Simulation Studies for Core Heating Properties in FIREX-I

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Abstract. Two-dimensional coupled Fokker-Planck and radiation-hydro simulations showed that for efficient ion heating in FIREX-I class small-sized DT cores ($\rho R \sim 0.2\text{g/cm}^2$), because of short confinement time, short duration and low temperature fast electron beam is required compared with high-gain class targets. In the case of fast electron beam with the energy of 4kJ, duration of 5ps, slope temperature of 0.5MeV and the intensity of $1.1\times10^{20}\text{W/cm}^2$, the energy coupling from fast electron beam to dense core of 49\%, heated bulk electron and ion temperatures of 8.0keV and 4.6keV and neutron yield of $1.1\times10^{14}$ are obtained. The fuel material dependence of heating properties are also discussed.

1. Introduction

On fast ignition integrated experiments for cone-guided CD targets [1], efficient heating of imploded cores (~800eV) was demonstrated with PW laser (several hundred J / sub ps). As the next step, FIREX (Fast Ignition Realization E\textsuperscript{X}periment) project [2] has been started. In the phase I (FIREX-I), a cryogenic DT target is imploded with the present GekkoXII laser and the compressed core is heated with the LFEX laser. The goal of FIREX-I is core heating up to the ion temperature of ~5keV. In FIREX-I, heating laser energy (10kJ), pulse duration (~10ps) and the fuel material (foam-cryogenic DT) differ from those in the previous experiments.

Recently [3], we carried out two-dimensional (2D) fast heating simulations for pre-compressed core plasmas by assuming uniform heating rates per bulk electron. The core size is so small ($\rho R \sim 0.2\text{g/cm}^2$) in FIREX-I that the confinement time is short, which requires the rapid heating ($\leq 10\text{ps}$). On the other hand, when the heating time is too short, the heated bulk electron temperature becomes excessively high, which hastens core disassembly and then prevents the efficient ion heating via relaxation process. It was found that the optimum heating duration exists for a given core heating energy. With increasing the heating energy, the optimum duration to maximize the ion temperature becomes long. If the same heating condition is assumed for DT and CD cores, the bulk electron temperature becomes higher and the relaxation time becomes longer in the DT case because of the less total number of bulk electron, less bulk electron number density and less effective charge for DT core. Compared with CD targets, hence, the ion heating is inefficient in the DT targets. As the results of parametric simulations, we found the required condition for 5keV ion heating: the core density $> 200\text{g/cc}$, the core heating energy $>2\text{kJ}$ ($>20\%$ coupling from 10kJ LFEX laser to core) and heating duration $< 10\text{ps}$.
As the next step, we carried out core heating simulations with fast electron transport, where the various beam conditions are assumed, and required fast electron beam condition is investigated.

2. Simulation Condition

2D core heating simulations were carried out using “FIBMET” [4], which is based on 1-fluid 2-temperature Eulerian hydrodynamic code written in cylindrical coordinates \((r–z)\). The Thomas-Fermi and the Cowan models are adopted for the equations of state for 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. The core heating by fast electron is treated by the relativistic Fokker-Planck transport model. The evolution of self-generated fields is calculated by combining the generalized Ohm’s law for bulk electron, the Ampere-Maxwell equation and Faraday’s law, where the displacement current is neglected. In this model, the magnetic fields are generated due to the fast electron current \(\nabla \times (\eta \vec{j}_e)\) and thermo-electric force \(\nabla \times [(\eta e)\vec{V}_{pe}]\), where \(\eta\), \(\vec{j}_e\), \(n_{be}\), \(p_{be}\) and \(e\) are resistivity, fast electron current, bulk electron density, bulk electron pressure and elementary charge.

Spherically-compressed stationary plasmas are assumed as imploded core profiles at the beginning of simulations. The spatially-uniform temperature profile \((T_i = T_e = 0.4\) keV\) is assumed and the Gaussian distribution (the half width at half maximum (HWHM) is \(r_{HWHM} = 10\) μm, the density at the centre is \(\rho_0 = 200\) g/cm\(^3\)) is assumed for the density profiles. The fuel mass and the areal density are \(M_f = 0.002\) mg and \(\rho R = 0.22\) g/cm\(^2\), respectively. A fast electron beam having slop temperature \(T_{fe}\) is injected at the point 50 μm away from the core center. The super Gaussian distribution (HWHM = 15μm) and the flat pulse with the duration \(\tau_{fe}\) are assumed for radial and temporal intensity profile.

The injected beam energy is fixed as 4kJ, which corresponds to 40% coupling from the LFEX laser to the fast electron beam. In the following, we evaluate dependences of core heating properties on fuel material, pulse duration \(\tau_{fe}\) and beam temperature \(T_{fe}\).

3. Results and Discussion

3.1. Properties of core heating by fast electron beam

Figure 1 shows the temporal evolution of (a) core heating power and (b) spatially-averaged bulk electron and ion temperatures \(<T_{be}>_{DT}\) and \(<T_{i}>_{DT}\) (weighted by DT reaction rates) when the fast electron beam with \(T_{fe} = 1\) MeV and \(\tau_{fe} = 10\) ps (the beam intensity of \(I_{fe} = 5.7 \times 10^{19}\) W/cm\(^2\) at the beam centre) is injected into a DT core. In the early phase \((t < 2.3\) ps\), the fast electron beam is pinched by the magnetic fields generated around the beam edge due to \(\eta \nabla \times \vec{j}_e\) and break into some filaments. Due to the beam pinching, the core heating rate increases. On the other hand, large spatial gradient of \(T_{be}\) (bulk electron temperature) in z-direction is caused around the beam edge by the fast electron heating.

Figure 1.Temporal evolution of (a) core heating power and (b) spatially-averaged bulk electron and ion temperatures. The fast electron beam condition is \(\tau_{fe} = 10\) ps, \(T_{fe} = 1.0\) MeV and energy of 4kJ.
Since the directions of $\nabla T_{be}$ and $\nabla n_{be}$ is not parallel around the core edge, the magnetic field is generated due to thermo-electric force and the direction of this field is opposite to the direction of the $\eta \nabla \times \vec{j}_\omega$ oriented field. The fast electron around the beam edge is hence scattered at the core edge away from the dense core by this field and then the core heating rate becomes smaller. This effect becomes remarkable from $t \sim 2.3$ps. After $t = 5$ps, the core is heated by the beam component remaining around the beam centre and then the heating rate is nearly constant. In this case, the energy coupling from the fast electron to the core of $\eta_{fe\rightarrow core} = 31\%$ is obtained and the collisional processes between fast electrons and bulk electrons are the dominant heating mechanism; 96% of the deposited energy is via the collisional processes. Due to this heating, $<T_{be}>_{DT}$ reaches 5keV at $t \sim 10$ps. At this moment, the temperature equilibrium has not been reached between the bulk electron and ion; $<T_i>_{DT}$ is lower than $<T_{be}>_{DT}$. After finishing beam injection, both of the temperatures ($<T_{be}>_{DT}$ and $<T_i>_{DT}$) start to decrease due to the core expansion. The maximum value of $<T_i>_{DT}$ (3.6keV) is hence lower than $<T_{be}>_{DT}$.

3.2. Material dependence
Figure 2 shows the temporal evolution of (a) core heating power and (b) $<T_{be}>_{DT}$ (or DD) and $<T_i>_{DT}$ (or DD) for DT and CD cores having the same mass and density profile. The beam condition is the same as before. The magnetic field due to $\eta \nabla \times \vec{j}_\omega$ and then the pinching effect are larger in the CH core since $\eta \propto Z$ ($Z$ is effective charge). In addition, the CD core is optically thicker for fast electrons. Hence, in the CD case, the core heating rate is larger in the early stage, and then the $<T_{be}>_{DD}$ becomes higher. Since the relaxation time $\tau_{ei} \propto A/\langle Z^2 \rangle$, $A$ is ion mass number is shorter in the CD case, the temperature difference between bulk electron and ion is small. Thus, $<T_i>_{DD}$ is also higher in the CD case. The high temperature leads to rapid expansion. In the CD case, thus, the core heating rate becomes lower in the later phase than that in the DT case, and the decrease in temperature starts earlier. The value of $\eta_{fe\rightarrow core}$ obtained in the CD core (27%) is slightly lower than that in the DT case. However, $<T_i>$ reaches a higher value (4.75keV) in the CD core because of the higher heating rate in the early stage and of the shorter relaxation time. These results show that the ion heating is more efficient in CD core.

3.3. Beam duration and temperature dependences
Figure 3(a) shows the dependence of core heating properties on beam duration $\tau_{fe}$ ($5 \sim 15$ps) for the DT core. In this figure, $<T_{be}>_{DT,\text{max}}$ is the maximum value of $<T_{be}>_{DT}$ and $Y_{n_{DT}}$ is DT neutron yield. Here, the beam energy and temperature are fixed as 4kJ and 1MeV, respectively. Since the beam current density becomes large with decreasing the duration for fixed beam energy and temperature, the field effects become large. However, $\eta_{fe\rightarrow core}$ slightly depends on the pulse duration. As for the heated core temperature, the expansion loss energy during fast electron heating is lower in the shorter pulse.
case, which results in higher $<T_e>_{DT,\text{max}}$ and $<T_i>_{DT,\text{max}}$. In the region of $T_i < 10 \text{keV}$, since a DT reaction parameter $\sigma v$ has a strong dependence on ion temperature, $Y_{ndT}$ is more sensitive to $\tau_{fe}$; $Y_{ndT}$ for $\tau_{fe} = 5 \text{ps}$ is nearly three times larger than that for $\tau_{fe} = 15 \text{ps}$.

Figure 3(b) shows the dependence of core heating properties on beam temperature $T_{fe}$ ($0.5 \sim 2.0 \text{MeV}$) for the DT core, where the beam energy and duration are fixed as 4kJ and 5ps, respectively. It is found that $\eta_{fe,\text{core}}$ strongly depends on $T_{fe}$. The averaged range $\rho A_{fe}$ of fast electrons having temperature $T_{fe}$ is approximated by $\rho A_{fe} \approx 0.6 T_{fe} \text{[g/cm}^2\text{]}$ [5]. Thus in the case of $T_{fe} = 0.5 \text{MeV}$, $\eta_{fe,\text{core}} = 49\%$, $<T_e>_{DT,\text{max}} = 8.0 \text{keV}$, $<T_i>_{DT,\text{max}} = 4.6 \text{keV}$ and $Y_{ndT} = 1.1x10^{14}$, and these values decrease with increasing $T_{fe}$. In the case of a FIREX-I class small-sized core, the excessive heating of the bulk electron leads to the rapid core disassembly before the ion is sufficiently heated. Thus, the difference between $<T_e>_{DT,\text{max}}$ and $<T_i>_{DT,\text{max}}$ becomes large with decreasing $T_{fe}$.

4. Concluding Remarks
The 2D core heating simulations for FIREX-I, where the fast electron transport is included, showed that the magnetic fields affect core heating not directly but though the beam transport in low dense region. The magnetic field generated due to the fast electron current pinches the beam and contributes to enhancement of core heating rate. On the other hand, the magnetic field due to the thermo-electric force scatters the fast electron around the beam edge, which leads to decrease in the heating rate. In a FIREX-I class small-sized core, the ion heating is inefficient in DT fuel compared with CD fuel. For efficient heating in FIREX-I class DT cores ($\rho R \sim 0.2 \text{g/cm}^2$), short duration ($\sim 5 \text{ps}$) and low temperature ($\sim 0.5 \text{MeV}$) beam is required. When the fast electron beam with the energy of 4kJ, $\tau_{fe} = 5 \text{ps}$, $T_{fe} = 0.5 \text{MeV}$ and the intensity of $1.1x10^{20} \text{W/cm}^2$ is injected into the DT core, we obtained $\eta_{fe,\text{core}} = 49\%$, $<T_e>_{DT,\text{max}} = 8.0 \text{keV}$, $<T_i>_{DT,\text{max}} = 4.6 \text{keV}$ and $Y_{ndT} = 1.1x10^{14}$.

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