*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.018 (2006)*

Thermal effects on Raman amplification in plasma

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Introduction Stimulated Raman backscattering in plasma has been suggested as a mechanism for the amplification of short laser pulses to high powers without breakdown of the medium [1]: a pump pulse is scattered by a longitudinal plasma wave and transfers energy to a counter-propagating probe pulse. The most suitable regime for amplification is reached when the probe is sufficiently intense to deplete the pump, since in this case the energy transfer is efficient, and the superradiant scaling results in short amplified pulses. This scaling, where the amplitude of the probe grows linear with propagation distancewhile its width decreases, has been demonstrated in experiments [2]; however, a frequency chirp of the pump wave [3, 4], or a ramped plasma density [5] lead to similar scaling.

Here, we investigate the effect of finite temperature and heating on the dispersion of the plasma wave.

Raman scattering at finite temperature We describe the transverse pump and probe waves by envelopes a_0 and a_1, respectively, of the reduced vector potential $e\vec{A}/mc$, and the longitudinal plasma wave by the envelope f of the scaled longitudinal electric field $eE_z/(m\omega_p c)$. The corresponding phases are $\varphi_0 = \omega_0(t+z/c)$ for the pump, $\varphi_1 = \omega_1(t-z/c)$ for the probe, and $\varphi_\| = \varphi_1 - \varphi_0 = -\Delta\omega\, t - k_\| z$ for the plasma wave, where $\Delta\omega = \omega_0 - \omega_1$, and $k_\| = (\omega_0+\omega_1)/c$; the group velocities of the transverse waves are approximated by c, the vacuum speed of light.

The plasma wave is driven by the ponderomotive force associated with the beat of the transverse waves, and these are scattered by the density modulations of the plasma wave. Close to the plasma resonance $\Delta\omega = \omega_p \equiv \sqrt{e^2 n_0/(\varepsilon_0 m)}$ (where $-e$ and m are the electron charge and mass, respectively, n_0 their number density, and ε_0 is the permittivity of free space), the three-wave interaction is described by the equations

$$[\partial_t - c\partial_z + (\omega_p/\omega_0)^2 \nu_\perp/2]a_0 = -\omega_p f^* a_1/2, \qquad (1)$$

$$[\partial_t + c\partial_z + (\omega_p/\omega_0)^2 \nu_\perp/2]a_1 = \omega_p f a_0/2, \qquad (2)$$

$$[\partial_t + (\nu_\| + \nu_L)/2 + i(6\theta\omega_0^2/\omega_p - \delta)]f = \omega_0 a_0^* a_1/2, \qquad (3)$$

where ∂_t and ∂_z are partial time and z-derivatives, respectively.

The last equation, for the longitudinal wave, takes into account the two effects of finite temperature: first, the electron pressure leading to a shift $6\theta\omega_0^2/\omega_p$ in the resonance frequency, where $\theta = k_B T/(mc^2)$ is the scaled temperature; and second, Landau damping expressed by the rate

$$\nu_L = \sqrt{\pi/2}\,\omega_p/(k_\parallel^3\lambda_D^3)\,e^{-1/(2k_\parallel^2\lambda_D^2)}, \tag{4}$$

with $\lambda_D = v_{th}/\omega_p$ the Debye length, and in turn, $v_{th} = \sqrt{k_B T/m}$ the thermal velocity. The frequency detuning from the plasma resonance is $\delta = \Delta\omega - \omega_p$, $|\delta| \ll \omega_p$. Also, $\omega_p \ll \omega_0$, thus $\omega_1 \approx \omega_0$ (except in $\Delta\omega$) and the slow propagation of the longitudinal wave (with group velocity $v = 6v_{th}^2\omega_0/(\omega_p c)$) has been neglected.

Collisional damping is represented by the rates $\nu_\perp$ for the transverse waves, and $\nu_\parallel$ for the longitudinal wave. These can be found by substituting the laser and plasma frequency, respectively, into the expression [6]

$$\nu = \frac{Zr_e\omega_p^2}{3\sqrt{2\pi}c}\,\theta^{-3/2}\left[\ln\left(\frac{4\theta mc^2}{\hbar\omega}\right) - \gamma\right], \tag{5}$$

where $r_e = e^2/(4\pi\varepsilon_0 mc^2)$ is the classical electron radius, and $\gamma = 0.577$ is Euler's constant. This is valid for $\omega \ll k_B T/\hbar$ (where $\hbar$ is Planck's constant), and velocity amplitude $v_0 \ll v_{th}$. For higher amplitudes the rates decrease, see [6].

The equations for the waves are supplemented by one for the evolution of the temperature:

$$\partial_t\theta = \nu_\perp(|a_0|^2 + |a_1|^2)/3 + (\nu_\parallel + \nu_L)|f|^2/3. \tag{6}$$

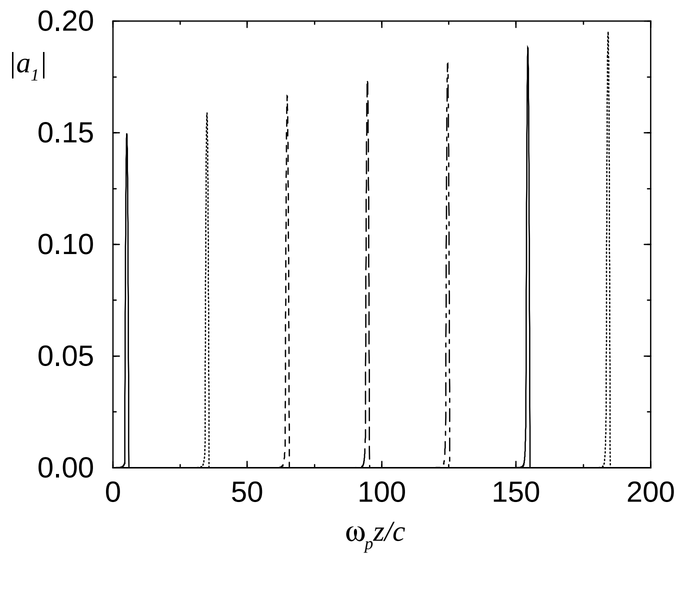

Figure 1: Snapshots of probe amplitude - simulation.

Figure 1 shows snapshots of the probe amplitude determined with equations (1) to (6), for pump amplitude $|a_0| = 4.4 \cdot 10^{-3}$, and initial temperature $T_0 = 5$eV, with plasma frequency $\omega_p = 4.8 \cdot 10^{13}\mathrm{s}^{-1}$, and laser frequency $\omega_0 = 2.4 \cdot 10^{15}\mathrm{s}^{-1}$. There is very little amplification of the probe, due to the strong Landau damping, $\nu_L = 0.27\omega_p$ for these parameters. Varying the initial temperature or detuning, or chirping the pump frequency hardly changes the evolution.

Weak and strong Landau damping As mentioned above, the two effects of finite temperature are a shift of the resonance frequency, and Landau damping. Absorption of laser energy in the plasma makes the frequency shift time-dependent, at a rate $\alpha = 6\omega_0^2\dot{\theta}/\omega_p$. This is similar to a position-dependent plasma frequency, or a chirped pump pulse, which lead to superradiant scaling [3, 4, 5]. If heating is only by the pump wave, $\alpha = 2\nu_\perp\omega_0^2|a_0|^2/\omega_p$, which can be compared with (the square of) the Raman growth rate, $\gamma_0 = \sqrt{\omega_0\omega_p}|a_0|/2$. If the ratio $\alpha/\gamma_0^2 = 8\nu_\perp\omega_0/\omega_p^2$ is (at least) of order unity, the chirp should result in superradiant scaling of the probe, provided that damping of the waves does not destroy the effect. The collisional damping rates are small, except for very low temperature, while Landau damping becomes important at temperatures of about 3 eV (for $\omega_0 \approx 50\omega_p$). While this seems to indicate a temperature range where damping is negligible, inevitable heating will often lead out of this range, towards a regime where Landau damping is strong, as in the simulated case. To model this, we neglect the collision rates, and also the shift of the resonance frequency. For small scattered field we choose the constant pump amplitude a_0 real, and obtain

$$(\partial_t + c\partial_z)a_1 = \omega_p f a_0/2, \quad (\partial_t + \nu_L/2)f = \omega_0 a_0 a_1/2. \tag{7}$$

The damping can be taken into account by an exponential factor $e^{-\nu_L(t-z/c)/2}$, which transforms the equations to the form of those without damping; these have a self-similar solution depending on the product $\xi = z(t-z/c)$:

$$a_1 = zA(\xi)e^{-\nu_L(t-z/c)/2}, \quad f = F(\xi)e^{-\nu_L(t-z/c)/2}. \tag{8}$$

Upon substitution into equation (7), we find

$$c(A + dA/d\xi) = \omega_p F a_0/2, \quad dF/d\xi = \omega_0 a_0 A(\xi)/2. \tag{9}$$

Eliminating A yields $\xi d^2F/d\xi^2 + dF/d\xi = \gamma_0^2 F/c$, with solution

$$F(\xi) = F(0)\mathrm{I}_0(2\gamma_0\sqrt{\xi/c}) \Rightarrow A(\xi) = A(0)\mathrm{I}_1(2\gamma_0\sqrt{\xi/c})/(\gamma_0\sqrt{\xi/c}), A(0) = \omega_p a_0 F(0)/2, \tag{10}$$

where $\mathrm{I}_{0,1}$ are modified Bessel functions.

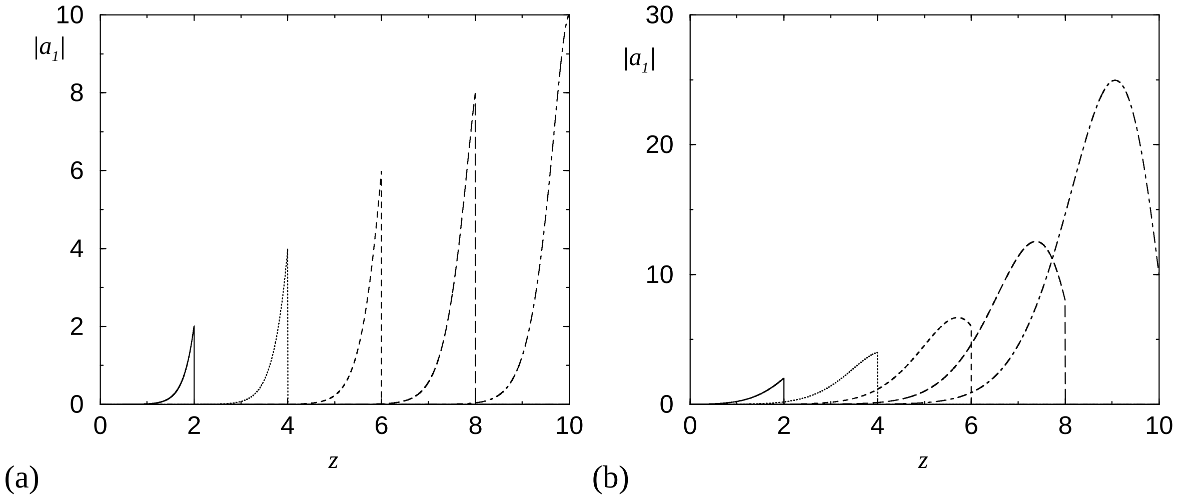

Figure 2: Snapshots of probe amplitude - self-similar solution for (a) high and (b) low Landau damping rate.

Figure 2(a) shows snapshots of the self-similar probe amplitude. Although the pulses look quite different from the simulation results, they have to be understood as the response to a short seed, whereas Fig. 1 shows the sum of both. Figure 2(b) shows similar snapshots, but for lower Landau damping rate. It shows that after initially the damping dominates, later amplification takes off.

Discussion We have developed the envelope equations for Raman backscattering in plasma at finite temperature, and started to investigate the effects caused by the chirp of the resonance frequency, and in particular strong Landau damping.

Acknowledgements We acknowledge support by the UK research councils.

References

[1] V. M. Malkin, G. Shvets, N. J. Fisch, Phys. Rev. Lett. **82**, 4448 (1999)

[2] W. Cheng, Y. Avitzour, Y. Ping, S. Suckewer, N. J. Fisch, M. S. Hur, J. S. Wurtele, Phys. Rev. Lett. **94**, 045003 (2005)

[3] B. Ersfeld, D. A. Jaroszynski, Phys. Rev. Lett. **95**, 165002 (2005)

[4] R. A. Cairns, B. Ersfeld, D. A. Jaroszynski, R. Trines, EPS 2006 conference, poster P5.013

[5] R. W. Short, A. Simon, Phys. Plasmas **11**, 5335 (2004)

[6] Y. Shima, H. Yatom, Phys. Rev. A **12**, 2106 (1975)