Optimization of some laser and target features for laser-plasma interaction in the context of fusion

S. Depierreux, C. Labaune\textsuperscript{1,2}, D.T. Michel, V.T. Tikhonchuk\textsuperscript{3}, V. Tassin, C. Stenz\textsuperscript{4}, N.G. Borisenko\textsuperscript{5}, W. Nazarov\textsuperscript{5}, M. Grech\textsuperscript{4}, S. Hüller\textsuperscript{6}, J. Limpouch\textsuperscript{7}, P. Loiseau, P. Nicolai\textsuperscript{8}, D. Pesme\textsuperscript{6}, W. Rozmus\textsuperscript{8}, C. Meyer\textsuperscript{9}, P. Di-Nicola\textsuperscript{9}, R. Wrobel, E. Alozy, P. Romary\textsuperscript{9}, G. Thiell\textsuperscript{9}, G. Soullié, C. Reverdin, B. Villette, M. Rabec-le-Gloahec\textsuperscript{7}, C. Godinho\textsuperscript{2}

CEA/DIF, BP 12, 91680 Bruyères-le-Châtel, France
1) Institut Lasers & Plasmas – Université Bordeaux 1, TALENCE cedex, France
2) LULI, Ecole Polytechnique, 91128 Palaiseau cedex, France
3) CELIA, Université Bordeaux 1, 351 cours de la Libération, 33405 Talence cedex, France
4) Lebedev Physical Institute, 53 Leninskiy Prospect, Moscow, 119991 Russia
5) University of StAndrews, Fife KY16 9ST, Scotland, UK
6) Centre de Physique Théorique, Ecole Polytechnique, 91128 Palaiseau cedex
7) FNSPE, Czech Technical University in Prague, 115 19 Prague 1, Czech Republic
8) Theoretical Physics Institute, University of Alberta, Edmonton T6G2G7, Canada
9) CEA/Cesta, BP 2, 33114 Le Barp, France
E-mail: sylvie.depierreux@cea.fr

Abstract. This paper presents experimental results obtained at LULI 2000 and LIL about (i) the compared laser plasma coupling at 526 (2\(\lambda_0\)) and 351 nm (3\(\lambda_0\)) and (ii) the early laser imprint suppression using foam targets as plasma smoother of the laser beam. Both experiments are described, part of the experimental results are presented and discussed.

1. Introduction
Two series of experiments have been conducted on complementary laser systems: (i) The LULI 2000 facility at Laboratoire pour l’Utilisation des Lasers Intenses (Ecole Polytechnique, France) and (ii) the LIL facility [1] at CEA/Cesta (Le Barp, France).

These experiments addressed two questions relevant to the nanosecond laser and target specifications in the context of direct drive compression of a fusion target: (i) optimum wavelength of the nanosecond compression laser and (ii) smoothing of the laser beams in the early stage of the laser pulse as to suppress seeds for the Rayleigh Taylor instability growth. This paper describes the two experiments. Experimental results and their preliminary interpretation are given.

2. The LULI 2000 experiment : laser plasma interaction at 526 and 351 nm
This part of our study uses the 2 beams of the LULI 2000 laser facility. Each beam delivers 300 J in a 1.5 ns square pulse after frequency conversion to the second or third harmonics of the 2 kJ Nd laser beams.

The experiment was designed as to specifically address the question of laser plasma interaction in fusion scale plasma at 526 and 351 nm. Such a question about the laser wavelength arises because,
from an optical point of view, the 2ω operation offers many advantages compare to the 3ω operation [2]: (i) increased optical damage threshold, (ii) lower growth rate for the damages after their creation and as a result (iii) lower operation costs and (iv) increased laser energy deliverable on target. On the other side, the laser plasma coupling seems more efficient at shorter wavelength because of (i) higher absorption rate [3], (ii) lower linear growth rate for parametric instabilities and (iii) increased implosion velocities as required for the classic direct drive compression scheme. For these reasons, the coming megajoule scale facilities in France (LMJ) and USA (NIF) have been designed for 351 nm operation. However, a detailed analysis for the specific case of mm scale plasmas as expected in megajoule fusion targets shows that the laser beams are totally absorbed before reaching their critical density either at 526 or 351 nm. Also, even if the linear growth rate (G ∝ n_i/λc^2) for parametric instabilities is higher at longer wavelength, these instabilities are expected to be in a saturated regime either at 526 or 351 nm in these mm scale plasmas [4,5]. In this specific case of high linear gains (>15), the instabilities will be saturated with a backscattering level fixed by the saturation mechanisms that may not depend on the initial interaction wavelength.

Thus, if the 3ω operation conserves its advantages for the classic direct drive scheme, the choice is less obvious for the indirect drive and fast ignitor schemes. More specifically, the fast ignitor scheme implies relaxed constraints on the implosion velocity because it does not rely on the creation and heating of a central hot spot. As a result, a 2ω operation could appear really suitable in the case of the HiPER laser facility [6]. The remaining question concerns the saturation levels for laser backscattering instabilities at the two wavelengths. In the LULI 2000 experiment, we have measured the saturated levels for the stimulated Brillouin backscattering (SBS) instability at 526 and 351 nm in a 1 keV plasma presenting an exponential density profile which contains the critical density at both wavelengths.

2.1. Description of the experiment

The experimental set-up is summarized in Figure 1. It has been designed for (i) a good 2ω/3ω comparison and (ii) reaching the SBS saturation regime at both wavelengths (G>30 for 2 and 3ω at maximum energy). The two beams are always fired at the same wavelength. The first beam (South) creates the plasma from a 50 µm thick CH foil. It is smoothed by a random phase plate with elements chosen as to produce a 300 µm focal spot after focusing by the 800 mm, f/4, lens. At the end of the South beam pulse, the North beam is fired, incident almost normal to the target surface, at 45° of the South beam. The interaction beam wave-front is corrected with an adaptive optics operated in the laser bay. The beam quality is further increased by reducing its aperture from f/4 to f/8. After focusing on target, the resulting spot size is 50 µm (containing 90% of the total energy). The maximum energy available on this interaction beam at 2 or 3ω is 110 J, corresponding to a maximum intensity at best focus of 3×10^{15} W/cm².

Figure 1: experimental set-up for the LULI 2000 experiment.

The backscattered light is collected in the incident interaction beam aperture and analysed by the backscattering station which measures the stimulated Brillouin scattering power and the time-resolved spectrum. This station is designed with reflective optics only as to minimize the reconfiguration time between the 351 and 526 nm experiments. Absolute in situ calibrations were performed at both wavelengths.
2.2. Experimental results
The stimulated Brillouin backscattering levels in the saturated regime are ~ 7-10 % either at 526 or 351 nm. The saturation occurs for interaction beam intensities of ~ 5×10^{14} W/cm^2. The Brillouin backscattered light wavelength is plotted as a function of time for the 2ω and 3ω experiments and compared to linear SBS gain calculations (PIRANAH) on figure 2. These plots correspond to an interaction beam intensity of 5×10^{15} W/cm^2 at 3ω and 4×10^{14} W/cm^2 at 2ω. At both wavelengths, the SBS light is blueshifted indicating that the Brillouin instability developed in the expanding underdense plasma. The narrow SBS spectra measured at 526 and 351 nm indicates that SBS is growing over a localized region which is identified as a local velocity minimum that forms in the velocity profile. Such a hydrodynamics feature is typical of direct drive interactions after the laser intensity ramps from low to high power [5,7]. A good agreement is found between the PIRANAH calculations and experimental measurements. The difference observed at 2ω may be due to a degraded propagation of the 2ω beam which is not included in the PIRANAH calculation. Further investigation is in progress with the 3D paraxial code HERA.

![Figure 2: SBS wavelength as a function of time compared to linear gain calculations (PIRANAH).](image)

3. The LIL experiment: plasma smoothing of the laser beam in foam targets
This experiment uses the four beams of the first quad of the LIL laser facility. For this experiment, the quad delivers ~ 10 kJ at 351 nm in a 2.7 ns square pulse.

The purpose of this experiment was to test a new concept for smoothing the laser beams in the early stage of the laser pulse. Such an early smoothing is necessary because: (i) at the very beginning of the pulse, the laser directly heats the target surface where the ablation and critical surfaces are superimposed and (ii) the instantaneous SSD focal spot has a 100% contrast [8].

The proposed smoothing scheme [9] uses a low density foam (underdense to the laser beam, ρ < 30 mg/cc) inserted in front of the capsule. The foam is directly heated by the laser which launches a supersonic ionization wave. The foam ionization results in an underdense plasma with small scale inhomogeneities. This plasma is very efficient in smoothing the laser beam as soon as its length exceeds a few tenth of μm. The need for a supersonic ionization wave implies a condition on the minimum laser intensity (minimum plasma temperature) and the maximum foam density [10]. The combination of a 10 mg/cc foam density with a few 10^{14} W/cm^2 theoretically leads to an ionization wave supersonic for more than 1 ns which corresponds to a propagation length of ~ 500 μm. These parameters have been chosen for the LIL experiment. The specific goals of this experiment, which will pursue with further shots in the coming months, were (i) to test the effectiveness of the foam for laser plasma smoothing, (ii) to measure the foam ionization energy budget, (iii) to evaluate backscattered light levels with the foam present, (iv) to observe the propagation of the ionization front.

The experimental set-up is shown in Figure 3. It uses five complementary diagnostics available on the LIL facility as to address the questions previously listed. A series of six shots have been obtained over a period of two weeks on the LIL facility. The targets were either foam alone, composed target containing a foam plus a Cu foil on its back surface or Cu foil alone. The different diagnostics provide
consistent information about the laser propagation through the foam. They all indicate that a 500 µm long, 10 mg/cc foam is fully ionized in 1.2 ns. The time resolved SBS spectrum measured on a composed target (500 µm foam + Cu) is shown in Figure 4. It presents two features separated in time by 1.2 ns. They correspond to SBS from the foam (early time) and then SBS from the Cu foil when the foam is fully ionized. SBS from the foam is red-shifted by 6 Å which corresponds to an electron temperature of 1.3 keV assuming a homogeneous foam plasma (no plasma flow). The foam smoothing effect has been directly evidenced by (i) direct imaging of the foil emission in the focal plan with DP 1.06, (ii) direct measurement of the angular distribution of the beam transmitted through the foam with DP 1.03.

![Figure 3: experimental set-up for the LIL experiment](image)

**Figure 3: experimental set-up for the LIL experiment**

![Figure 4: SBS spectrum measured on a Cu + 500 µm foam composed target and SBS signal as function of time.](image)

**Figure 4: SBS spectrum measured on a Cu + 500 µm foam composed target and SBS signal as function of time.**

Further shots on this topic will be devoted to measurement of the ionization front propagation and evaluation of the foam smoothing scheme at lower foam density and lower laser intensity. Other shots will be made as to quantify the laser backscattering instabilities (i) without dopant added to the foam material, (ii) in three complementary targets consisting of foam, foam + foil and foil alone.

**Acknowledgments**

The authors gratefully acknowledge the efficient participation of the LIL and LULI 2000 facilities operating teams that makes the success of these two experiments.

**References**

[1] J.M. Di-Nicola et al., J. Phys. IV France 133, 595 (2006)
[2] H. Bercegol et al, Proc. of SPIE, Vol. 5273, 312 (2004)
[3] C. Labaune et al., Phys. Rev. Lett. 48, 1018 (1982).
[4] B. J. MacGowan et al., Phys. Plasmas 3, 2029 (1996)
[5] J.C. Fernandez et al., Phys. plasmas 4, 1849 (1997) - 7, 3743 (2000)
[6] HiPER technical report
[7] J. Myatt et al., Phys. Plasmas 11, 3394 (2004)
[8] D.H. Kalantar et al, Phys. Rev. Lett. 76, 3574 (1996)
[9] J. Limpouch et al, Plasma Phys. Control. Fusion 46, 1831-1841 (2004) and references therein
[10] A. Caruso et al., Journal of Russian Laser Research, vol. 18, 5, 464 (1997).