Nanosecond laser-plasma interaction studies in the context of the LIL facility

Olivier Morice, Michel Casanova, Pascal Loiseau, Denis Teychenné and Christophe Rousseaux

Commissariat à l’énergie atomique, centre DAM Île-de-France, BP 12 – 91680 Bruyères-le-Châtel, France
E-mail: olivier.morice@cea.fr

Abstract. We present some numerical studies about laser-plasma interaction (LPI) in experiments which have recently been carried out on the LIL facility. We first show hydrodynamic simulations and modeling of the various kinds of experiments of the campaign. Then we discuss our methodology to study them under the angle of LPI. Several tools, from the simplest to the most accurate one, have been developed for that purpose. We finally present some preliminary experimental results of one of these experiment, and we benchmark them with linear Raman and Brillouin gain computations.

1. Introduction

The Ligne d’intégration laser (LIL) facility is a new laser that has been built in France near Bordeaux in order to validate one quadruplet of the future laser Mégajoule (LMJ) [1]. The LIL is now fully operational and specific experiments are being carried out on it to overcome the main issues [2] regarding the LMJ. Laser-plasma interaction (LPI) might be one of the most crucial of these issues. More precisely, LMJ targets might backscatter a relevant part of the laser energy by stimulated Brillouin scattering (SBS) or stimulated Raman scattering (SRS) effects, this backscattered energy being lost for target compression and thermonuclear fusion achieving. LPI-devoted experiments have thus recently been carried out on the LIL facility. Although the energy available in this quadruplet is comparable to the one of the NOVA and OMEGA facilities (15 kJ at 351 nm), the LIL now opens new areas of LPI. Indeed, in these experiments, an entirely new method for beam optical smoothing (the longitudinal smoothing by spectral dispersion [3]) is being tested.

The LPI campaign on LIL facility has been designed to approach as close as possible the LMJ conditions with respect to LPI criteria. Cavity experiments have thus been chosen, rather than easier-achievable exploding foils or gas bags, and dimensions of these cavities have been calculated so that LPI-relevant parameters (such as reduced electronic density $n_e/N_e$, or product $k\lambda_D$ of the plasma wave wavenumber by the Debye length) were close to future LMJ ignition experiments. LIL experiment cavities are tube-shaped gold cavities, filled with pentane gas, and closed with one or two plastic windows. Lengths and diameters of these cavities varied from 3 to 5 mm and from 1.4 to 2.4 mm respectively. The laser energy was 12 kJ at 351 nm wavelength, and the pulse shape was a 4 ns prepulse followed by a 2 ns main pulse.
2. Hydrodynamic simulations and modeling of the LIL experiments
It is well known that LPI is very sensitive to the hydrodynamic conditions of the plasma. Hydrodynamical parameters of the experiment have thus to be studied carefully. Consequently, we proceed in two steps: a Lagrangian hydrodynamics code with ray-tracing (FCI2), developed at CEA, computes the electronic density, temperatures and velocity profiles during the experiments. Then we try to deduce from our global comprehension of the hydrodynamical evolution, some phenomenological scalings which would be of some use for more specific LPI studies.

Figure 1. Contour plots of the reduced electronic density \( n_e/N_c \) at different instants of the experiment, as computed by the FCI2 Lagrangian code. Case of the two-window (type A) experiment.

Figure 2. Contour plots of the reduced electronic density \( n_e/N_c \) at different instants of the experiment, as computed by the FCI2 Lagrangian code. Case of the one-window (type B) experiment.

Figure 1 shows the time evolution of the electronic density in the case of the two-window experiment. One can see that the time evolution of this density for \( t < 5 \text{ ns} \) is rather complex. Hole boring and density bumps are observed. From \( t = 5 \text{ ns} \) the profile exhibits a density plateau. The conditions to study LPI becomes thus more acceptable. In case of a single-window experiment (fig. 2), behaviors essentially differs by the existence of a gold jet which builds up from the back of the cavity. As a consequence, the plasma ejection out of the cavity is enhanced as compared with the scenario in the two-window cavity. The plasma is very inhomogeneous, particularly in short cavities.

One may model the global hydrodynamical behaviour as follows (fig. 3):

- The density is first hollowed by laser heating, until the induced acoustic wave bounces against the walls and comes back to the plasma. One thus observes density oscillations, the period of which being about \( D/c_s \), \( D \) being the cavity diameter and \( c_s \) the velocity of sound (\( c_s \approx 0.5 \text{ mm/ns} \)).
Figure 3. Modeling of the global plasma behaviour. On the left, time evolution of the mean density \( \frac{n_e}{N_c} \) and electronic and ionic temperatures. Then, velocity profiles at two instants of the experiment.

- The energy \( E_{\text{abs}}(t) \) absorbed by the matter is related to the laser energy \( E_{\text{las}}(t) \) by the relation: 
  \[ E_{\text{abs}}(t) = \min\{1, L/L_{\text{abs}}(t)\} \times E_{\text{las}}(t), \]
  \( L \) being the cavity length and \( L_{\text{abs}}(t) \) the light absorption length. One may deduce the following law for the electronic temperature:

  \[ T_e(t) \propto \left( \frac{n_e}{N_c} \frac{E_{\text{las}}}{D^2} \right)^{0.4}. \]

- The ionic temperature \( T_i \) is deduced from the electronic one by the relation:
  \[ \frac{dT_i}{dt} = \frac{T_e - T_i}{\tau_{ie}}, \]
  where \( \tau_{ie} \) is the electron-ion relaxation time (\( \tau_{ie} \simeq 3 \, \text{ns} \)). This simple model (which could be improved) gives a \( T_i \sim 25\% \) lower than the simulation.

- Finally the velocity presents two stages of evolution. First the gas is convected inside the cavity, then the gas velocity becomes mainly longitudinal, like an exploding foil.

3. Analysis of LIL experimental results

A first LPI campaign has been carried out on the LIL facility with a type B (one window) cavity. Two identical shots were tested in order to check the reproducibility of the results. The results were very similar.

We analyzed our results following a 3-step procedure: (1) Macroscopic hydrodynamic parameters were given by the FCI2 hydro code. (2) Raman and Brillouin activity zones were identified using our PIRANAH post-processor which gives linear amplification gains. (3) Activity zones were studied more closely using our HERA platform \cite{4} which includes more LPI physics.

In Fig. 4, the rather good agreement between experimental and theoretical spectra can be explained by the strong sensitivity of LPI to hydrodynamics. Particularly, the time evolution of the Raman shift can be successively related to:

- the density hole boring and the radially expanding plasma which follows the laser pulse penetration inside the cavity;
- the density build-up which appears on the symmetry axis of the cavity after the reflexion of the expanding plasma on the cavity walls;
- the longitudinal expansion of the plasma outside the cavity at the end of the laser pulse.

It should be noticed that at time \( t \simeq 3.5 \, \text{ns} \), the strong intensity which is visible on the experimental spectrum is not well reproduced by the theoretical spectrum whereas the shape of the spectrum is satisfactorily reproduced. The origin of this discrepancy could be the kinetic effects related to the Raman instability in the nonlinear regime, which are not taken into account in our calculation.
Concerning the Brillouin spectrum, the main difference between the two spectra is a peak intensity at time $t \approx 2.5$ ns which is only visible on the experimental spectrum. We have no explanation for this feature which has been observed on our two shots and which is all the more surprising because it happens in the prepulse before the main pulse.

References
[1] Besnard D 2006 *Eur. Phys. J. D* e2006–00165–4
[2] Holstein P A, Casanova M, Casner A, Is C C, Dattolo E, Disdier L, Galmiche D, Giorla J, Houry M, Jadaud J, Laffite S, Liberatore S, Loiseau P, Lours L, Masse L, Monteil M, Morice O, Naudy M, Philippe F, Poggi F, Renaud F, Riauzelo G, Saillard Y, Seytor P, Vandenboomgaerde M and Wagon F 2006 *Eur. Phys. J. D* e2006–00175–2
[3] Garnier J and Videau L 2001 *Phys. Plasmas* 8 4914
[4] Ballereau P, Casanova M, Duboc F, Dureau D, Jourdren H, Loiseau P, Metral J, Morice O and Sentis R 2007 *J. Sc. Comput.* 33 1