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Low-level stimulated Brillouin scattering saturation in high-intensity laser-plasma interactions

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We present a new kinetic scenario for low-level stimulated Brillouin backscattering (SBBS). The laser-driven ion-acoustic waves break and form plasma cavities which induce a saturation of SBBS. This mechanism provides strong electron heating and ion acceleration and confirms the importance of kinetic effects for Brillouin saturation. The parameters used in the simulations are of relevance for laser-plasma interactions and for inertial confinement fusion.

In recent years there has been renewed interest in the laser-plasma interaction (LPI) community in kinetic processes for stimulated Raman- and Brillouin-backscattering (SRBS, SBBS) [1, 2]. The availability of large computing powers and massive parallel calculations makes it possible to employ realistic physics models for backscattering without having to use reduced models. Full PIC calculations (which assume mobile ions and electrons) for SRBS and SBBS have shown that both species induce nonlinear effects for both instabilities. A multitude of nonlinear saturation mechanisms has been advanced and it is not clear which mechanism is dominant under what conditions. Nevertheless the saturation levels obtained in experiments and in simulations seldom agree. A comprehensive understanding of SRBS and SBBS is not only of general interest for plasma physics but also important to make viable estimates of energy losses in LPI in the context of inertial confinement fusion.

We present full PIC calculations which demonstrate a new kinetic scenario for SBBS evolution, inducing a low-level saturated state for the reflectivity [3, 4]. The simulations are one-dimensional in space and two-dimensional in velocity space. The mass ratio is $m_i/m_e = 1836$ and the temperature ratio is $ZT_e/T_i = 50$ with $Z = 1$ and $T_e = 500$ eV. In the following results are presented for the intensity $I\lambda_o^2 = 1 \cdot 10^{16}$ Wμm^2/cm^2. The plasma density is set to $n_e = 0.3n_c$, where n_c is the critical density, in order to avoid SRS. The plasma length is $38\lambda_o$ surrounded by vacuum regions of similar extension. The time evolution of the density profile (Fig. 1) shows the appearance of density cavities after several picoseconds into the interaction process. The cavity formation is the final

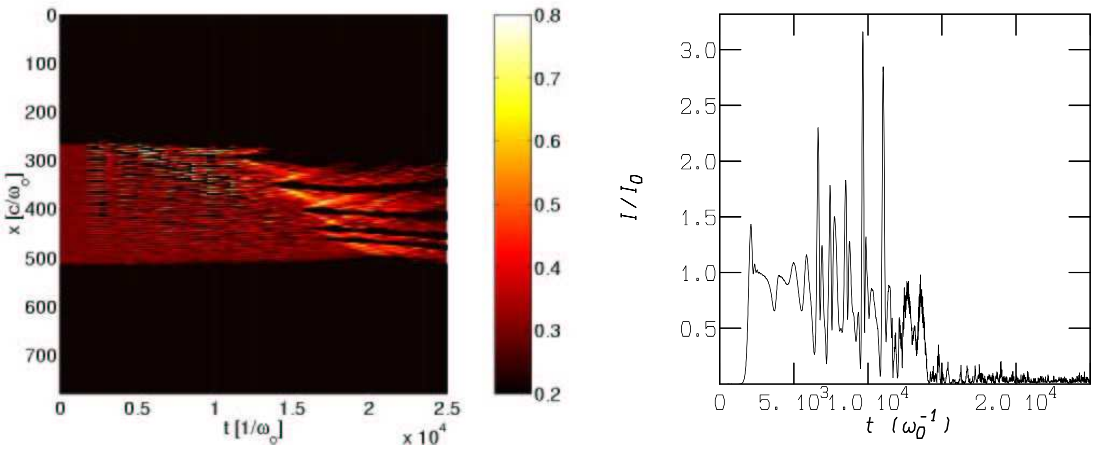

FIG. 1: *Time evolution of the density in units of the critical density (left) and temporal variation of the backscattered intensity with respect to the incident laser intensity (right).*

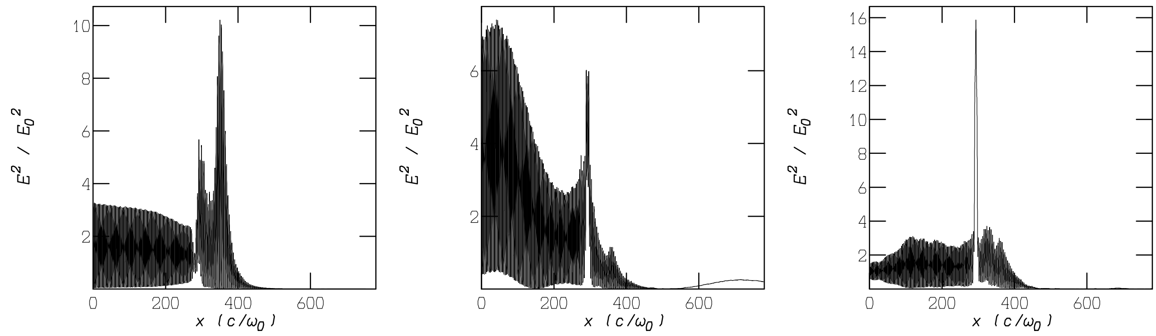

FIG. 2: *Oscillations of the transverse electromagnetic field energy (left to right) for times* 5.25, 5.5, 6 ps*, the left plasma boundary is at* $250\ c/\omega_o$ *and the cavity position is at* $290\ c/\omega_o$*.*

state of the steepening of a driven IAW packet. The continued driving by the incident electromagnetic wave induces a three-step transition from (i) an originally nonlinear hydrodynamic regime (harmonics and steepening) via (ii) a mixed hydro-kinetic regime (large population of trapped ions and X-type wave-breaking) to (iii) a purely kinetic regime beyond the wave-breaking limit (Coulomb explosions, ion and electron heating and the disappearance of the resonance IAW). The density evolution reflects itself in the time evolution of the reflectivity (Fig. 1) which, with the appearance of the cavities, terminates in a low-level, quasi-stationary saturated state. Several reasons can be advanced for the fact that no new Brillouin build-up take place: a reduced gain length, modified growth rate due to heating and a broadband state of fluctuations for low k which have a short correlatiobn length and therefore a small gain.

Large spatial oscillations of the transverse electromagnetic field indicate the location

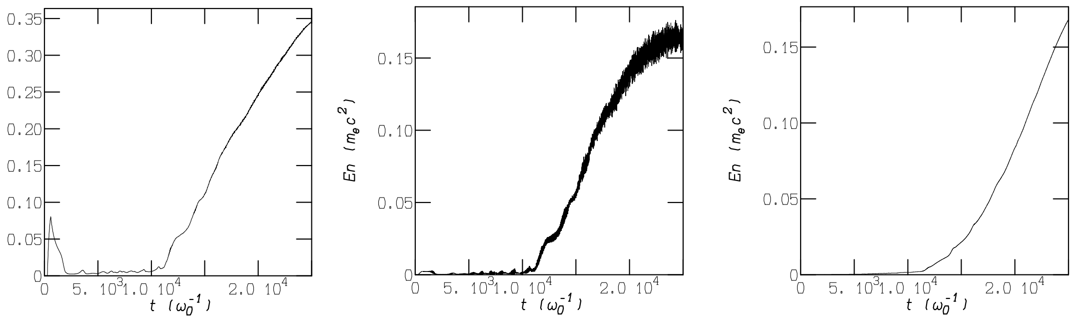

FIG. 3: *Percentage of absorbed laser intensity (left); actual kinetic energy minus initial kinetic energy content for electrons (middle) and ions (right) in units of the electron rest energy $m_e c^2$.*

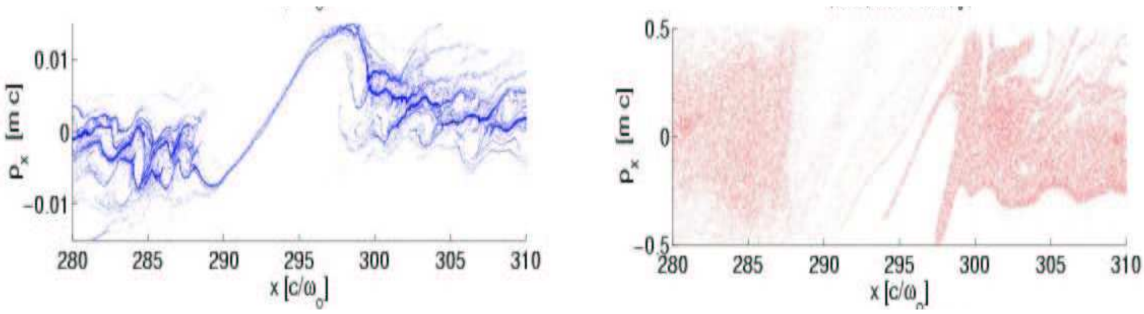

FIG. 4: *Blow-up of parallel momentum phase space ($p_{e,i} = \gamma_{e,i} m_{e,i} v_{e,i}$) at first cavity formation location for ions (left) and electrons (right) at* $t = 6$ ps *(the initial temperatures would correspond to* $p_e = 4.5 \cdot 10^{-2} m_e c$ *and* $p_i = 1.4 \cdot 10^{-4} m_i c$*).*

where a cavity is about to form (Fig. 2). The final state is a soliton-like, stationary structure displaying a strong intensity enhancement with respect to the incident laser intensity. These oscillations in the field are correlated with the large oscillations in the reflectivity (Fig. 1). The overshooting of the reflectivity is linked to the periodic collapse of the wave packet which liberates the stored electromagnetic energy in a flash.

The cavitation process goes along with strong kinetic effects. Strong absorption of the laser energy sets in with the appearance of the first cavity (Fig. 3). Even after all cavities have been formed, transmission of the laser light remains at a low 20%. The remaining energy is absorbed by the turbulent plasma. Due to ponderomotive acceleration and heating by the parallel field, the electrons are accelerated up to energies of 50 keV. Similarly the ions attain maximal energies of the order of 40 keV (Fig. 4).

Varying the temperature ratio ZT_e/T_i $(= 50,\ 10,\ 5)$ while keeping the electron temperature fixed at 500 eV does not change the final result of a low-level saturated reflectivity state. The temperature ratio only affects the onset of cavitation and the number/distribution of the cavities formed. This is an important result as it implies that linear Landau damping is ineffective in the high-intensity regime. Similarly, reducing the intensity, for fixed $ZT_e/T_i = 50$, again only affects the onset of cavitation. Supposedly the mechanism will produce itself provided the plasma length and the duration of the interaction are such as to allow a sufficiently strong SBBS gain factor. Finding the threshold would require extensive PIC-calculations (in particular for lower intensities) as the first cavity only produces itself after several picoseconds. However, at lower intensities other saturation mechanisms might be at work, which induce a SBBS saturation before cavitation sets in.

In summary, we draw attention to the importance of kinetic effects in general and to the non-adiabacity of the electrons in particular for SBBS saturation. Significant electron acceleration and heating are the characteristics of the new saturation scenario for SBBS presented in this paper. As the dimensions of the cavities are small with respect to typical parallel scale lengths and small compared to the transverse size of a laser beam the 1D approximation is considered valid and the mechanism likely to reproduce itself in higher dimensions with similar effects for the reflectivity. A complete understanding of backscattering processes requires the use of multi-dimensional kinetic simulation tools for large plasmas (several 10s of microns in 1D) and long interaction times (several 10s of picoseconds). Care has to be taken that reduced models are only employed under conditions where kinetic effects do not play a role.

References

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