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Isochoric heating of solid-density plasmas beyond keV temperature by fast thermal diffusion with relativistic picosecond laser light

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Exploring how to generate a high-energy-density plasma is essential for applications in laboratory astrophysics, laser-driven particle sources, and ultimately, laser inertial confinement fusion. Especially in the context of fast-ignition laser fusion, one of the most critical issues is to elucidate the isochoric heating mechanism by the heating laser to pursue energy efficiency. In the conventional theoretical model of isochoric heating by fast electron beam, there are three main heating processes: joule heating, drag heating, and thermal diffusion, and the dominant heating mechanism shifts from joule heating via drag heating to thermal diffusion with time [1].

There are about two orders of magnitude discrepancies in the transition time for thermal diffusion to become dominant between the conventional theoretical model and the recent experimental and simulation results. The experiments have been conducted using the heating laser with relativistic intensity and femtosecond to sub-picosecond pulse throughout the past couple of decades. As the conventional theoretical model predicts, Joule heating and drag heating have been considered the dominant heating mechanisms in such situations. The recent experiment has achieved an ultra-high-energy-density state with high energy efficiency [2]. The experimental result has indicated that thermal diffusion is dominant when irradiating a relativistic intensity and over-picosecond pulse [2]. However, the conventional theoretical model predicts that thermal diffusion takes several hundred picoseconds to dominate when considering typical parameters. The recent simulation result also has demonstrated that the transition time of the dominant heating mechanisms from fast electron heating to thermal diffusion is a few picosecond timescales [3].

In order to explain the recent experimental and simulation results theoretically, this paper aims to develop a theoretical model of isochoric heating. Our model assumes the isochoric heating process by a kilojoule-class petawatt laser with relativistic intensity and pulse duration longer than picoseconds. Especially it sheds light on "thermal diffusion" and depicts the details of its heating mechanism. Note that this paper assumes a one-dimensional situation where the laser spot radius is sufficiently large compared to the system.

The theoretical model we proposed in this paper considers the time evolution of the laser-plasma interaction region [4]. The conventional model predicts that thermal diffusion requires several hundred picoseconds to become dominant because it assumes a plasma with uniform density. In this assumption, a fast electron beam heats a region of the same length as the mean free path of the fast electrons to a uniform temperature. Then the heat propagates from the region to the outside. On the other hand, our model assumes that the preplasma and the solid density region are Joule heated. Hence, due to the density difference between the preplasma and the solid region, the temperature difference at the boundary drives thermal diffusion at almost the same time scale as Joule heating. These assumptions are premised on the following: the laser interacts with the plasma at a relativistic cutoff density to generate a fast electron beam, which penetrates from the preplasma region to the solid region without spatial attenuation invoking a mega-ampere class current. Based on these ideas, we developed a simple yet convincing theoretical model of "fast thermal diffusion." We derived the scaling equation for the propagation speed of fast thermal diffusion.

We successfully proposed a physical picture of fast thermal diffusion. We verified the equation with a series of one-dimensional collisional particle-in-cell simulations [5] by varying the laser normalized vector potential, the number density of the target plasmas, and the scale length of the preplasma as simulation parameters. We confirmed that the scaling equation is in good agreement with the simulation results. The simulation results demonstrate that fast thermal diffusion can heat a large volume of solid-density plasmas over the keV temperatures in picoseconds. The developed model resolves discrepancies between the recent experimental results and the theoretical model. It describes that it takes a few picoseconds for fast thermal diffusion to become dominant in solid-density regions when considering typical parameters. It provides a guideline for future experimental design of isochoric heating using kilo-joule class petawatt lasers. It paves the way for exploring high-energy-density physics.

References

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