Backward Raman amplification in extended regimes of pump pulse parameters

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Introduction

The maximum output in intensities reachable through backward Raman amplification of laser pulses in plasma can, in principle, exceed by orders of magnitude methods based on material gratings and amplifiers. The backward Raman amplification (BRA) in plasma is a resonant interaction in which a long duration laser pulse (pump) transfers most of its energy to a counter propagating short duration laser pulse (seed) via the mediation of the Langmuir wave.

In cold plasma the BRA in plasma, taking into account the lowest order relativistic electron nonlinearity and group velocity dispersion effects for the amplified pulse, can be described by one-dimensional fluid model in the form of coupled 3-wave equations [1]:

$$a_t + c_a a_z = V_3 b f\ ,\quad f_t = -V_3 a b^*,$$
$$b_t - b_z c_b = -V_3 a f^* - i\kappa b_{tt} + iR|b|^2 b. \tag{1}$$

Here a, b, and f are envelopes of the pump, seed and Langmuir wave. The envelopes normalized to electron quiver velocities in fields of the pump, seed, and Langmuir wave, respectively. The subscripts t and z signify time and space derivatives; c_a and c_b are group velocities of the pump and amplified pulses; V_3 is the 3-wave coupling constant ; R is the coeffcient of nonlinear frequency shift due to the relativistic electron nonlinearity (REN); κ is the group velocity dispersion (GVD) coefficient; The relativistic electron nonlinearity is taken into account only for the seed pulse, because the seed is ultimately amplified to intensities much higher than that of the pump. The group velocity dispersion is also taken into account only for the seed pulse, because the seed is of much shorter duration than the pump, and therefore more sensitive to the dispersion effect.

Relativistic electron nonlinear regime

For pump intensity below the wavebreaking it was assumed that the maximum output intensity can be obtained when the leading spike of the pi-pulse reaches saturation. The saturation of the leading spike is the result of the relativistic electron nonlinearity which induces a phase shift between the three waves. At the saturation point the accumulated phase shift is large and as a

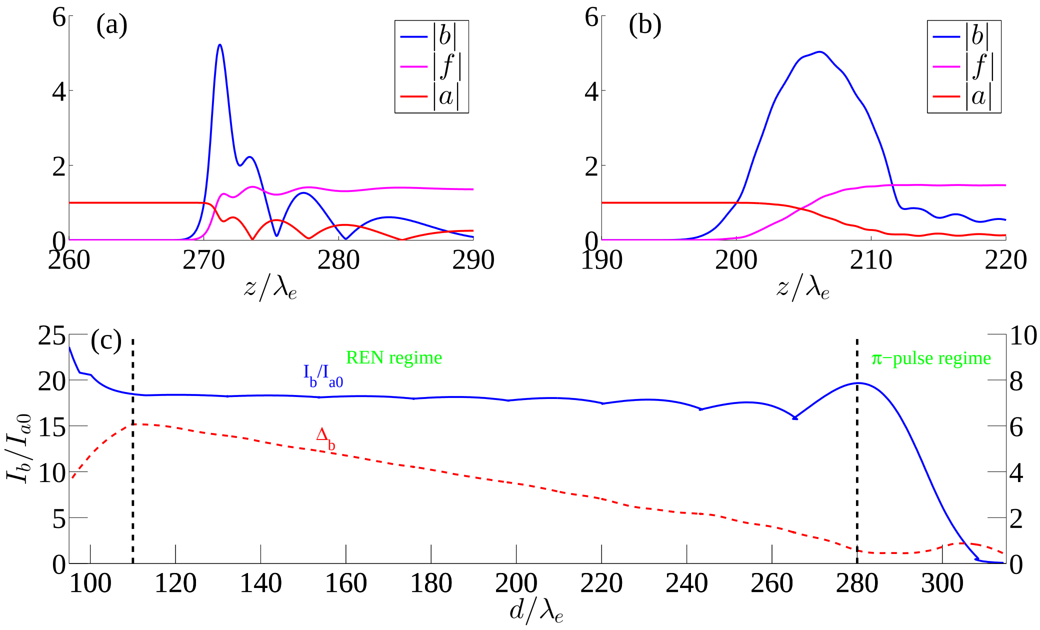

Figure 1: The three envelopes when the has traversed a length of (a) 64 μm (π-pulse regime) and (b) 137 μm (REN regime). (c) The seed amplitude and width as function of the seed peak location.

result prevents from efficient energy transfer from the pump to the amplified seed. The concern was that immediately this point a modulational instability or pulse breakup could be developed. Thus, to avoid from reaching the modulational instability, the pump width was limited (and also the plasma length) till the saturation point.

However, we present an illustrative example of seed amplification beyond the saturation point (a general formulation can be found in Refs. [1] and [2]). Consider an injected pump intensity of 55 PW/cm^2 with a wavelength of 0.351 μm, injected into a 354 μm long plasma. The initial counter-propagating seed has intensity of 4 PW/cm^2 with duration of 13.2 fsec. The plasma density is $n_e = 8 \times 10^{20}$ cm^{-3}. Fig. 1c shows in the pi-pulse regime, that the amplified pulse intensity is 1.045 EW/cm^2 with full width at half maximum (FWHM) duration of 4.7 fsec after the seed has traversed a length of 64 μm. In this example the dispersion parameter is $Q = 0.23 > 0.03$ and as a result it is expected the GVD will be a dominant effect. Since the strong GVD tends to stretch the width of the seed, the overall effect with the Raman amplification is that the amplified pulse appears as a single spike. In this example when the amplified seed travels a distance of 137 μm (Fig. 1d), the intensity is 0.99 EW/cm^2, with a FWHM duration of about 52.8 fsec. Hence, while the ratio between the seed intensities in the REN regime to the pi-pulse regime is nearly the same the fluence ratio is about ten times larger.

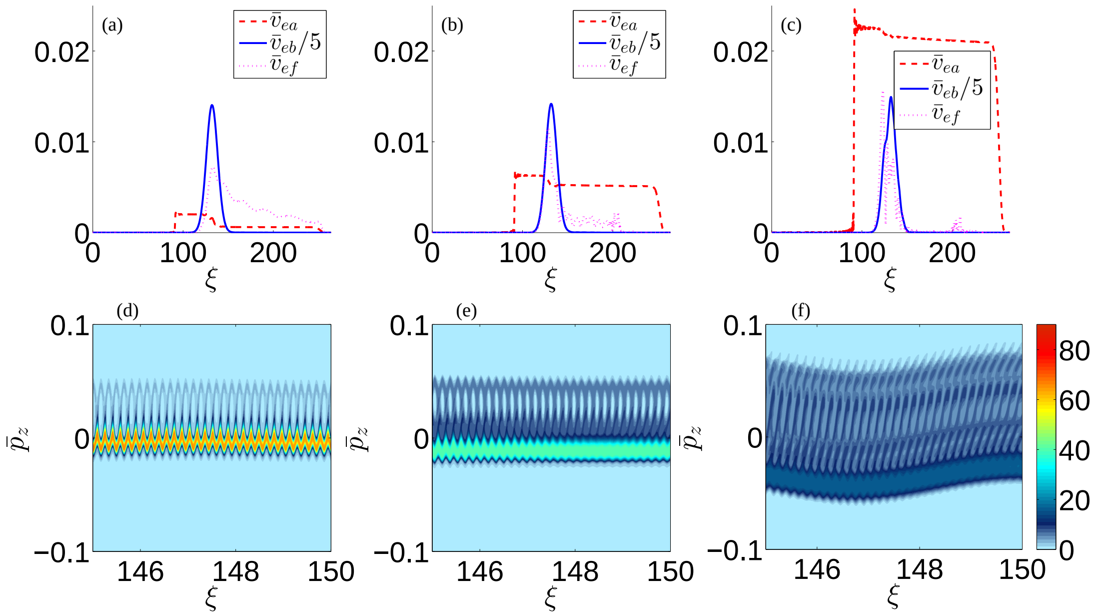

Figure 2: (a) Envelopes of the pump (dashed curve), the seed (solid curve), and the Langmuir wave (dotted curve) for pump amplitude $v_{ea}/v_{br} = 0.5$, which is below the wavebreaking threshold; (b) pump amplitude $v_{ea}/v_{br} = 1.5$, which is in the mild wavebreaking regime; (c) pump amplitude $v_{ea}/v_{br} = 5.5$, which is in the strong wavebreaking regime. (d)-(f) The corresponding electron phase space distributions in the region behind the seed pulse maximum spike.

Wavebreaking regime

The BRA can be used to compress soft X-ray of nano meter wavelength laser pulses, where the laser to plasma frequency ratio is significantly larger on the order of 20 or more than in the optical regime. In this soft X-ray regime the dominant degrading effect is Langmuir wavebreaking assuming the plasma temperature low enough to avoid Landau damping. Langmuir wave-breaking occurs when the longitudinal quiver velocity of electrons is approximately equal to the phase velocity of the Langmuir wave. The electrons can then no longer perform simple oscillatory option in support of the wave. Based on the Manley-Rowe relations the threshold for the Langmuir wavebreaking can be expressed in terms of the initial pump amplitude. More specifically, the wavebreaking threshold is $v_{br} = c(2\omega_a/\omega_e)^{-3/2}$, where v_{br} is the electron quiver velocity in the pump pulse.

To explore the Langmuir wavebreaking, we consider the case where $\omega_a/\omega_e = 20$. In addition, to avoid Landau damping, the initial electron temperature is set to 10 eV. Since the wavebreaking is a kinetic effect, the BRA was calculated by a Vlasov-Maxell (VM) code [3]. In the regime where the initial pump amplitude is below the wavebreaking threshold ($v_{ea}/v_{br} = 0.5$) the pump depletion is 90% (Fig. 2a). For initial pump amplitude that is 1.5 larger than the wavebreaking threshold (mild wavebreaking regime) the pump depletion is reduced to about 30% (Fig. 2b). For pump amplitude significantly larger than the wavebreaking threshold ($v_{ea}/v_{br} = 5.5$) the pump depletion is reduced to about 10% (Fig. 2c). While in the regime below the wavebreaking (Fig. 2d) and in the mild wavebreaking regime (Fig. 2e) most of the electrons are distributed according to the initial Maxwellian distribution, in the strong wavebreaking regime, a large fraction of particles are accelerated (Fig. 2f).

The VM code confirmed that moderate efficient BRA can occur for pump intensity up to a few times larger than the wavebreaking threshold. However, for initial pump intensity larger than more by ten times the wavebreaking threshold, the amplification efficiency decreases. Another important result is that in the mild wavebreaking regime increasing the initial seed intensity increases the depletion of the pump, whereas in the strong wavebreaking regime the pump depletion is not seen affected by an intense seed pulse.

Conclusions

To summarize, below the Langmuir wavebreaking and at plasma temperature in the region where the Landau damping and inverse bremsstrahlung can be neglected, the amplification efficiency is mainly limited by the relativistic electron nonlinearity and seed group velocity dispersion. Our numerical simulations indicate that the seed can be amplified beyond the saturation of its leading spike, in other words, beyond the so-called π-pulse regime. More specifically, for large dispersion paramter or dense plasma the amplitude of the seed is saturated and its width can be increased substantially by a factor of ten due to the strong GVD which leads to high output fluence.

In addition to the possible extension of the pump width, it turns out that the pump intensity can exceed the Langmuir wavebreaking threshold. More specifically, for pump intensity up to a few times the wavebreaking threshold, it is still possible to have moderately efficient Raman amplification. However, for pump intensities larger than tenfold the wavebreaking threshold, the efficiency significantly decreases.

References

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