Electron energy deposition to the fusion target core for fast ignition

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Abstract. Heating of the target core for fast ignition by electron beams is investigated by two-dimensional collisional particle-in-cell simulations. It is found that the electron beams emitted from the core surface with the initial energy of 1.4 MeV, 2.4 MeV, and 4.2 MeV can heat most efficiently the core with $\rho r = 0.75 \text{g/cm}^2$, 1.5 g/cm$^2$, and 3 g/cm$^2$, respectively, when taking $\rho = 300 \text{g/cm}^3$, where $\rho$ and $r$ are the mass density and radius of the core, respectively.

1. Introduction

As an alternative route to realize laser fusion energy, the fast ignition (FI) scheme has attracted significant attention since it was proposed by Tabak \textit{et al.} some 15 years ago \cite{tabak01}. The first FI integrated experiments were conducted by Kodama \textit{et al.} in 2001 \cite{kodama01}. In their experiments the ‘cone-guiding’ technique was used to reduce the propagation distance of electron beams to the core and consequently 20 – 30\% coupling from the ignition laser to the core was obtained. Subsequently many relevant studies have been reported, referring to hot electron production and optimization \cite{honrubia11, chrisman17, wu12}, the electron beam transport in coronal plasmas \cite{gilbert10, masuda18, li19}, and the core heating mechanism \cite{sanaka11, shen12, shen13}, as well as integrated studies of these processes \cite{brown14, chrisman15, chrisman16, chrisman17}. In particular, Honrubia \textit{et al.} investigated the process of the transport of electron beams produced at the cone tip to the fusion target core with hybrid particle-in-cell (PIC) simulations \cite{honrubia11}; The studies by Chrisman \textit{et al.} include all of the relevant physical processes except the laser propagation in the cone using collisional PIC simulations \cite{chrisman17}. Both of these results show that collisions dominate core heating.

Previous studies for the core heating usually follow the sequential procedure according to the actual processes, i.e. from the hot electron generation to the core heating. Here, we follow a different procedure in order to find the optimized laser and target parameters for the FI realization. In this procedure, first, assuming electron beams have reached the core surface, one studies the electron beam energy requirement to heat the core most efficiently, where collisional stopping is most significant; secondly, assuming electron beams have been produced at the cone tip, one studies how to get the optimum beam energy required in the previous step when the
beams have transported through the coronal plasmas of about 100\(\mu\)m, where collective stopping is significant; thirdly, one studies the parameters for the ignition lasers and targets, which may lead to more optimal electron beams. Every step can be performed numerically using the same plasma density and size as the actual experiments, which provides realistic reference for integration simulations and experiments. The current paper presents simulation results aiming at the first step mentioned above.

2. Simulation Results

Since the core heating in this step is dominated by collisions between particles and collective effects can be ignored, we use a collisional PIC code without solving the Maxwell’s equations, setting the electromagnetic fields vanished in the extremely high density core. The collision of weighted macro-particles is treated according to Refs. [18, 19, 20].

In the two-dimensional PIC simulations, we take the core as uniform deuterium tritium plasma with the density of \(5 \times 10^4 n_c\) (corresponding to \(\rho = 300 g/cm^3\)) and distributing within the circle with the radius \(r = 25 \mu m\), where \(n_c = 1.1 \times 10^{21} cm^{-3}\). The plasma density outside the core decreases exponentially (following \(exp(-r/r_0)\) with \(r_0 = 9.2 \mu m\)) and the coronal plasma on the right side of the core is neglected, which enables us to calculate the energy deposition only inside the core more exactly. The plasma electron and ion temperatures are all at 300 eV. The test beams have the density of \(n_c\), include 10000 electrons, and distribute within 1\(\mu\)m \(\times\) 1\(\mu\)m. The beams are initially located on the left surface of the core from \(x = 199 \mu m\) to \(x = 200 \mu m\). The beam electrons have the same energy moving along the +x-direction only. For convenience we take the period \(T_0\) of 1\(\mu\)m wavelength lasers as the time unit (i.e. 3.3\(fs\)).

![Figure 1](image1.png)

**Figure 1.** Temporal evolution of energy deposition of beams, where the black broken line, blue solid line, and red dotted line represent the total beam energy, the beam energy inside the core, and the beam energy outside the core, respectively. The initial energy of beams is 1.0\(MeV\), 1.4\(MeV\), and 2.0\(MeV\) in (a), (b), and (c), respectively.

The temporal evolution of energy deposition of beams is displayed in Fig. 1. One can see that the strong collision between the beam electrons and the core particles leads to the gradual energy deposition of beams and thus the residual energy of electrons inside the core reduces with time. For low energy beam, e.g. 1\(MeV\), the two curves for the total beam energy and...
the beam energy inside the core nearly coincide, which implies that the beam electrons deposit almost all energy to the core and they cannot flee from the core area [also see Fig. 2(a)]. The corresponding energy deposition ratio, which is defined as the deposited energy inside the core region divided by the total beam energy, is 99% obtained from Fig. 1(a). Increasing the beam energy to 1.4MeV, some of electrons can escape from the core, as seen from Fig. 2(b) clearly. Furthermore, one can see that electrons flee away mainly in the transverse direction due to their large transverse momenta accumulated during collisions. The energy deposition ratio in the core area is decreased to 90% obtained from Fig. 1(b). When the beam electrons have higher individual energy, e.g. 2MeV, most electrons are left with high residual energy after they propagate through the core, mainly in the longitudinal direction [see Figs. 1(c)], and the energy deposition ratio in the core area drops considerably to 51%, as obtained from Fig. 2(c). It should be noticed that the results above have some difference from the reference [21] because different models are taken, which will be studied further.

![Figure 3](image3.png)  
**Figure 3.** The energy deposition ratio (circles) and the average effective deposition energy (triangles) of electrons as a function of the initial beam energy.

The blue line with circles in Fig. 3 shows the energy deposition ratio as a function of the initial beam energy. One can see that the energy deposition ratio reduces gradually from 1MeV to 1.4MeV. However, from 1.4MeV to 2MeV the energy deposition is diminished rapidly because more electrons with higher residual energy go through the core. For the beams with energy higher than 2MeV, the deposition goes down continuously and it becomes only 14% at 5MeV. This is because when electrons have higher energy, their collision frequencies become smaller.

We obtain the average effective deposition energy of electrons, which is a product of the energy deposition ratio and the corresponding initial beam energy, as shown by red line with triangles in Fig. 3. One can see that the maximum average effective deposition energy is about 1.3MeV, which appears at the initial beam energy of 1.4MeV. This value goes down when increasing the beam energy. Thus for the size and density of the core with $\rho = 300g/cm^3$ and $\rho_r = 0.75g/cm^2$, the optimum beam electron energy is 1.4MeV for energy deposition. This optimum beam energy is about the value with which some beam electrons start to go through the core region along the longitudinal direction. Obviously, this indicates that the ignition laser intensity should be controlled at certain magnitude so that the average electron energy is around the optimum value for efficient core heating.

In the same way, we obtain the optimum beam energy for the cores with the radii of 25μm ($\rho_r = 1.5g/cm^2$) and 100μm ($\rho_r = 3g/cm^2$), respectively, which are presented in Fig. 4. One
can see that the optimum initial beam energy is 2.4\,MeV and 4.2\,MeV for the cores with the radii of 50\,\mu m and 100\,\mu m, respectively. The corresponding average effective deposition energy is about 2.2\,MeV and 3.9\,MeV, respectively. Also, these optimum beam electron energy is about the values with which some beam electrons start to go through the cores in the longitudinal direction.

It should be pointed that the optimum beam energy presented above can provide a reference for the energy level of electrons for effective absorption at the given target size. For larger size, the optimal energy shall be larger. Since electrons produced by intense lasers usually have broad energy spectra, electrons with different energy will deposit their energy in different positions. Our simulation may help to estimate where the target achieves the highest temperature by fast electron heating.

3. Conclusion
In summary, preliminary investigation on the energy deposition of electron beams incident from the core surface to the fusion core has been conducted by use of collisional particle-in-cell simulation. It is found that the low energy beams (i.e. 1\,MeV) can transfer almost all of their energy to the core. When increasing the beam energy, the energy deposition will decrease gradually. When the beam energy rises to the value with which the beam can just go through the core, a slight growth in the beam energy can cause a rapid decrease of the energy deposition ratio. The optimum beam energy for the core heating is about this value. For the three typical cores with $\rho r = 0.75\,\mathrm{g/cm}^2$, 1.5\,g/cm$^2$, and 3\,g/cm$^2$, the optimum beam energy is 1.4\,MeV, 2.4\,MeV, and 4.2\,MeV, respectively.

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