An optimum design of implosion with external magnetic field for electron beam guiding in fast ignition

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Abstract. Compression of solid spherical target under the strong external magnetic field is studied using two dimensional radiative magneto-hydrodynamic (MHD) simulation code for fast ignition. The simulation results show that a compression of a solid sphere target is stable, and it is possible to achieve a high areal density core plasma. Assuming the GXII scale laser, it will be $\rho R = 60-80 \text{mg/cm}^2$. Due to the magnetic diffusion in the solid target, the magnetic mirror ratio is less than 4, which does not reflect most of the hot electrons for heating core. These properties are preferable for fast ignition scheme.

1. Introduction
In the first ignition scheme, formation of a high dense core plasma is required in implosion process, as well as the high heating efficiency in heating the core process. Recent studies show that heating efficiency from laser to core is very low due to the large divergence angle of the hot electron beam generated by an ultra-intense laser. A reliable beam convergence method is necessary to improve it. External magnetic field is a possible candidate for the purpose. Recently, the beam divergence method is confirmed computationally and experimentally [1, 2].

However, the strong magnetic field may affect the implosion dynamics where electron heat conduction is anisotropic depending on the angle between the ablation surface direction and the magnetic field line [3]. In our previous work, we showed that imploding CD shell was broken during the acceleration phase in an implosion [4]. Controlling the implosion dynamics in order to avoid or delay the fatal break is extremely difficult by changing the target thickness or laser irradiation laser patterns. Furthermore, at the maximum compression time, the compressed magnetic field formed a mirror structure between the tip of the cone and dense core. Its mirror ratio was high enough to reflect the hot electrons. Therefore, we should introduce an alternative scheme to achieve high dense core plasma which has preferable properties for fast ignition under these conditions.

Here, we investigate a possibility of the solid target for fast ignition. The compression of solid target is hydrodynamic instability free and the life time of the core is longer than shell implosion. Therefore, it is assumed to be more reliable target to achieve high dense core under such extreme conditions.
However, maximum density is not high enough as ideal conventional shell implosion, and intensity of magnetic field may be reduced by the diffusion in the solid target. 2-D radiative MHD simulation is conducted to confirm the possibility of the target in this study.

2. Computational simulations

2.1. Simulation method
We have conducted computational simulations using 2-D radiative magneto-hydrodynamics simulation code (PINOCO-MHD) [4] for this study. PINOCO-MHD is designed for single-fluid two-temperature hydrodynamics with thermal transport, radiation transport equations, equation of state (QEOS), laser ray-trace and absorption, resistive MHD models and so on. The diameter of the deuterated polystyrene (CD) solid target is 200 \( \mu \)m (Fig.1). The solid target is inserted by a gold conical target of which open angle, and thickness are 45 degree and 15 \( \mu \)m respectively. The distance between tip of the cone and center of the solid target is 60 \( \mu \)m. The laser energy, wavelength, and pulse shape are 2.0 kJ with 9 beams of GXII laser, 0.53 \( \mu \)m, and Gaussian (pulse width: 1.3 ns) respectively. Several simulations are conducted for different initial magnetic field strength, 0, 0.2, 0.5 1.0, 1.5, and 2.0 kilo-Telsa (kT), of which directions are parallel to the symmetric axis. Braginskii’s electron heat conduction coefficient [3] is applied in the MHD simulation. Magnitude of magnetic pressure is estimated. In the result, it is very small at whole region during the compression. The ratio of the pressure plasma to the magnetic pressure \( \beta \) is \( \beta >100 \). Therefore magnetic pressure is not taken account into this study.

2.2. Simulation results
Figures 2 show mass density contours at the maximum compression time for \( B_0 = 0, 0.5, 2.0 \) kT. The targets are fairly compressed in spite of the strong magnetic field and the existence of the gold cone. The maximum core densities are reached \( \rho_{core} \) are 60-80 g/cm\(^3\) for all cases. Due to the suppression of the electron heat conduction which cross the magnetic field lines, core is compressed asymmetrically, and the core becomes cigarette shape, of which radius is about 20 \( \mu \)m, whereas it is about 30 \( \mu \)m in without magnetic field case. This narrow cross section leads the low heating efficiency. However it will be improved if elliptic solid target and/or sophisticatedly controlled non-uniform laser irradiation is applied.

Figures 3 show the magnetic field lines at...
the maximum compression time for $B_0=0.5$ and 2.0 kT cases. The line colours indicate the magnetic field strength. For ideal MHD assumption, magnetic field at the compressed core will be $B_{\text{core}}=3-4$ and 13-17 kT for $B_0=0.5$ and 2.0 kT cases respectively. However, it is only a quarter to the ideal cases, due to the magnetic diffusion transport at solid target area. Because the solid target is kept low temperature and solid density until the shockwave pass through, the magnetic diffusion is dominant during the compression process. This is preferable fact for heating process, and finally the magnetic mirror ratio is limited in $R_M < 4$ for all the cases. In these conditions, most of the electron beam for heating can be transported into the compressed core.

Temporal averaged areal densities for $B_0=0, 0.5, 1.0$ and 2.0 kT are plotted in Fig. 4. The maximum areal densities increase as a function of the $B_0$, and they are higher than the case without magnetic field, because the suppression of the thermal conduction enhances the compression toward the radial direction. The maximum times of the case with magnetic field are 170-190 picoseconds earlier than the case without magnetic field also. This difference should be paid attention in experiment. The life time of the high dense core are about 100 picosecond, which is longer than shell implosion case which is a few tens of picosecond. This means that heating trimming is less sensitive for solid target case. However, the tip of the cone is exposed to the high pressure for longer period. Optimization of the heating timing is still significant issue.

In the result we conclude that a solid target is probable target for electron beam heating fast ignition. This is preliminary simulation with Gaussian shaped pulse. The solid target has high potential to obtain higher compression if we can use sophisticated tailor laser pulse [5].

In order to investigate the detail performance of the solid target, integrated simulations of whole process of fast ignition [6] is necessary. Some preliminary simulations show that 2 kT of the magnetic field at the injection point of the hot electron to guide them toward the high dense core [7].

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**Fig. 3.** Magnetic field lines at the maximum compression time for $B_0=0.5$ and 2.0 kT. The line colours indicate the magnetic field strength.

**Fig. 4.** Temporal averaged areal density (left axis; g/cm²) and laser intensity (right axis; TW/cm²).
3. Summary
We have studied the compression of solid target with gold conical target under the strong external magnetic field using two dimensional radiative MHD simulation code. The simulation results show that a compression of a solid sphere target is stable, and it is possible to achieve a high areal density core plasma. Assuming the GXII scale laser, it will be $\rho R = 60-80$ mg/cm$^2$. In the solid target magnetic diffusion is dominant and it is diminished. The magnetic mirror ratio is less than 4 which does not reflect most of the hot electrons for heating core at the maximum compression time.

In this study laser pulse shape is Gaussian shape only. With a sophisticated tailored pulse and target we can achieve higher compression with the solid target.

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