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Simulation of nonlinear, kinetic stimulated Brillouin scattering

F. Detering[1], P.E. Masson-Laborde[1], S. Hüller[1], D. Pesme[1]

[1] *CPHT, Ecole Polytechnique, CNRS UMR 7644, 91128 Palaiseau Cedex, France*

Abstract

A parameter study of stimulated Brillouin scattering is presented, that covers a large parameter space of laser intensity and plasma density ($I = 1-10\ 10^{14}$W/cm^2, $n/n_c = 0.03-0.69$). The relative importance of kinetic effects in SBS driven ion-acoustic waves is examined in a hybrid PIC model in which electrons are approximated by an isothermal Boltzmann distribution and which allows the detailed study of ion kinetic effects. A regime of weak kinetic effects, where phenomenological terms within a fluid model are likely to work is identified. The hydrodynamic model HarmoNHY [1], using a reduced decomposition model complements the investigation and allows to define the phenomenological parameters of the nonlinear frequency shift within the regime of weak kinetic effects.

A recent analysis [2] of the parametric instability of ion acoustic waves has emphasised the importance of the parametric decay of the driven ion acoustic wave into subharmonics. Indeed the inclusion of subharmonics into HarmoNHY is found to be one of the necessary ingredients to reproduce the kinetic results.

Introduction

In the framework of inertial confinement fusion, the development of predictive modeling tools of laser-plasma interaction is an ongoing effort due to the complex interplay and large range of physical scales concerned in the experiments [3].

Kinetic effects have long been identified as one of the necessary ingredients to describe the saturation of stimulated Brillouin scattering (SBS) [4]. Several cases have already been studied that demonstrated the effects of frequency detuning, subharmonic decay, kinetic ion heating and coupling with higher harmonics and flow generation in certain regimes where a heuristic model for a fluid-type code could reproduce the major features of SBS [5]. A systematic prescription for the inclusion of ion-kinetic effects into a hydrodynamic model with a cor-

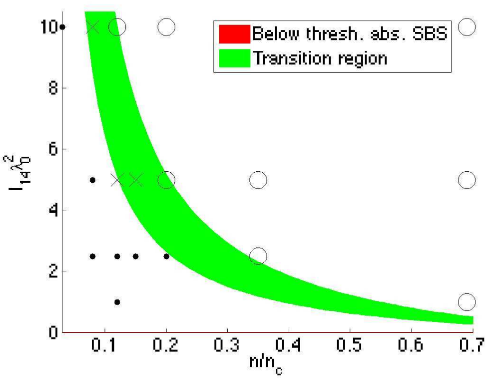

Figure 1: The SBS evolution for $ZT_e/T_i = 18.5$. Dots indicate weakly kinetic cases, crosses and circles to strongly kinetic cases.

responding specification of the validity and verification through a kinetic simulation model of such a model is however long outstanding and the object of this contribution. The final goal is the hydrodynamic modelling of large plasma volumes which takes into account kinetic effects in a defined regime of physical parameters where the model has been validated by a kinetic model. Most importantly the goal is to provide a prescription of the kinetic modelling that is free of adjustable parameters. The first step is thus a study of the SBS evolution with a hybrid kinetic model for a range of densities, intensities and temperatures to identify the regime where the currently used model for nonlinear, kinetic effects [6] can be expected to be a useful approximation.

Parameter Scan of SBS in exploding foil plasma

All the simulations were carried out in the geometry of an expanding plasma foil. The initial profile was a homogeneous plasma sheath of thickness $L_p = 728 k_0^{-1}$, limited on each side by a vacuum into which the plasma expands hydrodynamically. Here, k_0 denotes the laser light wave vector in vacuum. The plasma parameters were the following: the electron temperature was $T_e = 1$keV, the electron density was varied between $n/n_c = 0.03 -$ -0.69. The electron-ion temperature ratio was varied between $6.06 < T_e/T_i < 18$ in order to consider differently damped regimes (between $\gamma/\omega_s = 10^{-1}$ and $\gamma/\omega_s = 10^{-3}$, where $\gamma/\omega_s$is the linear Landau damping rate). The laser intensity was varied in the interval $1 - 10\,10^{14}$W/cm^2 for a wavelength of $\lambda_0 = 1\mu$m.

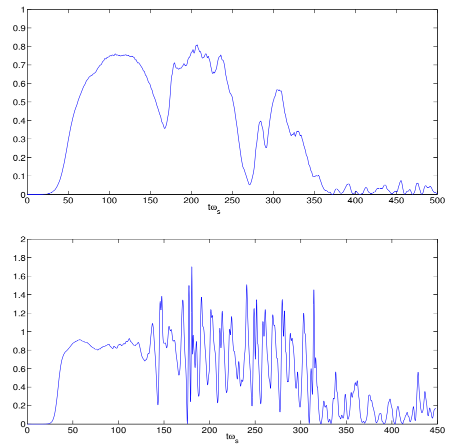

Figure 2: Top panel : Reflectivity for $I_{14}\lambda_0^2 = 2.5$, $n/n_c = 0.12$, $T_e/T_i = 18.5$, Bottom panel :Reflectivity for $I_{14}\lambda_0^2 = 5$, $n/n_c = 0.15$, $T_e/T_i = 18.5$.

Weakly and strongly kinetic regime

Putting the results with this qualitative analysis in the (n,I)-plane in Fig. 1, we identify regions of qualitatively different behaviour.

We find that roughly above the isoline of growth of absolute SBS $\gamma_{SBS}/\omega_s = 0.06$ the reflectivity displays bursty behaviour and below a much smoother evolution as shown in two examples in Fig. 2.

A closer look at the kinetic evolution in Fig. 3 reveals significant differences in the ion distribution function for the two extreme regimes. The bulk of the distribution remains nearly Maxwellian over a long time for the weakly kinetic regime, wheres the bulk of the ions is significantly heated in the strongly kinetic regime. Significant increase in Landau damping is a likely reason for the decay of SBS. In conclusion we note that the model of a modification of the distribution only around the phase velocity, which results in a nonlinear frequency shift on the ion sound waves, is limited to the regime that we have identified and mapped as the "weakly kinetic" regime. Additionally, strong subharmonic decay is occuring almost universally in this regime [7], so that the inclusion of the evolution of subharmonics has to be included in the fluid-type modelling.

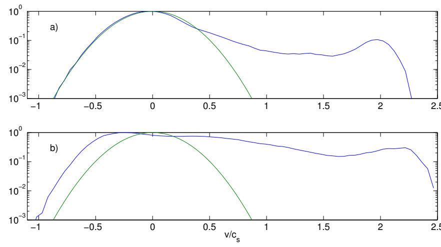

Figure 3: Distribution near the entrance of the plasma for (a): $I_{14}\lambda_0^2 = 2.5$, $n/n_c = 0.12$, $T_e/T_i = 18.5$ at $t\omega_s = 150$ and (b): $I_{14}\lambda_0^2 = 5$, $n/n_c = 0.15$, $T_e/T_i = 18.5$ at $t\omega_s = 132$

Fluid modeling of kinetic effects

The fluid-model HarmoNHY1D [1] describes the evolution of the SBS interaction using a decomposition of the spatial scales to efficiently accelerate the calculation. The long-scale plasma evolution is described by conventional hydrodynamics, and the plasma waves and laser fields by time and space enveloped equations. This decomposition allows also the introduction of subharmonic components n_{p/p_f} behaving like $\exp\left(ip/p_f k_s x\right)$, for each of which an additional equation is introduced together with its own harmonics. Convergence of the results was obtained for six subharmonics ($k_s/6$) which was consequently used in remainder. Kinetic effects are included through two additional terms in the ion acoustic wave equations,

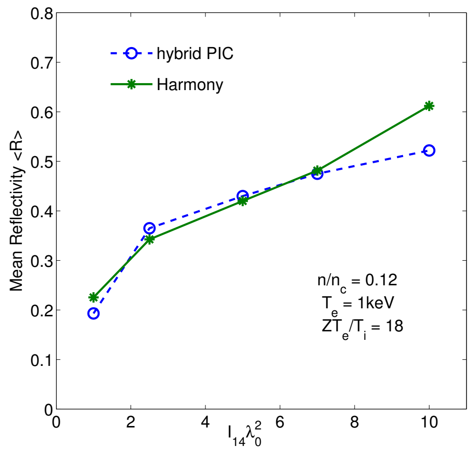

Figure 4: Comparison between fluid and kinetic mean reflectivities.

$$L_{p/p_f}\{n_{p/pf}\} + \left[(p/p_f)\nu_s(t) - i(p/p_f)\eta\|\delta n/n\|^{1/2}\right] n_{p/p_f} = \text{source} + \text{coupling terms.} \quad (1)$$

Here, L is the sound wave propagator and the second term accounts for the decrease of Landau damping due to trapping of the form $\nu_s(t) = (\nu_s/\omega_s)/(1+t/\tau)$ where $\tau = 2\pi/\omega_b$ and ω_b is the bounce frequency. The third term models the nonlinear frequency shift induced by trapping [6], where η is treated as an adjustible parameter.

The value of η is varied to match the saturation value of the reflectivity and the time-averaged value of the kinetic simulations. The results for a specific set of parameters $T_i/ZT_e, n/n_c, T_e$ that are displayed in Fig. 4 were obtained with a single value of η and confirm furthermore that reliable modeling in the regime of strong kinetic effects is not possible within the framework of a simple, nonlinear frequency shift.

Conclusions

With a kinetic model, we have identified the regime of densities and laser intensities where only weak kinetic effects occur and fluid-modeling with phenomenological kinetic terms is likely to succeed. With the fluid-type model HarmoNHY [1] we have demonstrated that the inclusion of subharmonics and the kinetic frequency shift [6] are necessary components to reliably recover the overall features of the SBS activity in the kinetic model. The value of η depends on the parameters $T_i/ZT_e, n/n_c, T_e$. The ongoing effort is to determine the value of η by the procedure described in this paper for a range of T_i/ZT_e and $n/n_c, T_e$ to provide a general prescription for further predictive fluid-modeling.

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