Smoothing of laser beam intensity fluctuations in low density foam plasmas with the LIL laser

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Intensity fluctuations of high-energy laser beams present a danger for efficient compression and ignition of the target in the direct-drive scheme for inertial confinement fusion (ICF). Temporal smoothing techniques become operational only after several hundred picoseconds and inhibition of the effect of initial laser intensity perturbations on the ablation pressure remains therefore a crucial problem for target design. This paper presents the first experimental results on the laser imprint reduction in fusion scale plasmas using a low-density foam layer. Experiments were conducted with the LIL laser facility using a pulse energy of 12 kJ with millimeter-size plasmas. The configuration used in the experiment reproduces well the initial phase in the direct-drive scheme. The experimental results demonstrate efficient laser energy absorption in the foam, supersonic propagation of the ionization wave, and an efficient smoothing of the laser beam.

The development of efficient and robust methods for controlling Rayleigh-Taylor instabilities relains an outstanding problem in ICF. The diffusive heat conduction smoothes the laser intensity fluctuations and assures a homogeneous ablation pressure if the distance between the ablation front and the absorption surface is larger than the perturbation wavelength and if the time is longer than the laser beam correlation time. Therefore the most dangerous intensity perturbations are those during the first few hundreds of picoseconds of the laser pulse, when the heat conduction distance is very short and the temporal beam smoothing is not yet operational.

Smoothing of the laser intensity distribution by propagation through a plasma, called plasma-induced smoothing, is by now well established experimentally [1], in the theory and in simulation [2]. It has been demonstrated in small scale systems that the spatial and temporal coherence of a laser beam was strongly reduced after propagation through a plasma of a few hundreds of microns length [3]. It has been observed that the inhomogeneities in the initial beam were reduced and its intensity distribution smoothed [4]. Two fundamental regimes have been identified: at low laser intensity, multiple scattering on small self-induced density perturbations and, at higher laser intensities, forward scattering processes, such as filamentation, self-focusing and stimulated forward Brillouin scattering.

It had been proposed and was verified experimentally [5] that employment of a high-Z material allows to produce a short X-ray flush which subsequently ionizes the foam. However, this approach introduces undesired entropy in the fuel and affects its compression. In the approach presented in this paper the foam is ionized with the laser itself. This requires the ionization front to penetrate into the foam with a supersonic velocity, as otherwise the pressure perturbations created on the absorption surface will be transported to the shell with the inward travelling shock. Intensity, foam length and density have to be specifically arranged in order to attain the regime where the ionization wave is supersonic [6].

In the experiment four beams of the first quadruplet of the LIL laser were used to irradiate through a random phase plate a target composed of a thin copper foil on which a low density polymer-foam, $\rho \sim 10$ mg/cc was deposited. The laser energy of 12 kJ at the wavelength 351 nm delivered in a 2.7 ns square pulse. The focal spot was roughly a square of 1 mm side and the average intensity was $3.3 \times 10^{14} \mathrm{W/cm^2}$. The foam was doped with chlorine to enhance X-ray emissivity for diagnostic purposes. The main diagnostic employed was space and time-resolved X-ray emission to measure the velocity of the ionization front. The foam smoothing effect was studied with temporally resolved 2D X-ray images of the foil emission in the focal plane and by measuring the angular distribution of the beam transmission through the foam.

The first principal result of the experiment is the confirmation that the supersonic regime of foam ionization was attained. The combination of the above specified laser intensity and a the foam of 950 μm length created a supersonic ionization wave for more than 1 ns for a propagation length of 500 μm. The initial propagation speed of 0.7 mm/ns is continually reduced to 0.4 mm/ns by the time the wave reaches the rear side of the foam, see Fig. 1. Even the final value is larger than the acoustic velocity, $c_s \simeq 0.25$ mm/ns, which is deduced from the rarefaction wave front and corresponds to an electron temperature of less than 2 keV. This value agrees with the estimate obtained from stimulated Brillouin backscattering spectra.

Due to the long pulse duration, the ionization wave proceeds in isothermal conditions. The decrease of the ionization velocity is related to multiple scattering on large density fluctuations in the foam plasma and the laser energy bremsstrahlung absorption. Energy balance estimates show that about 5 kJ of the total energy is used for ionization, an amount which is negligible in ICF-context. The resulting plasma density is of the order a quarter of the critical density.

Confirmation of the smoothing effect stems from two observations: the laser intensity distribution in the far field and the laser beam angular spreading. The two-dimensional time-resolved X-ray images of the copper foil show that without foam the spatial scale of the intensity fluctuations is the same as in the focal spot distribution. In the shot with a foam the large-scale inhomogeneities of size 50 μm have been removed, and the amplitude of small-scale fluctuations is strongly reduced. Angular broadening is observed in time-integrated near-field images of the quadruplet. In vacuum the four beams of the quadruplet are clearly separated whereas with foam the angular divergence is increased by more than two times, causing the individual beams to overlap. The overall large-scale contrast of the intensity distribution is strongly reduced to the level of less than 10% inside and outside the beam area.

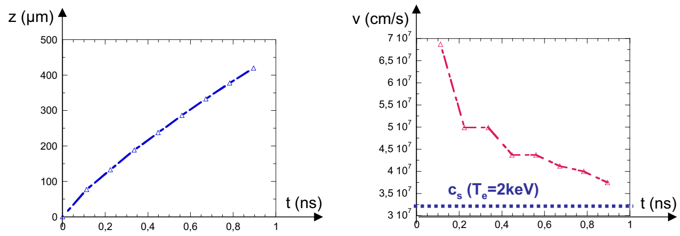

Figure 1: Time dependence of the position of the ionization front (a) and the ionization front velocity (b) for the laser pulse interaction with a 10 mg/cc foam target.

Three possible sources for the smoothing effect by the plasma are considered. The first is speckle self-focusing which causes the laser beam to filament and thereby broadens the light spectrum. No diagnostic was on place to measure this effect. The second mechanism may be called ionization smoothing induced by multiple scattering of the laser light on the decaying density fluctuations produced during the homogenization stage of foam ionization and plasma expansion. Finally there is multiple scattering on the self-induced density fluctuations and the associated forward stimulated Brillouin scattering (FSBS).

The critical power for ponderomotive self-focusing is given by: $P_c = 34\sqrt{1-n_e/n_c}T_e[keV]/(n_e/n_c)$MW. For the laser/plasma configuration employed the critical power amounts to 136 MW, which has to be compared to the power in the average speckle of 78 MW. Speckle self-focusing is therefore likely to play a role as $P_{sp}/P_c \sim 0.3-0.6$. Due to the intensity distribution of a RPP beam there are definitely speckles with intensities $2-3$

times above the average. They become unstable and filament.

Density fluctuations with a wavelength of a few microns which scatter the laser light in a cone of about 10° are not related to foam remnants. The ion collision time is about 100 ps and the ion mean-free-path of the order of $10-30\ \mu$m. Therefore the density perturbations of interest in the conditions of the experiment are collisionless and subject to Landau damping. For a temperature ratio $ZT_e/T_i < 6$, the ion-acoustic damping parameter is $\gamma_s/\omega_{cs} > 0.1$, and the perturbations are damped in a few periods. As the wave period is about 10 ps the damping time is not more than a 100 ps. As this time is much shorter than the foam burnthrough time, such fluctuations can only exist in the vicinity of the ionization front.

Multiple scattering of laser-induced fluctuations leads to smoothing distances of 0.5 mm for a density of the order of $0.1n_c$ and fluctuation amplitudes of $\sim 10\%$. However, the amplitude of ponderomotively driven fluctuations is only about 1% for the mean laser intensity. The difference is accounted for by nonlocal effects as the electron mean-free-path, 10μm, is much larger than the perturbation wavelength.

In conclusion it has been shown that correctly designed foam targets together with a supersonic ionization regime can efficiently smooth laser beams under realistic ICF-conditions.

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