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Heating a solid isochorically over keV temperature high energy density state by a multi-picosecond intense laser light

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An intense laser expectedly heats a dense plasma with relativistic electron beam (REB) heating, i.e. resistive heating and drag heating. We have reported an additional isochoric heating mechanism, which could work effectively in a multi-picosecond (ps) time scale, driven by an intense laser light interacting with the dense plasma directly. Because of such the direct interaction, the plasma surface is heated up over keV, and then the target is heated diffusively in addition to the REB heating. Here we demonstrate a creation of high energy density (HED) plasmas over keV temperature driven by a multi-ps intense laser light using collisional two-dimensional Particle-in-Cell (PIC) simulations. Such a high energy density plasma, sufficiently long-lived, well-characterized, as a sample of HED matter in the laboratory, is important to explore HED science.

As an example of experimental result, the Fast Ignition Realization Experiments (FIREX) had been conducted using the Gekko XII (GXII) + LFEX, a multi-ps kJ intense laser, at the Institute of Laser Engineering, Osaka University. Delivering REB with guidance of external magnetic field at ~ kT had been demonstrated [1]. The energy coupling of REB to the core was significantly enhanced to the level of 7%, which is an order of magnitude higher than that without the external B-field. Additionally, Cu tracers, which were doped in the core as ~ a few percent of hydrogen ions, emit L-like and He-like emission lines; indicating the core temperature exceeds keV at density of ~ 6 g/cc. Such remarkable high temperature in the core is difficult to explain only by the REB heating at the current core density.

Having a high contrast ($< 10^{-10}$) intense multi-ps laser light; the laser can directly interact with a solid, and thus it can heat the surface without being interfered by large preformed plasmas. Then a high energy density plasma with keV temperature at solid density, which is equivalent to a pressure exceeding gigabar, can be formed. The laser is capable to push the plasma and form a sharp interface of dense plasma. This process is referred to as the laser hole boring (HB). Based on the balance relation between the laser radiation pressure and plasma pressure, the limit density for HB is derived theoretically. The maximum plasma density the laser can reach by HB is given as $8Ra^2n_c$ where a is the normalized laser field amplitude, R the reflectivity, and n_c the critical density [2], respectively. At the steepened interface, the laser produces the REB; moreover, the laser heats the dense plasma surface directly in the skin depth via diffusive collisional processes. Therefore, the surface has a steep temperature gradient. If such temperature gradient is hold over picoseconds, a diffusive heat wave is launched and propagates with a speed of a few micron per picosecond, so that the plasma gets heated up collisionally. The heating mechanism is identified as diffusive heating from the hot surface. Such the diffusive heating process is critically important, since it could heat a solid over keV temperature isochorically, for applications in high energy density physics, i.e. compact keV x-ray and neutron sources, laboratory astrophysics, and the fast ignition in the inertial confinement fusion as an ultimate goal.

We had derived the theoretical scaling of the diffusive heating and also the condition to have the diffusive heating during the laser-plasma interaction. The scaling tells that we could control the diffusive heating with laser amplitude and pulse length, and a plasma with a few hundred eV to over 10keV at solid density is producible. We performed a two-dimensional PIC code, PICLS [3], which is capable to simulate the collisional diffusive processes including ionization dynamics. In the PICLS simulation, we study the isochoric heating of a solid aluminum target with changing the pulse duration and intensity while keeping the pulse energy. The simulation results show that the target is heated over 10 keV in only the case which satisfies the diffusive condition that we have derived. This diffusive heating could explain the keV temperature inside the dense core indicated by hot K-shell signals from the Cupper tracers in the FIREX experiment [1]. As a conclusion, a series of PIC simulations indicate that the diffusive heating of multi-ps laser light with intensity of ~ 10^{18} W/cm^2 is the most effective for bulk electron heating in a solid. Furthermore, we discuss self-generated resistive magnetic fields in a solid and the radiative cooling effect, which cools down the bulk electron temperature so that it affects to the heat transport.

References

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