Scaling Law for Fast Electron Beam Intensity in Fast Ignition

H Sakagami¹, T Johzaki², H Nagatomo², T Nakamura² and K Mima²

¹ Department of Simulation Science, National Institute for Fusion Science, Toki, Gifu 509-5292, Japan.
² Institute of Laser Engineering, Osaka University, Suita, Osaka, 565-0871 Japan.
sakagami.hitoshi@nifs.ac.jp

Abstract. FI³ Integrated simulations with the heating laser whose pulse duration is 10[ps] have been performed to investigate the core heating property of FIREX-I experiments. As the preformed plasma was pushed by the Ponderomotive force, the electron density increased in time and the fast electron beam intensity decreased. It was found that the fast electron beam intensity well scaled as the inverse square root of the electron density at the laser front. If the preformed plasma had the short scale length profile, the average core temperature quickly rose but shortly saturated because the fast electron beam intensity decreased. With the longer scale length preformed plasma, the beam intensity of fast electrons was maintained and the core heating was sustained for a longer time, the core reached higher average temperature.

The goal of FIREX-I project, in which a cone-guided cryogenic DT target is imploded by the present Gekko XII laser system and its compressed core is heated by the LFEX laser, is to demonstrate that the imploded core could be heated up to the ignition temperature, 5[keV]. Efficient heating mechanisms and achievement of such high temperature have not been, however, clarified yet, and we must estimate scheme performances of the fast ignition prior to experiments. Thus we have been promoting the Fast Ignition Integrated Interconnecting code (FI³) project [1,2] to understand overall complicated physics in the fast ignition. Under this project, the Arbitrary Lagrangian Eulerian radiation-hydro code (PINOCO), the collective Particle-in-Cell code (FISCOF), and the relativistic Fokker-Planck code (FIBMET) are dispatched for appropriate physics and integrated with data exchanges among these simulation codes to boldly explore fast ignition frontiers.

To simulate FIREX-I experiments with FISCOF, the heating laser is set to λₜ=1.06[μm], τₜₜ=375[fs], τ₀=10[ps], τₜₜ=375[fs], I₀=10²⁰[W/cm²], and the Au-cone tip is introduced as 10[μm], 500ncr, real mass and Z=30 plasma with preformed Au plasma, which has an exponential profile of the scale length Lₐ=1, 5 or 10[μm] with density from 0.1ncr up to 500ncr. The cone tip plasma is followed by 50[μm] long imploded CD plasma with 500ncr, A=7 and Z=3.5. The energy of fast electrons is observed in CD plasma, 10[μm] behind the Au-CD boundary. It is noted that an average ionization degree of Au is estimated with simulation results of PINOCO.

The preformed plasma is pushed by the Ponderomotive force, and the profile steepening at the laser front occurs. Thus the heating laser directly interacts with the sharp edge plasma, whose density is much over critical and increases in time as compression goes on. This leads to reduce the fast electron beam intensity, and it is found that the fast electron beam intensity well scales as the inverse square root of the electron density at the laser front. As the preformed plasma with longer scale length
prevents a quick rise of electron density, the beam intensity of fast electrons does not drop and efficient core heating is retained. Using time-dependent energy distribution of fast electrons after passing through the cone tip, calculated by FISCOF, we have carried out the core heating simulations with FIBMET. The imploded core profile at the central axis computed by PINOCO was used as the bulk plasma profile, and fast electrons were injected just behind the cone tip [3]. We have evaluated time evolution of ion temperature obtained by averaging over dense core region ($\rho > 100 \text{g/cm}^3$) and found that the temperature increment for the preformed plasma with $L_f=10 \mu \text{m}$ was three times larger than that with $1 \mu \text{m}$.

1. Fast Electron Beam Intensity and Electron Density

Fast electrons are mainly generated by so-called relativistic J x B heating [4] near the critical density point. This generation mechanism is due to the oscillating component of the Ponderomotive force of the laser, and it depends on the large gradient of the laser field at the interaction region. The ultrahigh intense laser also generates the higher pressure than the plasma pressure, even for extremely overdense plasmas. As the temporal pulse length is long enough for Au ions even with real mass, the Au plasma is pushed by the light pressure and snowplowed to higher density. The profile steepening also occurs; hence the laser directly interacts with the sharp edge plasma.

Time evolutions of fast electron beam intensity and electron density at the laser-plasma interaction front for $L_f=1, 5$ and $10 \mu \text{m}$ are shown in figure 1 (a). As the laser rises up to a maximum intensity at 1[ps], the fast electron beam intensity also rises up at the same time. The laser keeps its maximum intensity up to 10[ps], however, the intensity of the fast electron beam quickly drops to one third of the maximum value when the electron density increases in the case of $L_f=1 \mu \text{m}$. The oscillating Ponderomotive force on electrons is given by the following equation [5].

$$f_p = -\frac{\partial}{\partial x} \left( \frac{mv_{osc}^2}{2} \frac{4 \omega_{pe}^2}{\omega_{pe}^2} e^{-2\omega_{pe}x/c} \left[ 1 + \cos \left( \frac{2 \omega_{pe} t}{c} \right) \right] \omega_p \left( \frac{v_{osc}}{c} \right)^2 \frac{c}{\omega_{pe}} \right).$$

(1)

The magnitude of the force is proportional to $c/\omega_{pe}$, namely $(n_e/n_0)^{1/2}$. As intensity is obtained by multiplying a force by a velocity, the beam intensity of fast electrons that are generated by the Ponderomotive force can be estimated by multiplying $f_p$ by the velocity. Because the laser intensity is relativistic, the velocity of fast electrons can be assumed to be a light speed. Thus the fast electron beam intensity would be proportional to $f_p$, hence to the inverse square root of the electron density. As the electron density goes up, less fast electrons are generated by the weakened force and the beam intensity is also reduced. Fast electron beam intensity as a function of electron density at the interaction front is shown in figure 1 (b) for $L_f=1, 5$ and 10[\mu\text{m}]$. As the underdense plasma is swept away from the interaction region and the laser immediately irradiates the snowplowed plasma, the beam intensity well scales as the inverse square root of the electron density independent of the scale length of the preformed plasma [6].

To prevent the preformed plasma from being snowplowed and consequently less efficient core heating by the relativistic heating laser, we have performed integrated simulations with a lower intensity laser with $I_L=2 \times 10^{19}\text{[W/cm}^2\text{]}$ and the other parameters are as same as previous. Time evolutions of fast electron beam intensity and electron density at the laser-plasma interaction front for different scale lengths with this lower intensity laser are shown in figure 2 (a). In the case of $L_f=1 \mu \text{m}$, the fast electron beam intensity drops as the electron density rises, but the increment of the density is small compared with the previous case and the decrement of the beam intensity is only 35%. In the case of $L_f=5$ and $10 \mu \text{m}$, the electron density does not rise up and the beam intensity also does not drop. Fast electron beam intensity as a function of electron for the lower intensity laser is shown in figure 2 (b). The lower intensity is not so relativistic than that of the previous laser and the oscillating
Ponderomotive force is relativistic effect. Thus the dependence of the beam intensity on the electron density is weakened and the scaling law is changed from \(-(1/2)\) to \(-(1/4)\).

Figure 1. Fast electron beam intensity and electron density at the laser-plasma interaction front. (a) Time evolutions of fast electron beam intensity (solid line) and electron density (circle) and (b) Fast electron beam intensity as a function of electron density. Colors of red, light blue and purple indicate \(L_f=1, 5\) and \(10\) \(\mu m\), respectively.

Figure 2. Fast electron beam intensity and electron density at the laser-plasma interaction front for lower laser intensity. (a) Time evolutions of fast electron beam intensity (solid line) and electron density (circle) and (b) Fast electron beam intensity as a function of electron density. Colors of red, light blue and purple indicate \(L_e=1, 5\) and \(10\) \(\mu m\), respectively.

2. Core Heating Property
As the core heating is greatly affected by the fast electron energy spectrum, hence the scale length of the preformed plasma, we have performed FI3 integrated simulations to estimate core temperatures [6]. Time evolutions of core electron temperatures, which are averaged over the dense region \((\rho>10^3 [g/cm^3])\), are shown in figure 3 (a) for \(I_L=10^{20}[W/cm^2]\), \(L_f=1, 5\) and \(10\) \(\mu m\). In the case of the short scale length, the average core temperature quickly rises but shortly saturates because the fast electron beam intensity decreases. With the longer scale length preformed plasma, the beam intensity of fast electrons are maintained and the core heating is sustained for a longer time, the core reaches higher average temperature. The temperature increment for the preformed plasma with \(L_f=10\) \(\mu m\) is three times larger than that with \(1\) \(\mu m\). Time evolutions of core electron temperatures for the lower intensity are shown in figure 3 (b) as solid lines. As the increment of the electron density is suppressed due to the lower intensity of the laser, the core heating does not saturate even for \(L_e=1\) \(\mu m\). In the case
of $L_f=5$ and $10[\mu m]$, the electron density does not rise up and the beam intensity is maintained constant, so the core temperature evolves in almost the same manner for both cases. We have also performed integrated simulations with a short pulse laser for $I_L=2.35\times10^{20}[W/cm^2]$, $\tau_{FWHM}=750[fs]$ Gaussian. To investigate the core heating dependency on the pulse duration and intensity of the heating laser, these parameters are chosen to have the same total laser energy of the lower intensity laser. Time evolutions of core electron temperatures for the short pulse are shown in figure 3 (b) as dash lines. Within the short pulse results, $L_f=5[\mu m]$ is an optimum scale length for the core heating, which is determined by a tradeoff between sloshing electrons and fast electron energy spectrum [7]. In the case of $L_f=1[\mu m]$, the short pulse is too short to snowplow the plasma and better for the core heating than the lower intensity. When the scale length is long enough and the electron accumulation effect can be ignored, the short pulse is worse than the lower intensity because the intensity of the short pulse is much higher that of the lower intensity laser and more energetic electrons, which are less efficient for the core heating, are generated.

![Figure 3](image-url)  
**Figure 3.** Time evolutions of averaged core ($\rho>10[g/cm^3]$) temperature of electrons. (a) $I_L=10^{20}[W/cm^2]$ and (b) lower intensity (solid line) and short pulse (dash line). Colors of red, light blue and purple indicate $L_f=1$, 5 and $10[\mu m]$, respectively.

### 3. Concluding Remarks

When the intensity of the heating laser is extremely high, we should coat the Au cone with low-density materials (such as aerogel) to prevent the increase of the electron density for efficient core heating. If the scale length of the preformed plasma is short, we should use the relatively low intensity and long pulse laser also to prevent the increase of the electron density. However, if the pulse is too long, the core may disassemble before it is well heated. So the optimum pulse duration and intensity for the fixed total laser energy may exist. Comparing with previous simulation results [7], we emphasize, finally, that characteristic of the dependence of the core heating on the scale length of the preformed plasma in short pulse lasers is completely different from that in long pulse lasers.

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### References

[1] H. Sakagami and K. Mima, Laser Part. Beams 22, 41-44 (2004).
[2] H. Sakagami, et al., Laser Part. Beams, 24, 191-198 (2006).
[3] T. Johzaki, et al., Proc. 33rd EPS Conf. on Plasma Physics, P1.016 (2006).
[4] W. L. Krueer and K. Estabrook, Phys. Fluids 28, 430-432 (1985).
[5] S. C. Wilks and W. L. Krueer, IEEE J. Quantum Electronics 33, 1954-1968 (1997).
[6] H. Sakagami, et al., Proc. 34th EPS Conf. on Plasma Physics, P2.002 (2007).
[7] T. Johzaki, et al., to be published in Laser Part. Beams (2007).