Mitigation of Laser Imprinting with Diamond Ablator for Direct-Drive Inertial Confinement Fusion Targets

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Abstract. We propose a novel scheme to mitigate the initial perturbation imprinting due to irradiation non-uniformity. Diamond was potential candidate for the ablator material for ICF targets due to its stiffness. The stiffness is very important parameter for imprint mitigation because the laser imprint is primary as a function of pressure perturbation due to lase irradiation non-uniformity. We measured the imprint amplitude of diamond foils and plastic (CH) foils. The experimental data suggest the initial imprinting is drastically mitigated for the diamond foils.

1. Introduction

Hydrodynamic instabilities are still the most crucial issue on inertial confinement fusion (ICF) targets. Among the instabilities, Rayleigh-Taylor instability (RTI) gives the largest growth factor during the implosion process because the perturbations on the target surface grow exponentially with time [1]. Initial perturbations on the target surface are due mainly to target fabrication and to imprinting by laser irradiation non-uniformity. For direct-drive ICF targets, the initial imprinting is the most important issue to seed the RTI. Previous experimental and theoretical studies revealed the detailed physics of the laser imprinting [2-5].

The imprinting is modelled as imprint efficiency, which is the equivalent perturbation amplitude on the surface normalized by the laser intensity modulation. The imprint efficiency is defined by the incompressive model as [5]:

\[ \eta_{\text{imp}} = \frac{k d_0}{3 \gamma + 1 + 0.2(k d_0)^2} F(k, D_{sb}, d_0) \]

where \( k \) is wave number of the perturbation, \( d_0 \) is initial target thickness, \( \gamma \) is specific heat ratio, and \( D_{sb} \) is standoff distance. \( F \) is the smoothing factor of the imprint efficiency, and approximated to be \( 2/k^2 D_{sb}^2 \). This suggests that, in order to reduce the imprint efficiency, thermal smoothing is very controllable with several technique. Previous investigation for mitigation of laser imprinting were

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carried out with x-ray pre-irradiation [6], picket pulse [7], low density foam target [8], high-Z dopant [9], and so forth. These technique are very effective for small wavelength perturbation, however in many cases, the adiabat of the target is increased prior to shock transition due to the process of enhancing the standoff distance.

Other possible mitigation scheme is to change the target stiffness $\gamma$. We here focus on diamond, which is the hardest material, to be a candidate for the direct drive ablator because the diamond is low-Z material, easy to handle, and possible to fabricate to hollow shell. The diamond ablator has been employed as a possible candidate for indirect-drive NIF ignition target [11]. Diamond also has very large Hugonit elastic limit (HEL: $\sim 200$ GPa) [10], which means the compression below the HEL is very small. For example, The effective $\gamma$ below the HEL at 100 GPa is more than 20 whereas the $\gamma$ for CH is 2. This fact suggests that very strong mitigation is probable for the stiffer material. Thus we carried out a proof of principle experiment in order to demonstrate the effect on imprinting mitigation in the aspect of the material stiffness.

2. Experiments
Experiments were done on GEKKO-XII laser facility at Institute of Laser Engineering. The setup and overall experimental conditions were similar to previous hydrodynamic instability experiments [12, 13]. We observed the perturbation growth of the accelerated foils due to the RTI, in which the initial perturbation was seeded by a spatially modulated foot pulse laser. Schematic view of the experimental setup is shown in Figure 1.

Figure 1. Experimental set up and typical pulse shape

Target foils were irradiated by three beams of the GEKKO-XII laser ($\lambda$: 0.527 $\mu$m). The pulse duration of each beam we 1.3 ns. Each pulse with time delay which made a foot pulse followed a main drive pulse. The typical stacked pulse shape is shown in Figure 1. Spot diameter on the target was 300 $\mu$m. We put a grid mask for the imprint beam just in front of the irradiated foil in order to make a spatial pattern on the foil. The period of the grids were 50 and 100 $\mu$m. The main drive beam followed the foot pulse for amplification of the imprinted surface by the RTI because the imprint amplitude is usually too small to detect. Intensities of the foot pulse and the main pulse were $4 \times 10^{12}$ W/cm$^2$ and $8 \times 10^{13}$ W/cm$^2$, respectively. The backlighter beam was irradiated $\sim 1.0$ ns after the onset of the main drive pulse when the imprint perturbation was amplified due to the RTI.

The targets on the measurements were single crystal Type-Ib diamond foils with thickness of $\sim 10$ $\mu$m. The orientation of the target surface was (000). We also employed polystyrene (CH) foils with thickness of 25 $\mu$m in order to obtain reference data.
Imprint amplitude is evaluated by measuring areal density perturbation of the laser-irradiated foil. The real density was measured by a conventional face-on backlighting technique. Copper or zinc foils were employed for generation of 1~1.5 keV x-rays. The backlit x-ray was imaged by a slit (10 μm-width) onto a photocathode of an x-ray streak camera. For the analysis of the areal density perturbation, the spatial resolution of the whole diagnostic system was separately measured by taking a grid backlit image. Temporal resolution was ~ 100 ps. We also measured the target trajectories for both targets with side-on x-ray backlighting in order to determine the target acceleration.

3. Experimental results

Figure 2 shows raw streaked images by the face-on backlighting measurements. The origin \((t=0)\) is the onset of the main drive pulse. In the measurements, we observed later timing of the main pulse by changing the time delay of the backlighting laser pulse. Significant modulation of the x-ray intensity is seen for the CH foil whereas there is no clear modulation for the diamond foil. The experimental results were analysed to obtain the temporal evolution of the areal density perturbation. In the analysis process, we took into account the spatial resolution function and the mass absorption ratio of the x-ray backlight x-ray for Cu and Zn.

Figure 3 shows the analysed temporal evolution of areal density perturbation for both targets. The amplitudes shown in Fig. 3 is sums of the Fourier amplitude for the wavelength of 45 – 70 μm because the perturbations on the experiments have a lot of wave numbers although the grid mask is with the single mode perturbation. This is probably due to diffraction by the grid, “hole closure” by plasmas, and other reasons. The areal-density perturbation for the CH grows with time whereas no clear growth is found for the diamond target. The dotted line in Fig. 3 is the detection threshold of the measurement which is determined by the white spectrum of the Fourier amplitude. That means the areal density perturbation for the diamond foil is nearly the noise level.

Figure 2. Raw streaked backlit images for CH and diamond foils

Figure 3. Areal density perturbation or CH and diamond foils for wavelength of 45 -70 μm. Dotted line is detection threshold for the diagnostic system
4. Discussions and Conclusion
The measured imprinting is apparently reduced for the diamond ablator. In this experimental condition, there are few differences between the diamond and the polystyrene targets. This fact could conclude that the imprint mitigation for the diamond is due to its stiffness. Although we observed the significant mitigation of the imprinting, imprint efficiency should be quantitatively obtained. We are planning to carry out next experiment to use grid at far field position in order to produce a single mode imprint beam pattern to characterize the imprint efficiency. Also we are going to compare with the imprint model with one-dimensional code for further understanding of the imprint mitigation, and to apply for the optimization of diamond ICF targets.

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