32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, O-2.026 (2005)

Generation and amplification of ultra-short light pulses in the strongly coupled regime of SBS in plasma

A.A. Andreev[1], C. Riconda[2], V.T. Tikhonchuk[2], S. Weber[2,3]

[1] *Vavilov State Optical Institute, St. Petersburg 199064, Russia*

[2] *Centre Lasers Intenses et Applications, Université Bordeaux 1, 33405 Talence, France*

[3] *Centre Physisque Théorique, Ecole Polytechnique, 91128 Palaiseau, France*

The generation of short and intense light pulses is of importance to many scientific and technical applications. Standard approaches [1, 2] are limited by technological constraints and the parameters that can be achieved. The pulse energy is limited by the thermal damage of the optical elements, in particular by the grating damage in compressors. The compression schemes based on the backward parametric amplification in gases or liquids offer much higher damage thresholds but there the pulse length is limited by the phonon period of the order of 100 ps[3].

These limitations can be overcome by using plasmas as amplifying medium [4, 5, 6]. In this case the coupling between the seed pulse and the pump pulse delivering the energy takes place via a 3-wave coupling mechanism where the role of the third wave is taken up by either the electron plasma wave (stimulated Raman scattering, SRS) or by the ion-acoustic wave (IAW) (stimulated Brillouin scattering, SBS). In the ideal case the backward propagating short pulse completely depletes the pump energy as it advances in the amplifying medium and reaches intensities far above the pump intensity.

The use of SRS-based amplification schemes in the weak coupling regime of plasmas has been exploited theoretically and experimentally recently [6]. Compression of a light pulse in a plasma in the weak coupling regime of SBS was considered in [5]. SBS has several advantages for pulse compression with respect to SRS: a small frequency shift, higher amplification coefficient and weak sensitivity to density perturbations. Historically SBS has been disregarded as the compressed pulse duration is limited to π/ω_{cs}, i.e. half an ion-acoustic wave period. However, the SBS response time can be decreased by passing into the strong coupling regime, which we are studying here. There the ion-plasma response is characterised by the frequency $\omega_{sc} \sim \left(k_o^2 v_E^2 \omega_{pi}^2/\omega_o\right)^{1/3}$ [7], which is of the order of ion-plasma frequency $\omega_{pi} = (4\pi n_i Z^2 e^2/m_i)^{1/2}$. This corresponds to the time of a few tens of fs. In addition the IAW-spectrum is rather broad and the amplification gain is not too sensitive to the frequency mismatch. Due to the ratio of IAW-frequency and light frequency which is of the order $\omega_o/\omega_{pi} \geq 100$ very little photon energy is lost. However one needs to understand how stable SBS amplification would be in the strong coupling limit and what parameters of pulse compression could be achieved.

SBS in the regime of strong coupling can be described by a set of three coupled equations for the amplitudes of the incident, E_p, and scattered, E_s, electromagnetic waves and for the amplitude of the density perturbation δn_p ($\delta n_s = \delta n_p^\star$):

$$(\partial_t \pm v_g \partial_x) E_{p,s} = -i \frac{\omega_{pe}^2}{2\omega_0} \frac{\delta n_{p,s}}{n_e} E_{s,p},$$
$$(\partial_t^2 + 4k_o^2 c_s^2) \frac{\delta n_p}{n_e} = -k_o^2 \frac{E_p E_s^*}{4\pi n_c m_i}, \qquad (1)$$

where $c_s = \sqrt{ZT_e/m_i}$ is the ion acoustic velocity and $v_g = k_o c^2 \sqrt{1-n/n_c}/\omega_0$ is the electromagnetic wave group velocity. One has $\omega_{cs} = 2\omega_o \sqrt{1-\omega_{pe}^2/\omega_o^2}\, c_s/c_o$, where c_o, c_s and $\omega_{pe} = \sqrt{4\pi n_e e^2/m_e}$ are the vacuum speed of light, the ion-acoustic speed of sound and the electron plasma frequency, respectively. In the linear regime the growth rate is given by [7]:

$$\gamma_{sc} \approx (\sqrt{3}/2)\omega_0 (v_E \omega_{pi}/c\omega_0)^{2/3} (1-n_e/n_c)^{1/3}, \qquad (2)$$

where $v_E = eE/m_e\omega_o$ is the quiver velocity and in the strong coupling regime $\gamma_{sc} \gg k_o c_s$.

An efficient SBS compression requires certain conditions on the plasma and the pump laser parameters. The plasma length L_p and the pump pulse duration t_p should be related as $L_p \approx v_g t_p/2$. This assures the interaction of the seed pulse with all parts of the pump. Density and temperature of the plasma have to be chosen such that the SBS amplification from the thermal noise level I_{cs} is not depleting strongly the pump: $I_{cs}\exp(\kappa_p) \ll I_p$, where κ_p is the total gain over the plasma length and I_p is the laser intensity in the focal spot. In the strongly non-stationary regime considered here, for which $v_E^2 \gg c c_s (\omega_{cs}/\omega_{pi})^2$, the total gain is given by $\kappa_p \sim \gamma_{sc} t_p \sim \gamma_{sc} t_p^{2/3} (L_p/v_g)^{1/3}$. In addition there should be no plasma heating from the pump during the pulse duration t_p and small losses from Raman activity. As far as the seed pulse is concerned, the criterion of pump depletion has to be satisfied: $I_{s0}(\gamma_{sc} t_{s0})^{3/2} \approx I_p$, with I_{s0} the initial seed pulse intensity and t_{s0} its initial duration. Under these conditions the maximal attainable output intensity will be: $I_s \approx I_{s0}(L_p \gamma_{sc}/v_g)^{3/2} \approx I_p (L_p/v_g t_{s0})^{3/2}$. This defines the Stokes intensity gain factor as $\sim (I_p/I_{s0})(L_p/v_g t_{s0})^{3/2}$ and the pulse compression is $(L_p/v_g t_{s0})^{1/2}$.

We have investigated SBS pulse compression and amplification by means of one-dimensional PIC-code [8]. In the numerical simulations the amplifying medium has a length of 80 λ_o with $\lambda_o = 1\,\mu$m the laser wavelength of the pump. In order to suppress SRS amplification, the density is set at $0.3\,n_c$. The electron temperature is 500 eV and the temperature ratio $ZT_e/T_i = 50$. The pump laser grows exponentially in time over 100 fs to an intensity of $I = 10^{16}$ W/cm^2 and then remains constant. The seed pulse has a sin^2-shape with a FWHM of 100 fs and peak intensity of

$I = 10^{15}$ W/cm^2. The seed pulse is launched once the pump is present everywhere in the plasma. The frequency of the seed is downshifted by $\Delta\omega = 1.2 \times 10^{-3}\,\omega_o$ where ω_o is the frequency of the pump laser. The downshift corresponds to the ion-acoustic wave frequency for a plasma of 500 eV.

The spatial resolution is of the order of the Debye length $\lambda_D = \sqrt{T_e/4\pi n_e e^2}$ and the time step for integration is $\Delta t = 0.05\,\omega_o^{-1}$. 40 macro-particles per computational cell are used. No initial seed for the ion-acoustic wave is given. The 3-wave interaction is generated from noise directly.

For the initial parameters one finds $\gamma_{sc} \approx 0.02\,\omega_0$, which is more than 10 times the IAW frequency. By solving the equations (1) in the reference system of the SBS pulse, one finds that the amplitude of the SBS pulse increases as $E_s \sim E_0(\gamma_{sc} t)^{3/4}$ as it traverses the plasma and its width decreases as $\Delta x \sim c\gamma_{sc}^{-3/2} t^{-1/2}$, so that the total SBS pulse energy increases with time while the pulse length decreases. For the conditions we are considering here, the characteristic gain length is $c/\gamma_{sc} = 50\,c/\omega_0$ and the pulse amplitude can grow up to a maximum of $5-6$ times the corresponding seed amplitude, $E_{s\,max} \sim E_0(L_p\gamma_{sc}/c)^{3/4}$. This gives an intensity amplification by a factor ≈ 30. This describes well the initial phase of amplification where the acoustic nonlinearity is small. During the subsequent nonlinear phase the pulse amplitude in the simulations show a further increase by a factor $2-3$. The Stokes pulse duration decreases according to the above model prediction by a factor 3 and is slightly higher than the simulation results.

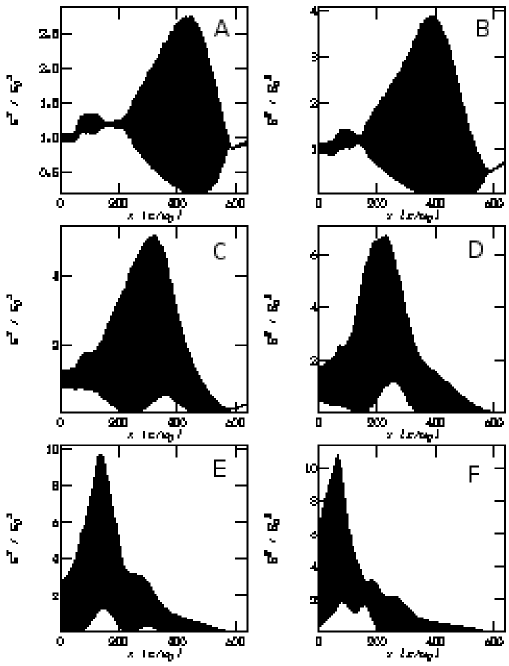

Figure 1: SBS-pulse amplification for the times: $t = 1050\,\omega_o^{-1}$, $1150\,\omega_o^{-1}$, $1250\,\omega_o^{-1}$, $1350\,\omega_o^{-1}$ $1450\,\omega_o^{-1}$, $1550\,\omega_o^{-1}$. The pump is incident from the left and the seed from the right. The figure shows the total intensity with the scale being normalized to the pump laser intensity. The intensity snapshots are averaged over $\approx 3 \times 2\pi/\omega_o$. The plasma is located between $50c/\omega_o$ and $600c/\omega_o$.

Figure 1 shows the time evolution of the pulse from the moment it enters the plasma. The plasma is located between $50\,c/\omega_o$ and $600\,c/\omega_o$. Clearly the pulse gets amplified to about 10 times the pump intensity, i.e. $I = 10^{17}$ W/cm^2, which is an amplification factor of order 100 with respect to the original intensity. At the same time the pulse is compressed to a FWHM of about 50 fs. The injected pulse completely depletes the pump, taking up almost all the laser energy present in the plasma. Behind the pulse no laser is present anymore. Characteristic is the multiple-peak structure of the amplified pulse with a leading spike which contains about 90% of the energy and a series of trailing spikes.

According to the equations (1) the initial phase is over after the maximum of the pulse has traversed about $200\,c/\omega_o$ of plasma (snapshot at $1150\,\omega_o^{-1}$ in Fig. 1). From that time onwards a new feature appears in the amplified pulse: behind the leading spike several smaller spikes appear which modulate the intensity envelope of the pulse. As the seed pulse attains an intensity comparable to the pump pulse intensity, energy is transferred back and forth between the two pulses. This effect is responsable for smaller spikes appearing. It is characteristic for the nonlinear phase of amplification.

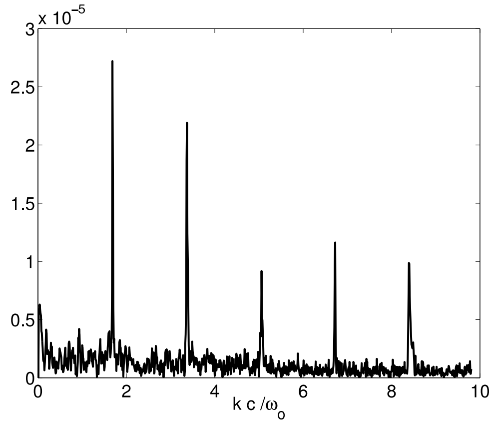

Figure 2: The k-spectrum of the electrostatic field taken at the final time ($t = 2000\,\omega_o^{-1}$) of the simulation after the pulse has left the amplifying medium.

Figure 2 gives the k-spectrum of the electrostatic field at the end of the simulation time. It shows the ion-acoustic wave fundamental and its harmonics proving that the amplification is due to Brillouin. During the amplification process no signature of Raman is visible in the frequency spectrum.

The simulations so far show that amplification beyond the linear estimates outlined above can be achieved. A more refined analysis on the model and detailed parameters studies are under way to well characterize the optimal conditions and the limitations of SBS amplification. In higher dimensions additional effects such as filamentation might intervene and limit amplification. 2D-studies are intended for the future.

References

[1] M. Maier, W. Kaiser, J.A. Giordmaine, Phys. Rev. Lett. **17**, 1275 (1966)

[2] G.A. Mourou, C.P.J. Barty and M.D. Perry, Phys. Today **51**, 22 (1998)

[3] V.A. Gorbunov, S.B. Papernyi and V.R. Starsev, Sov. J. Quantum Electron. **13**, 900 (1983)

[4] C.E. Capjak, C.R. James and J.N. McMullin, J. Appl. Phys. **53**, 4046 (1982)

[5] A.A. Andreev and A.N. Sutyagin, Sov. J. Quantum Electron. **17**, 36 (1985)

[6] V.M. Malkin, G. Shvets and N.J. Fisch, Phys. Rev. Lett. **84**, 1208 (2000)

[7] D.W. Forslund, J.M. Kindel and E.L. Lindman, Phys. Fluids **18**, 1017 (1975)

[8] A.A. Andreev, C. Riconda, V.T. Tikhonchuk and S. Weber, *Nonlinear Light Pulse Amplification by Stimulated Brillouin Scattering*, Phys. Rev. Lett. submitted (2005)