Laser-plasma interaction physics in multi kilojoule experiments

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Abstract. An experiment carried out on the LIL facility is presented. The experiment was designed to investigate the propagation of a multi-kJ laser beam through a plasma produced by the irradiation of a low-density plastic foam. Laser beam self-smoothing has been observed and its consequences on laser imprint and Stimulated Brillouin Scattering (SBS) are discussed.

1. Introduction

Laser-plasma interaction physics (LPI) is one of the most critical issues for the success of laser ignition. After long standing efforts, a significant progress in the understanding of the coupling mechanisms has been obtained and theoretical modeling is now close to a predictive capability for experiments. A large part of this progress has been obtained thanks to numerous experiments done in well-controlled interaction conditions that allowed to test and to improve the physics included in the models. These experiments were carried out on small systems producing a large number of shots and equipped with sophisticated diagnostics having high spatial resolution. These results have been obtained at the cost of a low total energy and, consequently, with small-size and low temperature ($T_e \leq 1 \text{ keV}$) plasmas. Now, there is a strong need for investigating interaction physics in multi-kilojoule experiments with large, hot, fusion-size plasmas, despite the fact that the number of shots is reduced. Inertial Confinement Fusion at megajoule laser facilities, NIF and LMJ, requires an efficient propagation and coupling of the laser beams to plasmas both for the direct and indirect drive approaches.

2. The LIL experiment

We have designed an experiment based on the multikilojoule system LIL (Ligne d’Integration Laser) aimed at achieving well-defined interaction conditions by using a large focal spot (mm), thus
producing hot plasmas ($T_e \geq 2$ keV) with one-dimensional expansion along the laser axis. Among the possible targets (thin exploded foils, thick foils, gas jets, gas bags, hohlraums) we chose low-density (sub-critical average density) foam targets to produce long (mm) underdense plasmas [1]. They have shown favorable conditions for fusion studies (long scale-lengths of several hundreds microns) at high temperatures (keV range) that last for times of the order of the pulse duration [2]. Underdense foams have been used in many interaction experiments related to fundamental material properties [3], production of controlled density fluctuations [4] and interaction physics [5].

The objectives of our experiment were to study the propagation of a high intensity laser beam in a long and warm plasma, to measure the modifications of its coherence properties [6] and their consequences on laser imprint and parametric instabilities. These objectives were met by using a combination of three targets: i) a cylinder of low-density foam, ii) the same cylinder of foam with a 10 µm thick copper foil at the back, iii) a 10 µm thick copper foil. The targets of the first type make it possible to study the propagation of the laser beam through the underdense plasma, produced by the foam irradiation, the analysis being based on the transmitted light features. The targets of the second type allow to study interaction physics both in the foam and in the copper plasmas irradiated by laser light transmitted through the foam plasma. The targets of the third type allow to investigate interaction physics in copper plasma alone. A scheme of the experiment is shown in Fig. 1.

![Figure 1](image)

**Figure 1.** Scheme of the LIL interaction experiment.

The foam densities and lengths were chosen based on numerical simulations using the radiation hydrodynamic code CHIC [7] as well as preliminary experimental studies using the LULI installations. The foams were either TAC (C$_{15}$H$_{20}$O$_6$) or TMPTA with densities between 3 and 10 mg/cc which correspond to electron densities of 10 to 35 % of the critical density for 3w light. The scale length of the initial pore structures were in the submicron range and the foam lengths, along the laser axis, were varied between 300 µm and 1 mm. The LIL laser delivered $\sim 12$ kJ at 351 nm in a 2.7ns square pulse. The main diagnostics were the temporally and spectrally resolved measurements of stimulated Brillouin and Raman scattering, the temporally and angularly resolved analysis of the transmitted light, and spatial and temporal hard x-rays images in the domain of 1 – 5 keV x-rays.

3. **Experimental results**

With the foam alone, the time-resolved transmitted light and the transverse x-ray streak camera provided consistent information about the laser propagation through the foam. We found that 500 µm long, 10 mg/cc foam was fully ionized in 1.2 ns. The corresponding average speed of the ionization
front was 0.5 mm/ns. This value is larger than the acoustic velocity, \( c_a \sim 0.32 \text{ mm/ns} \), which was deduced both from the trajectory of the rarefaction wave front in the x-ray image, as well as from temperature measurements from SBS spectra. So, the first result is that a combination of a 10 mg/cc foam density with a few \( 10^{14} \text{ W/cm}^2 \) irradiation intensity provides a supersonic ionization wave, sustained for a time longer than 2 ns [8].

The second result concerns the modification of the spatial coherence property of the transmitted light, which was demonstrated via the angular broadening of the light transmitted through the foam. Inside the incident cone, as well as outside, we observed broadening of the transmitted light through the foam compared to vacuum. An example of the angular diagram outside the incident cone in the case of a 500 \( \mu \text{m} \)-long, 7 mg/cc, foam is shown in Fig. 2. Some light is scattered outside the initial 6° aperture, with a half angle of 16° and a sharp profile. The angular broadening of the transmitted radiation is due to multiple scattering of the laser light on the laser-induced density fluctuations caused by forward stimulated Brillouin scattering (FSBS). FSBS of the RPP beam is responsible for self-induced smoothing. Calculations, using the hydrodynamic plasma parameters, show that the interaction conditions are above the FSBS threshold [8, 9].

Figure 2. Angular distribution of the transmitted light outside of the incident cone.

The reduction of the laser imprint caused by the laser beam smoothing due to its propagation through the foam was demonstrated by the comparison between the 2D x-ray images, integrated over 200 ps, of the laser imprint on the Cu foil alone and on the Cu foil covered with a 500 \( \mu \text{m} \), 10 mg/cc foam. The comparison was done at the very beginning of the laser impact on the foil, which corresponds to the time \( t = 0 \) for the foil alone and to \( t = 1.2 \text{ ns} \) for the foil covered with 500 \( \mu \text{m} \)-long 10 mg/cc foam. Large intensity fluctuations with the same spatial scale as in the focal spot distribution in vacuum are observed when the foam is absent (panel a in Fig. 3). The emission of the copper foil covered by the foam plasma (panel b) is much smoother than in the previous case. The inhomogeneities of size \( \sim 50 \text{ \( \mu \)m} \) have been removed and the amplitudes of small-scale fluctuations have been strongly reduced.

Figure 3. Two-dimensional x-ray images of the Cu foil emission integrated over 200 ps and recorded at the very beginning of the emission: a) Cu alone; b) Cu foil covered with 500 \( \mu \text{m} \) of foam.
The last results concern the SBS emission in the backward direction for the three types of targets, as shown in Fig. 4. With the foam alone, the SBS emission occurs at the beginning of the laser pulse and lasts for less than 1 ns. Similar behavior, with even shorter peak, is observed for the Cu foil alone. For the combined target (foam + copper), two distinct temporal components of SBS emission are observed. The first one is similar to the one recorded for the foam alone, while the second one starts 1.2 ns (~1.9 ns) later for the 500 (750) µm-long foam. This second signal is clearly associated with the combination foam layer/Cu foil, as it occurs later when the foam length is longer, consistently with the increased delay of the Cu foil irradiation. These results are presently being analyzed by means of our LPI code in which the plasma density and temperatures profiles are imported from the radiation hydrodynamic calculations [10]. Our numerical results show the existence of a dip in the expansion flow spatial profile in the vicinity of the foam/Cu interface, resulting in a high SBS gain factor. The low SBS reflectivity is then being interpreted as due to the laser beam self-induced smoothing.

![Figure 4](image)

**Figure 4.** Temporal evolution of the SBS reflectivity inside the laser pulse in backward direction from three types of targets

4. Conclusion

In conclusion, the LIL experiment, in the multikilojoule regime, has demonstrated that the propagation of a laser beam through a thin (~ 500 µm), low density (~ 10 mg/cc), foam located in front of a solid target leads to an efficient beam smoothing and reduces the laser imprint consequently. These results show that it would be possible to design new ablators for direct-drive ICF targets with enhanced absorption and improved smoothing characteristics. The modification of SBS reflectivity from a Cu foil covered by the foam is another consequence of the beam smoothing effect.

Acknowledgments

The authors gratefully acknowledge the efficient participation of the CEA/DCRE group and LIL facility operating teams that made the success of these experiments. This work was partly supported by the ANR contract CORPARIN and by the computing centre IDRIS of the CNRS.

References

[1] Figueroa H et al. *Phys. Fluids* 1984 27 1887.
[2] Tanaka K A et al. *Phys. Fluids* 1985 28 2910.
[3] Koch J et al. *Phys. Plasmas* 1995 2 3820.
[4] Moody J et al. *Phys. Plasmas* 2000 7 2114.
[5] Limpouch J et al. *Plasma Phys. Controlled Fusion* 2004 46 1831.
[6] Labaune C et al. *C.R. Acad. Sci.* 2000 4 727.
[7] Maire P-H, Abgrall R, Breil J and Ovadia J *SIAM J. Sci. Comput.* 2007 29 1781.
[8] Depierreux S et al. *Phys. Rev. Lett.* 2009 102 195005.
[9] M. Grech et al., Phys. Rev. Lett. 102, 155001 (2009).
[10] Hüller S et al. *Phys. Plasmas* 2006 13 022703 ; *J. of Physics: Conf. Series* 112, 022031 (2008).