Laser Smoothing and Imprint Reduction with a Foam Layer in the Multikilojoule Regime

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This Letter presents first experimental results of the laser imprint reduction in fusion scale plasmas using a low-density foam layer. The experiments were conducted on the LIL facility at the energy level of 12 kJ with millimeter-size plasmas, reproducing the conditions of the initial interaction phase in the direct-drive scheme. The results include the generation of a supersonic ionization wave in the foam and the reduction of the initial laser fluctuations after propagation through 500 μm of foam with limited levels of stimulated Brillouin and Raman scattering. The smoothing mechanisms are analyzed and explained.

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Inhomogeneities of the intensity distribution of the incident laser beam can be a source of fast growing perturbations of the target shell during the acceleration and deceleration phases of direct thermonuclear target compression [1]. Development of efficient and robust methods of control of Rayleigh-Taylor instabilities is one of the outstanding problems in inertial confinement fusion (ICF). The diffusive heat conduction smooths the ablation pressure front and ensures its homogeneity if the distance between the ablation and the absorption surfaces, D_{ac}, is larger than the perturbation wavelength λ_p [2] and if the heat diffusion time is larger than the laser beam correlation time [3]. The most dangerous intensity perturbations are those during the first few hundreds of picoseconds of the laser pulse, when the thickness of the heat conduction zone is very small and the temporal beam smoothing is not yet efficient. This is the so-called problem of "laser imprint" [4], where the initial laser pulse intensity fluctuations are imprinted in the target shell and are amplified later on, during the acceleration and deceleration phases. Optical smoothing techniques are inefficient to avoid this early imprint because the instantaneous laser intensity distribution always remains highly nonuniform and fast variation of the laser intensity distribution requires a very large laser bandwidth [3].

To reduce the laser imprint, it has been suggested to cover the target shell with an overcritical foam through which a supersonic heat wave was created by an x-ray flash [5]. This supersonic heat wave enabled the creation of a conduction zone (D_{ac} almost set by the foam thickness, typically of a few tenths of microns) before the laser reached the target, thus ensuring the thermal smoothing of perturbations of the ablative pressure with wavelength $\lambda_p < D_{ac}$. Although this idea was confirmed in experiments [6], it has been abandoned because the x-ray flash introduced undesired entropy in the fuel and spoiled the compression efficiency.

The idea of the approach presented in this Letter is to use a foam not for smoothing the pressure inhomogeneities directly, but the laser intensity itself. In this new scheme, a low-density (undercritical) foam is ionized directly by the laser beam. It is important to choose the interaction parameters so that the ionization wave in the foam is supersonic [7], thus avoiding the creation of pressure perturbations at the ablation surface. This idea follows from plasma induced beam smoothing that has been observed in different experiments [8] and interpreted with theory and simulations [9]. Two plasma-smoothing regimes have been identified: at high intensity, the combination of filamentation, self-focusing (SF) and the filament instability (FI), and at low laser intensity, stimulated forward Brillouin scattering (FSBS), are responsible for the smoothing effect [10].

The purpose of the experiments presented in this Letter is to test this type of smoothing under conditions close to those anticipated with the Laser MegaJoule (LMJ) and to demonstrate how it can provide a reduced imprint of the laser inhomogeneities while reflectivities associated with parametric instabilities were kept at an acceptable level. The results demonstrate for the first time the smoothing of initial intensity perturbations of a multikilojoule laser beam by propagation through a few hundreds microns of a low-density (<10 mg/cc) foam layer and its consequence on the reduction of ablation pressure inhomogeneities on a foil with limited levels of stimulated scattering.

The four beams of the LIL (Ligne d'Integration Laser) laser were used to irradiate a target composed of a thick foil with a low-density material deposited on it. The scheme of the experiment is shown in Fig. 1(a). The total laser energy was 12 kJ in 2.7 ns square pulse at the wavelength 351 nm. Each beam in the quadruplet had a square shape of 36 cm in the near field, and they were focused all together with an optical system of 8 m focal length through random phase plates (RPP). In purpose, we used a narrow laser bandwidth of 2 GHz created by the SSD (smoothing by spectral dispersion [11]) which is set up to suppress stimulated Brillouin scattering in the laser optics. The target was placed 5 mm in front of the focal plane to increase the beam spot size and to produce large-scale inhomogeneities ($\sim$ few tenths of μm) of intensity due to a slight separation of the four beams as shown in Fig. 1(b). The shape of the focal spot was approximately a square of 1 mm side and the average intensity was $\langle I \rangle \sim 4 \times 10^{14}$ W/cm^2. Shots used alternatively thick copper foils (10 μm thickness), foams, and composed targets (foam + foil). The foams were low-density polymer $C_{15}H_{20}O_6$ with small ($\sim$1 μm) cell structures. They were doped with 1% Cl to increase the x-ray emissivity for diagnostic purposes. The foam was hold in a cylinder of 2.5 mm in diameter and 0.5–1 mm long supported by a washer of a 6 mm diameter with a 1 mm slit for side view diagnostics, as shown in Fig. 1(c).

Five diagnostics provided complementary informations on the laser propagation through the foam. The space and time-resolved evolution of the side x-ray emission was recorded to measure the velocity of the ionization front in the foam. The smoothing effect was studied with (i) temporally resolved two-dimensional x-ray images of the foil emission with an eight-frame camera and by (ii) measurements of the angular distribution of the beam transmitted through the foam. The intensity, spectral and angular distribution of stimulated Brillouin and Raman scattering were measured in backward and near backward directions as well as the total energy budget.

The first result concerns the speed of the ionization process. The foam density was chosen according to numerical simulations carried out with the nonlinear hydrodynamic code CHIC [12] which indicated that a combination of a 10 mg/cc foam density with a few 10^{14} W/cm^2 irradiation intensity provided a supersonic ionization wave, sustained for more than 2 ns, with a velocity exceeding 0.5 mm/ns. The temporal evolution of the x-ray emission as a function of the distance along the target is shown in Fig. 2(a) for a target composed of 950 μm of 10 mg/cc foam in front of a copper foil. Because of partial absorption of the laser light in the foam plasma, the front velocity, shown in Fig. 2(b), decreased as a function of time from 0.7 mm/ns initially to 0.4 mm/ns at the moment when it arrived at the rear side of the foam. It significantly exceeded the acoustic velocity, $c_s \sim 0.32$ mm/ns, which was deduced from the trajectory of the rarefaction wave front in Fig. 2(a). This value agrees well with the electron temperature $T \sim 1.8$ keV estimated from the stimulated Brillouin scattering spectra and from the energy balance, as well as from the hydrodynamic simulations. This result demonstrates the supersonic

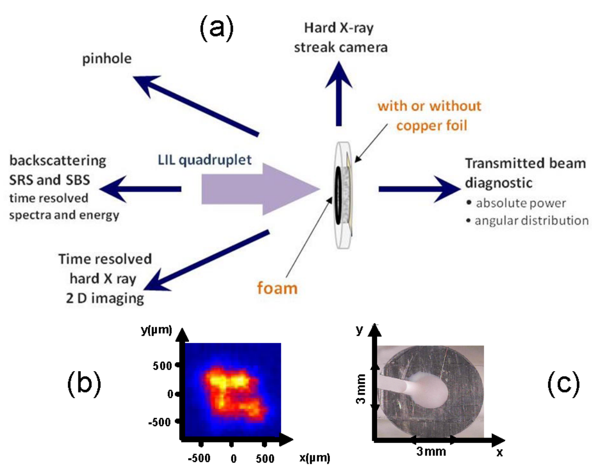

FIG. 1 (color online). (a) Scheme of the experiment with the main diagnostics. (b) Far field image of the laser beam at the target plane. (c) View of a foam target with the support and a slit for side observations.

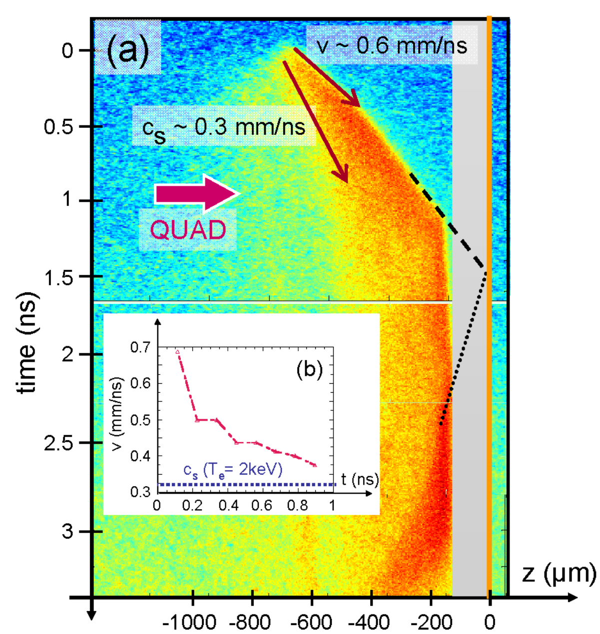

FIG. 2 (color online). (a) Time-resolved x-ray emission from the foam along the direction of propagation, showing the propagation of the ionization front. (b) Temporal evolution of the ionization front velocity as extracted from panel (a).

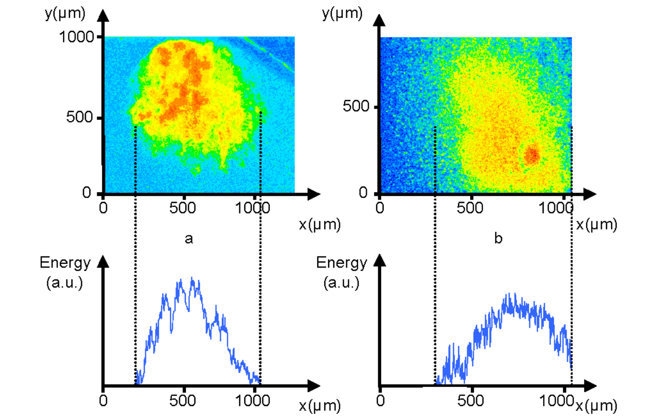

FIG. 3 (color online). 2D x-ray images of the Cu foil emission integrated over 200 ps and recorded at the very beginning of the emission. (a) Cu foil alone; (b) Cu foil +500 μm of foam.

propagation of the ionization wave, which is supported by a direct laser energy deposition at the ionization front. This ionization front velocity is approximately the same as the one measured on the PALS laser facility [13] for similar irradiation conditions, but with a shorter pulse duration of 350 ps.

The observation of the laser intensity smoothing came first from the x-ray framing images of the emission of the copper foil placed behind the foam. Two images of a copper foil alone and of the same foil covered with 500 μm of 10 mg/cc foam are presented in Fig. 3. The images are integrated over 200 ps and are recorded at the very beginning of the foil emission, i.e., when the laser beam reached the foil. With no foam, Fig. 3(a), at the beginning of the laser pulse, $t = 0$, we observe large intensity fluctuations with same spatial scale as in the focal spot distribution in vacuum [see Fig. 1(b)]. The foam, Fig. 3(b), becomes transparent for the laser beam after 1.2 ns which is in agreement with both the previously discussed result and the time-resolved transmitted light through a free standing foam target and with CHIC simulations. The copper foil emission behind the foam plasma is much smoother than in the previous case. The inhomogeneities of size $\sim$50 μm have been removed, and the amplitude of small-scale fluctuations was strongly reduced.

The modification of the angular distribution of the transmitted laser beam confirms the foam spatial smoothing effect. In Fig. 4, the time-integrated forward near field images of the beam are compared for vacuum, Fig. 4(a), and after propagation through 900 μm of 6.5 mg/cc foam, Fig. 4(b). In vacuum, the four beams of the quadruplet are clearly separated, each having a divergence of 2.6°. After propagation through the foam, the angular divergence has increased by more than 2 times as compared to vacuum and the overall large-scale contrast of the intensity distribution was strongly reduced to the level of less than 10% inside and outside the beam area.

An important concern with such a smoothing technique was the possible growth of stimulated Brillouin and Raman scattering in the quasihomogeneous plasma produced from the foam. The detailed analysis of stimulated Brillouin and Raman backscattering showed that the reflectivity levels

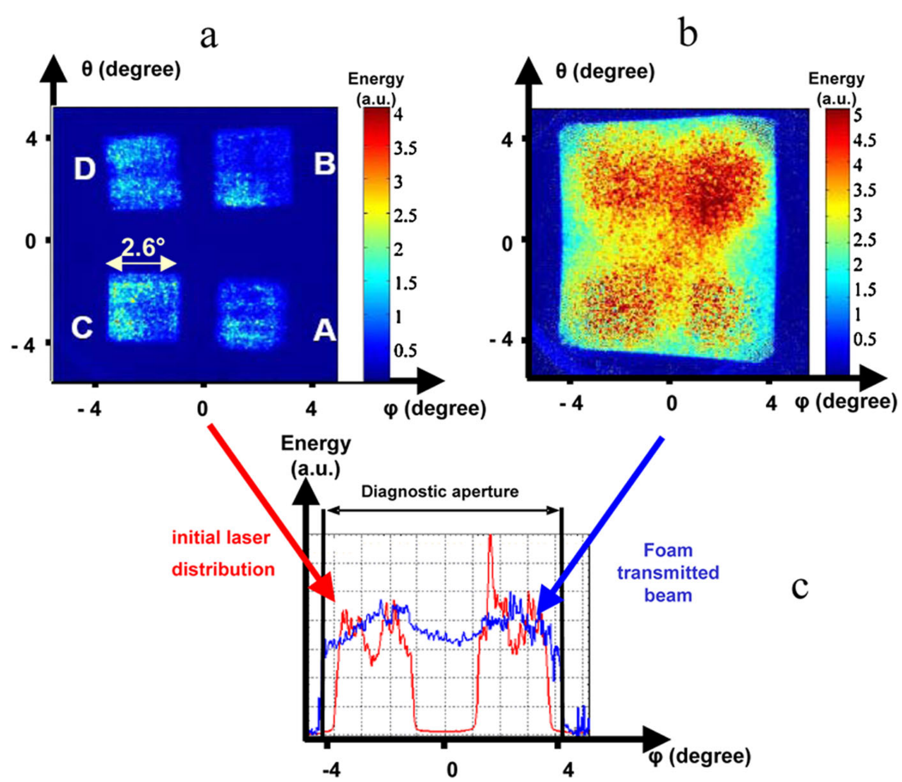

FIG. 4 (color online). Time-integrated near field images of the laser beam. (a) in vacuum; (b) after propagation through the 900 μm long, 6.5 mg/cc, foam.

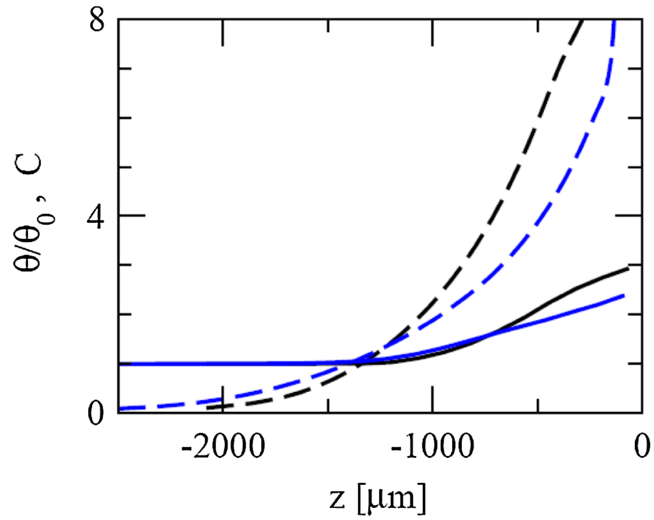

FIG. 5 (color online). Numerical evolution of (i) the laser aperture angle θ normalized to the incident aperture θ_0 (solid curves) as a function of the propagation distance (z) at two different times: $t = 100$ ps (black) and 500 ps (blue) after the laser burnthrough; (ii) the figure of merit for collective FSBS as introduced in Ref. [14]: $C = \eta(P/P_C)(\omega_s/\gamma_s)$ (dashed curves). FSBS-induced beam spray is expected to happen for $C > 1$. The foam density is 10 mg/cc.

were below 8% and 4%, respectively. These levels of backscattering are affordable because they concern only a small part of the laser energy at the beginning of an ignition pulse. The detailed energy balance shows that around 1 kJ of laser light was needed to ionize and heat a foam volume of 0.5 mm^3. Approximately 70% goes into the plasma internal energy, 15% in its kinetic energy, and 15% is radiated. Therefore such a smoothing technique requires about 12 kJ of laser energy for a 1 mm radius target, which is a relatively minor part of the energy budget in an LMJ-scale experiment.

We estimated that beam smoothing due to multiple scattering on either decaying density fluctuations produced in the homogenization stage of the foam ionization or density perturbations driven by the speckles themselves was marginal. Indeed, the ion acoustic waves damping in $C_{15}H_{20}O_6$ foam plasma is mainly due to collisions between the heavy carbon and oxygen ions and to Landau damping from the light hydrogen ions. Under our experimental conditions, the normalized ion acoustic damping rate for wavelength of a few microns, which are of interest for the observed smoothing, is $\gamma_s/\omega_s \sim 0.1$. The ion acoustic perturbations are therefore damped in a few periods. Considering wave period of $\sim$10 ps, their damping time is of the order of 100 ps, which is much shorter than the foam burnthrough time. These fluctuations therefore exist only in a very close vicinity of the ionization front. Assuming that this front propagates toward the foil with a velocity of the order of 0.5 mm/ps, one can estimate this region to have a width of $\sim$50 μm. On such a distance, strong density perturbations ($\delta n/n_c \sim 0.15$) might contribute to the beam angular spreading and consequently to the homogenization of the ionization front. However, their effect is not maintained on a time long enough to allow the laser beam smoothing to be efficient during the few hundred picoseconds after the foam burnthrough required to create the conduction zone in the foil.

Plasma induced smoothing can also follow from laser light multiple scattering on laser induced density perturbations due to FSBS, FI or the speckle SF. The relative importance of each of these processes depends on the ratio of the average power in a speckle P to the critical power for SF [14] $P_C = 34(1 - n_e/n_c)^{1/2}(n_e/n_c)^{-1}T_{\text{kev}}$. For an electron density of $(0.25\text{–}0.35)n_c$, estimated from the complete ionization of the foam, and a plasma temperature $T =$ 1.8 keV, we find a critical power $P_c = 136$ MW for a foam density of 10 mg/cc and 246 MW for a density of 7 mg/cc. The speckle pattern was calculated using the code MIRO in which the real laser parameters were introduced. Because of defocusing, two speckle mean radii coexist in the focal volume: $\rho = \lambda_0 f \sim 7.8$ and 3.1 μm for $f \sim 22.2$ and 8.9, respectively, corresponding to independent or superimposed beams [15]. The corresponding average powers in a speckle were $P = \rho^2\langle I\rangle \sim 240$ MW and 38 MW. Most of the speckles in the first case carry a power above the critical power P_C and are unstable with regards to SF and FI. Strong SF and associated beam spray are therefore expected. In the second case, $P \sim 38$ MW $\sim$ (15%–28%) P_C. In this regime, plasma induced beam-smoothing follows from collective FSBS. It is shown in a recent work [16] that spectral broadening and beam spray occur if $\eta(P/P_c)(\omega_s/\gamma_s) > 1$, where the factor $\eta \sim (2\text{–}8)$ accounts for both ponderomotive and thermal effects on the excitation of acoustic waves by the laser. This criterion is satisfied for our conditions.

Three-dimensional simulations with the laser-plasma interaction code PARAX [17], using plasma parameters provided by the code CHIC, confirm the effect of both SF and FSBS on the induced spatiotemporal incoherence of the laser light. As can be observed in Fig. 5, the power threshold is strongly exceeded for our experimental conditions and the beam angular aperture is increased by a factor 2–3 during the beam propagation. The reduction of the spatial coherence of the laser light allows smoothing of structures with wavelengths larger than a few microns while the broadening of the temporal spectrum (up to $c_s/\rho' \sim 80$ GHz) provides a homogeneous fluence of the transmitted light. Moreover, hydrodynamic simulations show that a conduction zone in the CH foil with a width $D_{ac} \sim 40$ μm was created 600 ps after the burnthrough (similar results have been obtained in Ref. [5]). It was observed in our simulations that the smoothing remained efficient until this time.

In conclusion, we have reported the first observation of laser beam smoothing and reduced imprint in the multikilojoule regime, using a thin (~500 μm) low-density (~10 mg/cc) foam in front of a solid target. The supersonic ionization wave propagates faster than the shock and reduces the pressure fluctuations at the ablation surface. The foam plasma provides laser beam smoothing before the absorption zone and a homogeneous ablation pressure during the time of foam decay. This time is long enough for creating the thermal conduction zone inside the target. It has also been demonstrated that stimulated scattering reflectivities remained at an acceptable level. These experimental results validate a new scheme for direct-drive ICF targets where a thin layer foam reduces the laser imprint.

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