Analysis of Core Plasma Heating and Ignition by Relativistic Electrons

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Abstract. Possibility of pre-compressed plasma heating and ignition by relativistic electrons injected into the core region is analyzed within the framework of one-dimensional calculation. First, feature of the energy deposition process of relativistic electron beams is examined by means of Fokker-Planck calculation. Importance of including the long-range collective mode is shown. Next, on the basis of Coupled Fokker-Planck and hydrodynamic calculations, the heating and ignition property of pre-compressed planar target is discussed. The ignition boundary is shown in terms of the intensity and temperature of laser-produced fast electron beams.

1. Introduction

In the scheme of fast ignition (FI) for inertial confinement fusion [1], an ultra-intense short-pulse laser is focused on pre-compressed fuel to heat it to ignition temperature. Compared with the standard central spark ignition scheme, the FI could attain a high gain with a small driver energy.

One of the basic issues of the FI scheme is clarification of the core heating by fast electrons produced by relativistic laser-plasma interaction. Since the collisions between the fast electrons and the bulk plasma particles become significant in the dense region, the Fokker-Planck (FP) calculation seems appropriate for analyzing the core plasma heating. Moreover, to investigate the ignition dynamics, overall calculation including the heating process, both by fast electrons and by alpha-particles, and the hydrodynamic evolution of bulk plasma is indispensable.

So far, the core heating requirement for FI was intensively studied by Atzeni [2] through 2-D simulations. In his calculations, however, the transport and energy deposition process of fast electrons was not explicitly taken into account. Djaoui [3] made 1-D simulation to evaluate the target gain as a function of intensity and duration of the heating laser pulse, showing that the ignition energy requirement evaluated for 1-D planar target with free boundary condition agrees with Atzeni's 2-D results [2] in order of magnitude. This implies that 1-D simulation in planar geometry is still useful for evaluating the ignition condition. In Ref.[3], however, the core plasma heating was evaluated using a simple energy loss formula scaled so as to recover the penetration depth. For more accurate evaluation of the core plasma heating, transport calculation for fast electrons is desirable.

In the present paper, we examine the feature of core plasma heating and discuss the injected electron beam condition required for FI, on the basis of coupled 1-D transport–hydrodynamic simulations. The results are compared with those previously obtained.

2. Fokker-Panck Transport Model for Relativistic Electrons

The general form of the relativistic FP collision term was derived by Bramms & Karney [4]. Nakashima & Takabe [5] reduced the collision term to a simpler form by assuming

$$|\boldsymbol{u}-\boldsymbol{u}_j| \sim |\boldsymbol{u}|, \qquad (1)$$

where $\boldsymbol{u} = \boldsymbol{p}/m_e$, $\boldsymbol{u}_j = \boldsymbol{p}_j/m_j\,(j=e,i)$, $\boldsymbol{p}$ ($\boldsymbol{p}_j$) the momentum of fast electrons (bulk species), and m_e (m_i) the electron (ion) rest mass. We also adopt the same assumption as in Ref.[5]. Moreover, to incorporate the collective effect, *i.e.* the energy loss via Langmuir wave excitation [6] into the transport equation, we extend the collision term so as to include the Coulomb logarithm for the wave excitation. Then, the relativistic FP transport equation in 1-D planar coordinate system is written as

$$\begin{aligned} &\frac{\partial f}{\partial t}+\frac{p\mu}{\gamma m_e}\frac{\partial f}{\partial x}-\frac{eE\mu}{p^2}\frac{\partial\left(p^2 f\right)}{\partial p}+\frac{eE}{p}\frac{\partial}{\partial\mu}\left[\left(1-\mu^2\right)f\right] \\ &\quad=\left(\frac{Y_{ee}n_e}{m_e}+\frac{Y_{ei}n_i}{m_i}\right)\frac{m_e^2}{p^2}\frac{\partial}{\partial p}\left(\gamma^2 f\right)+\frac{1}{2}\left(Y_{ee}n_e+Y_{ei}n_i\right)\frac{m_e}{p^3}\frac{\partial}{\partial\mu}\left[\gamma\left(1-\mu^2\right)\frac{\partial f}{\partial\mu}\right]+S, \end{aligned} \tag{2}$$

$$Y_{ej}=4\pi\left(Z_j e^2/4\pi\varepsilon_0\right)^2\left(\ln\Lambda_{ej,BC}+\delta_{ej}\ln\Lambda_{ej,WE}\right)\quad\left(j=e,i\right), \tag{3}$$

where $f(x,p,\mu,t)$ is the momentum distribution function of fast electrons, γ is the Lorentz factor, n_e (n_i) the number density of the bulk electrons (ions), $S(x,p,\mu,t)$ the source, and μ the directional cosine of momentum vector $\boldsymbol{p}$. The Coulomb logarithm for binary e-e collision, for example, is given by [7]

$$\ln\Lambda_{ee,BC}=\frac{1}{2}\left\{\ln\frac{1}{2\tau_{\min}}+\frac{1}{8}\left(\frac{\tau}{\tau+1}\right)-\frac{(2\tau+1)}{(\tau+1)^2}\ln 2+1-\ln 2\right\}, \tag{4}$$

$$\tau_{\min}^{1/2}=\left(ƛ_{DB}/2\right)/\lambda_D\,, \tag{5}$$

where $\tau=\gamma-1$, and $ƛ_{DB}$ is the de Broglie wave length. The Coulomb logarithm for the wave excitation is given by

$$\ln\Lambda_{ee,WE}=\frac{1}{2}\ln\left(\frac{2}{3}\frac{v^2}{\omega_p^2\lambda_D^2}\right)-\frac{1}{2}, \tag{6}$$

where v is the velocity of the transport electron.

In the above equation, the magnetic field was neglected, while the electric field is taken into account by assuming a current neutrality condition [8]. Thus, the electric field E appearing in Eq.(2) is evaluated in terms of the plasma resistivity η and the return (background electron) current density J_r, that is $E=\eta J_r$. The return current density is calculated using $f(x,p,\mu,t)$ by

$$J_r=-J_f=e\iint\frac{p\mu}{\gamma m_e}f\left(x,p,\mu,t\right)dp\,d\mu\,. \tag{7}$$

The plasma heating rate by fast electrons consists of the energy deposition rates due to binary collisions P_{BC} and Lagumuir wave excitation P_{WE}, and the Joule heating rate P_J. The rate are evaluated by

$$P_{BC}+P_{WE}=-\sum_j\int m_e c^2(\gamma-1)\left(\frac{Y_{ee}n_e}{m_e}+\frac{Y_{ei}n_i}{m_i}\right)\frac{m_e^2}{p^2}\frac{\partial}{\partial p}\left(\gamma^2 f\right)d^3\boldsymbol{p}\,, \tag{8}$$

$$P_J=\eta J_r^2\,. \tag{9}$$

3. Energy Deposition of Relativistic Electrons in Stationary Plasma

We considered mono-energetic relativistic electron beams (REB) injected into a stationary planar plasma (ρ = 300 g/cm^3) and calculated the energy deposition rate. The energy lost by the wave excitation was assumed to be directly deposited to the plasma. **Figure 1** shows the result of FP transport calculation for 0.5~5 MeV source electrons. The width of energy deposition region (or penetration depth) for 3-MeV electrons, for example, is about 3 g/cm^2 in the plasma considered here. The degree of the energy deposition via Langmuir wave excitation is comparable to that through binary electron-electron collisions; thus the calculation neglecting the wave excitation considerably underestimates the energy deposition rate at each spatial point. The energy deposition via the return current (*i.e.* Joule heating) was found small.

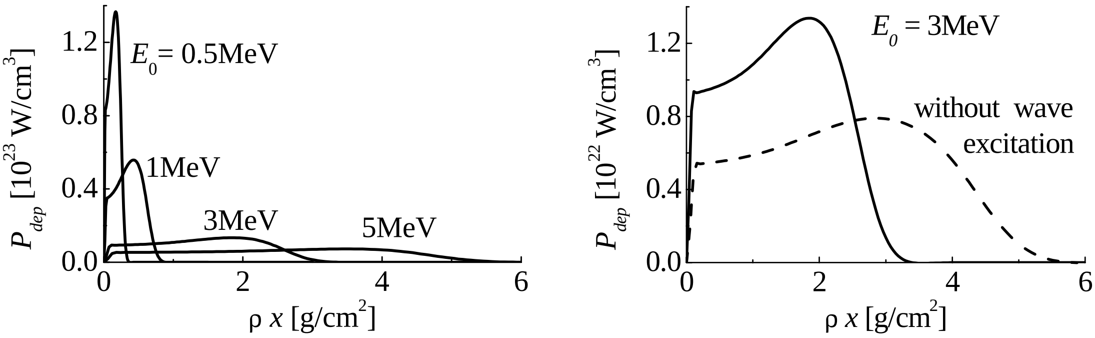

Fig.1 Spatial profiles of energy deposition rate (I_h=10^{20} W/cm^2, T_i = T_e = 0.5 keV)

4. Core Plasma Heating Required for Ignition

We made coupled FP transport-hydrodynamic simulations in 1-D planar system to estimate the electron beam requirement for ignition using a code system consisting of FP transport routine for fast electrons, non-local alpha-particle heating code, and radiation- hydrodynamics one for bulk plasma. Each code is being written for Eulerian coordinates. The alpha-particle heating is calculated by multi-group diffusion model [9]. The radiation effect is treated using flux-limited 1-group diffusion model. The hydrodynamic code adopts 1-fluid 2-temperature model. The ideal-gas model is employed for the equations of state.

4.1 Initial plasma configuration

The simulations were launched with such an initial state that the target is regarded to be at the maximum compression. We assumed a stationary planar DT plasma whose density and temperature are shown in **Fig.2.** The optical thickness ρX of core plasma is 1.6 [4.0] g/cm^2, corresponding to ignition-experiment-grade [reactor-grade] target of ρR = 0.8 [2.0] g/cm^2. The electron beam having relativistic Maxwellian distribution at a given temperature T_h (**Fig.3**) was assumed to be injected into the plasma from the left boundary with the intensity I_h of (0.2~2.0)×10^{20} W/cm^2 and the pulse duration τ_h of 10ps.

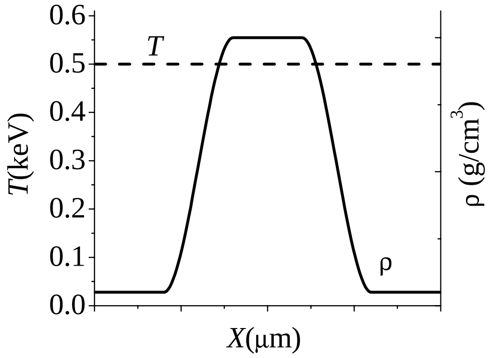

Fig.2 Initial plasma configuration

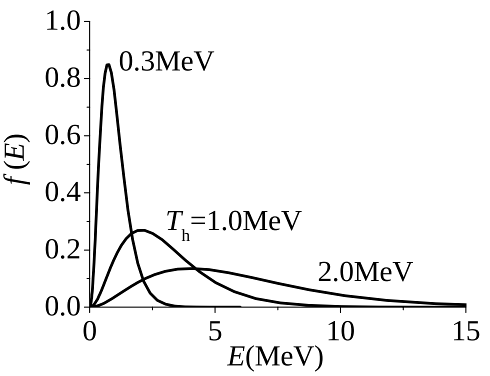

Fig.3 Initial energy distribution of REB

4.2 Results and discussion

Under the conditions described above, we examined the ignition boundary in terms of the REB intensity I_h and temperature T_h. Here, "ignition" means that the target gain far above unity is obtained. The results are plotted in **Fig.4**.

In the case where $T_h < 0.5$MeV, the injected electrons efficiently heat the region near the left boundary of core plasma; the width of heating region is below 2g/cm^2, and the both targets can be ignited with the lowest beam intensity of I_h~5×10^{19} W/cm^2. With increasing kinetic energy, the range of beam electrons becomes long, and more beam electrons escape from the right boundary of the core plasma before slowing down. The beam intensity required for ignition $I_{h,thr}$ hence increases with increasing T_h. In the region where $T_h > 1$MeV, the value of $I_{h,thr}$ is found almost proportional to T_h. When T_h = 2MeV, for example, $I_h \geq 1.8$ [1.1]$\times10^{20}$ W/cm^2 is required for igniting the ignition-experiment-grade [reactor-grade] target considered here; about 70% [40%] of injected beam electron energies leaks out of the former [latter] target model.

As a consequence of the above calculations, it is found that for achieving the fast ignition efficiently, beam electrons with relatively "low" energy ($T_h < 1$MeV) are desirable.

a) Ignition-experiment-grade target (ρ =200g/cm^3, ρX =1.6g/cm^2) b) Reactor-grade target (ρ =300g/cm^3, ρX =4g/cm^2)

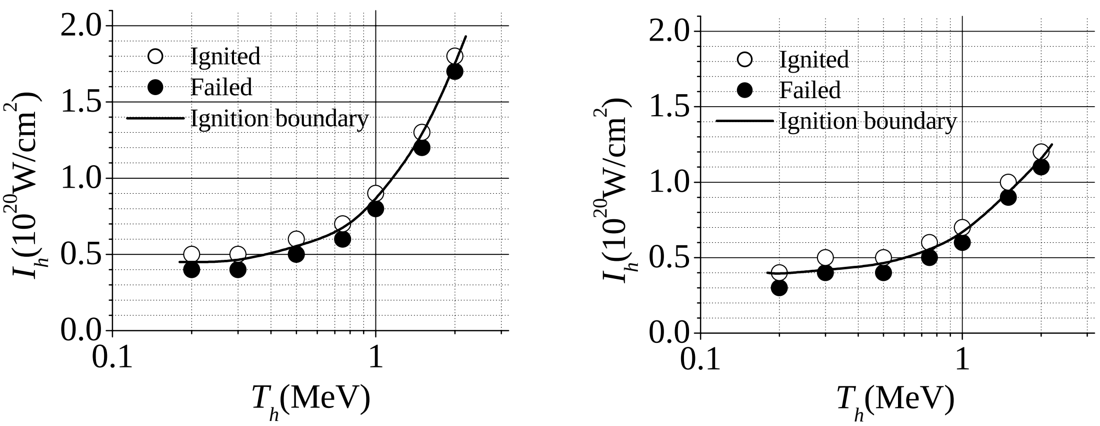

Fig.4 Threshold value of I_h as a function of T_h ($T_i = T_e = 0.5$keV, τ_h = 10ps)

Now let us compare the above results with Atzeni's one derived from 2-D hydrodynamic calculation [2]. In our coupled FP-hydrodynamic calculation for 1-D planar target, the beam electron intensity required for ignition is: $I_h \geq 5\times10^{19}$W/cm^2 when τ_h = 10ps and T_h = 0.2~0.5 MeV. In this beam condition, the width of heating region (or penetration depth) is 1~2g/cm^2. In Atzeni's 2-D simulation for spherical target, it was assumed that beam particles heat uniformly a small cylindrical volume near the surface of the sphere during given pulse durations τ_h. The beam intensity required for ignition is: $I_h \geq (5\text{~}7)\times10^{19}$W/cm^2 if τ_h = 10ps, and the depth and radius of heating region are 0.3~1.2g/cm^2 and 1.0~1.5g/cm^2, respectively. In these both cases, the beam particle's energy is well deposited to the plasma. One of the reasons for small difference in the required beam intensity would be such that in 1-D calculation for planar target, energy losses (due to expansion, thermal conduction, etc.) in the direction other than x-axis are not taken into account.

5. Concluding Remarks

We have examined the core plasma heating and ignition property of pre-compressed fuel within the framework of 1-D calculation for planar target. The plasma heating process both by injected beam electrons and fusion-born alpha-particles were explicitly included in the calculation. It was found that for achieving the ignition efficiently, beam electrons with relatively "low" energy (*e.g.*,$T_h < 1$MeV) are desirable. The estimated beam intensity required for ignition of planar target was shown to be a little smaller than the values for spherical targets.

In the present study, we assumed that the beam electrons, having a relativistic Maxwellian energy distribution at an arbitrary given temperature T_h, enter the core plasma. This assumption would be not always valid. For more accurate and practical studies of ignition process, we need reliable information on (a) energy distribution of fast electrons generated by the laser-plasma interaction, and (b) propagation of the beam electrons to the dense core region. Development of relativistic FP transport code in 2-D coordinate system is also indispensable.

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