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Two-dimensional particle-in-cell simulations of plasma cavitation at non-relativistic laser intensities

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Stimulated Brillouin backscattering (SBBS) is a fundamental phenomenon in laser-plasma interaction. It corresponds to the decay of the incident electromagnetic wave into another backward propagating electromagnetic wave an the forward propagating ion acoustic wave. It plays an important role in the inertial confinement fusion (ICF) as it might strongly decrease the laser coupling efficiency. The SBBS nonlinear saturation was up to now studied in detail at low laser intensities. Considering the laser-plasma interaction for higher intensities, of the order of a few times $10^{16}\,\mathrm{W/cm^2}$, gives rise to several new phenomena. This strong-coupling regime [1] is characterized by a fast growth rate and a strongly modified frequency of the excited ion wave. Previous one-dimensional (1D) particle-in-cell (PIC) simulations have shown the possibilities to create plasma cavities and transverse electromagnetic solitons which have a profound effect on the time evolution of the reflectivity [2, 3] and lead to an efficient electron heating and ion acceleration.

Considering SBBS in the high-intensity regime allows for reflectivity saturation on short time scales and therefore might open up new scenarios for the ICF. These intensities are also in line with recent experimental achievements in the LULI, LANL and LLE, which are now able to explore these extreme conditions of laser-plasma interactions. The present paper shows that the mechanism of SBBS-induced plasma cavitation and heating found in 1D is also present in 2D (details are presented in Ref. [4]).

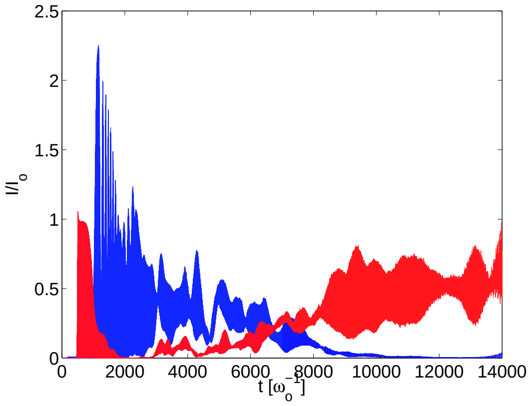

Figure 1: Averaged reflectivity (blue) and averaged transmission (red). The data are normalized to the incident laser intensity.

The simulations were performed with the 2D-PIC code emi2d using mobile electrons and ions with a realistic mass ration of $m_i/m_e = 1836$. In order to study SBBS only, the density was set at $n_e = 0.3n_c$. The plasma is represented by a plateau of $\sim 10\lambda_o$ width and length $\sim 55\lambda_o$ (parallel to the propagation of the incident laser). The laser itself is represented by a plane wave in order to suppress the self-focusing.

The incident electromagnetic wave excites a strong SBBS activity in the front part of plasma.

The initial behavior of the reflectivity is characterized by strong, very regular pulsations of a duration about $100\,\omega_o^{-1}$ showing the reflectivity values of up to 200% (see Fig. 1). This bursty regime of SBBS is typical for the strong coupling regime and it was observed in our 1D simulations before. On a longer time scale, the filamentation of the incident plane wave sets in. Contrary to the standard view of a single beam filamentation, these filaments are not at all stationary. They move around and produce local transient intensity maxima similar to the dancing filament scenario, discussed in Refs. [5, 6] for lower intensities. This highly dynamical behavior of the filaments is due to the strong density variations in the plasma. Figure 2 shows the plasma after several cavities have been formed.

These density cavities are filled with the electromagnetic fields forming the transient electromagnetic solitons. Due to the additional degree of freedom no stable coupling between the solitary structure and the incident laser can be achieved as the light is diffracted on the cavities once they are formed. The solitons are interacting strongly with electrons and therefore are dissipating their energy on very short time scales of a few hundred laser periods. This is contrary to the 1D simulations where they were kept in place and act as converters responsible for a continuous heating of the plasma. Similar to what has been found in 1D, the precursor to cavitation are plasma modes excited below the local plasma frequency. As electrostatic and electromagnetic modes can no longer be clearly separated in 2D the corresponding frequencies show up for all three fields: E_y, B_z and E_x.

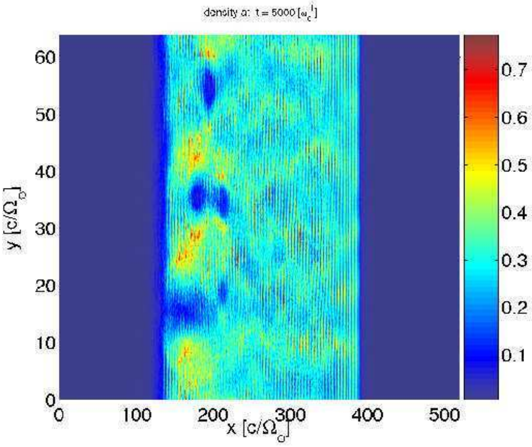

Figure 2: Plasma cavities produced by an electromagnetic wave coming from the left.

Figure 3 shows the distribution of the E_y field intensity in one of the cavities as well as the field structure outside the cavity. One can clearly see that the electromagnetic field is strongly modified inside the cavity. Analysis of the k-spectrum and the frequency spectrum of this structure shows the appearance of a low-k component and frequencies below the ambient plasma frequency. Nevertheless, the soliton-field is polarized predominantly in the original transverse direction with respect to the laser propagation.

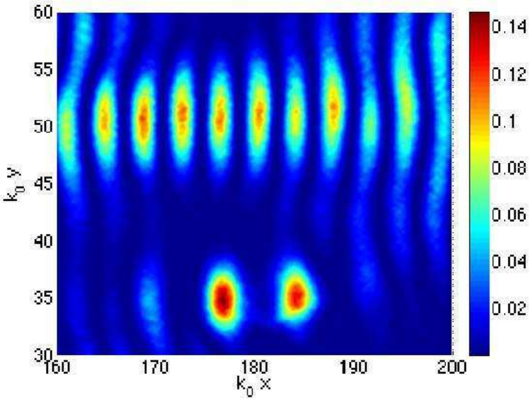

Figure 3: Distribution of E_y^2 in the cavity.

The creation of this solitary structure is accompanied by fast electron heating and subsequent ion acceleration. The electron energy increases to the level of 100 keV within $1-2$ ps after the first cavity formation. This is due to electron interaction with the electrostatic and electromagnetic waves excited in the soliton. The energy curve displays a characteristic jump-like behavior associated with the cavity creation process. This sudden increase in the kinetic energy is linked to the occurrence of Coulomb explosions and ion acceleration. The electron heating implies also a change in the growth rate of the parametric processes.

The cavitation process continues till the whole plasma volume is filled by cavities and their remnants. The asymptotic state of the interaction process is therefore characterized by very irregular structures with many small regions where large plasma fluctuations are present. The standard deviation of the density fluctuations is of the order of $\delta n_e/n_e \approx 0.2$. Correspondingly, this results in a short coherence length $L_c \sim n_c/(k_o \delta n_e) \sim 3\lambda_o$, which prevents any large gain SBBS. A plane wave incident on such a plasma structures is submitted to a strong loss of spatial and temporal coherence. The plasma acts as a dynamic random phase plate which destroys the phase relation of the electromagnetic field without producing any intense hot-spots. This specific interaction process is therefore an example of self-induced laser beam smoothing in plasma.

Figures 1 and 4 show a disparity between the time evolution of the reflectivity at a given transverse location and the reflectivity averaged over the whole transverse direction. After an initial coherent phase SBBS activity develops independently in small locations throughout the plasma. Once cavitation has taken place the reflectivity is saturated throughout the plasma and the transmission of the laser light starts to increase again as heating is limited to the initial phase given by cavitation and the life-time of the solitons.

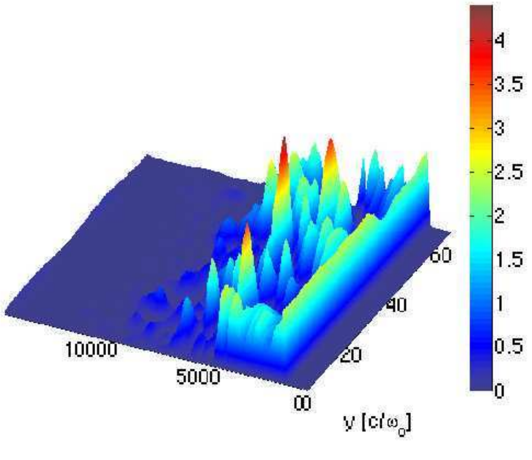

Figure 4: Time evolution of the reflectivity as function of the transverse location.

The time evolution of the reflectivity can be divided into three distinct intervals. Initially a coherent plasma response takes place where local and global averaged reflectivity are basically identical, that is, the interaction process is essentially 1D SBBS. The subsequent phase is the filamentation of the incident plane wave. It creates a multi-speckle structure where the local and global reflectivities differ but the phase relation is still intact. The final phase is characterized by strong density modulations and cavitation, which induce a loss of the phase relation across the plasma. The phase becomes increasingly randomized and the electromagnetic field approaches a state of a homogeneous turbulence. This final state is irreversible and strongly affects all subsequent laser light entering the plasma. As far as the asymptotic reflectivity is concerned, 1D PIC simulations give reliable estimates whenever cavitation occurs. This presents considerable computational advantages.

From the results obtained in 1D and 2D simulations, it can be safely conjectured that the cavitation mechanism is also present in 3D and will be equally responsible for low-level saturated SBBS reflectivities. The simulations confirm that solitary structures, plasma cavitation and the excitation of plasma modes below the plasma frequency are a rather universal feature of laser-plasma interaction, even for non-relativistic intensities. As in 1D, it was found that lowering the intensity or increasing the electron temperature affects the time scale of cavitation but does not prevent it. The differences between 1D and 2D simulations, namely increased smoothing and higher transmissivity, present themselves as advantages for possible applications.

To the long list of mechanisms invoked for the saturation of SBBS reflectivity, the plasma cavitation has to be added. It operates in the SBBS strong coupling regime and it produces an efficient plasma heating, suppression of backscattering and smoothing of the transmitted light. As the cavities are relatively long-lived (a few ps) and large enough (a few microns), it should be possible to verify their existence by the interferometry or recently devised proton imaging technique. The more profound and extensive the cavities are the stronger is the diffraction effect. There are already indirect indications for cavities from existing experiments which showed that the opening angle of the transmitted light increases with increasing intensity [7].

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