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Raman amplification in plasma: thermal effects and damping

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Abstract
The influence of thermal effects on Raman amplification is investigated. It is shown that the Bohm-Gross shift of the resonant plasma frequency due to heating by inverse Bremsstrahlung acts in a similar way to a chirped pump or plasma gradient, and can avoid significant lengthening of the amplified probe without accessing the pump depletion regime. Landau damping is found to be negligible for sufficiently high plasma densities, due to the increase in the phase velocity of the excited plasma wave. It is shown that the shift in resonance due to heating may not be sufficient to suppress the parasitic amplification of noise.

Introduction
Raman amplification in plasma is a potential method for the creation of ultra-short, ultra-intense laser pulses[1], which have both direct uses over a wide range of science and engineering applications, and as a building block for systems such as laser-wakefield accelerators[2]. As plasma can withstand extremely high intensities, its use as an amplifying medium removes the need for compression gratings which become large and expensive at high powers. Furthermore, the process itself can lead to compression of the amplified pulse.

Raman amplification is a three wave interaction, in which two laser pulses of different frequencies beat and drive a plasma wave through the action of the ponderomotive force. The resulting density perturbation acts as a moving Bragg grating, scattering photons from the higher frequency pulse to the lower one. A counterpropagating geometry allows a short probe pulse to interact with the entire length of a long pump pulse, allowing it to grow to intensities greater than that of the pump.

In the linear regime[3], characterised by negligible pump depletion and relatively weak ponderomotive forces, the beat of the lasers is sufficient only to drive a Langmuir wave at the resonant plasma frequency, resulting in a very narrow amplification bandwidth. The amplitude of the probe grows exponentially, but its length increases proportional to the propagation distance. This renders the regime unsuitable for most practical applications.

However, this limitation can be avoided through the exploitation of nonlinearities. In the pump depletion regime[4] amplification to the rear part of the probe is limited by the reduction in the pump intensity, to give superradiant scaling, with the probe amplitude increasing linearly with propagation distance and self-similar contraction.

However, the same scaling can be achieved in the linear regime by making use of inhomogeneities[5]. While the resonance relation between pump, probe and Langmuir wave must still be satisfied, the narrow amplification bandwidth is overcome by using a chirped pump or a plasma density gradient. Frequency components in phase near the head of the probe will destructively interfere further behind, leading to pulse compression. The amplitude grows linear with propagation distance as each frequency component of the probe will only be in resonance for a finite duration.

While plasma can withstand high intensities, the associated thermal effects can have a significant impact on the amplification mechanism. This work investigates the effect of damping of the laser pulses and Langmuir wave and the shift in plasma response at finite temperature.

Thermal effects
The pump, probe and Langmuir wave can be described using the slowly varying envelope equations, which determine the evolution of the envelopes of the three waves coupled by the Raman interaction. These can be written to include the thermal effects[6], as follows:

$$\left(\frac{\partial}{\partial t} - c\frac{\partial}{\partial z} + \left(\frac{\omega_p}{\omega_0}\right)^2 \frac{\nu_\perp}{2}\right) a_0 = -\frac{\omega_p f^* a_1}{2} \quad , \qquad (1)$$

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z} + \left(\frac{\omega_p}{\omega_0}\right)^2 \frac{\nu_\perp}{2}\right) a_1 = \frac{\omega_p f a_0}{2} \quad , \qquad (2)$$

$$\left(\frac{\partial}{\partial t} + \frac{\nu_\parallel}{2} + i\left(\omega_p' - (\omega_0 - \omega_1)\right)\right) f = \frac{\omega_0 a_0^* a_1}{2} . \qquad (3)$$

Here $a_{0,1} = eE_{0,1}/m\omega_{0,1}c$ are the reduced vector potentials of the pump and probe, respectively, with $E_{0,1}$ and $\omega_{0,1}$ the associated electric field amplitudes and frequencies. $f = eE_z/m\omega_p c$ is a normalised form of the plasma wave amplitude, E_z, with $\omega_p = \sqrt{(ne^2/\varepsilon_0 m)}$ the plasma frequency. n is the plasma electron density, $-e$ and m the electron charge and mass, ε_0 the permittivity of free space and c the vacuum speed of light.

The collisional damping rates for the laser pulses and Langmuir wave, $\nu_\perp$ and $\nu_\parallel$, are obtained by substituting the laser and plasma frequencies, respectively, into the inverse Bremsstrahlung damping rate:

$$\nu = \frac{Ze^2\omega_p^2}{6(2\pi)^{3/2}\varepsilon_0 mc^3}\theta^{-3/2}\left[ln\left(\frac{4\theta mc^2}{\hbar\omega}\right)-\gamma\right] \quad (4)$$

where Z_e is the ion charge, $\theta = k_B T/mc^2$ the normalised temperature, $\hbar$ Planck's constant and γ Euler's constant. The Landau damping rate for a Langmuir wave of wavenumber $k_\parallel$ is given approximately by

$$\nu_L \approx \frac{\pi\omega_p^2}{2}\frac{\omega}{k_\parallel^2}\frac{\partial f(v)}{\partial v}\Big|_{v=v_{ph}} \quad (5)$$

The rate at which the plasma is heated is then

$$\frac{\partial\theta}{\partial t} = \frac{1}{3}\left(\nu_\perp\left(|a_0|^2+|a_1|^2\right)+\left(\nu_L+\nu_\parallel\right)|f|^2\right) \quad (6)$$

The resonant frequency of the plasma, ω'_p, taking in to account the Bohm-Gross shift, is:

$$\omega_p' = \sqrt{\omega_p^2+3\theta c^2k_\parallel^2} \quad (7)$$

Simulation results

Simulations have been carried out using a 1-dimensional fluid model based on the slowly varying envelope equations given in Eqs. (1-3). Parameters are chosen to be similar to those used in recent experimental works[7,8], shown in Table (1).

Pump wavelength 800 nm	Pump length 20 ps FWHM (1 ps rise time)	Probe length 100 fs FWHM Gaussian
Plasma Length 4 mm	Plasma density 2×10^{19} cm^{-3}	Initial plasma temperature 5 eV ($\theta = 1 \times 10^{-5}$)

Table 1. Parameters used for simulations

Figure 1 shows how thermal effects can significantly change the interaction of the pump and probe. Using the cold plasma model, the process rapidly enters the pump depletion regime. However, using the thermal effects model, pump depletion tends to a constant value, as expected for a chirped pump[5,9]. The amplified probe for the two models are similar, with high intensities, short durations and a trail of pulses following the lead pulse. However, they are the product of different regimes of the Raman amplification process.

Figure (2a) shows the effect of varying the plasma density, comparing the cold plasma model and the thermal effects model, both including and omitting Landau damping. In the linear regime, the growth rate increases proportional to $\sqrt[4]{n}$. In the pump depletion regime, the effect of varying plasma density is small, although, following Manley-Rowe[10], a larger fraction of the pump energy will be deposited in the plasma wave at higher densities. It can be seen that for densities above 1.5×10^{19} cm^{-3}, Landau damping becomes negligible. This can be explained by considering the phase velocity of the plasma wave. For a resonantly excited Langmuir wave, the phase velocity is approximately given by $v_\phi \approx \omega_p c/2\omega_0$. As Landau damping is the result of particles with velocities close to the phase velocity interacting with the wave, as n_e increases, the number of particles with thermal velocities close to v_ϕ will decrease, until the effect becomes negligible.

Noise is an important concern for Raman amplification. If efficient systems are to be realised, it is necessary to operate in the pump depletion regime. However, in this regime, the probe amplitude will grow linearly with distance, while small signal noise, such as spontaneous pump backscatter from thermal fluctuations, will be amplified exponentially. The introduction of a chirp has been suggested as a method of suppressing the amplification of noise[9]. All signals are amplified linearly with distance, with efficient amplification still possible for a sufficiently intense input probe. It has further been suggested that the varying plasma resonance due to the thermal gradient should suppress noise in the same way[11].

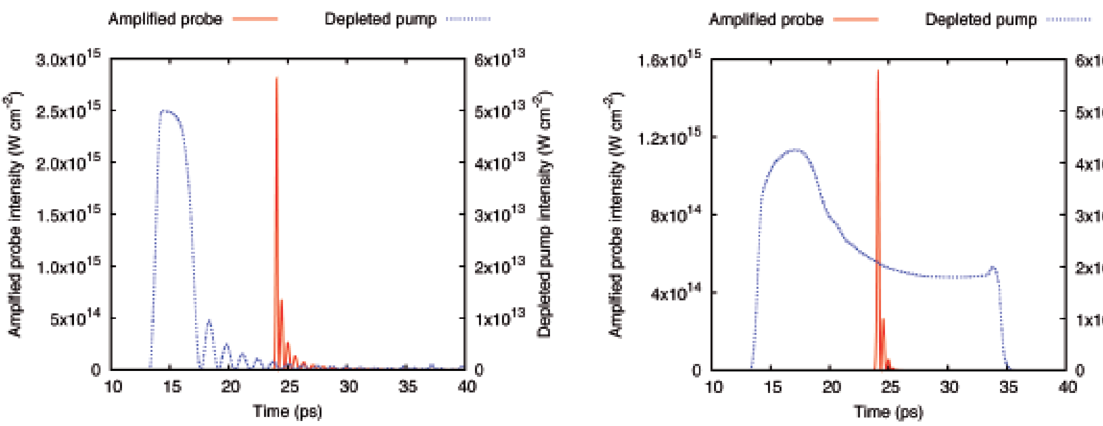
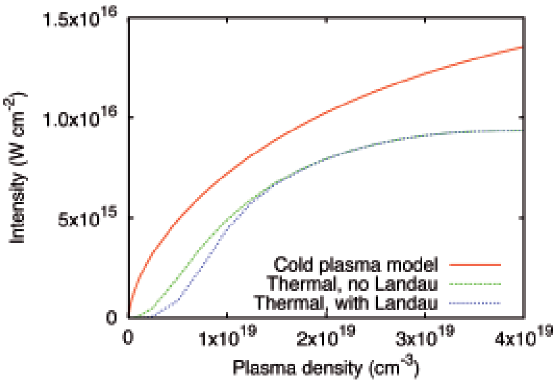


Figure 1. Intensity plots of pump and probe as they leave the plasma. Comparison between (a) cold plasma model and (b) thermal effects model. Monochromatic pump of intensity 5×10^{13} W cm^{-2}, probe intensity 1×10^{12} W cm^{-2}, other simulation parameters are as shown in Table (1).



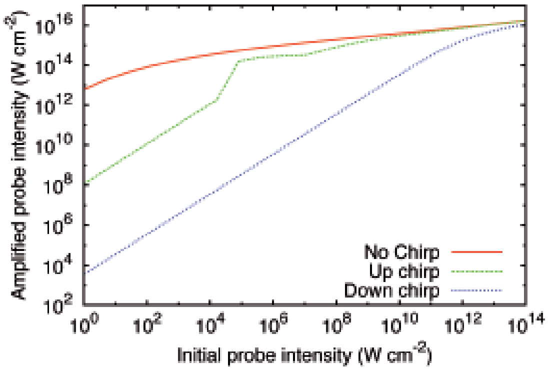


Figure 2. (a) Amplified probe intensity for varying plasma density. Comparison between cold plasma model and thermal effects model, both with and without Landau damping. Monochromatic pump of pump intensity 1×10^{14} W cm^{-2}, probe intensity 1×10^{12} W cm^{-2}, other simulation parameters are as shown in Table (1). (b) Amplified probe intensity for varying input probe intensity. Comparison for pump pulse with no chirp (monochromatic), up-chirp and down-chirp ($\Delta\omega_0/\omega_0 = 0.01$). Pump intensity 1×10^{14} W cm^{-2}, other simulation parameters are as shown in Table (1).

Figure (2b) shows the peak intensity of the amplified probe for varying input intensity. It can be seen that the shift in resonance due to heating may not provide sufficient suppression of noise for longer amplification lengths. As expected, a down-chirp provides better suppression of noise, as the detuning due to the chirp will add to the detuning due to the Bohm-Gross shift. Using an up-chirp, the two partially cancel. The sudden increase in intensity seen for the up-chirp case around 5×10^4 W cm^{-2} is due to collisional damping of the Langmuir wave. For sufficiently high probe intensities, the additional contribution to the temperature gives a larger Bohm-Gross shift, which better counteracts the chirp of the probe pulse.

Conclusion

We have shown that thermal effects can play a significant role in Raman amplification. A new variation of the chirped pulse regime is shown, where a pulse amplified by a monochromatic pump in plasma of uniform density may maintain its short length without reaching the pump depletion regime, due to heating of the plasma by the pump.

It is found that Landau damping becomes negligible at sufficiently high densities, due to the increase in phase velocity for a resonantly excited Langmuir wave.

The shift in resonance due to heating does contribute to the suppression of noise, but for high growth rates and/or long interaction lengths, this may not be sufficient. A chirped pump pulse may be used to compliment the detuning due to heating.

Acknowledgements

We acknowledge the support of the UK EPSRC, the Laserlab-Europe consortium and the Extreme Light Infrastructure (ELI) project.

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