Probing the Strength of Iron at Ultra-High Pressures and Strain Rates

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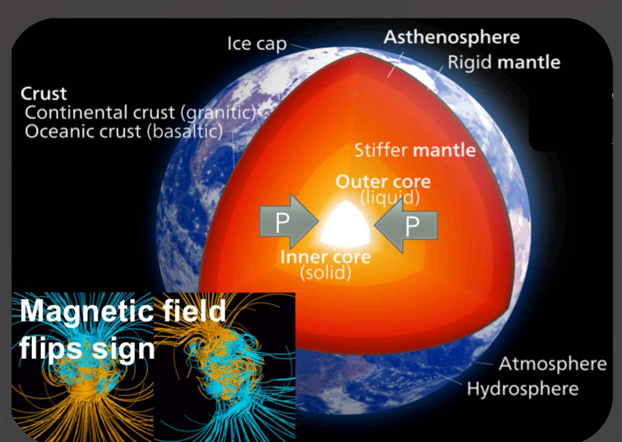
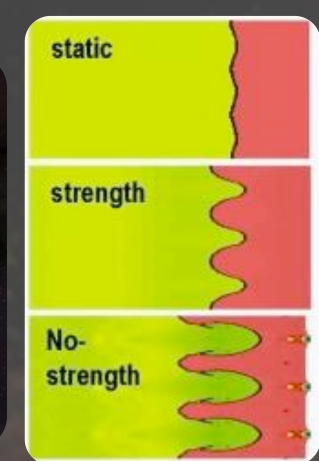
Motivation and Objectives

Iron is the major component of the Earth's core. Determining its strength at extreme conditions is crucial to understanding core rheology, geophysical observations, and the origin of the geodynamo. Objectives of this study are:

- Advance fundamental knowledge of the strength and constitutive behavior of iron at extreme pressure, temperature, and strain rate conditions.
- Investigate the role of material strength on Rayleigh-Taylor (RT) stabilization in 2D and 3D.
- Reconcile discrepancies in the literature around the strength of iron at extreme conditions.

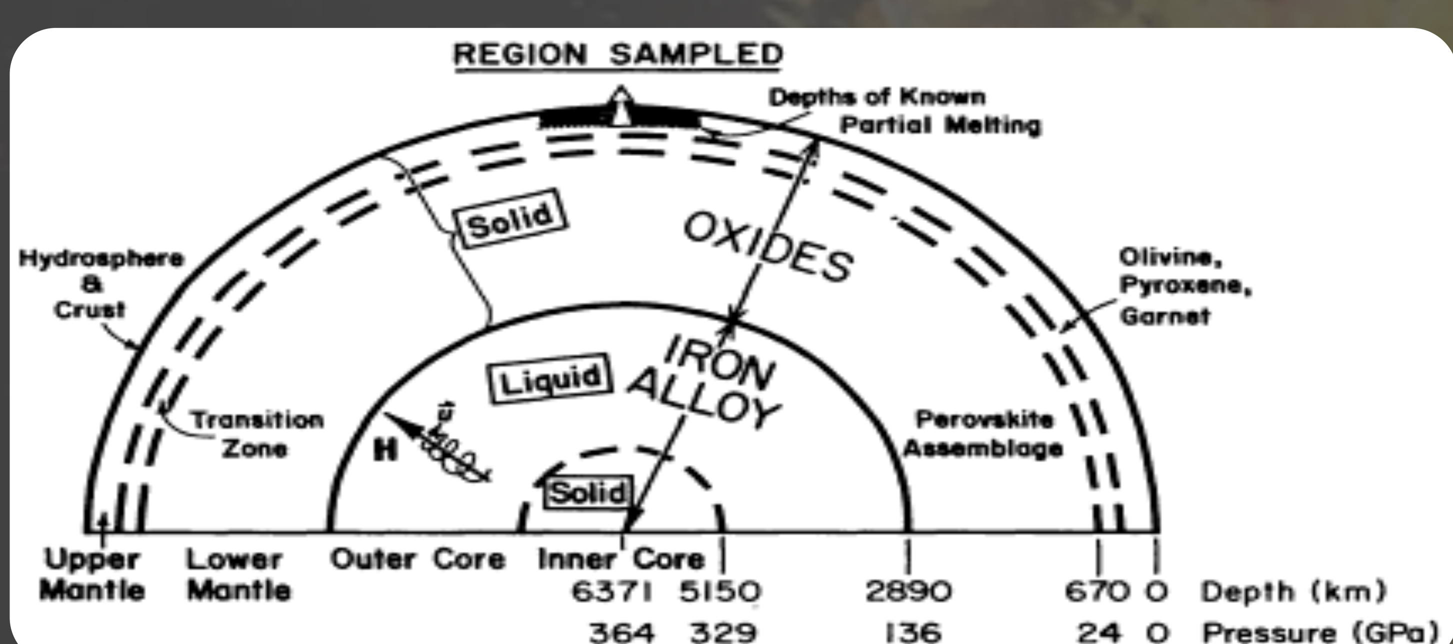




Matija Cuk and Sarah Stewart, " Making the Moon from a Fast-Spinning Earth: A Giant Impact Followed by Resonant Despinning," Science, Vol. 338, Issue 6110, pp. 1047-1052, Nov 2012.

Background

- The Earth's core is an iron-nickel alloy containing roughly 4% Ni. Core pressures and temperatures range from 136 - 364 GPa and 4000K respectively.
- Existing data on iron strength and constitutive behavior is limited and inconsistent. Resolution of discrepancies will help calibrate existing theories on Earth core formation and geodynamo processes. A higher determined strength will point to slower core formation and geodynamo.

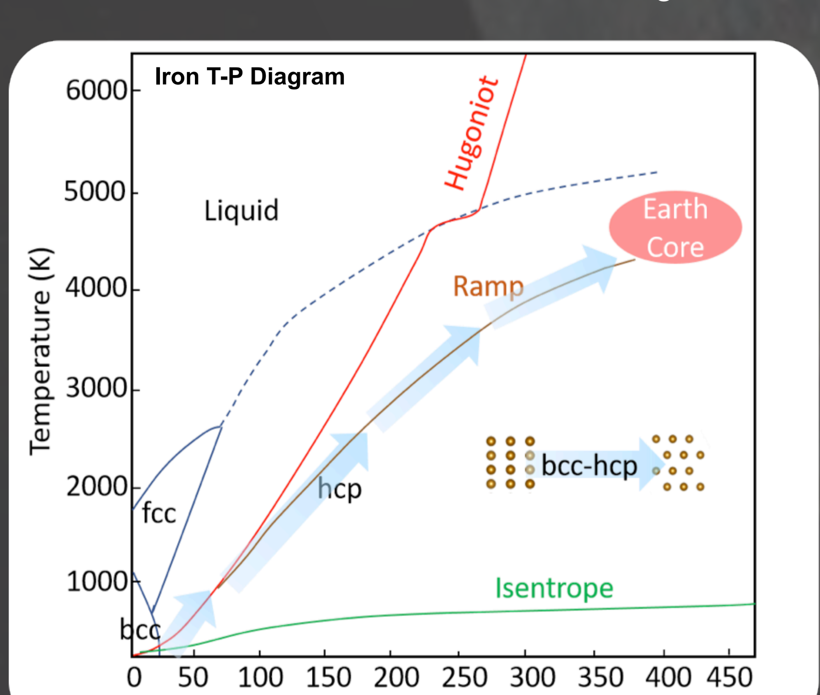


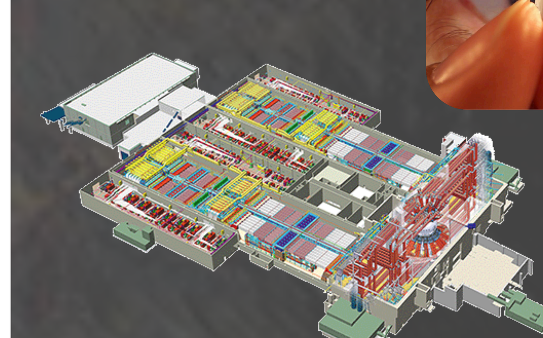
R. Jeanloz, "The nature of the Earth's core," Annu. Rev. Earth Planet. Sci. 18, 357-386, 1990.

- Measurement of RT ripple growth can give insight into the strength and constitutive behavior of iron. The Omega laser, at 130 GPa (below core conditions), wasn't able to create appreciable ripple growth.

Facility – NIF

The National Ignition Facility (NIF) is the most powerful laser facility in the world; capable of generating 1.85MJ during only 10-20ns. This uniquely allows iron strength measurements at pressures above 3.5 Mbar (350 GPa), temperatures above 4000 K, and strain rates of 10^7 - 10^8 s^{-1}; simulating earth core conditions.





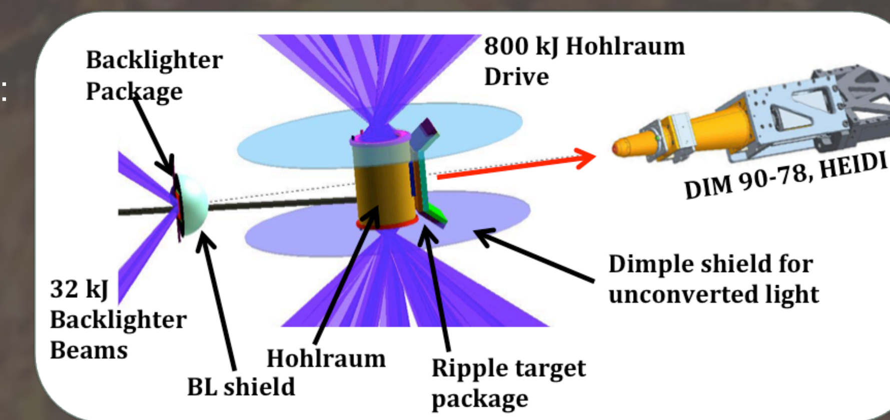
This facility spans a size of 3 football fields and has 192 separate laser beams, all of which can combine into a single millimeter-scale focal point (such as in a gold Hohlraum – shown above).

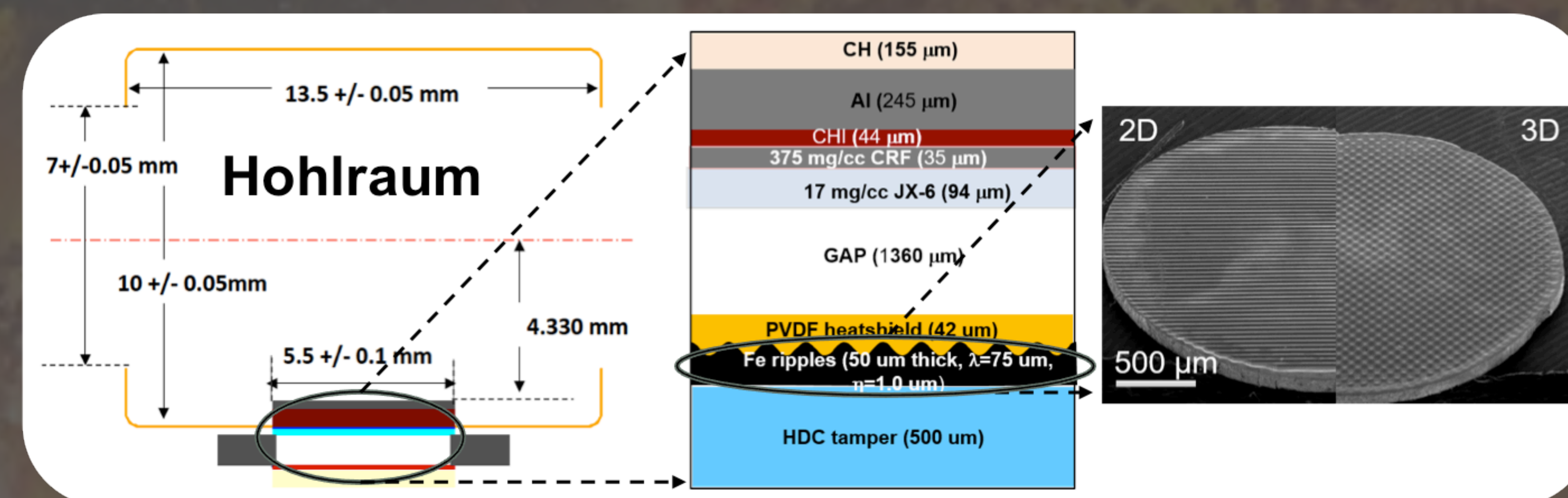
National Ignition Facility, LLNL

Experimental Setup

Methods are based on existing, proven NIF-RT platforms:

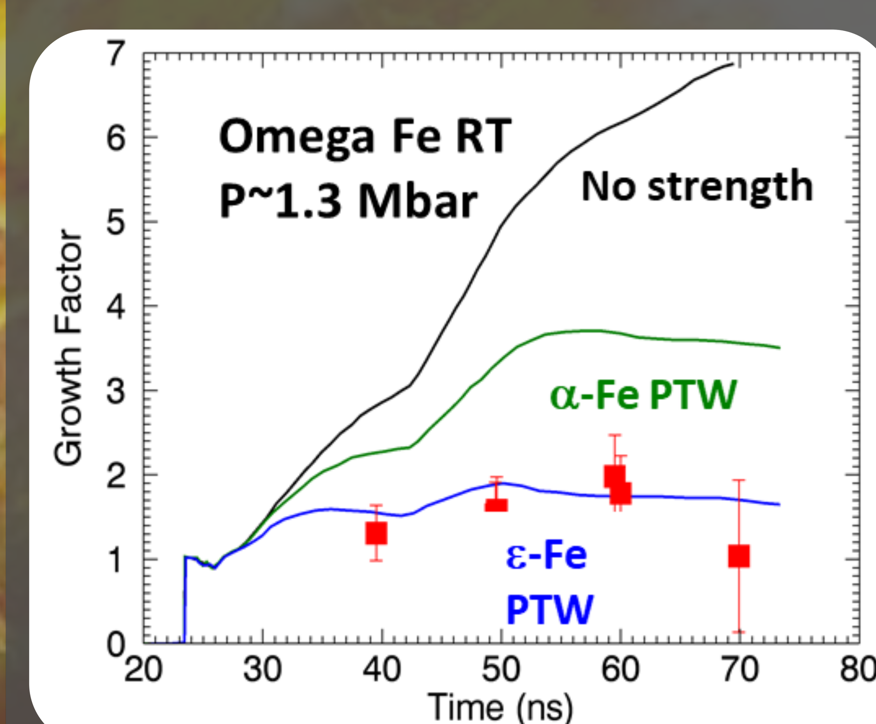
- Indirect-drive Hohlraum to launch stress pulse.
- Calibrated ablator reservoir to obtain the desired ramp pulse shape.
- Precise diamond turning to fabricate rippled (2D) and eggshell (3D) targets through General Atomics.
- Slit-point backlighter package currently used for the NIF-RT platform.



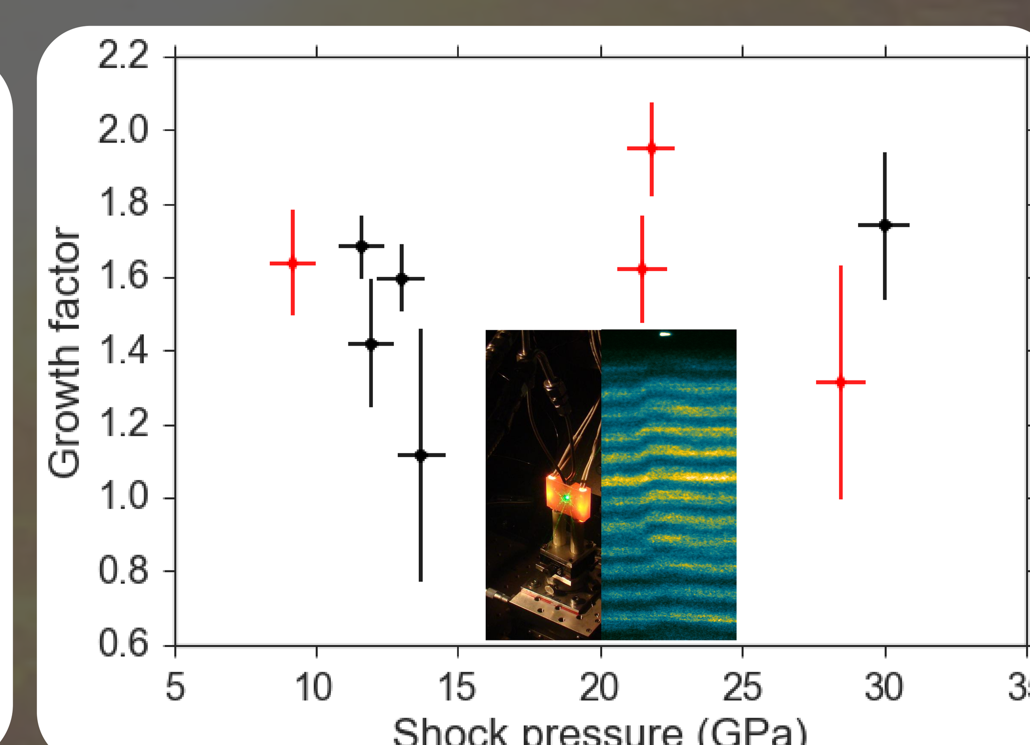


Previous Results

Previous ramp compression experiments at Omega and shock-recovery experiments at Janus, both at a lower pressure, suggest that iron shows a very low growth factor. This provides evidence that iron is much stronger at elevated pressures than previously thought.



C. Hungtington et al., SCCM, 2010



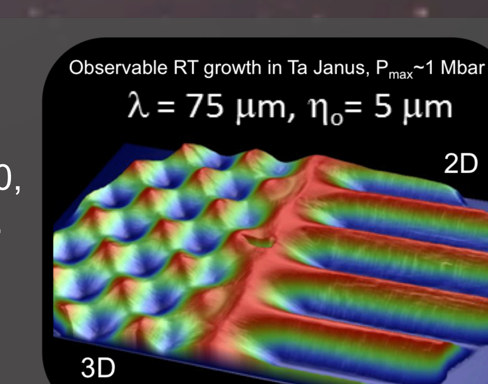
Z. Steinberger et al., in preparation

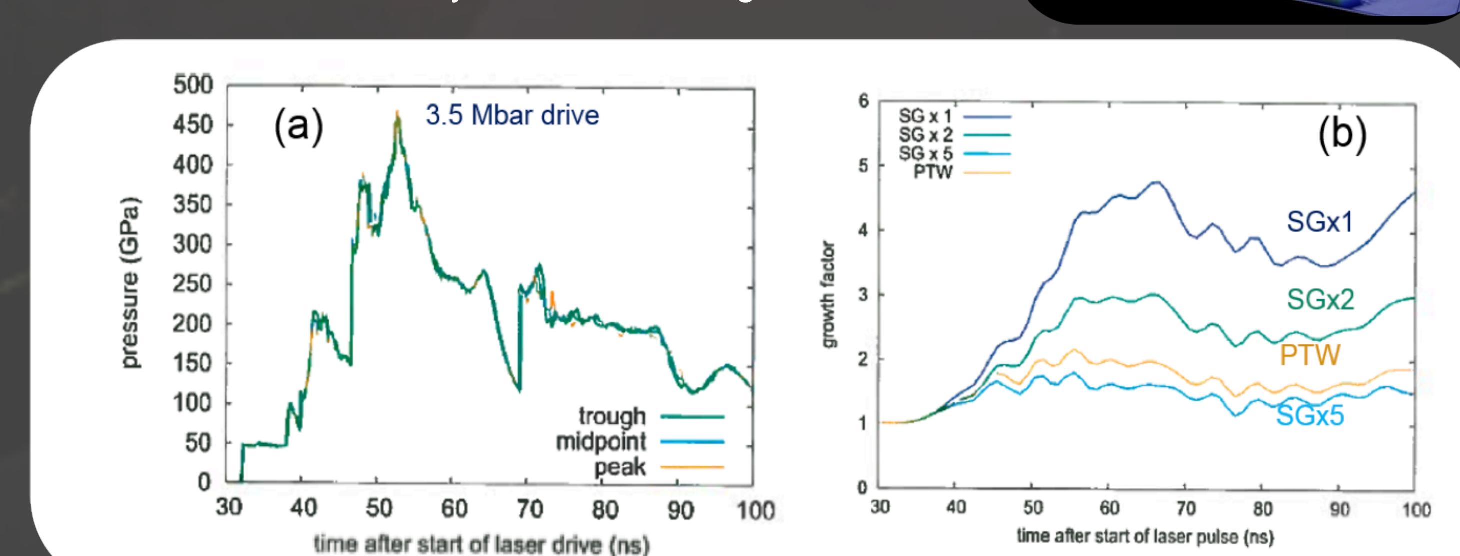
Omega Experiment
Drive: Ramp wave
Diagnostics: In-situ radiography

Janus Experiment
Drive: Ramp wave
Diagnostics: In-situ radiography

Metrics of Success

- Strength data will be determined from RT growth data. RT growth data will be collected for both 2D and 3D ripple types as well as for varying wavelengths of 50, 75, and 100 µm. RT observations have previously been successful for Tantalum.
- Expected pressure profiles on Iron sample using the existing NIF strength ramped drive (a) and expected ripple growth factors (b). The growth factor measurements show the sensitivity to different strength models.
- SG is the Steinberg-Guinan model with 1x, 2x, and 5x standard ambient yield strength and PTW is the Preston-Tonk-Wallace model with parameters from Belof, 2012.



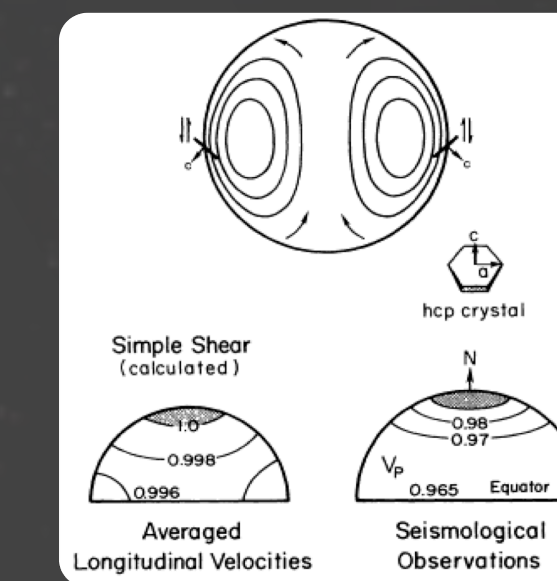


J. L Belof, et al. Rayleigh-Taylor strength experiments of the pressure-induced α→ε→α' phase transition in iron, AIP Conf. Proc. 1426, 1521 (2012)

Discussion

Iron strength measurements at Earth core conditions will provide, for the first time, realistic temperature, pressure, and strain-rate dependent rheology data and improve the understanding of geodynamo and Rayleigh-Taylor instability growth.

- Iron strength plays a significant role in the geophysical processes of our planet. For instance, seismological body-wave studies of the Earth's inner core have revealed that compressional waves travel faster along the rotational axis than in the equatorial plane.
- These experimental observations indicate that the microstructure of the Earth's core is inherently anisotropic, which affect the strength of the core.
- Our preliminary constitutive modeling shows that the strength of iron can be varied significantly by only varying the grain size.



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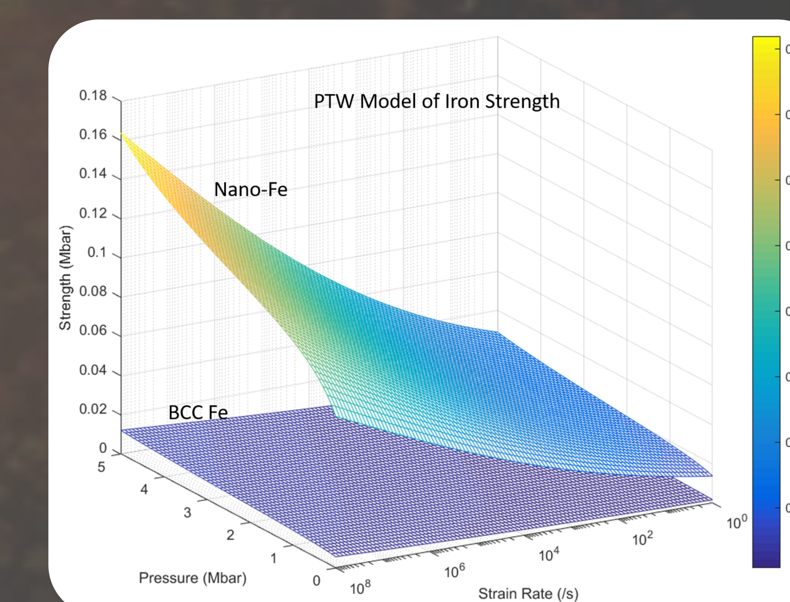
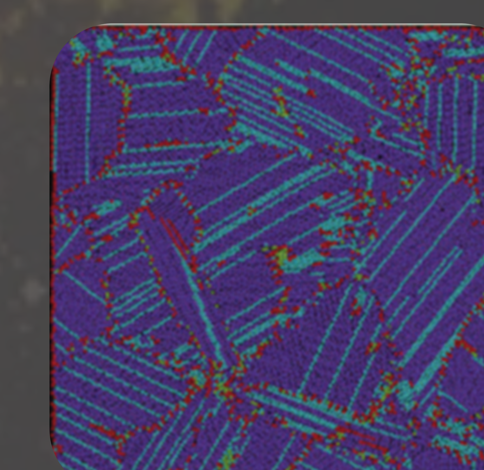


- Accurate measurement of iron strength in the core will help to improve the accuracy of the constitutive models at extreme conditions of high pressures and strain rates.
- Grain size effect is another parameter that needs to be taken into account. This useful information can then be integrated into models of the Earth's core formation.



Bringa et al., PRB, 2012

- Parallel MD simulations can also shed more light on the atomistic deformation mechanism of iron under extreme conditions.
- The interatomic potential for iron is well developed.

Summary

- Rayleigh-Taylor experiments at ultra-high pressures (above 3.5 Mbar) will significantly advance fundamental scientific knowledge relevant to High Energy Density sciences.
- The science of phase transforming materials under extreme conditions is of relevance to HED science. The proposed work will result in the understanding of the origins of strength and plastic flow in a phase transforming model bcc material (Fe) at extreme conditions of loading enabled by NIF.
- An essential and necessary component of these experimental studies is parallel MD simulations. The close coupling of experiments, modeling, and analysis will advance the state-of-the-art in understanding the plastic flow, strength, and ductility properties of metals at high pressures, temperatures, and strain rates.
- Our experiments will probe this completely new frontier of science for the first time. Such unique science could only be done on the NIF Laser Facility, and by our team of outstanding scientists.

Acknowledgements

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Planetary impact, National Geographic