Femtosecond X-ray imaging of isochorically heated solid-density plasmas with XFELs

The advent of chirped pulse amplification (CPA) technology [1], which earned the Nobel Prize in Physics in 2018, has revolutionized laser science by enabling the production of ultra-intense laser beams. These powerful laser beams can accelerate free electrons to high energies, generating forward-directed electron beams. Such beams have numerous applications, including compact electron accelerators and secondary sources of radiation such as X-rays and γ-rays, and particle beams (ions and neutrons). Additionally, the extreme material conditions induced by energetic electron impacts are of great interest across diverse fields such as astrophysics, aerospace engineering, and fusion energy research.

For more than two decades, high-intensity, short-pulse lasers have been used to study matter under extreme conditions. Energetic (fast) electrons, which carry extremely high currents (mega-amperes) less than tens of picoseconds, rapidly heat targets before significant expansion occurs. This process, known as isochoric (constant volume) heating, is critical to applications such as fast ignition laser fusion [2], where laser-driven charged particle beams assist in initiating fusion reactions. However, diagnosing these highly transient target conditions is challenging due to the lack of diagnostics with sufficient spatial and temporal resolution. In addition, probing the interior of dense materials requires external hard X-ray beams.

Here, we report the first femtosecond and micron-scale resolved measurements of isochorically heated solid-density copper foils using an X-ray free electron laser (XFEL). The experiment was conducted at SACLA **BL2** EH6, combining a high-power, femtosecond laser with an XFEL beam. The experimental setup is illustrated in Fig. 1(a). A 2-μm thick copper foil was irradiated by the optical laser at a peak intensity of ~2×10^{18} W/cm^2, while a 10-fs collimated X-ray pulse provided 2D imaging of the heated region at various delay times.

An initial X-ray image of the foil, captured prior to laser irradiation, showed the unperturbed foil condition. Following laser irradiation, X-ray images revealed slight changes in transmission intensity, as depicted in Fig. 1(c). Division of pre- and post-irradiation images pronounced the transmission-affected region (Fig. 1(d)). By varying X-ray probe energies (9.05, 8.92, 9.12, and 8.05 keV) and delay timings, we measured the temporal evolution of the electron-heated region's size. This approach represents a novel use of spatiotemporally resolved transmission images to characterize heat front propagation [3] and diagnose plasma conditions within the heated material [4].

Figures 2(a–d) show X-ray transmission ratios measured at photon energies of 9.05 keV and 8.92 keV at different delays. At 9.05 keV (above the Cu K-edge of 8.99 keV), the heated foil exhibited

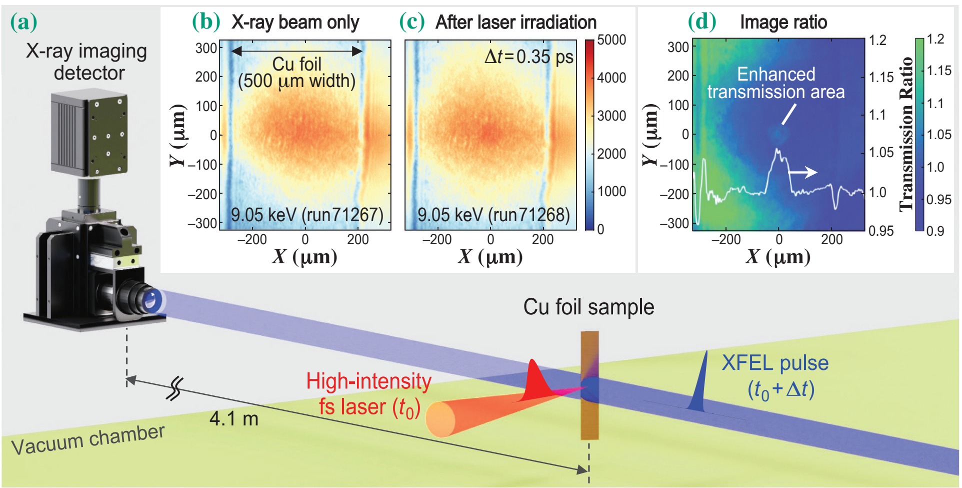

Fig. 1. **(a)** Schematic of the experiment at SACLA BL2 EH6. Measured X-ray transmission images **(b)** before and **(c)** after laser irradiation. **(d)** A transmission ratio image obtained by dividing the two images.

increased transmission and expansion up to ~1.5 ps. Conversely, at 8.92 keV (below the Cu *K*-edge), a decrease in transmission was observed. The energy-dependent transmission changes are attributed to smearing of the *K*-edge spectrum under metal-like conditions (i.e., Fermi degenerate matter) [5], which enabled us to infer an electron temperature of 7~18 eV behind the heat front. The observed expansion of the heated region was compared with 2D particle-in-cell simulations, which constrained the ionization state of the copper foil (mean charge state $\bar{Z}$) to be between 2 and 4, as shown in Fig. 2(e).

Figure 3 summarizes the experimental and simulated results in an electron temperature and density contour map [4]. The inferred plasma conditions (electron temperature T_e of 7~18 eV and $\bar{Z}$ of 2~4) fall within the warm dense matter (WDM) regime, which lies between ideal plasmas and strongly coupled and Fermi degenerate matter. This study reveals that the heated copper foil exhibits two distinct plasma regions: a highly ionized, hot plasma near the laser interaction spot, surrounded by a Fermi degenerate WDM region. Notably, our measurements validate the simulations only for the latter region, highlighting the need for further improvement to accurately characterize the simulated hot plasma condition. These results provide new insights into fast electron heating dynamics in solid-density materials, advancing our understanding of dense plasma heating in high-energy density science and fast ignition research.

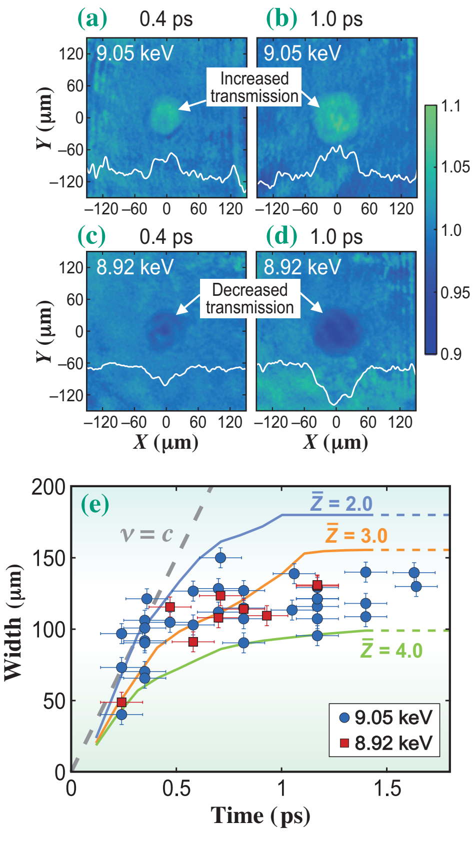

Fig. 2. Measured X-ray transmission ratio images for 9.05 keV at **(a)** 0.4 ps and **(b)** 1.0 ps delay times, and for 8.92 keV at **(c)** 0.4 ps and **(d)** 1.0 ps. **(e)** Comparison of the measured heated width with simulated ionization states between 2 and 4.

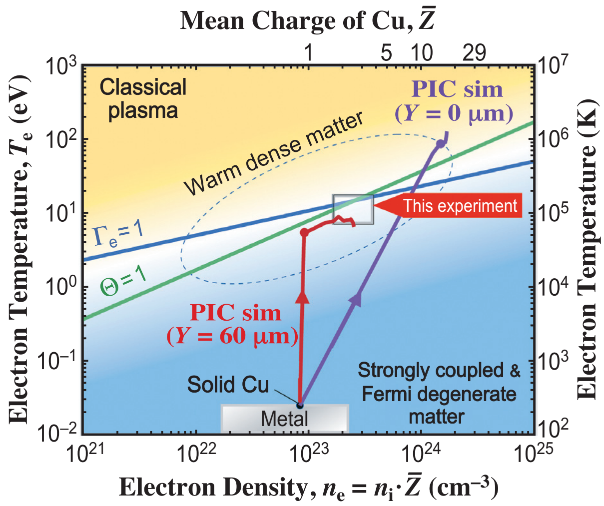

Fig. 3. An electron temperature-density contour. The inferred conditions are illustrated with a white box. Solid lines with arrows represent simulation results near the laser interaction point in purple and a periphery region in red.

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