Transverse dynamics of seed pulses during Raman and sc-Brillouin amplification

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Plasma based amplification of short seed laser pulses via stimulated Raman (SRS) or strongly-coupled (sc) Brillouin (sc-SBS) backscattering is receiving growing interest as these schemes may become a key technology for the next generation of ultra-high intensity lasers [1,2,3]. In order to reach intensities up to the Exawatt-Zettawatt level, the pump beam, delivering energy to the seed pulse, and the amplified seed pulse itself, will have large transversal diameters in order to stay within the weakly relativistic field intensity regime within the amplifier. As a result, the pulses will be vulnerable to transverse instabilities. Using multi-dimensional three-wave fluid models and kinetic (Particle-in-cell and full Maxwell-Vlasov) simulations we discuss the limitations of Raman and sc-Brillouin amplification with respect to seed pulse filamentation.

Typical lengths of plasma-based amplifiers are foreseen to be on the order of a few mm, i.e. the interaction between pump and seed pulse will last for several pico-seconds [1]. For most of this time the interaction will take place in the nonlinear pump-depletion regime. Within this regime the seed pulse will undergo self-similar amplification and compression dynamics (see e.g. [2] for SRS and [3,4] for sc-SBS). The seed pulse will eventually reach amplitudes a magnitude larger than the pump pulse. To obtain pulses that carry energy up to kJ level, but keep the local amplitudes sub-relativistic, laser beams have to become very wide. This opens up the possibility of transverse filamentation of the seed and the pump.

Filamentation is a well-known effect, but treated analytically mostly through plane-wave approximations. In our scenario, we have short pulses that exhibit transient behavior due to the simultaneous amplification. For typical pump intensities of 10^{15} W/cm^2 plane wave calculations predict growth of transverse modulations on the time-scale of several 100 ps. At intensities of 10^{17} W/cm^2 the time-scale reduces to a few ps. The latter is well in the regime of typical time scales on which amplification will take place. Hence, we focus on the filamentation of the seed pulse, which will eventually be amplified up to about 10^{17} W/cm^2.

To study the influence of transverse perturbations of the seed during amplification, we make use of three-wave envelope models. In these models we describe the interaction of pump, seed and plasma wave. Let E_p, E_s, and N be the amplitudes of pump, seed and plasma wave, respectively. Then the equations for the laser fields are

$$(\partial_t + v_1\partial_x - i\,\alpha_1\, \partial_x^2 - i\,\kappa_1 \nabla_\perp^2)\, E_p = -N^* E_s + i(\chi_{11}\, |E_p|^2 + \chi_{12}\, |E_s|^2)E_p\,, \quad (1)$$

$$(\partial_t + v_2\partial_x - i\,\alpha_2\, \partial_x^2 - i\,\kappa_2 \nabla_\perp^2)\, E_s = -E_p N + i(\chi_{21}\, |E_p|^2 + \chi_{22}\, |E_s|^2)E_s. \quad (2)$$

The equation for the plasma wave amplitude N becomes

$$\partial_t N = E_s\, E_p^*, \quad (3)$$

in the case of SRS, and

$$(\partial_t^2 - c_s^2/c^2\, \partial_x^2)N = -i\,\nu\, E_s E_p^* \quad (4)$$

in the case of sc-Brillouin.

For SRS amplification, it is assumed that the beat of pump and seed wave is resonant with a Langmuir wave [2], whereas for sc-Brillouin the beat will drive an ion quasi-mode of the plasma which has a frequency larger than $\omega_{IAW}=kc_s$ [3,4]. In the context of one-dimensional geometry both amplification processes have been investigated in many works (see e.g. [2,3,4,5,6]). Only a small number of publications yet discussed multi-dimensional aspects of parametric short pulse amplification (see [7,8,9] for SRS and [10,11] for sc-SBS).

Let us focus on SRS amplification, for which we find that plane wave estimates may not give correct predictions for the filamentation of the seed pulse. To demonstrate this, we simulate Eqs. (1)-(3) in two- and three-dimensional geometry.

First, without any initial perturbation on the seed pulse, we notice that the transverse profile of the pump will influence the transverse profile of the seed. When the pump has a Gaussian transverse profile, we observe that the seed intensity fronts are curved, see Fig. 1. This curvature is due to the fact, that the central pump amplitude is larger than the amplitude in the wings. In the pump-depletion phase a finite duration seed will undergo a self-similar evolution [2] and this processed depends on the pump amplitude. Hence, the inhomogeneous transverse profile of the pump will be imprinted on the seed.

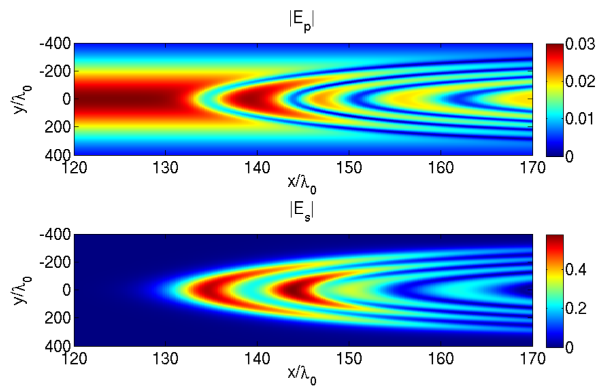

Fig. 1: Magnitude of pump and seed envelopes in the nonlinear phase of SRS amplification in dimensionless units. The seed is propagating to the left. Curving of the intensity fronts of the seed occurs due to differences in the pump amplitude between the central part and the wings. See [9] for details.

The level to which seed is amplified at the center is close to the value predicted by the corresponding one-dimensional simulation. However, in more than one dimension filamentation may occur. The source for filamentation is the weakly relativistic non-linearity, which may have the same effect as a plasma density modulation in transverse direction. In contrast to a density modulation, the weakly relativistic nonlinearity is a local and instantaneous nonlinearity.

For plane waves filamentation can be discussed on the basis of Eqs. (1)-(2) in the case of counter-propagating waves. The presence of the counter-propagating second wave may decrease the minimum wavelength of the unstable mode spectrum [9] compared to the single wave case. This could lead to even tighter restrictions in the maximum feasable transverse beam diameter for amplification. The influence of the second beam on the transverse instability however is largest, when both beams have comparable intensities. In the amplification scenario the seed amplitude is larger than that of the pump. Thus the single wave analytical treatment should yield according estimates for the time-scale of filamentation.

When we simulate the filamentation of a soliton (i.e. a stationary solution of Eq. (1) where E_s=N=0), we observe filamentation with the wavelength and growth-rate predicted by plane wave theory. Thus, the predictions of the plane wave theory carry over to localized pulses.

When we simulate the amplification of a short laser pulse which is initially perturbed by transverse modulations, we observe that the first oscillation of the seed pulse stays either completely free of filamentation or is at least less affected by filamentation than predicted by plane wave theory.

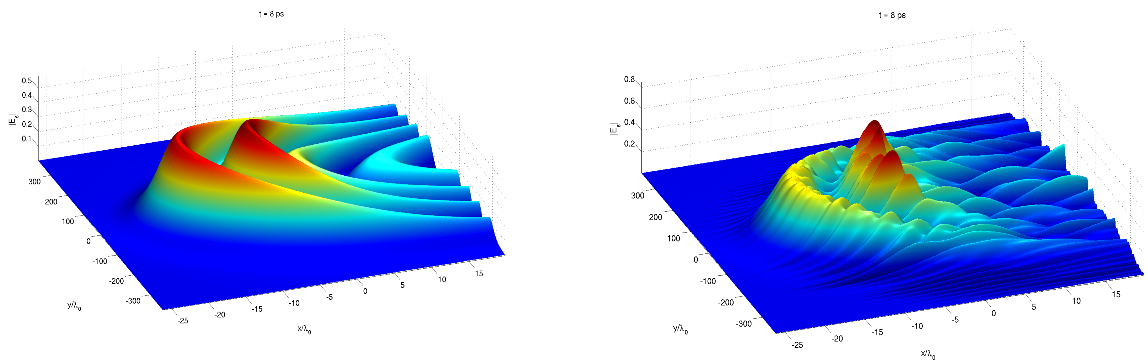

Fig. 2: Unperturbed seed (left) and initially perturbed seed (right) after 8 ps of SRS amplification. Pump intensity is 10^{15} W/cm^2 (corresponds to 0.03 in dimensionless units) and plasma density is 0.01n_c. The initial seed pulse had a duration of 50 fs. The first oscillation of the seed envelope stays unaffected by filamentation; only the subsequent envelope oscillations suffer from filamentation.

The observation that the seed front stays unaffected from the transverse instability may seem surprising at first. The reason for the stability of the seed front lies in the interplay of longitudinal amplification dynamics and transverse filamentation. The seed pulse experiences a superluminal re-shaping in the nonlinear phase. This causes the seed maximum to move forward in a frame of reference co-moving with the seed group velocity v_2. This effect is known for SRS and sc-SBS amplification [4,6]. The transverse perturbation on the other hand does not move in the co-moving frame. In this way the seed sheds the transverse perturbation from the first oscillation of the envelope and only subsequent envelope oscillations are affected. The details of the superluminal dynamics depend on the pump amplitude and the initial seed duration. The shortest seeds only have a short superluminous phase, i.e. will not be able to shed the unstable modes completely from the region of the seed maximum. On the other hand, longer seeds experience a longer superluminous phase and can outrun the unstable modes more easily. This effect can be observed in 2D and 3D simulations of the system (1)-(3).

Secondary oscillations of the seed envelope may eventually be suppressed due to kinetic effects such as particle trapping, wave breaking or Landau damping. To this end we carried out a comparison between results from one-dimensional simulations of a SRS three-wave model, a PIC code and a full Maxwell-Vlasov code. The parameters were chosen such that kinetic effects are expected. In this case, all three models agreed well on the first envelope oscillation, but secondary oscillations were suppressed in the kinetic codes. For details the reader is referred to [9]. In conclusion, the maximum usable amplifier length is not necessarily limited by transverse filamentation of the seed. Our results have been derived on the basis of a three-wave interaction model, but comparisons to kinetic results indicate that the key mechanisms are reflected correctly.

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