

Direct heating of compressed core by ultra-intense laser

A Sunahara¹, T Johzaki², H Sakagami³, H Nagatomo⁴, K Mima⁵, Y Abe⁴, Y Arikawa⁴,
S Fujioka⁴, H Shiraga⁴, H Azechi⁴, Y Mori⁵, Y Sentoku⁶ and Y Kitagawa⁵

¹ Institute for Laser Technology, 2-6 Yamadaoka Suita Osaka 565-0871, Japan

² Graduate school of Engineering, Hiroshima University,
1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527, Japan

³ National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

⁴ Institute of Laser Engineering, Osaka University,
2-6 Yamadaoka Suita, Osaka 565-0871, Japan

⁵ The Graduate School for the Creation of New Photonics Industries,
Kurematsuchou, 1955-1 Nishi-ku, Hamamatsu 431-1202, Japan

⁶ Department of Physics, University of Nevada, Reno
1664 N. Virginia St. Reno, NV 89557, USA

E-mail: suna@ilt.or.jp,

Abstract. We propose a new scheme for heating an imploded core in the fast-ignition scheme. In this method, a heating laser irradiates an imploded core plasma directly. The accelerated fast-ions as well as fast-electrons heat the core. Two-dimensional particle in cell (PIC) simulation confirmed that carbon C⁶⁺ and deuteron D⁺ ions were accelerated as well as fast electrons when ultra-intense laser irradiates the CD plasma. In order to estimate the temperature scaling of the heated core in this scheme, we conducted transport simulations in the one-dimensional conical geometry. Our results show that 5 keV of ignition temperature can be achieved at the intensity of 10²¹ W/cm², and 1.5 ps pulse for the compressed CD plasma with 10g/cm³ density.

1. Introduction

In the fast ignition scheme of inertial confinement fusion (ICF), the conventional method uses laser-accelerated fast electrons only to heat the imploded core plasma. The plasma core is heated by the energy deposition of fast electrons up to the temperature required for initiating the thermonuclear ignition [1]. The final temperature of the compressed core plasma should reach at least 5 keV in order to ignite the thermonuclear burn. At the institute of Laser Engineering at Osaka University, we have been conducting the Fast Ignition Realization Experiment (FIREX) [2], demonstrating an increase of the neutron yield with increasing heating laser energy [3]. In order to ignite the thermonuclear burn with minimal heating energy, the energy coupling efficiency from heating laser to the core heating should be large. Therefore, we proposed an alternative method that included a fast ion based ignition scheme [4, 5, 6, 7, 8]. In this presentation, we propose a new approach, in which the imploded core is directly heated by an ultra-intense laser to increase the energy coupling as shown in Fig. 1. As in the conventional fast ignition, we use a cone attached shell target to prevent the interaction of heating laser with the long scale coronal plasma generated in the implosion. When the high pressure of



imploded core plasma breaks up the tip of the cone, the heating laser can directly irradiate the imploded plasma expanding into the cone. As the result, the heating laser directly irradiates the imploded core. This is a straightforward way to improve the energy coupling from the laser to the core heating. Although this scheme requires the exact simultaneous occurrence of the break up of the tip and irradiation of the heating laser, it allows generation of fast-ions, as well as the fast electrons, and both fast electrons and fast-ions also contribute to heating of the core. In order to estimate the temperature scaling of the core in this scheme, we simulated the temperature of the core plasma heated by the fast-electron and ions. In Sec. II, we estimate the generation of fast ions and electrons. The heating model is described in Sec. III. In Sec. IV, we estimate the core temperature. Our summary and conclusion are in Sec. V.

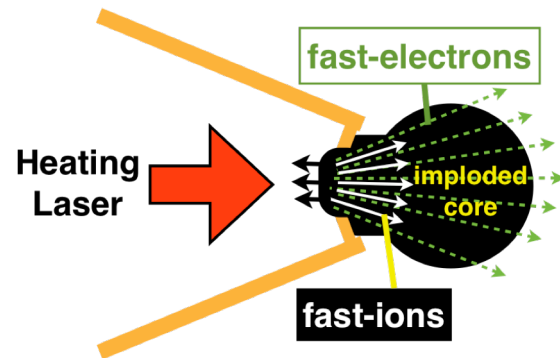


Fig.1 Schematic of our heating concept. Heating laser irradiate the imploded CD core directly through the hole of cone target. White solid lines show accelerated fast-ions. Dotted lines show fast electrons.

2. Generation of fast ions and electrons

When an ultra-intense laser irradiates an imploded plasma core, the laser interacts with the critical density plasma that is a relatively lower density part of the plasma surrounding the high-density core. In the laser-irradiated region, the fast electrons are accelerated by the ponderomotive force of the ultra-intense laser, while the fast ions are accelerated by the electric field caused by charge separation [9]. In order to estimate generation of fast-ions and electrons, we have conducted 2D Particle in Cell (PIC) simulations. In the simulation, a 10 μm thick and 10 μm wide fully ionized CD target with pre-formed plasma having the scale length of 5 μm , and the electron density n_e of 0.1 n_c to 10 n_c is irradiated by $\lambda_L = 1 \mu\text{m}$ wavelength laser. Here n_c is the critical density. The laser temporal profile is a 1 ps flat pulse. The grid size is set to $\lambda_L/64$. The maximum electron density is 100 n_c . The estimated conversion efficiency from the ultra-intense laser to the fast ions and electrons at varying laser intensities are shown in Table. I. The conversion efficiency $\eta_{C^{6+}}$ of fast-carbon is limited to be of the order of 1-3% of incident laser energy, and η_e of fast electrons is over 70%. However, even a small number of the fast ions can contribute the core heating due to its shorter stopping range compared to that of fast electrons.

Table. I
PIC calculated conversion efficiency of fast- electron, carbon ion, and deuteron, in function of laser intensity, respectively.

I_L (W/cm ²)	η_{e^-} (%)	$\eta_{C^{6+}}$ (%)	η_{D^+} (%)
1e19	71.4	1.2	0.2
3e19	69.4	2.2	0.6
1e20	84.8	3.0	0.7

3. Core heating model

In order to estimate the temperature of the core plasma heated by both fast-ions and fast-electrons, we constructed 1D integrated heating model, based on the 1D fluid equation coupled with the transport of ions, electrons, and the radiation. For the transport of the fast electrons, we use the ray-tracing method. This treatment is valid in the condition where the change of the electrons kinetic energy ΔE during transport is negligible compared to the kinetic energy E . We assume the energy spectrum of fast electrons at the injection point as

$$f_e(E) = n_{e0} \exp(-E/T_{\text{slope}}). \quad (1)$$

Here, E and T_{slope} is the kinetic energy and the slope temperature of fast electrons, respectively. n_{e0} is the electron number density at velocity = 0. We divided energy spectrum in 100 bins of rays in the energy range of 0 to 50 MeV. For fast electrons, we calculated the drag-heating and ohmic-heating with Spitzer resistivity at each spatial mesh. For the ion heating, we inject the ion particles having the monotonic energy estimated from the momentum balance between laser and accelerated ions [9]. The ion-stopping range is estimated by Mehlhorn [10]. The ionization degree and heat capacity of CD plasma is calculated using Thomas-Fermi model. We also include the electron-ion temperature relaxation and the radiation energy loss due to the brems-strahlung from CD plasma.

4. Simulation

In order to carry out simulation in the realistic condition by our 1D model, we assume the conical plasma region in the calculation shown in Fig.2. Here, the diameter D of fast electrons and ions at the injection point are assumed to be $50\mu\text{m}$ of the current LFEX laser spot diameter [2]. Here, we use the constant plasma density with immobile bulk CD plasmas. In order to set different divergence angle of fast electron and ions, we set the angles of the conical regions to be $\theta_e = 35$ deg (half angle) for the fast electrons and $\theta_i = 20$ deg for the fast ions, respectively. We set the plasma size, ℓ is set to $200\mu\text{m}$, and the initial temperature of the core plasma to $T_i(x) = T_e(x) = 500\text{eV}$. The plasma density is set to 100g/cm^2 . The wavelength of the heating laser is $1.05\mu\text{m}$, and the laser pulse duration is 1.5 ps. The slope temperature of fast electrons T_{slope} is given by the scaling law of Wilks [9] and Haines [11] as a function of the laser intensity. The conversion efficiency from the laser to the forward-moving fast electron is set to 0.4, estimated by PIC simulation. T_{slope} may be higher than that expected by Wilks and Haines scaling, due to the existence of coronal plasma with the long density scale length. A way of avoiding this is to use a membrane.

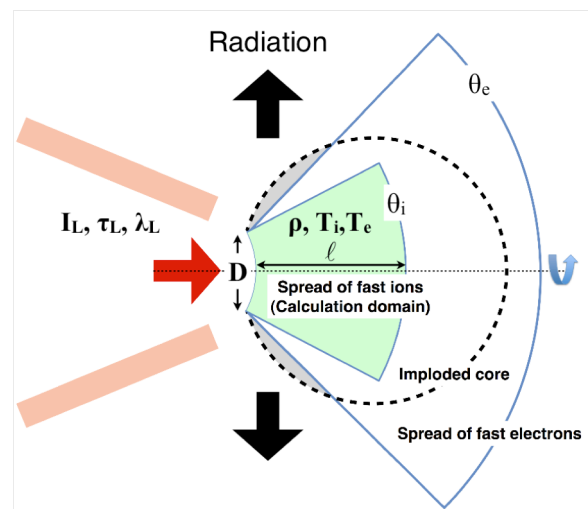
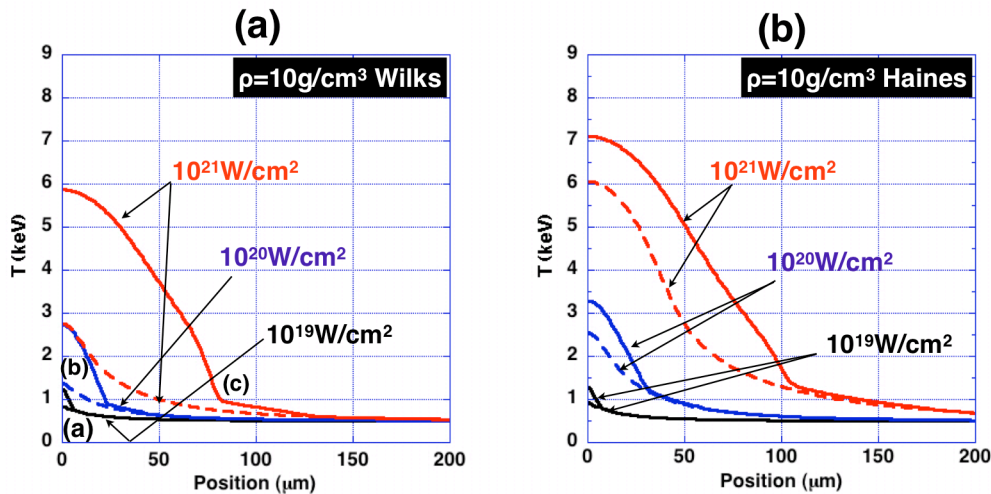


Fig. 2. Simulation condition

The temperature of fast electrons T_{slope} is given by the scaling law of Wilks [9] and Haines [11] as a function of the laser intensity. The conversion efficiency from the laser to the forward-moving fast electron is set to 0.4, estimated by PIC simulation. T_{slope} may be higher than that expected by Wilks and Haines scaling, due to the existence of coronal plasma with the long density scale length. A way of avoiding this is to use a membrane.

In Figs. 3(a) and (b), we show the temperature profiles of the heated core of 100g/cm^3 , using Wilks model for the electron slope temperature shown in Fig. 3(a), and those using Haines model in Fig. 3(b), for the heating laser intensity of 10^{19}W/cm^2 , 10^{20}W/cm^2 , and 10^{21}W/cm^2 , respectively. These profiles correspond to the timing when the ion temperature is maximum just after the relaxation time between electrons and ions of several ps. Here the energy of the heating laser at the intensity of 10^{21}W/cm^2 corresponds to 30 kJ. In Figs. 3(a) and 3(b), we see the temperature rise, which is composed of three different components: for long scale heating component is due to fast electrons. middle-range component due to D^+ ion heating, and the Short-range temperature rise due to C^{6+} , respectively. Figure 3(a) shows that the maximum temperature is 1 keV at 10^{19}W/cm^2 corresponding to the laser intensity of the current FIREX experiment [2]. Also, as the laser intensity increases, contribution from the ion heating increases. In comparison of the temperature with or without the ion heating, the condition of fast electron heating only gives the maximum ion temperature of 2 keV at the intensity of 10^{21}W/cm^2 . However, the case including both fast electrons and ions at the same intensity yields the maximum ion temperature of 6 keV, showing that the contribution of the fast ions is significant. In Fig. 3(b), we observe that the contribution of fast electrons to the core heating is larger than that shown in Fig. 3(a). This is because of the difference of the slope temperature of fast electrons



Figs. 3(a) and (b) Temperature profile of heated core with density of 10g/cm^3 . (a) Wilks model is used for the electron slope temperature, (b) Haines slope temperature is used. In each figure, solid lines include both of electron and ion heating. Broken lines show electron heating (ohmic + drag) only. The heating laser intensity (a) 10^{19}W/cm^2 , (b) 10^{20}W/cm^2 , and (c) 10^{21}W/cm^2 , respectively.

given by Wilkes and Haines. Haines scaling law shown in Fig. 3(b) gives lower slope temperatures of fast electrons. Therefore, Fig 3(b) using Haines slope temperature shows a more efficient heating, compared to that of Fig. 3(a) for the same initial condition.

5. Summary

We propose a new scheme for heating the plasma in the fast-ignition scheme. In this method, a heating laser *directly* irradiates the imploded core through the hole of a cone attached to the shell. Consequently, we can use both the fast ion and the fast electrons for heating of the core. We estimated the temperature scaling of the CD core, using our conical-1D integrated model. The contribution of fast ion is not negligible in the range of the laser intensity from 10^{19} to 10^{21}W/cm^2 . Our results show that 5 keV of ignition temperature at the intensity of 10^{21}W/cm^2 and 1.5 ps pulse in CD plasma is achievable.

Acknowledgements

This work is partially conducted under the joint research of the ILE, Osaka University (FIREX-project), and JSPS KAKENHI Grant Number 24540545 and 15K05368), and Japan-US Joint Institute for Fusion Theory (JIFT) 2014, 2015.

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