Raman amplification in plasma: influence of heating

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Abstract. A comparison is made between a simple three-wave model and a Particle in Cell (PIC) code for the study of Raman amplification. Away from regimes of particle trapping and wave breaking, the three-wave model is found to have several advantages: reduced computational overheads, less susceptibility to instabilities, and the flexibility to include additional effects in a phenomenological manner. One example is damping and heating, which is illustrated here. It is found that, for the parameters studied, thermal effects can lead to a reduction in pump depletion without a significant reduction in peak probe amplitude.

1. Introduction

Raman amplification has been suggested as 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, reducing both the cost and footprint of the laser system.

Raman amplification is achieved by colliding two counterpropagating laser pulses of different frequencies in plasma. The resulting beat wave drives a plasma oscillation and the associated density perturbation acts as a moving Bragg grating, scattering the higher frequency pump into the lower frequency probe pulse. The phase velocity of the plasma wave is such that the Doppler shift for the scattered wave satisfies the frequency matching conditions.

In the Raman regime, the electrostatic force of the plasma wave is dominant, and efficient amplification requires the detuning between the laser pulses be chosen to resonantly drive a Langmuir wave.

Several specific cases can be identified. In the linear regime, pump depletion is negligible and the amplification bandwidth is narrow, resulting in a probe with an amplitude which grows exponentially, but a length which increases proportional to the propagation distance.

In the pump depletion regime[3], the reduction in pump amplitude reduces amplification to the rear of the probe pulse. This leads to superradiant growth, with the probe amplitude increasing linearly with propagation distance and self-similar contraction of the probe length.

Self-similar scaling of the probe can also be achieved by using a chirped pump pulse[4]. The frequency matching condition between pump, probe and plasma wave must still be satisfied, but the varying pump frequency leads to an increase in the amplification bandwidthallowing pulse compression.

This type of three wave interaction is common throughout physics, with analytical solutions possible for simple cases, and numerical results found for more complex cases. In Section 2 we compare a simple three-wave model to a fully kinetic Particle in Cell (PIC) code. In Section 3 we then illustrate one advantage of the three-wave model, by modifying it to include heating and damping effects.

2. Comparison of models

The slowly-varying envelope equations for Raman amplification[3] are widely used, with analogues used in many other areas of physics. This three-wave model has the advantage that it can be solved numerically very quickly, and its simplicity allows additional effects to be added with relative ease. PIC codes, widely used for applications such as wakefield acceleration, are computationally intensive and subject to numerical instabilities. However, as they provide a full kinetic model, they are not limited to the Raman regime, and can be used to investigate related effects such as Langmuir wavebreaking, the Compton regime and particle trapping at high temperatures.

The PIC code VORPAL[5] is used to make the comparison. We use cold, collisionless plasma, for both monochromatic and chirped pump cases, away from regimes of wave breaking and particle trapping. Parameters are chosen to be achievable in university scale facilities: a flat-top pump of wavelength 1054 nm and intensity 1×10^{14} W cm^{-2} is collided with a 100 fs FWHM probe of the same intensity in a 2mm plasma of density 1×10^{19} cm^{-3}. The probe frequency is downshifted from that of the pump by the plasma frequency.

The comparison, shown in Fig (1), shows good agreement for the peak amplitude, but the solutions diverge behind the first peak. This is attributed to the development of numerical instabilities in the PIC code, which are known to increase with distance behind a driver pulse[6]. Better agreement is found for a smaller ratio ω_0/ω_p[7] or for lower intensities, i.e. further from wavebreaking, allowing Burnham-Chiao ringing to be seen in the PIC code.

While plasma can withstand high intensities, the associated effects of heating and damping can have a significant impact on the amplification mechanism. PIC codes are typically unsuitable for modelling effects such as collisional damping which require particle-particle interactions. We illustrate one advantage of the three-wave model by modifying it to include thermal effects and damping.

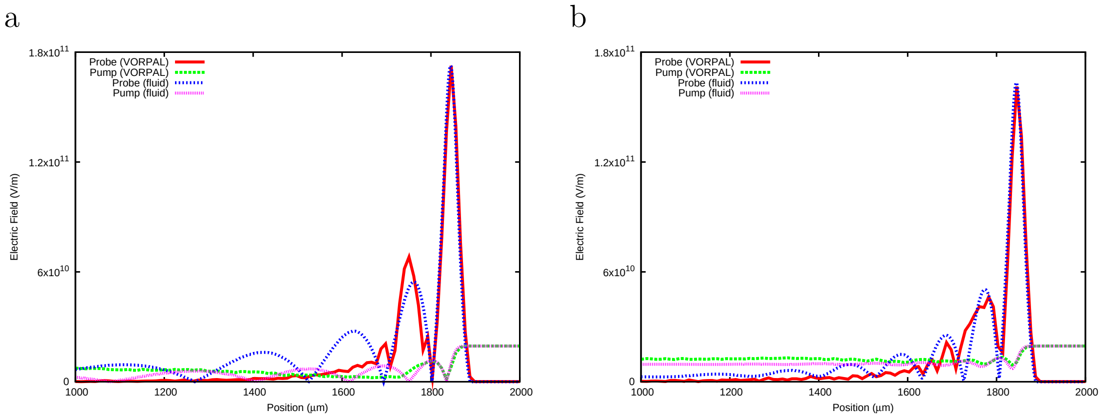

Figure 1. Comparison between three-wave and PIC code simulation results for (a) monochromatic pump (b) chirped pump ($\Delta\omega_0 = 0.12\omega_p$)

3. Thermal three-wave model

The slowly varying envelope equations can be rewritten to include thermal effects[8]. The laser pulses are subject to collisional damping, while the plasma wave is be subject to both collisional and Landau damping. In addition to the direct effects of damping, the plasma will be heated, which leads to a Bohm-Gross shift in plasma resonance, which further influences the interaction.

The three-wave model used in Section 2 is modified to include these thermal effects, and used to investigate their influence on the Raman interaction. An initial temperature of 5 eV is used, typical for spark ionised plasmas in capillaries.

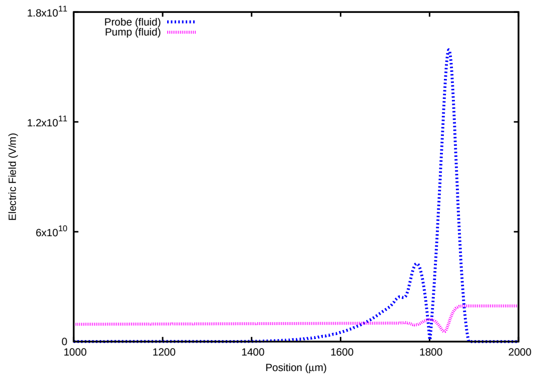

Figure 2. Three-wave simulation results for thermal effects case

Fig. 2 shows one example of the influence thermal effects and damping can have on the interaction of the pump and probe. Using the cold plasma model, the process rapidly enters the pump depletion regime, as seen in Fig. (1.a). However, using the three-wave model modified to include thermal effects, pump depletion tends to a constant value. This is expected, as the shift in plasma resonance due to heating by the pump will lead to an increase in the amplification bandwidth, in much the same way as a chirped pump, as shown in Fig. (1.b). Although the peak probe amplitude for the two models are similar, they are the product of different regimes of the Raman amplification process. Burnham-Chiao ringing is suppressed in this case, due to damping of the plasma wave. For the parameters used, thermal effects are beneficial, as the peak amplitudes achieved are similar, but more of the pump survives, making it suitable for multi-pass systems[9].

4. Conclusion

We show that away from wavebreaking and particle trapping regimes, a simple three-wave model gives good agreement to a fully kinetic PIC code for peak probe intensity. The simplicity of the three-wave model allows reduced computational overheads, means it is not subject to many of the instabilities which occur in PIC codes, and also allows it to be modified with relatively little effort to include effects such as heating and damping phenomenologically, which many PIC codes do not include. We illustrate one example in which damping of the pump leads to a shift in plasma resonance, allowing pulse compression with relatively low pump depletion. Damping of the plasma wave further reduces pump depletion, which may render this regime more suitable for multi-pass systems.

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References

[1] Shvets, G., Fisch, N. J., Pukhov, A., and Meyer-ter Vehn, J. *Phys. Rev. Lett.* **81**, 4879 (1998).
[2] Jaroszynski, D. A. et al. *Nucl. Instrum. A.* **445**, 317 (2000).
[3] Malkin, V. M., Shvets, G., and Fisch, N. J. *Phys. Rev. Lett.* **82**, 4448 (1999).
[4] Ersfeld, B. and Jaroszynski, D. A. *Phys. Rev. Lett.* **95**, 165002 (2005).
[5] Nieter, C. and Cary, J. *J. Comp. Phys.* **196**, 448 (2004).
[6] Cormier-Michel, E. et al. *Phys. Rev. E* **78**, 016404 (2008).
[7] Wang, T.-L. et al. *Phys. Plasmas* **16**, 123110 (2009).
[8] Lui, C.-S., "Parametric instabilities in laser plasma interaction," in [*From Particles to Plasmas*], Van Dam, J., ed., ch. 9, 141, Addisson-Wesley, California (1989).
[9] Ren, J., Cheng, W., Li, S., and Suckewer, S. *Nat. Phys.* **3**, 732 (2007).