Ultrafast time-resolved measurements of relativistic electron heating in solid-density plasmas

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A copious number of relativistic electrons generated in an intense short-pulse laser-plasma interaction has advanced applications of laser electron accelerators, the generation of secondary sources, and the creation of high-energy-density (HED) matter.[1] The transport of such electrons in a metal foil rapidly heats and transforms it to an ionized solid density matter in the warm dense matter (WDM) regime before it hydrodynamically expands. Furthermore, this heating scheme with high-energy, petawatt-class lasers has the potential to create hot dense matter with a keV temperature [2], giving access to matter in unexplored temperature-density domain with existing drivers.

The underlying physics of relativistic electron isochoric heating has been investigated for over two decades.[3] Recently, time-integrated monochromatic x-ray imaging revealed that the dominant mechanisms in a solid titanium foil are resistive and diffusive heating.[4] However, diagnosing transient material conditions has been limited in spatiotemporal resolutions up to date. The recent advent of a high-intensity laser combined with an x-ray free electron laser (XFEL) has offered a novel pump-probe platform enabling ultrafast time-resolved measurements of solid and high-density matter.

Here, we capture femtosecond dynamics of plasma formation driven by relativistic electrons in solid metal for the first time. In this work, we demonstrate a diagnostic with femtoseconds and micron-scale resolution using SACLA XFEL pulses in two experimental setups. Edge-on imaging presented in Figure 1 determines the onset of dense plasma expansion to be 50~100 ps after the laser irradiation. In a face-on geometry, we visualize the propagation of the ionization front in a solid copper as a signature of the plasma creation.[5] The novel x-ray transmission imaging with x-ray wavelengths tuned to near the Cu K-edge provides information on the target's temperatures and ionization states from a smeared K-edge profile and the evolution of the electron-impacted area. Our result reveals that the fast propagation of the ionization wave produces strongly coupled Fermi degenerate matter. Information on the non-equilibrium WDM could be used to validate quantum molecular dynamics and plasma atomic physics calculations in WDM, such as ionization potential depression.

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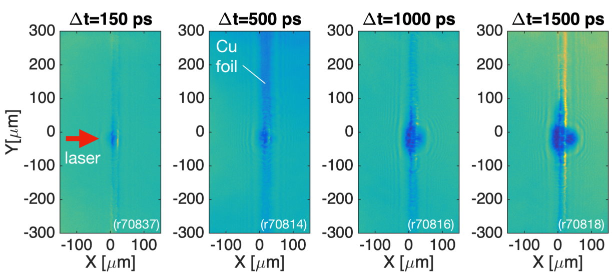

Figure 1 A sequence of edge-on x-ray images of a solid copper foil irradiated by a femtosecond laser at 2×10^{18} W/cm^2. The timing delay between XFEL and the optical laser varied from 50 to 1500 ps.