

## Development of Dynamic Ellipsometry for Measurements of Iron Conductivity at Earth's Core Conditions

Participants: S. Grant, A. Bernstein (CHEDS, University of Texas).

J. Lin (Mineral Research Group (MRG), University of Texas).

T. Ao, J. Davis, D. Dolan, C. Seagle (Sandia National Laboratories).

The CHEDS researchers are engaged in a collaborative research project to study the properties of iron and iron alloys under Earth's core conditions. The Earth's core, inner and outer, is composed primarily of iron, thus studying iron and iron alloys at high pressure and temperature conditions will give the best estimate of its properties. Also, comparing studies of iron alloys with known properties of the core can constrain the potential light element compositions found within the core, such as fitting sound speeds and densities of iron alloys to established inner-Earth models [1, 2]. One of the lesser established properties of the core is the thermal conductivity, where current estimates vary by a factor of three [2, 3, 4]. Therefore, one of the primary goals of this collaboration is to make relevant measurements to elucidate this conductivity.

In order to estimate the thermal conductivity, we have proposed measuring the electrical conductivity through ellipsometry, a technique commonly used to measure refractive index, and thus electrical conductivity, in static or slowly changing conditions. To do this we are developing a time-resolved ellipsometry diagnostic that is capable of measuring electrical conductivity *in situ*. Previously, we confirmed the basic operation of the diagnostic on static samples and made design improvements to transfer the diagnostic to a single stage gas gun at Sandia National Laboratories, where we performed initial experiments looking at birefringence in shocked BK7 windows.

The ellipsometry diagnostic design is shown in figure 1, the free-space optics set and analyze the polarization state while the fiber optics transport the light into and out of the target chamber. We use a 1550 nm CW fiber-coupled laser as the light source. Further details of the diagnostic and results of the BK7 experiments are available in our conference proceedings [5].

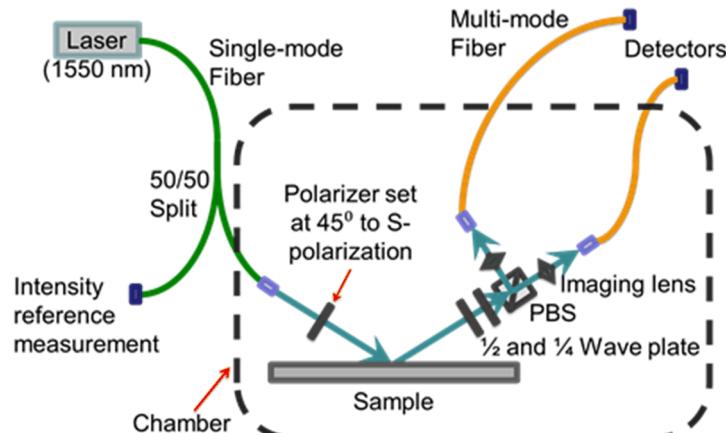
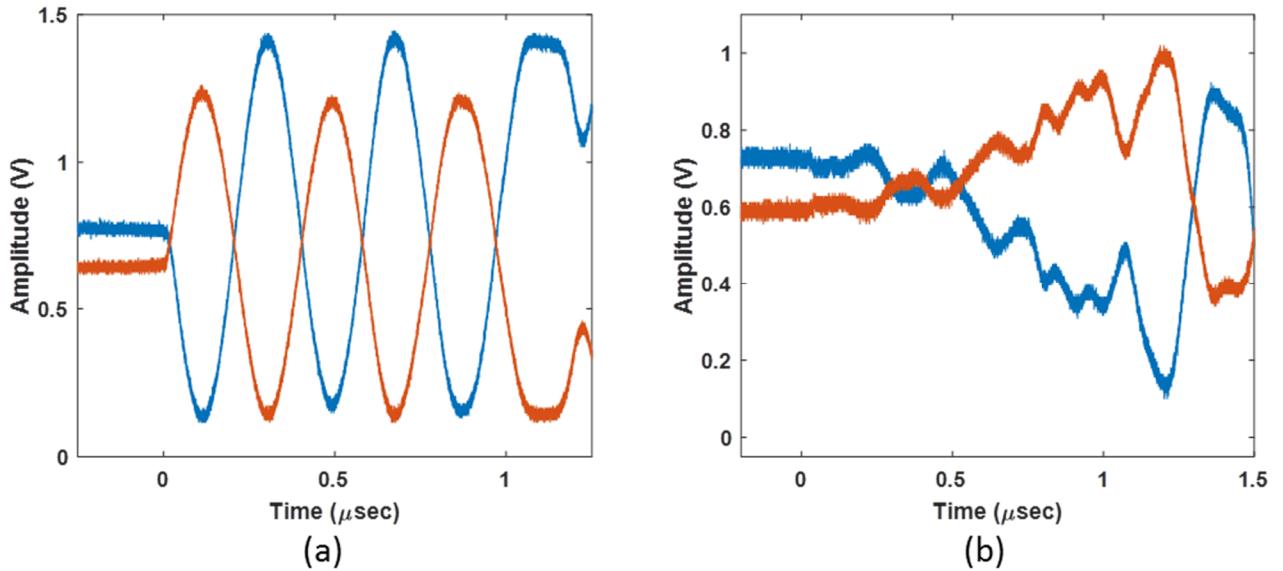


Figure 1: A schematic of the ellipsometry diagnostic. A combination of free-space and fiber optics are used to optimize delivery and maintain full polarization information of the probe beam.

By performing a new series of experiments on the gas gun at Sandia National Laboratories' DICE facility, our research has continued to progress well in 2016. These experiments looked at the effect of sample and impactor configurations on the clarity of the resulting data. A first round of experiments, which simply imaged the profile of the beam reflected off the sample showed that direct impact on a thin film reflective sample did not maintain a good reflective surface, at least unless the impactor was extremely well polished. The second round of experiments investigated the effect of a LiF window on our ellipsometry diagnostic. While we expected that a LiF window would have a more complicated elastic precursor behavior than the BK7 windows used in our experiments from 2015, these experiments revealed the behavior of LiF to be considerably less predictable. Figure 2 shows the comparison between the clean sinusoid that was reproduced in this round of experiments from a BK7 backing window, and the signal produced from a LiF backing window. Both experiments had similar impactors and impact conditions. The signal produced by the LiF window does not fit well to the growth of a consistent precursor, nor a precursor which is experiencing monotonic decay. This confirmed our suspicion that LiF may only be suitable as a window if the shock is strong enough to overdrive any precursor behavior.



**Figure 2: (a) Ellipsometry data from a shocked BK7 window. A clean sinusoidal pattern indicates a steadily growing birefringent region. (b) Ellipsometry data from a shocked LiF window. While the phase difference between the two polarization signals shows change, it is not consistently increasing or decreasing.**

For the next stage of the research, we performed our first round of experiments on the larger two-stage gas gun at Sandia National Laboratories' STAR facility. The purpose of these experiments was to observe dielectric changes in reflective metal samples, specifically solid-solid and solid-liquid phase changes in iron and solid-liquid phase change in tin. The first two experiments were identical to each other aside from the metal used for the thin deposition onto the window, one using tin and the other iron. The shock pressure of 52 GPa was high enough to melt the tin, but not the iron – though the iron was likely to have undergone the bcc-to-hcp phase transition. Figure 3 shows the results from the tin experiment. While these two experiments look very

similar overall, the tin data shows a larger drop in the signals at shock impact than the iron, an indication of the more significant phase change that occurred.

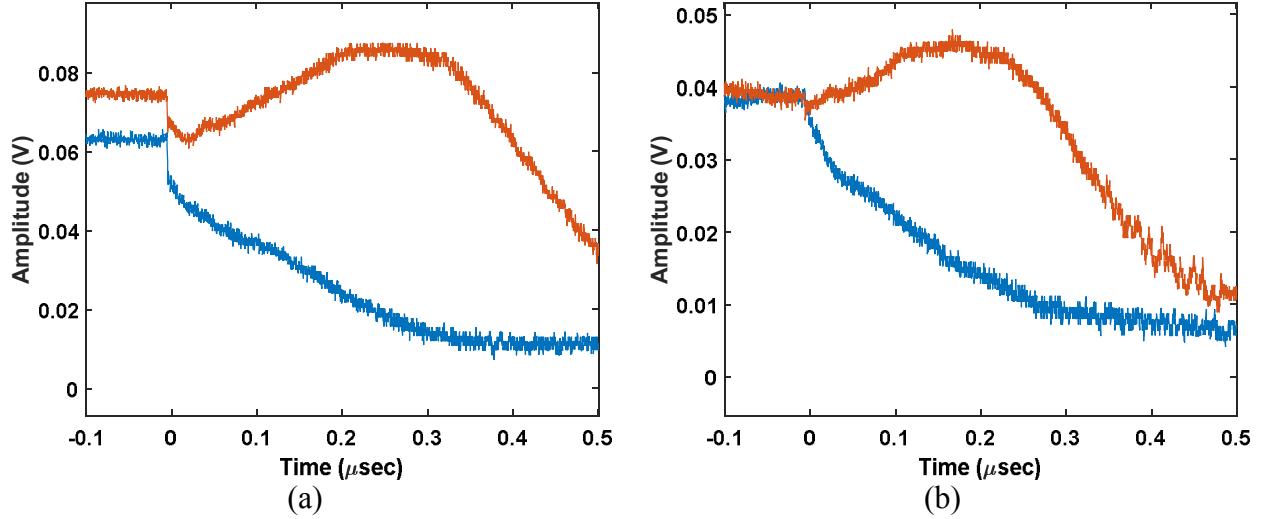
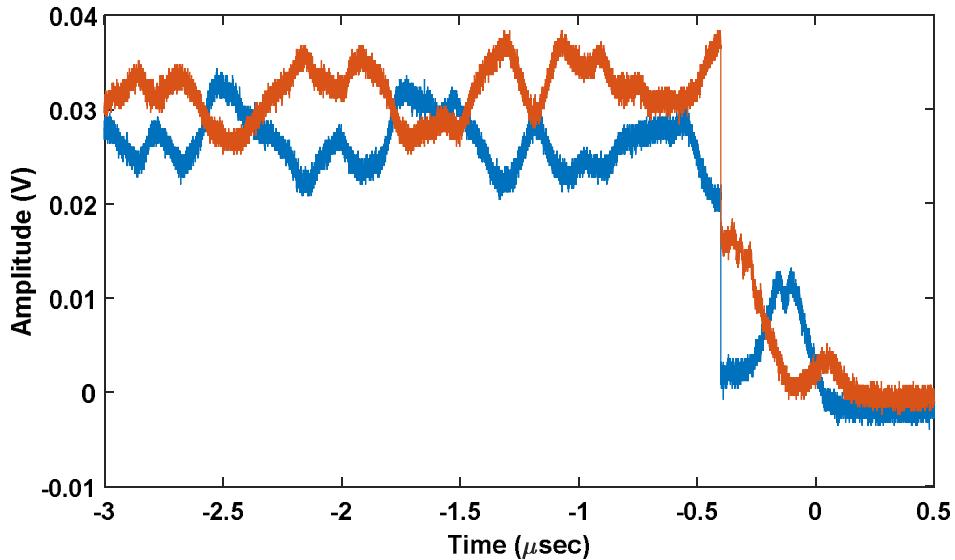


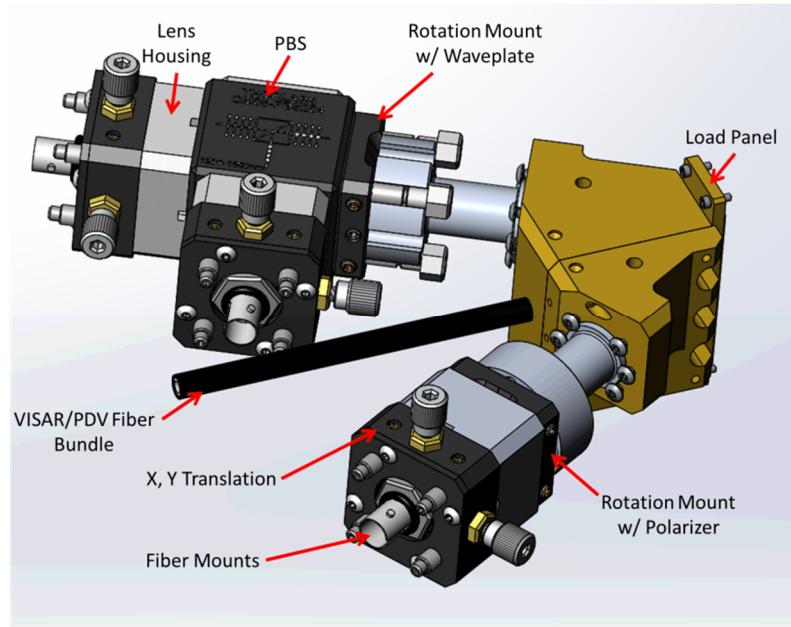
Figure 3: Ellipsometry data from shocked tin (a) and shocked iron (b). There is a larger drop in the signals at shock impact in tin indicating the transition to a molten state. The post-shock behavior indicates that window birefringence may still be present as there is not a steady state.

The second two experiments were both on iron at larger impact pressures than the first. The fastest experiment reaching 270 GPa in the iron, enough to shock-melt it. Both of these experiments show some anomalous behavior. The first experiment, shown in figure 4, has oscillations in the data that begin even before impact, and seem to be linked to the polarization of the light as the two signals stay 180 degrees out of phase with each other, maintaining a consistent total reflectivity. Alternatively, the second experiment shows odd oscillations after impact which do not maintain a consistent total reflectivity. These two experiments plan to be repeated in 2017 to determine if the behavior is repeatable or just the result of loose optics, for example.



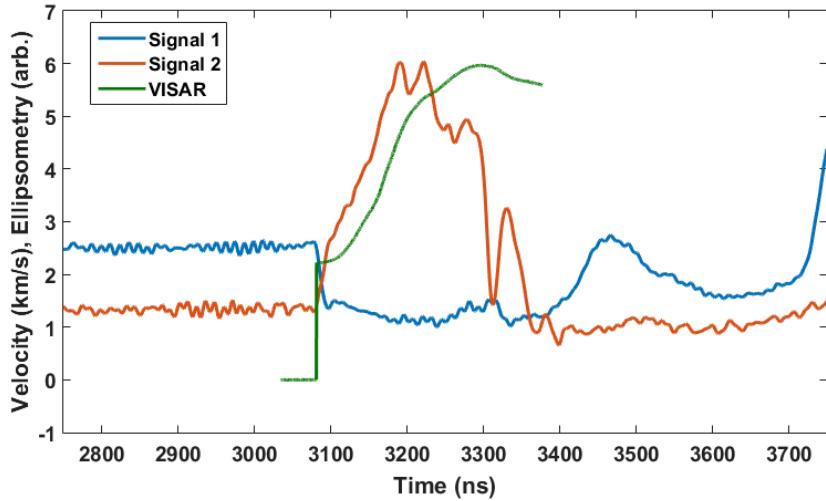
**Figure 4: Ellipsometry data from iron impacted at 6.2 km/s. There are oscillations in the signal even before impact – the large jump in the signals at -0.4 us.**

Finally, in preparation for our dedicated shots through the Z Fundamental Science Program on the Z machine at Sandia National Laboratories, we fielded our ellipsometry diagnostic as a ride-along on several experiments at Z. These experiments have measured the background levels present during the relevant time, and tested engineering necessary to effectively couple our probe light under the new restrictions that are specific to the harsh environment of Z. The probe body design, which involved a significant deviation from the standard design and thus considerable effort by the Sandia design engineers, is shown in figure 5.



**Figure 5: Ellipsometry probe body design for Sandia's Z machine. A series of custom and off-the-shelf optic parts are mounted off a brass probe body housing which attaches to the panel hardware (not shown) which contains the experiment samples.**

We have obtained a good measure of the background light, both with and without implementations to mitigate it. A notch filter at our laser wavelength (1550 nm) is sufficient to cut down the background light during the relevant experimental time. The engineering still requires some improvements, as the coupling of the ellipsometry light needs to be optimized. Figure 6 shows the data from our most recent ride-along experiment, a shock-ramp of a tin sample. This data is overlaid with velocimetry information from the tin reflective surface via VISAR (Velocity Interferometer System for Any Reflector). We were not able to properly align our probe beam as a result of time and engineering limitations. The detectors were only catching the periphery of the beam, thus even small movements of the beam could have caused large shifts in the apparent intensity of the return. This makes quantitative analysis of the ellipsometry data difficult.



**Figure 6: Ellipsometry data, Signal 1 and 2, overlaid with VISAR. The ellipsometry signals have been scaled to visually match VISAR. The time is relative to machine trigger time.**

Our upcoming work will focus on procedures and engineering changes that will optimize the light return from our Z experiments, of which we have two dedicated shots in 2017 and one in 2018. We will also repeat the experiments at the STAR facility two-stage gas gun as well as pursue new experiments there.

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

#### References:

- [1] H. Huang, Y. Fei, L. Cai, F. Jing, X. Hu, H. Xie, Z. Lianmeng, Z. Gong, "Evidence for an oxygen-depleted liquid outer core of the Earth," *Nature*, **479**(7374), 513–516 (2011). DOI:10.1038/nature10621
- [2] C. Seagle, E. Cottrell, Y. Fei, D. R. Hummer, V. B. Prakapenka, "Electrical and thermal transport properties of iron and iron-silicon alloy at high pressure." *Geophysical Research Letters* **40**.20: 5377-5381 (2013). DOI: 10.1002/2013GL057930.
- [3] N. De Koker, G. Steinle-Neumann, V. Vlcek, "Electrical resistivity and thermal conductivity of liquid Fe alloys at high P and T, and heat flux in Earth's core.,," *Proceedings of the National Academy of Sciences of the United States of America*, **109**(11), 4070–3 (2012). DOI:10.1073/pnas.1111841109.
- [4] M. Pozzo, C. Davies, D. Gubbins, D. Alfè, "Thermal and electrical conductivity of iron at Earth's core conditions," *Nature*. **485**(7398), 355–8 (2012). DOI:10.1038/nature11031
- [5] S. Grant, T. Ao, A. Bernstein, J. Davis, T. Ditmire, D. Dolan, J. Lin, C. Seagle, "Implementation of Single-Shot Ellipsometry on Gas Gun Experiments," *Shock Compression of Condensed Matter – 2015 AIP Conf. Proc.* **1793**, 060009-1–060009-5. DOI: 10.1063/1.4971565