Simulation of laser-plasma interaction experiments with gas-filled hohlraums on the LIL facility

P. Loiseau¹, P.-E. Masson-Laborde¹, D. Teychenné¹, M.-C. Monteil¹, M. Casanova¹, D. Marion¹, G. Tran¹,², G. Huser¹, C. Rousseaux¹, S. Hüller², A. Héron² and D. Pesme²

¹ CEA, DAM, DIF, 91297 Arpajon, France
² Centre de Physique Théorique, CNRS, École Polytechnique, 91128 Palaiseau, France
E-mail: pascal.loiseau@cea.fr

Abstract. Laser-plasma interaction is a major issue for achieving ignition in inertial confinement fusion schemes, and still a major concern for the upcoming french laser megajoule (LMJ) program. In order to mitigate the deleterious effects due to laser-plasma instabilities (LPI), clearly evidenced during the recent US National Ignition Campaign conducted on the National Ignition Facility, we use the LIL facility as a demonstrator for LPI studies. In this article, we focus on preliminary results regarding the propagation of a typical LMJ quadruplet through gas-filled hohlraums. Results on hohlraum energetics will then be discussed.

1. Introduction

One major goal of the Laser MegaJoule facility (LMJ) [1], currently under completion in France, is to achieve fusion ignition and thermonuclear gain from a target driven with a laser. First attempts to achieve ignition will be undertaken as soon as the facility is 2/3 completed. In this configuration the laser is able to deliver up to 1.2 MJ and 390 TW at peak power, at 0.351 μm.

An ignition indirect drive target has been designed for the 2/3 LMJ step [2]. It requires 0.9 MJ and 260 TW of laser energy and power, to achieve a 300 eV radiative temperature in a rugby-shaped hohlraum and to give a yield of about 20 MJ. This achievement relies firstly on the mitigation of laser plasma instabilities (LPI). First experiments conducted on the National Ignition Facility [3] and recent ones [4] illustrate the fact that LPI is not the sole reason for implosion degradation, but it does obscure the understanding of the target performance. Such issues can be addressed by conducting laser-plasma interaction campaigns on the LIL facility, using various lengths of gas-filled hohlraums.

The LIL facility is a prototype of one quadruplet of the LMJ. Three different gas-filled hohlraums have been designed in order to mimic plasma conditions that are expected along two particular beam paths in ignition hohlraums [5,6]. We focus on the open cylinder targets, 1.5- or 4-millimeter long and 1 atm neo-pentane gas-filled. The target material is mainly gold. The LIL quadruplet is aligned along the hohlraum axis and delivers a 6-ns long pulse with 15 kJ at 3ω.

Many optical diagnostics were activated during the campaign, see Fig. 1, giving a full temporal and angular description of parametric instabilities such as stimulated Brillouin (SBS) or Raman (SRS) scattering. X-ray diagnostics were used for measuring the radiative temperature, and
transmission beam diagnostics were activated. Finally, this whole set of diagnostics allows a full measurement of hohlraum energetics.

Figure 1. LIL diagnostics and targets.

In the following, we will present and discuss hydrodynamic calculations together with preliminary results of the LPI campaign.

2. Simulation of LIL experiments

The modelling of laser-plasma interaction experiments is usually made by using radiative-hydrodynamic codes, such as FC12. In this case, the laser-plasma interaction is often reduced to a collisional absorption of the electromagnetic wave - via the inverse Bremsstrahlung mechanism -, and the laser propagation is described by ray-tracing packages. This modelling is adapted to the long hydrodynamical time and spatial scales that are favored in nanosecond experiments. However, laser-plasma interactions that arise during the experiment, are not coherently taken into account, nor the rich laser-plasma interaction in general. In order to simulate experimental results, such as the radiative temperature characterizing the drive on an ignition capsule, we need to remove the energy losses due to LPI, essentially the backscattered energies, from the incident laser pulses delivered by the facility. Using LIL’s results, we address the question to what extent this usual recipe is realistic or not.

Backscattered measured energies on the LIL facility, essentially from SRS, were respectively \( \sim 30\% \) and \( \sim 5\% \) of the laser incident energy for the 4-mm (long) and 1.5-mm (short) hohlraums. We measured a moderate effect of the nominal optical smoothing scheme, based on a spectral dispersion and a focusing grating. Simulations were done using a modified laser pulse, taking into account the SRS temporal behaviour. As expected, the calculated maximum radiative temperatures are correct.

Once the simulation is done, it is now interesting to compare the SRS spectrum to the simulated one. SRS spectra both reveal the electron density and temperature evolutions. Those quantities are seldom measured on large laser facilities. Fig. 2 shows the calculated Raman spectra for the long (a) and short (b) hohlraums, and the SRS experimental wavelength time evolution. The early part of the signal, up to 3 ns, is related to a density channel created by the
Figure 2. Simulated SRS spectra for the long (a) and short (b) hohlraums. The connected points correspond to the time evolution of the measured backscattered wavelength.

The later part of the SRS signal is caused by hydrodynamic motion inside the hohlraum, where shock waves rebound off the walls. A frequency shift between calculated and measured wavelength is clearly seen for both hohlraums. This could be the signature of nonlinear kinetic effects, those effects being beyond the validity range of a linear gain calculation.

Transmission measurements indicate that only $\sim 1.5$ kJ and $\sim 4.5$ kJ laser energies exit respectively long and short hohlraums. In radiative-hydrodynamic codes, the transmission is defined as the unabsorbed laser energy. We find that simulations predict $\sim 4.0$ kJ and $\sim 8.0$ kJ respectively for long and short hohlraums. This discrepancy is surprising and highlights the inaccuracy of laser beam propagation models in hot plasmas. A slight benefit from optical smoothing is only observed in the shorter hohlraum. Some insights can be found in the time integrated beam transmission diagnostic where strong spatial incoherence is observed, especially for short hohlraums.

3. Discussion

The previous simulation results exhibit conflicting conclusions: the amount of energy injected in the simulation is right regarding radiative temperature measurements, but SRS calculated spectra are shifted, and too much laser energy is unabsorbed (transmitted) in simulation. Regarding SRS spectra, several reasons can be raised. First, because hydrodynamic conditions were not measured, plasma conditions can be miscalculated. Besides, due to laser self-focusing or filamentation, laser intensities may also be incorrect, affecting plasma conditions. During the second stage of the pulse, the laser power is four time higher and could lead to self-focusing of the beam. Actually, Raman spectra are quite similar whatever the optical smoothing scheme is, indicating that self-focusing is not solely responsible for the discrepancy. Varying atomic physics packages and electron thermal conduction models did not improve the spectrum. Also, removing the measured SRS power is a poor model of laser-plasma coupling. In particular, such a model underestimates the real amount of SRS energy by not considering a potential SRS light absorption inside the plasma. Accordingly, Raman light absorption can modify local electron temperature. Because linear gain calculations do not take into account non-linear frequency shifts arising from a strong modification of the electron distribution function, SRS calculated spectra miss the right resonance.

This confirms the need of a kinetic Raman model. We are developing a three-wave coupling
Raman solver in multi-dimensions with nonlinear kinetic capabilities [7, 8]. We show in Fig. 3 first results, in one-dimension (1D) for a short hohlraum. The plasma parameters are taken at 4 ns corresponding to the observed Raman peak power. The matching conditions for the three waves are imposed at $10\%n_c$, corresponding to the maximum density, and $5\%n_c$ corresponding to the expected resonant density deduced from the experimental spectrum. SRS wavelengths ($k\lambda_D$ parameter) are respectively 540 nm (0.27) and 480 nm (0.4) for the $10\%n_c$ and $5\%n_c$ cases. Both simulations produce a high 1D reflectivity, around 20%. This was expected for the $10\%n_c$ case but not for the $5\%n_c$ case. Moreover, the resonance at low density disappears when kinetic effects are not taken into account. This interesting result proves that our modeling is able to catch those new features and could explain the experimental spectrum. Finally, we use the 3D paraxial code HERA [9, 10] to investigate the propagation of the LIL quad, by means of massively parallel simulations. The Raman model is intended to be introduced shortly in HERA.

**Figure 3.** Spatial localization of Langmuir waves at 10, 20 and 30 ps for two matching electron densities: $5\%n_c$ and $10\%n_c$. The wave amplitude is given in relative density variation $\delta n/n$. The laser propagates from the left to the right.

4. Conclusion

The mitigation of LPI is a major issue for ignition achievement. It relies on our capabilities to model LPI but also on our capability to predict the plasma parameters such as the electron density and temperature. Radiative-hydrodynamic simulations of LIL experiments emphasize the difficulty of predicting all the measured quantities. As a matter of fact, single beam propagation experiments on LIL illustrate the difficulty of securing a safe inner beam propagation in ignition hohlraums.

References

[1] C. Lion, J. Phys.: Conf. Ser. 244, 012003 (2010).
[2] S. Laffite and P. Loiseau, Phys. Plasmas 17, 102704 (2010).
[3] S. H. Glenzer et al., Phys. Rev. Lett. 106, 085004 (2011).
[4] D. Callahan and D. Hinkel talks, IFSA Conference (2013).
[5] O. Morice et al., J. Phys.: Conf. Ser. 112, 022037 (2008).
[6] A. Casner et al., J. Phys.: Conf. Ser. 244, 032042 (2010).
[7] H. X. Vu et al., Phys. Plasmas 9, 1745 (2002).
[8] P-E. Masson-Laborde et al., Phys. Plasmas 17, 092704 (2010).
[9] P. Loiseau et al., Phys. Rev. Lett. 97, 205001 (2006).
[10] P. Ballereau et al., J. Scient. Comput. 33, 1 (2007).