Integrated Simulations for Transport of Laser-Produced Relativistic Electrons in Solid Targets

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Abstract. On the basis of the integrated simulations for ultra-intense laser-matter interactions, we demonstrated the long-scale (~20μm) low-density plasma generation by the irradiation of low intensity pre-pulse and its effects on the fast electron generation. It is also found that the resistivity jump at the material contact surface in the low-temperature multi-layer solid target generates the strong magnetic field when the direction of gradient of resistivity is nearly perpendicular to the fast electron beam direction. The fast electron beam is scattered by this field, which strongly affects the target heating properties.

1. Introduction

The energetic particles generated by ultra-intense short-pulse lasers are expected to be used for many applications e.g., compact accelerator, cancer therapy, laboratory astrophysics and fast ignition laser fusion. For practical use, the clarification of detailed mechanism of their generation and energy transport in the matter is indispensable. Such relativistic laser plasmas have been widely investigated by ultra intense laser experiments and numerical simulations. In experiments, the fast electron energy transport in solid targets is investigated by means of spectrum measurement of x-ray emitted from tracer material, measurement of target rear side UV emission, and so on. However, it is almost impossible to directly observe the laser-plasma interaction and the energetic particle transport in the matters. The numerical simulations play an important role in elucidation of the details.

In ultra-intense laser-matter interactions, various phenomena having different scales (e.g., overall macro-scale hydrodynamics and micro-scale laser-plasma interactions) are coupled to each other. To simulate such complicated physics phenomena and identify the crucial physics in the fast heating, we developed a multidimensional integrated code system “Fast Ignition Integrated Interconnecting code” (FI² code) [1]. In the FI² code, the overall target dynamics is simulated by the two-dimensional (2D) ALE-CIP radiation-hydro code “PINOCO” [2]. The 2D collective PIC code “FISCOF2”[3] simulates the relativistic laser-plasma interactions and evaluates the fast electron profiles. The fast electron transport in a dense material is simulated by 2D relativistic Fokker-Planck code “FIBMET”[4].

In the present paper, we performed the integrated simulations to analyze the transport of laser-produced fast electrons in solid materials. First, we discuss the prepulse effects. The low intensity prepulse produces the low-density blow-off layer on the target surface, which affects the following main pulse - plasma interactions and the resultant fast electron profiles. The other topic is the dependence of fast electron transport on the target material. In low temperature (T < 1keV) solid...
targets, the resistivity plays important roles, e.g., electric fields generation and bulk electron heating due to the Ohmic process and magnetic fields generation due to a spatial gradient of resistivity. The resistivity strongly depends on the temperature, and this dependence is different by a material. We will show the simulation results for fast electron transport in the multi-layer solid targets and discuss the effect of the resistivity on the fast electron transport process.

2. Pre-plasma formation
The blow-off plasma generated by the prepulse was evaluated with PINOCO in 2D cylindrical geometry. An Al solid planar target (2.3g/cm³, 0.01eV, 20μm thickness, 200μm width) is irradiated by low-intensity prepulse. The prepulse parameters are 1.06μm wavelength, the Gaussian pulse with 1ps full width of half maximum (FWHM), 20μm spot size (Gaussian) and 3x10¹⁵ W/cm² peak intensity. The peak intensity of prepulse locates 0.4ns before the main pulse. Following this pulse, we introduced an ASE light with constant intensity of 10¹¹W/cm² until the main pulse irradiation. These prepulse profiles are similar to the ILE GMII 50TW laser facility.

The spatial profile of electron density and temperature at t = 0.4ns (just before the main pulse irradiation) are shown in Fig.1. The long scale broow-off plasma is foamed on the target surface along the laser axis. The laser critical density point (nₑ = 10²¹/cm³) is located ~ 60μm away from the initial target surface. The scale length of pre-plasma along the laser axis is 20μm for low-density region (from underdense to 10nₑ) and 0.7μm for high-density region (> 10nₑ).

3. Fast electron generation
The interaction between the ultra-intense main-pulse laser and the solid target was simulated with FISCOF2. As the initial density profile of pre-plasma, we use the blow-off plasma profile in the region of 12 μm < z < 95.3 μm and r < 25 μm obtained at the radiation-hydro simulation. In the PIC simulation, a 2D planar geometry (83.3μm x 50μm) is assumed and the maximum value electron density nₑ is assumed as 40nₑ which is sufficient for evaluation of generated fast electron profiles. The electrons and the ions (Al⁺) are mobile. The initial electron temperatures is 500eV, and ions are initially cold.. The main pulse laser (the Gaussian pulse of 600fs FWHM, 1.06 μm wavelength, 14μm spot size (Gaussian) and peak intensity of I_L = 3x10¹⁸ W/cm²) is irradiated on the target surface with normal incident angle. The fast electron profiles are observed at x=78.0μm (at 40nₑ region) and 14μm < y < 44μm.

Figure 2 shows the temporal evolution of the energy spectra of forward-directed fast electrons. The laser field is modulated by expanding pre-plasma. Thus, the strong self-focusing is observed, which results in generating the relatively high energy electrons. Due to the self-focusing and interactions with long scale length underdense plasmas, the generated fast electron temperature (~2MeV at the peak) is higher than the various models [5, 6, 7, 8]. The electron beam intensity and the energy of fast electrons decrease with distance from the laser axis and also changes with time. The peak values are obtained at t ~ 1.2ps from the beginning of main pulse irradiation, which corresponds to the electrons generated at the laser peak intensity. (The
laser peak reaches the critical surface at \( t \sim 1\text{ps} \). These results show that the preplasma profile affects the generated fast electron profile, and then the prepulse information (spatial and temporal profiles) is important in estimation of fast electron generation.

4. Fast electron transport in multi-layer solid materials

The fast electron energy transport in solid targets was investigated with Fokker-Planck simulations (FIBMET) in 2D planar geometry. In low temperature (<10eV) solid targets, the collision between fast electrons and bound electrons and the resistive heating are the dominant processes of energy transfer from fast electron to bulk particles. In addition, the macro-scale magnetic field generated due to \( \nabla \times \left( \eta \vec{j}_f \right) = \eta \left( \nabla \times \vec{j}_f \right) + \left( \nabla \eta \right) \times \vec{j}_f \), where \( \eta \) is the resistivity and \( \vec{j}_f \) is the fast electron current density, affects the fast electron transport. Thus, the resistivity is important. The temperature dependences of conductivity, which is \( 1/\eta \), for solid CH and Al were shown in Ref.[9]. In the low temperature region (Te < 10eV), the resistivity of CH is higher than that of Al and the temperature dependence is different between two materials. We carried out the fast electron transport simulations in multi-layer targets consisting of CH and Al, and evaluated the effect of resistivity jump at the material contact surface on fast electron transport.

The simulation box size is 100µm thickness in \( x \)-direction and 40µm width in \( y \)-direction, and the reflection boundary is assumed at \( y = 0 \). The size of solid target is the same as that of the simulation box. The fast electrons are injected at the left boundary of the box. As the fast electron source profile in the Fokker-Planck simulations, we use the fast electron profiles obtained with 2D PIC simulations shown in Sec.2. The simulations were carried out for two types of solid targets.

4.1. Target (a)
The target (a) is an Al layer \((0\mu m < y < 15\mu m)\) surrounded by a CH layer \((15\mu m < y < 40\mu m)\). Figure 3 shows the spatial profiles of (a) resistivity \( \eta \), (b) magnetic-field \( B_z \) and (c) fast electron density \( n_{fe} \) at \( t = 0.5\text{ps} \). In Fig.3(a), the fast electron current density \( \vec{j}_f \) is plotted by arrows. At this moment, the temperature of bulk electron is lower than 10eV in the whole region, and then \( \eta \) in CH region is much higher than that in Al. Hence the large spatial gradient of \( \eta \) in \( y \)-direction exists at the material contact surface. The direction of \( \nabla \eta \) is nearly perpendicular to the direction of \( \vec{j}_f \). Thus the strong magnetic-field is generated due to \( \nabla \eta \times \vec{j}_f \). This magnetic field scatters the fast electrons across the contact surface into the CH region, and then the beam divergence becomes large. Figure 4 shows the spatial profiles of bulk electron and ion temperatures \( T_{be}, T_{bi} \) in \( y \)-direction at \( x = 40\mu m \) at \( t = 2\text{ps} \) for the target (a) and a pure Al target. Because of the scattering of fast electrons due to the magnetic field at \( y = 15\mu m \), the heating region is broadened in the perpendicular direction in the target (a), i.e., the temperature is higher in the target (a) in the outer region \((y > 25\mu m)\). This result qualitatively agrees with the experimental observation [10].

![Figure 3. Spatial profiles of (a) resistivity \( \eta \), (b) magnetic field \( B_z \) and (c) fast electron density \( n_{fe} \) at \( t = 0.5\text{ps} \).](image)

![Figure 4. Spatial profiles of bulk electron and ion temperatures \( T_{be}, T_{bi} \) in \( y \)-direction at \( x = 40\mu m \) at \( t = 2\text{ps} \) for the target (a) and a pure Al target.](image)
4.2. Target (b)
The target (b) is a 5 μm thickness Al layer sandwiched between CH layers of which thicknesses are 40 μm in the front side and 55 μm in the rear side. Figure 5 shows the spatial profiles of (a) $B_z$ at $t = 1.0$ps, (b) $T_{be}$ at $t = 0.5$ps and (c) $T_{be}$ at $t = 2.0$ps. In the target (b), though $\nabla \eta$ exists at the material contact surface, the directions of $\nabla \eta$ and $j_f$ are nearly parallel (or anti-parallel). Therefore, the generation of magnetic field due to $\nabla \eta \times j_f$ is not large and the scattering of fast electrons is weak compared with that in the target (a). The difference in the temperature dependence of $\eta$ causes the difference in the Joule heating rate and then $T_{be}$ between Al and CH layers. In the early stage when $T_{be} < 10$eV, $\eta$ of Al is lower than that of CH, then $T_{be}$ is lower in the Al layer (Fig.5(b)). Contrary to this, in the later stage when $T_{be} > 10$eV, the magnitude relation of $\eta$ is reversed between Al and CH, and then $T_{be}$ in the Al layer becomes higher than those in the surrounding CH layers (Fig.5(c)). Compared with the simulation results of LSP [11] for analysis of the VULCAN petawatt laser experiments [12], our simulation results show the same tendency though the temperature of heated region is low because of the low heating laser energy.

5. Concluding remarks
The integrated simulations for ultra-intense laser-matter interactions demonstrated that the low-intensity prepulse generates a long-scale low-density blow-off plasma on target surface, which affects the main pulse laser propagation and the generated fast electron profiles. These results indicate that not only the main pulse information but also the prepulse’s one (spatial and temporal profiles) is important in analysis of ultra-intense laser-material interaction. We also showed that the importance of resistivity in the fast electron transport in the low-temperature solid materials. In the low temperature multi-layer targets where each layer has the different temperature dependence of $\eta$, the heating property is different between the layers. In addition, when the direction of $\nabla \eta$ at the material contact surface is nearly perpendicular to the direction of the fast electron current density, the strong magnetic field is generated and it scatters the fast electron beam.

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