Computational design of high-pressure iron Rayleigh-Taylor strength experiments for the National Ignition Facility

CMEC CENTER FOR MATTER UNDER EXTREME CONDITIONS

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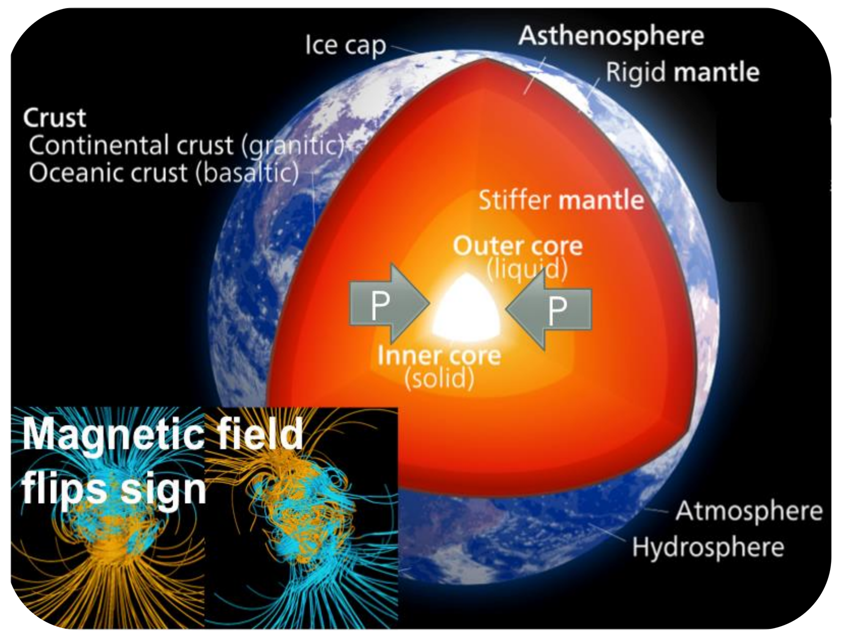
MOTIVATION AND BACKGROUND

Motivation: Why study iron at extreme conditions?

- Determining iron strength at extreme conditions is crucial to understanding Earth core rheology, geophysical observations, and the origin of the geodynamo.
- Iron is also one of the most important structural materials, making up the majority of steels, high entropy alloys, etc.
- Advance fundamental knowledge of the strength and constitutive behavior of iron at extreme pressure, temperature, and strain rate conditions.

Iron in geophysics

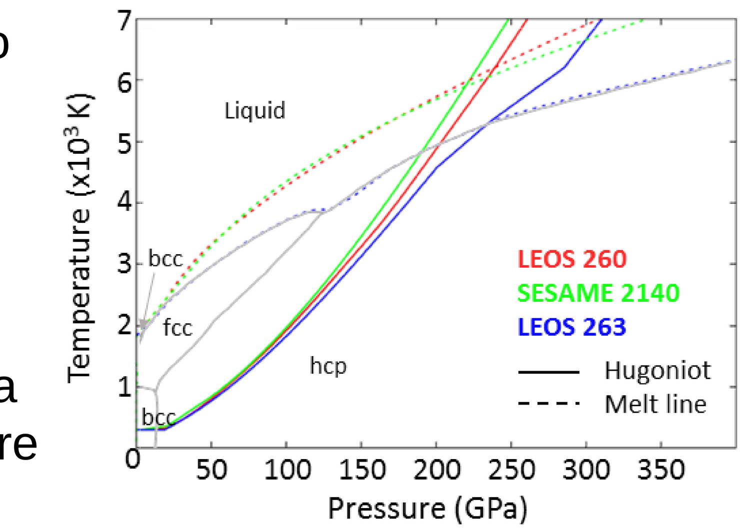


Kelvinsong, The internal structure of Earth, 2014.

- Core pressures and temperatures range from ~136 – 364 GPa and ~4,000 – 6,000 K
- 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.

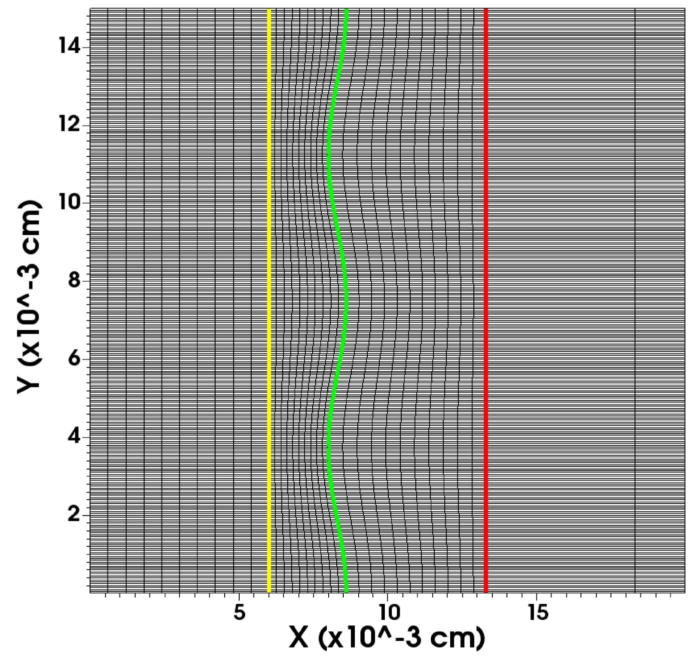
Experimental design challenges

- Structural α-ε phase transition unavoidable – occurs at 5% core pressure
- Strength models developed for α-Fe do not extrapolate well into ε phase
- α-ε phase transition induces microstructural change
- Indirect-drive designs cannot produce a broad range of temperatures at pressure



Computational Details (Hydra and Ares codes)

Mesh – purely Lagrangian motion



Equation of State

- LEOS 260
- SESAME 2140
- LEOS 263

} Multiphase models

Boundary Conditions

- Front: fixed
- Back: free
- Sides: reflecting

Strength

- Steinberg-Guinan – thermally activated dislocation motion and work hardening

$$G(P,T) = G_0\left[1 + (G'_P/G_0)P\eta^{-\frac{1}{3}} - (G'_T/G_0)(T - 300K)\right] \qquad Y = Y_{wh}\frac{G(P,T)}{G_0}$$

- Preston-Tonks-Wallace – thermally activated dislocation motion and drag-controlled kinetics

$$\hat{\tau} = \hat{\tau}_s + \frac{1}{p}(s_0 - \hat{\tau}_y)\ln\left[1 - \left(1 - exp\left(-p\left(\frac{\hat{\tau}_s - \hat{\tau}_y}{s_0 - \hat{\tau}_y}\right)\right)\right) \times exp\left(\frac{-p\theta\epsilon}{(s_0 - \hat{\tau}_y)\left(exp\left(p\left(\frac{\hat{\tau}_s - \hat{\tau}_y}{s_0 - \hat{\tau}_y}\right)\right) - 1\right)}\right)\right]$$

SUMMARY AND ACKNOWLEDGEMENTS

- Lack of clear experimental results on iron strength at Earth core conditions motivates these direct-drive shots which need extensive design as they have never been attempted before.
- Growth factors of 3-10 are predicted based on the optimal target and pulse shape with minimal variation based on the EOS used.

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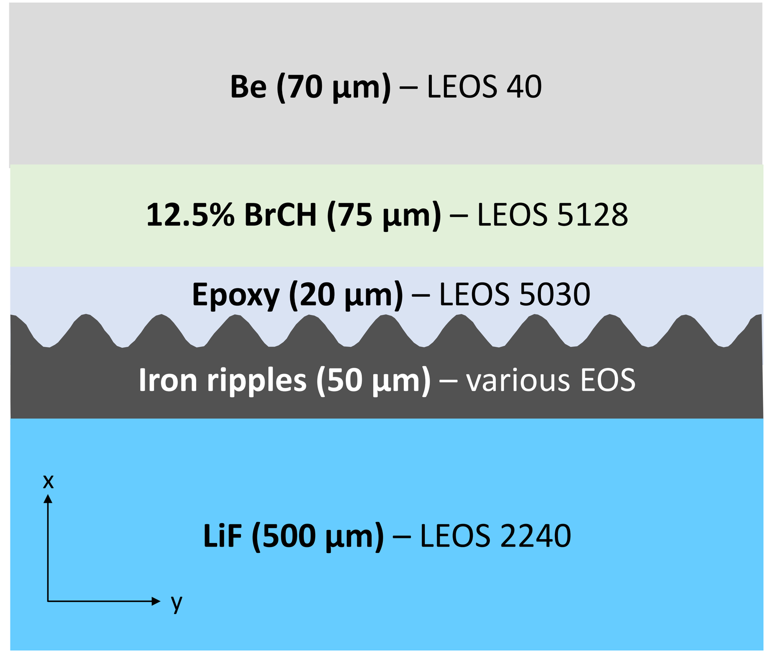
Results: the first RT strength design for Earth core conditions

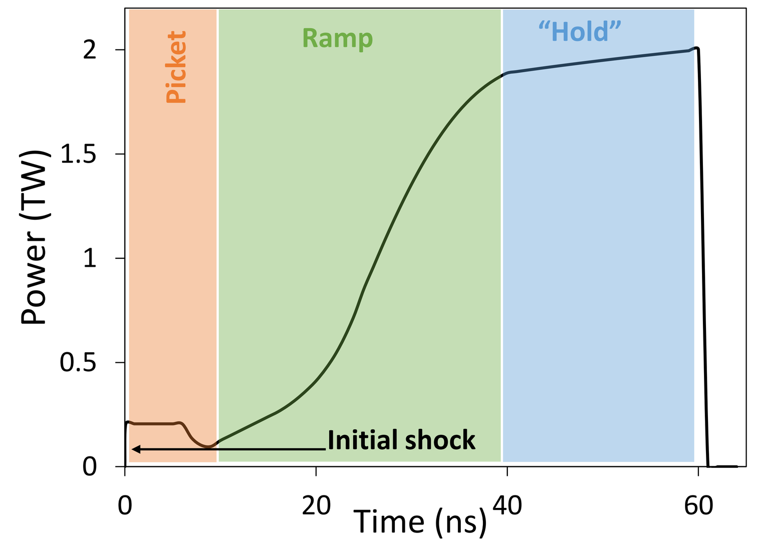
Target

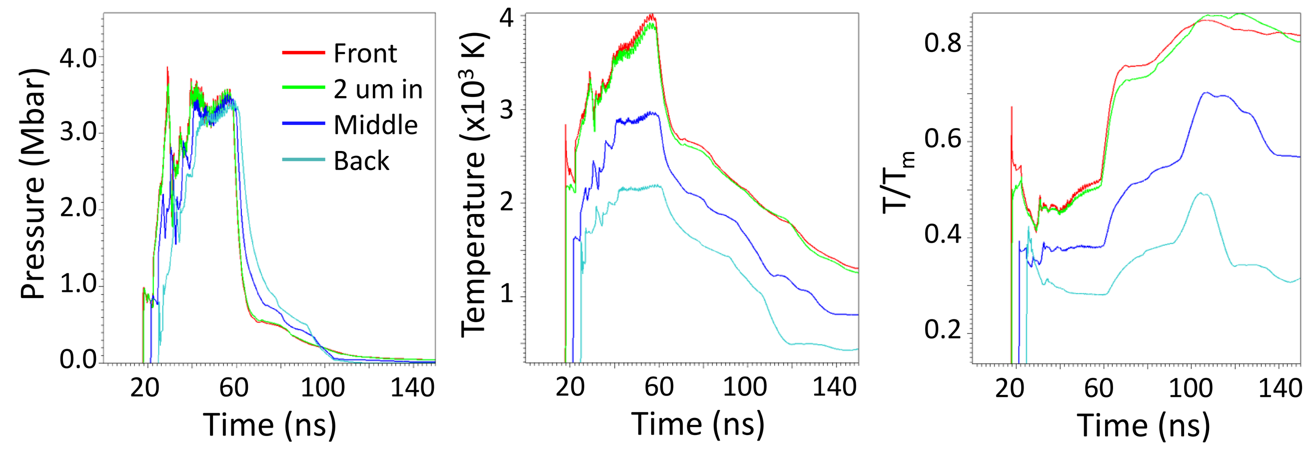
- Be ablator – produce a plasma that rapidly expands causing a pressure wave to travel into the target
- BrCH heat shield – prevent unwanted heating in the iron due to x-rays
- Epoxy pusher – allows RT unstable ripples to grow
- Iron sample
- LiF tamper – pressure tamper



Pulse Shape

- Uniquely long (60 ns) laser pulse is only available at the NIF
- The NIF has incredibly fine control, both spatial and temporal, over the laser drives it can produce.





- GF range will produce robust signal-to-noise ratio in collected radiography data

RT Growth