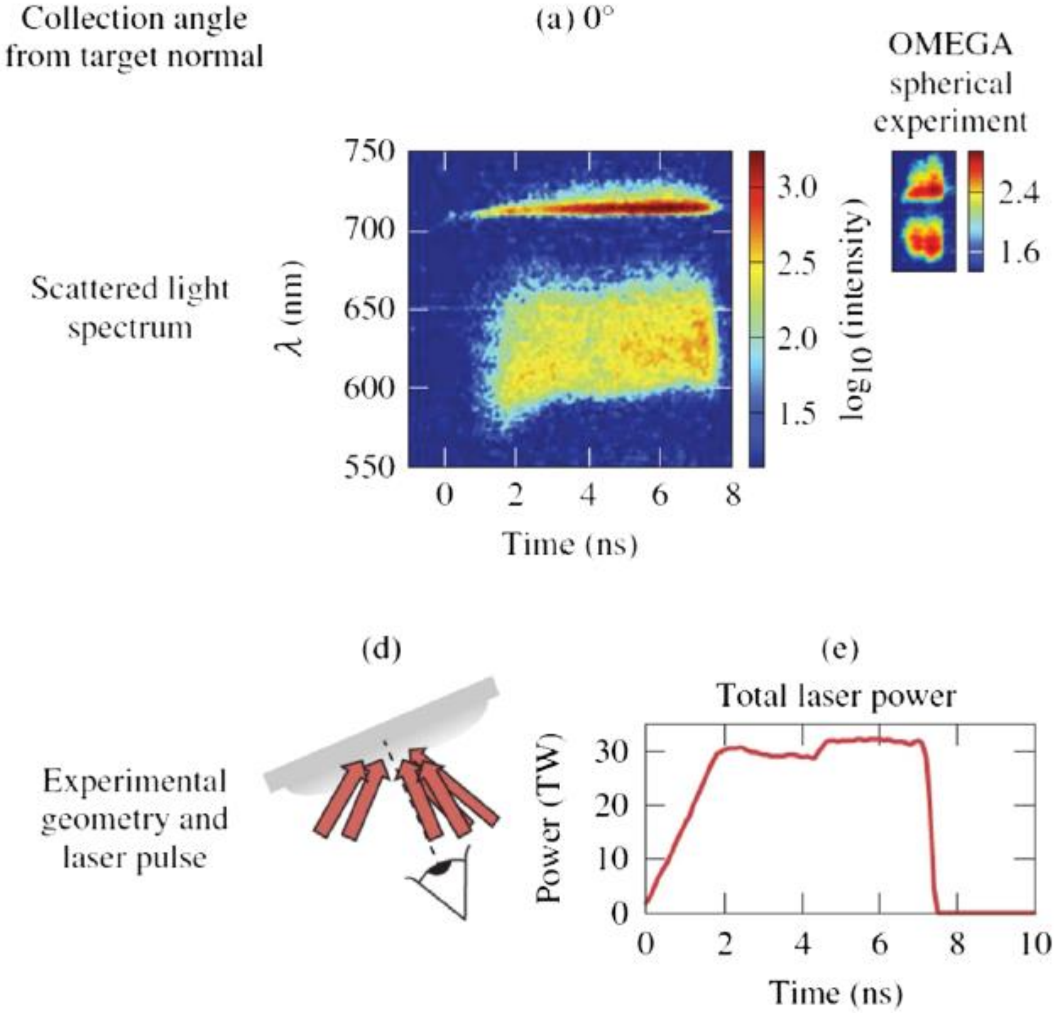
30% of laser being backscattered by
stimulated Raman instability
How it can be remedied or avoided?
We must first understand the physics.

Direct Drive

PHYSICAL REVIEW LETTERS **120**, 055001 (2018)

Origins and Scaling of Hot-Electron Preheat in Ignition-Scale Direct-Drive Inertial Confinement Fusion Experiments

M. J. Rosenberg,[1,*] A. A. Solodov,[1] J. F. Myatt,[1,†] W. Seka,[1] P. Michel,[2] M. Hohenberger,[2] R. W. Short,[1] R. Epstein,[1] S. P. Regan,[1] E. M. Campbell,[1] T. Chapman,[2] C. Goyon,[2] J. E. Ralph,[2] M. A. Barrios,[2] J. D. Moody,[2] and J. W. Bates[3]



Review of early theoretical work:

1. Excitation of Plasma Waves by Two Laser Beams. M. N. Rosenbluth and C. S. Liu. Phys. Rev. Lett. **29**, 701 (1972)
2. Parametric Backscattering Instabilities of Electromagnetic Waves in Underdense, Inhomogeneous Plasmas COO3237 (1972) C. S. Liu and M. N. Rosenbluth, un-published
3. Raman and Brillouin scattering of electromagnetic waves in inhomogeneous plasmas. Physics of Fluids 17, 1211 (1974) C. S. Liu, Marshall N. Rosenbluth, and Roscoe B. White
4. Parametric instabilities of electromagnetic waves in plasmas Physics of Fluids 17, 778 (1974) J. F. Drake, P. K. Kaw, Y. C. Lee, and G. Schmidt, C. S. Liu and Marshall N. Rosenbluth

How I Started the Laser Plasma Studies in 1971 with Rosenbluth?
Him Question to me: Can we use laser to heat plasmas in Tokamak?
My answer: by beating two lasers to produce a plasma wave and use plasma wave to accelerate electrons.

Excitation of Plasma Waves by Two Laser Beams*

M. N. Rosenbluth and C. S. Liu
Institute for Advanced Study and Plasma Physics Laboratory, Princeton, New Jersey 08540
(Received 29 June 1972)

We analyze the effects of (i) the nonlinearity of the large-amplitude plasma wave, and (ii) the inhomogeneity of the plasma, on the excitation of the plasma wave by beating two laser beams.

$$d^2\xi_x/dt^2+\omega_p^2\xi_x=(e/mc)(\dot{\xi}_y^{(1)}B_z^{(2)}+\dot{\xi}_y^{(2)}B_z^{(1)})$$

$$\ddot{\xi}_x+\omega_p^2\xi_x=-\left(\frac{e}{m}\right)^2\frac{E_1E_2^*\Delta k}{4\omega_1\omega_2}\left(\frac{1}{i}\sum_l J_l(\Delta kA)\exp\{i[(\Delta k+lk_0)x_0-(\Delta\omega+l\omega_p)t+l\varphi]\}+\text{c.c.}\right)$$

$$Ak_0=(\tfrac{1}{16}\alpha_1\alpha_2)^{1/3}\ll 3$$

Dream Laser Accelerator for Electrons

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

3 experimental articles demonstrating the mono energetic electron acceleration by laser wakefield in Nature in 2004

Raman and Brillouin scattering of electromagnetic waves in inhomogeneous plasmas

Physics of fluid, 1974

C. S. Liu, Marshall N. Rosenbluth, and Roscoe B. White

Institute for Advanced Study, Princeton, New Jersey 08540

Parametric instabilities of electromagnetic waves in plasmas

J. F. Drake, P. K. Kaw, Y. C. Lee, G. Schmidt*

Department of Physics, University of California at Los Angeles, California 90024

C. S. Liu and Marshall N. Rosenbluth

Institute of Advanced Study, Princeton, New Jersey 08540

Physics of fluid, 1974

TABLE I. THRESHOLD VALUES AND GROWTH RATES FOR RAMAN AND BRILLOUIN SCATTERING

Instability	Plasma Density	Growth Rate	Threshold
Raman Backscatter	$\omega_0 > 2\omega_p > (\frac{v_c}{c})^2 \omega_0$	$(\frac{v_0}{c})\sqrt{\omega_0 \omega_p}$	$(v_0/c)^2 k_0 L > 1$
Raman Backscatter	$\omega_0 \approx 2\omega_p$	$(\frac{v_0}{c})\omega_0$	$(v_0/c)^2 (k_0 L)^{4/3} > 1$
Raman Side Scatter	$\omega_0 > 2\omega_p > (\frac{v_e}{c})^2 \omega_0$	$\frac{(1+2\alpha)^{1/2}}{(1+2\alpha \frac{\omega_p}{\omega_0})} (\frac{v_0}{c})\omega_p$	$\frac{(v_0/c)^2 (k_0 L)^{4/3} > 1}{(1+2\alpha)^{1/3}}$
Brillouin Backscatter	$\omega_p > \frac{T_i}{mc^2} \omega_0$	$\frac{v_0}{\sqrt{2cc_s}} \omega_{pi}$	$(\frac{v_0}{v_c})^2 (\frac{\omega_p}{\omega_0})^2 k_0 L_u > 1$
Brillouin Side Scatter	$\omega_p > \frac{T_i}{mc^2} \omega_0$	$\frac{(1+2\alpha)^{1/2}}{(1+2\alpha \frac{\omega_p}{\omega_0})} (\frac{v_0}{c}) (\frac{\omega_0}{\omega_p}) (\frac{L_n}{L_u})^{\frac{1}{2}} \omega_{pi}$	$(\frac{v_0}{v_c})^2 (\frac{L_n}{L_u}) (k_0 L_u)^{4/3} (1+2\alpha)^{1/2}$ $(1 + L_u/L_n)^{2/3} > 1$

PARAMETRIC INSTABILITIES IN INHOMOGENEOUS, SPHERICAL PLASMAS*

C.S. LIU, M.N. ROSENBLUTH, R.B. WHITE

Abstract

PARAMETRIC INSTABILITIES IN INHOMOGENEOUS, SPHERICAL PLASMAS.

Temporally growing instabilities for Raman and Brillouin sidescattering are found to persist in an inhomogeneous, expanding spherical plasma with non-uniform expansion velocity. Their growth rates and thresholds are modified by the spherical geometry because of the wave refraction.

$$\left(\frac{v_{0\infty}}{c}\right)^2 = 0.24 \left(\frac{c}{\omega_0 L}\right)^{4/3} \left(\frac{\omega_p}{\omega_0}\right)^{2/3} \left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{\frac{1}{2}} \frac{\left[1+2\frac{L}{r}\left(\frac{\omega_0^2}{\omega_p^2} - \frac{2\omega_0}{\omega_p}\right)\right]^{1/3}}{\left(2-2\frac{\omega_p}{\omega_0} - \frac{\omega_p^2}{\omega_0^2}\right)} \qquad (13)$$

where $(v_{0\infty}/c) = (eE_0/m\omega_0 c)$ is the oscillating velocity in the incident wave, which is increased locally to $(v_{0\infty}/c)[\omega_0^2/(\omega_0^2 - \omega_p^2)]^{1/4}$ due to the swelling factor of the electric field.

TABLE I. Threshold and growth rates for Raman and Brillouin scattering in an inhomogeneous plasma.

Instability	Plasma density	Growth rate	Threshold	Nature
Raman backscatter	$\omega_0 > 2\omega_p > \left(\frac{v_e}{c}\right)^2 \omega_0$	$\left(\frac{v_0}{c}\right)(\omega_0\omega_p)^{1/2}$	$(v_0/c)^2 k_0 L > 1$	Convective in x
Raman backscatter	$\omega_0 \sim 2\omega_p$	$\left(\frac{v_0}{c}\right)\omega_0$	$(v_0/c)^2(k_0L)^{4/3} > 1$	Absolute
Raman side scatter	$\omega_0 > 2\omega_p > \left(\frac{v_e}{c}\right)\omega_0$	$\left(\frac{v_0}{c}\right)\omega_p$	$(v_0/c)^2(k_0L)^{4/3} > 1$ and $(v_0/c)(\omega_p/\omega_0)k_0L_y > 1$	Temporally growing but convective in y
Brillouin backscatter	$\omega_p > \frac{T_i}{mc^2}\omega_0$	$\frac{v_0}{(2cc_s)^{1/2}}\omega_{pi}$	$\left(\frac{v_0}{v_e}\right)^2\left(\frac{\omega_p}{\omega_0}\right)^2 k_0 L_u > 1$	Convective in x
Brillouin side scatter	$\omega_p > \frac{T_i}{mc^2}\omega_0$	$\left(\frac{v_0}{c}\right)\frac{\omega_0}{\omega_p}\left(\frac{L_n}{L_u}\right)^{1/2}\omega_{pi}$	$\left(\frac{v_0}{v_e}\right)^2\left(\frac{L_n}{L_u}\right)(k_0L_u)^{4/3}$ $(1 + L_u/L_n)^{2/3} > 1$	Temporally growing but convective in y for finite k_y
Brillouin scatter (quasimode)	$\omega_p > \frac{T_i}{mc^2}\omega_0$	$\frac{3^{1/2}}{2^{1/3}}\omega_{pi}^{2/3}(k_0v_0)^{1/3}$	$\left(\frac{v_0}{c}\right)^2 > (k_0\lambda_D)^2(\omega_{pi}/\omega_0)$ and $\left(\frac{v_0}{v_e}\right)^2(k_0L_n) > 1$	Convective in x and y

Early experiment on Raman scattering

Stimulated Raman Scattering from uv-Laser–Produced Plasmas

K. Tanaka, L. M. Goldman,[a] W. Seka, M. C. Richardson, J. M. Soures, and E. A. Williams
Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627
(Received 14 December 1981)

Time-integrated, spectrally resolved measurements between 400 and 750 nm have been made of light backscattered from plasmas produced by 450-psec pulses from a 351-nm laser at 10^{13} to 10^{15} W/cm^2. Threshold and saturation behavior for the two-plasmon decay and the absolute and convective Raman instabilities have been observed. The scattered light spectra suggest the presence of a steepened density profile at the quarter critical density.

Experimental evidence of Raman Sidescattering

Efficient Raman Sidescatter and Hot-Electron Production in Laser-Plasma Interaction Experiments

R. P. Drake, R. E. Turner, B. F. Lasinski, K. G. Estabrook, E. M. Campbell, C. L. Wang, D. W. Phillion, E. A. Williams, and W. L. Kruer
Lawrence Livermore National Laboratory, Livermore, California 94550

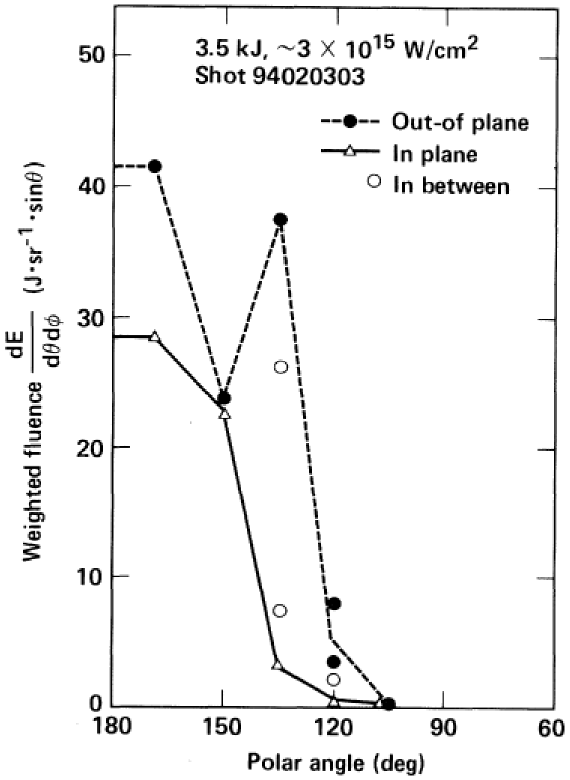


FIG. 1. Angular distribution of Raman-scattered light.

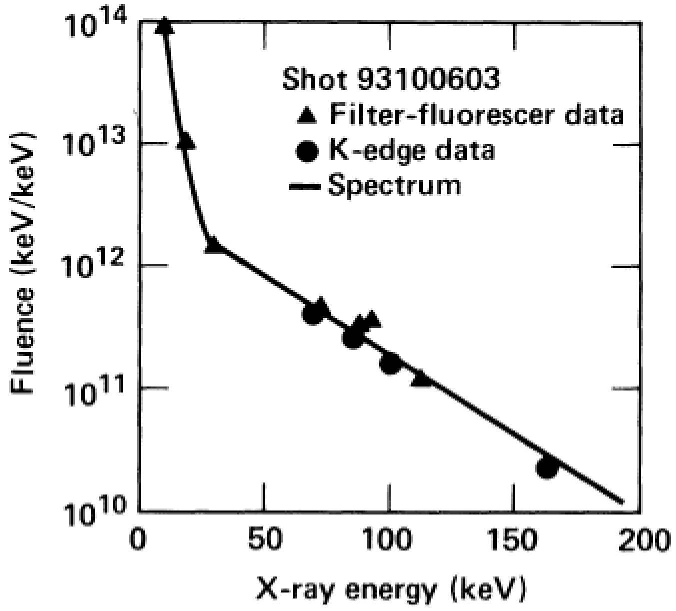


FIG. 2. The hard x-ray spectrum from a Au disk. Irradiation conditions: 3.6 kJ, 1 ns, 740-μm spot.

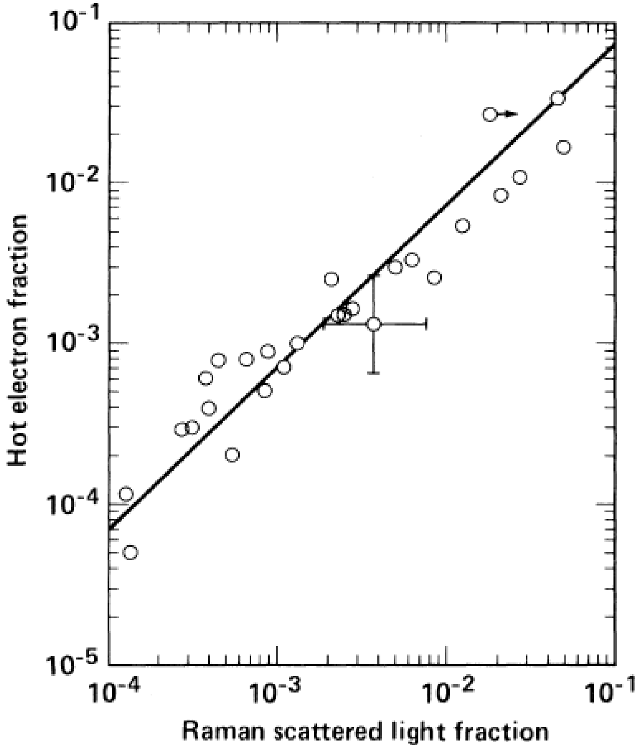


FIG. 3. The hot-electron fraction is well correlated with the Raman light fraction. These quantities are inferred from data like those shown in Figs. 1 and 2.

Drake also observed the importance of the absolute Raman instability with much higher reflectivity, 1985

Dependence of SRS on kλd of plasma wave

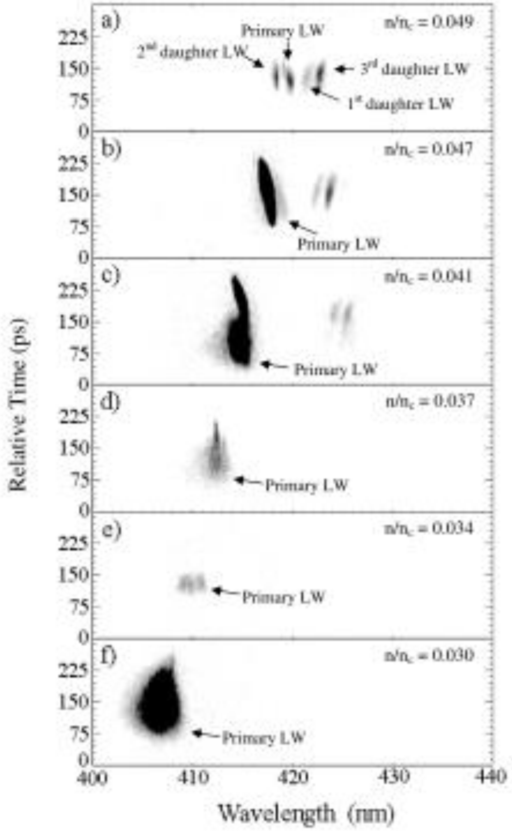


FIG. 2. Thomson streak records of Langmuir waves at six different average values of $k\lambda_D$. For the six shots the electron temperature was 620 eV at the center of each record and the average values for $k\lambda_D$ and the SHS intensity were (a) $k\lambda_D = 0.267$, $I_0 = 4.4 \times 10^{15}$ W/cm², (b) $k\lambda_D = 0.276$, $I_0 = 3.1 \times 10^{15}$ W/cm², (c) $k\lambda_D = 0.296$, $I_0 = 4.4 \times 10^{15}$ W/cm², (d) $k\lambda_D = 0.316$, $I_0 = 8.6 \times 10^{15}$ W/cm², (e) $k\lambda_D = 0.33$, $I_0 = 2.6 \times 10^{15}$ W/cm², and (f) $k\lambda_D = 0.352$, $I_0 = 1.1 \times 10^{16}$ W/cm².

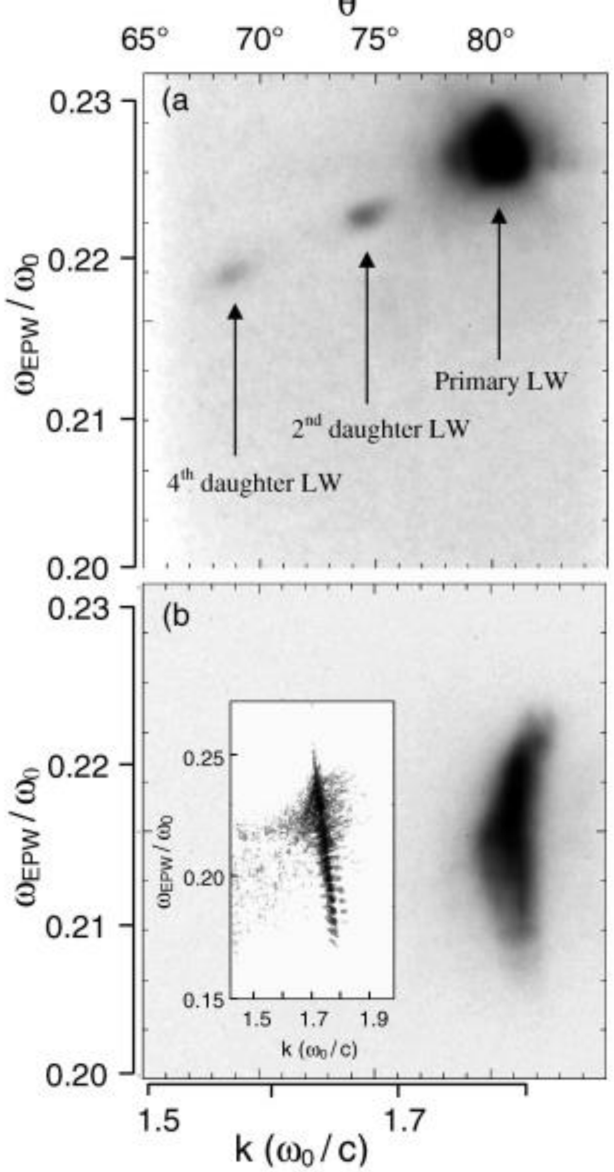


FIG. 3. Thomson scattering LW (ω, k) spectrum for (a) $k\lambda_D \sim 0.29$ showing the primary SRS LW and two copropagating LDI daughter LWs and for (b) $k\lambda_D \sim 0.34$ in the kinetic regime showing a broad frequency spectrum with a narrow wave-number spectrum. The inset in (b) shows a PIC simulation at $k\lambda_D = 0.30$ in which the (ω, k) spectrum is broad in ω and narrow in k, qualitatively consistent with the measurement. Electron trapping is observed in phase space for the simulation.

[1] J.L. Kline et al., *Phys. Rev. Lett.* **94**, 175003 (2005).

Importance of trapped electron effects of Raman backscatter

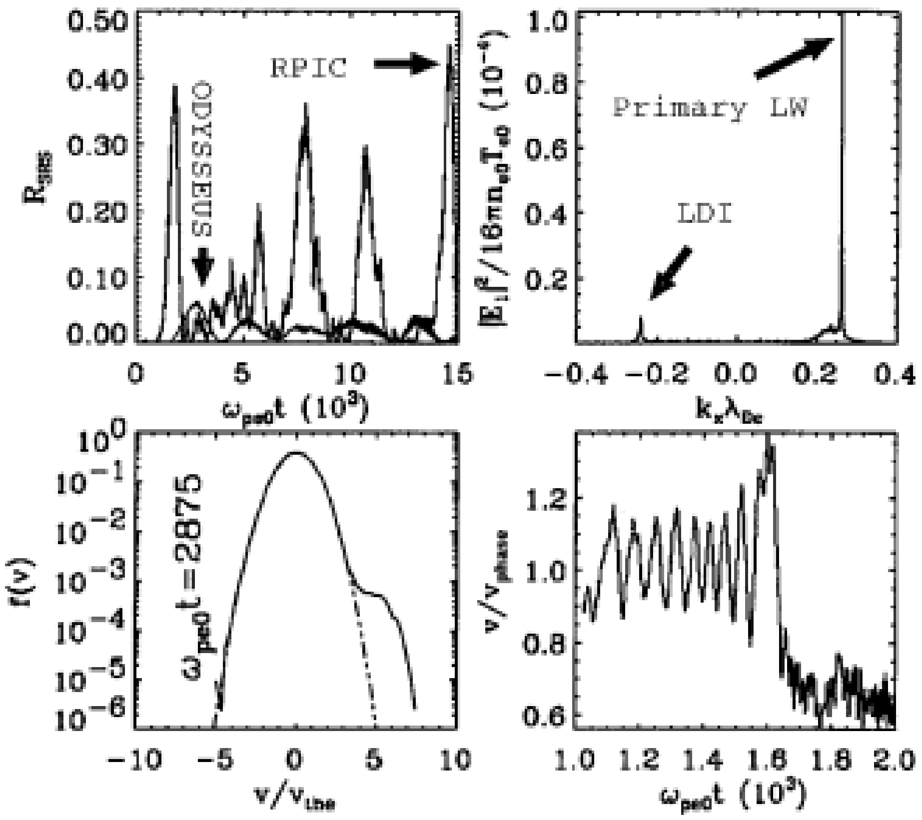


FIG. 1. BSRS reflectivity (top left), LW spectrum (top right), electron distribution function (bottom left), and particle orbit (bottom right). The BSBS reflectivity (not shown), is not significant for the times shown.

[1] H.X. Vu, D.F. DuBois, and B. Bezzerides, *Phys. Rev. Lett.* **86**, 4306 (2001).

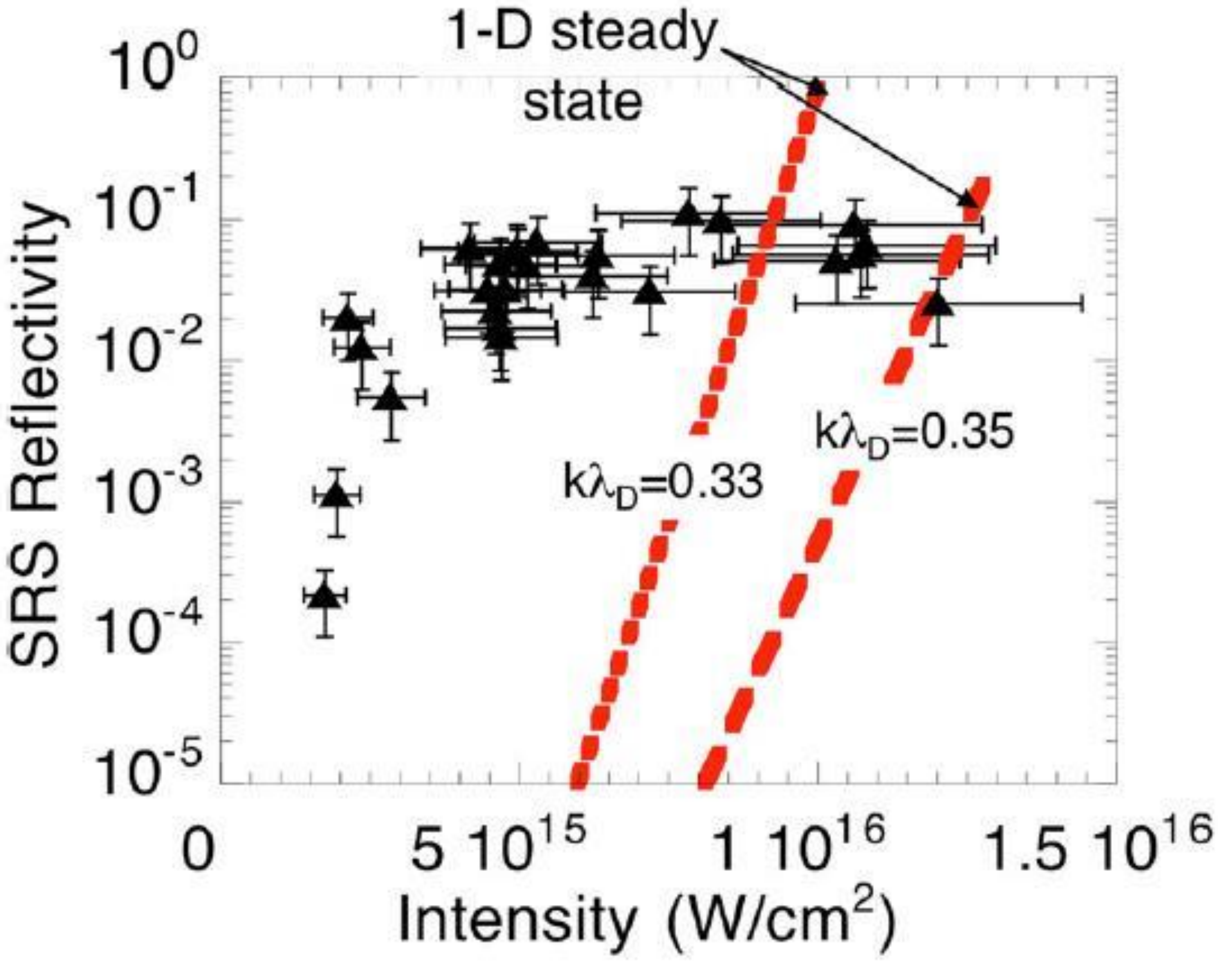
Recent Review Article

- David S. Montgomery, Two decades of progress in understanding and control of laser plasma instabilities in indirect drive inertial fusion, *Phys. Plasmas* **23**, 055601 (2016).
- Trident laser plasma system: Highly reproducible plasma formed in the laser hot spot for laser plasma interaction studies.

Nonlinear Transformation from Convective to Absolute Raman (2018)

Two graduate students of Peking University. Yenxia Wang and Qing Wang

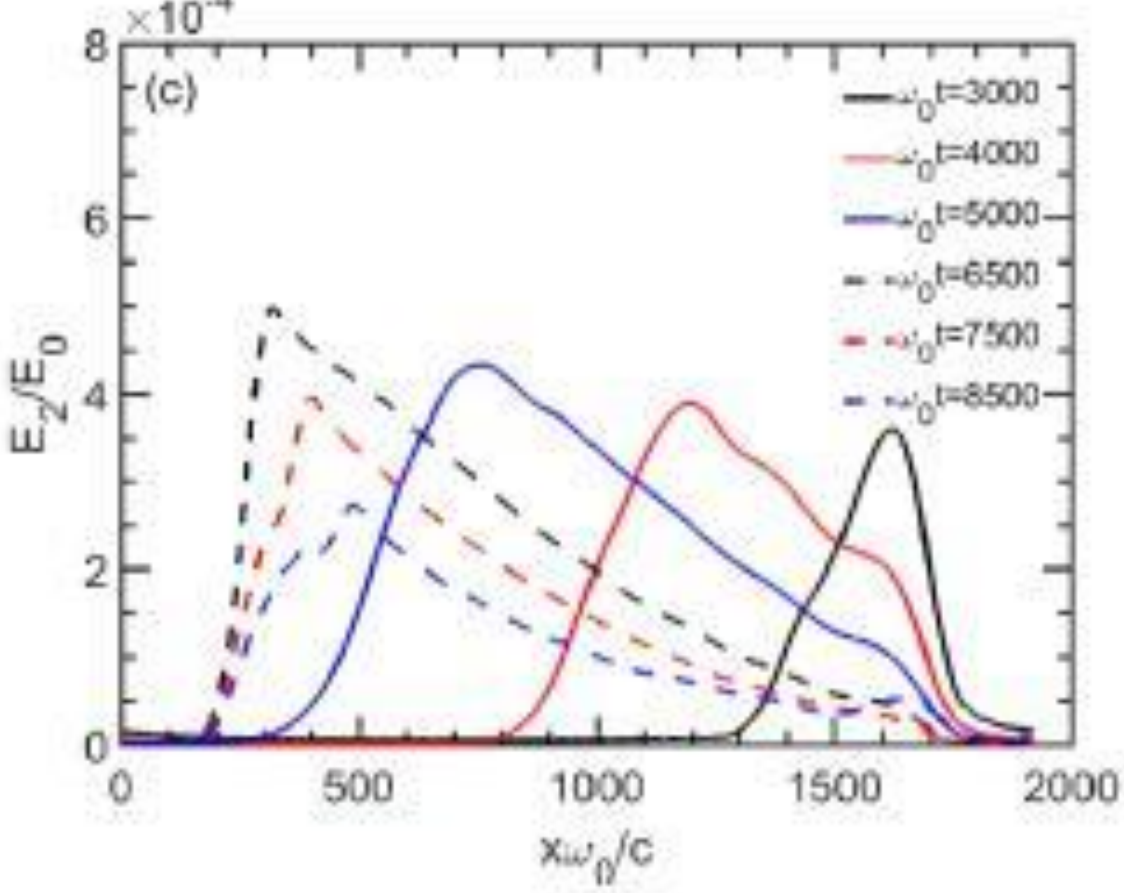
Inflation of Laser Reflectivity by stimulated Raman backscattering: sudden jump of reflection coefficient by 4 orders of magnitude

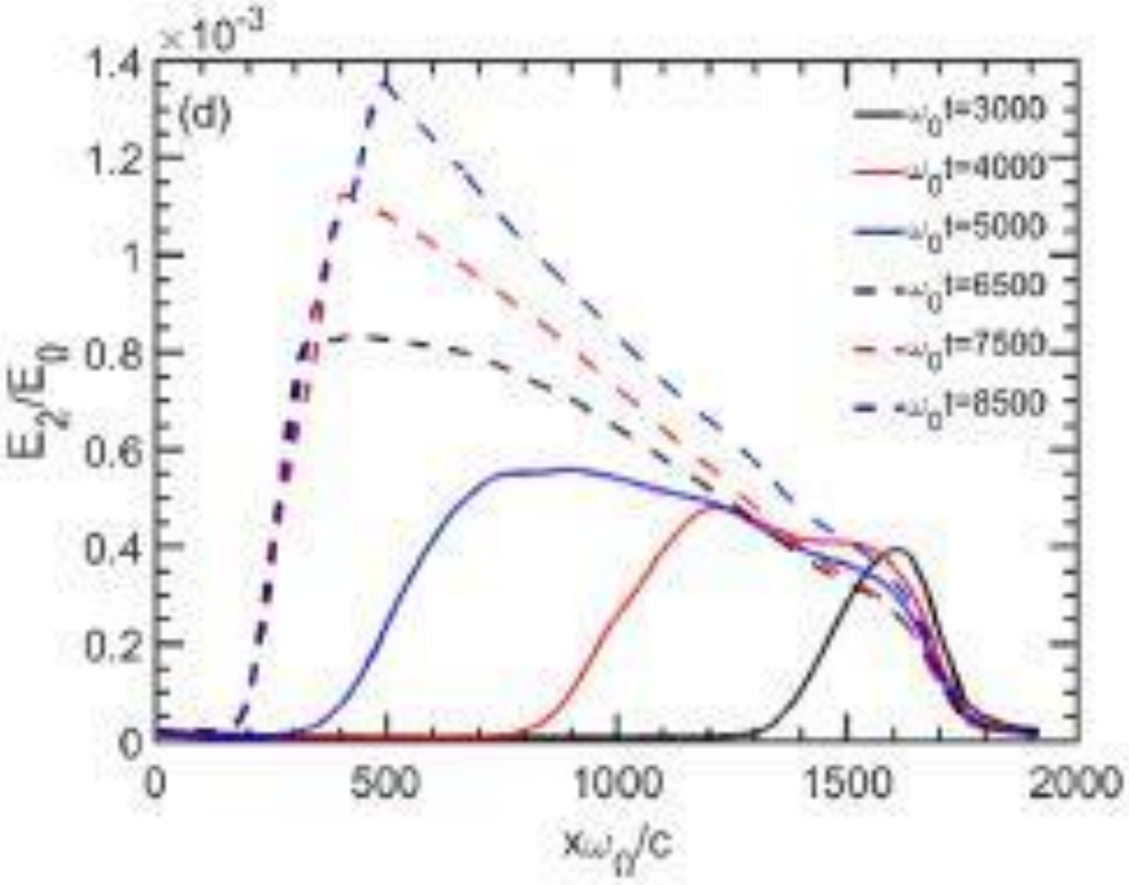


D. S. Montgomery, POP 23,055601(2016).

Convective instability

Absolute instability





Absolute Instability in a homogeneous plasma with a finite length L

$$\nu_1 a_1 + \partial a_1/\partial t + v_1 \partial a_1/\partial x = \gamma_0 a_2 e^{i\kappa' x^2/2}, \quad \nu_2 a_2 + \partial a_2/\partial t - v_2 \partial a_2/\partial x = \gamma_0 a_1 e^{-i\kappa' x^2/2},$$

Laplace transform with variable p

$$\frac{\partial^2 a}{\partial x^2} + \left[\frac{\gamma_0^2}{v_1 v_2} - \frac{1}{4}\left(\frac{p+\nu_1}{v_1} + \frac{p+\nu_2}{v_2}\right)^2\right] a = 0$$

Standing wave condition
$kL = n\pi$

$$\boldsymbol{a = A \sin kx} \qquad \boldsymbol{a(0) = a(L) = 0}$$

$$\frac{\gamma_0^2}{v_1 v_2} - \frac{1}{4}\left(\frac{p+\nu_1}{v_1} + \frac{p+\nu_2}{v_2}\right)^2 = \left(\frac{n\pi}{L}\right)^2$$

solving for growth rate $p(n=1)$

$$\boldsymbol{p = \left[2\sqrt{\frac{\gamma_0^2}{v_1 v_2} - \left(\frac{\pi}{L}\right)^2} - \left(\frac{\nu_1}{v_1} + \frac{\nu_2}{v_2}\right)\right] \Big/ \left(\frac{1}{v_1} + \frac{1}{v_2}\right)}$$

Condition for absolute instability

positive real p solution to exist

$$\boldsymbol{\frac{\gamma_0^2}{v_1 v_2} > \left(\frac{\pi}{L}\right)^2 + \frac{1}{4}\left(\frac{\nu_1}{v_1} + \frac{\nu_2}{v_2}\right)^2}$$

M. N. Rosenbluth R.White and CS Liu,PRL (1973).

Convective Instability with a Heavily Damped Plasma Wave in a finite plasma with L:

$$\nu_1 a_1 = \gamma_0 a_2$$

$$\begin{cases} \nu_1 a_1 = \gamma_0 a_2 \\ \nu_2 a_2 + u_2 \dfrac{\partial a_2}{\partial x} = \dfrac{\gamma_0^2}{\nu_1} a_2 \end{cases}$$

Convective amplification

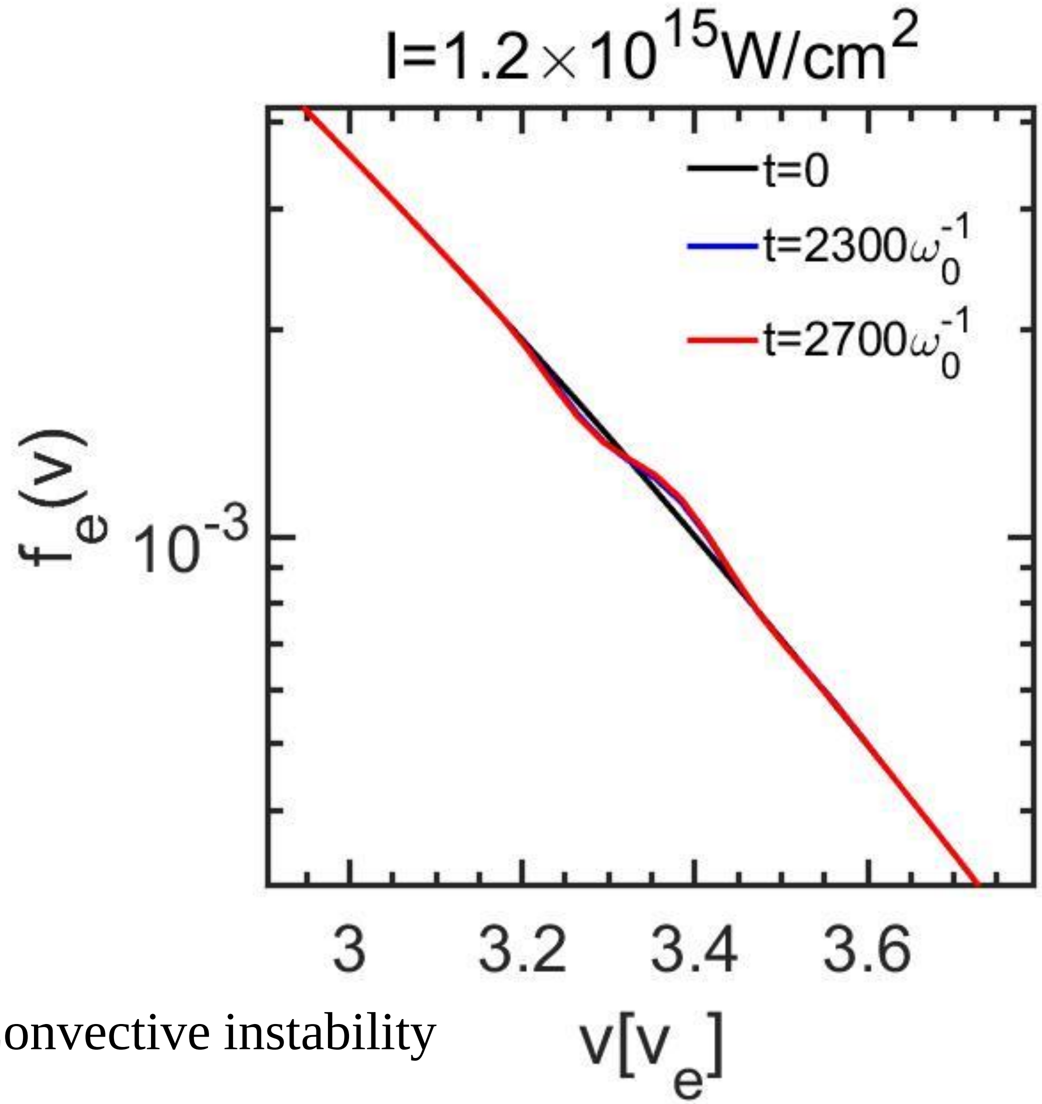
$$\frac{1}{a_2}\frac{\partial a_2}{\partial x} = \frac{\gamma_0^2}{\nu_1 u_2} - \frac{\nu_2}{u_2}$$

$$a_2 = a_{20}\exp\left[\left(\frac{\gamma_0^2}{\nu_1 u_2} - \frac{\nu_2}{u_2}\right) L\right]$$

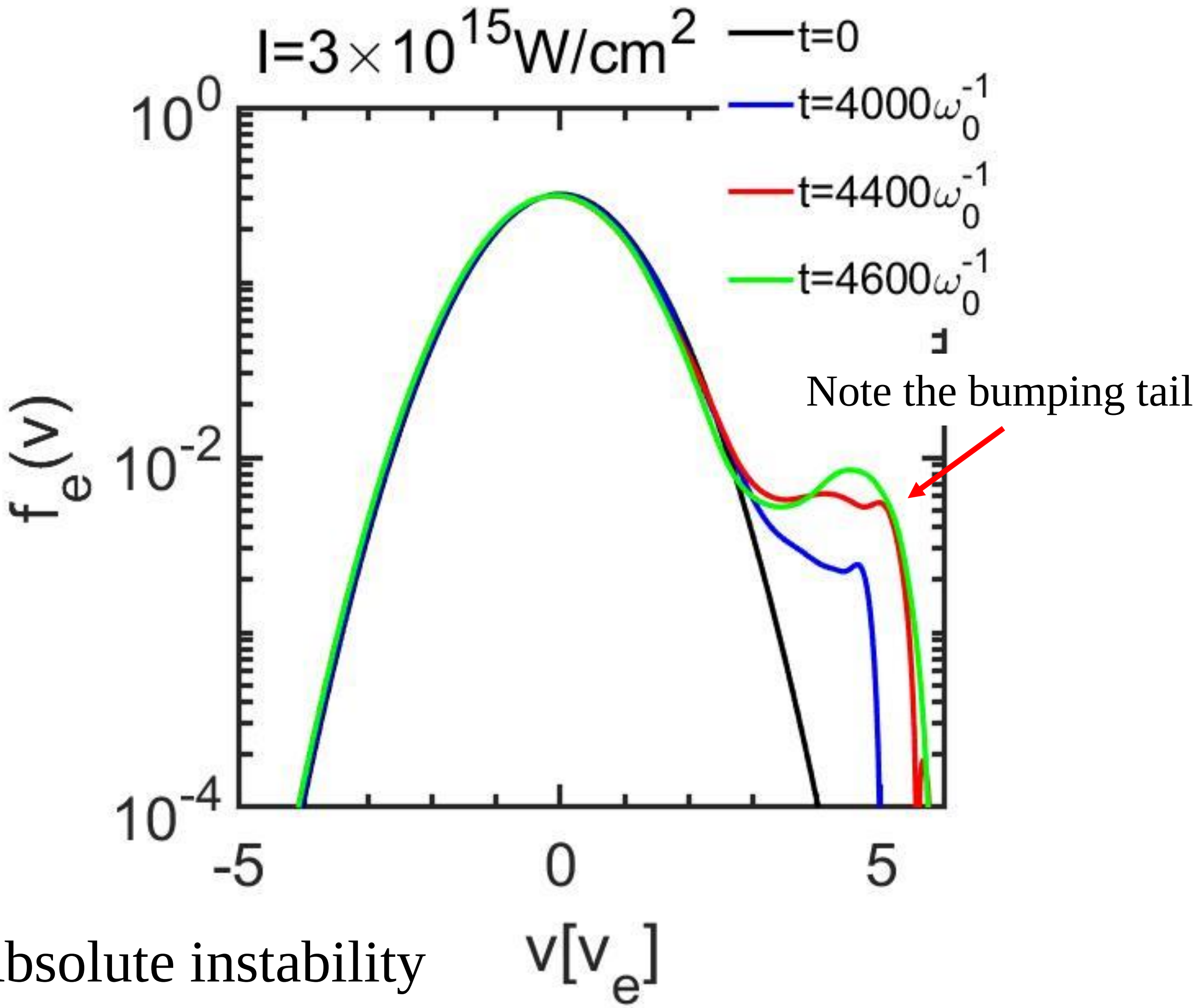
Unstable if $\gamma_0^2 > \nu_1 \nu_2$ and $\left(\frac{\gamma_0^2}{\nu_1 u_2} - \frac{\nu_2}{u_2}\right) L \gg 1$

1-D Vlasov simulation of electron distribution function at different laser intensities

Trappe electron effect

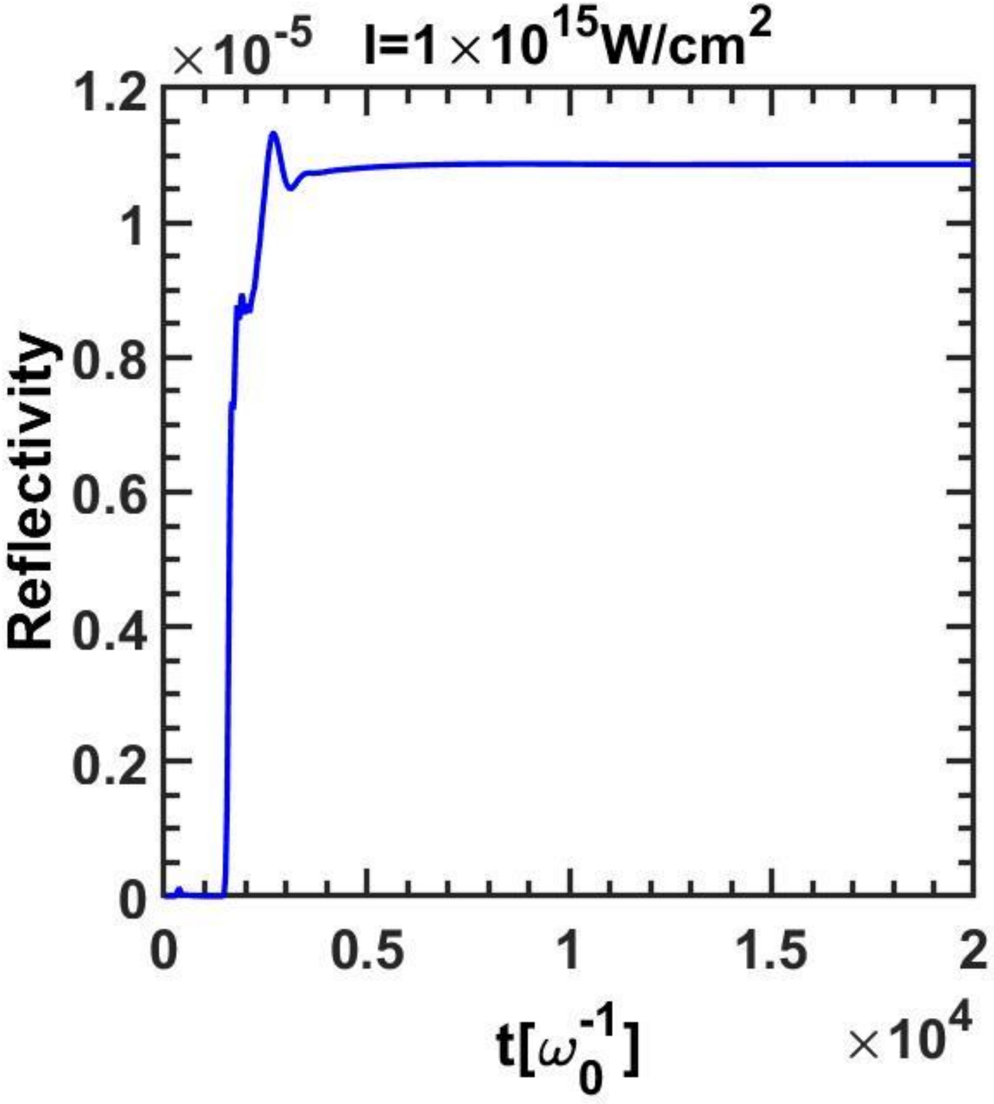


Convective instability

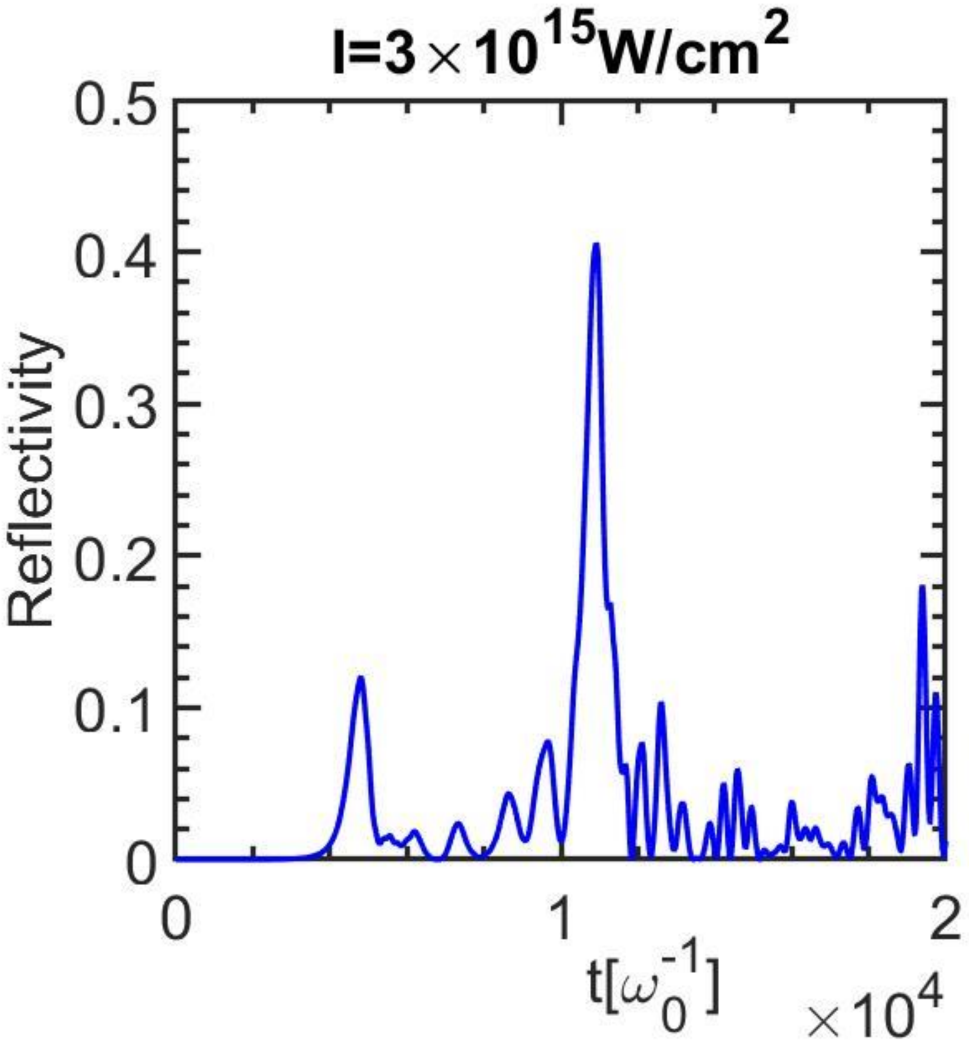


Absolute instability

Reflectivity at different intensities, note 4 orders of magnitudes difference



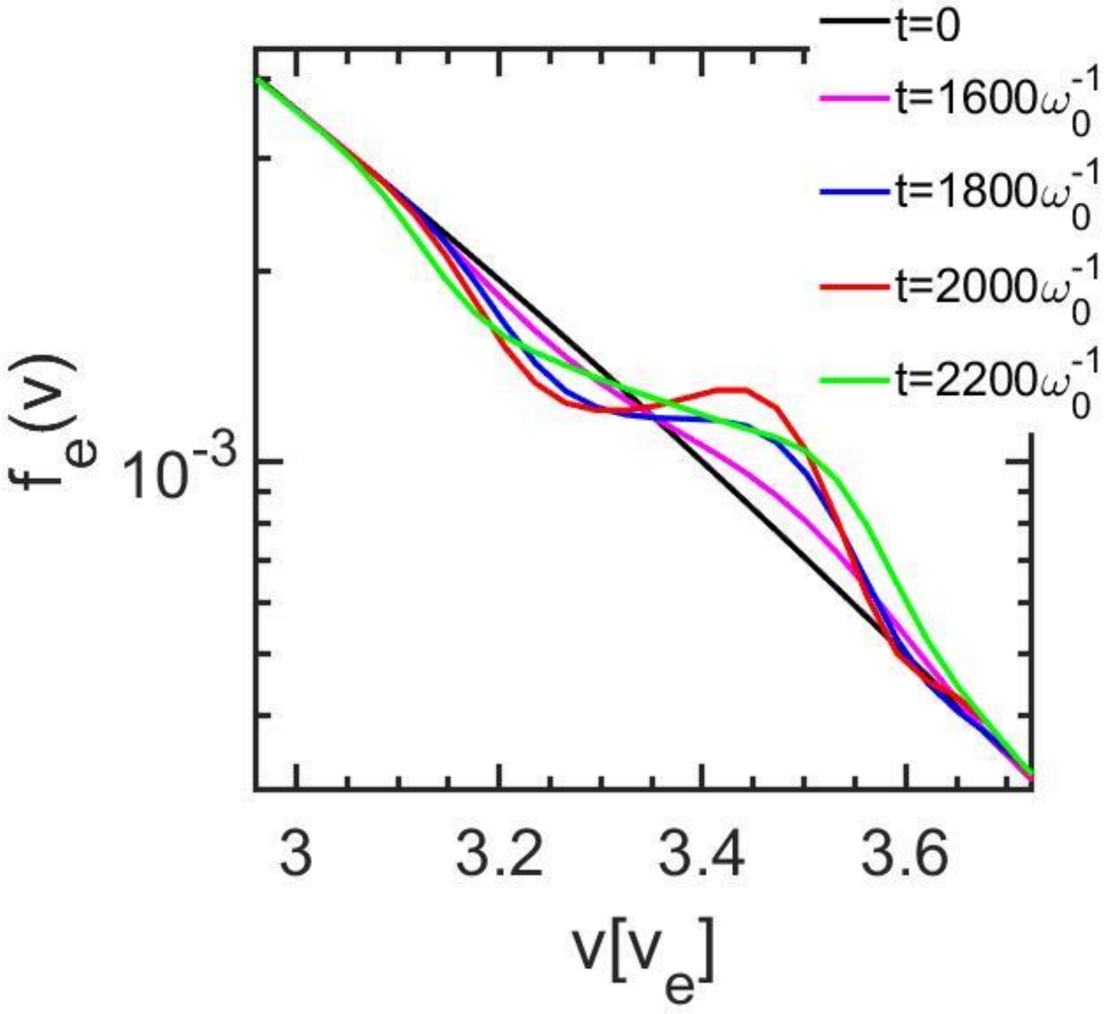
Convective instability



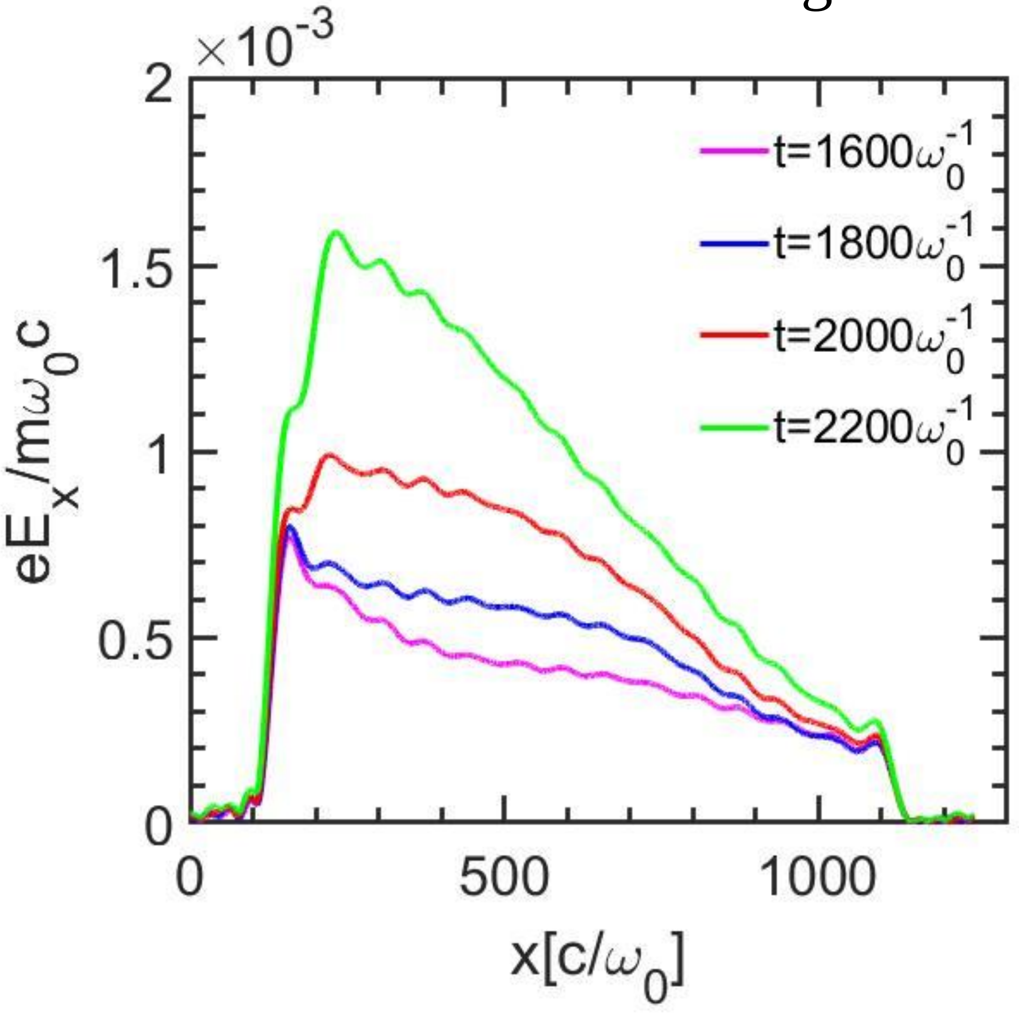
Absolute instability

$I = 3 \times 10^{15}\, W/cm^2$ **Absolute** instability

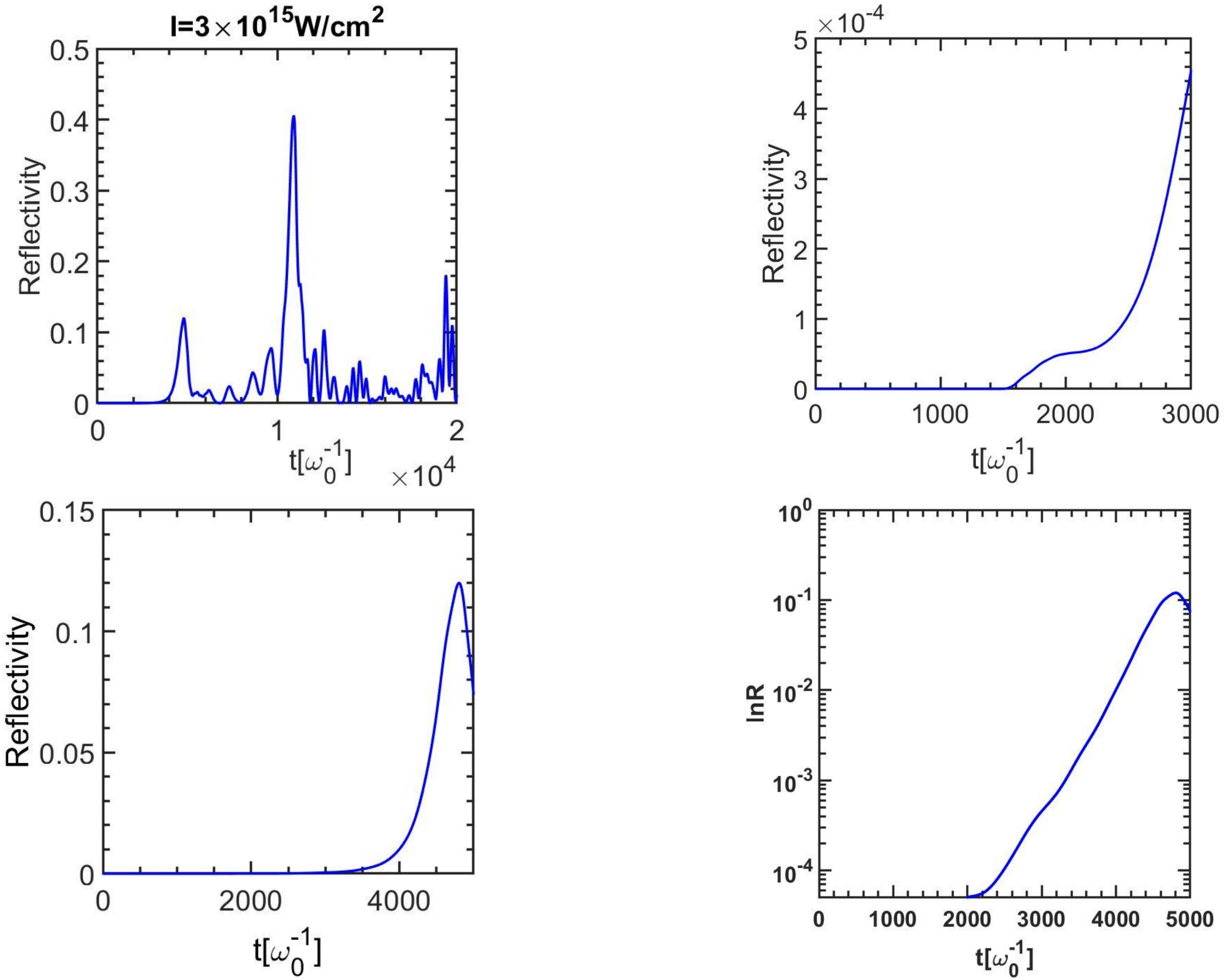
Distribution function



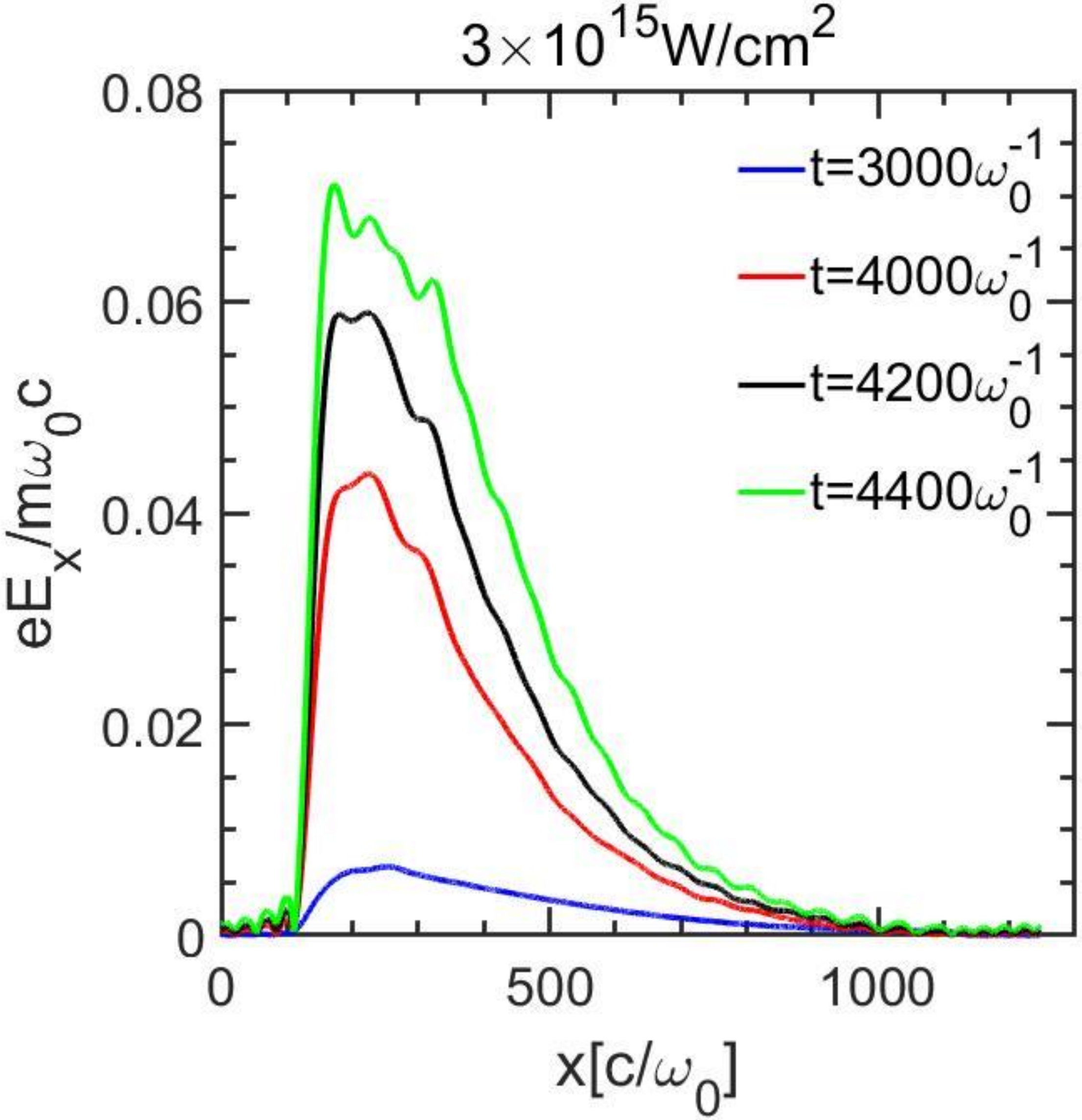
Plasma wave growth



Growth of Reflectivity

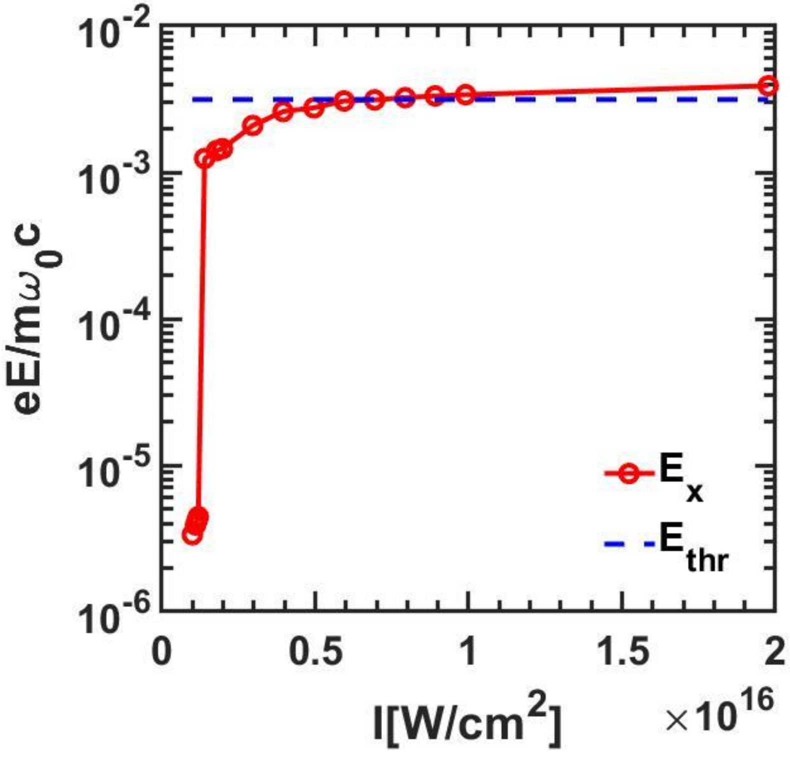


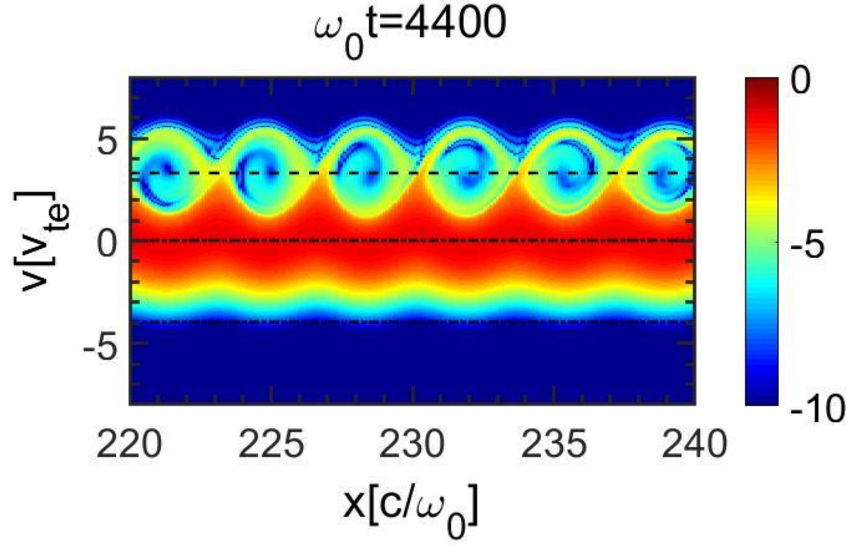
Soliton and wave breaking

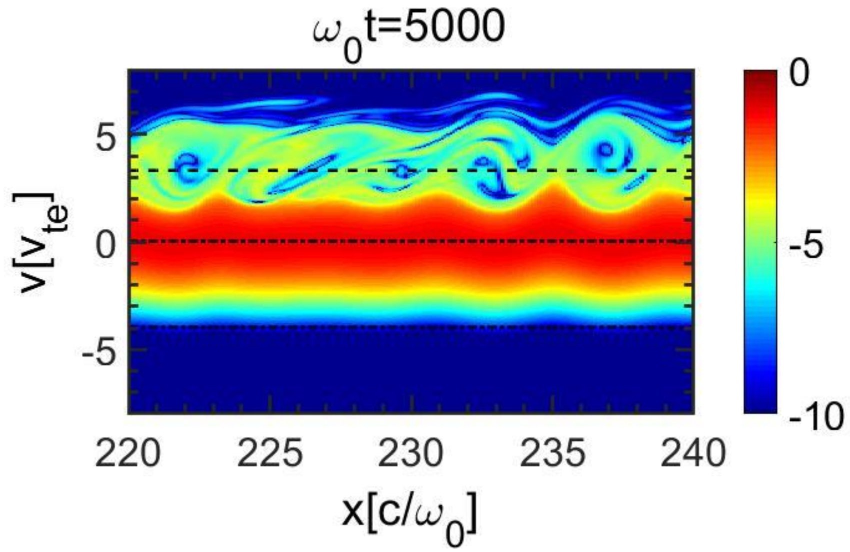


Nonlinear effects: side band instability, SBS suppression of Raman, soliton and caviton, etc

Example: Plasma wave breaking

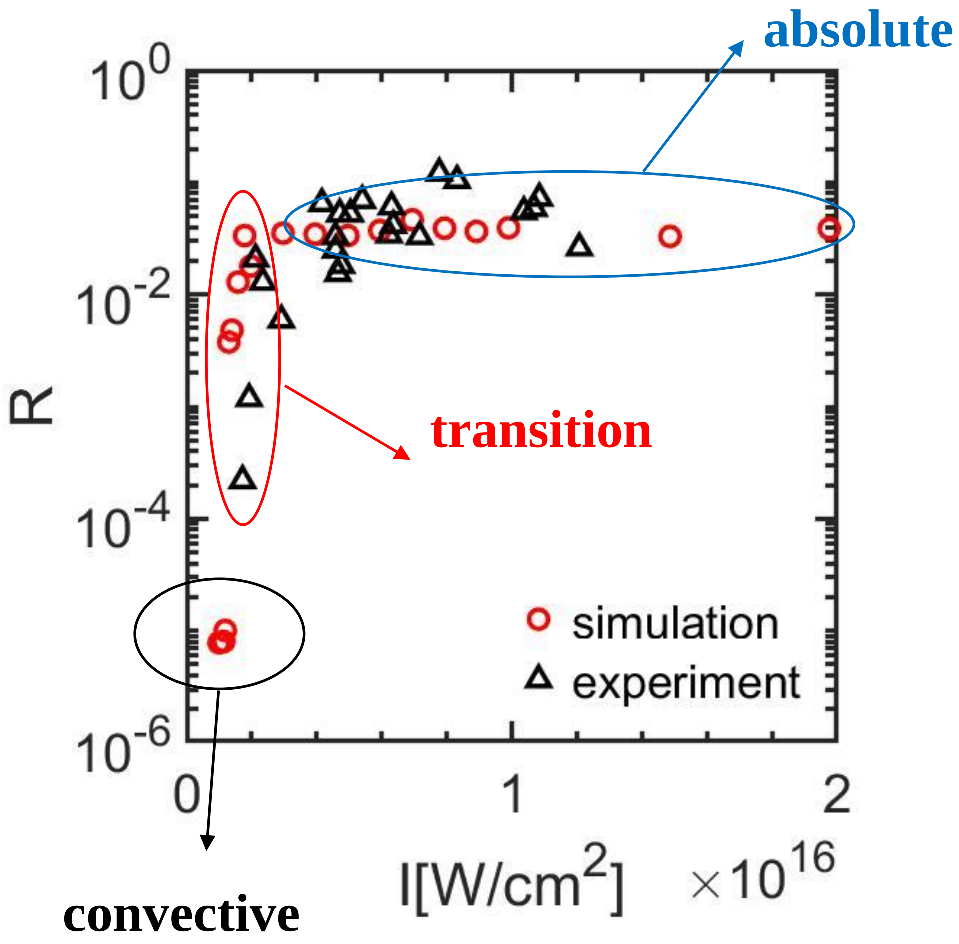






1D Vlasov Code result compared with experiment

Experimental data ： D. S. Montgomery et al. POP 9,2311 (2002)



$T_e = 0.5keV$

$n_e = 0.025n_c$

$k\lambda_D = 0.35$

$I = 1 \times 10^{15} - -2 \times 10^{16}\, W/cm^2$

$\lambda_0 = 0.527\mu m$

To show the transition to absolute instability, we need to evaluate the nonlinear damping of the plasma wave:
Transition from Landau damping to bounce resonance damping

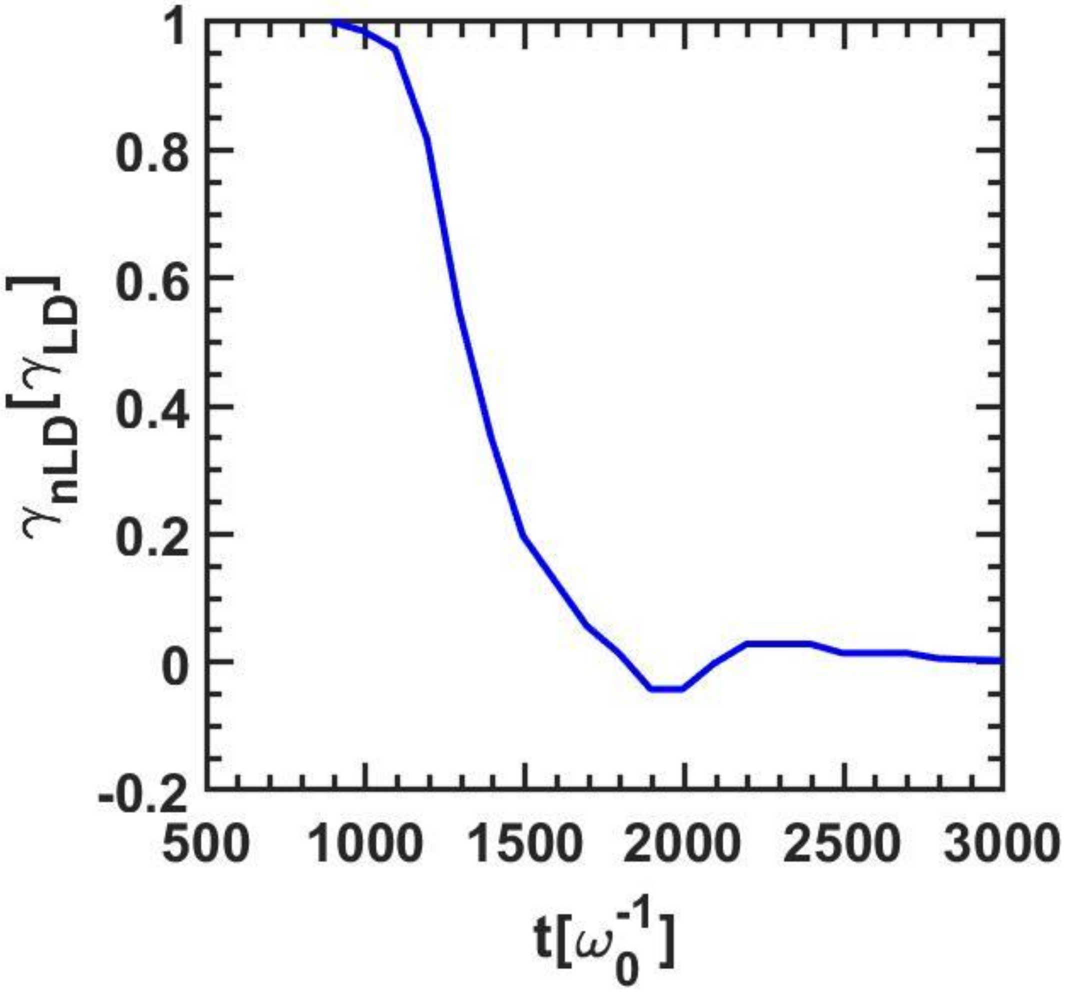
Vlasov equation in action angel variable :

C. S. Liu, J. Plasma Physics (1972)

$$J(\epsilon) = \oint dx\, m v(\epsilon, x), \theta(\epsilon, \tilde{x}) = \omega_b(\epsilon) \int_{x_T}^{\tilde{x}} dx / v(\epsilon, x),$$

$$\frac{\partial f_1(\epsilon, \theta, t)}{\partial t} + \omega_b \frac{\partial f_1}{\partial \theta} = \frac{\partial \epsilon_1}{\partial \theta} \frac{\partial f_0}{\partial J} (2\pi),$$

$$\nu_l = \frac{2\omega_t^2 k_0 m}{k^2} \int_0^{\epsilon_m} d\epsilon \left[\frac{\omega_b df / d\epsilon J_1^2(ka)}{(\omega - k v_p)^2 - \omega_b^2} \right]$$



Nonlinear effects: soliton

$$\frac{\partial^2 A}{\partial t^2} = -\omega_{p0}^2 A + 3v^2 \frac{\partial^2 A}{\partial x^2}$$

$$A = a(x,t)e^{-i\omega_p t}$$

$$-2i\omega_p \frac{\partial a}{\partial t} - \omega_p^2 a + \omega_{p0}^2 a - 3v^2 \frac{\partial^2 a}{\partial x^2} = 0$$

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{v_0}{c}\right)^2}} \Rightarrow \omega_p^2 = \omega_{p0}^2 \left[1 - \frac{1}{2}\left(\frac{v_0}{c}\right)^2\right]$$

Nonlinear Schrontinger equation:

$$-2i\omega_p \frac{\partial a}{\partial t} - 3v^2 \frac{\partial^2 a}{\partial x^2} + \frac{1}{2}\frac{e^2}{m^2}|a|^2 a = 0$$

Accelerating solitons in inhomogeneous plasma and chaos of plasma wave

Solitons in Nonuniform Media*

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(Received 7 June 1976)

Nonlinear wave propagation in inhomogeneous media is studied analytically in the model of the nonlinear Schrödinger equation. Exact solutions in the form of multisolitons, accelerated in the nonuniform medium, are obtained.

Wave package soliton acceleration by plasma inhomogeneity

$$\dot{v}_g = \frac{3\dot{k}_x v_e^2}{\omega_p} = \frac{3v_e^2}{\omega_p}\frac{\partial\omega}{\partial x}\bigg|_k = \frac{3v_e^2}{L}$$

$$i\frac{\partial E}{\partial t} + \frac{\partial^2 E}{\partial x^2} + (-2\alpha x + 2|E|^2)E = 0$$

$$E = A(x, t)\exp[i\varphi(x, t)]$$

$$(A^2)_t + 2(A^2\varphi_x)_x = 0,$$

$$-[2\alpha x + (\varphi_t + \varphi_x^2)]A + A_{xx} + 2A^3 = 0.$$

$$\varphi = 2(\xi - \alpha t)x - 4[\tfrac{1}{3}\alpha^2 t^3 - \alpha\xi t^2 + (\xi^2 - \eta^2)t] + \varphi_0$$

$$A = 2\eta\,\mathrm{sech}\,2\eta(x + 2\alpha t^2 - 4\xi t - x_0),$$

$v_g < c_s$ (i.e., $k\lambda_D << \sqrt{\frac{m}{M}}$)

Nonlinear and relativistic effect in plasmas (V. Stefen, ed) AIP press.

Solitons and Chaos in Resonance Absorption of EM Waves in Inhomogeneous Plasmas

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$$i\frac{\partial A}{\partial t} - xA + \frac{\partial^2 A}{\partial x^2} + P|A^2|A = 1$$

$$i\frac{\partial E}{\partial t} - xE + \frac{\partial^2 E}{\partial x^2} = E_d,$$

$$\frac{dV_g}{dt} = \left(\frac{\partial^2\omega}{\partial\kappa^2}\right)\dot{\kappa} = -\left(\frac{\partial^2\omega}{\partial\kappa^2}\right)\left(\frac{\partial\omega}{\partial x}\right)$$

$$\omega_2 = (\eta_1^2 - \eta_2^2)\frac{P}{2}$$

Soliton Emission and Acceleration

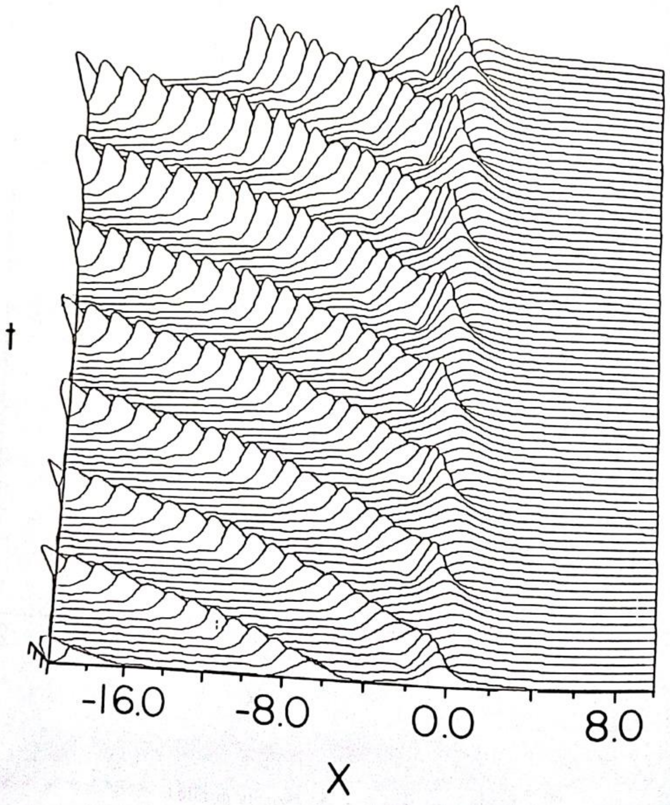

Figure 2. (c) 3-D plot of wave amplitude as a function of x and t for P = 0.8.

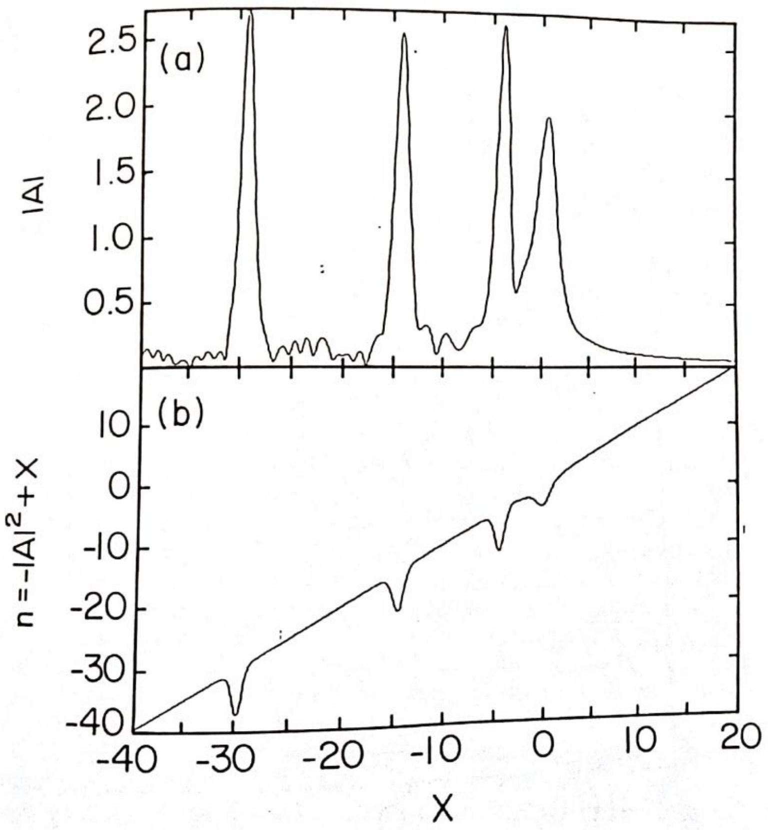

Figure 2. (a) Wave amplitude vs. x. (b) Density profile $n = -|A|^2 + x$ vs. x.

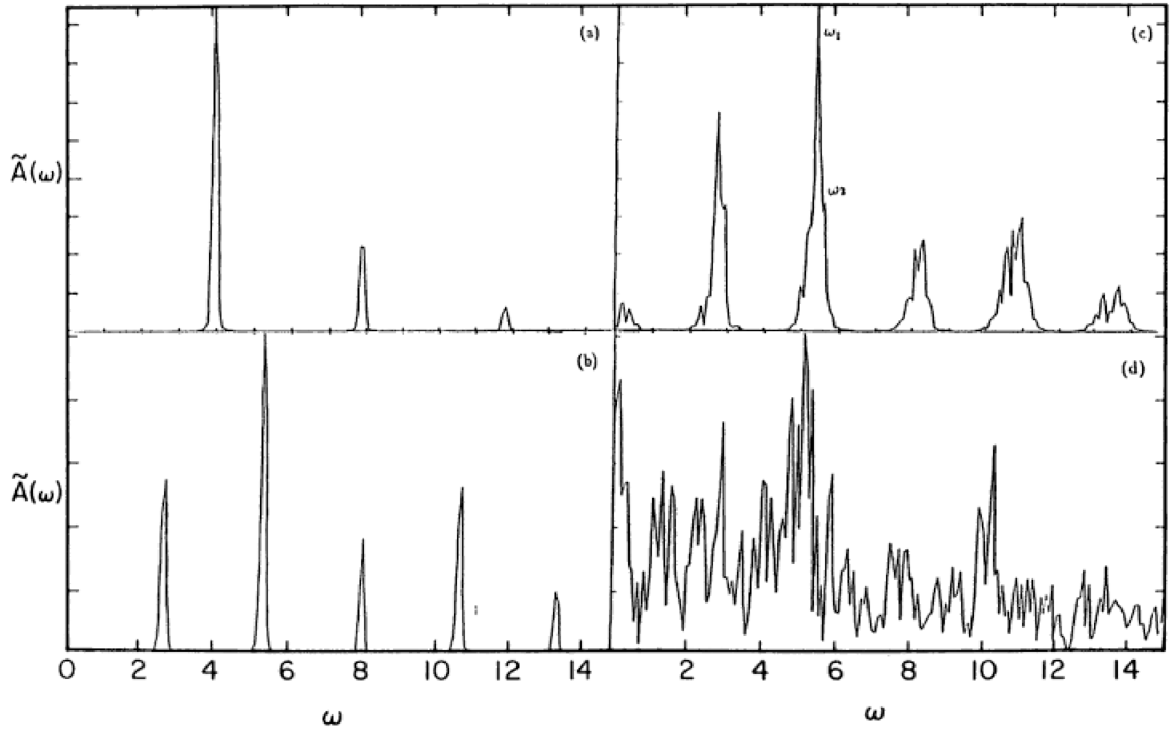

Figure 4. The frequency spectrum at x = 0. (a) Periodic state (P = 0.8), $\omega_1 \sim 4.0$, (b) period doubled (P = 1.15), $\omega_1 \sim 5.2$, $\omega_1/2 \sim 2.6$, (c) quasiperiodic (P = 1.2), $\omega_1 \sim 5.4$, $\omega_2/2 \sim 5.6$ (d) chaotic state (P = 1.275).

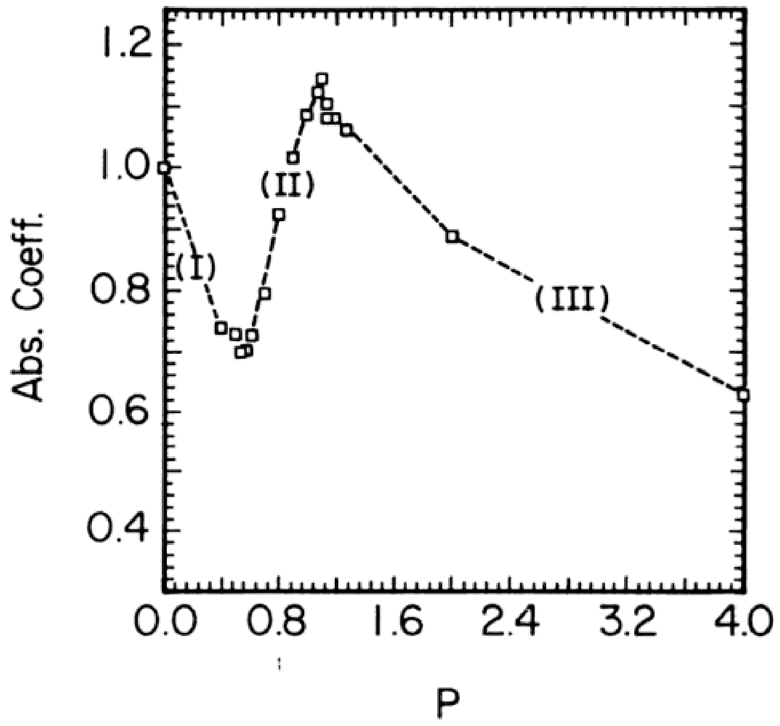

Figure 6. Absorption coefficient vs. P. Region (I): steady state (0 < P < 0.575), Region (II): periodic state (0.575 < P < 1.09), Region (III): quasiperiodic and chaotic state 1.09 < P < 4.0.

Numerical results:

- In the range $0 \le P \le 0.575$, the solution is steady state much like the Airy function for $P = 0$. This solution is well known.
- $0.575 < P < 1.088$. Periodic emission of solitons to the underdense region is observed.
- $1.088 < P < 1.155$. The time evolution of the wave amplitude at $x = 0$ undergoes period doubling.
- $1.1575 < P < 1.255$. A small frequency modulation appears.
- $P > 1.255$. The emission of soliton shows chaotic behavior.

Plasma wave break and surfing electron acceleration to high quality electron beams (on-going research)

Conclusion

- Lots more interesting works need to be done to understand laser plasma collective interactions.
- Physics understanding is critical to the success of fusion.
- We need collaborations of theory, computation and experiments. We need interdisciplinary, international, intercultural communication and collaboration.
- We need intergenerational collaboration as fusion is a business of several generations. We may learn from high energy physics community (Higgs boson) and LIGO for gravity waves.

1D High Power Raman Scattering

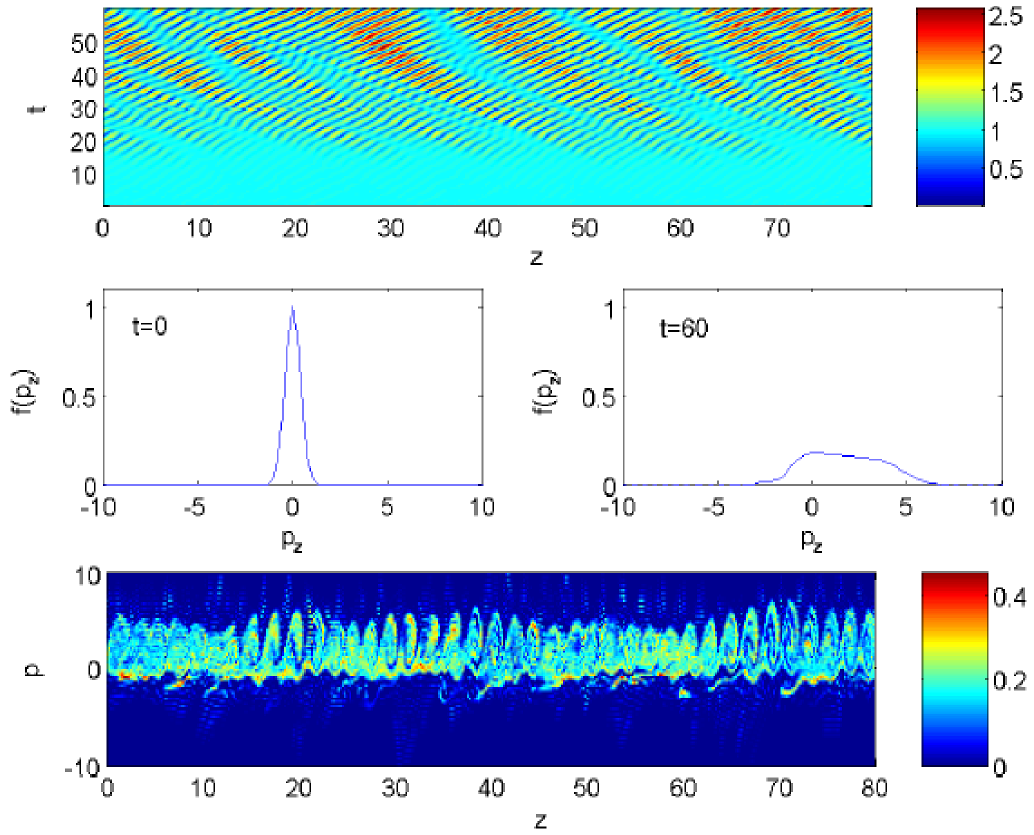

Figure 2. The nonlinear saturation of relativistic stimulated Raman scattering. The upper panel shows the time development of the EMW envelope, the middle panels show the electron distribution function at time $t = 0$ (the left panel) and $t = 60$ (the right panel), and the lower panel shows the electron distribution function at time $t = 60$. Initially, the EMW amplitude is $A = 1.0$, and the pump wavenumber is $k_0 = 3.0$.

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Laser light triggers increased Raman amplification in the regime of nonlinear Landau damping

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Stimulated Raman backscattering (SRS) has many unwanted effects in megajoule-scale inertially confined fusion (ICF) plasmas. Moreover, attempts to harness SRS to amplify short laser pulses through backward Raman amplification have achieved limited success.

Thanks for your attentions!