Implosion Physics and Robust Target Design for Fast Ignition Realization Experiment

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Abstract. Fast ignition is an attractive scheme in laser fusion. At the first phase of the scheme, highly compressed fuel core plasma is formed by implosion laser, and then, just around the maximum density time, it is heated by heating laser to achieve a fusion burning condition. A shell targets for Fast ignition is fitted with reentrant gold cone target to preserve a path for heating laser. Therefore, understanding of the cone guided implosion dynamics is one of significant problem. We have been studying these physics and design, especially a formation of high density core plasma, and breakdown of the tip by using two-dimensional radiation hydrodynamics simulation. In these work, we have found that RTI causes tip breakdown in early phase, and decrease of fuel core plasma density. A dynamics of massive jet which hit the tip is evaluated also. These serious problems can be avoided by using the sophisticated laser pulse shape and irradiation pattern for slow velocity, and low adiabat implosion. In this paper, we will describe design principles of Fast ignition which are revalidated with the simulations, and more robust target design is proposed for Fast ignition experiment.

1. Introduction

Fast ignition is an attractive scheme in laser fusion [1,2]. At the first phase of Fast ignition, highly compressed fuel core plasma is formed by nano-second-order implosion laser, and then, just around the maximum density time, it is heated by heating laser to achieve a fusion burning condition. Mostly, a shell target for Fast ignition is fitted with reentrant gold cone target to preserve a path for heating laser. Therefore, understanding of the cone guided implosion dynamics is one of significant problems. We have been studying the formation of high density core plasma, and breakdown of the tip using two-dimensional radiation hydrodynamics simulation code, PINOCO [3]. In the result, we have proposed an advanced target for the scheme [4, 5]. However, these studies are ideal cases, and realistic conditions must be taken account into the simulations. In general, formation of hot-spot is not required in imploded core plasma for Fast ignition because external heating is driven by external laser. But this leads to misunderstanding that the hydrodynamic instability of imploding shell target is considered less serious. In this paper, design principles of Fast ignition are revalidated and more robust target design is proposed for the margin of GXII experiments.

2. Effect of Rayleigh-Taylor Instability in Non-spherical Implosion

The effect of Rayleigh-Taylor instability on formation of a high density core and timing of tip breakdown are investigated in cone-guided shell implosion by using two-dimensional radiation hydrodynamic simulation (PINOCO), in which ALE hydrodynamics, equation of state (QEOS), flux-limited thermal diffusion, laser ray-tracing, multi-group diffusion type radiation transport are included.

2-1. Numerical Conditions

A target size and laser conditions are relevant to FIREX-I (Fast Ignition REalization Experiment, Phase-I), which have been carrying out by Gekko-XII and LFEX lasers at ILE Osaka University. The gold cone with an opening angle of 30 degree is attached to a spherical CD shell target (8 μm thick). The distance between the tip of the cone and the center of the shell, and the thickness of the tip of the cone are 50 μm and 8 μm respectively. (Fig.1) In order to investigate the effect of hydrodynamic instability, target surface is perturbed initially. The amplitude of initial target surface perturbation is shown in figure 2. Red line ("measured" line) indicates a typical target roughness which was measured at ILE. The measured imprint is modeled [6] and imposed on the target surface roughness, of which amplitude is indicated as blue line ("imprint model" line). And the sum of these amplitudes is indicated as black line ("total" line). From the linear theory must be taken account. However, due to the limitation of computational resources, the mode numbers are considered in this study. The shell target is irradiated by uniform laser of which wavelength, energy and pulse duration are $\lambda = 0.53$ μm, 3.0 kJ, and 1.5 ns respectively. During the target acceleration phase, Rayleigh-Taylor instability grows rapidly and reaches non-linear phase. The shell and the tip are broken at 400 ps and 100 ps before the maximum compression time respectively. At the maximum compression time, high density jet is already expanding toward the cone in the case of surface perturbed target (Figure 3(a)). The time history of angular averaged areal density is shown Fig. 3(b). In perturbed case, the maximum areal density is only 0.15 [g/cm^2], which is about one third of the unperturbed case. Stagnation cannot be observed clearly, and the sharp density and areal density peaks are not appeared. Therefore shell breaking must be avoided.

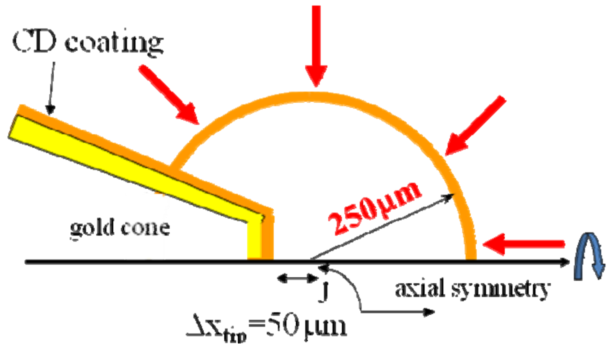

FIG. 1. Configuration of target, which is typical size and materials for GXII experiment. Thickness of the tip is 8 μm, and opening angle of the cone is 30 degree.

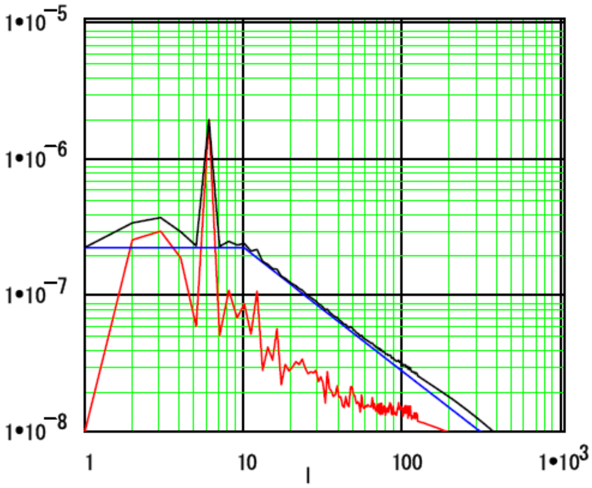

FIG. 2. Amplitude of initial target surface perturbation. Red line ("measured" line) indicates a typical target roughness. The measured imprint is modeled and imposed on the target surface roughness, of which amplitude is indicated as blue line ("imprint model" line). The sum of these amplitudes is indicated as black line ("total" line).

From the linear perturbation theory, initial perturbation of mode number $l < 200$ is necessary in this kind of simulations. However, due to the limitation of computational resources, it is imposed to be $l < 80$. That is to say, severer condition is predicted in experiment. Robust target against hydrodynamic instability must be designed. A slow implosion method [6] is one of the attractive methods, where thick and massive shell is imploded with a low implosion velocity to achieve high areal density. In order to avoid the fateful shell breaking, slow implosion scheme [7] is effective way. In this scheme, implosion velocity is below 2×10^7 cm/s and the size of hot-spot is relatively small compare to that of central ignition scheme. In-flight target thickness is thick enough to prevent the crucial target breakdown caused by the hydrodynamic instability. In our preliminary study using 1-D implosion code, optimum target designs for FIREX-I (10 kJ) and –II (200 kJ) are surveyed. In result, for FIREX-I, thicker (thickness; 15 μm) and smaller (radius; 240 μm) CD shell target which is accelerated by tailored laser pulse is optimum. In this case, target is more stable in acceleration phase and shell would not be broken. The areal density is increased by 10%. Two-dimensional radiation hydrodynamics simulations will be carried out with the same conditions to confirm the effectiveness.

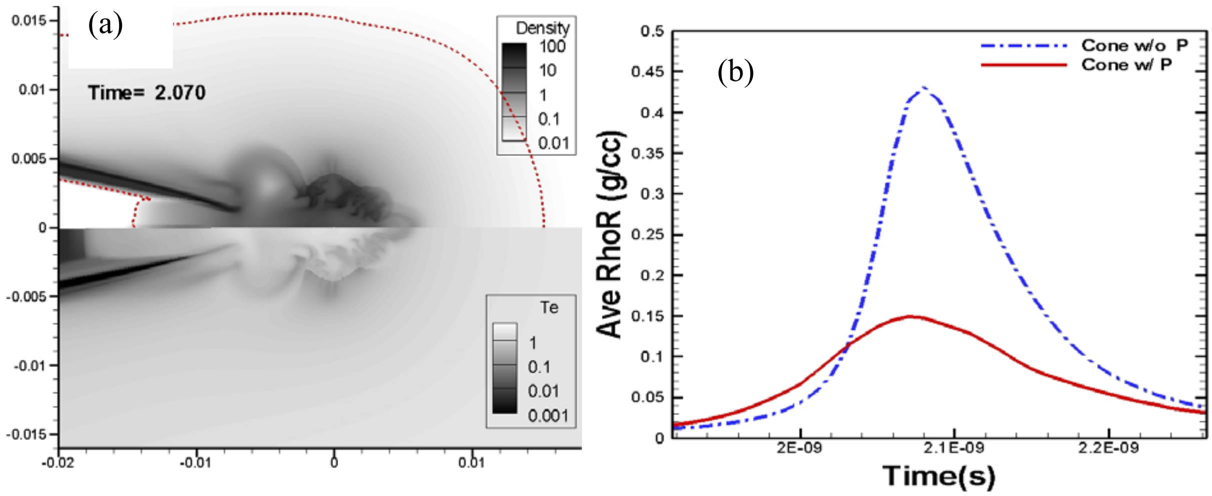

FIG. 3 (a) Mass density contours (top) and electron temperature contours (bottom) at maximum compression time in the implosion of initially perturbed cone-guided shell target. (b) Time history of averaged areal density (ρR [g/cm^2]). An unperturbed initial target case (Dot-dash line), and perturbed initial target case (solid line).

3. Dynamics of Compressed Core and Massive Jet Flow

We also concern about a massive jet flow from the compressed core toward the tip of the cone. The 2-D simulation have predicted that the velocity of the jet flow was strongly depends on the irradiation pattern which causes imbalance of momentum in the imploding shell. If the laser energy is not supplied sufficiently to the shell target nearby the cone, speed of the jet is increased. This fact was also observed in GXII experiment [8]. We have confirmed that the jet is controlled by laser irradiation balance. The material and thickness of the cone tip are significant factors as well, not only from the viewpoint of implosion, but also from the viewpoints of laser plasma interaction and hot electron transport [9].

In order to simulate the detail dynamics of the compressed core and the massive jet flow in non-spherical implosion, development of 3-D radiation-hydrodynamic simulation code was started. Fully integrated simulation of the implosion was quite difficult and expensive. Therefore, simple Cartesian code is applied here. Initial conditions for the 3-D calculations

are interpolated from 2-D simulations. Figure 4 shows an example of the initial density profile which is 200 ps before the maximum compression, where 3-D velocity perturbation of mode 1, and amplitude 5% is given. The computational grid size is 401x401x200 with 0.6 μm of each cell size.
In this case, areal density, average density, and jet speed are not affected by the perturbation significantly because the perturbation is relatively smaller than realistic cases. In near future the large computational box and realistic initial condition with higher mode perturbations on initial target surface, which is discussed in section 2 will be performed.

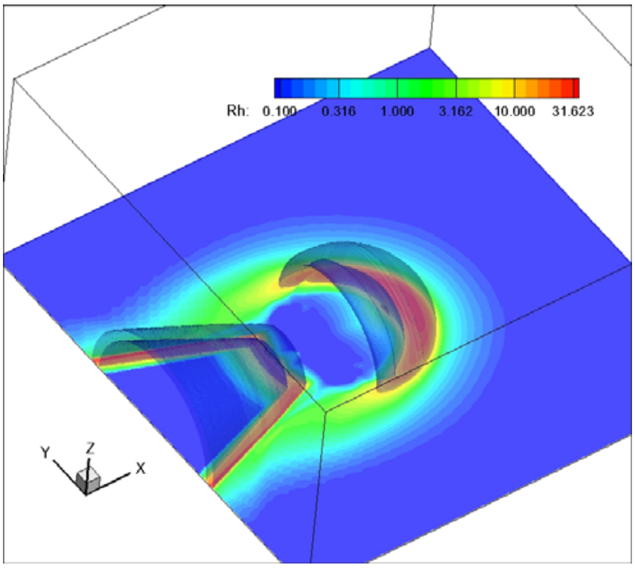

FIG. 4. Initial density profile of 3D simulation, which is interpolated from 2-D radiation hydro simulation.

4. Summary

A preliminary study of the effect of hydrodynamic instability is presented. The simulation results suggest that in cone-guided implosion with perturbed target shell, the tip of the cone is destroyed earlier than the ideal unperturbed case. The maximum areal density is one fourth of unperturbed case, and the maximum compression time comes earlier than that of unperturbed case. The implosion design of Fast ignition is different from the conventional central hot-spot type implosion. For the future, specialized target design for Fast ignition is necessary. A slow implosion method which can achieve high density and high areal density is effective way. In this method, in-flight target thickness is thick enough to prevent the crucial target break-down caused by the hydrodynamic instability. Controlling the formation of the jet flow from core plasma toward the tip of the cone must be considered carefully. They will be considered in our next advanced target design.
The material and thickness of the tip are very significant factors not only from the viewpoint of implosion, but also from the viewpoints of laser plasma interaction and hot electron transport [9]. However, they are not discussed in this paper. Fully integrated simulation where implosion, LPI, and hot electron transport code are linked will be carried out in near future for our next advanced target design.
Understanding of the 3-D dynamics of compressed core and massive jet flow is important, and numerical analysis is carried on.

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