Electron beam guiding by external magnetic fields in imploded fuel plasma

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Abstract. For enhancing the core heating efficiency in fast ignition laser fusion, we proposed the fast electron beam by externally-applied the kilo-tesla (kT) class longitudinal magnetic field. We evaluated the imploded core and the magnetic field profiles formed through the implosion dynamics by resistive MHD radiation hydro code. Using those profiles, the guiding effect was evaluated by fast electron transport simulations, which shows that in addition to the feasible field configuration (moderate mirror ratio), the kT-class magnetic field is required at the fast electron generation point. In this case, the significant enhancement in heating efficiency is expected.

1. Introduction

One of the most crucial issues of electron-driven fast ignition is efficient core heating by laser produced relativistic electron beam (REB). Two factors, which mainly degrade the efficient heating, are (1) too high electron energy, and (2) too large beam divergence. For improving the efficiency in FIREX project [1], we proposed the REB guiding by externally applied kilo-tesla (kT) -class longitudinal magnetic fields generated by a capacitor-coil target [2] and evaluated its effects by 2D PIC simulations[3,4]. It was demonstrated that the REB with a large divergence angle generated by a relativistic laser plasma interaction with a laser of intensity 3×10^19 W/cm^2 and duration 1 ps can successfully focused by the moderately-converging fields (mirror ratio RM ≤ 20) [4]. In addition, formation of a magnetic-pipe like structure due to the resistive effects was shown, which indicates a possibility of the beam focusing even under the higher mirror fields that may be achieved in the ignition-scale or high-gain target implosion. However, in the implosion simulation [5] for a cone-attached CD shell target with externally-applied B-field by a one-turn coil, the ratio of B-field strength at the cone tip to that in the region between cone tip and dense core reaches RM > 100 at the maximum compression. In such a case, the fast electrons could not pass the very high RM region and could not reach the core, so that the core heating would be very inefficient. Hence it is critical to check the electron transport in more realistic configuration formed through the compression dynamics.

In the present paper, we discuss the core heating properties for the dense core with the converging magnetic field configuration formed through the implosion of cone-attached CD spherical solid target.
on the basis of integrated simulations [6, 7]. In the following, we present the integrated simulation results for core heating by REB with large beam divergence under the compressed core and magnetic fields.

2. Simulation model

To obtain the imploded core profile and magnetic field configuration, the implosion simulations were carried out for a Au cone attached CD spherical solid target using a 2D radiation-hydro code PINOCO [8], which is designed for single-fluid two-temperature hydrodynamics, thermal transport, radiation transport equations, equation of state and laser absorption, is extended to make a resistive magnetohydrodynamic code [5]. The implosion simulation conditions are based on the feasible conditions for the GEKKO-XII (GXII) laser system at ILE Osaka University. The total energy and the wavelength of the laser are 1.5 kJ on target and 0.53 \( \mu \text{m} \), respectively. The pulse shape is Gaussian with 1.3 ns (FWHM) and the peak timing is 1.5 ns.

Using the obtained core and magnetic-field profiles, the core heating by the REB was simulated by FIBMET [9], where the transport of REB is solved by particle scheme instead of Fokker-Planck equation. In the present study, we did not consider the fast electron generation process. The REB was injected at the tip of cone. We used the experimentally observed energy spectrum [10], where \( f(E) \propto 0.95\exp(-E/0.9[\text{MeV}]) + 0.05\exp(-E/5[\text{MeV}]) \) (\( E \) is electron energy in MeV). The beam divergence angle of 45 degree half angle was assumed. The Gaussian profile with 1 ps duration (FWHM) and the Super Gaussian with 20 \( \mu \text{m} \) radius (HWHM) were assumed for temporal and spatial profiles. The peak REB intensity was assumed as 1.55x10^{19} \text{W/cm}^2. The injected REB energy was 410 J.

3. Simulation results

3.1. Implosion of cone-attached CD solid spherical target

The implosion simulation was carried out for a cone-attached CD spherical solid target (Fig.1). In the simulation, the uniform magnetic field with the strength of 0.2kT was initially applied in \( z \)-direction. The obtained density and magnetic field profiles at the maximum compression are shown in Fig.2. In the conventional shell implosion simulation for GXII, the core density reached \( \rho_{\text{core}} \sim 100 \text{ g/cm}^3 \) [5]. Contrary to this, in the present simulation for the solid target, the density is lower (\( \rho_{\text{core}} \sim 30 \text{ g/cm}^3 \)). The obtained fuel \( \rho R \) at the maximum compression is 0.1 g/cm\(^2\) in \( z \)-direction and 0.06 g/cm\(^2\) in \( r \)-direction, which is comparable to that obtained in the shell implosion. The achievement of comparable \( \rho R \) despite the lower density is due to the larger mass of the solid target than that for the shell target.

As for the magnetic field profile, the magnetic-field lines are smooth and the mirror ratio (the ratio of magnetic field strength at the cone tip to that in the compressed core) is \( R_M \sim 4 \). Such a moderate mirror configuration is feasible for REB guiding and focusing [4]. Such a moderate compression of magnetic field and mirror ratio is due to the lower compression of the fuel target and the high magnetic diffusivity in the cold CD solid region.
3.2. Core heating of imploded core by fast electron beam

Using the fuel and magnetic field profiles at the maximum compression, we carried out the core heating simulations. The REB having above noted profiles is injected in the cone tip. To evaluate the dependence of magnetic field strength, the magnetic field strength shown in Fig.2 was multiplied by 0, 1, 2.5, 5, 10. Each multiplying factor corresponds to the magnetic field-strength at the injection point 0, 0.2, 0.5, 1.0, 2.0 kT, respectively.

Fig.3 shows the fast electron energy density profiles at the peak REB intensity. If the external field is neglected (upper figure), the REB is diverged due to the large beam divergence though the part of the fast electrons are focused at the central axis at \( z = 40 \mu m \) by the self-generated magnetic fields. Since the magnetic field strength of \( B_{z0} = 0.2 \) kT at the REB injection region is not strong enough to trap the MeV-class fast electrons, the REB is also diverged in this case (middle figure). When \( B_{z0} = 2 \) kT (lower figure), most of the fast electrons are trapped by the magnetic fields and moves along the magnetic field lines, then the REB is focused at the central axis at \( z = 60 \mu m \). In Figure 4, the energy deposited by the fast electrons in the dense core region (\( \rho > 5 \) g/cm\(^3\)) is plotted as a function of \( B_{z0} \). The energy coupling efficiency from the heating laser to the core is shown in the right axis, where the experimentally measured conversion efficiency from the laser energy to the REB energy, 31%, is used. The heating efficiency is monotonically increases in the sub-kT region, and the enhancement is saturated in the kT-class region. The heating efficiency for \( B_{z0} = 2 \) kT becomes about twice larger than that for the case without external field. It is found then that for effective guiding by external magnetic field, kT-class magnetic field is required at the injection point. This is because the MeV-class fast electrons should be confined within \( r = \text{several} \sim 10\text{'}s \) \( \mu m \). Otherwise, the fast electron escape from the strong magnetic field region (see Fig.2). This requirement is consist with the previous PIC simulations [3, 4].

The direct measurement of energy coupling efficiency is difficult in the experiments. Instead, the neutron yield \( Y_{n,dd} \) and neutron weighted ion temperature \( <T_i>_{n,dd} \) will be measured. So, the dependences of \( Y_{n,dd} \) and \( <T_i>_{n,dd} \) on \( B_{z0} \) are evaluated and plotted in Fig.5. For the case without REB heating, \( Y_{n,dd} \) is less than \( 10^5 \) and \( <T_i>_{n,dd} \) is about 0.5 keV. When the REB is injected without the external magnetic field or with sub-kT external field, \( Y_{n,dd} \) and \( <T_i>_{n,dd} \) are increased slightly. However, such small enhancement cannot be observed experimentally due to the existence of large noise. If the kT-class field is applied, the heating effect becomes pronounced and
then the clear enhancements in $Y_{n,dd}$ and $<T_i>_{n,dd}$ can be observed. For $B_{z0} = 2$ kT, $Y_{n,dd}$ is $10^7$, which is larger than that for the case without external field by two orders of magnitude, and $<T_i>_{n,dd} = 1.06$ keV, which means 0.5 keV enhancement from the case without REB heating. These clear enhancements in $Y_{n,dd}$ and $<T_i>_{n,dd}$ could be measured in the experiments.

**Figure 5.** Neutron yield $Y_{n,DD}$ (left) and neutron-weighted ion temperature $<T_i>_{n,dd}$ as a function of magnetic field strength at the injection point $B_{z0}$

### 4. Conclusion

The integrated simulation for evaluation of fast electron guiding effect by external magnetic field showed that for the cone-attached CD solid spherical target case, the compression of magnetic field by implosion is not so high, then the feasible mirror ratio ($R_M \sim 4$) is obtained. From the transport simulations for REB using the imploded core and magnetic field profiles obtained from implosion simulation, it is found that not only the magnetic field configuration (mirror ratio), the strength of magnetic field at the fast electron generation region is important. The kT-class magnetic field is required around the fast electron generation point to confine them in the strong magnetic field region.

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