Target Design for High-density Non-spherical Implosion in Fast Ignition

H. Nagatomo¹, T. Johzaki¹, A. Sunahara², T. Nakamura¹, H. Sakagami³, K Mima¹

¹Institute of Laser Engineering, Osaka University, 2-6, Yamada-oka, Suita, Osaka, 565-0871, Japan
²Institute for Laser Technology, 2-6, Yamada-oka, Suita, Osaka, 565-0871, Japan
³National Institute for Fusion Science, Oroshi-cho, Toki, Gifu, 509-5292, Japan

E-mail: naga@ile.osaka-u.ac.jp

Abstract. A high \(\rho R\) core which is formed by non-spherical cone-guided implosion is required in fast ignition. Contrary to the central-hot-spot scheme, high temperature is not necessary in the implosion process. Therefore, relatively slow implosion design could be effective using a massive shell target. In this work, two-dimensional simulations of such slow implosions are performed to achieve high \(\rho R\) core. In the result, the higher \(\rho R_{\text{max}}\) can be obtained if the target mass is increased. In this study, an implosion with a foot pulse laser is examined also. In the initial phase, during the foot pulse irradiation, ablated plasma affects the gold cone surface, and the gold plasma expands, which leads pernicious effect on the implosion process.

1. Introduction

Fast ignition is an attractive scheme of laser fusion [1]. In fast ignition, at first, high-density fuel core plasma is assembled by implosion laser, and then, just around the maximum density time, it is heated by peta-watt laser to achieve a fusion burning condition. In the central-hot-spot (CHS) scheme, a highly uniform laser irradiation and strict power balance of a multi-beam laser system are required. On the other hand, such a requirement is relaxed in fast ignition, and the only requirement is to achieve high-density compression. Some experiments were already performed at Osaka University. Kodama et al. [2] demonstrated a fast ignition experiment where the cone-guided shell target was directly driven by the GEKKO XII (GXII) laser system initially. And the heating physics of hot spark formation will be clarified by the Fast Ignition Realization Experiment (FIREX) project [3] at Osaka University. The first stage of FIREX (FIREX-I) was started in 2003 for a duration of seven years. The final goal of FIREX-I is to achieve \(10^{14}\) neutron yield by integrated experiment. For the final goal, we have to assemble high areal density (~0.3 g/cm\(^2\)) and high maximum density (~250 g/cm\(^3\)) of DT fuel. In this paper, we focus on the formation of high-\(\rho R\) cone-guided implosion design with plastic (CH) target shell for the study of physics in cone-guided implosion. The knowledge can be extended to DT cryogenic shell implosion which is necessary for FIREX-I experiment.

Betti et al., suggested that a massive shell target can be imploded with low implosion velocity to achieve high-\(\rho R\) core [4]. Although their study is based on one-dimensional simulations, two-dimensional (2-D) simulations are necessary for non-spherical implosion because the gold cone affects the implosion dynamics and hot spot can be eliminate in the center of imploded core plasma. In this
preliminary study, the effect of massive shell target is investigated numerically using 2-D radiation hydrodynamic simulation.

2. Simulations

The 2-D radiation hydrodynamic code, PINOCO [5] is used for this simulation where mass, momentum, electron energy, ion energy, equation of states, laser ray trace, laser absorption, radiation transport, surface tracing, equation of states and other related equations are solved simultaneously. For the preliminary study, the radiation transports are not taken account to save the computational time. Although the final goal of the FIREX-I is to demonstrate fast ignition with DT fuel, a CH shell is assumed to observe the characteristic of implosion. The laser conditions are based on current GXII performance. The energy and the wavelength of the direct drive laser are assumed as 4.5 kJ and 0.53 μm respectively. The laser pulse shape is limited to be Gaussian.

2.1. Target Geometry and Laser Pulse Shape

Figure 1 shows an overview of the target structure. The gold cone with an open angle of 30 degrees is attached to a spherical CH shell. The thickness and the radius of the tip of the cone are 6 μm and 29 μm, respectively. The very low density CH plasma (1.0x10^6 g/cm^2) is filled in the shell for numerical reason. The radius and the thickness of the CH shell are tunable parameters which are defined as table 1. Case 1 is typical target for current GXII experiments, and in order to increase the target mass, thicker target is assumed (Case 2). Also, the same reason, thicker and larger target radius is assumed (Case 3). For the low adiabatic implosion, double Gaussian pulse is assumed. The open angle of the cone and the distance between the tip of the cone and the center of the shell are 30 degree and 50 μm respectively, which are not optimized in this study. These parameters could be optimized for achieving higher ρR also. But it have been optimized and determined to be 30 degree from the points of the laser plasma interaction and heating core plasma problem which include hot electron transport [6]. The laser pulse is simple Gaussian or double Gaussians of which pulse duration is optimized in one-dimensional simulation by ILESTA1D.

![Diagram showing target structure and parameters](image)

Figure 1 Computational condition. Target radius and thickness are tunable parameters which are shown in table 1.

|       | radius (μm) | thickness (μm) | pulse shape, [HMFWS] ns |
|-------|-------------|----------------|-------------------------|
| Case 1| 250         | 8              | single Gaussian, 1.5 ns  |
| Case 2| 250         | 10             | single Gaussian, 1.5 ns  |
| Case 3| 300         | 10             | single Gaussian, 1.8 ns  |
| Case 4| 300         | 10             | double Gaussian, 1.5 ns  |

Table 1 Target specification and pulse shape
2.2. Simulation Results

Before running 2-D simulations, 1-D simulations (ILESTA-1D) are executed to confirm the implosion performances. In table 2, the maximum areal density $\rho R_{\text{max}}$ and the maximum implosion velocity $v_{\text{max}}$ in 1-D simulations are summarized. In the 1-D cases, the higher $\rho R_{\text{max}}$ can be obtained if the target mass is increased. In case 4, the time duration of the foot pulse is optimized to be 0.9 ns (HWHM) in order to maximize the $\rho R_{\text{max}}$.

| condition | $\rho R_{\text{max}}$ (g/cm$^2$) | $v_{\text{max}}$ (cm/s) |
|-----------|-------------------------------|-------------------------|
| 1-D       |                               |                         |
| Case 1    | 0.33                          | 3.39x10$^7$             |
| Case 2    | 0.35                          | 3.02x10$^7$             |
| Case 3    | 0.38                          | 3.10x10$^7$             |
| Case 4    | 0.44                          | 3.22x10$^7$             |
| 2-D       |                               |                         |
| Case 1    | 0.50                          | 3.60x10$^7$             |
| Case 2    | 0.51                          | 3.16x10$^7$             |
| Case 3    | 0.60                          | 2.80x10$^7$             |
| Case 4    | N/A                           | N/A                     |

Table 2 Summary of the simulation results. $\rho R_{\text{max}}$ and $v_{\text{max}}$ are measured at a cross section perpendicular to the symmetric axis.

Figure 2 shows overview of the 2-D simulation results of the standard cone-guided implosion (case 1). The ablated plasma from gold cone is expanding, and affects to the imploeding shell. But implosion process is finished before the effect travel through the CH plasma region. In cases 1-3, the implosion performance is similar to that of the 1-D cases qualitatively except the case 3. In case 3, non-uniformity in acceleration of the shell is observed clearly, the velocity of the shell on the axis opposite side of the cone is larger than that of the shell at perpendicular to the axis, where implosion velocity is dropped to be 2.80x10$^7$ cm/s (Fig.3a). Inside the shell, after the first shock hits the cone surface, it begins expanding and affect to the imploeding shell. This non-uniformity is caused by the effect of the gold plasma which makes the longer standoff distance near the cone. For the same reason, but more critical break up is occurred in case 4. Figure 3b shows the mass density and electron temperature contours before breaking up. The ablation effect of the gold cone propagates with the velocity of the sound of speed. For the robust target design, whole implosion process should be finished before the effect travel through, or effect of the cone should be reduced.

Also, the large in-flight aspect ratio (> 200) causes the critical condition. The thicker target can be designed to stabilize the instability of CH shell target.
These simulations are preliminary study where some simple assumptions are included. And the result does not mean foot pulse is ineffective. With sophisticated target (shell and cone), laser beam configurations, and duration time of foot pulse, the effect of gold cone could be reduced in next step.

The radiation transport is an important physics in gold cone-guided implosion [5]. The detail design work should be done with the radiation transport calculation, as well as the D₂ and DT cryogenic target.

3. Summary
Two-dimensional cone-guided implosion simulations are performed for preliminary target design of FIREX-I, fast ignition experiment. In the cases of using a single Gaussian pulse, \( \rho R \) increases as the initial total mass increases. An implosion with a foot pulse case, a target cannot be accelerated uniformly, and finally it is broken up. It seems that the implosion must be finished before the ablated plasma from the cone affects to the dynamics of imploding shell. More sophisticated target and laser pulse shape designs for the reduction of gold-cone effect are necessary to achieve the FIREX-I requirement.

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