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Integrated simulations of core heating in cone-guiding fast ignition, FIREX-I

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Abstract. The core heating properties of a Au cone-attached CD shell target in FIREX-I were investigated by the integrated simulations with FI³ code systems. The importance of fast electron transport in the deformed cone tip was shown. In addition to the collisional scattering and drag in the Au cone, the strong resistive magnetic field is generated at the top of the cone tip when the tip shape is deformed. Due to this field, the fast electrons are strongly scattered, and then the core heating efficiency becomes smaller compared with the case neglecting the magnetic field.

1. Introduction

In the cone-guiding fast ignition, an imploded core is heated by the energy transport of fast electrons generated at the cone inner surface. In FIREX-I [1], our goal is the demonstration of efficient core heating ($T_i \sim 5$keV) using a newly developed 10kJ- LFEX laser.

We evaluated the core heating in FIREX-I by the 1D PIC and Fokker-Planck (FP) simulations [2], and also 2D FP simulations [3]. In the high-Z cone case (e.g., Au), the rapid density steepening of the interaction surface and the strong scattering due to highly ionized atoms occur, which reduce the conversion efficiency of heating laser to fast electrons. In addition, since the Au atoms in cone tip reaches highly ionized state rapidly, the fast electron beam quality deteriorates due to the collisional and resistive drags and scattering by Au ions in the cone tip. As the results, the core heating rate becomes lower with time even for the fast electron beam with the constant intensity. Thus, we proposed a low-Z material (e.g., CH) as an alternative of cone tip material to reduce the collisional effects. We also found in the 2D simulations assuming a spherical core that the magnetic field generated around the core edge due to the thermoelectric current weakens the self-guiding effect [3, 4, 5] due to the resistive magnetic field, which reduces the core heating efficiency.

In the above simulations [2, 3], we did not consider the implosion dynamics. In the implosion of cone-attached shell targets, the core shape is far from the spherical one and the cone tip is deformed by the jet-like plasma flow from the imploded core, which may affect the core heating properties. In the present paper, on the basis of integrated simulation using FI³ code system [6], we evaluate the core heating properties in FIREX-I; e.g., the effects of core and cone tip deformation.
2. Implosion simulation for cone-guiding CD shell target

First, we carried out an implosion simulation with a 2D radiation-hydro code “PINOCO” [7] for a CD shell target (8 μm thickness, 250 μm inner radius and $10^{-4}$g/cm$^3$ gas in the shell). An Au cone (30 degree opening angle, 50μm offset from the shell center, 10μm tip inner radius, 7μm tip thickness and 5μm wall thickness near the tip) is attached to the shell. The shell is uniformly irradiated by 2.5kJ Gaussian-pulse-shaped green laser ($\lambda_L = 0.53 \mu m$). The compressed core profiles are shown in Fig.1. The maximum compression is obtained at $t = 2.02$ns. The most part of the shell was highly compressed although the imploding shell contacting to the cone wall rolled up and was dragged by the Kelvin-Helmholtz instability. The core density reaches higher than 120 g/cm$^3$ at the maximum. Because of the pressure imbalance due to the existence of the cone, the hot spot is moved toward the cone tip. This flow hits the cone tip 50ps before the maximum compression. At the maximum compression, the cone tip considerably collapsed and the low density plasma penetrates into the vacuum region inside the cone, which is not preferable for core heating. Thus, in the following core heating analysis, we use the imploded core profile at $t = 1.97$ns. At this moment, the cone tip is already deformed, but the vacuum region inside the cone is still kept clean. The optical size of the core is $\rho dz \sim 0.14$g/cm$^2$.

![Figure 1](image1.png)

Figure 1. Imploded core profiles obtained from a PINOCO simulation; (a) temporal profile of maximum density ($\rho_{\text{max}}$), maximum ion temperature ($T_{\text{max}}$) and DD fusion reaction rate ($R_{\text{DD}}$), (b) spatial profiles of density and ion temperature at 1.97ns and (c) spatial profiles at 2.02ns.

3. Core heating by fast electron

Using the imploded core profile at $t = 1.97$ns (Fig.1 (b)) as the initial bulk plasma profile, we carried out the core heating simulations, where the bulk plasma is treated with radiation-hydro model and the fast electron transport is treated with Fokker-Planck transport model [3, 8]. The fast electron beam having the slope temperature of $T_{\text{le}} = 1.0$MeV, the superr Gaussian radial profile with $r_{\text{FWHM}} = 15\mu$m, the angular spread of 20 degree full angle and the duration of $\tau_{\text{le}} = 5$ps (constant intensity during $\tau_{\text{le}}$) is injected inside the Au cone tip. The injected beam energy $E_{\text{le}}$ is 5kJ, which corresponds to the energy coupling of $\eta_{\text{L} \rightarrow \text{le}} = 50\%$ from the 10kJ LFEX laser to the fast electron beam. To evaluate the magnetic field effects, we carried out the simulations assuming two different field conditions (with and without the magnetic-field).

In Fig.2, the spatial profiles of fast electron heating rate at $t = 3$ps are shown for the cases without and with the magnetic field. As was pointed out in our previous work [3], when a high-Z material such as Au is used as the cone material, the fast electrons lose their kinetic...
energy in the cone tip due to the collisional and resistive drag. Thus in Fig.2, high heating rates in the cone tip are observed in the both cases in Fig.2. As for the heating rate in the dense core, the uniform heating is observed in the case without magnetic-field. Contrary to this, in the case with the magnetic field, the multi-spots of heating rate are observed in the core region. In addition, the heating by the transverse fast electron flow is observed in the plasma surrounding the cone side wall. These are caused by the magnetic-field around the cone tip.

The spatial profile of azimuthal magnetic field observed at $t = 3$ps is shown in Fig.3. Together with the result of the present simulation including magnetic field, the magnetic field profile obtained at $t = 3$ps in the previous work [3] is shown, where the “clean” cone tip (not deformed) and spherical CD core were assumed and the fast beam condition was the same as that in the present simulation. Even in the “clean” cone tip case (Fig.3(b)), the strong magnetic field generated around the cone side wall, which is due to the resistivity jump at the material contact surface between Au cone and the imploded CD plasma [9, 10]. Compared with the outer coronal CD plasma, the inner Au cone has a larger resistivity because of the larger $Z$, so that the resistive magnetic field ($\nabla \eta \times j_f$, where $\eta$ is the plasma resistivity and $j_f$ is the fast electron current density) is generated at the contact surface. However, at the top of the cone tip, the directions of $\nabla \eta$ and $j_f$ are nearly parallel in the “clean” cone tip case, so that the magnetic field is not strong. On the other hand, in the case using the imploded core profile (Fig.3(a)), the cone tip is deformed by the attack of the plasma flow from the imploded core. At the top of the cone tip, hence, $\nabla \eta$ and $j_f$ are not parallel, which results in generating the strong magnetic field. The fast electrons are hence scattered by this magnetic field. In addition to the collisional scattering in the Au cone, because of the scattering by the magnetic field, the beam divergence becomes larger and the self-guiding magnetic field, which is observed at the core heating simulations neglecting the fast electron transport in the cone tip [3, 4, 5], is not clearly formed. As the result, the fast electron beam breaks into several filamentous beams, which results in the multi-spot heating of the core.

The temporal evolution of $<T_e>_{DD}$ and $<T_i>_{DD}$ are shown in Fig.4, where $<T_e>_{DD}$ and $<T_i>_{DD}$ are the spatially-averaged bulk electron and ion temperatures weighted by DD reaction rates. The initial peak of $<T_e>_{DD}$ observed around $t = 0.6$ps results from the heating in the low density region between the cone tip and the dense core. At the initial phase, the fusion reactions mainly occur at this low-density and relatively-high-temperature region, since the temperature in the dense core region is so low ($<0.2$keV) (shown in Fig.1). With time passing, the temperature in dense core region rises due to the fast electron heating, and the fusion reactions mainly take place in the dense core region. So, the $<T_e>_{DD}$ after $t = 1.5$ps represents the mean

![Figure 3. spatial profile of azimuthal magnetic field [T] observed at $t = 3$ps obtained for the cases for (a) using the imploded core profile and (b) assuming “clean” cone tip and spherical core. The density contours are presented by red thin lines.](image3)

![Figure 4. Temporal evolution of $<T_e>_{DD}$ and $<T_i>_{DD}$ for the cases with (solid) and without (broken) magnetic field](image4)
temperature of the dense core region. The difference between \( T_{e>DD} \) and \( T_{i>DD} \) comes from the slower temperature relaxation compared with the bulk electron heating by the fast electrons. Between the two cases (with and without magnetic field), the difference in \( T_{e>DD} \) is small in the early phase \( (t < 3.0\text{ps}) \). However, in the later phase, \( T_{e>DD} \) for the case with the magnetic field becomes smaller compared with the case without the magnetic field since the scattering by the magnetic field becomes significant. This result is contrary to the simulations without the fast electron transport in the cone tip, where the core heating rate and the resultant core temperature are enhanced due to the self-guiding resistive fields. The present simulation result indicates the importance of inclusion of the fast electron transport in the cone for evaluating the core heating. The core heating properties are summarized in Table I. The energy coupling of the fast electron to the core and the maximum values of \( T_{e>DD} \) and \( T_{i>DD} \) are \( \eta_{fe-core} = 20.8\% \), \( T_{e>DD,max} = 4.15\text{keV} \) and \( T_{i>DD,max} = 3.06\text{keV} \) for the case including the magnetic field, and the values are smaller than those for the case neglecting the magnetic field.

| B-fields | \( E_{dep,core}(\eta_{fe-core}) \) | \( T_{e>DD,max} \) | \( T_{i>DD,max} \) |
|----------|-----------------------------------|-----------------|-----------------|
| w/o      | 1.83kJ (36.6\%)                  | 4.63keV         | 3.70 keV        |
| with     | 1.04kJ (20.8\%)                  | 4.15 keV        | 3.24 keV        |

* \( E_{dep,core} \) and \( \eta_{fe-core} \) are the fast electron deposited energy in the core \( (\rho > 5g/cm^3) \) and the energy coupling of fast electron to the core.

4. Summary

The core heating properties of a Au cone-attached CD shell target in FIREX-I were investigated by the integrated simulations with FI3 code systems [6] and the importance of the transport in the deformed cone tip was shown. In addition to the collisional scattering and drag in the Au cone, the strong resistive magnetic field is generated at the top of the cone tip if the tip shape is deformed. The fast electrons are strongly scattered by this magnetic field and then the core heating efficiency becomes smaller compared with the case neglecting the magnetic field. Under such a situation, the self-guiding due to the resistive field can no longer be expected.

In the present study, we assumed an ideal fast electron beam profile. Further investigation including fast electron generation is required for overall understanding of the core heating dynamics.

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