Determining thermal conductivity at extremes using X-ray Free Electron Lasers

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Abstract

The determination of thermal conductivity at extreme pressure and temperature conditions is a main branch of high pressure experiments and has various outputs for planetary science. Thermal conductivity at extremes determines planetary evolution as well as current dynamics. While there exists a variety of techniques already employed for thermal conductivity determination, a number of discrepancies persist for some of the key materials present in terrestrial planets. One of the most striking cases is Fe alloys at Earth's core conditions. A convincing assessment of such quantities requires new techniques benchmarked at very extreme conditions. Here, we present three recent developments based on a combination of X-ray Free Electron lasers, high-pressure diamond anvil cell (DAC) experiments, and numerical modeling that can be used to constrain thermal conductivity at extremes. We show how adjusting numerical models to match experimental x-ray diffraction data, optical temperature measurements, or post-mortem micro-analysis of recovered samples all offer novel solutions to assessing extreme thermal conductivity, reaching into high pressure liquid states.

Our first approach presents DAC experiments where volumetric x-ray heating was employed to bring metallic samples up to several thousands of K [Husband et al. 2021]. Using Finite Element Modelling (FEM), the time-dependent volume evolution of the crystal lattices upon heating can be reproduced [Edmund et al. 2024]. Model adjustments benefit from the thermal conductivity dependence of that evolution.

In a second approach, we demonstrate how measured temperature oscillations resulting from serial XFEL irradiation can allow fitting of the sample thermal conductivity. We characterize temperature oscillations measured on very short timescales with streak optical pyrometry and show how solid and liquid thermal conductivities can be determined from these data.

Finally, we introduce a melt volume-based analysis of thermal conductivity in X-ray heated samples, using recovered sample textures in cross-sectional measurements to establish melting extent. Simulations of the melt extent show that, for equal temperatures, the melt extent depends on the thermal conductivity of the sample predominantly for insulating pressure media. In particular, this technique is sensitive to the thermal conductivity of the liquid volume.