Ionization and structural dynamics in solid hydrogen and deuterium

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The thermodynamic properties of even the simplest element hydrogen remain elusive when it comes to extreme conditions. Knowledge of the equation of state of hydrogen and its isotope deuterium is hence critical for modeling stellar and planetary interiors, as well as for ICF experiments. Microscopic properties related to reflectivity, electrical and thermal conductivity are tied to dynamic energy transport between electrons and ions.

In 2014, we reported on time-resolved XUV measurements [1] where ultra-fast electron heating is initiated by a 10^{13} W/cm² intense 300 fs short burst from the FLASH XUV-FEL at 13.5 nm wavelength. A second pulse probes the sample via XUV scattering at variable time delay. From the ion-ion structure factor S(k~0), we found that the molecular ice dissociates in 0.9 ps, transitioning into a dense atomic plasma with a final ion temperature $\leq$ 1 eV at 0.08 g/cm^3, which poses several challenges to the employed plasma models and equation-of-state tables.

New unpublished data obtained in 2015 with 60 fs temporal resolution employed a Schwarzschild EUV microscope [2] capable of single-shot sub-µm imaging. We monitored the hydrogen jet's structure by single-shot Mie scattering patterns. The time-resolved scattering suggests that 500 fs after XUV pump photo- and impact ionization have reached a maximum and subsequently the solid-plasma transition takes place due to electron-ion heat transfer, and is finished around 700 fs after excitation. First microscopic particle-in-cell simulations support this interpretation. We also present an outlook about repeating the experiment on deuterium, where the electronic excitation is comparable to hydrogen while the electron-ion energy transfer is slower due to the heavier deuteron mass.

[1] U. Zastrau, P. Sperling, *et al.*, Physical Review Letters **112**, 105002 (2014).

[2] U. Zastrau, C. Rödel, *et al.*, Review of Scientific Instruments **89**, 023703 (2018).