Self-similar laser pulse amplification via strongly coupled Brillouin scattering in plasma

G. Lehmann and K.H. Spatschek
Institute for Theoretical Physics I
Heinrich-Heine University, D-40225 Düsseldorf, Germany

Amplification of ultra-short high energy laser pulses in plasmas via Raman and Brillouin scattering is currently discussed as central part of the next generation of high power laser systems, aiming for the exawatt-zetawatt regime [1]. Using plasma as amplification medium allows to circumvent damage thresholds of current solid state technology. In the proposed schemes stimulated Raman and Brillouin processes, respectively, are used to transfer energy from a long pump pulse to a short seed pulse. Amplification of ultra-short, few fs, pulses based on Raman backward scattering is already widely discussed in literature and many aspects are well understood. Brillouin scattering in the strongly coupled (sc) regime provides a second possibility for the amplification of high intensity fs pulses [2,3].

Typically the interaction of pump, seed and plasma wave is described by three-wave interaction models for Raman [4] and sc-Brillouin [2,3]. These models describe the interaction of pump field E_p, seed field E_s and plasma wave N. For sc-Brillouin the equations are, in dimensionless units,

$$\left(\frac{\partial}{\partial t} + \frac{\partial}{\partial x}\right) E_p = -\mathrm{i} N^* E_s ,$$

$$\left(\frac{\partial}{\partial t} - \frac{\partial}{\partial x}\right) E_s = -\mathrm{i} N E_p ,$$

$$\left(\frac{\partial^2}{\partial t^2} - \frac{c_s^2}{v_g^2}\frac{\partial^2}{\partial x^2}\right) N = -E_s E_p^* .$$

Different from models for backward scattering no phase-matching is assumed in the equation for *N,* since for sc-Brillouin the ion oscillation is a driven mode and not a plasma eigenmode. Figure 1 shows the evolution of a short and a long seed pulse under the influence of a seed pulse of amplitude $|E_p|$=1. Both seed pulses are Gaussian shaped with FWHM σ=0.41 (short seed) and σ=3.3 (long seed), respectively. The initial amplitude of both seed pulses is $|E_s|$ = 0.01, i.e. we start in the linear regime where we may assume E_p=*const*. We observe that both seed pulses are amplified, however only the longer seed undergoes direct amplification. The shorter pulse first develops a tail and only this tail is then amplified. This leads to a longer linear phase compared to the evolution of the long seed pulse.

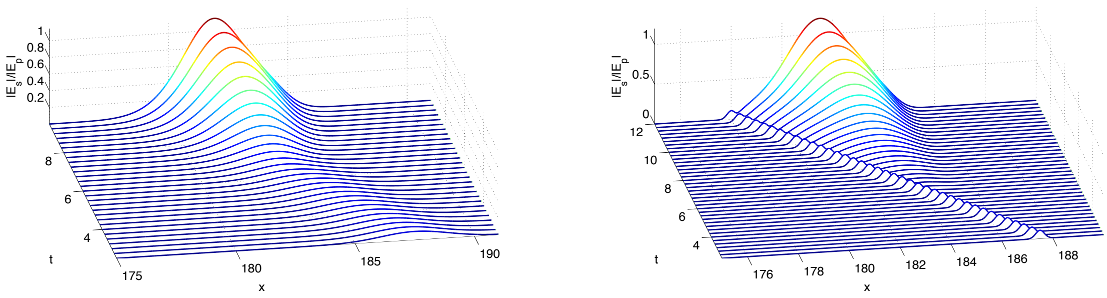

Fig 1: Temporal evolution of two seed pulses in the linear stage of sc-Brillouin amplification. Left: Evolution of a seed pulse with FWHM of σ=3.3 (long seed). Right: Evolution of a seed pulse with FWHM of σ=0.4 (short seed). Not shown is the pump pulse with $|E_p|=1$.

The reason for this qualitative difference in the evolution of both seed pulses lies in the spectral width of the seed spectra compared to the bandwidth of the sc-Brillouin instability [3,6]. The spectrum of the longer pulse is narrower than that of sc-Brillouin, i.e. all frequencies are amplified almost at the same rate. On the other hand, the spectrum of the short seed pulse is much broader than that of sc-Brillouin, i.e. only the central part of the spectrum is exponentially amplified. This behavior can also be found in Raman amplification [4].

Once the seed amplitude is comparable to the pump amplitude, the process enters the nonlinear regime. Figure 2 shows the evolution of the short seed pulse from the linear phase to the nonlinear phase, where pump depletion becomes visible. Even though the seed amplitude exceeds the pump amplitude the seed is still amplified further by the pump. The seed develops oscillations at its backside, similar to the π-pulse oscillations observed in Raman amplification, compresses and grows. The growth of the maximum seed amplitude is algebraic and no longer exponential.

Analytically a family of self-similar solutions can be found for the three-wave model above. The solutions are of the form $\zeta=x+t$, $\xi=\zeta\, t^{1/2}$, $E_p = A_p(\xi)$, $E_s=A_s(\xi)t^{3/4}$, $N=t^{-1/4}B^*(\xi)$. The functions A_p,A_s, and B are obtained as solutions of a system of coupled ODEs. Setting $A_p(0)=1$ we are left with one free parameter ε which we identify as seeding power i.e. $A_s(0)=\varepsilon$. Figure 3 shows two solutions for $A_p(\xi)$ and $A_s(\xi)$, obtained for $\varepsilon = 0.1$ and $\varepsilon = 0.3$, respectively. We observe that the maximum of A_s depends on ε.

When we evaluate the growth of short and long seed pulses as obtained from simulations we find that only short seeds grow $\sim t^{3/4}$, i.e. the predicted rate from the analytical model for self-similar solutions. Figure 4 shows the evolution of the maximum of $|E_s|$ for the long seed and the short seed and asymptotic fits. The initially longer seed pulse grows $\sim t^{1/2}$ and thus slower than predicted by the self-similar solution. This reduction of the exponent can be interpreted as a varying seeding power. For this interpretation we take the seed pulse from our simulations and match for every instance in time a solution from the family of self-similar solutions to it. This requires determining ε such that the self-similar solution for a this ε would grow to the same maximum amplitude in the same time. In this way we determine the effective seeding power ε_{eff}. For the short seed pulse we find that this effective seeding power is almost constant. In case of the long seed the effective seeding power decreases during the amplification. A similar observation was made for Raman amplification [5].

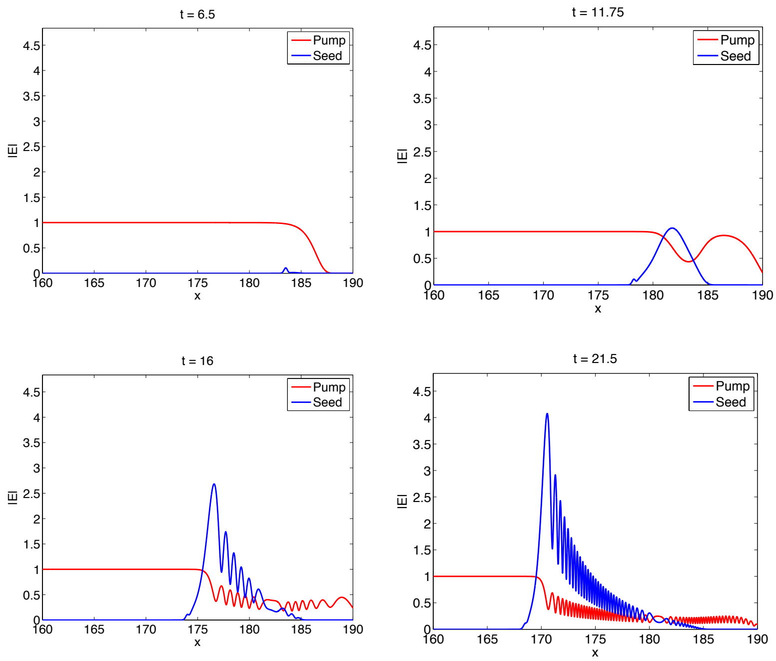

Fig. 2: Amplification of a short seed (FWHM σ=0.41) from linear to nonlinear phase. In the nonlinear stage pump depletion sets in and the seed undergoes a self-similar evolution.

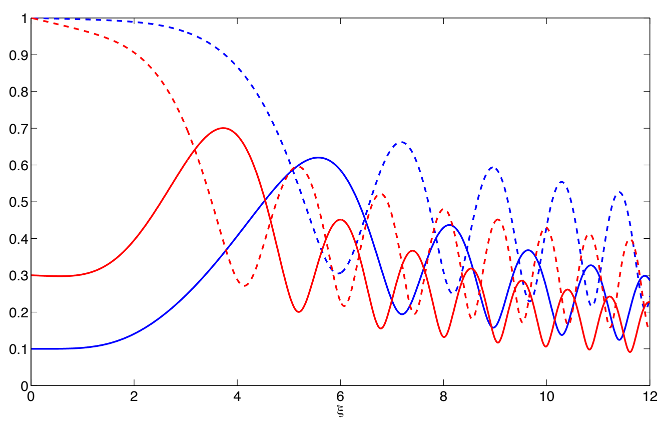

Fig. 3: Self-similar solutions for A_s (solid line) and A_p (dashed line). The figure shows solutions for ε = 0.1 (blue set of lines) and ε = 0.3 (red set of lines).

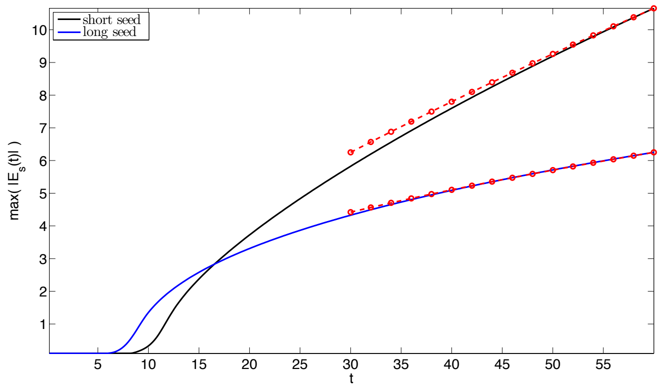

Fig. 4: Evolution of max($|E_s|$) for short (black) and long (blue) seed pulse. After an initially exponential phase we observe algebraic growth in the pump depletion regime. The red lines represent asymptotic fits. For the short seed the fit is $\sim t^{3/4}$, and for the long seed the fit is $\sim t^{1/2}$.

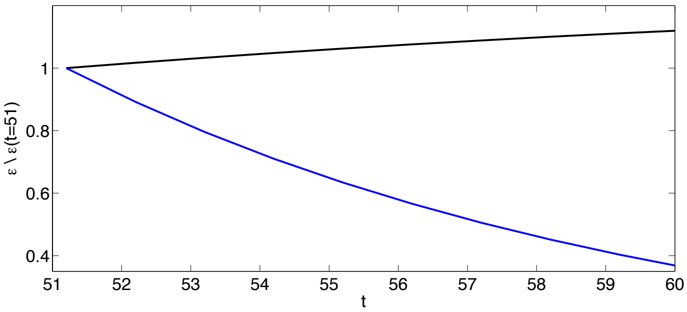

Fig. 5: In the nonlinear regime the value $\varepsilon = \varepsilon_{\mathrm{eff}}$ has been determined as a function of time for the short seed (black) and the long seed (blue). The effective seeding power for the short seed is almost constant, whereas it decreases during the amplification of the long pulse.

Summarizing, amplification of short laser pulses is possible using stimulated sc-Brillouin scattering. The seed pulse duration has an influence on the linear and the nonlinear stage of the amplification. The behavior in the pump depletion stage can be understood in terms of self-similar solutions of the three-wave model. For short pulses we find pulse growth as predicted for a self-similar solution. For long seed pulses the growth is slower than predicted. The interpretation via self-similar solutions is still possible by mapping the solution on the manifold of self-similar solutions at every instance in time. We find that now the seeding power, a free parameter in the family of the attractor solutions, decreases in time. Thus, the pulse growing from a long seed is moving along the manifold of self-similar solution while it undergoes amplification.

[1] G.A. Mourou, N.J. Fisch, V.M. Malkin, Z. Toroker, E.A. Khazanov, A.M. Sergeev, T. Tajima, and B. Le Garrec, *Optics Communications* **285**, 720 (2012)

[2] A.A. Andreev, C. Ricionda, V.T. Tikhonchuck, and S. Weber, *Phys. Plasmas* **13**, 053110 (2006)

[3] G. Lehmann and K.H. Spatschek, *Phys. Plasmas* , in print (2013)

[4] G. Lehmann, K.H. Spatschek, and G. Sewell, *Phys. Rev. E* **87**, 063107 (2013)

[5] N. A. Yampolski, V.M. Malkin, and N.J. Fisch, *Phys. Rev. E* **69**, 036401 (2004)

[6] G. Lehmann, F. Schluck, and K.H. Spatschek, *Phys. Plasmas* **19**, 093120 (2012)