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Efficient fast isochoric heating process visualized with spatial-temporal-resolved x-ray imaging

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Here we report the mechanism of plasma heating by magnetized fast-isochoric (MFI) heating scheme (1). The mechanism was visualized experimentally by combining spectroscopic and spatially- and temporally-resolved X-ray imaging techniques. The MFI scheme employs an external magnetic field for guiding a high-intensity relativistic electron beam (REB) generated by relativistic laser-plasma interactions to a small and dense fuel core along magnetic field line. Our studies clarified the followings; (i) the REB guiding resulted in doubling the drag heating efficiency up to 8% (2), (ii) ultra-high-energy-density region having 2.0 keV of temperature and 2.2 Peta-Pascal of the pressure was created with 12% of energy coupling efficiency through the diffusive heating process, namely by heatwave propagating in the core with 10^{8-9} cm/s of the speed (3), (iii) 8% of the current drag coupling efficiency is scalable to >15% of the efficiency in an ignition-scale high area-density core (> 0.5 g/cm2) and heating laser intensity (1 x 10^{20} W/cm^2) based on a model (4) that are fairly consistent with the experimental observations. This efficiency is >3 times higher than that of the currently pursed central ignition scheme.
The fast-isochoric heating may produce the ignition spark with avoiding ignition quench caused by the fluid mix between the spark and a cold fuel layer. This mix is a crucial problem of the adiabatic compression heating in the central ignition scheme. In the fast-isochoric heating scenario, a relativistic intensity laser, namely heating laser, generates the high-intensity REB. The REB carrying a significant fraction of the heating laser energy travels in an over-dense plasma from its generation zone to the pre-compressed fuel core. Part of the REB's kinetic energy is deposited in the pre-compressed core, and then the heated plasma core becomes the ignition spark. There are two major mechanisms in the fast-isochoric heating process as illustrated in Fig. 1. One is the drag heating mechanism, where energy is transferred from REB to the fuel core by electron-electron binary collisions. The other is the diffusive heating mechanism, where energy is transferred by thermal conduction to a cold plasma from a high-temperature plasma that is heated by the resistive return current induced by the forward REB current. Kilo-tesla magnetic field is required to guide the forward REB current and also the return current within a diameter of the pre-compressed core. A laser-driven capacitor-coil target was used to generate a kilo-tesla magnetic field (5,6).

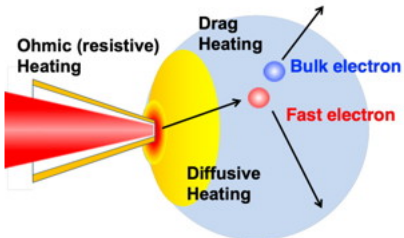

Figure 1: Schematic of energy transfer mechanisms in the fast-isochoric heating scheme. Drag heating is the energy transfer through electron-electron binary collisions in the core. Diffusive heating is caused by thermal conduction from the laser-heated plasma to the cold core.

A solid ball was compressed by six beams of fuel compression laser in this experiment. The Cu and Ti atoms contained in the ball were tracers for the measurement of laser-to-core coupling and electron temperature of the core. The solid ball was attached to a gold cone. The heating laser was focused on the tip of the cone to produce the REB. The center of the coil was located at 230 μm from the center of the solid ball. The drag mechanism heats uniformly the entire pre-compressed plasma because of long range (0.5 g/cm^2 for 1 MeV REB) of the REB. The diffusive mechanism heats a smaller part of the pre-compressed plasma to higher temperature than those heated by the drag mechanism due to shorter range of thermal electrons than that of REB. The visualization of He_alpha X rays emitted from the heated region enables us to evaluate the efficiency of the diffusive heating process in addition to the drag heating efficiency that was evaluated from the absolute yields of electron collision-induced K_α X rays. The visualization of He_α X rays emitted from the heated region enables us to evaluate the efficiency of the diffusive heating process in addition to the drag heating efficiency that was evaluated from the absolute yields of electron collision-induced K_α X rays. Hydrodynamic motion of the heated plasma is negligible during the drag heating time-scale, on the other hand, the diffusive heating is slower than the drag heating. Time and spatial scale of the diffusive heating process are several tens ps and μm respectively, therefore, hydrodynamic motion can affect the evaluation of the diffusive heating efficiency. < 15 μm and < 10 ps of spatial-temporal resolutions are required for evaluating the diffusive heating efficiency. It was difficult to utilize a fast and high-spatial resolution x-ray imaging technique under the harsh radiation environment produced by high-intensity laser-plasma interactions because the intense radiation causes a noisy background in the images. We visualized the heating area correlated with a plasma density profile by using quasi-monochromatic x-ray imagers and/or a thin-photo-cathode x-ray image detector that is insensitive to hard X-rays (7).

A number of K_α photons emitted from the tracers correlates with energy deposited in the core via the drag heating mechanism. The internal energy of a heated plasma was obtained by combining two-dimensional (2D) electron temperature distributions obtained from 2D He_α x-ray images and 2D density ones that were separately measured with an X-ray backlight technique. X rays from He-like ions (He_α) are emitted from a high-temperature region, and its yield depends on electron temperature of the region. The diffusive heating efficiency was calculated as a ratio between evaluated internal energy and heating laser energy. The measurements revealed moderate heating of the entire core by the drag mechanism with 8% of energy coupling (2) and 12% of the diffusive heating efficiencies for 0.1 g/cm^3 of areal density in our experiment, respectively. As shown in Fig. 2, the drag and diffusive heating processes were visualized with Fresnel phase zone plates (FPZPs), whose spatial resolution and gating time are 5 μm and 10 ps, respectively. The drag heating is the dominant process in the dense region because this is caused by electron-electron binary collisions, and the diffusive heating localized in the less compressed region near the cone because the heatwave propagation velocity is inversely proportional to the plasma density.

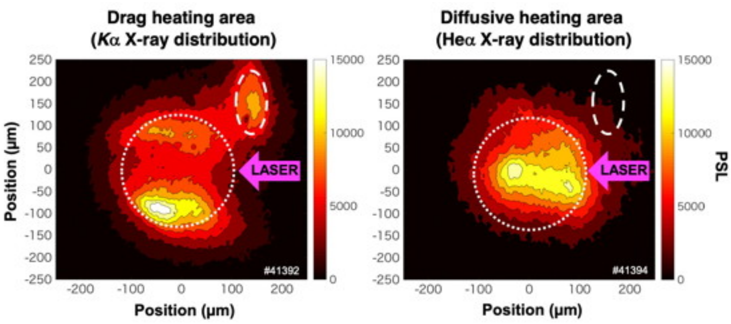

Figure 2: (Left) Drag heating area visualized as K_α X-ray emission region (Right) Diffusive heating area locates near the cone that was visualized as He_α X-ray emission region. The white dotted and broken lines indicate size of the compressed plasma and a K_α fiducial mark attached to the cone, respectively.

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