Measuring the Thermal Conductivity of Iron Alloys Near Planetary Core Conditions at the OMEGA Laser Facility

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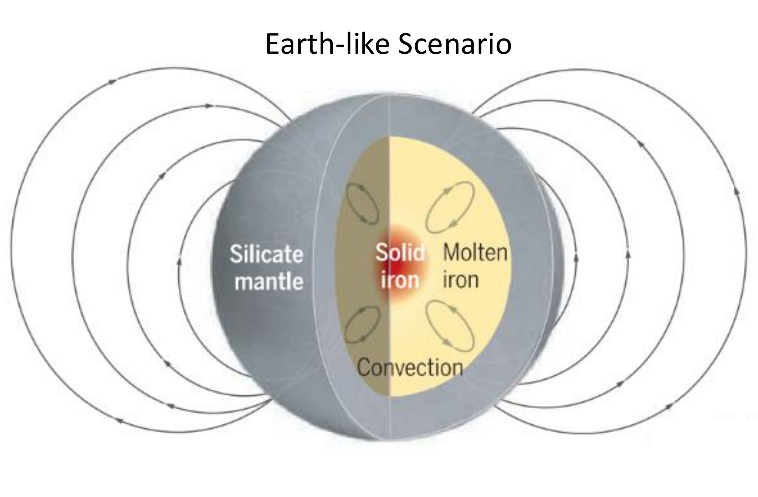
Abstract

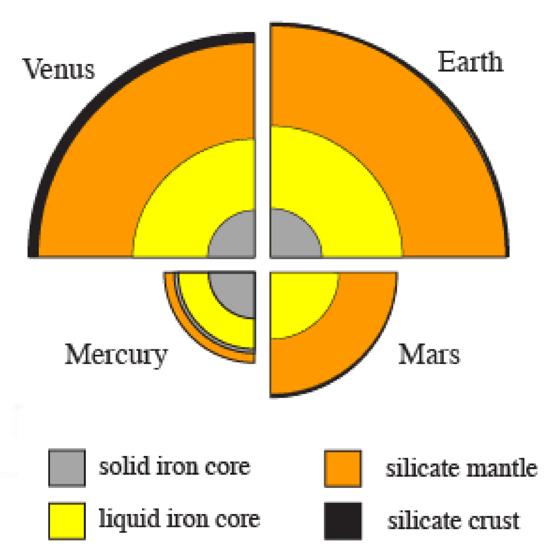
Understanding the thermal conductivity of materials found in the cores of rocky planets can help us predict planetary evolution and understand the mechanisms necessary for the existence of organic life. However, significant variations in scientific modeling and a scarcity of experimental measurements limit our understanding of materials at the extremes of temperature and pressure. We propose to use our isochoric heating platform developed for the OMEGA 60 Laser System to recreate the conditions close to those found in the interiors of Earth-like planets. We will subject a 5 µm Fe/Ni (95/5 %wt) alloy wire (representing an iron planetary core) with a 10 µm borosilicate glass encasing (representing the silicate mantle) to planetary core conditions. After pressure equilibration, the shape of the density profile across the Fe95/Ni5-glass interface evolves primarily through thermal conductivity. This profile will be measured with a spatial resolution on the order of 1 µm, in line with previous work[1,2,3]. This will enable the accurate extraction of the conductivity scale length, which in turn will be used to validate competing theoretical models.

Motivation

Why Iron?



Magnetic field of Earth-like planet[4]

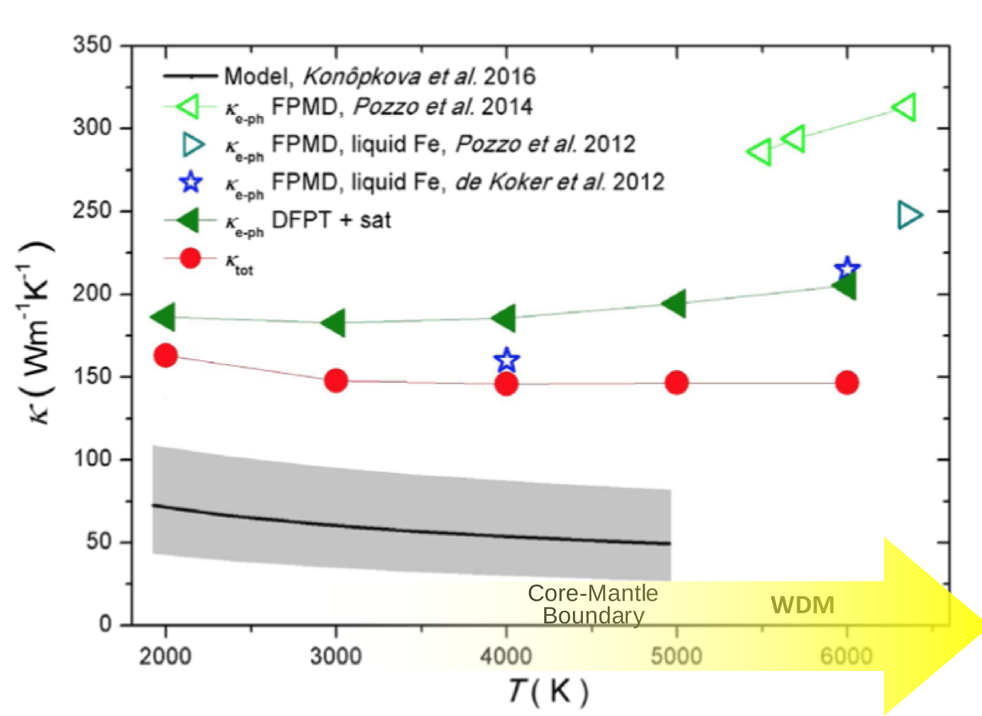


Relating known terrestrial planet interiors[5]

- The warm dense matter (WDM) regime is of particular interest in astrophysics.
- Understanding thermal properties of planetary interiors can provide insight into:
  - —Planetary evolution
  - —Planetary interior dynamics
  - —The existence of life on exoplanets

Transport Properties in WDM Require Experimental Benchmarking

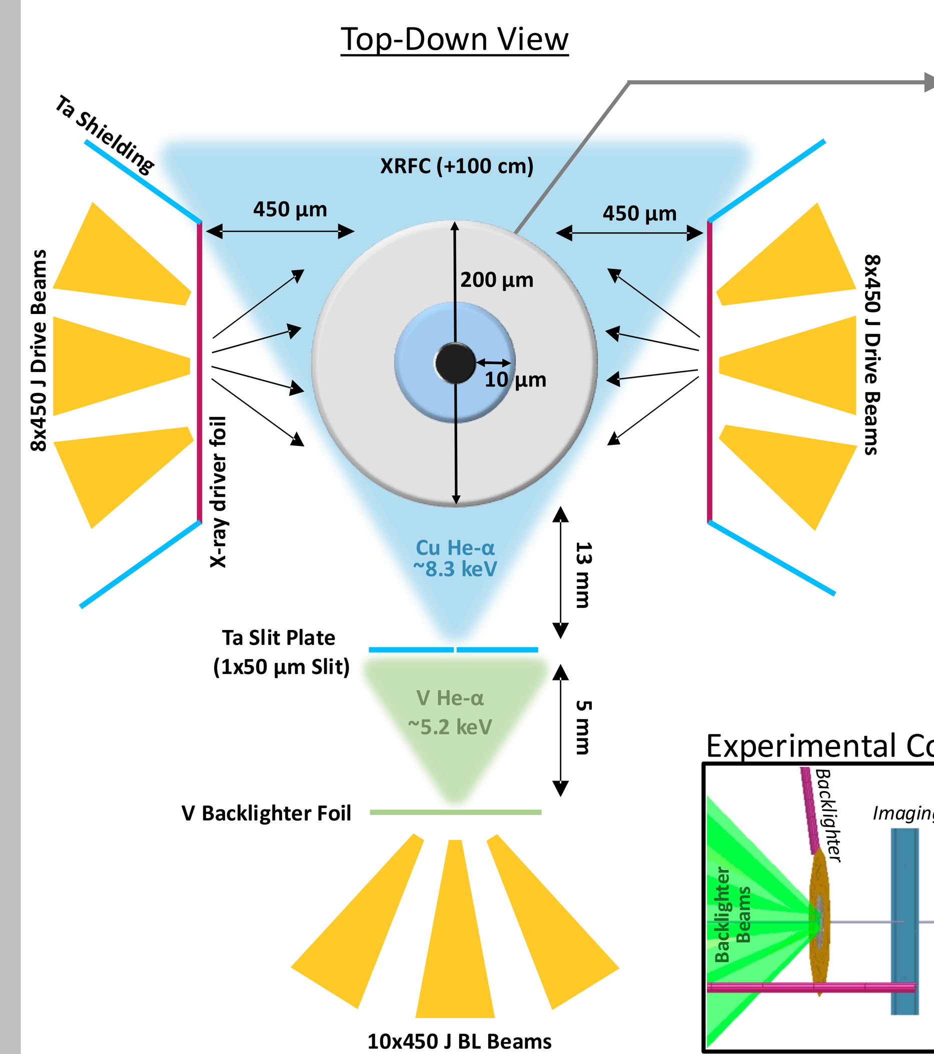
- WDM is challenging to model as it resembles both condensed matter physics and classical plasma physics without being easily described by either.
- Thermal properties of materials under planetary core conditions are not well understood:
  - —Large variations in theoretical predictions
  - —Lack of experimental measurements

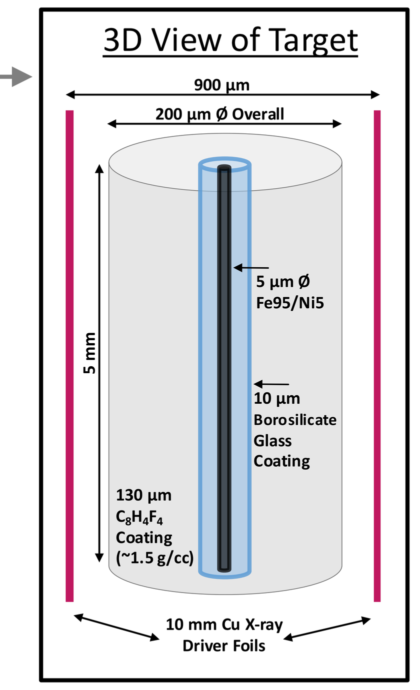


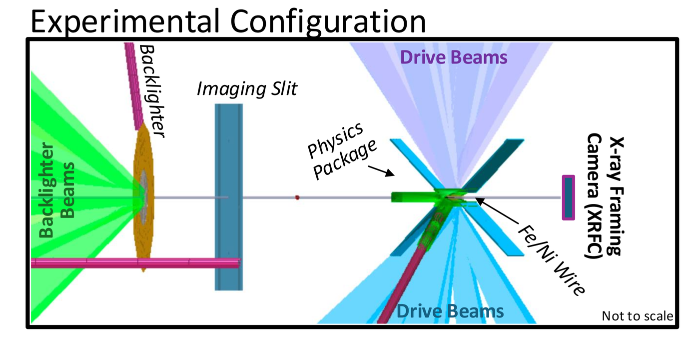
- Models of thermal conductivity of iron at Earth-core conditions show large variation.
- At temperatures approaching planetary core conditions, the models show increased divergence in thermal conductivity. The significant differences between the theoretical techniques highlight the importance of experimental verification.

Experimental Design

Utilizing Established Experimental Platform

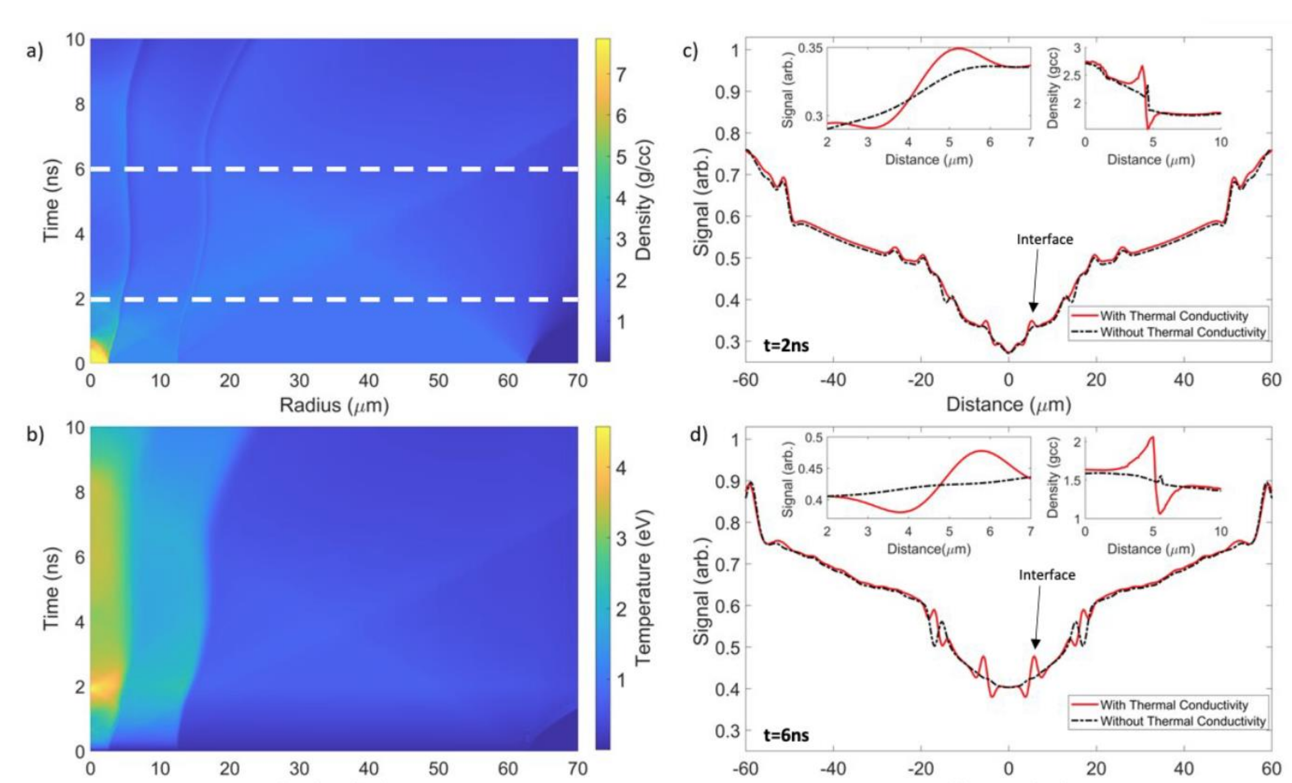






- The platform developed for OMEGA 60 utilizes a buried-wire target consisting of a thin, high-density metal wire encased in glass, all coated with a thick layer of plastic
  - —Diameter of the metal is chosen to minimize pressure equilibration time
  - —Diameter of the plastic is chosen to maximize experiment lifetime and minimize X-ray attenuation
- The wire is isochorically heated by a He-α X-ray source generated by laser irradiation of thin foils. This causes the wire to expand rapidly.
- The interface is imaged through refraction enhanced point-projection radiography
  - —A 1 µm-wide imaging slit is utilized to allow for sensitivity to refraction and diffraction features at the interface

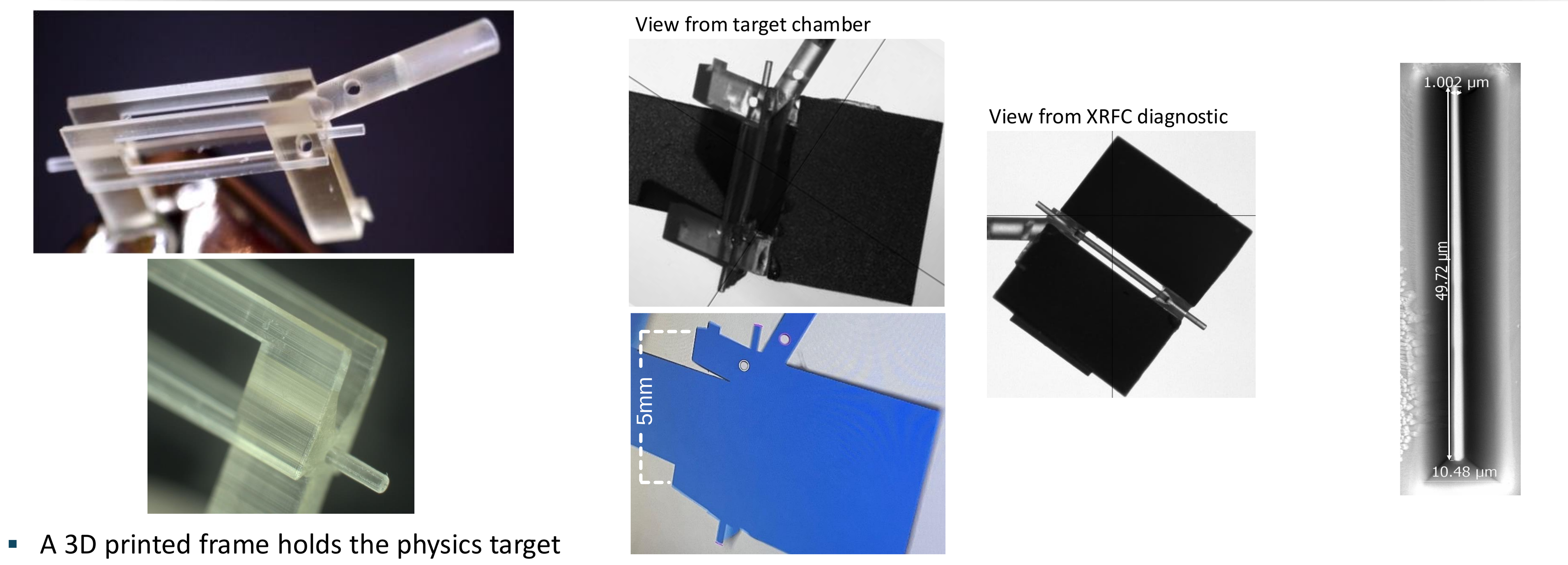
X-ray Diffraction Simulations



- Hydrodynamic simulations show the evolution of the density (a) and temperature (b) of a CHF-coated, glass-insulated Fe/Ni wire system after irradiation with a ~2 ns 6.2 keV X-ray pulse from Mn X-ray drivers:
  - —The metal core releases a shock into the glass as it rapidly expands until the pressure across the sample equilibrates.
  - —The density profile between the two materials is subsequently modified by thermal conduction from the hot metal into the colder glass.
- Panels (c) and (d) show the density profiles and diffraction pattern predictions at 2 ns and 6 ns calculated from the target's complex transmission function.

Current Experiments: Astrophysically Relevant Iron Alloys

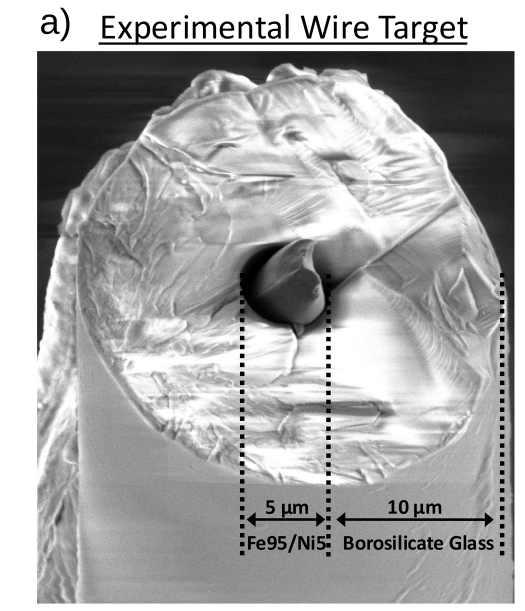
Developments in the Platform



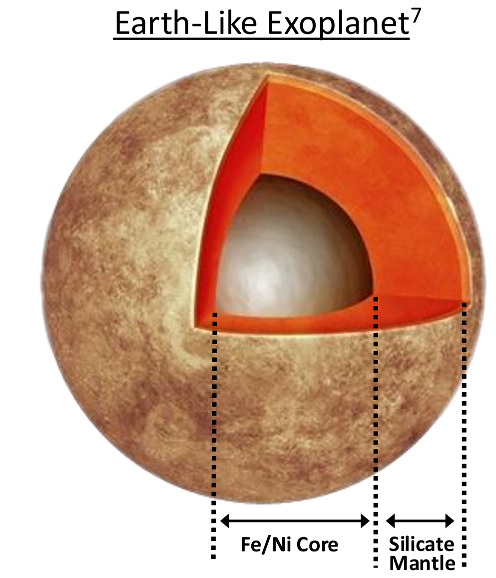
- A 3D printed frame holds the physics target (Fe/Ni wire), driver foils, and shields.
- Success of the experiment relies on fully resolved alignment features.
- Alignment view from the target chamber and from the primary diagnostic of OMEGA 60 highlights the importance of accurate alignment features.
- 1um slit was cut using a Focused Ion Beam.

Preliminary Data on Fe/Ni (95/5 % wt) Target

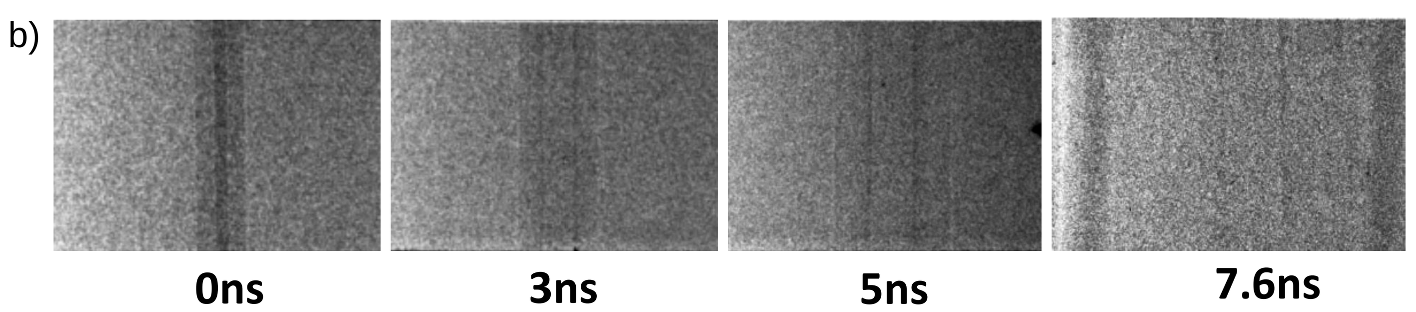
a) Experimental Wire Target

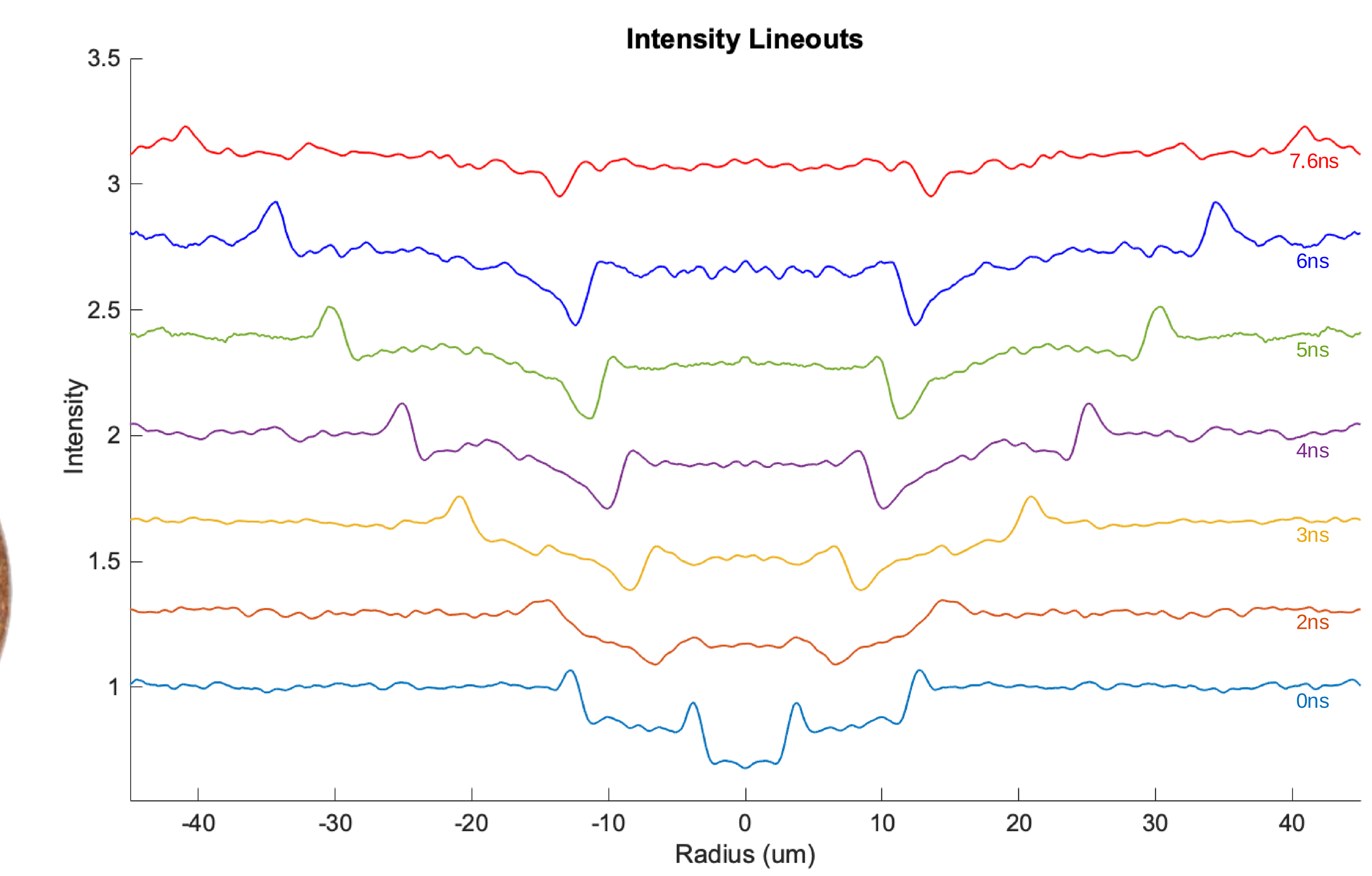


Earth-Like Exoplanet[7]



b)





a)
- The Fe/Ni wire interior represents an Earth-like iron core, and the surrounding silicate glass mimics the silicate mantle.
- Oxidation is the main challenge in producing iron microwires at small scales.
  - —Oxidation changes material properties, increases brittleness, and decreases breaking load.
- Wire targets were manufactured by Goodfellow via a modified Taylor-Ulitovski method.

b)
- Preliminary data from our April 2024 experiment on OMEGA 60 showing opacity lineouts of the expanding Fe/Ni-glass interface.
- The density evolution is dominated by thermal conduction across the interface and will be used to extract the thermal conductivity of our sample materials.

References

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