Electron transport estimated from electron spectra using electron spectrometer in LFEX laser target experiments

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Abstract. Hot electrons which are generated from targets irradiated by a high-intense laser are measured by two electron spectrometers (ESMs). However, total electron energy observed by the ESM is only less than 1 %. Hot electrons are confined by self-fields due to the huge current. When an external magnetic field of several hundred Tesla is applied during the laser irradiation on targets, the ESM signals always increase. In the simulation, the same result can be obtained. The reason is that the Alfvén limit can be mitigated due to the external longitudinal magnetic field.

1. Introduction

In the fast ignition (FI) [1,2], it is a key issue whether enough energy to ignite can be deposited to the imploded core. The most traditional scheme of FI is to utilize hot electrons, which are generated by the interaction between the guiding cone and the ultra-high intense laser. We have measured the hot electrons, which are emitted to the vacuum region by using the electron spectrometer (ESM) [3] in various fundamental and integrated target experiments. However, the observed total energy of the hot electrons is less than 1 % of the input laser energy. The reason is that the electron current up to the Alfvén limit can be only emitted to the vacuum because the electron current is huge and the self-magnetic field is too large. Additionally, the sheath potential [4] created by escaped electrons from targets pulls the electrons to the targets.

The electron behavior has been investigated by the PIC simulation [5]. The injected laser is partially reflected on the target surface. The remaining laser accelerates electrons in pre-formed plasma, created by the pre-pulse of the heating laser. However, the electrons are trapped by the self-magnetic field B since the return current is not enough on the front surface although the electron current is huge. Electrons run on the surface by $E \times B$ drift (similar to the skin effect), where $E$ is the sheath electric field. Residual electrons enter to the target if those energies are high enough. In the target, the electrons go almost straight because sufficient return currents are supplied. However, when the electrons reach the rare surface, the electrons are trapped by the self-fields again. The electrons can be observed by the ESM when they overtake those fields. Therefore, when two ESMs are located in...
different ports, the electrons are observed even at the front surface side. Those tendencies are in agreement with the simulation result.

Here we discuss the electron behavior from the laser reflection, the result of the ESM, and the X-ray measurement. To investigate the behavior precisely, we explain the ESM results (increasing electron/ion fluxes) when the external magnetic field is applied. Finally, we discuss about the proper target in which the effective electron deposition can be expected.

2. Laser Reflection
Target experiments have been performed in the target chamber I of the Gekko XII (GXII) facility, where GXII imploding laser and LFEX heating laser are settled. The detail of the experimental setup is shown elsewhere [6]. The part of the laser is reflected on the front surface according to the simulation. We measured the LFEX laser reflection at various targets. In the experiments, two beams in LFEX (four beams) were used. A reflection plate was located at the lack of the beam inlet. The reflection light was observed by a CCD camera with a filter. The results are shown in Fig. 1. There is the target material dependence in the laser reflection. The reflection in a diamond-like-carbon (DLC) is higher than that in Au. The reflection decreases at the higher laser energy. According to the simulation by Cai et al. [7], the reflection decreases at the longer scale length of the pre-formed plasma. The pre-pulse, which creates the pre-formed plasma, is a positive correlation to the laser energy if the beam contrast is maintained. The scale length in the Au is smaller than that in DLC experimentally. The experimental result is agreed with the simulation result. If we remove the pre-pulse and obtain the lower effective hot electron temperature ($T_{\text{eff}}$) in order to obtain the high target coupling efficiency, the reflection may increase. Therefore, the beam contrast may be the trade-off between the laser absorption and the hot electron deposition.

![Figure 1. Laser reflection on targets.](image1)

Reflection in Au is smaller than that in DLC (5mm length), DLC short (2mm) because the scale length in Au is shorter than that in DLC. DLC w. coat(Au coated DLC); Hole DLC(Au): (DLC(Au) with a hole instead of cone tip).

![Figure 2. Electron energy measured by ESM (Energymeas).](image2)

Energyhalf is the energy assuming Alfvén limit. Upper is the incident laser energy.

3. Electron behavior
Part of the electrons, which are accelerated in the pre-formed plasma, run on the surface by $E \times B$ drift. Here the self-$B$ appears due to insufficient cancellation of the return current on the surface. Residual electrons enter to the target if those energies are high enough. In the target, the electrons move straight
because there are sufficient return currents. According to the electron coupling efficiency measurement using Ta Kα by Zhang et al. [8], about 40% of the electrons can enter the thick Ta block, which has a solid angle of 2π. However, many electrons may move around the row dense ablation plasma region same as was observed in the simulation, but not in the core because the realistic core is much smaller than the thick Ta block. When the electrons reach the end of the target, the electrons are trapped by the self-fields again on the rare surface. Therefore, less than 1% of the hot electrons can emit to the vacuum due to the Alfvén limit and the sheath electric field. Figure 2 shows the comparison between the electron energy observed by the ESM and the Alfvén limit. The discrepancy between the Alfvén limit and the observed electron current may mean the effect of the sheath potential.

![Figure 3](image-url)  
**Figure 3.** Electron flux with/without the \( B_{ext} \) in plain targets. (lines: with \( B_{ext} \); dot: without \( B_{ext} \)).

![Figure 4](image-url)  
**Figure 4.** Electron flux with/without the \( B_{ext} \) in integrated targets. (lines: with \( B_{ext} \); dots: without \( B_{ext} \)).

![Figure 5](image-url)  
**Figure 5.** Simulation results with/without the \( B_{ext} \). Electron flux increases by the \( B_{ext} \).

![Figure 6](image-url)  
**Figure 6.** Ion spectra with/without the \( B_{ext} \). Low energy ion flux increases by the \( B_{ext} \).

4. **External Magnetic Field**

The increase of the electron flux measured by the ESM has been studied when the external longitudinal magnetic field \( B_{ext} \) is applied along the LFEX laser direction. The \( B_{ext} \) of several hundreds Tesla can be generated by the one-turn coil connected with two condenser plates. Three beams of GXII (not used for implosion) irradiates those plates and induces the huge current. The detailed setup is mentioned elsewhere [9]. The \( B_{ext} \) was introduced originally to converge the hot electron and to improve the electron-target coupling. In this concept, the \( B_{ext} \) is created by laser induced current on the capacitor plates before the target implosion and the LFEX injection. The magnetic field, which stays in the shell target, is converged with the implooding shell during the implosion phase. The hot electron
are trapped and focused by the converged magnetic field line of the $B_{ext}$ and heat the core effectively. Even if there is a large laser spot size (in order to prevent energetic tail of hot electrons which reduces the core deposition), the high coupling efficiency can be expected.

The electron flux just behind the target should increase. However, the electron flux measured by the ESM should not be changed because the ESM is located far from the target (90 cm). Figures 3 and 4 show the electron flux with/without the $B_{ext}$ on the plain and on the integrated targets, respectively. When the $B_{ext}$ is applied, the electron fluxes increase both on plain and integrated targets. In PIC simulation at the same condition, the flux clearly increases when the $B_{ext}$ is applied, as shown in Fig. 5. This means that the vertical magnetic field line against the target surface, which can easily extract the trapped electrons to the vacuum, can be created. Therefore, the electron flux increases because the Alfvén limit is mitigated by the vertical magnetic field. The ESM has the ability to measure the ion spectrum (mainly proton) at the same time. As shown in Fig. 6, low energy ions remarkably increase. The sheath potential created by the escaped electron also increases because the electron flux increased when the $B_{ext}$ is applied. Low energy ion is extracted by the sheath potential.

From these results, the hot electrons stay around the target by the self-magnetic field addition to the sheath potential if the $B_{ext}$ is not applied. Unfortunately, those electrons are not effectively contributed to heat the core from the results of integration experiments. Those electron energies are lost due to the radiation induced by collision between the electrons and the low density plasma surrounding the core.

5. Summary
Most of the hot electrons are trapped by the self-magnetic field and sheath potential around the target. They lose their energy by the radiation, without heating the core. Residual electrons enter to the target and heat it only once. In the FI, the high coupling efficiency can be expected if the hot electrons effectively irradiate the core geometrically and if there is enough areal density ($\rho R$) in the targets. However, much effort to converge the hot electrons within the core diameter is necessary. The large $\rho R$ requires much heating laser energy in order to heat the targets because the fuel amount is also large. Therefore, the laser intensity on targets becomes higher, and higher $T_{eff}$ reduces the target coupling efficiency as a result. One of the procedures to achieve FI is by using wide laser spot so as not to produce the energetic electron tail. The high coupling efficiency can be obtained by converging the hot electrons by the $B_{ext}$. However, this process does not promise the success of the FI at the moment. Based on the above experimental results, we propose another candidate of electron-based FI, where the hot electrons are used to heat the target many times. If the heating laser irradiates the inside of the hole-shell just before the implosion, the hot electrons may be able to be used effectively [10].

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7. References
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