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# Microscopic and Macroscopic Simulation of Ultra-Short-Pulse Laser Processing by CIP Method

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We performed 1.5-dimensional simulation of the Fokker-Planck equation using the CIP method to investigate femto-second-laser heating processes. We found that the heat flux in the solid part approaches a classical thermal conduction theory like the Spitzer-Härm theory on quite a short time scale $\omega_p t < 100$, while the heat flux on the vacuum side becomes free streams that don't depend on the temperature gradient. On the basis of this result, we performed a hydrodynamic simulation using the CIP method with classical thermal conduction. The experimental ablation depth was replicated very well, showing that even fs pulse laser processing can be satisfactorily described by classical heat conduction.

**Keywords:**
femto-second laser, plasma, laser processing, simulation, CIP method

Recently, there is a growing interest in fs-ps short pulse laser experiment [1,2], though simulations have rarely been performed. In fs pulse laser ablation, though skin depth is a few nano meters, experiments show an ablation of 10–100 times larger depth. Furthermore, ablation depth deepens in accordance with intensity, though it seems logical that ablation depth would not change much even if laser intensity increases, if only the area of skin depth is heated and ablated. The purpose of this investigation was to clarify the mechanism in the event reported in the experiment by simulating the ablation process of the ultra-short pulse laser using microscopic [3] and macroscopic equations with the CIP method [4,5].

In the microscopic model, the advection of the electron distribution function in the phase space is solved by the Fokker-Planck equation as in a previous study on non-local heat flow [6], but with the CIP method [3] in this paper. The Maxwell equations are solved simultaneously, and the effect of magnetic fields is neglected.

We assume that the initial electron distribution $f_0$ is Maxwellian, having uniform temperature. Initial density distribution is that the high-density ($5n_0$) layer (solid part) and the low-density ($0.5n_0$) plasma layer (less than 1/10 of solid part) are connected exponentially with a width of 200 $\lambda_D$ ($\lambda_D$ is Debye length at $n_0$). The calculation area is assumed to be 1,000 $\lambda_D$ in the $x$ direction. The laser light represented by the electric field $E_{ex}$ ($= E_0 \sin(\omega t)$) parallel to the $x$ axis is added to the critical surface of the plasma. This electric field is added in the region 17 $\lambda_D$ from the critical surface of the plasma in consideration of the laser cut-off. Numerical grid points are 120 in the $x$ direction, 29 in the $u_x$ direction and 17 in the $u_y$ direction. We set the collision frequency with the thermal velocity to be $\nu/\omega_p = 0.01$.

Open circles and the solid line in Fig. 1 (a) indicate temperature and heat flux distributions, respectively. We assumed that the laser is incident from the low-density plasma side ($x > 0$) to the high-density side ($x < 0$). The relation between heat flux (divided by free streaming limit $Q_{fre}$) and temperature gradient (normalized by the collision mean free path $\lambda_{fre}$ estimated at each local point of $x$) at $\omega_p t = 100$ is plotted in Fig. 1 (b) and compared with the theoretical curve based on the Spitzer-Härm theory $q = -\kappa \nabla T$ [7]. The calculated heat flux in the high-density region stays along the theoretical curve (solid line), whereas it departs

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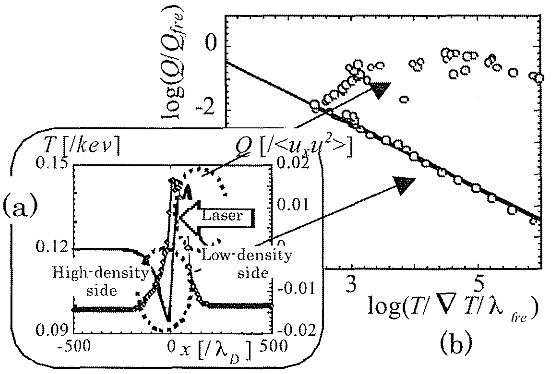

Fig. 1 (a) Temperature and heat flux distribution at $\omega_p t = 100$. (b) The vertical axis shows heat flux divided by free streaming limit $Q_{\rm fre}$. The scale length of temperature gradient is normalized by collision mean free path $\lambda_{\rm fre}$.

seriously on the vacuum side. The simulation shows that some of the electrons streaming into the vacuum are reflected back to the solid density by a virtual cathode, and contribute to the heat flux in the high-density region.

Having in mind such a microscopic simulation revealing that the classical thermal conduction is quickly established, we performed further macroscopic calculation by fluid dynamic code with classical heat conduction. The simulation was for copper with laser pulse 150 fs and wavelength 780 nm by setting the absorption rate to 30 %. In analyzing the experimental result of [2] (The experiment was performed in vacuum using imaging geometry. The ablation depth of the experimental results in Fig. 3 was the ablation depth per pulse as estimated from several shots.), we must be careful about the spot size because the fluence in experiments was estimated based on crater size on the target surface [8]. As the simulation result shows in Fig. 2, however, the crater size seriously differs from the laser spot size.

In order to be consistent with experimental results, we re-scaled the fluence in Fig. 3 according the crater-size obtained at the end of the calculation. Conversely, if we use the laser spot size for estimating fluence, we are not able to replicate the experiment, as indicated by the dashed line in Fig. 3. This result demonstrates that the previous experiments can be replicated well even with the classical mechanism if the proper experimental conditions are used, and we therefore do not need to rely on other exotic mechanisms such as those discussed in ref. [2].

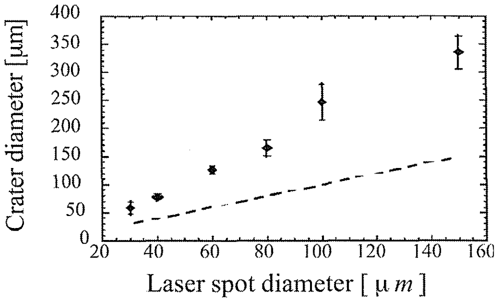

Fig. 2 Calculation results of crater diameter for various laser spot diameter, where the fluence is changed from 113 to 4,266 mJ/cm$^2$. The error bar indicates the change of crater diameter for different fluence.

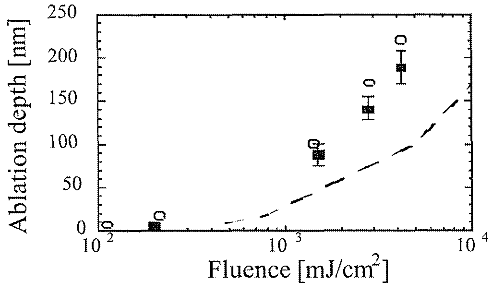

Fig. 3 Ablation depth versus effective fluence. Circles show the simulation results with 80 $\mu$m laser-spot diameter for laser energy from 20 $\mu$J to 754 $\mu$J but the fluence was estimated by the crater size in Fig. 2, while the dashed line is the simulation result estimated by laser spot size. The squares with error bar show the experimental results [2].

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