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COMPUTATIONAL STUDIES FOR FAST HEATING IN FIREX-I

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1. Introduction

On the fast ignition integrated experiments for cone-guided CD targets with GekkoXII+PW laser systems [1], the efficient heating of imploded cores (~800eV) was demonstrated, where the implosion laser was operated with the energy of 2.5kJ and the duration of 1.2ps (flat top) and the heating laser was operated with the power of 0.5PW and the duration of 0.6ps (the Gaussian). As the next step, FIREX (Fast Ignition Realization EXperiment) project [2] has been started. In the phase I (FIREX-I), a foam-cryogenic DT target is imploded by the GekkoXII laser operated with higher energy mode and the imploded core is heated by the 10kJ LFEX laser. The goal of FIREX-I is the core heating up to ion temperature of ~5keV. From the previous experiments, the heating laser energy and duration, the implosion laser energy and the fuel material are different in FIREX-I. In the present study, on the basis of core heating simulations for pre-compressed core plasmas, we evaluate those effects and show the requirement for achieving the goal of FIREX-I, 5keV heating.

2. Simulation Model

The 2D core heating simulations were carried out using "FIBMET" [3], which is based on 1-fluid 2-temperature Eulerian hydrodynamic code written in 2D cylindrical coordinates (r - z) with axial symmetry. In this code, the Thomas-Fermi model and the Cowan model are adopted for the equations of states of electron and ion, respectively. In the energy conservation equation, electron thermal conduction, radiation effect, alpha-particle heating and external fast electron heating are taken into account. The radiation and alpha-particle transports are treated by multi-group diffusion models. As for the core heating process, we assumed the uniform heating rate per particle for the bulk electron. Uniformly-compressed stationary plasma spheres are assumed as imploded core profiles. The spatially-uniform temperature (T_i = T_e =0.35keV) is assumed and the Gaussian profile is assumed for the radial profile of density.

3. Core Heating Properties in CD Core

First, we evaluated the effect of increase in heating energy E_h by assuming a CD core, of which density at the centre ρ_0, and mass M_f are set so as to reproduce the neutron yield and heated core temperature measured at the previous GEKKO XII+PW experiments [1]; ρ_0 = 100g/cm^3, M_f = 0.0015mg, the areal density $\rho_0 R_0$ = 0.13g/cm^2 (R_0 is the initial core radius) and the internal energy E_{int} = 50.1J.

Figure 1 shows the heating energy dependences of the DD neutron yield Y_{DDn} and the average temperatures of electron and ion weighted with DD fusion reaction rates $\langle T_e \rangle_{DDn}$,

$<T_i>_{DDn}$. When $E_h \le 100$J, we assumed the Gaussian pulse (FWHM = 600fs) for heating pulse, which corresponds to the PW laser pulse shape at the previous experiments. When $E_h \ge 0.5$kJ, a 10ps flat pulse was assumed, which corresponds to the LFEX laser pulse shape. In the case of heating energy of 40~80J, $<T_i>_{DDn}$ of ~800eV and Y_{DDn} of ~ 10^7 are obtained. If the energy coupling from heating laser to core η_h is 20%, the heating laser energy becomes 200~400J. These values well agree with those at the previous experiments.

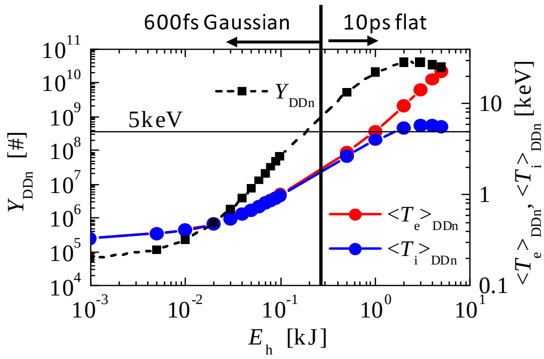

Fig.1 Y_{DDn}, $<T_e>_{DDn}$ and $<T_i>_{DDn}$ as a function of heating energy E_h in the case of a CD core with M_f = 0.0015mg, ρ_0 = 100g/cm^3.

When the heating pulse is assumed as 0.5~5kJ / 10ps, $<T_e>_{DDn}$ monotonically increases with E_h. The bulk ion is heated through the temperature relaxation between electron and ion, and then $<T_i>_{DDn}$ is lower than $<T_e>_{DDn}$. In addition, $<T_i>_{DDn}$ reaches a peak at E_h = 3kJ, and it decreases with increasing E_h in the higher energy region. The same tendency is observed in Y_{DDn}. The size of core generated by the present implosion laser is so small that the confinement time is short, and then the core is rapidly disassembled due to the heated electron pressure. In the case of such a small-sized core, hence, the excessive heating of the bulk electron leads to the rapid core disassembly before the ion is sufficiently heated. In the case of CD core of which size is the same as that generated at the previous experiments, the goal of FIREX-I, $<T_i>$ = 5keV, is achieved with E_h > 2kJ, which means that η_h > 20% is required. The required value for η_h is already realized at the previous experiments, where the estimated value of η_h was ~ 20% [1].

The GEKKO XII implosion laser will be operated with higher energy mode in FIREX-I than that at the previous experiments. Thus, the fuel mass and the imploded core density are expected to be larger, which leads to increase in the ion heating efficiency. We carried out the simulations for a larger and denser CD core (M_f = 0.002mg, ρ_0 = 200g/cm^3, $\rho_0 R_0$ = 0.22g/cm^2 and E_{int} = 84J). Since the number of electrons in the core increases with increasing fuel mass, the heating rate per electron and the resultant electron temperature become low for a given E_h. In Fig.2, E_{ei}/E_h and $<T_i>_{DDn}$ are plotted as a function of E_h, where E_{ei} is the energy transferred from electron to ion due to the relaxation process. Because of high density, E_{ei}/E_h is higher in the denser core. In the low heating energy region (E_h < 3kJ), $<T_i>_{DDn}$ in the case of the large and dense core is lower because of the low $<T_e>_{DDn}$ (a defect of increase in mass). In the high heating energy region (E_h > 3kJ), the density effect (*i.e.,* increases in E_{ei}/E_h) overcomes the defect of

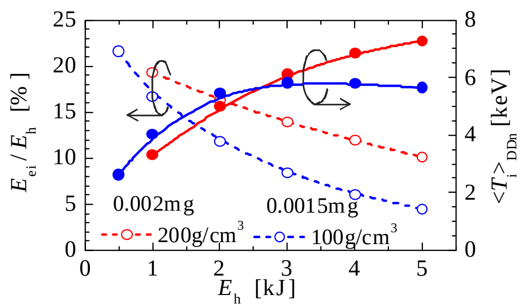

Fig.2 E_{ei}/E_h and $<T_i>_{DDn}$ in the different-sized CD cores as a function of E_h.

increase in mass, and then $<T_i>_{DDn}$ becomes higher in the case of the large and dense core.

The increase in $\rho_0 R_0$ enhances the energy coupling from fast electron to core, $\eta_{fe\text{->}core}$. In dense plasmas, the Coulomb interactions with bulk electrons are the dominant mechanism in the fast electron energy deposition process [4,5]. The collisional stopping power is proportional to the bulk electron number density n_e, and then the optical thickness of a dense core for fast electrons is roughly estimated by $2n_eR$ (R is the core radius). Thus, $\eta_{fe\text{->}core}$ will increases by ~70% when the $\rho_0 R_0$increases from 0.13g/cm^2 to 0.22g/cm^2.

In the case of the CD target, therefore, achievement of $<T_i>_{DDn}$ = 5keV in FIREX-I can be extrapolated on the basis of the imploded core parameters and η_h obtained at the previous experiment. By operating implosion laser with higher energy mode to implode a larger target and compress it into higher density than those at the previous experiments, the ion heating efficiency becomes higher, and then achievement of $<T_i>_{DDn}$ = 5keV will be more promising.

4. Core Heating Properties in DT core

For a fixed mass and density, the optical thickness of a core for fast electron is proportional to $n_e \propto Z/A$ (Z and A are the effective charge and mass number of fuel ion). Compared with a CD fuel, a DT fuel is optically thin for fast electrons by 20%, and then the energy coupling from fast electron to core will lower in the DT core. In addition, since the electron-ion temperature relaxation time τ_{ei} is proportional to $A/<Z^2>$, the ion heating rate is lower in the DT fuel. Thus, the ion heating in the case of the DT fuel is inefficient compared with the CD fuel.

In Fig.3, $<T_i>_{DDn}$ for the CD core and $<T_i>_{DT}$ for the DT core are plotted as a function of E_h, where M_f = 0.002mg, ρ_0 = 200g/cm^3 and $\rho_0 R_0$ = 2.2g/cm^2 for both fuels and E_{int} = 114J for the DT core. $<T_i>_{DT}$ is a DT reaction rate weighted average ion temperature. (Noted that to achieve the same density, five times higher compression from the solid state is required in the DT fuel.) To achieve the average ion temperature of 5keV, the higher heating energy is required in the case of DT core, *i.e.,* E_h > 3kJ (2kJ) is required in the DT (CD) case. Thus, the requirements for implosion and heating in a DT fuel are more severe than those in a CD fuel.

In Fig.4, $<T_i>_{DT}$ in the case of the 0.002mg DT fuel as a function of E_h, τ_h and ρ_0, where τ_h is the duration of heating pulse. There exists an optimum value of τ_h to maximize $<T_i>_{DT}$ for a given ρ_0 and E_h; it becomes long with increasing E_h and short with increasing ρ_0. With increasing density, the relaxation time becomes short, and then $<T_i>_{DT}$ increases. To achieve $<T_i>_{DT}$ = 5keV using DT fuels, ρ_0 > 200g/cm^3 (that is 1000 times solid density) is required. As for the heating parameters, τ_h =2~ 5ps (2~10ps) is required in the case of ρ_0 = 200g/cm^3 with E_h = 2kJ (3kJ) heating.

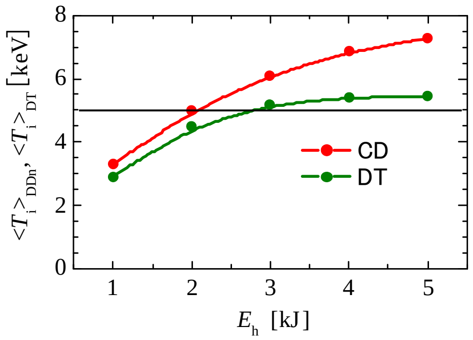

Fig.3 $<T_i>_{DDn}$ for the CD core and $<T_i>_{DT}$ for the DT core as a function of E_h, where M_f = 0.002mg and ρ_0 = 200g/cm^3.

We also evaluated the effect of the foam material [6]. To achieve the ignition and burning, the required mass density of foam in the solid state is less than 20mg/cm^3 [7] since the foam material increases the radiation loss from the heated region. However, in the FIREX-I class targets, the core is heated only by the external source and the core temperature rapidly decreases after finishing external heating due to the core disassembly since the core size is small. Under this situation, a small amount of foam material contribute to suppress the excessive increase in bulk electron temperature and to enhance the energy relaxation between bulk electron and ion. We found that when the density of foam material in the solid state is lower than 100mg/cm^3, the obtained $<T_i>_{DT}$ is higher than that in the pure DT case.

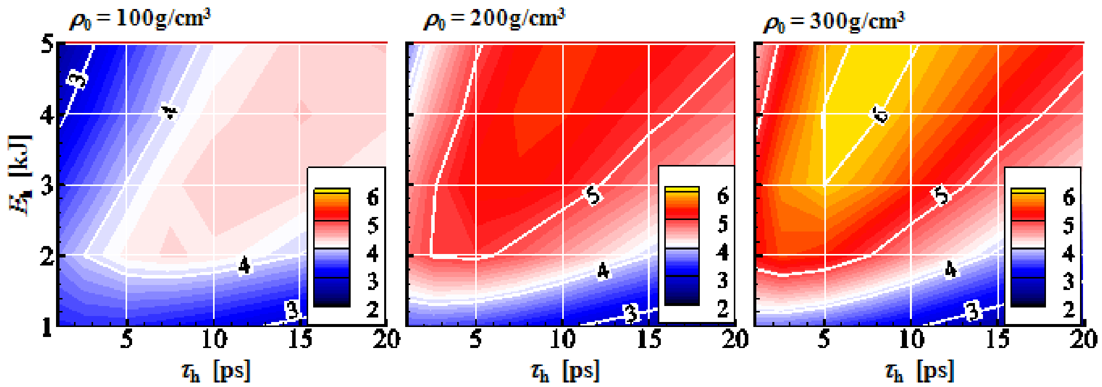

Fig.4 $<T_i>_{DT}$ in the case of the 0.002mg DT fuel as a function of E_h, τ_h and ρ_0.

5. Conclusion

On the basis of core heating simulations for the FIREX-I class CD and DT cores, we showed the importance of temperature relaxation between the bulk electron and ion. It is found that compared with the CD core, requirement for implosion and heating to achieve the core temperature of 5keV (the goal of FIREX-I) is severe in the DT core. The required condition for 5keV ion heating in the DT core is the core density > 200g/cm^3, the core heating energy >2kJ (>20% coupling from 10kJ LFEX laser) and heating duration < 10ps.

Acknowledgments

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