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Plasma cavitation and standing solitons due to stimulated Brillouin pulsations

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The problem of a comprehensive understanding of stimulated Brillouin (SBS) and Raman (SRS) scattering in the nonlinear regime is of widespread interest in the laser-plasma interaction community. In recent simulations of stimulated Brillouin backscattering (SBBS) [1, 2, 3, 4] for high laser intensities a new regime of SBS was shown to exist which is characterised by the appearance of electromagnetic solitons in its final low-level saturated state. The time evolution of the interaction process takes place in four distinct phases: an SBS pulsation phase, an SRS-type 3-wave coupling phase, a cavitation phase with associated frequency shift as well as strong electron and ion heating and, finally, the creation of standing electromagnetic solitons together with a low-level saturation of the Brillouin reflectivity.

The results were obtained by means of particle-in-cell (PIC) simulations using an exploiding foil configuration for the plasma. The plasma density was set above the quarter-critical density in order to avoid the excitation of SRS. The temperature ratio was set to $ZT_e/T_i = 50$ for $T_e = 500$ eV. Subsequent simulations showed that the mechanism is not too sensitive to the temperature ratio and the absolute electron temperature. The pump intensity was constant in time and of the order of 10^{16} W/cm^2 for a wavelength of $\lambda_o = 1\,\mu$m.

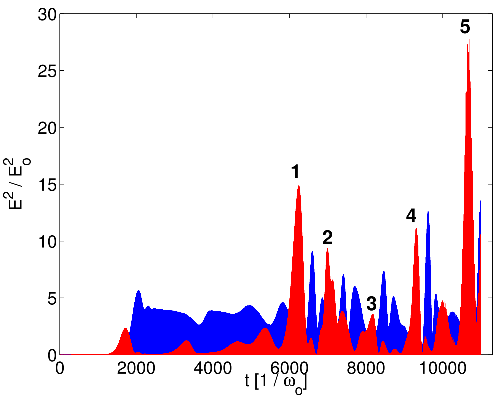

Figure 1: Time evolution of the reflected electromagnetic wave intensity inside the plasma (red) and in vacuum (blue). The numbered red pulses evolve into the adjacent blue ones located to the right.

At these high pump intensities SBBS is a highly non-stationary process. The reflected light consists of a series of short pulses which are amplified and compressed as they propagate along the plasma and induce strong pump depletion. Using a simple 3-wave model it can be shown that the pulse width decreases as $\Delta x \sim c\gamma_{sc}^{-3/2} t^{-1/2}$ and the pulse amplitude increases as $E \sim E_0(\gamma_{sc} t)^{3/4}$, such that the pulse energy $\sim E^2 \Delta x$ grows linearly in time. Here $\gamma_{sc} \approx$

$2^{1/3}\omega_0(v_E\omega_{pi}/c\omega_0)^{2/3}(1-n_{eo}/n_c)^{1/2}$ is the characteristic growth rate in the strong coupling regime with $\omega_{pi}=(4\pi n_i Z^2 e^2/m_i)^{1/2}$ the ion plasma frequency and $v_E=eE_o/m_e\omega_o$ the electron quiver velocity. For the parameters used in the calculations the electric field amplitude can grow by a factor 4-5 (see Fig.1).

This analysis fits well the time interval up to about $t\approx 6000\ \omega_o^{-1}$. Subsequently the pulsation behaviour becomes more complicated. The pulses are further compressed but at the same time undergo strong oscillations in amplitude. The pulses 1, 2 and 5 in Fig. 1 have a smaller amplitude in vacuum than in the plasma. This indicates that these strong pulses undergo a further process which is identified as an SRS-type instability. Of course it is not a standard SRS which would be forbidden at a plasma density of 0.3 n_c used in the simulations presented here.

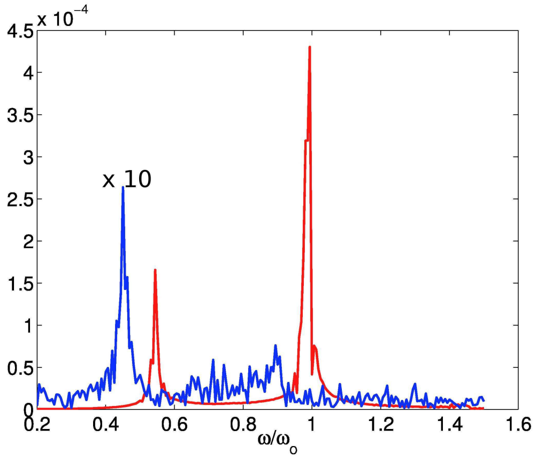

Figure 2: Spectra of the transverse (red) and longitudinal (blue) electric field intensities at the location of cavitation. The electrostatic spectrum is magnified 10 times.

Figure 2 clearly indicates a 3-wave interaction process inside one of the SBBS pulses. Here the pump wave at ω_o is coupled to a daughter wave at 0.55 ω_o, corresponding to the local plasma frequency $\omega_{pe}=\sqrt{n_e/n_c}$, and a longitudinal response at 0.45 $\omega_o = 0.8\ \omega_{pe}$. This latter collective response is a nonresonant kinetic electron mode.

It is similar to the KEEN-mode (kinetic electrostatic electron nonlinear) which can only be excited by sufficiently strong electric fields [5]. The transverse mode excited has the smallest possible frequency, i.e. the plasma frequency. Hence its group velocity, as was verified, is zero and therefore it is trapped in the plasma. Within a very short time interval the SBS-pulse feeds the SRS-type mode to a very high level. This very fast and localised increase of the field intensity forces the plasma to move. Within a few hundred femtoseconds a cavity of width $\approx 2\ \lambda_o$ is created. The transverse localised mode adapts its frequency to the lowest possible eigenmode in the cavity of decreasing density. The frequency of the mode is down-shifted

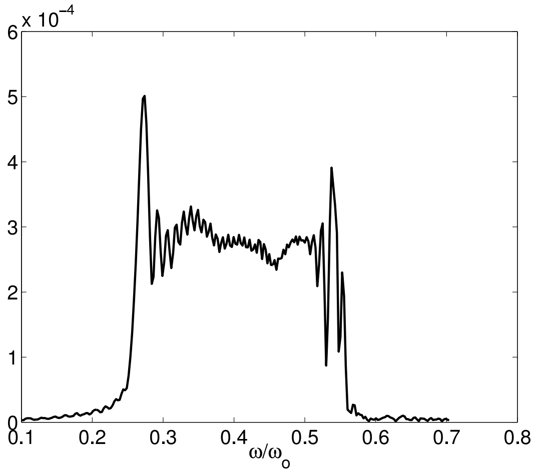

Figure 3: Spectrum of the transverse electromagnetic field intensity integrated over the time interval of cavitation.

from its original 0.55 ω_o to its final value of 0.25 ω_o. The spectrum is broad (Fig. 3) because the mode frequency sweeps from the original to the final value during the cavitation process. The final frequency is the lowest possible level in an almost empty cavity of width 2 λ_o. With the onset of the shift the resonant coupling between the three waves is destroyed and the amplitude of the collective electrostatic mode is strongly reduced. Nevertheless this collective mode continues to survive although the local plasma density in the cavity is reduced from 0.3 n_c to 0.01 n_c. The mode eventually is damped due to strong interaction with the electrons. The final outcome of the cavitation process is a standing half-cycle soliton of frequency $\omega_s = 0.25\ \omega_o$.

The cavitation process goes along with a very strong heating and acceleration of electrons and ions. The cavity is created within 600 ω_o^{-1}. The expelled ions are accelerated to velocities of the order of $v_i \approx \lambda_o/(600\ \omega_o^{-1}) \sim 0.01\ c$. This implies ion energies up to 80 keV. Similarly electrons attain maximal energies of 100 keV. After relaxation the electrons are characterised by a double Maxwellian of temperatures $\approx$ 10 keV and $\approx$ 200 keV. The average kinetic energies for electron and ions alike is 50 keV. This has to be compared with the initial thermal electron temperature of 500 eV. Even after all solitons are in place with stationary amplitude the plasma continues to be heated.

In fact the solitons act as a kind of converter which couples laser and plasma, transforming the transverse laser energy into thermal energy. The incident pump is coupled to the soliton replenishing the energy which is lost via some stochastic heating process to the plasma particles.

The solitons obtained compare well with a recent analytical model of large-amplitude solitons in hot plasmas [6, 7] (see Fig. 4). The model requires as input the ambient pressure and the width of the cavity. The spatio-temporal distribution of the soliton vector potential is then well approximated by

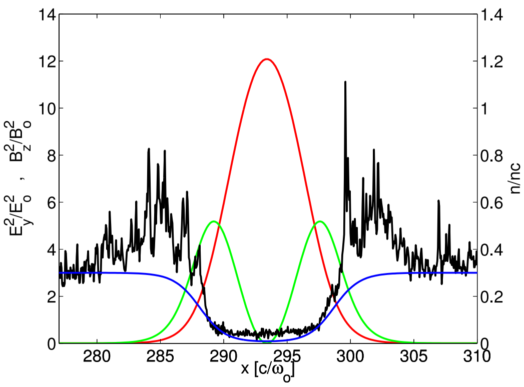

Figure 4: Density profile of cavity from PIC calculation (black). Superimposed the analytical model: density (blue), transverse electric (red) and magnetic (green) field intensities.

$$A(x,t) \approx c\sqrt{8\pi n_{e0}(T_e + T_i/Z)}\ \omega_s^{-1} \cos(x\omega_s/c)\ \cos(\omega_s t), \tag{1}$$

where the origin $x = 0$ is at the center of the soliton. The theory predicts the frequency of the soliton in the case of a deep cavity as:

$$\omega_s \approx \frac{\omega_{pe}\sqrt{2}}{a_o}\left[\lambda_e\left(1-\sqrt{\gamma}e^{-(\gamma-1-\varphi_o)/\lambda_e}\right)+\frac{\lambda_i}{Z}\right]^{1/2}, \quad (2)$$

with $\lambda_{e,i} = T_{e,i}/m_e c^2$, $\gamma = \sqrt{1+a_o^2}$, $\varphi_o = e\phi(x=0)/m_e c^2$, $Z = 1$ and $a_o = eA(x=0)/m_e c^2$. From the simulations one has that $a_o = 1.182$, $\varphi = 0.176$, $\lambda_e = 0.1$ and $\lambda_i = 0.05$. One obtains $\omega_s/\omega_o \approx 0.25$ which is in perfect agreement with the simulation and the estimate from the lowest possible cavity eigenmode. In the same way the amplitudes of the electromagnetic agree with the numerical simulations.

Laser-plasma interaction in the high-intensity regime is characterised by several new phenomena. The standard Brillouin backscattering evolves into a pulsation regime. The induced strong amplification of the SBS pulses invoke non-resonant electrostatic modes and the final outcome are standing large-amplitude solitons. The new feature of this specific Brillouin saturation process is the strong heating of electrons and ions. This confirms the importance of electron kinetic effects in the strongly nonlinear regime of ion-acoustic wave response [8]. The results show that even at very high pump intensities low-level saturated regimes of SBBS exist. This might open new possibilities for the design of hohlraums and targets for inertial confinement fusion applications.

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