Lawrence Livermore National Laboratory

Journey to the Center of a Super-Earth: Sound Speed and Density of Iron to 10 Mbar

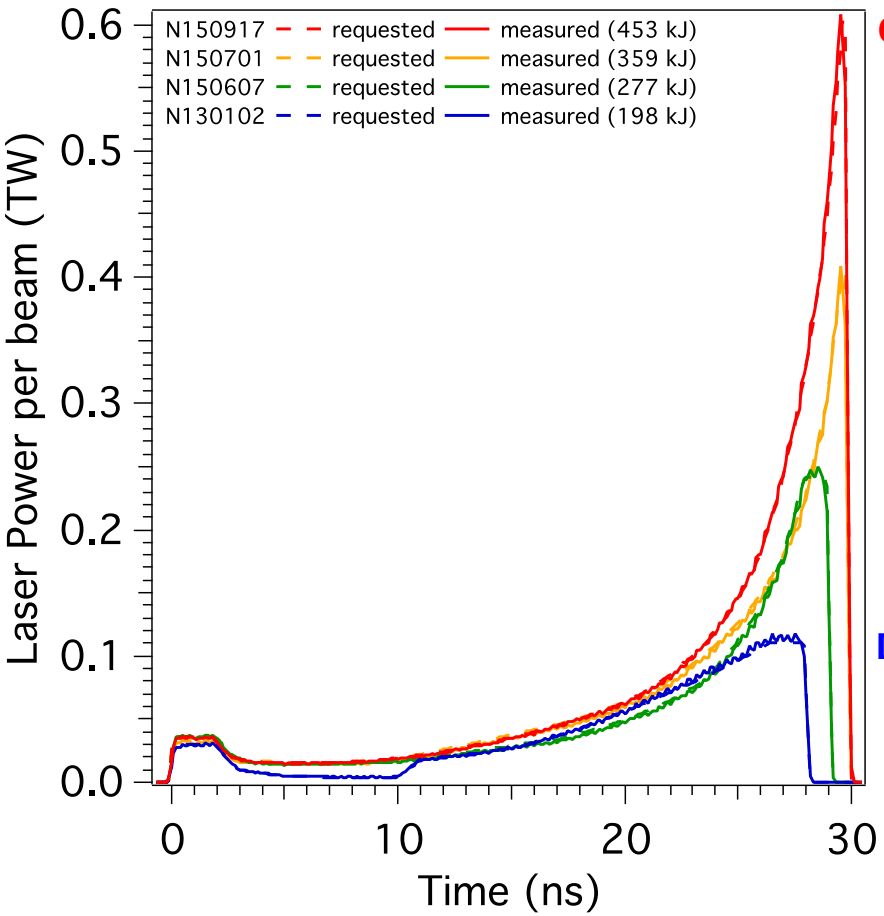
LLNL-PRES-683301

T. Duffy and J. Wicks (Princeton)

R. Jealoz (UC Berkeley)

R. Smith, D. Fratanduono, J. Eggert, D. Braun, et. al (LLNL)

Evolution of the campaign/ Importance of pulse shaping



Copper ablator, All 4 steps 1 steady shock

Copper ablator, All 4 steps 1 steady shock

Free surface velocities

Copper ablator, 1 steady shock " 3 thickest steps shocked again

Diamond ablator, 1 steady shock, all 4 steps 2 more shocks

Discovery Science, Iron EOS, 2013-2015

Using ramp-wave compression EOS technique that successfully compressed diamond to 50 Mbar, compress and measure the stress density of iron to over 10 Mbar.

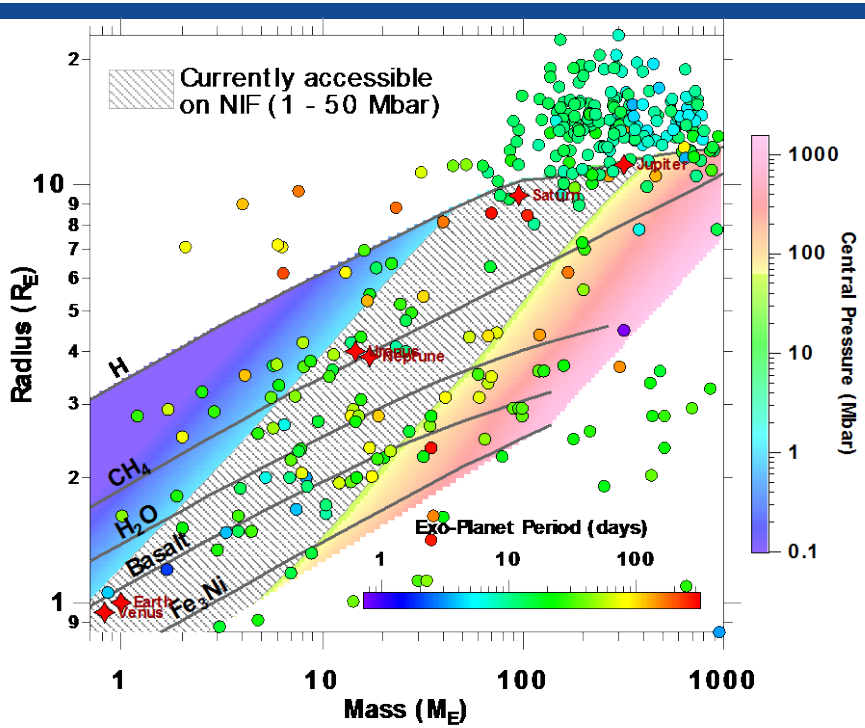
We used a single shock to overdrive the α-ε transition in iron with a single steady shock (~0.7 Mbar)

We took four shots:

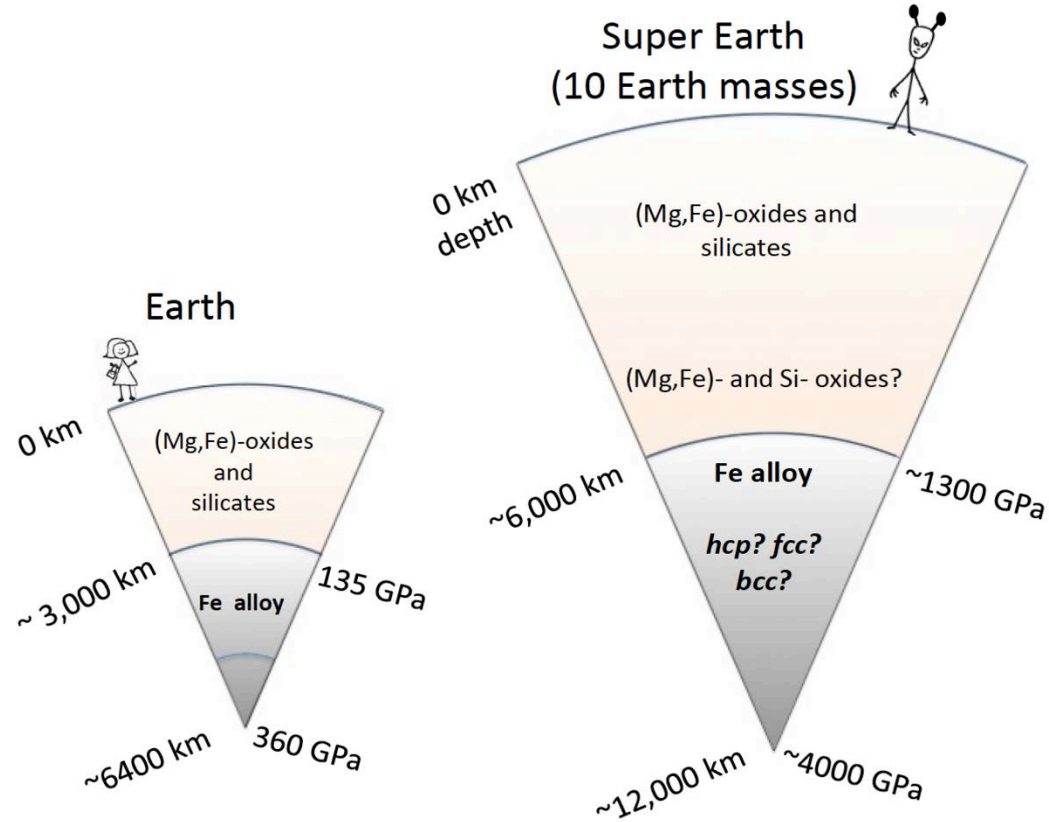
- **N130102-**8.5 Mbar, Diamond ablator, all four steps had 2 additional shocks.
- **N150607**-7.9 Mbar, Copper ablator, thickest 3 steps had an additional shock.
- **N150701**-9.8 Mbar, Copper ablator, all 4 steps had good ramps.
- **N150917**-14.8 Mbar, Copper ablator, all 4 steps had good ramps.
  This shot had issues with VISAR timing and is still being analyzed.

Review of technique
Data

Iron is a cosmo-chemically abundant element that plays a major role in terrestrial planetary interiors.

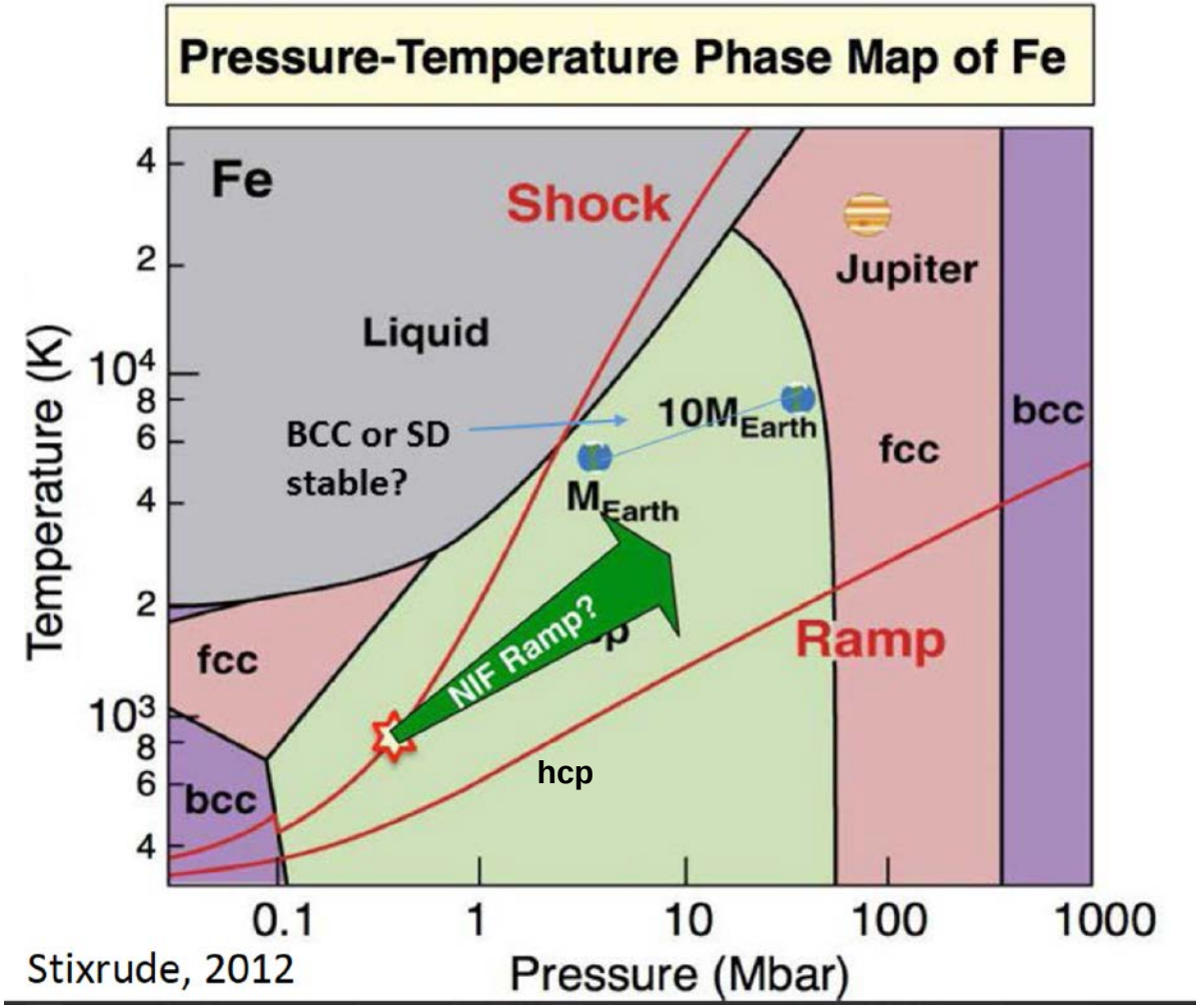


Exoplanet mass-radius plot



Iron density dominates a terrestrial planet's mass-radius relationship. A planet's metallic core is fundamental to understanding heat flow, interior dynamics, and magnetic field generation.

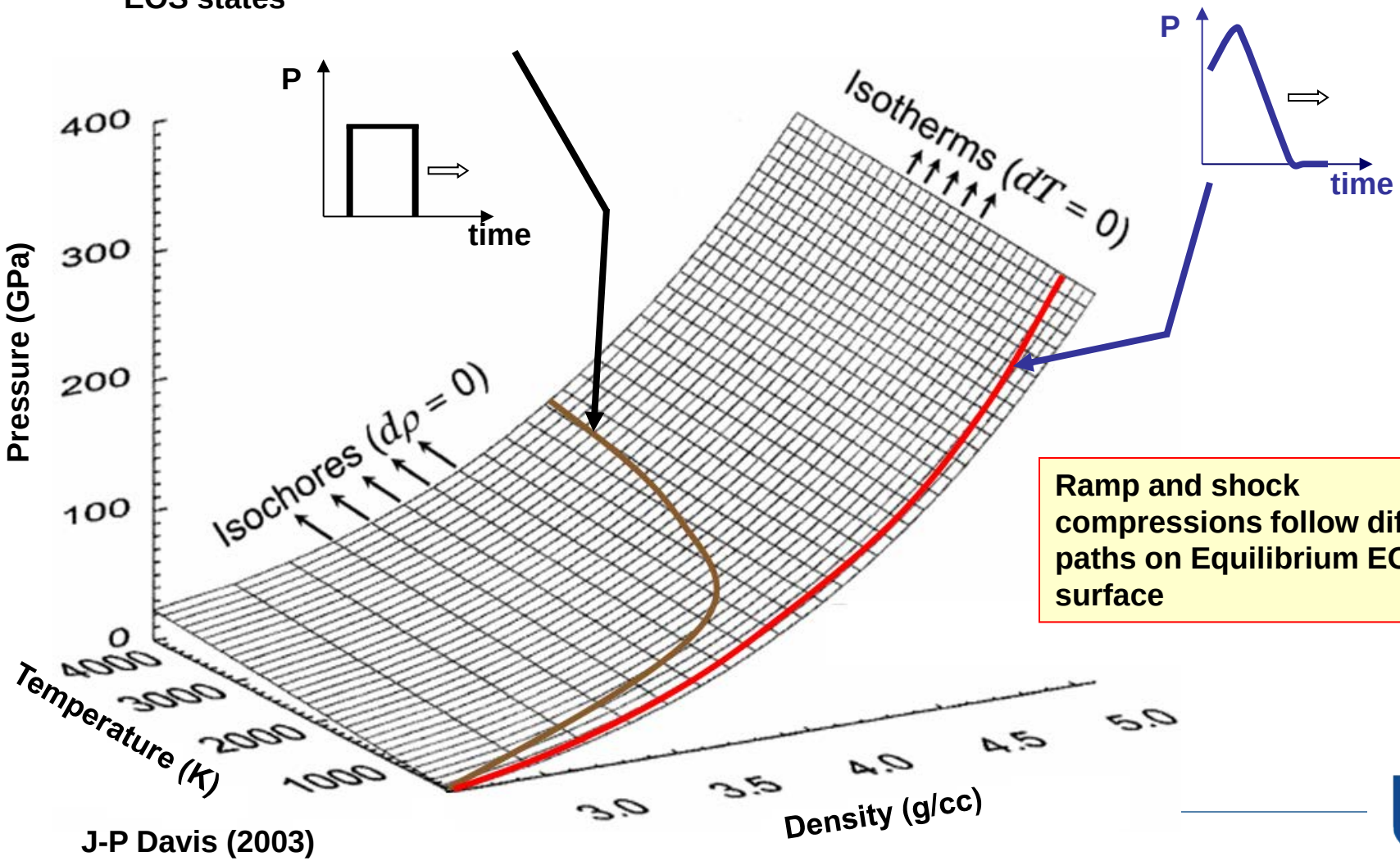
The extreme interior pressures of large extrasolar planets are accessible with few experimental techniques



Equilibrium thermodynamic behavior is described by an equation-of-state (EOS) surface

Shocks probe high Temperature EOS states

Ramped compression waves probes EOS at low temperatures close to the isentrope



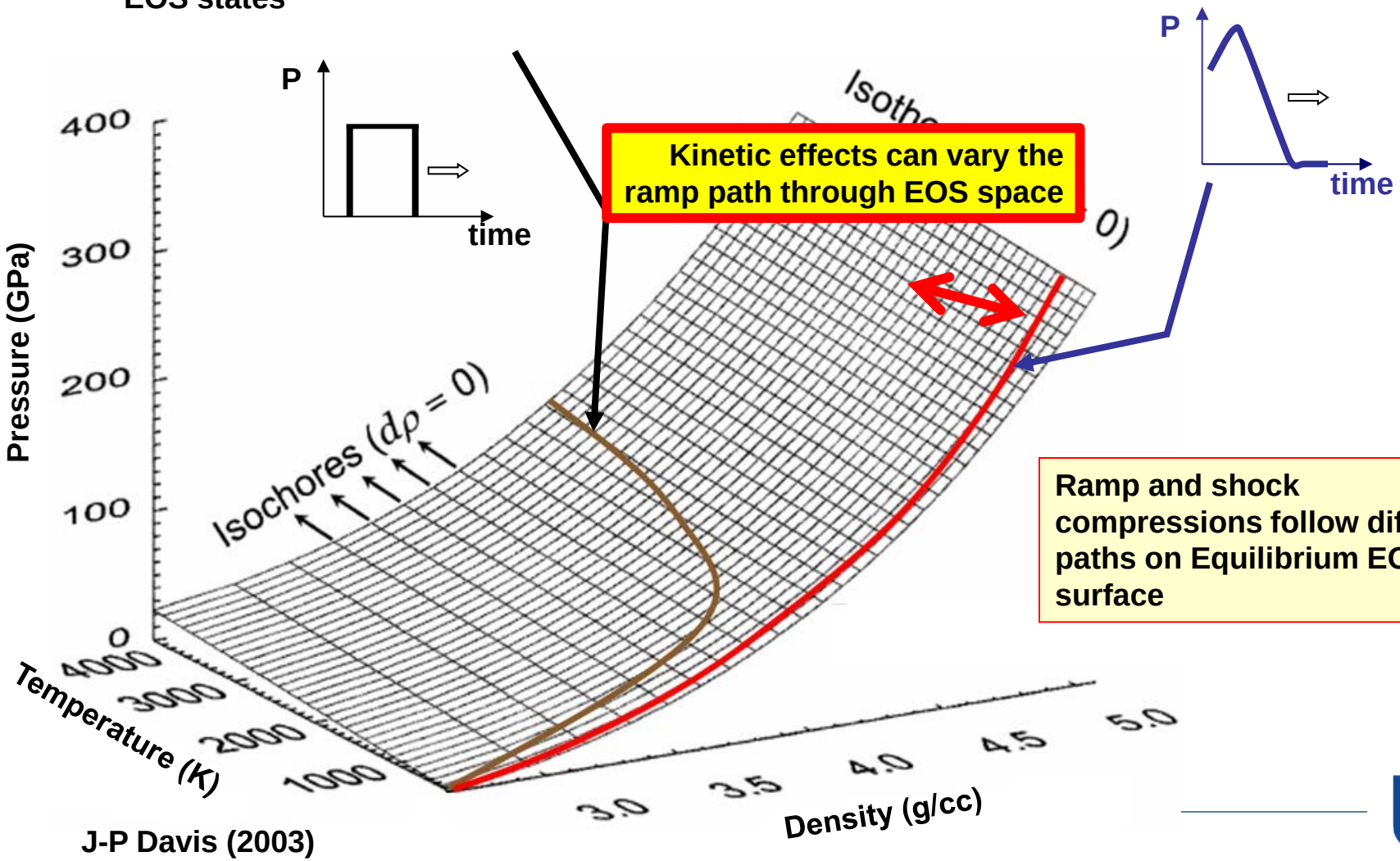
Ramp and shock compressions follow different paths on Equilibrium EOS surface

J-P Davis (2003)

Ramp compression access different regimes compared to shocks

Ramped compression waves probes EOS at low temperatures close to the isentrope

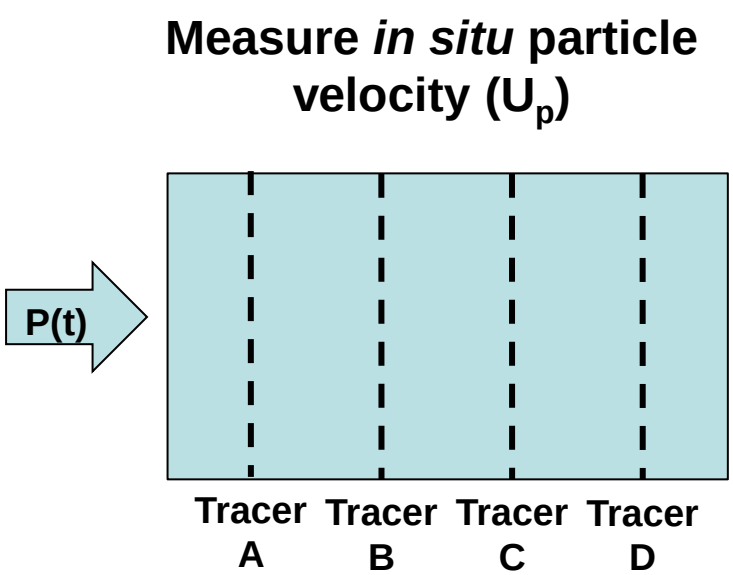
Shocks probe high Temperature EOS states

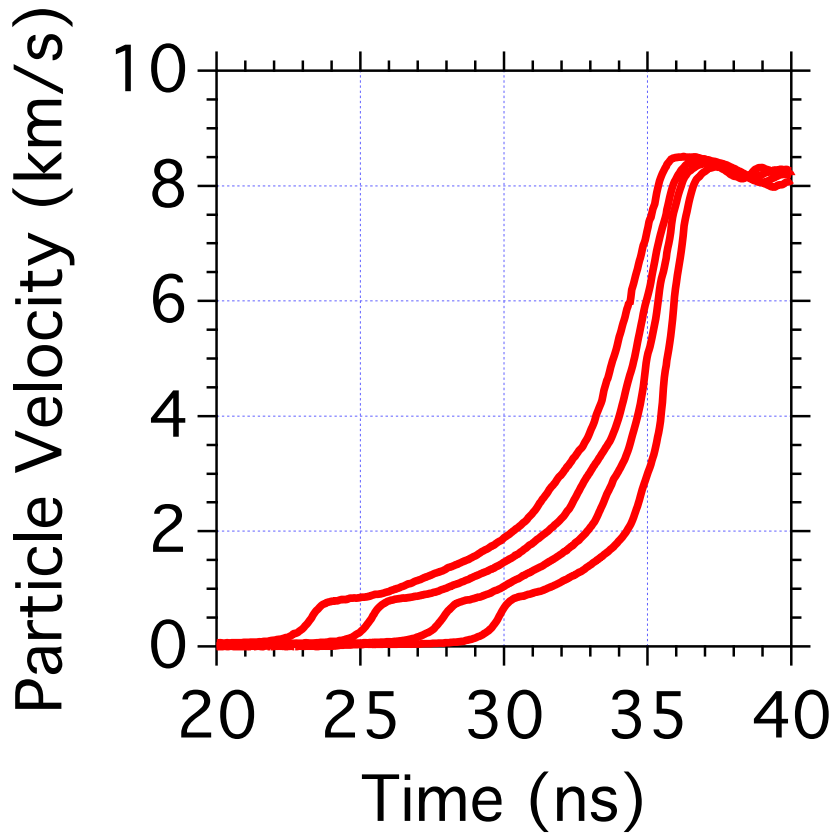


Ramp and shock compressions follow different paths on Equilibrium EOS surface

J-P Davis (2003)

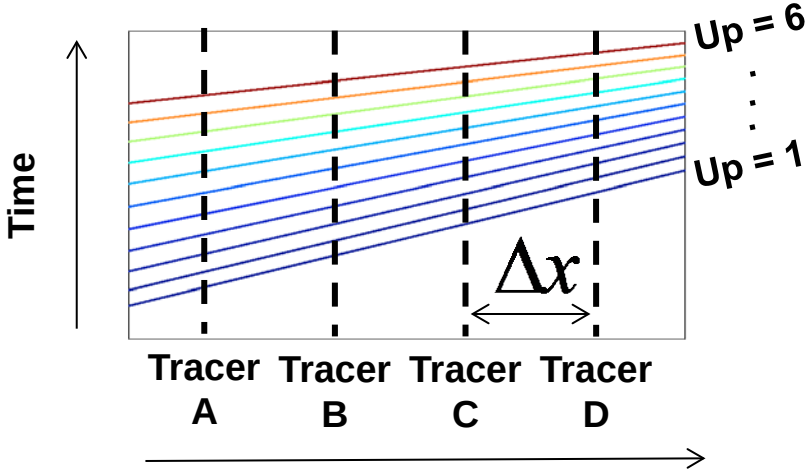
Velocity measurements are used to determine the material 'isentrope'



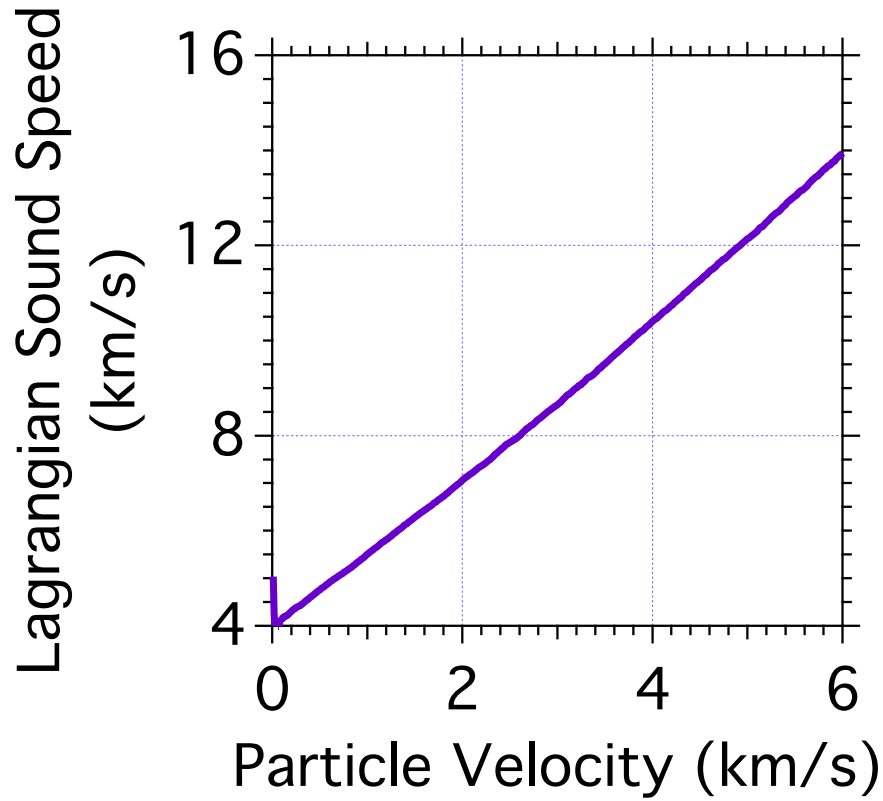


Velocity measurements are used to determine the material 'isentrope'

Acoustic Perturbations travel along characteristics (Up is constant along each line)



$$C_L = \frac{\Delta x}{\Delta t}$$



$$P = \rho_o \int C_L \, dU_p \qquad \rho = \rho_o \left(1 - \int C_L^{-1} \, dU_p\right)^{-1}$$

Analysis technique is complicated since the measurements are not *in situ* particle velocities but instead free surface velocities

Stress-Density

$$P = \rho_o \int C_L \, dU_P$$

$$\rho = \frac{\rho_o}{1 - \int dU_P / C_L}$$

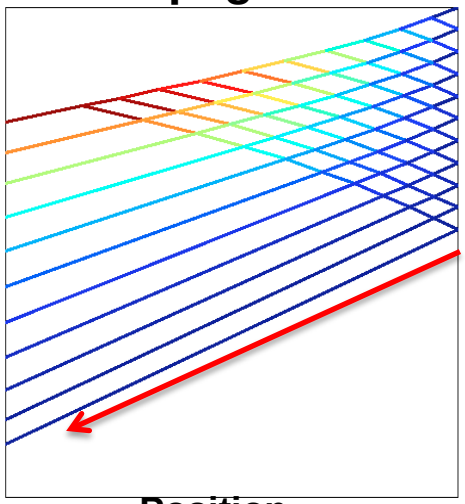
Iterate

Assume EOS

$C_L(P)$

$U_{FS}(t,h)$

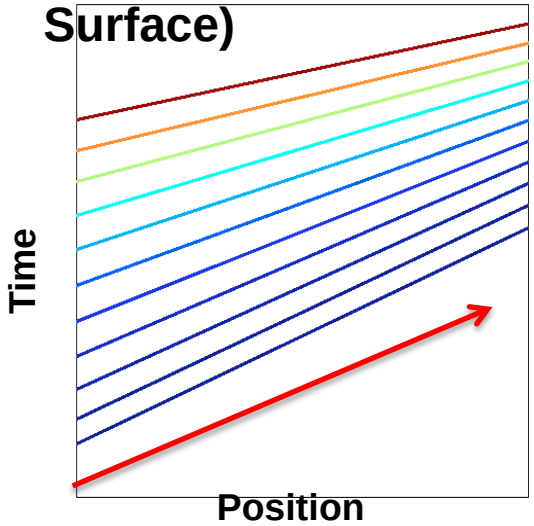
Backwards Propagation



Lagrangian Analysis

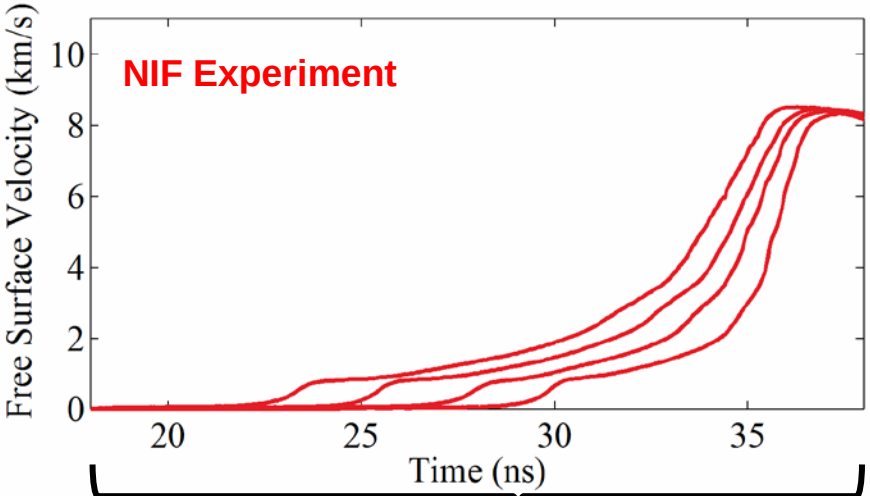
$$C_L(P) = \frac{h_2 - h_1}{t_2 - t_1}$$

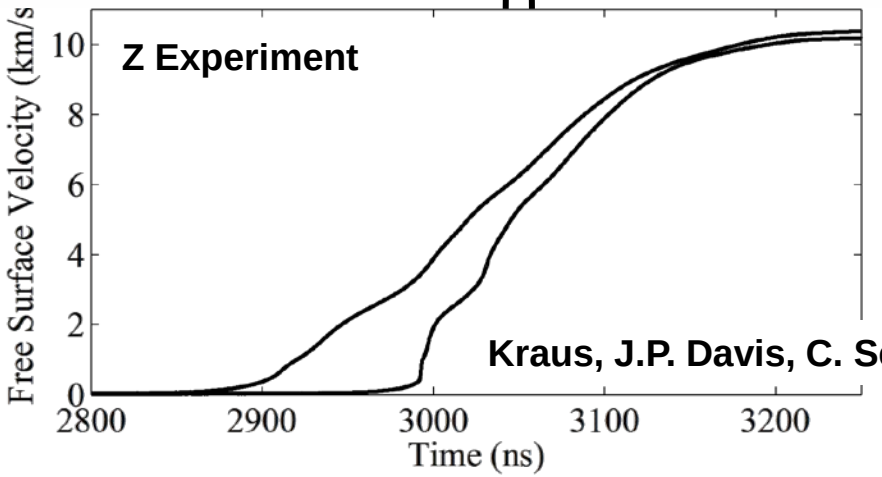
Forward Propagation (Correct for Free Surface)



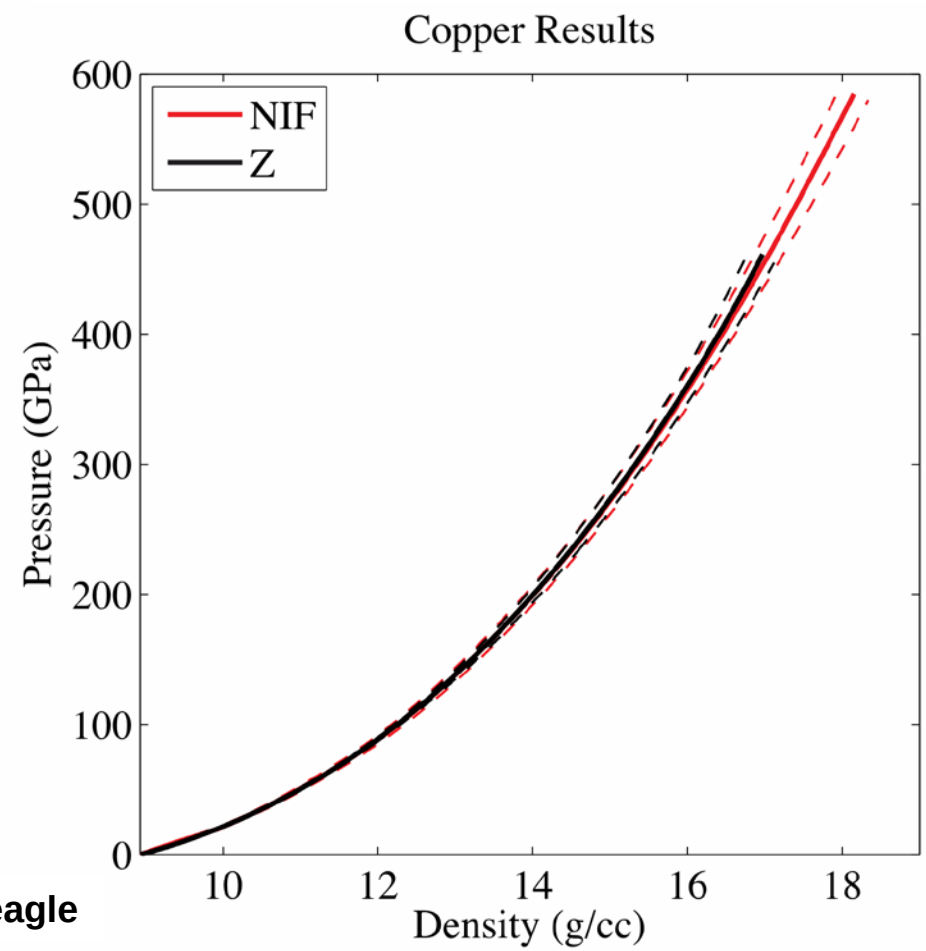
$P(t,0)$

We leveraged programmatic work on ramp compression of copper to improve this discovery science campaign

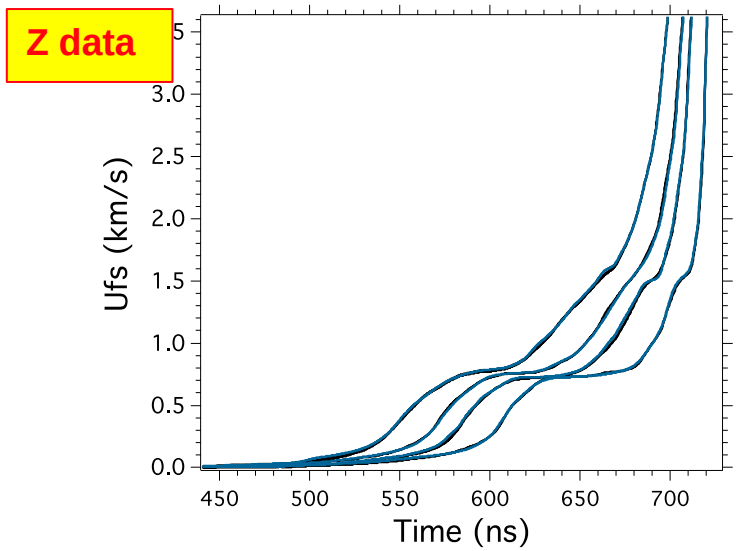


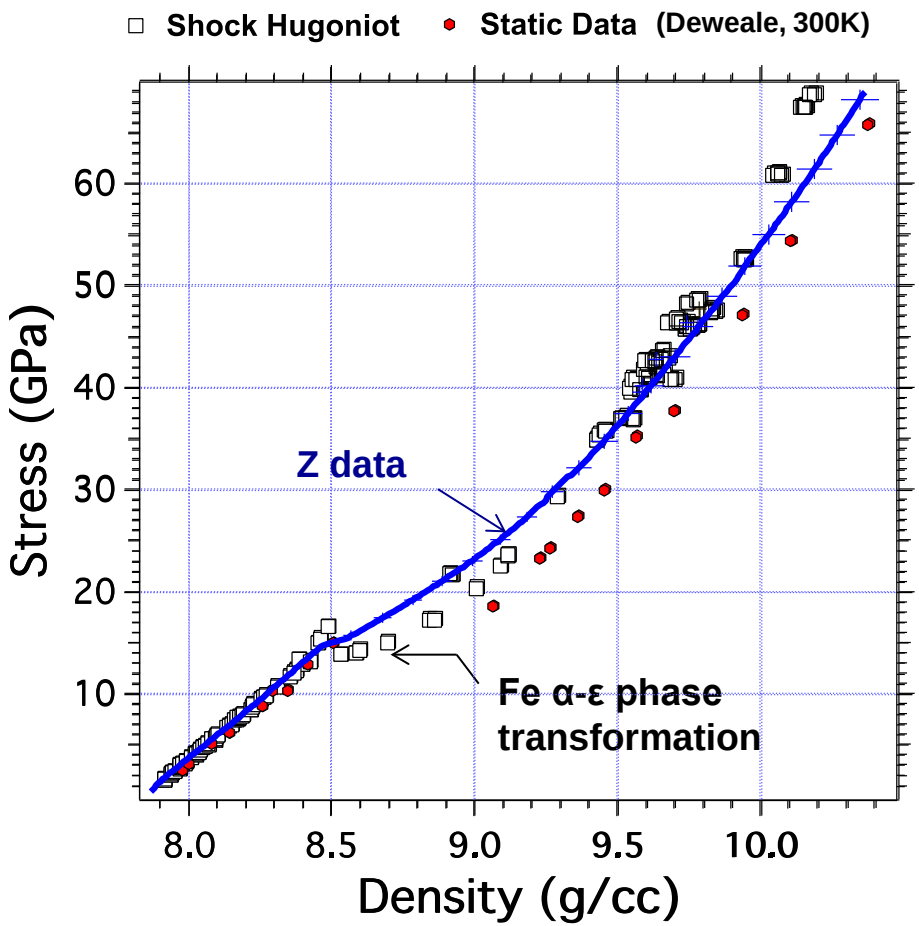


Kraus, J.P. Davis, C. Seagle



We have studied the kinetics of the Fe α-ε phase transformation using ramp compression at Omega and the Z-machine.





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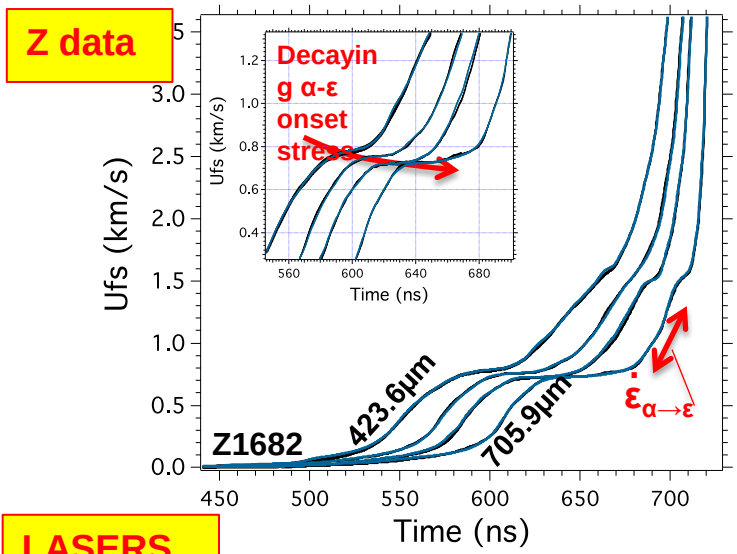
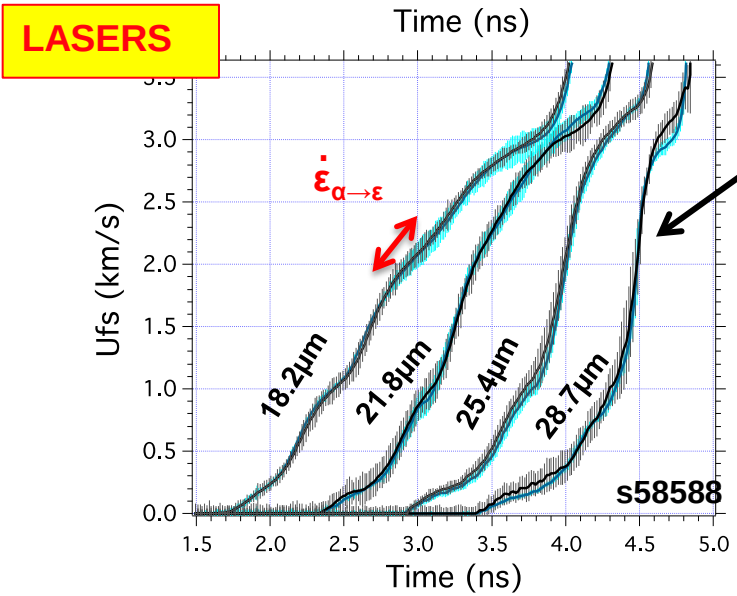
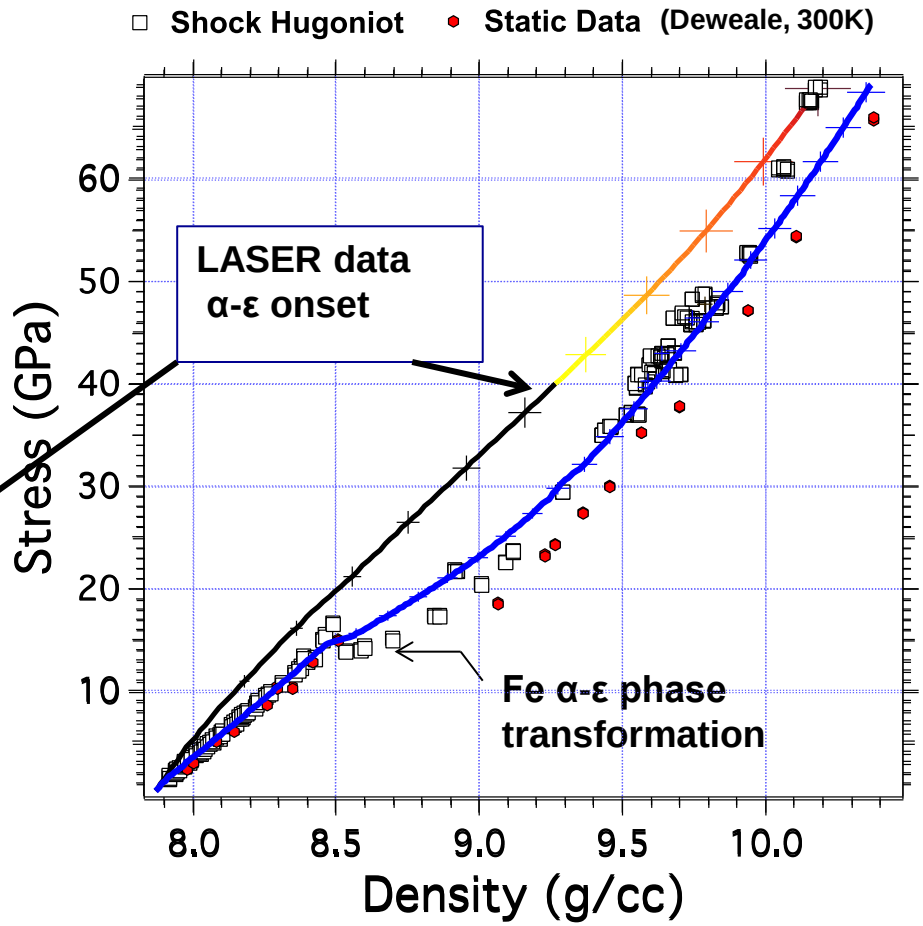
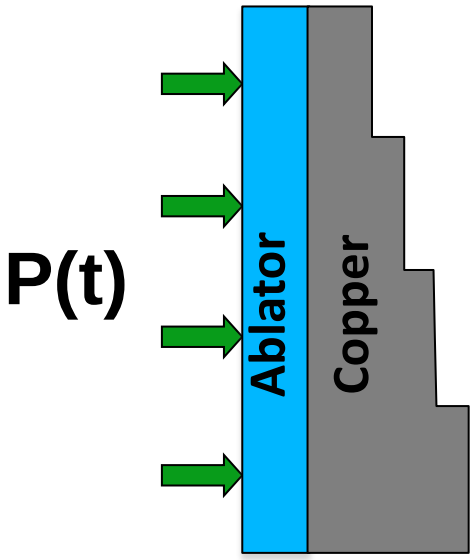




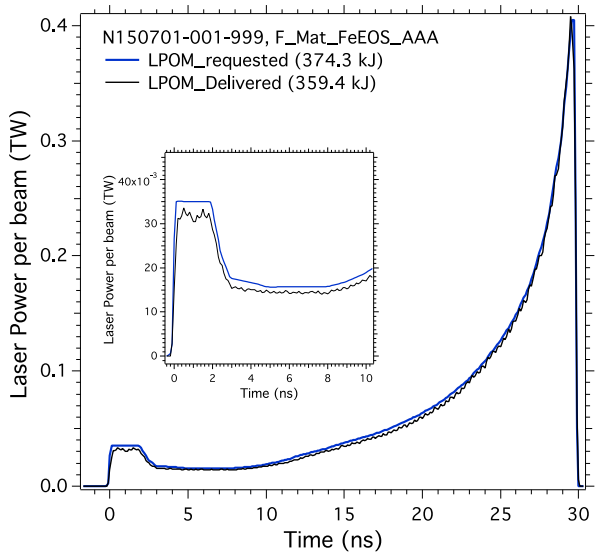


The NIF is well suited for ramp compression EOS experiments

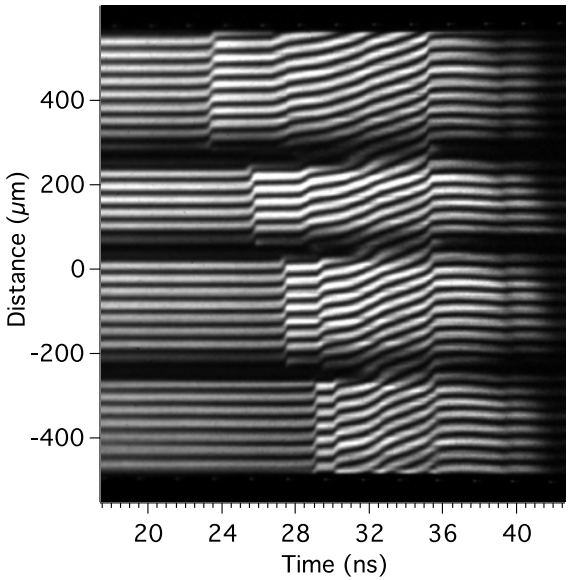
Large uniform drive regions allow multi-stepped targets



Pulse shape control enables precise design

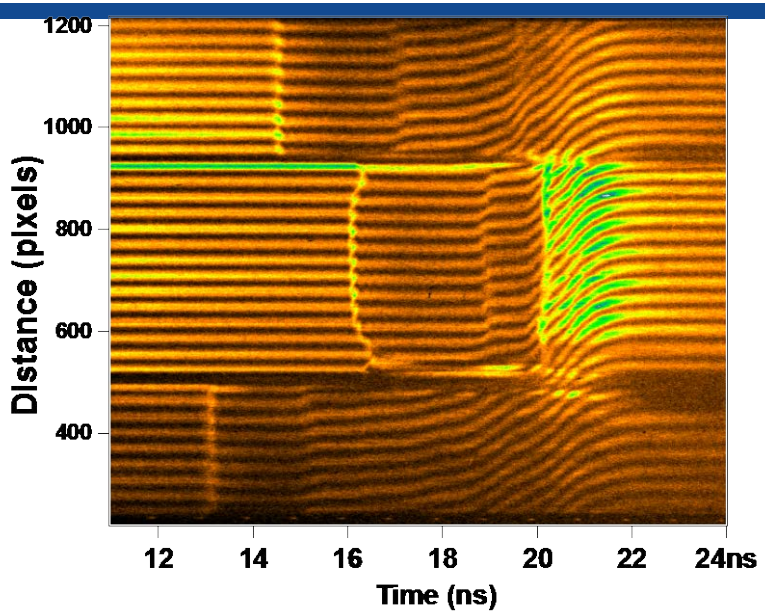


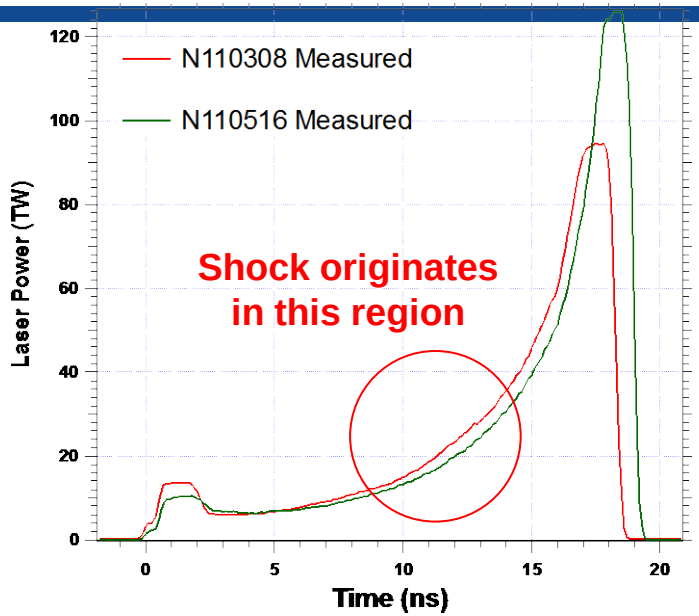
State of the art VISAR enables precise measurements



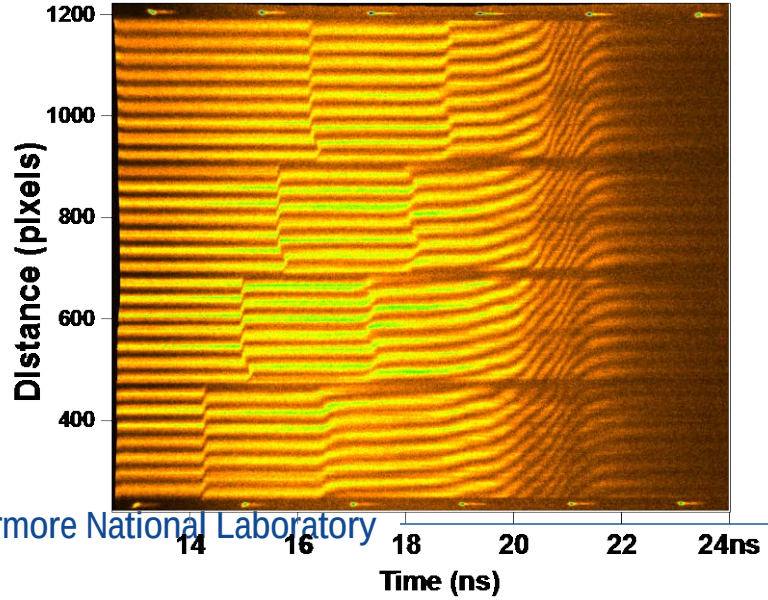
We are able to identify and correct regions responsible for growing shocks.

27 Mbar
N110308



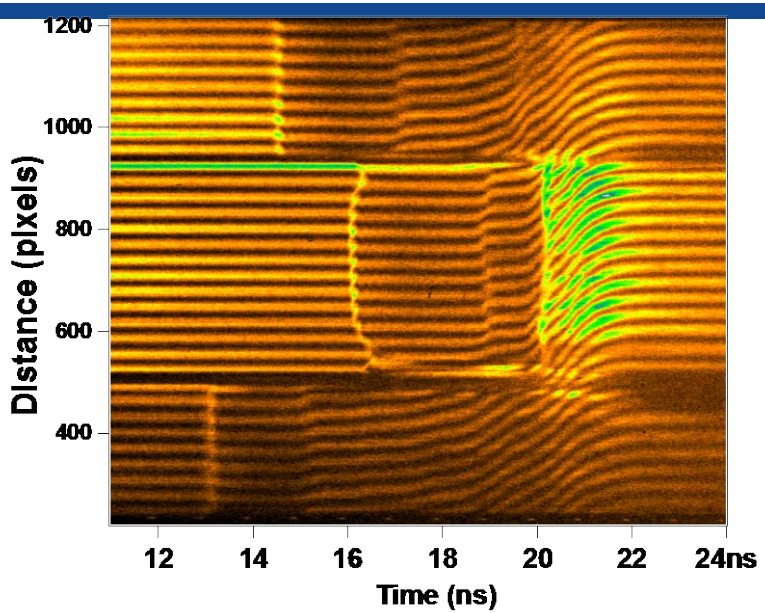


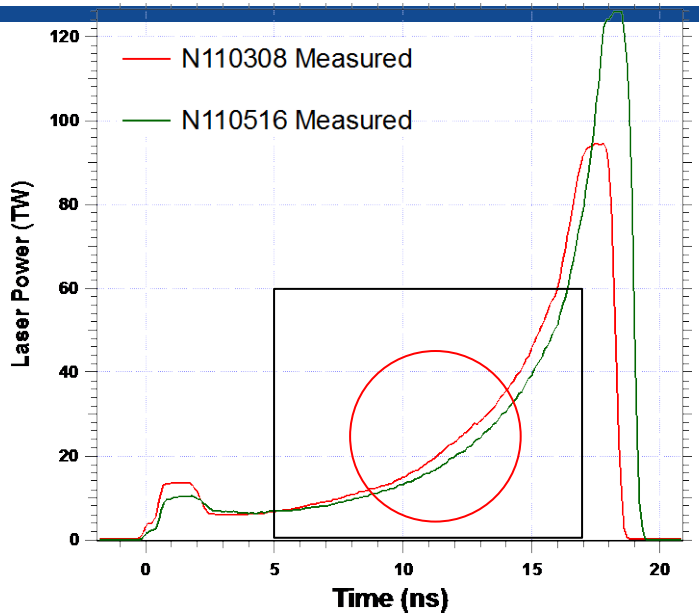
37 Mbar
N110516



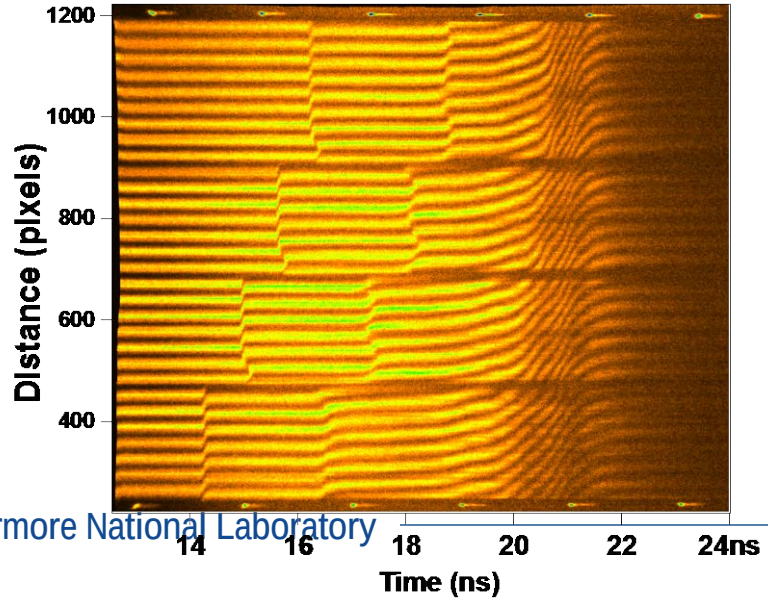
Pulse-shape correction works extremely well.

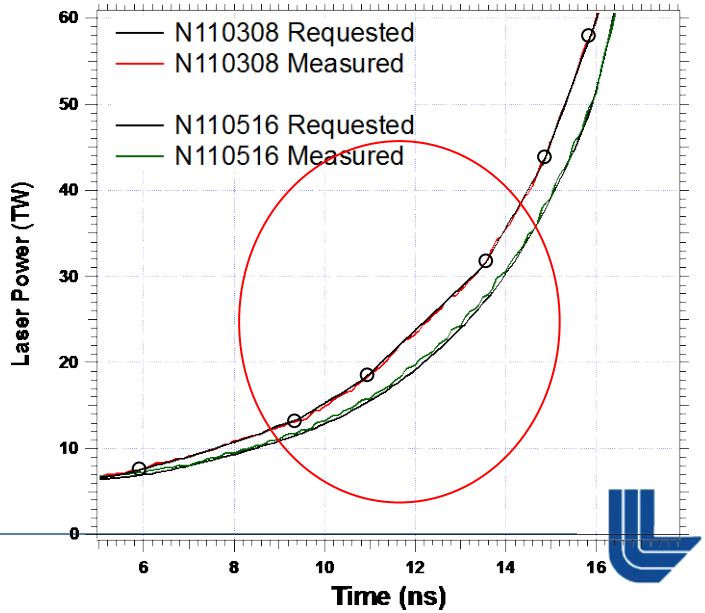
27 Mbar
N110308





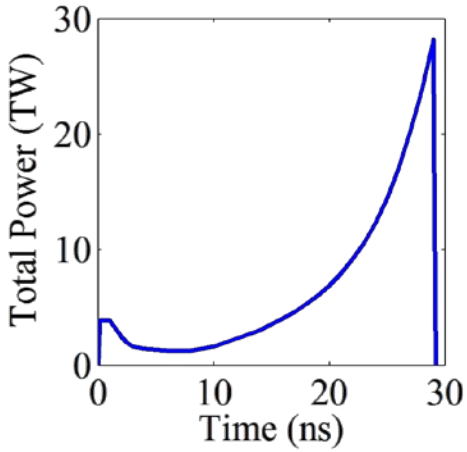
37 Mbar
N110516



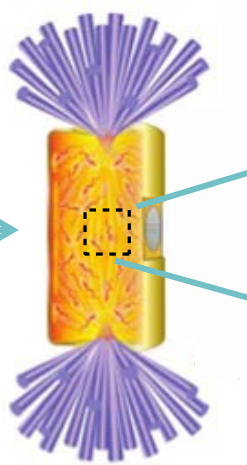


Experimental design requires radiation-hydrocode simulations

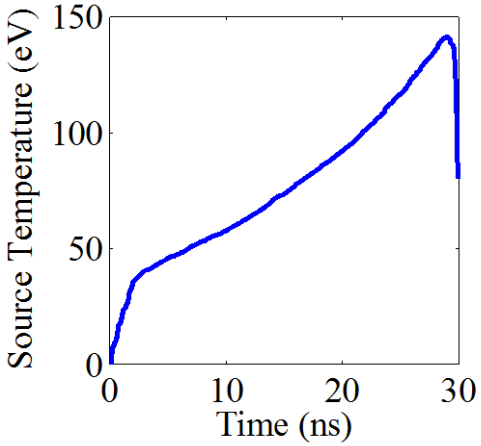
1.) Design Pulse shape



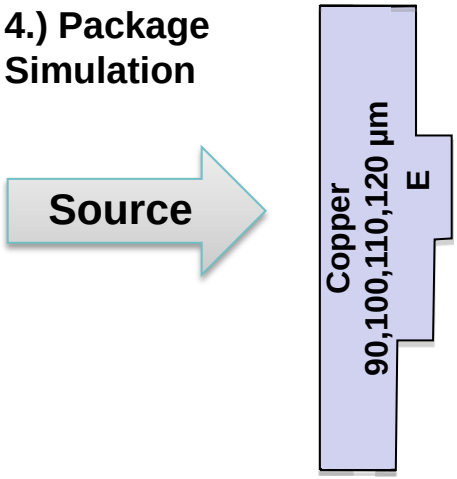
2.) Hohlraum Simulation



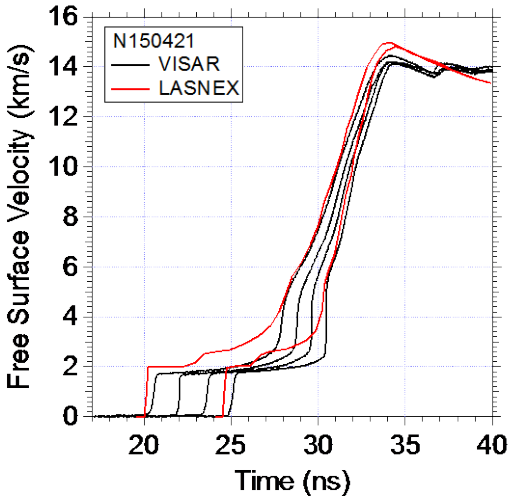
3.) Determine Source



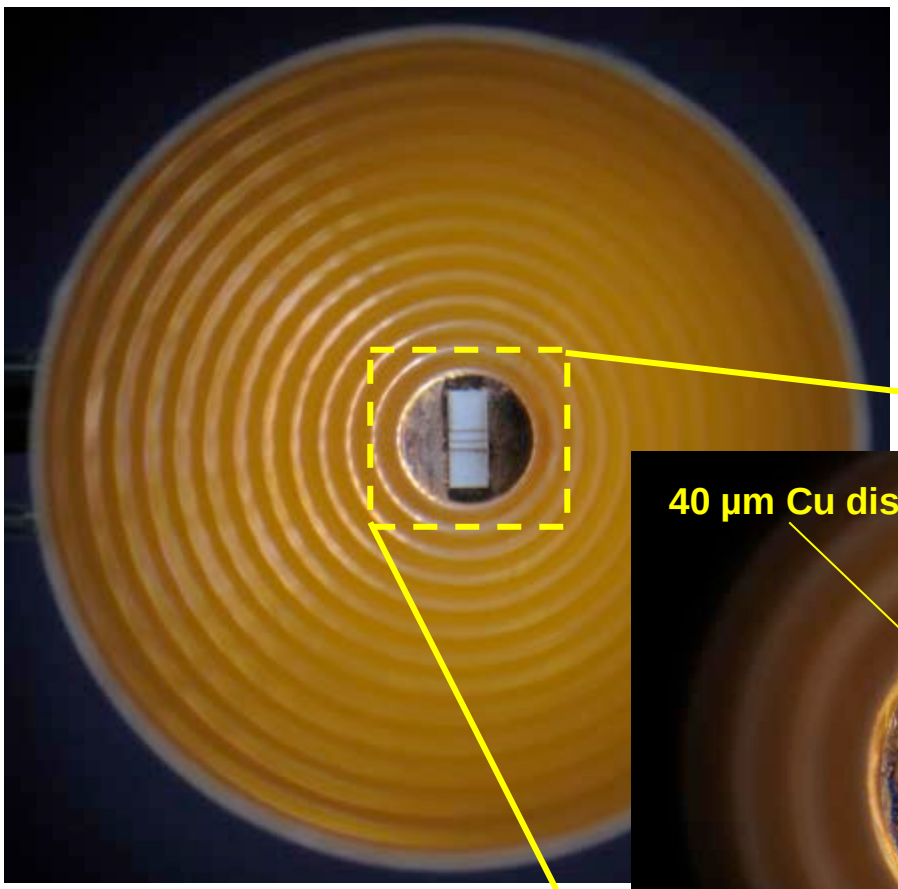
4.) Package Simulation

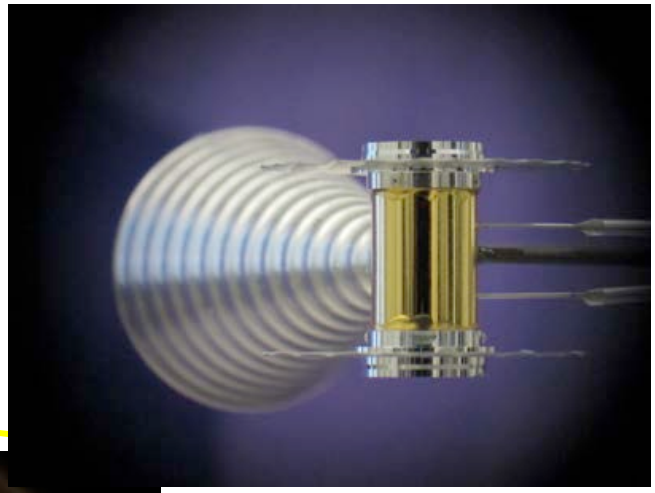


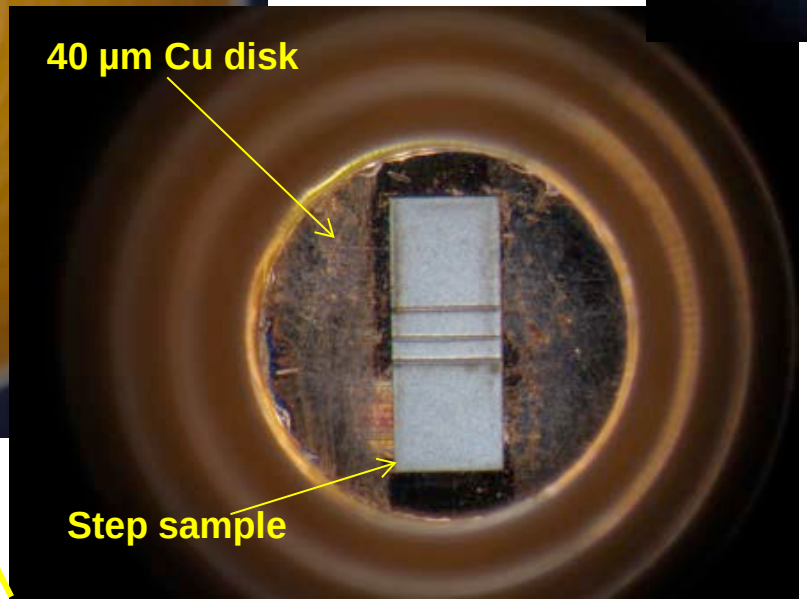
5.) Extract Observables



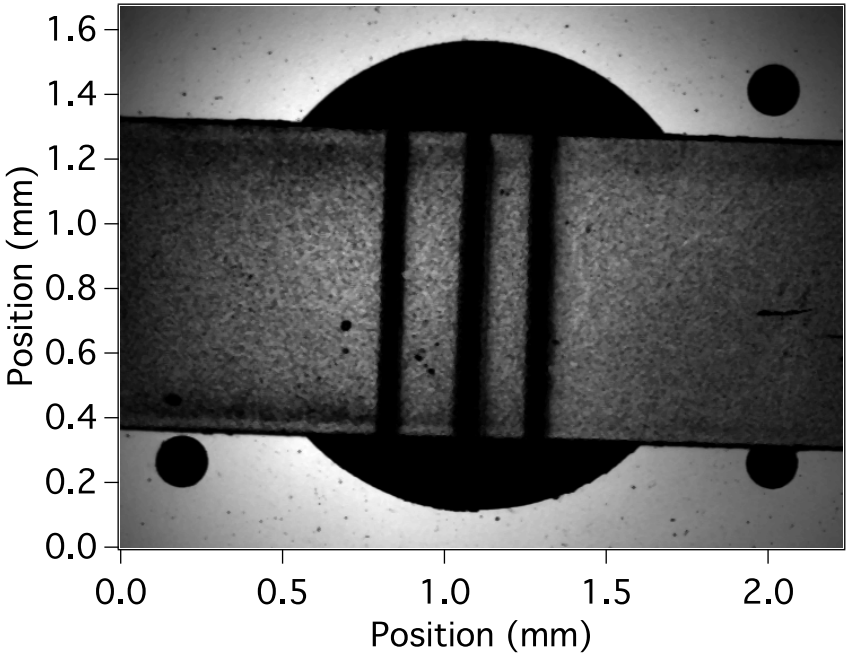
Iron physics package are side mounted on a hohlraum with cone to prevent VISAR blanking

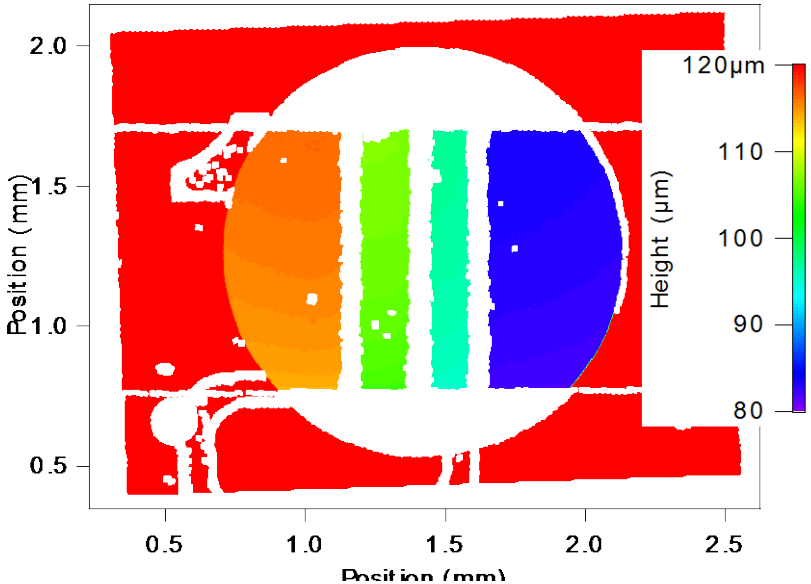


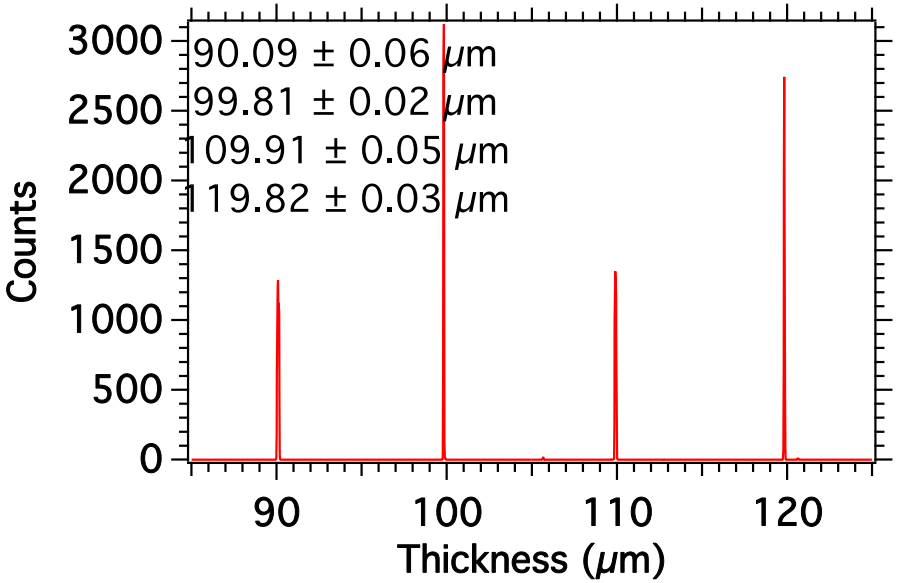




Accurate target metrology is required for precise EOS measurements



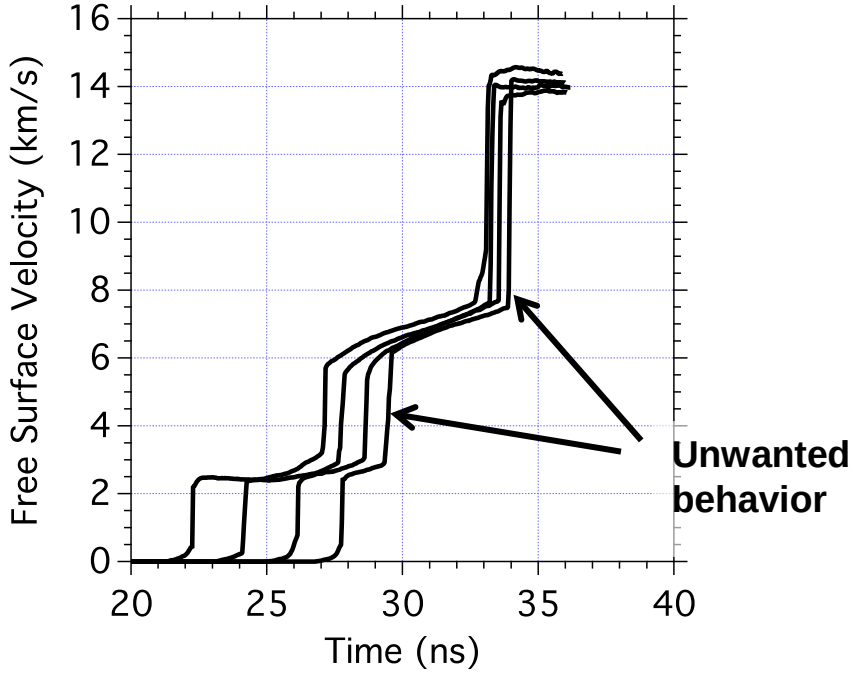




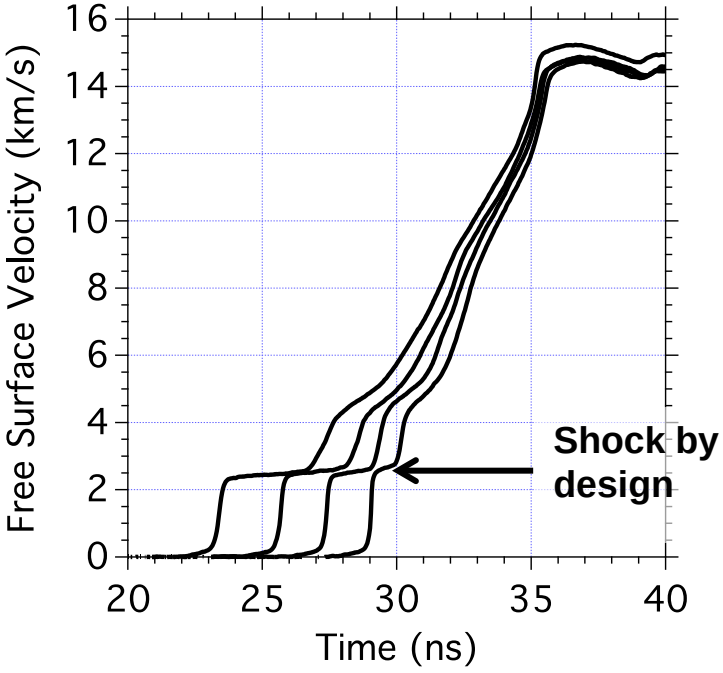
LLNL and GA delivered high-quality stepped targets which directly affected the success of these experiments

This discovery science campaign greatly benefited from collaboration with other programmatic campaigns

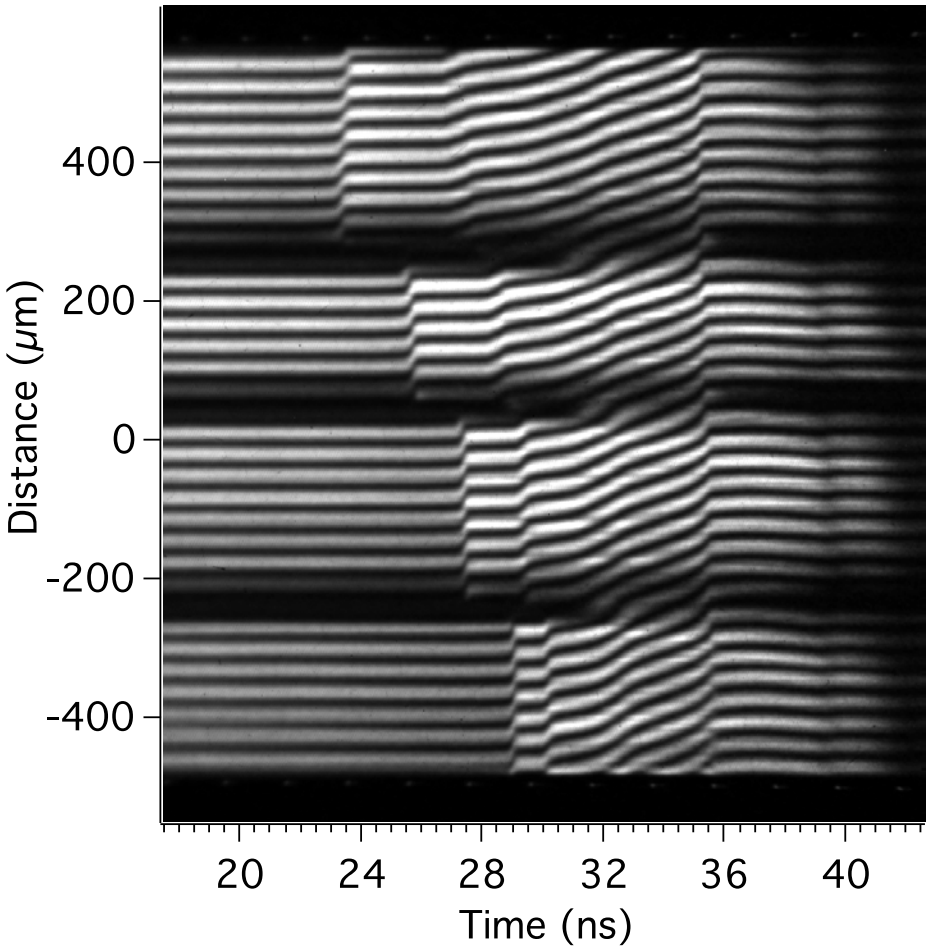
Diamond Ablator
(First D.S. Experiment)

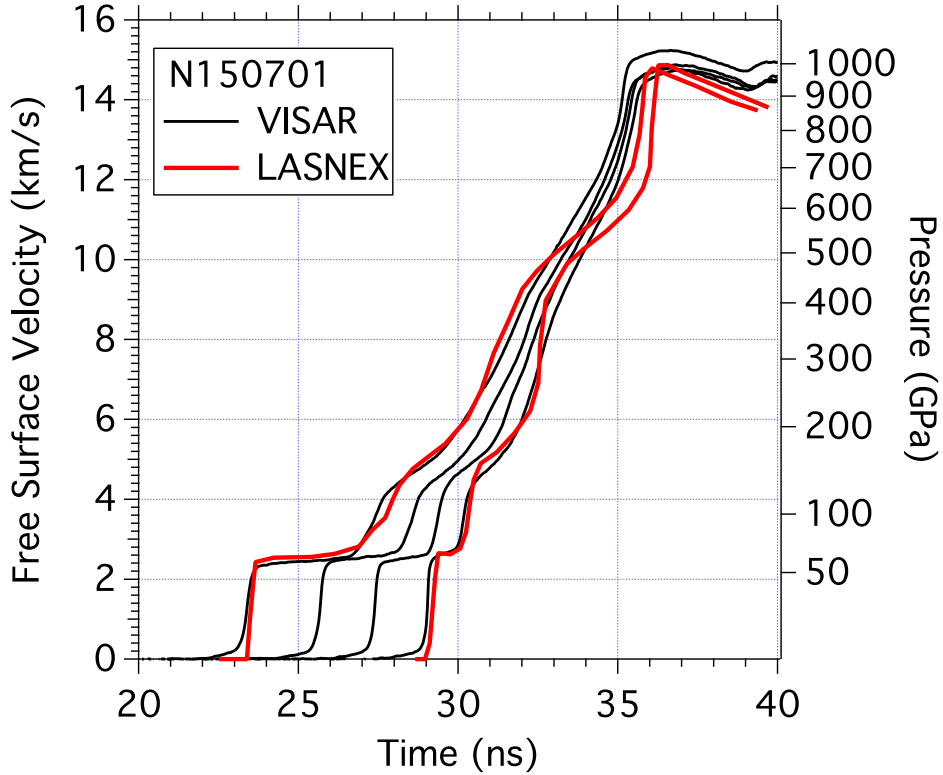


Copper Ablator
(Second D.S. Experiment)

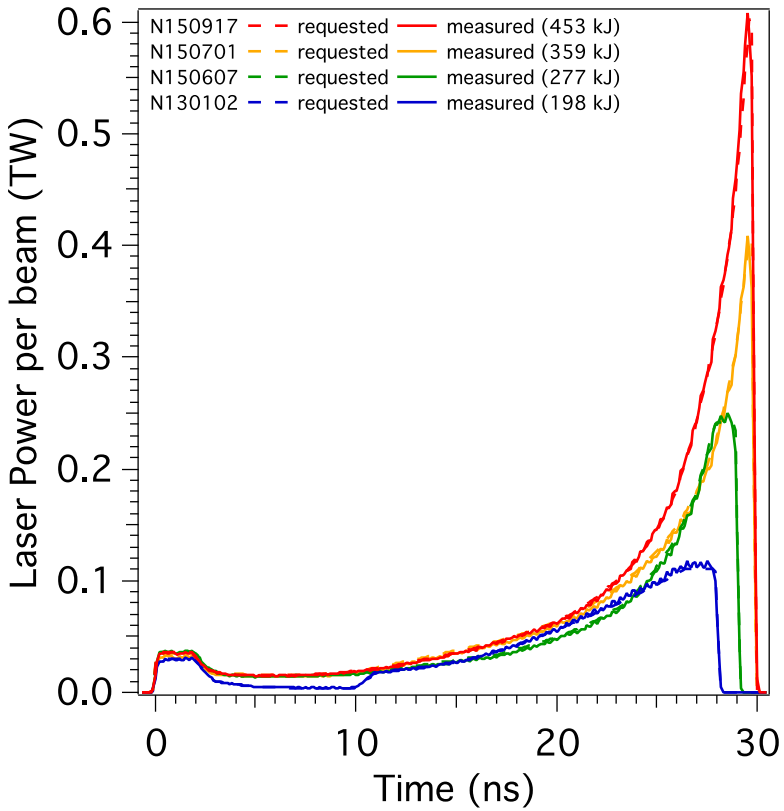


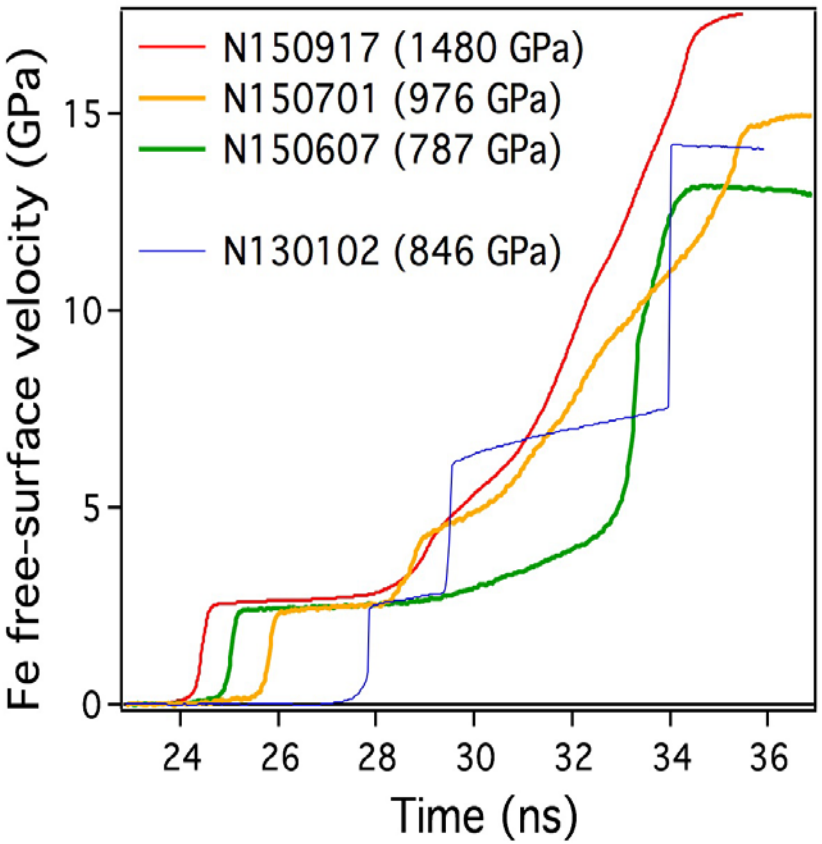
Using the alternate ablator, we ramp compressed iron to 10 Mbar



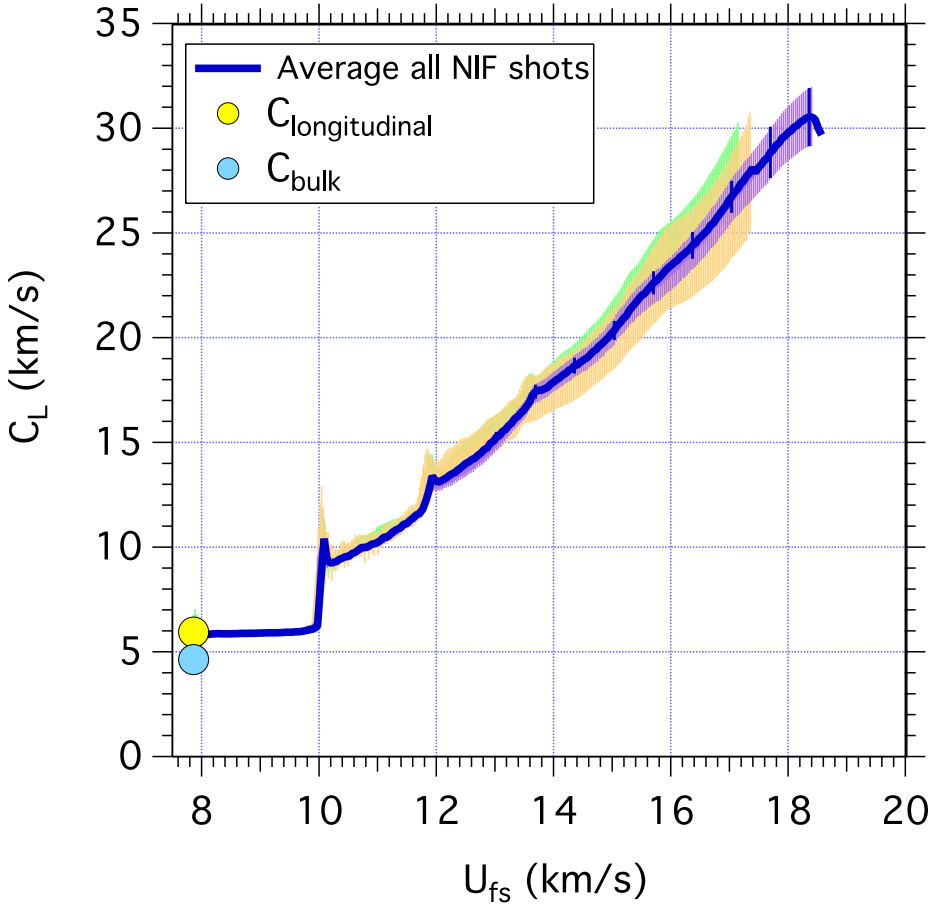


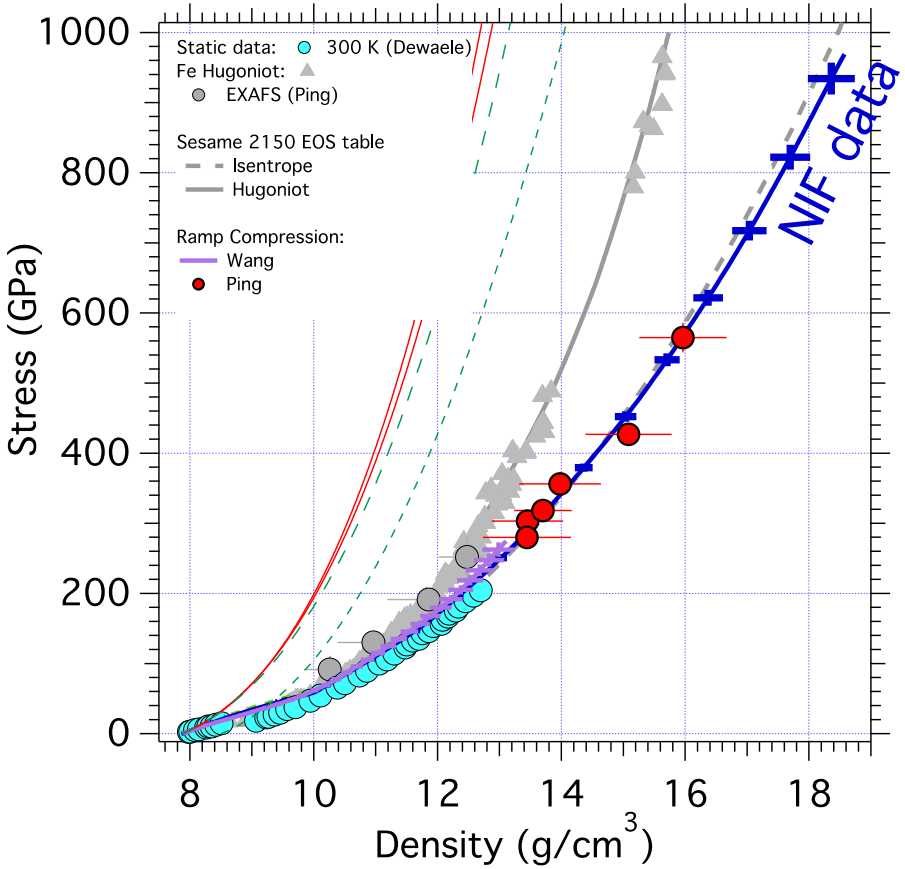
Evolution of the campaign/ Importance of pulse shaping



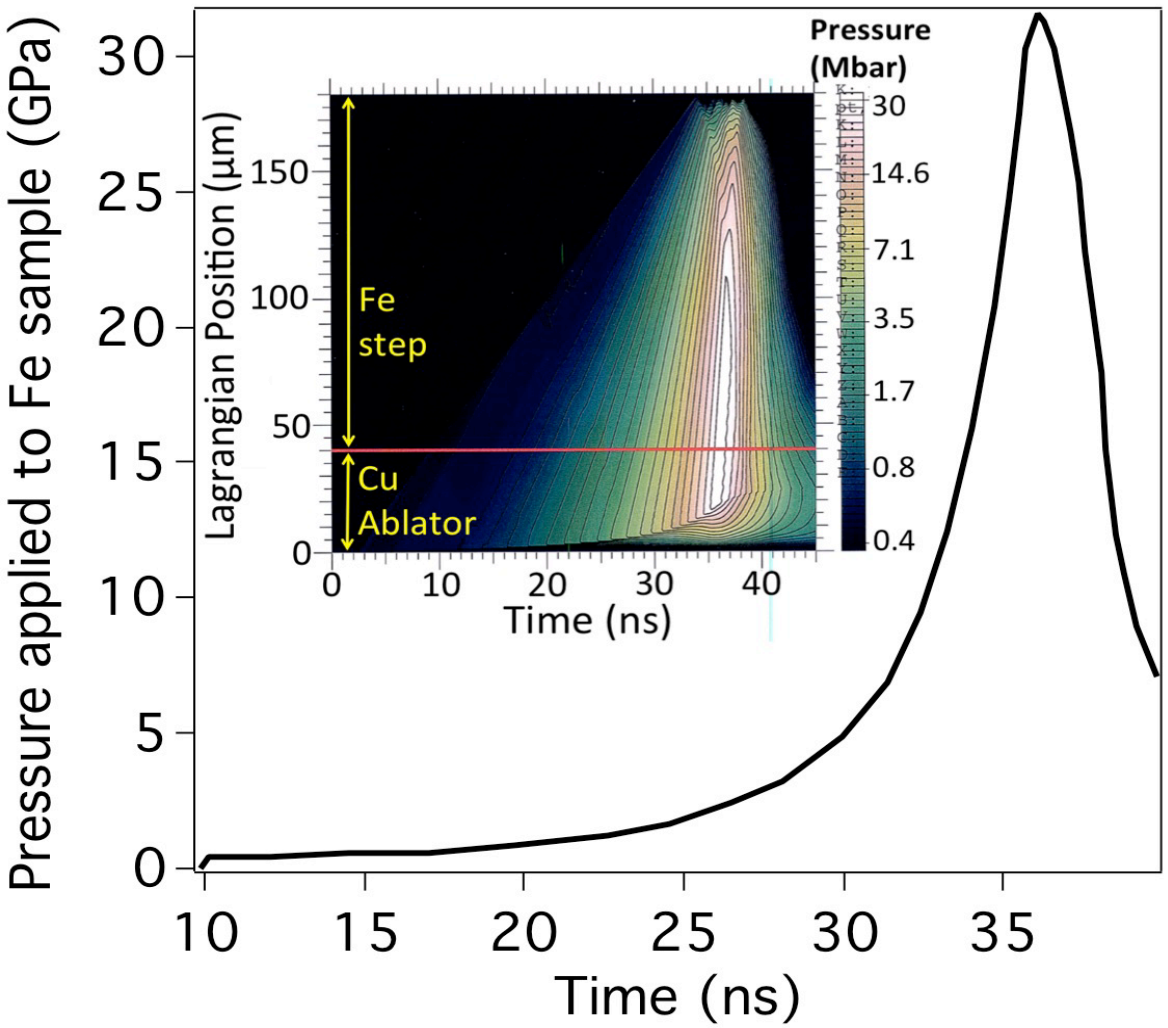


CL-Up and Stress Density





LASNEX simulations indicate that pressures of ~30 Mbar could be obtained for future work



Conclusions

We have measured the stress density and sound speed of iron up to 10 Mbar, pressures that exist within the cores of super-earths around 5 earth masses.

We succeeded in ramp compressing Iron to over 15 Mbar, but are still analyzing the data.

We have designs and believe we can reach 30 Mbar in ramp compressed Iron.