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Theoretical scaling of fast isochoric heating for laser fusion

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There are two relativistic electron beam (REB) heating mechanisms, resistive heating (Joule heating) and drag heating (direct collision between REB and bulk electrons). These REB heatings have been discussed intensively to assess the fast ignition (FI). However, such assessment had been done based on the experimental results using a sub-picosecond (ps) laser pulse and theories for them. Here we report an additional heating mechanism, thermal diffusion, to achieve the fusion temper-ature > keV, with much higher efficiency using a multi-ps relativistic laser light than the REB heating. We found that (i) a multi-ps laser is capable to maintain a steep interface with temperature over keV, and thus (ii) the thermal diffusion is initiated from the interface to the inside of the core plasma on top of the REB heating: resistive and drag. By considering the thermal diffusion along the REB heating, the requirement for the laser to achieve the ignition is mitigated rather than by taking ac-count into the REB only. Our result encourages the FI scheme as an alternative IFE approach.

The fast isochoric heating also known as the FI had been proposed as an alternative approach to the IFE. This approach separates compression and heating processes so that we can optimize each process individually. Recently we had demonstrated a more stable compression and a dense core using a solid ball target as implosion target. The core is then heated by an intense laser light, whose time scale is much shorter than the implosion time scale. Since the laser stops at its critical density in the coronal plasma before it reaches the core, the REB heating had been considered as the only way to heat the core.

The Fast Ignition Realization Experiments (FIREX) had been conducted using the LFEX, a multi-ps kJ intense laser, and GEKKO XII, at Institute of Laser Engineering, Osaka University. Delivering REB with a guidance of an 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. Recently we reported that we have achieved experimentally 2.2 Peta-Pascal (PPa) of ultra-high-energy-density (UHED) state with 4.6 kJ of the total laser energy [2] that is one order of magnitude lower than the energy used in the conventional direct implosion [3]. The generation of such a UHED state cannot be explained with the drag heating mechanism only. Collisional Particle-in-Cell (PIC) simulations with the experi-mental conditions confirm that the thermal diffusion mechanism plays an essential role to heat the core plasma over keV range on top of the drag heating and resistive heating, see Fig. 1. PIC simu-lations reveal that the heat wave propagates diffusively with velocity > 10 m/ps even after the heating laser irradiation terminated, and then the core region X < 30 m was heated over 1 keV electron temperature at t = 4.8 ps as Fig. 1(a) and (c). The pressure at the core region X < 30 m exceeded 1 PPa (Fig.1(b)).

When the laser intensity exceeds 1018 W/cm2 with multi-ps pulse duration, the radiation pressure of laser pulses reaches 0.1 PPa level, so that the laser is capable to push the dense plasma and form a sharp plasma interface. This process is referred to as the laser hole boring. The plasma surface is then heated to keV temperature by the laser light directly, and a large temperature gradient is established to drive the thermal diffusion as seen at X ~ 60 m in Fig.1 (d), (e) and contour lines of Fig.1(c). Such diffusive isochoric heating is realized by sustaining the temperature gradient over ps, thus we need a multi-ps relativistic laser light e.g. LFEX. Note here that a sub-ps laser could have the thermal diffusion however the diffusion occurs after the laser irradiation so that the achievable temperature is limited to a few 100s eV [4].

The propagation speed of the heat wave by the diffusion heat can be derived from the Fourier's law, q=∇Te ~ Te/L, and assuming the energy flux conservation from laser to plasma, neTeheat, here q= neTeheat is the heat flux, =3SH/128, SH is the thermal conductivity in Spitzer-Härm regime, Te the bulk electron temperature, L the scale length of the diffusion, the absorption coefficient, I the laser intensity, and ne the bulk electron density. By assuming, L≈ heat t, we obtain

where c is the light speed, =4(2)1/2e4ncL/(3me2c3), e the elementary charge, nc the critical density, L the laser period, me the electron mass, ln the Coulomb's logarithm, a the normalized laser amplitude, and t the heating time [2]. We confirmed that the heat with the simulation parameters is consistent with the speed of heat wave observed in the PIC simulations. Using Eq.(1) we can estimate the ignition scale experiment with the core about 10 times denser than the current experiment, i.e., 100 g/cm3, with the similar diameter 50 m, the heating laser (A) 10 times higher intensity and same duration or (B) same intensity and 10 times longer duration, thus 10 times higher energy than the current experiment. In this case the core can be heated by the heat wave with almost same speed as the current experiment. Note here in the ignition scale experiment, the REB is expected to deposit energy more efficiently via the drag heating to the dense core.

In conclusion, a multi-ps intense laser can heat the dense core isochorically over keV tem-perature via the thermal diffusion. The heat wave propagates with a few microns per ps. Our result encourages the FI scheme as an alternative IFE approach. By sustaining the hot surface over pi-cosecond with the intense laser, we can create plasmas with a sufficiently large volume of a few 10s micron3 and temperature over keV. Such high energy density plasmas can provide an optimal testbed for various applications, e.g, studies of stopping power of high-energy ions including α particles and opacities in extreme state matters, small-scale pulsed neutron sources, the laboratory astrophysics, and the fast ignition as our ultimate goal.

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