Stimulated Brillouin Scattering reduction induced by self-focusing for a single laser speckle interacting with an expanding plasma
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The origin of the low level of stimulated Brillouin scattering (SBS) observed in laser-plasma experiments carried out with a single laser speckle is investigated by means of three-dimensional simulations and modeling in the limit when the laser beam power P is well above the critical power for ponderomotive self-focusing We find that the order of magnitude of the time averaged reflectivities, together with the temporal and spatial SBS localization observed in our simulations, are correctly reproduced by our modeling. It is observed that, after a short transient stage, SBS reaches a significant level only (i) as long as the incident laser pulse is increasing in amplitude and (ii) in a single self-focused speckle located in the low-density front part of the plasma. In order to describe self-focusing in an inhomogeneous expanding plasma, we have derived a new Lagrangian density describing this process. Using then a variational approach, our model reproduces the position and the peak intensity of the self-focusing hot spot in the front part of the plasma density profile, as well as the local density depletion in this hot spot. The knowledge of these parameters then makes it possible to estimate the spatial amplification of SBS as a function of the laser beam power, and consequently to explain the experimentally observed SBS reflectivity, considerably reduced with respect to standard theory in the regime of large laser beam power.

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I. INTRODUCTION

In numerous single beam laser-plasma experiments, the backscatter reflectivities of Stimulated Brillouin Scattering (SBS) have been observed to be well below the predictions based upon the assumption of standard SBS convective amplification [1–7]. Most of the studies dedicated to the discrepancy between the theoretical predictions and the experimental results were concerned with saturation effects related to the nonlinearity of the SBS-driven ion acoustic waves (IAW), such as harmonic and sub-harmonic generation, combined with kinetic effects [2, 8–18].

In the present work, we reconsider the modeling and the interpretation of SBS in the case of a coherent single speckle, in the regime where the laser power P_f in the center of the linear focal spot is much greater than the critical power, denoted as P_{cf}, [19–22] for ponderomotive self-focusing (SF) at the point of linear focusing, denoted as z_f. We restrict ourselves to the case where this linear focusing point z_f corresponds to the point of maximum plasma density, denoted as n_f. A valid description of SBS in the regime $p_f \gg 1$, with $p_f \equiv P_f/P_{cf}$, is of major importance for the shock ignition approach in the context of laser-driven inertial confinement fusion (ICF) [23]. Shock ignition requires peak intensity values of the so-called spike laser pulse in the range of a few $10^{15} W/cm^2$ for a duration of a few hundreds of picoseconds. The control of the nonlinear coupling between SBS and self-focusing is a fundamental issue in this spike regime.

Many experiments with a single laser speckle have been carried out with exploding foils in this regime $p_f \gg 1$ [24–30]. Several of these experiments have been dedicated to the study of self-focusing [24] and of SBS [25–30] in a well defined inhomogeneous plasma. In this context, well diagnosed experiments represent a fundamental platform for comparing the experimental results with their numerical modeling.

In the present article, we develop a new approach to estimate the SBS reflectivity in the regime $p_f \gg 1$ for the case of a coherent laser speckle. Our approach follows from the observation, in our three dimensional (3D) simulations, that in this regime, past an initial short transient time, SBS takes place in a very limited spatial domain only, resulting from the nonlinear evolution, caused by self-focusing, of the initially unique laser speckle. Our numerical results were obtained with our codes Harmony [12] and Hera [31, 32] (these two codes have the same laser-plasma interaction module). Our approach to estimate the SBS reflectivity involves the combination of analytical approximations of the SBS gain factor and of the description of the self-focused laser pulse by means of simple parameters, these parameters being determined by solving a system of simple nonlinear differential equations.

The type of experiments that we describe by our nonlinear modeling corresponds to single beam experiments in the regimes where the maximum (in time) of the laser beam power at the focal spot denoted as $Max(P_f)$, satisfies the condition $Max(P_f) \geq P_{cf}$. We observe in our simulations, that the laser pulse begins to self-focus non-linearly in the spatial domain of maximum density, $z \approx z_f$, where the laser beam is linearly focused. The nonlinear self-focusing starts at the time, denoted as t_{sf}, when the SF condition $p_f = P_f/P_{cf} \geq 1$ is satisfied at the point z_f of maximum plasma density. Past this time t_{sf}, and as long as the laser power in vacuum P keeps increasing with time, the spatial domain for which the condition $P(n_e) > P_c(n_e)$ is locally fulfilled extends to the domain of plasma density n_e satisfying the condition $P(n_e) > P_c(n_e) = (n_f/n_e)P_{cf}$, i.e. to the density domain satisfying the condition $n_f\,[P_{cf}/P(n_e)] \leq n_e \leq n_f$. Here $P(n_e)$ and $P_c(n_e)$ denote the values of the laser beam power and of the critical power, respectively, in the spatial domain corresponding to the density n_e. If there was no absorption, $P(n_e)$ would not depend explicitly on space.

We take into account the laser beam absorption, so that the laser power $P(n_e)$ varies with space, and one has $P_f \equiv P(n_f) < P$. We observed numerically that during the temporal phase of *increasing* laser beam power, the spatial plasma domain where self-focusing takes place moves quickly back towards the domain of the laser wave entrance [33]. This transient motion of the SF domain lasts for a short time only. Past this initial transient phase, the spatial domain where self-focusing takes place in a non-filamentary way remains located in a narrow spatial domain, where the SF parameter $p(n_e) \equiv P(n_e)/P_c(n_e)$ is of the order of a few units. Further on inside the plasma, the incident laser beam behaves in a very chaotic way, spatially and temporally, because the laser beam filaments are unstable in the regime $p(n_e) \gg 1$ as theoretically predicted [34–38].

Concerning now the temporal phase of *decreasing* laser beam power, one observes a dramatic drop of the SBS reflectivity as soon as the laser intensity starts decreasing. Our interpretation of this fast drop is the following: when the laser intensity starts decreasing, the spatial domain where the SF parameter $p(n_e) = P(n_e)/P_c(n_e)$ is of the order of a few units moves forward (with respect to the laser wave direction) so as to find a larger density in order to compensate the temporal decrease of the laser beam power. Moving forward, the (spatially) first intensity bump moves in the spatial domain where the plasma density is turbulent as a result of the filament instability. This plasma turbulence stabilizes the Brillouin growth, so that the SBS reflectivity immediately drops to very small reflectivity values.

Our modeling, therefore, concentrates on the description of the laser wave (i) during the temporal phase of increasing laser beam power, and (ii) in the spatial domain of low plasma density where the SF parameter $p(n_e)$ is of the order of a few units, so that the self-focused laser beam no longer moves significantly, past the short initial transient phase during which the self-focusing laser speckle moves rapidly from the linear focusing point z_f to this lower density domain. It is indeed only during the temporal phase of increasing laser beam power and in this low density domain that the laser pump beam keeps its coherence and SBS may consequently develop at a significant level.

In order to capture analytically the description of the final steady state resulting from the nonlinear self-focusing in an inhomogeneous plasma, we have kept merely the following essential features for the sake of simplicity:

(i) we modeled the inhomogeneity of the expansion velocity under the form of a simple linear function of the longitudinal coordinate z; this approximation was checked to be well justified in the restricted spatial domain where self-focusing and SBS take place;

(ii) we ignored the inhomogeneity of the electron and ion temperatures: indeed, the first self-focusing takes finally place in a very narrow spatial domain, in which the spatial dependence of the temperatures can be ignored;

(iii) in the presentation of our numerical results, obtained with fluid type codes and concerning the coupling between self-focusing and SBS, we used a simple one fluid description in which the IAW frequency and damping are imposed by the proper choice of the simulations parameters. At this level, the temporal behavior of SBS and of self-focusing, intimately depending on their mutual coupling, do not significantly depend on the detailed level of their description.

(iv) we developed our Lagrangian model aimed at describing self-focusing in an inhomogeneous plasma as a one fluid model in which we just have to specify the ion acoustic wave velocity.

Our model can be seen as a generalization, in an inhomogeneous plasma, of the Lagrangian density corresponding to the nonlinear Schrödinger equation in the case of a homogeneous plasma [39]. By using such a variational approach, the position of the self-focusing speckle in the local plasma density, the over-intensity (defined by the ratio between the peak intensity values of the self-focused speckle and of the speckle at the 'linear' focal point, i. e. in absence of SF), and the local density depletion in the hot spot can be determined and used as input values to compute the spatial amplification of SBS and its corresponding reflectivity as a function of the beam power.

Our paper is organized as follows: the physical properties of the laser pulse and of the plasma conditions corresponding to our "reference simulations" are presented in Section **??**. Section **??** is devoted to the description of the SBS evolution as seen in our 3D simulations. Our Lagrangian model aimed at describing self-focusing in an inhomogeneous plasma is presented in Section **??**. The SBS gain factor is computed within our SF modeling in Section **??**. Finally, we discuss our findings and we conclude in Section **??**.

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