Controlling dynamics of imploded core plasma for fast ignition

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Abstract. In the Fast ignition, formation of highly compressed core plasma is one of critical issue. In this work, the effect hydrodynamic instability in cone-guided shell implosion is studied. Two-dimensional radiation hydrodynamic simulations are carried out where realistic seeds of Rayleigh-Taylor instability are imposed. Preliminary results suggest that the instability reduces implosion performance, such as implosion velocity, areal density, and maximum density. In perturbed target implosion, the break-up time of the tip of the cone is earlier than that of ideal unperturbed target implosion case. This is crucial matter for the Fast ignition because the pass for the heating laser is filled with plasma before the shot of heating laser. A sophisticated implosion design of stable and low in-flight aspect ratio is necessary for cone-guided shell implosion.

1. Introduction

Fast ignition is an attractive scheme in laser fusion [1]. At the first phase of Fast ignition scheme, 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 peta watt laser to achieve a fusion burning condition. Mostly, a shell targets for Fast ignition is fitted with reentrant gold cone target to preserve a path for heating laser which is ultra-intense short pulse. Therefore, understanding of the cone guided implosion dynamics is one of significant problem. We have been studied the problems, especially, on the formation of high density, and breakdown of the tip using two-dimensional radiation hydrodynamics simulation code, PINOCO [2]. In the result, we have proposed an advanced target for the scheme [3]. However, these studies are ideal cases, and realistic conditions must be taken account into simulation. In general, a high temperature hot-spot in imploded core is not required for Fast ignition before heating timing. But this leads to misunderstanding that the hydrodynamic instability of imploding shell target is considered less serious. Therefore, in this preliminary study, effect of Rayleigh-Taylor instability on formation of high density core and timing of tip breakdown is investigated numerically. A target and an implosion scales are relevant to FIREX-I (Fast Ignition REalization Experiment, Phase-I) at ILE Osaka University.
2. Simulation of coned-guided implosion

Two-dimensional radiation hydrodynamic simulation is performed. A configuration of a typical coned-guided shell target which is used in Gekko-XII experiment at ILE Osaka University is shown in figure 1. The gold cone with an opening angle of 30 degree is attached to a spherical shell of CD (8 \( \mu \text{m} \) thick). The tip position from center of the shell and thickness of the tip of the cone are 50 \( \mu \text{m} \) and 8 \( \mu \text{m} \) respectively. 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 [4] 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 \( l \approx 200 \) must be taken account. However, due to the limitation of computational resources, the mode numbers \( l \leq 80 \) are considered in this study. The shell target is irradiated by uniform laser of which wavelength, energy and pulse duration are \( \lambda = 0.53 \ \mu \text{m}, 3.0 \text{kJ}, \) and 1.5 ns respectively.

For comparison, two simulations with and without initial perturbations are executed. Figure 3 shows mass density and electron temperature contours at \( t=1.90 \ [\text{ns}] \) and at the maximum density time \( t=2.07 \ [\text{ns}] \) and \( t=2.08 \ [\text{ns}] \). In the perturbed target case, at \( t=1.90 \ [\text{ns}] \) during the target acceleration phase, Rayleigh-Taylor instabilities grow rapidly and reach non-linear phase. Some plasma expanded from broken shell has filled inside the shell already, where mass density is nearly solid density (figure 3(a)). This plasma inside the shell is compressed on the axis, and forms the massive jet flow which strikes toward the tip of the cone. Similar jet flow was observed in GXII experiment [5]. At the maximum compression time, the tip is already blown away (figure 3(b)). The distance between the critical density in the cone and the center of the imploded core is more than 150 \( \mu \text{m} \) which is too far to achieve the high heating efficiency. On the contrary, the tip of the cone survives, and the inside of the cone is kept clean in unperturbed target case (figure 3(d)). The maximum implosion velocities of perturbed target and unperturbed target are \( 2.7 \times 10^7 \ [\text{cm/s}] \), and \( 2.9 \times 10^7 \ [\text{cm/s}] \) respectively. In

Figure 1. Configuration of target, which is typical size and materials for GXII experiment. Thickness of the tip is 8 \( \mu \text{m} \), and opening angle of the cone is 30 degree.

Figure 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).
perturbed target case, the deceleration rate is higher than that of unperturbed target case, due to the plasma inside the shell. The radius of the compressed core is nearly 40 \( \mu \text{m} \), and the density of the core is less than 40 \([\text{g/cm}^3]\), which is insufficient to absorb hot electrons produced by heating laser.

![Figure 3](image-url)

Figure 3. In each figure, (top) mass density contour \([\text{g/cm}^3]\) and (bottom) electron temperature contours \([\text{keV}]\) are shown. (a) perturbed target at \(t=1.90\ \text{[ns]}\), (b) unperturbed target at \(t=1.90\ \text{[ns]}\), (c) perturbed target at \(t=2.07\ \text{[ns]}\), (d) unperturbed target at \(t=2.08\ \text{[ns]}\) are shown respectively.

Figure 4 shows the time history of angler averaged areal density. In perturbed target case, the maximum areal density is reached only 0.15 \([\text{g/cm}^2]\), which is about one fourth of the unperturbed target case. Stagnation cannot be observed clearly on the axis, and the sharp peak of density (or areal density) is not appeared, momentum energy remain.

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.
3. Conclusion and 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 [7]. 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.

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