9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

High-density plasma heating with non-local electrons accelerated at a steepened plasma surface formed by PW relativistic laser

Naoki Okuda[1], Natusmi Iwata[2], Yasuhiko Sentoku
[1]Department of Physics, Graduate School of Science, The University of Osaka,
[2]Institute of Laser Engineering, The University of Osaka
e-mail (speaker): u662508e@ecs.osaka-u.ac.jp.

Relativistic laser irradiation of overdense targets drives electrons with energies ranging from a few tens of keV up to several hundred MeV deep into the plasma, establishing strong energy fluxes and forming High-Energy-Density (HED) states. While electron fast ignition schemes traditionally focus on non-local transport by high-energy electrons (with mean free path $\lambda \gg$ the system scale length L), their low collisional frequency and low beam density near the relativistic critical surface ($\sim \gamma n_s$) often limit the bulk heating to sub-ignition temperatures (< 10 keV) in the core part. Conversely, bulk electrons with shorter mean free paths undergo frequent Coulomb collisions and transport energy diffusively according to the Spitzer–Harm (SH) formalism [1]. Recent experimental and theoretical studies have demonstrated that such diffusive transport can play an essential role in heating at near-solid densities (~1 g/cm³) [2,3].

In this study, we extend the investigation to higher density plasmas (10–100 g/cm³), where the relative contributions from non-local and diffusive transport remain largely unexplored. A particular focus is placed on identifying the laser–plasma conditions under which diffusive, collisional transport can play a significant role in isochoric heating of such dense targets.

We focus on the steepening of the laser–plasma interface, previously examined by Mishra et al. [7] and Kemp [8]. Collisional particle-in-cell (PIC) simulations [6] with a continuous PW relativistic laser irradiation ($a_0 = 30$) show the hole-boring up to several hundreds of the critical density with forming a sharp surface gradient. This leads to an injection of a dense population of electrons with reduced mean energy below ponderomotive energy, without significant loss in absorption efficiency reported in [5]. These lower-energy electrons (mean energies ~100 keV - a few MeV) exhibit mean free paths comparable to the typical core plasma size in the fast ignition. They deposit energy rapidly just behind the interaction surface. The timescale of interface formation is consistent with estimates from hole-boring theory [5,6], and serves as a criterion for the required pulse duration of the heating laser.

To evaluate the subsequent bulk electron heating, we conducted Monte Carlo–based collisional transport simulations imitating the fast electron spectrum in the PIC simulation as boundary conditions. The electrons propagate through a compressed core plasma imported from a 1D hydrodynamics simulation and drop their energy following the stopping power formula including the effects from Coulomb collision and wave excitation[8]. The resulting heating power density profile can be characterized by distinct two-regions. Near the laser plasma interface, the drag heating dominates because of the divergence of electrons and their short mean free path. The diffusive heating power shows a negative value balancing with the drag power. As a whole, the resulting steep thermal gradient drives a diffusive heat flux deep into the overdense region, effectively coupling the absorbed laser energy to the core.

We find that as the fast electron temperature decreases, the coupling to the bulk plasma improves, enhancing the diffusive heat flux and increasing the heat front propagation velocity. The resulting heat front advances in the core region at a speed of ~0.03c in the case of Thot = 1MeV. The core is then heated in ~10-20 ps to the bulk electron temperature of 10keV. In contrast, when the fast electron temperature is higher, the heating power is lower and its profile is broader, resulting in inefficient core heating.

These results suggest that the interface steepening and the associated lowering of fast electron temperature with multi picosecond laser irradiation are the keys to achieve efficient core plasma heating for fusion energy applications.

References

[1] L. Spitzer and R. Harm, Phys. Rev. 89, 977 (1953).
[2] N. Higashi et al., Phys. Rev. E 105, 055202 (2022).
[3] Y. Matsuo et al., Phys. Rev. Lett. 124, 035001 (2020).
[4] R. Mishra et al., Phys. Plasmas 16, 112704 (2009).
[5] A. J. Kemp, Phys. Rev. Lett. 101, 075004 (2008).
[6] Y. Sentoku and A. J. Kemp, J. Comput. Phys. 227, 6846 (2008).
[7] N. Iwata et al., Nat. Commun. 9, 623 (2018).
[8] A. A. Solodov and R. Betti, Phys. Plasmas 15, 042707 (2008).