Experimental Studies on Hydrodynamic Instability of Direct-Drive Laser Fusion on GEKKO XII

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Abstract. A series of elementary experiments on the hydrodynamic instability has been conducted at the GEKKO XII laser system to investigate hydrodynamic instability growth in planar foils directly irradiated by 0.53-μm laser light. The dynamic property of laser initial imprint was successfully obtained by the improved two-wavelength Young's interference method [1]. Two types of the "indirect/direct hybrid" schemes were also examined to quantify the effective mitigation of laser initial imprint. Especially, a multi-density foam layer was utilized for the first time to demonstrate the feasibility of the density varying target. Rayleigh-Taylor instability growth rate on the directly driven target around its maximum was also measured with the perturbation wavelengths less than 10 μm by a newly developed technique of x-ray moiré interferometry. [1]AZECHI, H., et al., Phys. Plasmas 4 (1997)4079-4089.

1. Introduction

Hydrodynamic stability is a key issue in the inertial confinement fusion research. It is the most important problem to be studied in experiments to know how hydrodynamic instabilities are initiated from the target roughness and from laser illumination nonuniformity(" laser initial imprint") and are developed to degrade the implosion performance. Fundamental experiments on the elemental phenomena under the idealized conditions are necessary to confirm our understanding and to make-up a reliable computer simulation code for the target design. Series of elementary experiments on the hydrodynamic instability have been conducted on GEKKO XII to measure hydrodynamic instability growth in planar foils directly irradiated by 0.53-μm laser light. In the previous series of experiments, it was shown that 1) static imprint with the perturbation wavelength longer than the target thickness is well described by the linear perturbation analysis, 2) x-ray pre-irradiation can effectively mitigate the initial imprint and 3) reduction of the linear growth rate of the Rayleigh-Taylor(R-T) instability by ablation stabilization can be explained by taking account of the non-local heat transport effect. A hydrodynamic mixing model based on a one-dimensional hydro-code, bench-marked with the above experiments, predicts that a high-gain target design can afford stable implosion using the external hybrid scheme and taking account of the non-local heat transport [2].

In the high-gain simulation, a cryogenically cooled D-T pellet is accelerated by partially coherent 0.36-μm light. Validity of the model and non-local heat effect under the condition similar to the high-gain design are to be examined at the bundled beam facility, "HIPER". Some basic processes such as the R-T growth in the shorter wavelength region and imprint by temporally modulated light must be investigated experimentally in advance. In this report, we will present recent results on the quantitative investigation of dynamic property of laser initial imprint, its reduction by the "indirect/direct hybrid schemes", and first observation of the R-T instability growth with the perturbation wavelengths less than 10 μm.

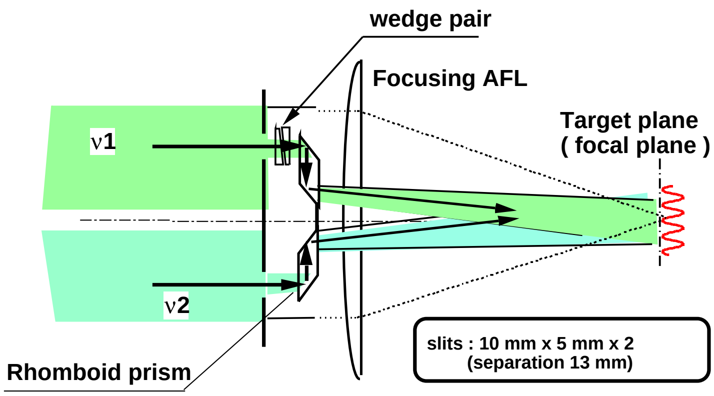

FIG. 1. Focusing optics for the two-wavelengths interferometry.

2. Dynamical Property of the Initial Laser Imprint

Propagation of rippled shock wave is one of the most important processes in the initial phase of the target implosion. In order to understand those processes quantitatively, simple analytic models were proposed and have been compared with the experimental results. Although imprint process with static single-spatial-mode illumination distribution was quantitatively investigated and was shown to be well predicted by those models [1]. The spatial profile of the illumination in the real situation, using the smoothing techniques such as SSD, is temporally varying. The imprint process by that time varying ("dynamic") profile has not been studied so far. To understand the process experimentally and to address the question about required laser bandwidth for optical smoothing, we started an experiment on the dynamic imprint by two wavelength Young's interference technique. In the previous experiment [1], superposed static perturbation of about 10 % hindered the observation of the imprint reduction by oscillation. Moreover, short perturbation wavelength and poor spatial resolution of the diagnostics degraded the quality of the experiment. This time, a pair of Rhomboid prisms were utilized to minimize the merging of the two beams and optimize the spatial wavelength of the intensity modulation to be longer than the diagnostic spatial resolution. Thus a typical wavelength of the intensity modulation was set as 40 μm.

In *FIG.1* depicted is the focusing optics for the Young's interferometer with two different wavelengths. Temporally moving interference fringes were produced successfully changing the wavelength-difference up to 0.1A (with the corresponding moving speed of the fringes of 2×10^7 cm/s on the target plane). Flat plastic (2, 2, 2-poly-trifluoroethyl-methacrylate (PTFMA : $C_6H_7F_3O_2$)) foils were irradiated with this dynamically modulated foot beam of 0.527-μm wavelength 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 subsequent R-T instability to be observed with the face-on x-ray backlight technique. Clear reduction of the initial imprint by dynamical beam smoothing has been observed. As the modulation frequency is increased, decreased is the contrast of the perturbation. (No clear growth was observed at the higher frequency than 2.5 GHz.)

In order to investigate the process theoretically, the linear analytic model [3] was used. Evolution of the perturbation amplitude of the rippled shock front, ablation front, and areal density were solved for the time-depending absorption laser intensity perturbation in the form of sinusoidal vibration with exponential decay to simulate the thermal smoothing. Calculated dependence on the vibration frequency of the areal density perturbation at the shock break-out time well explains the experimentally observed frequency dependence of the imprint.

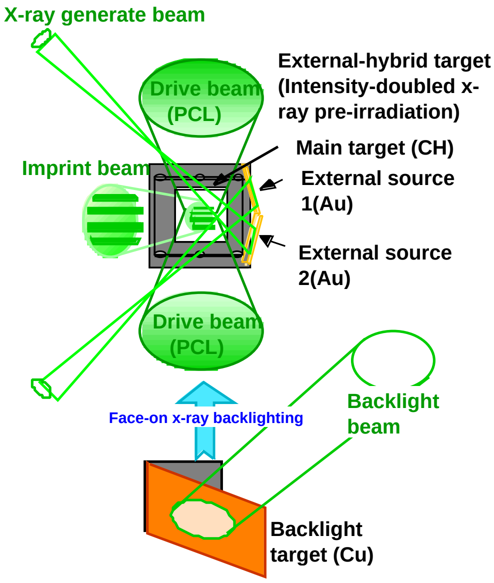

FIG 2. Schematic drawing of the experimental set-up for external hybrid elementary experiment. External x-ray irradiation intensity was doubled by using two gold foils and beams.

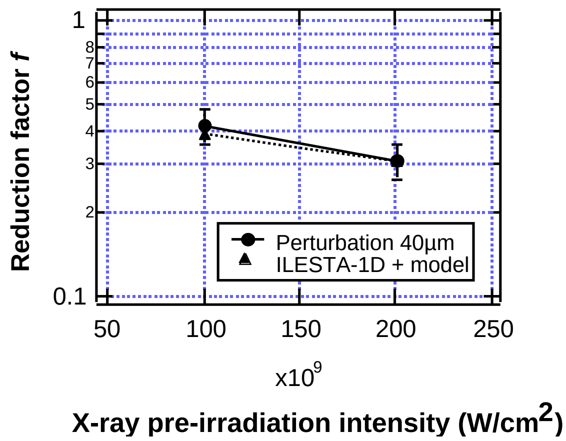

FIG. 3 .Intensity dependence of the imprint reduction by x-ray pre-irradiation.

3. Basic Experiment for Indirect/Direct Hybrid Scheme

Experiments on elemental process of the two types of indirect/direct hybrid implosion schemes have been conducted under the identical conditions with the previous experiments[5,6]. Flat plastic foils were illuminated by the spatially modulated foot pulse beam (with the averaged intensity of 3 x 10^{12} W/cm^2 and pulse duration of 2.2 ns) to imprint the illumination nonuniformity on their surfaces and accelerated by uniform main drive beams (with the averaged intensity of 5 x 10^{13} W/cm^2) in order to observe the development of the perturbation by Rayleigh-Taylor instability. Intensity profile of the foot beam was spatially modulated by the “image relay technique” as the previous experiments [4].

3.1 External X-ray Hybrid Experiment

In the first type of the schemes, called “external hybrid”, it is expected that preformed plasma with a finite density scale length generated by the x-ray pre-irradiation before main laser irradiation mitigates the initial laser imprinting due to the thermal smoothing in the ablation region. Pre-irradiating the flat plastic target by x rays from the additionally provided gold foil, areal density perturbation imprinted on the flat plastic target by the nonuniform foot pulse was shown to be reduced significantly by x-ray pre-irradiation [5]. In the present experiment, dependence on the pre-irradiation x-ray intensity was examined by changing the number of the external x-ray sources and beams using the targets shown in *FIG. 2*.

Evolution of the areal density perturbation on the targets was observed by the x-ray streaked backlighting measurement. Comparing the perturbation growth with and without the pre-irradiation beams, ratios of the perturbation growth (reduction factors) were deduced (*FIG. 3.*) Experimentally obtained dependence of the imprint reduction on the x-ray pre-irradiation intensity is consistent with the theoretical prediction based on a simple cloudy-day model of the thermal smoothing [5].

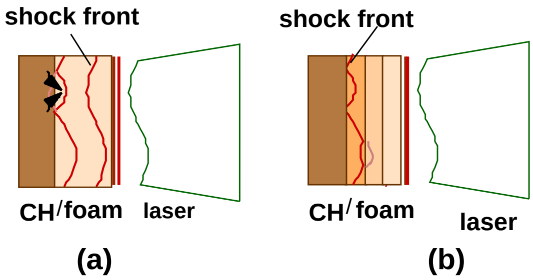

FIG. 4. Imprint mitigation by foam-hybrid targets. (a) conventional type, and (b) multi-density foam hybrid. Perturbation caused by passage of rippled shock wave is reduced when shock impedance mis-matching is small between different density layers.

3.2 Foam Hybrid Experiment

Another hybrid scheme, "foam hybrid", uses a low density foam layer to make-up a long separation distance between the ablation front and the laser-absorption region in the beginning of the laser irradiation. The capsule of this type of hybrid scheme has a low density foam lay-er over the capsule wall and a thin high Z (such as gold) outermost layer. In the very begin-ning of laser irradiation, x-ray radiation from the high Z layer propagates and ionize the foam layer to pre-form a long-scaled ablation structure. In the previous experiment using flat planar targets, although the imprint mitigation was clearly confirmed with the short wavelength of 40 to 80 μm, the perturbations of longer wavelengths were not reduced effectively [6]. Ac-cording to the two dimensional hydro-code simulations, this is attributed to perturbation growth caused by passage of the rippled shock wave through the contact surface between the low density foam layer and the dense plastic layer behind. Consequently, a multi-density foam layer was proposed and has examined to solve this problem by gradual density increase and suppress the long wavelength perturbations as well.

In the experiment, a three-stepped density target as, depicted in *FIG. 4 (b)*, was used. Densiti-es of each foam layer were chosen to be 40, 120, and 370 mg/cc. The thickness of each unit-foam layer was 5 μm. The integrated foam layer of 15 μm-thick was finally fitted directly onto a 6 μm-thick parylene (C8H8). The surface of the multi-density foam facing to laser ir-radiation side was first covered with a parylene foil of 0.15 μm-thick then 20 nm-thick gold was coated. Perturbation growth was observed in the similar way as the previous experiment. The imprint mitigation by the multi-step-density foam layer was found to be more effective than the single foam layer not only for the longer wavelength but also for the short wave-length perturbation.

4. Rayleigh-Taylor Instability Growth

In the acceleration phase, growth rate of the Rayleigh-Taylor instability is the most important quantity to be examined experimentally. We had observed various dependencies of the Rayleigh-Taylor growth rate (measured as the growth rate of the areal-mass perturbation) in the linear region on the perturbation wavelength, the laser intensity, and the target thickness. These experimental results are well explained by the Takabe formula on the ablation stabili-zation taking account of non-local heat transport [1]. According to the prediction by the for-mula, R-T linear growth rate in our typical experimental condition has its maximum around the perturbation wavelength of 20 μm and decreases to zero as the wavelength decreases tak-ing the cut-off wavelength of about 5 μm.

Although the dispersion relation of the linear R-T instability has been studied intensively, the cut-off wavelength of the dispersion has not been directly measured yet, due to the poor spatial resolution of the diagnostics. Not only for the physical understanding but for technological needs, It is important to investigate the R-T linear growth around the cut-off region and confirm the formulae which describe the dispersion relation of R-T instability. Techniques using phase plates, such as RPPs [9], to smooth laser illumination profile expect the ablation stabilization more or less. They transfer spectral energy of low spatial frequency components in the illumination intensity distribution into the higher frequency region where the ablation stabilization is effective to suppress the instability growth. It is essential to know the cut-off wavelength to design focusing optics including phase plates.

We adapted a moiré interferometry to improve the spatial resolution of an x-ray backlight imaging system[7]. The 16-μm thick plastic foil targets with the sinusoidal corrugations of 8.5, 5.7 and 4.7 μm wavelength (with moiré mask attached as in *FIG.5*.) were accelerated by the uniform PCL beams of 7 x 10^{13} W/cm^2 with flattop pulse shape. We successfully measured the R-T growth rates of the shorter wavelength perturbation than 10 μm for the first time. Although the growth rate was shown to decrease as the wavelength decreased below 10 μm, the cut-off wavelength was shorter than expected. The new experimental result (hydro99) is explained by the Betti's formula [8] coupled with the one-dimensional hydro-code simulation. It does not seem to be consistent with the previous results (hydro96) as is shown in *FIG. 6*. The explanation of this discrepancy is still in controversy.

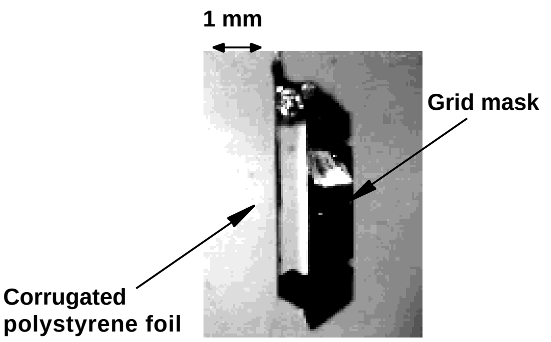

FIG. 5. RT experiment target for the x-ray moiré interferometry. A tantalum grid of 2.2 μm thickness supported on the silicon substrate is attached to the 16-μm thick polystyrene foil with corrugation.

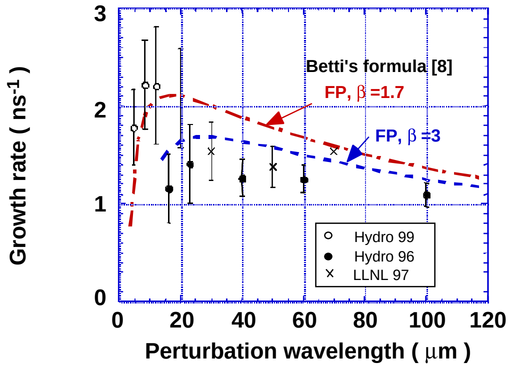

FIG. 6. The dispersion relation of RT growth rates. 16-μm thick polystyrene foils were illuminated by the partially coherent beams at the nominal laser intensity of 7x10^{13} W/cm^2.

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