Direct heating of imploded plasma in the fast ignition

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Abstract. We propose the direct heating of an imploded plasma core by ultra-intense lasers in inertial confinement fusion, to increase the heating coupling efficiency. In this scheme, both fast-electrons and fast-ions heat the plasma core. Experiments using this direct heating scheme has been carried out at GXII and LFEX laser facility at Osaka University. To model this direct heating scheme, we developed the 1D simulation model and carried out simulations using the experimental conditions. Comparison between results of the simulation and the experimental observations validates the simulation model. We show that even in the unoptimized experimental conditions used in simulations, our calculations show that the maximum temperature, 1.6 keV, of the CD plasma.

1. Introduction
In the fast ignition scheme of laser fusion, the laser-accelerated particles are used to heat an imploded plasma core. In this connection, we have been attempting to increase the energy coupling from the heating lasers to the plasma core by various methods such as generating fast electrons with improved high-contrast of the heating lasers, usage of magnetic fields, and optimization of the cone shape. For further increase of the energy coupling, we are currently trying to use laser-accelerated ions, in addition to electrons, for heating plasma. When deuterated carbon (CD) plasma is directly irradiated by an ultra-intense laser, carbon and deuteron ions and electrons are all accelerated. Estimates based on the hole-boring model by S. C. Wilks [1], give that the kinetic energy of the ions reaches to the order of MeV by the ultra intense laser, and its conversion efficiency from the laser to the fast ions is of the order of 1%. This ion acceleration is confirmed by PIC simulation using the FIREX condition. Sakagami et al.,[2]. In this paper, we show the numerical analysis of ion acceleration and its energy deposition.
to the plasma. Since we have already conducted the first experiment based on this idea using GXII and LFEX laser facility at Osaka University, we compare the numerical results with the experimental data. The comparison shows good agreement between the two. In Section 2, we present our numerical model, and in Section 3, the comparison of our calculations with the experimental observations, respectively. The conclusions are given in Section 4.

2. Heating model
We estimate heating of the imploded core by both fast-electrons and fast-ions. First, an ultra-intense laser irradiates and generates fast electrons and ions. In calculation of the conversion efficiency from laser to the electrons, we assume that the energy distribution of the fast electrons is given by \( \text{exp}(-E/T) \), where \( E \) is the electron energy in MeV and \( T \) the slope temperature in MeV, respectively. Also we assume that the total conversion fraction from the laser energy to the forward fast electrons is 0.4. We calculate the slope temperature using two models, i.e., Wilks model [1] and Haines model [3]. Transport of fast-electrons is calculated by the ray-tracing method using the stopping range in fully ionized CD plasma. We use the conical calculation volume, to take into account of the divergence angle of the fast electrons. In the present work, we set the 35 deg of the half-angle for the conical volume. The energy deposition of the fast electrons to the plasma is calculated using the drag heating and ohmic heating. In the drag heating, we used the stopping range of the fast electrons [4], and in the ohmic heating \( \eta j^2 \) at each point, respectively. Here \( j \) and \( \eta \) are the bulk electric current (equal to the fast electron current) and the resistivity, respectively. We use Spitzer resistivity \( \eta \) [5]. Subsequent to direct irradiation of the ultra-intense laser with the fully ionized CD plasma, \( C^{6+} \) and \( D^+ \) ions as well as electrons are accelerated. The fast electron are accelerated by the ponderomotive force of the laser. This leads to charge separation within the Debye length, and the ions in this range are accelerated by the electric field caused by the charge separation. This ion acceleration is studied by S. C. Wilks using PIC simulation of the hole-boring and ion acceleration [1]. He also calculated the velocity of accelerated ions using the momentum balance between the laser and the ions. We use the Wilks model in estimation of the kinetic energy and the conversion efficiency of the accelerated \( C^{6+} \) and \( D^+ \) ions. We also assume that these fast ions have the monotonic energy and the particle numbers given by Wilks and they are injected at the boundary of the simulation volume. The divergence half-angle of the fast ions is set to 20 deg. Transport of each ion particle is calculated based on the stopping range model of Mehlhone [6], where the stopping power is composed of three different processes; the nuclei, the valence electrons and the free electrons. From deceleration of the ion particles, we calculate the energy deposition of the fast ions to the plasma.

The energy equations of our model are;

\[
\rho c_v \frac{DT_i}{Dt} = -Q_{ei}, \quad (1)
\]

\[
\rho c_v \frac{DT_e}{Dt} = +Q_{ei} + \nabla \cdot (\kappa_e \nabla T_e) + S_e - S_r. \quad (2)
\]

In the above, \( T_i, T_e \) are the ion and electron temperatures, respectively. \( Q_{ei} \) is the electron-ion temperature relaxation given by the Spitzer model [5], and \( S_e \) is the heating term based on the energy deposition of the fast electron and the ions. \( \kappa_e \) is the electron thermal conduction with the flux-limited diffusion model with Spitzer conductivity. \( c_{ei}(\rho, T_i) \), \( c_{ev}(\rho, T_e) \) are the electron and ion specific heats, respectively. They are set to \((3/2)k_B\) and \((3/2)Zk_B\), respectively, where \( Z \) is the averaged atomic number, \( Z = 3.5 \) for CD plasmas, and \( \rho \) is the density of the core plasma, respectively. \( k_B \) is the Boltzmann constant. \( S_e \) is the radiation loss term, calculated from bremsstrahlung from the calculated volume.
3. Results
We calculated the temperature of the core plasma, base on the model described in Section 2, using the experimental conditions[7]. In the experiment, the ultra-intense laser LFEX pulse duration is 1.5ps, and Spot diameter was 60µm. The energy of LFEX laser was 400J, and 613J, respectively. We have conducted two shots in the LFEX and GXII laser facility, Osaka University. From the 2D hydrodynamic simulations, we estimated the core density to be 2g/cm$^3$, and the initial core temperature 0.8keV, respectively. We use these values for the initial core CD plasma conditions in our calculation. We calculated the heating of fast-ion and fast-electrons to the compressed CD core plasma when the heating laser energy is 613J. In Fig. 1, we show the temperature profiles for the conditions (a) both fast-ions and fast-electrons contributions are included, and (b) only the fast-electrons considered. In Condition (a), calculated values of the conversion efficiency from laser to fast C$^6^+$ ions, and the estimated kinetic energy is 1%, and 8MeV, respectively. The fast deuteron has the energy and conversion efficiency which are 1/6 of those of the fast C$^6^+$, since the mass of deuteron is 1/6 of carbon mass. In this figure, we see that the contribution of the fast-ions, mainly C$^6^+$, to the core heating is significant compared to that of the fast electrons. Here Wilks morel was used to estimate the slope temperature of fast electrons.

![Figure 1. Temperature profile of heated core CD plasma with (a) fast ions and fast electrons at 12.8 ps (solid line), and (b) fast electron alone at 9.6ps (dashed line).](image)

In order to compare our model calculation with the experimental observation, We also calculated the neutron yield of thermal fusion and the beam fusion, respectively, using the calculated temperature profile, and assuming that the core sustain duration time is given by dividing the core radius by the sound velocity at the maximum temperature at each computation mesh. In Fig. 2, we compare our calculated thermal- and beam - neutrons with the corresponding experimental data. The calculated curves for the beam and the thermal neutron are in reasonable agreement with the experimental data. Therefore, we conclude that our model simulates well the actual experiments.

Next, we calculated the neutron weighted core temperature using the slope temperatures of Wilks [1] and Haines [2], as a function of the heating laser energy. The heating laser spot size and the duration time are set to be 60µm and 1.5ps, respectively. Figure 3 shows that the core temperature increases with the heating laser energy, and 5 keV core temperature is achievable at the laser intensity of $10^{21}$W/cm$^2$ corresponding the laser energy of 30 kJ with 1.5ps duration and 60µm spot diameter. Here, both Wilks and Haines models are used to estimate the fast-electron slope temperature.

This is still not in the optimized conditions for achieving the ignition temperature, since the conditions such as the core density and the laser spot and the duration time are those given by the current experimental conditions and not optimized. However, even in this unoptimized conditions, the above calculated results are good and demonstrate that our new scheme of using
both the fast ions and the fast electrons in heating the core is a very promising one. and the ion assist in heating the core is not small compared to that of fast electrons.

4. Conclusion
We calculated heating of a compressed CD plasma core using an ultra-intense laser in a new fast ignition scheme. Our scheme simultaneously includes both fast-electron and ions. By a model based calculation using the conditions of the previous experiment, and we confirmed that our model is valid by comparing calculated results with the measurements. Based on this model, we calculated that the maximum temperature of the CD plasma obtained in the present example calculation is 1.6keV. At the laser intensity of $10^{21} \text{W/cm}^2$, and the 1.5ps duration laser pulse, calculation shows that the 5keV core temperature is achievable, even though the conditions are not optimized. In the future work, we will optimize the relevant conditions to achieve higher ignition temperatures in this scheme.

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