FUNDAMENTAL EXPERIMENTS ON HYDRODYNAMIC INSTABILITY IN DIRECT-DRIVE LASER FUSION AT GEKKO XII

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Abstract

A series of elementary experiments on the hydrodynamic instability in the inertial confinement fusion have been conducted at the GEKKO XII laser system. Perturbation growth of the target areal density due to the rippled shock wave driven from the perturbed surface and/or by nonuniform laser illumination has been extensively investigated to show an analytic model of imprint well predicts the experimental results under the condition that (perturbation wavenumber) x (thickness of the shock compressed region) < 1. Deformation of the laser illumination surface fed by the perturbation on the rear surface was examined using a planar target with flat (front) and corrugated (rear) surfaces. The displacement of the ablation front is quantitatively explained by the perturbation on the arrival time of the rippled rarefaction wave and that on the subsequent acceleration. Linear growth rate of the Rayleigh-Taylor instability has been measured for the various conditions to confirm the effect of the nonlocal electron heat conduction.

1. INTRODUCTION

Hydrodynamic instabilities, such as the Rayleigh-Taylor (R-T) instability, play a crucial role in inertial confinement fusion (ICF) as they finally cause fuel-pusher mixing that potentially quenches thermonuclear ignition. The implosion process of a typical direct-drive ICF target is roughly divided into three phases: initial phase, acceleration phase and deceleration phase. In the initial phase, first shock wave is travelling in a fuel capsule and the fluid in the capsule is accelerated mainly by the shock wave. The shell is ablatively accelerated inward in the second phase. Then, fuel is compressed heavily in the deceleration phase.In the initial phase, perturbations on the target surface are seeded by initial imprint due to laser irradiation nonuniformity, along with the original target surface roughness. These perturbations are accompanied by rippled shock propagation before the shock breaks out on the inner surface of the fuel capsule, and farther accompanied by rippled rarefaction propagation. The perturbations grown on the outer surface due primarily to the R-T instability in the second (acceleration) phase are then fed through on the inner surface. These, together with the initial inner surface roughness, will grow again during the deceleration phase, resulting finally in mixing between the hot spark and the main fuel, which could quench the ignition and burn. Thus, good understandings of the perturbation growth by the rippled shock and rarefaction ("Start-up problems") and the instabilities in the acceleration phase are necessary to limit the mixing within a tolerable level.

A series of experiments [1] has been conducted on the GEKKO XII laser facility to investigate the hydrodynamic instability growth in planar foils directly irradiated by 0.53-μm laser light. In this report, we will present accumulated database on the perturbation growth in the initial phase (Start-up problems) and the acceleration phase. Levels of laser imprint with various spatial and temporal frequencies of perturbations are evaluated as the “imprint efficiency”. Perturbation growth of the ablation surface due to the returned rarefaction from the corrugated rear surface (“Feed-out effect”) is reported. Parameteric study of R-T instability in the acceleration phase is also presented to show the reduction of the growth rate due to ablation stabilization enhanced by nonlocal heat transport [2].

2. START-UP PROBLEMS

In the initial phase, according to the surface roughness and non-uniform laser irradiation, the shock wave driven from the laser illumination surface and the returned rarefaction wave propagates rippling and leaves the areal density and also momentum perturbations in the shell [1,3]. The perturbation given to the shell is amplified by the subsequent Rayleigh-Taylor instability in the acceleration phase. Therefore, it is required to know how much perturbation is seeded in this phase as an initial condition for the subsequent R-T instability in the second phase. Especially it is of great interest to know how the laser illumination nonuniformity is converted into the ablation surface perturbation.

2.1. Initial imprint of laser illumination nonuniformity

Flat plastic foils were irradiated with the partially coherent light (PCL) pulse of 0.527-μm wavelength with 0.26-nm bandwidth on which a spatial nonuniformity [4] with the sinusoidal shape was imposed at an averaged intensity of (0.5 -1.0) x 10^{13} W/cm^2. The targets were accelerated subsequently by a uniform main laser pulse of 7 x 10^{13} W/cm^2 and imprinted perturbations were amplified by the R-T instability to be observed with the face-on x-ray backlighting technique. The initial imprint by single-mode static nonuniformity is reasonably explained by an imprint model [1] based on a linear perturbation analysis in which the pressure perturbation is smoothed by the cloudy-day effect. In order to compare the imprint level to the initial surface roughness of the target, “imprint efficiency”, which was defined as the equivalent target roughness divided by the target thickness and intensity modulation depth ($\delta I/I$), was figured out to be 0.02 to 0.08 in the wavelength range of 20 to 100 μm in our experimental condition (Fig. 1). Solid line in the Fig. 1 denotes the model calculation [1], which shows good agreement with the experimental data (solid circles) for the wavelength longer than 30 μm. This is consistent with the result of comparison of the model with the linear perturbation analysis by Ishizaki et al. [5], which predicts that our model overestimates the imprint for the case where (perturbation wavenumber) x (thickness of the shock compressed region) > 1.

Although, in the above experiment, spatial profile of the laser illumination distribution was fixed in time. That in the real situation using the smoothing techniques such as SSD is temporally varying. To address the question about required laser bandwidth for optical smoothing, we have

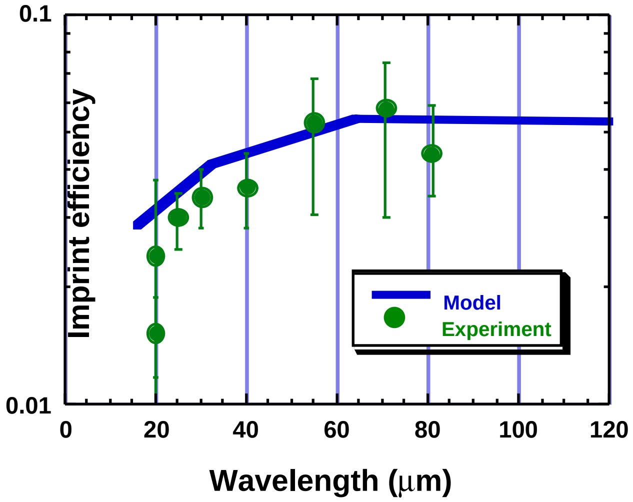


Fig. 1. Imprint efficiency was measured to show the validity of the imprint model for the stability analysis based on a one-dimensional computer simulation.[1]. Solid circles are the experimental results with 1.0-ns foot pulse and solid line denotes the calculated values for the experiment.

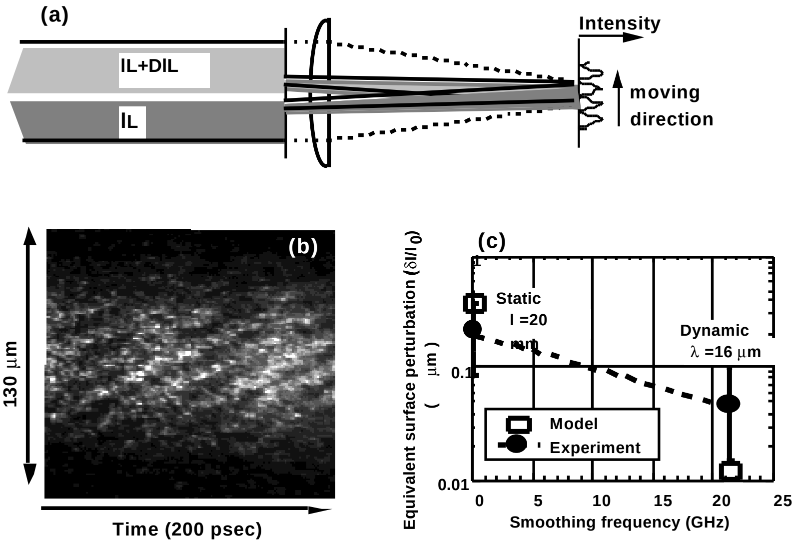
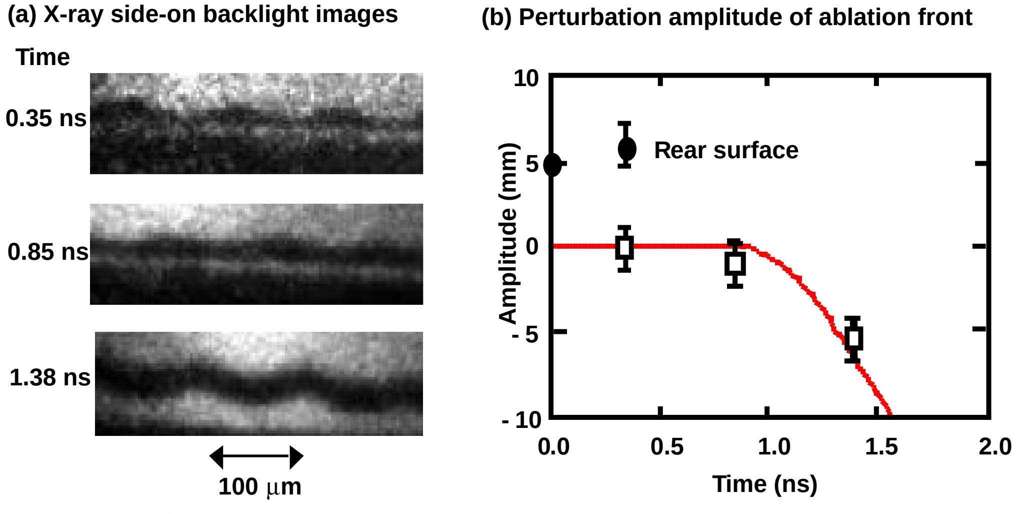


FIG. 2. (a) Setup of Young's interferometer with two different laser wavelengths, constructing moving interference fringe. (b) A streak record of the focal pattern on the target plane. Tilted lines are the moving fringe. (c) Deduced areal-mass perturbation divided by the instantaneous nonuniformity vs smoothing frequency. The target was a flat 2,2,2-poly-trifluoroethyl-methacrylate (PTFMA) foil with a 9-µm thickness.

started new experiments on the dynamic imprint by moving single-mode nonuniformity. The nonuniformity was constructed by Young's interference as was done in Ref.[6] but with two different laser wavelengths, as shown in Fig. 2 (a). Two laser beams each transmitted through a different rectangular aperture (8-mm wide and 10-mm high) construct interference fringes at the target plane. Due to the difference in the wavelength, the interference fringes move in a direction perpendicular to the fringe ridge. Figure 2.(b) clearly shows the moving interference fringe on the target plane. A single-mode imprint perturbation with 16-µm spatial wavelength was significantly suppressed for the moving nonuniformity with a 47-ps cycle(Fig. 2.(c)).


(a) X-ray side-on backlight images

(b) Perturbation amplitude of ablation front

FIG. 3. Feed-out effect has been examined by using a planar polystyrene target with sinusoidal corrugation on the rear surface. Perturbations of the laser irradiated surface and the rear surface were observed by the x-ray side-on backlight method (a). A 25-mm thick polystyrene foil with the perturbation wavelength of 100 µm and the initial amplitude of 5 µm was accelerated by the flat-topped laser pulse with 2.3-ns F.W.H.M. at the intensity of 6 x 10^{13} W/cm^2. (b) Evolution of the front surface(rectangular plot) was well reproduced by a simple calculation of the delayed acceleration(solid line).

2.2. Rippled rarefaction

After the first shock wave has arrived at the rear surface of the target, a rarefaction wave propagates back to the front surface producing the pressure gradient across the target and accelerating the fluid inward. If the shock wave is rippled or the rear surface is nonuniform, the reflected rarefaction is rippled. The rippled rarefaction perturbs the ablation front ("feed-out") and makes the initial condition for the subsequent R-T instability [7]. In order to investigate the "feed-out" effect, a plastic foil with an initial corrugation on the rear surface was irradiated by uniform PCL beams at the nominal intensity of 6 x 10^{13} W/cm^2. Temporal evolution of the surface displacement of both surfaces were observed by the side-on x-ray backlight method. Figure 3 shows the result for the perturbation wavelength of 100 μm.

Interaction of the uniform shock wave with the nonuniform rear surface returns a nonuniform rarefaction wave to the front. The front surface starts to accelerate after the rarefaction head has reached. The part where the rarefaction arrives earlier (later) accelerates earlier (later). The displacement of the front surface is easily deduced assuming that the velocity of the rarefaction and the acceleration of the front is uniform. The result is plotted in Fig. 3 as a solid line, showing a good agreement with the experiment.

3. RAYLEIGH-TAYLOR INSTABILITY

We have observed various dependencies of the R-T growth rate (measured as the growth rate of the areal-mass perturbation) on the perturbation wavelength (16 - 100 μm), the laser intensity ((0.4, 0.7, 1.4) x 10^{14} W/cm^2), and the target thickness (10, 16, 25 μm) [1]. The difference between the measured growth rates and the calculated results based on the Spitzer-Härm classical heat transport model increases for shorter perturbation wavelengths, higher laser intensities, and thinner target thicknesses. These experimental results are most likely explained by non-local heat transport, in which high energy electrons in the tail of Maxwell distribution penetrate into and preheat the target, thereby reduce the target density and thus increase the ablation velocity to enhance the ablation stabilization.

4. SUMMARY

Experimentally observed perturbation growth on the laser illumination surface by rippled shock wave and ripped rarefaction wave were well explained by a simple analytic model. Various dependencies of the Rayleigh-Taylor growth rate infers the necessity of the nonlocal treatment of the electron heat conduction in the ablation region.

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