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LLNL-CONF-425256

Laser-induced Ramp Compression of Tantalum and Iron to Over 300 GPa: EOS and X-ray Diffraction

J. H. Eggert, M. Bastea, D. Braun, D. Fujino, R. Rygg, R. Smith, J. Hawreliak, D. G. Hicks, G. Collins

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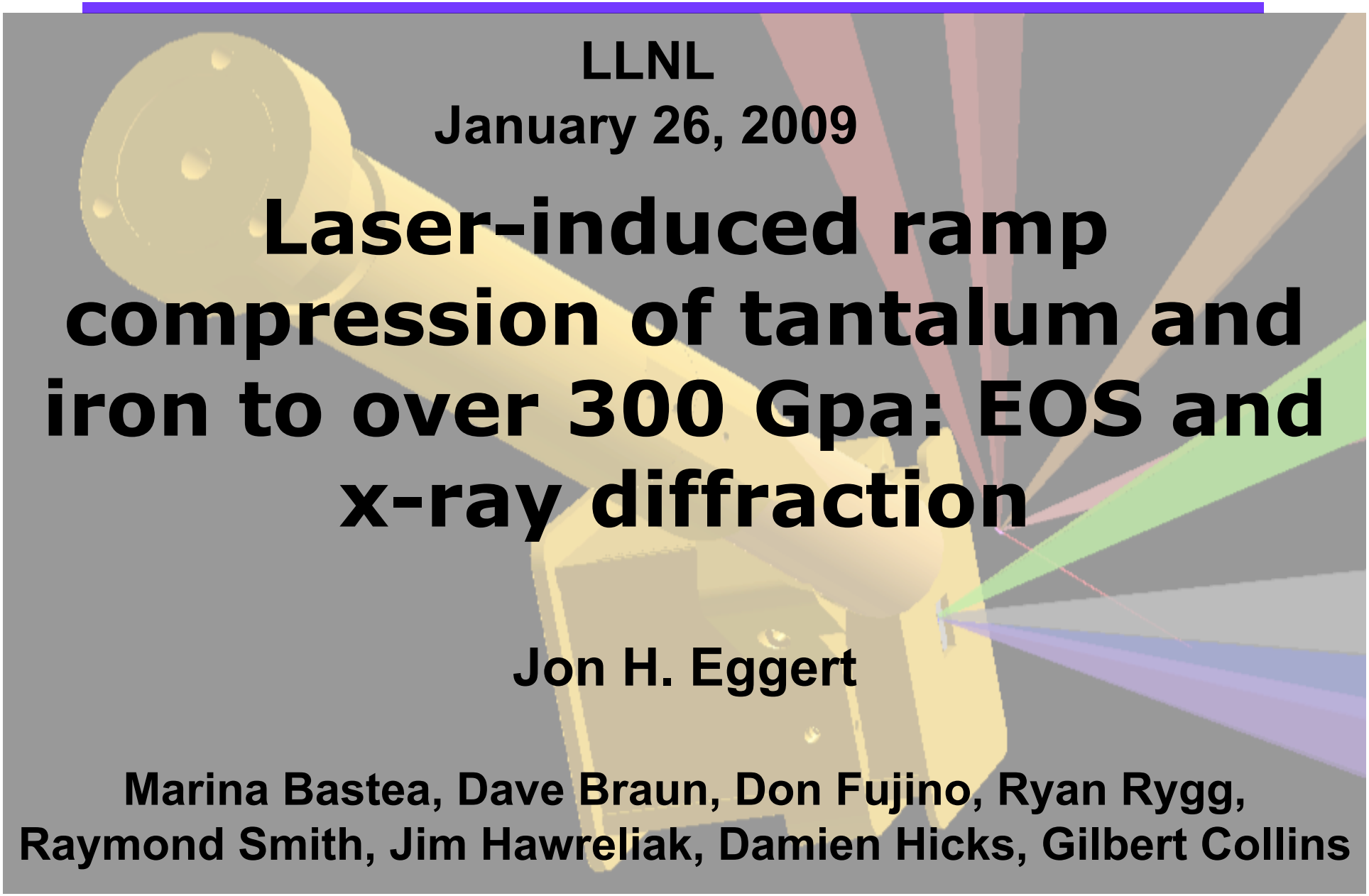
JOWOG-32, 2010
Livermore, CA, United States
January 25, 2010 through January 29, 2010

Disclaimer

Jowog-32, 2010



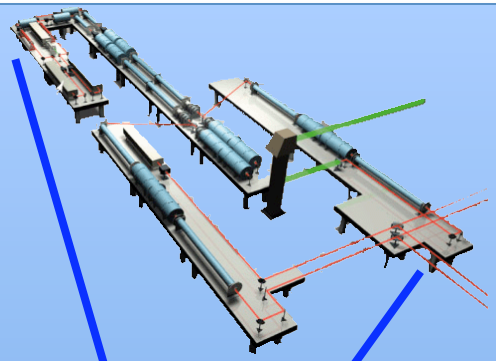
LLNL
January 26, 2009

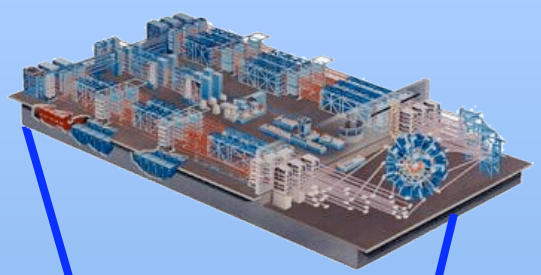
Laser-induced ramp compression of tantalum and iron to over 300 Gpa: EOS and x-ray diffraction

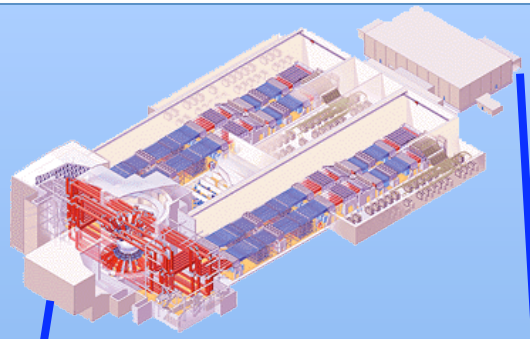
Jon H. Eggert

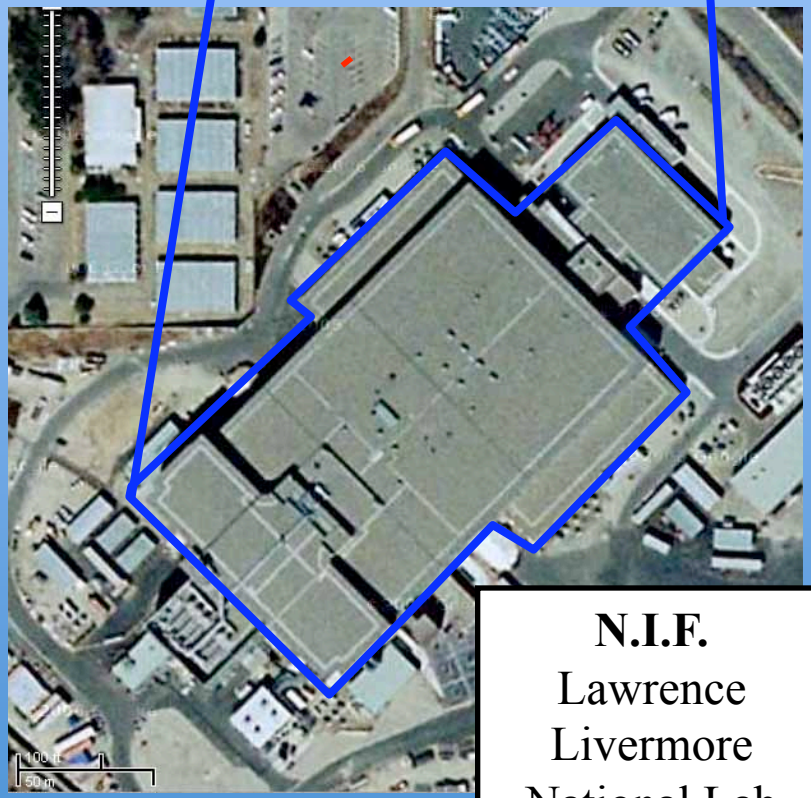
Marina Bastea, Dave Braun, Don Fujino, Ryan Rygg, Raymond Smith, Jim Hawreliak, Damien Hicks, Gilbert Collins

Laser Facilities









Janus
Lawrence Livermore National Lab (CA)

2 beam
1 kJ

100 meters

Omega
University of Rochester (NY)

60 Beams
30 kJ

192 Beams, 2 MJ

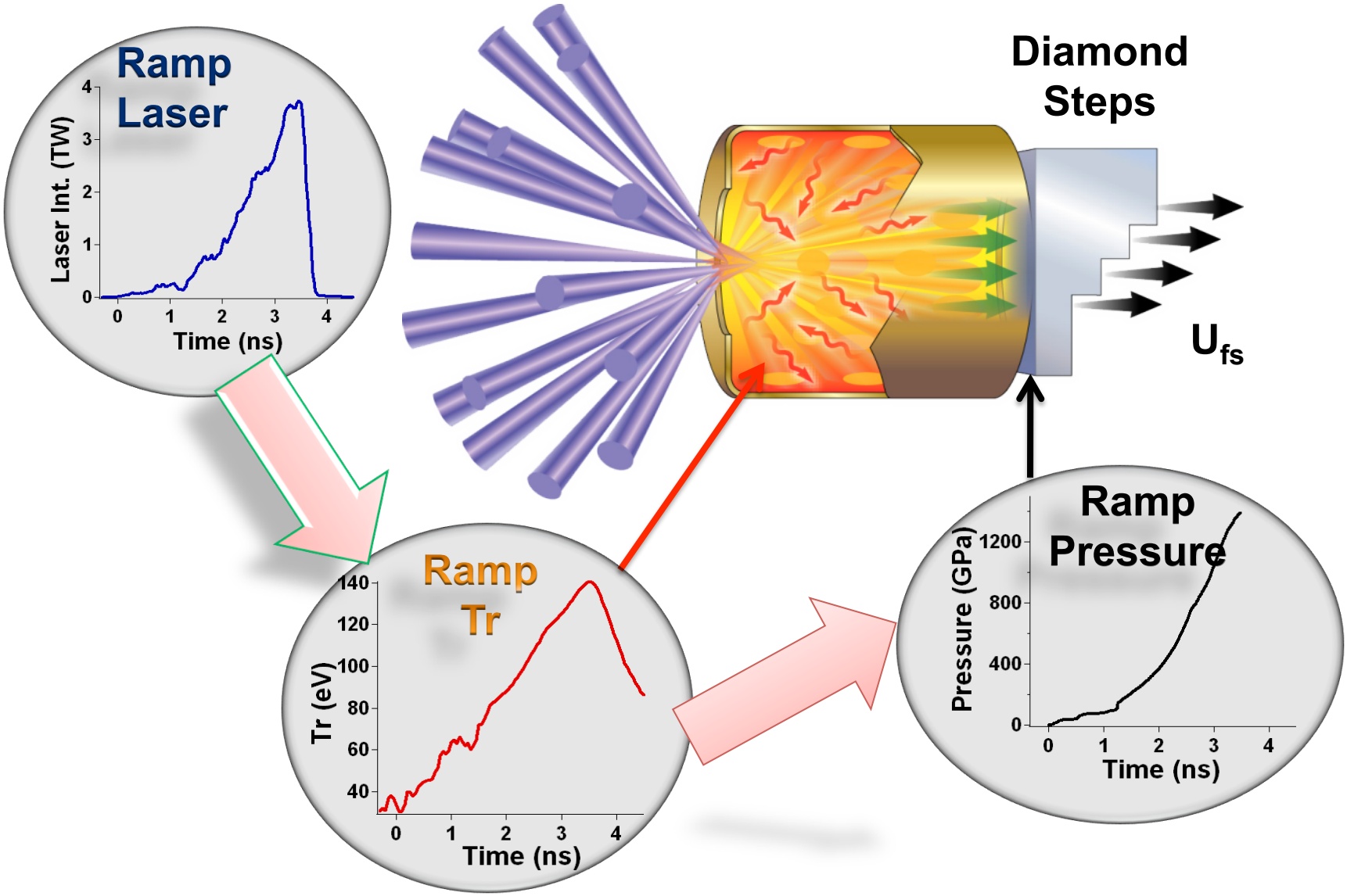
N.I.F.
Lawrence Livermore National Lab

Outline

Laser-Driven Ramp Compression Experiments

- Introduction
- Ramp-Compression EOS on Tantalum to 320 GPa
  - Cold Sample
  - Absolute Stress-Strain
- X-ray Diffraction on Iron to 470 GPa
  - Far Above Shock Melting on Hugoniot
  - Still Solid
  - Consistent with HCP
- On to NIF . . .

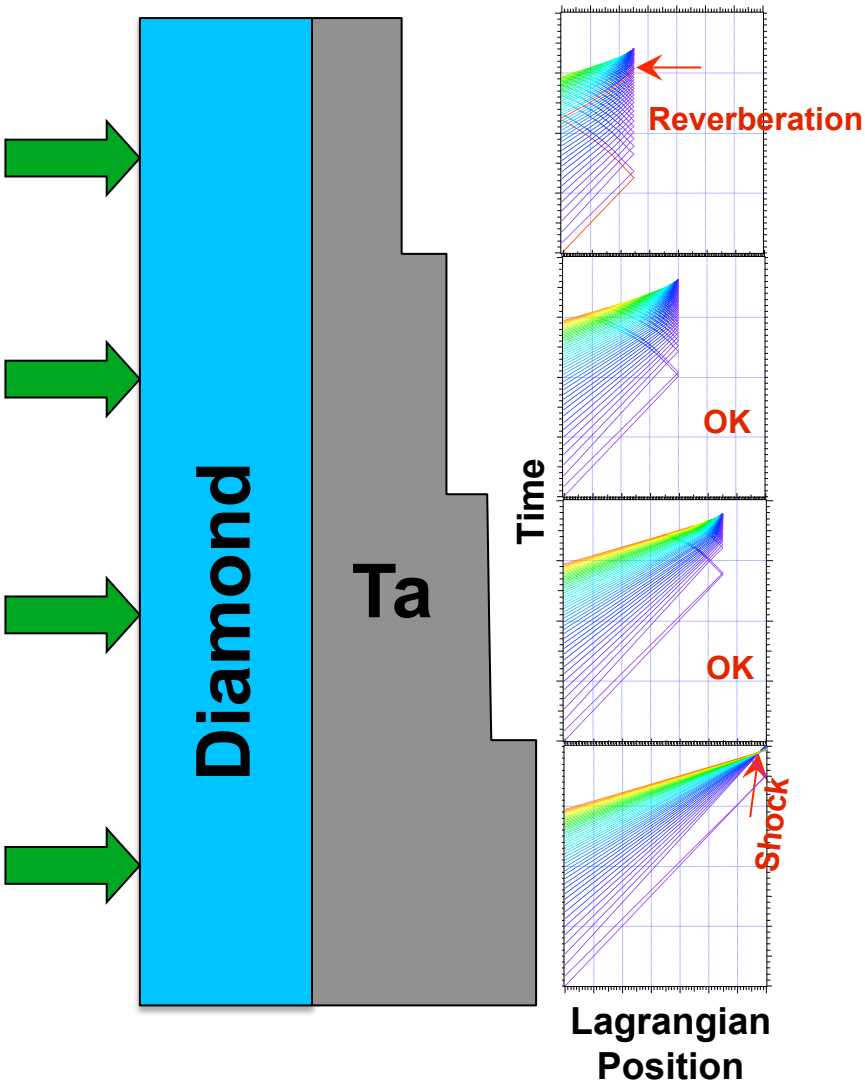
We ramp compressed diamond to 1500 GPa

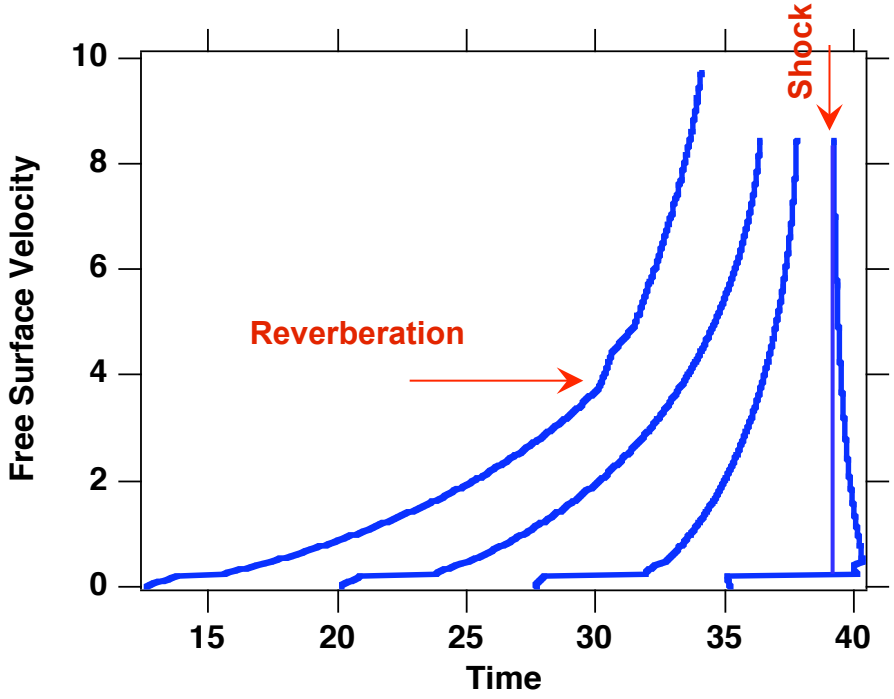


Apply this drive to Tantalum

Ramp-Wave EOS

--Design Requirements--



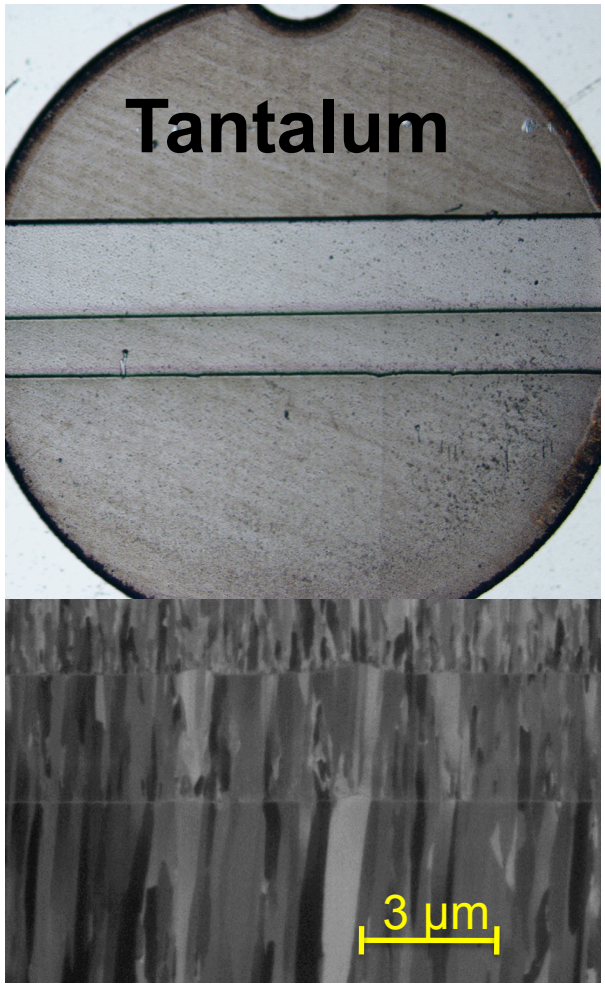


No reverberation

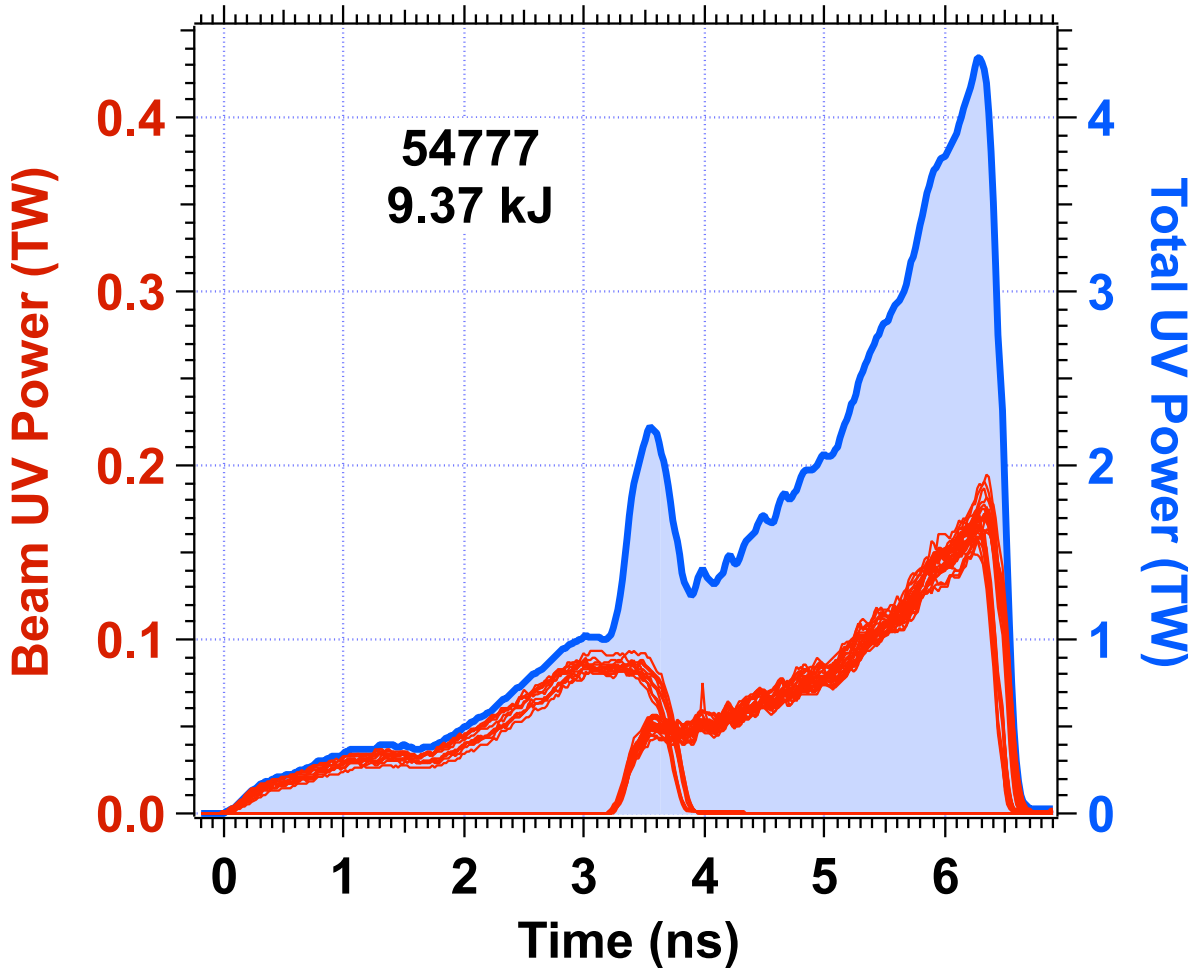
--and--

No Shock.

Target Metrology and Pulse Shape



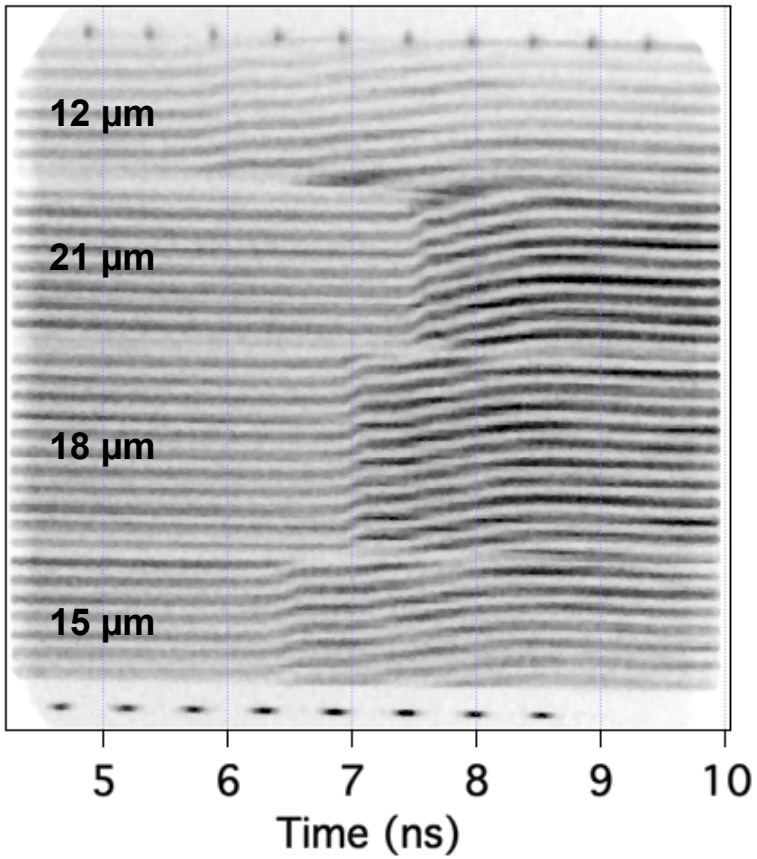
d_A=11.24±05 μm
d_B=13.83±05 μm – 2.59 μm
d_C=16.54±05 μm – 2.71 μm
d_D=19.35±05 μm – 2.81 μm

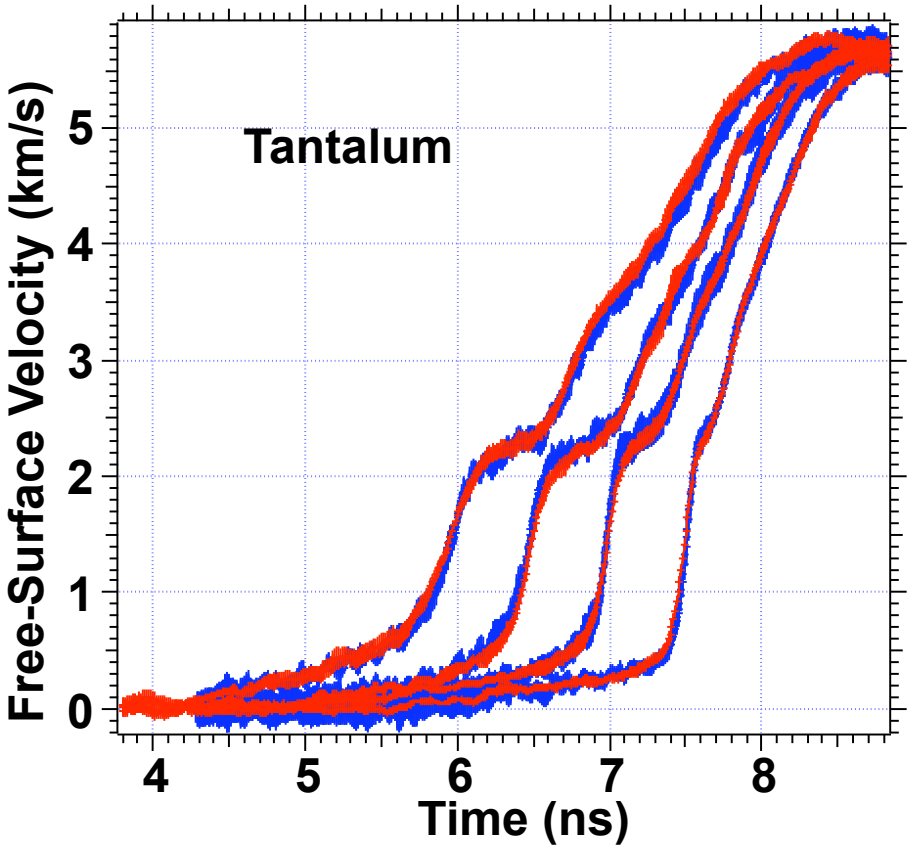


Tantalum deposition: Paul Mirkarimi
and Kerry Bettencourt.

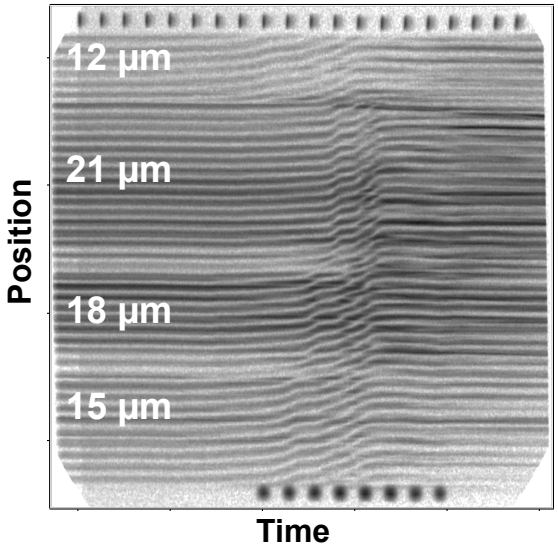
VISAR Wave Profiles

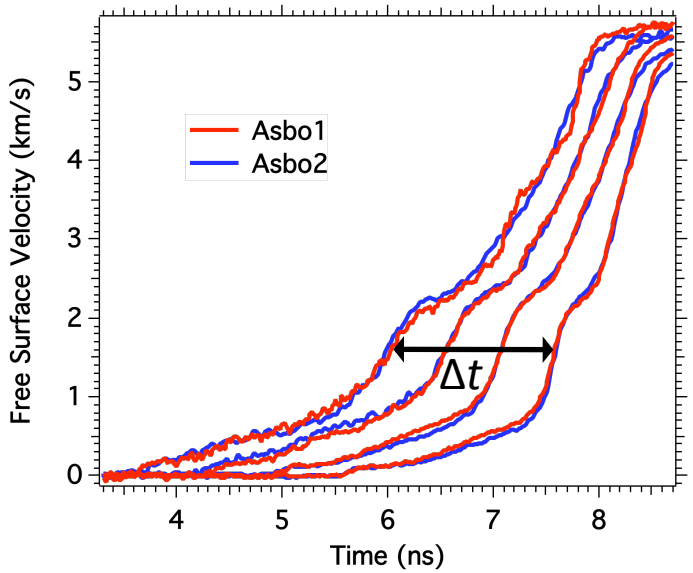
Shot 54777





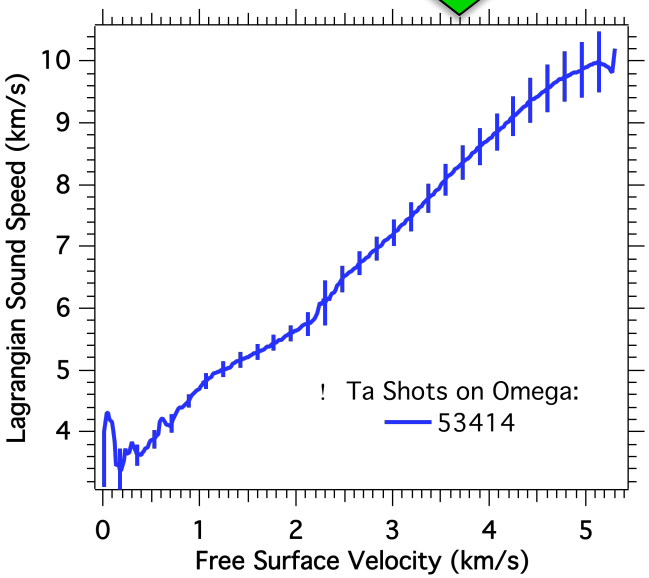
We collect data using a line visar and use an iterative Lagrangian Analysis (Rothman, et al., (2005)





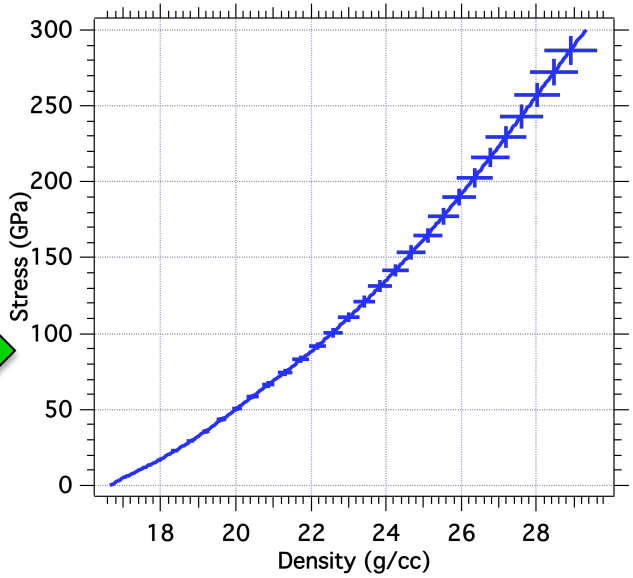
$$C_L(u) = \frac{\Delta x}{\Delta t}$$

Since we measure free surface velocity, not *u* we must use an iterative correction developed by Rothman (2005)

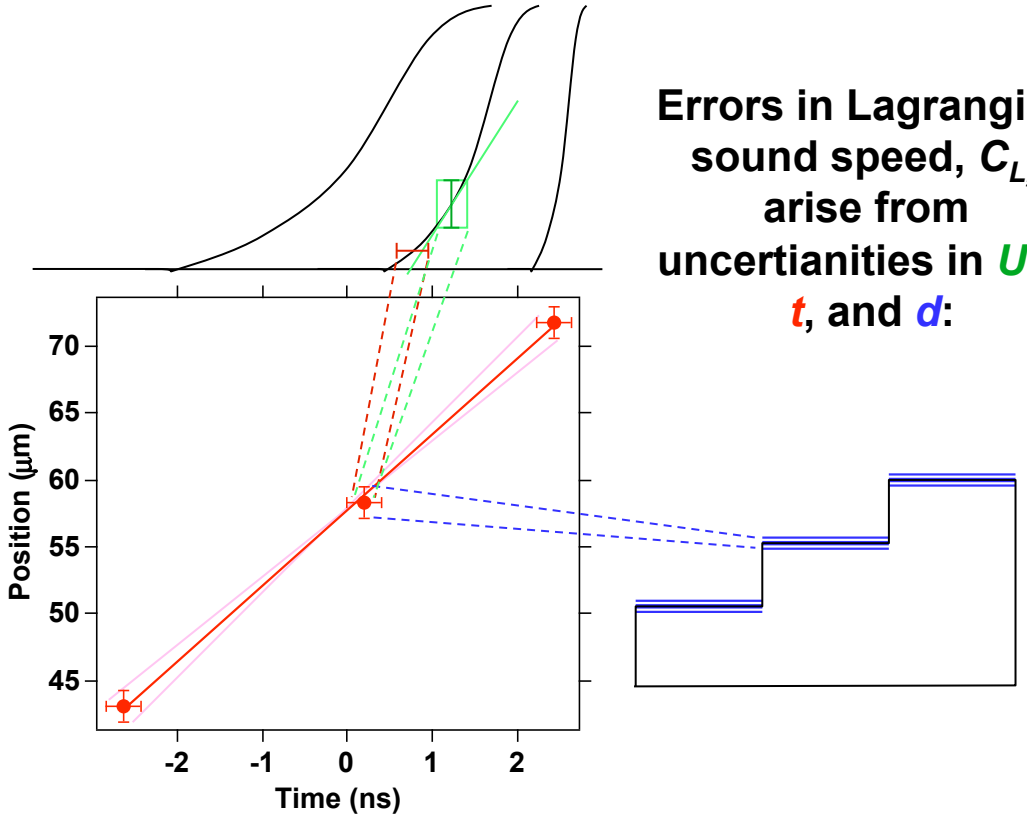


$$\rho(u) = \rho_0 \left(1 - \int du/C_L\right)^{-1}$$

$$P_x(u) = \rho_0 \int C_L \, du$$



We propagate uncertainties throughout the iterative analysis



Errors in Lagrangian sound speed, $C_{L,i}$ arise from uncertianities in U_{FS}, t, and d:

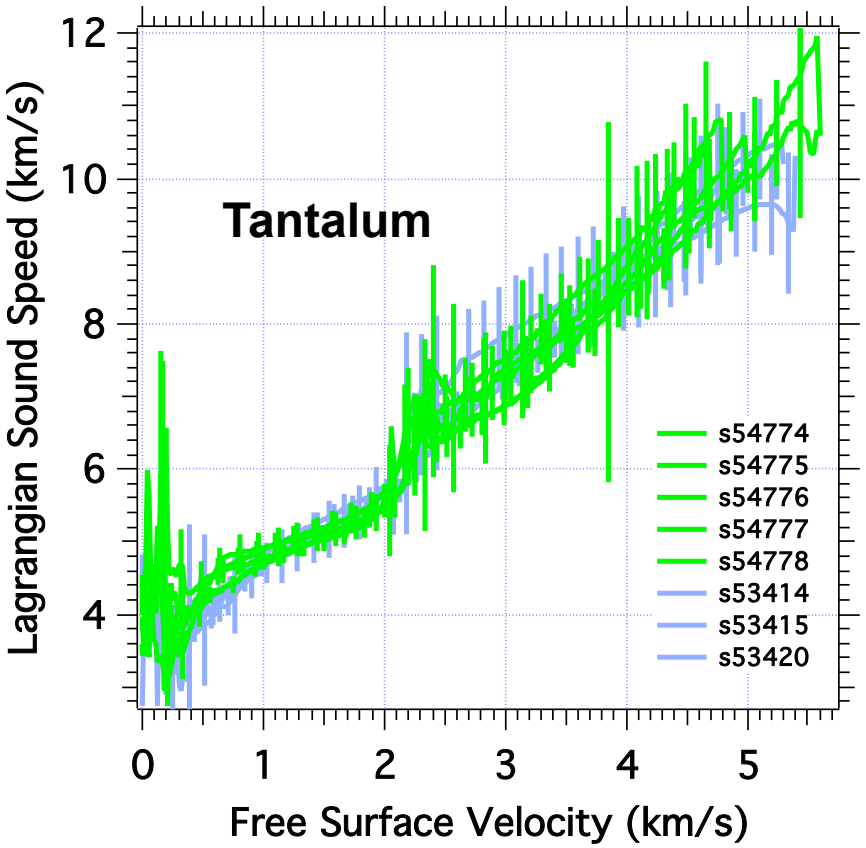
Dominant uncertainties are *not* independent as a function of U_{FS} (e.g. thickness, streak camera warping, visar laser speckle). Thus the errors propagate linearly to strain and stress:

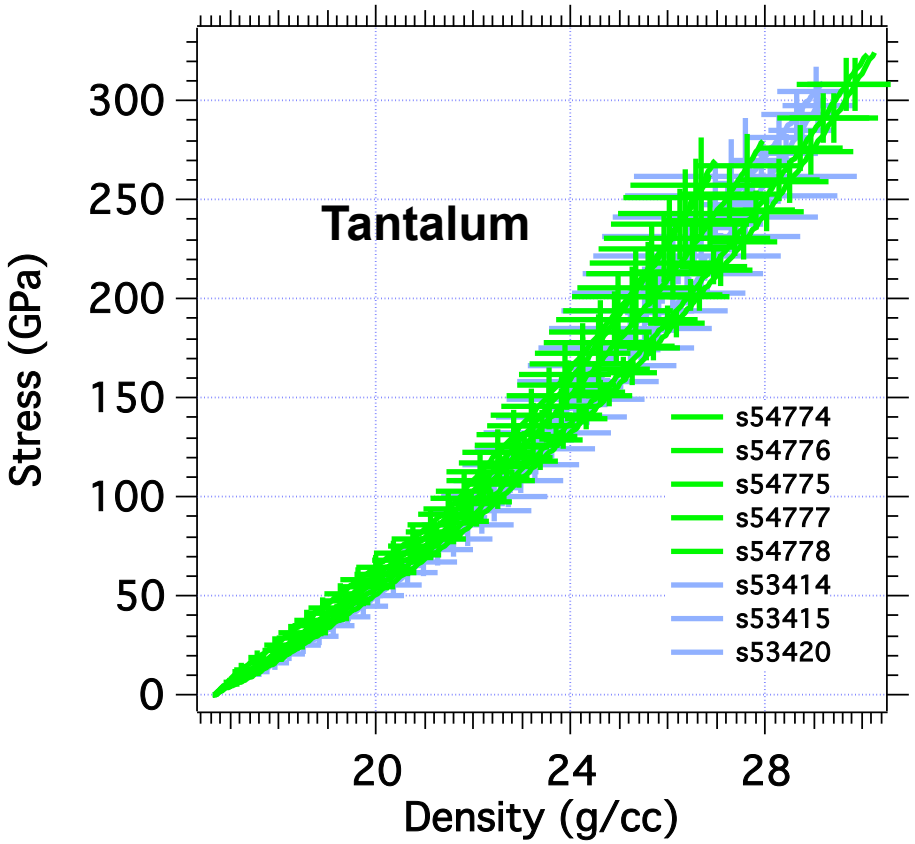
$$\delta\varepsilon_j = \Delta Up\left(\frac{\rho}{\rho_0}\right)^2 \sum_{i=0}^{j} \frac{\delta_{C_L,i}}{C_{L,i}^2}$$

$$\delta P\left(Up_j\right) = \rho_0 \Delta Up \sum_{i=0}^{j} \delta_{C_L,i}$$

Uncertainties continue to grow at high pressure.

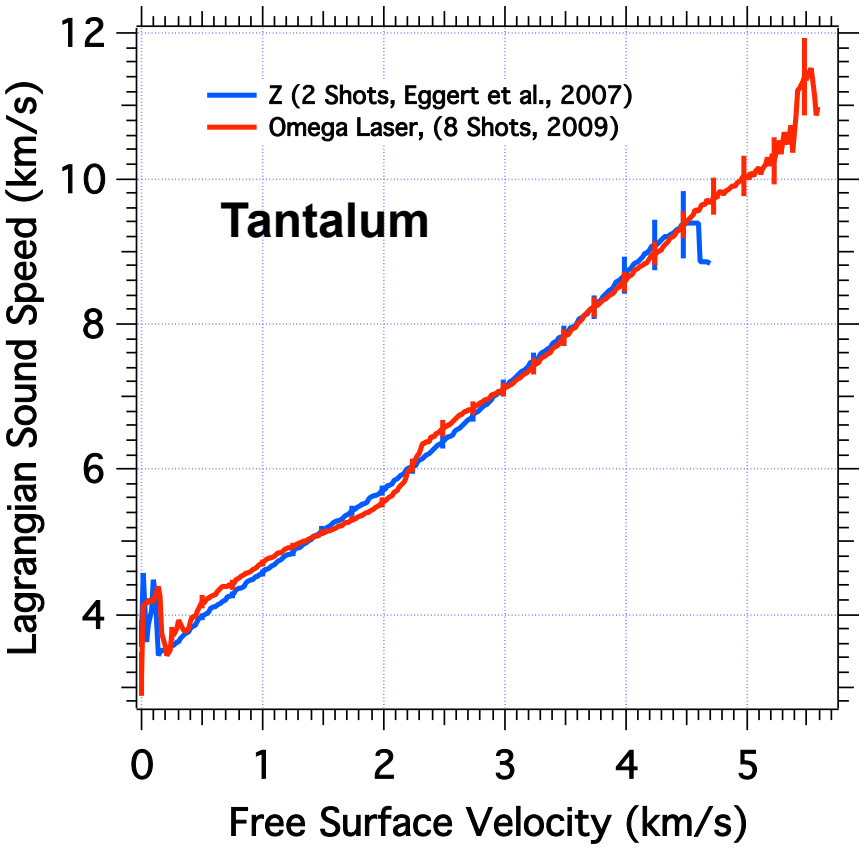
8 Shots—Highly Consistent Results

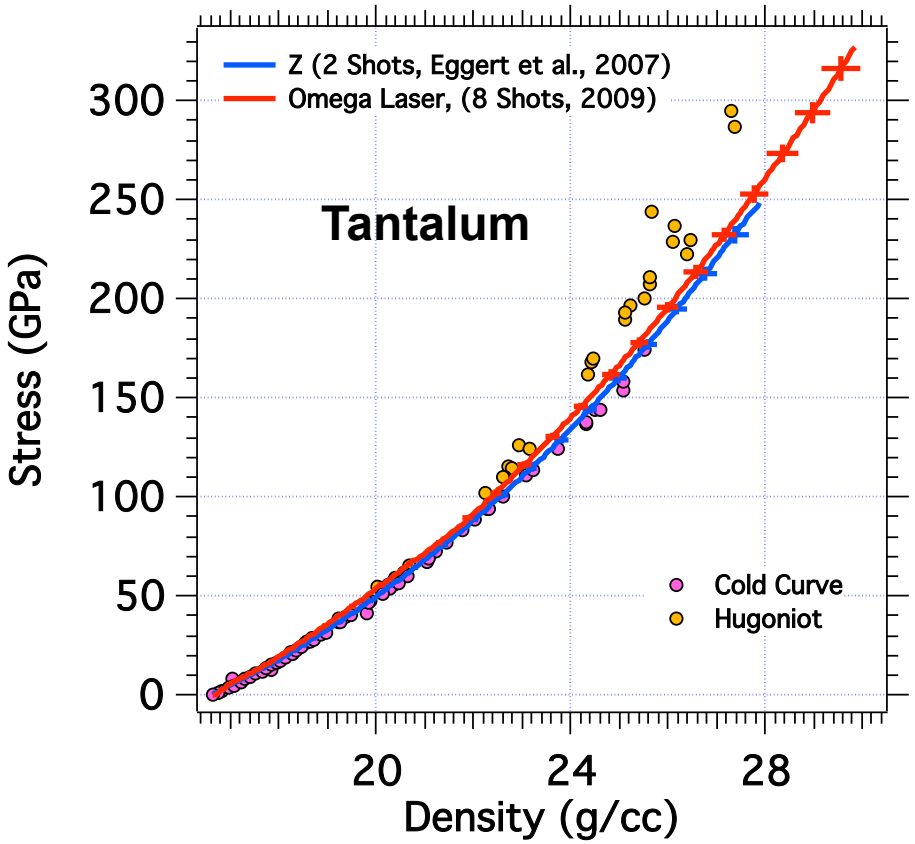




8 Shots on the Omega Laser in 2009
100% Data Return

Averaging All Laser Shots



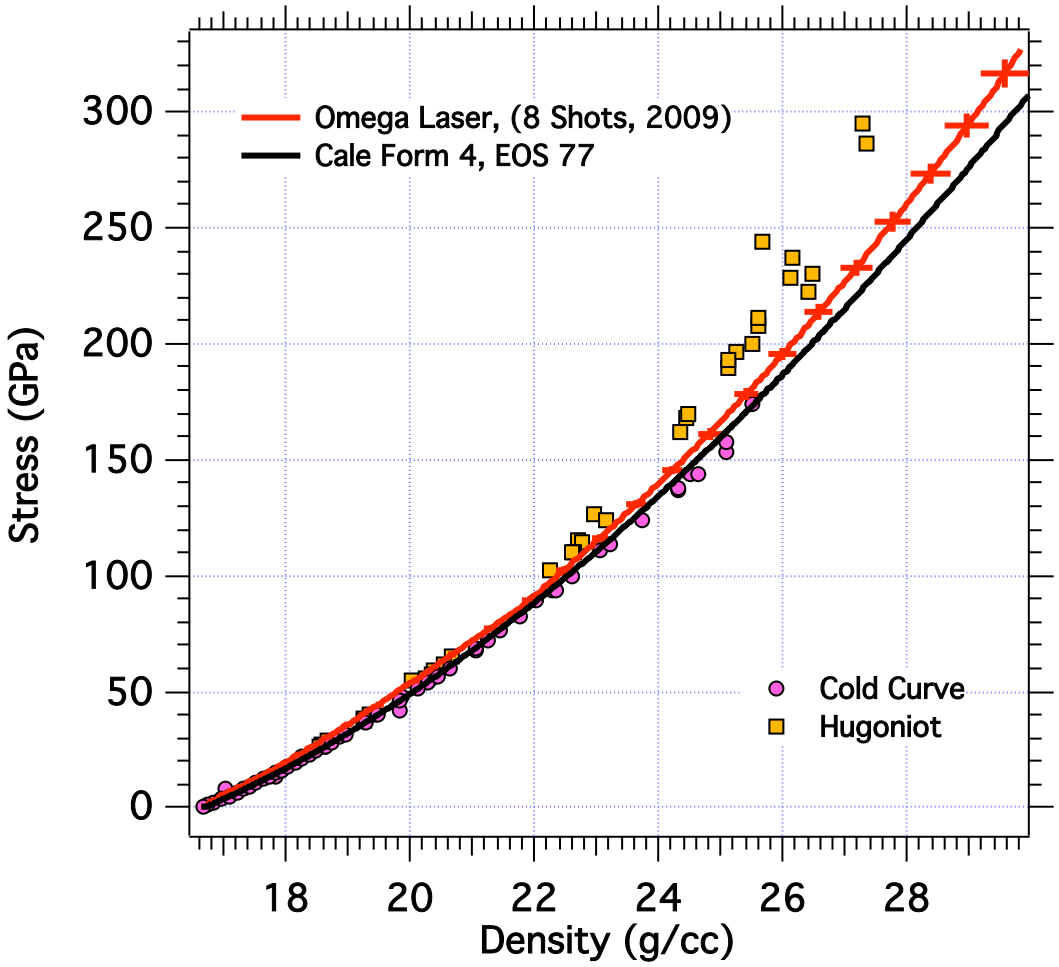


Ramp Compression Tantalum Equation of State

- **Stress-density on 8 shots to over 300 GPa.**
- **Very consistent with previous Z shots.**

Next Year: NIF experiments to 500 GPa and more . . .

To Estimate Plastic Work Heating We Estimate Deviatoric Stress or "Strength"

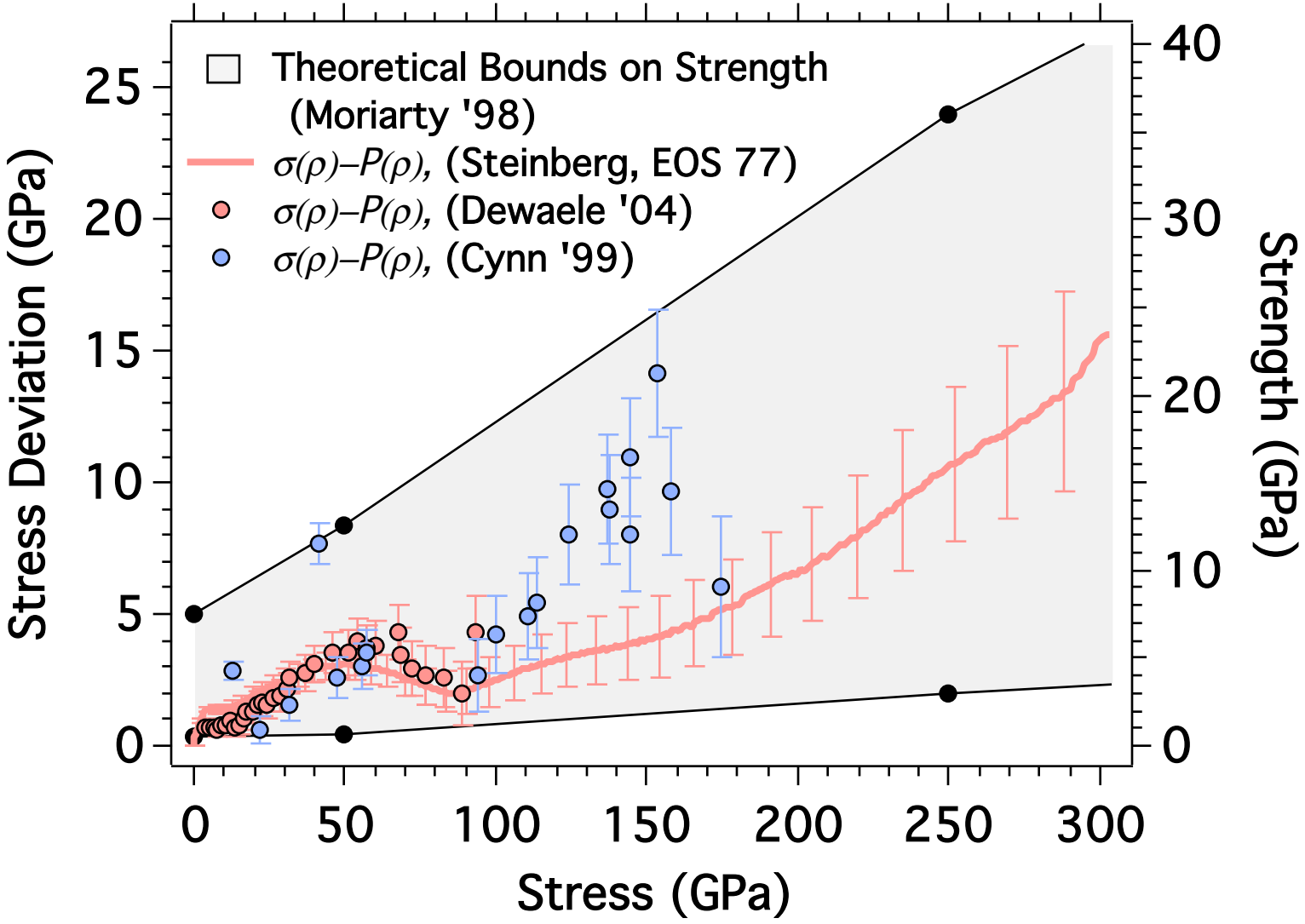


We equate the deviatoric stress with the strength,

$$Y = \frac{3}{4}\left[\sigma(\rho) - P(\rho)\right]$$

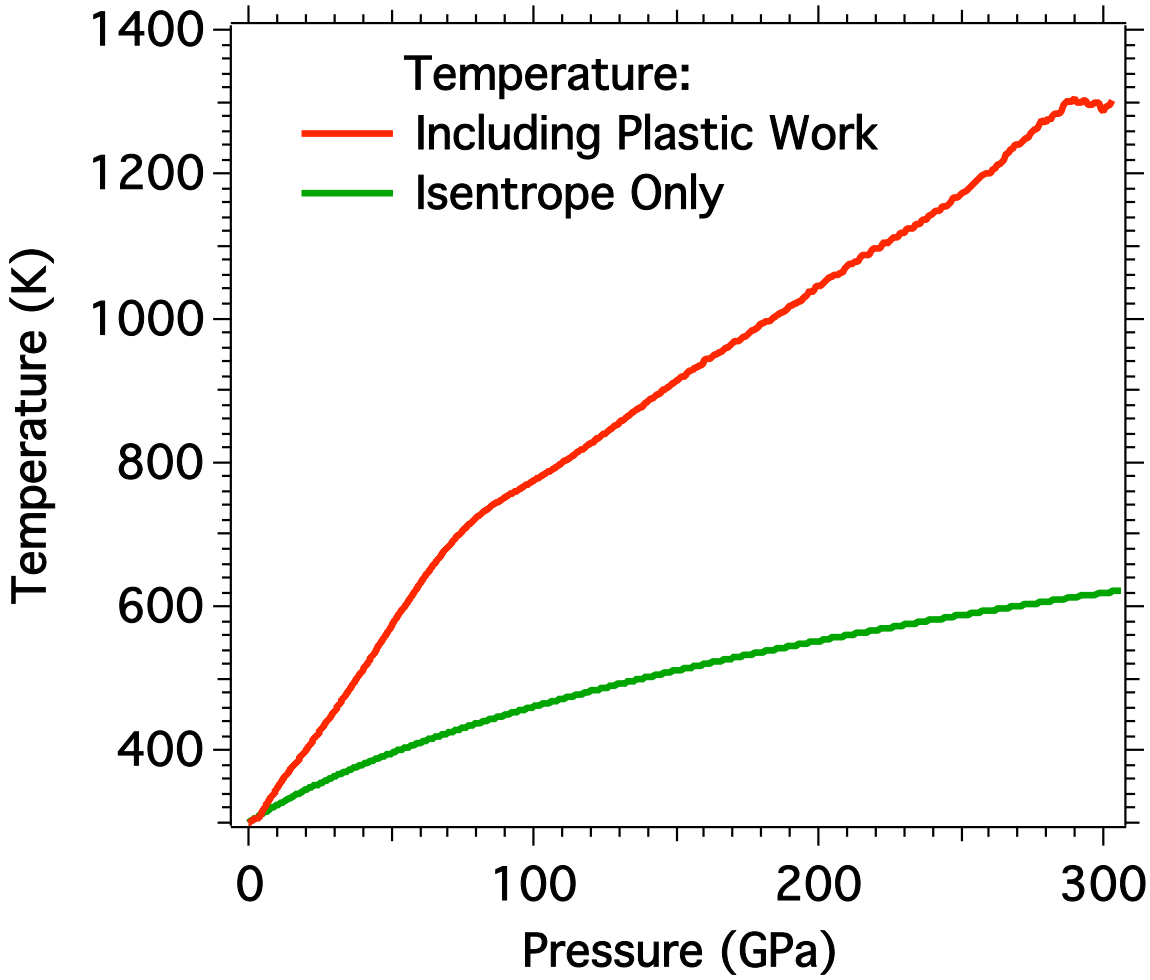
For simplicity, we will compare our with CALE Form 4, EOS 77, and with two sets of DAC isothermal EOS measurements:

Estimate of Strength Used to Calculate Plastic-Work Heating.



Data falls within theoretical bounds on strength. **(Moriarty, 1998)**

We Estimate the Temperature due to Plastic-Work Heating



Assuming Dulong-Petite limit for specific heat. Iterative approach used to correct strength for thermal pressure.

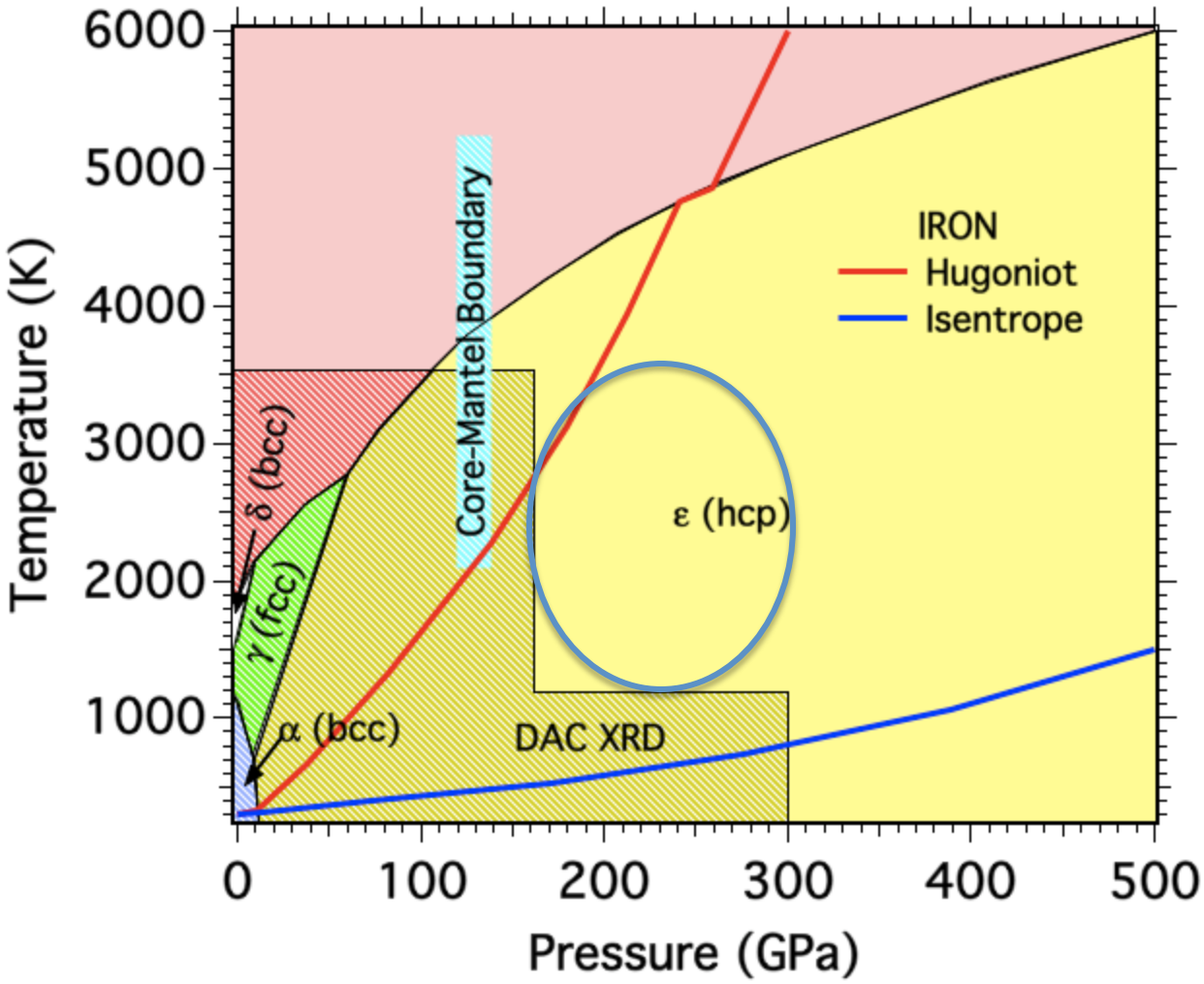
Future Directions

- We are currently working to compress Iron to 300 GPa at Omega.
- Analysis that accounts for kinetics.
- Separation of EOS and strength.
- Determination of crystal structure.
- Temperature determination.

X-Ray Diffraction

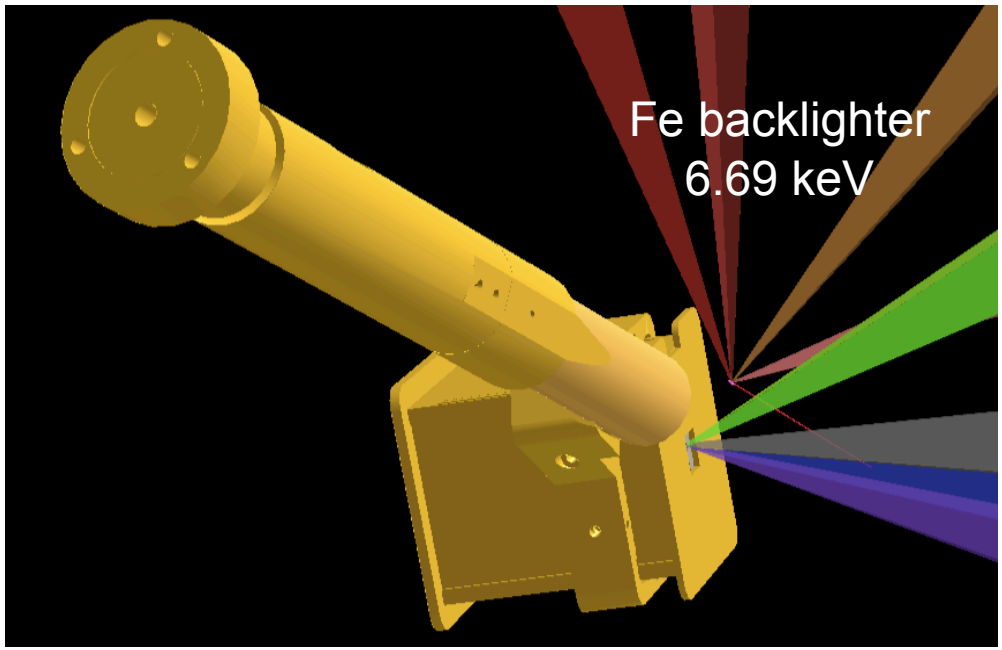
- Diffraction -- Most direct way to determine crystal structure
- Laser Drive -- Ideal for X-ray diagnostics
- Ramp Compression -- limits shock heating, very high pressures in solid phase.

Iron Phase Diagram



- Diffraction above the shock melting pressure?

X-Ray Diffraction at Omega Laser



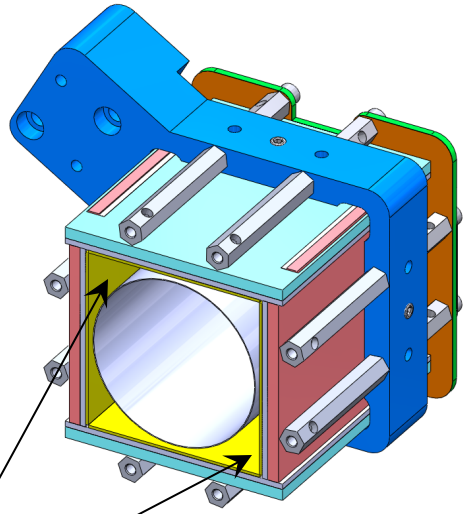
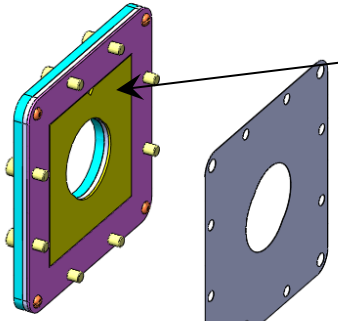
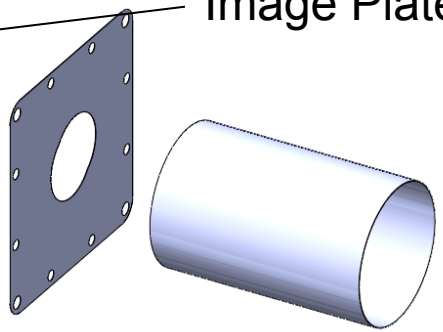


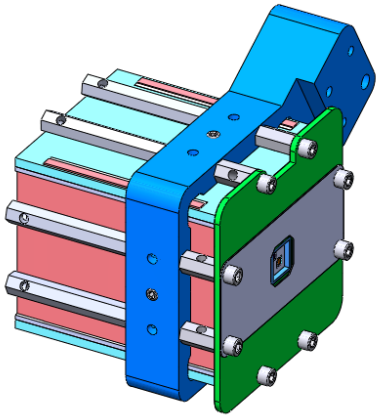
Image Plates



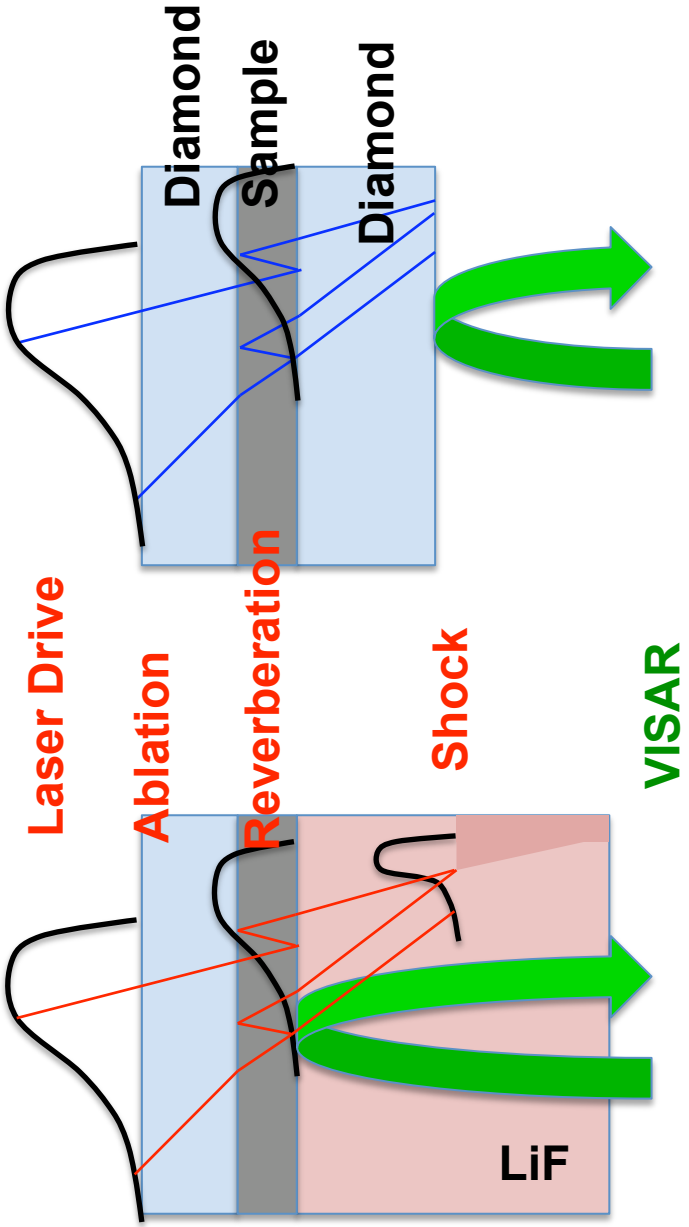
Back Plate



Kapton Shields



Sandwich Ramp-Compression



As long as the sample is hydrodynamically thin, *P* and *u* at the LiF or Diamond interface is the same as in sample

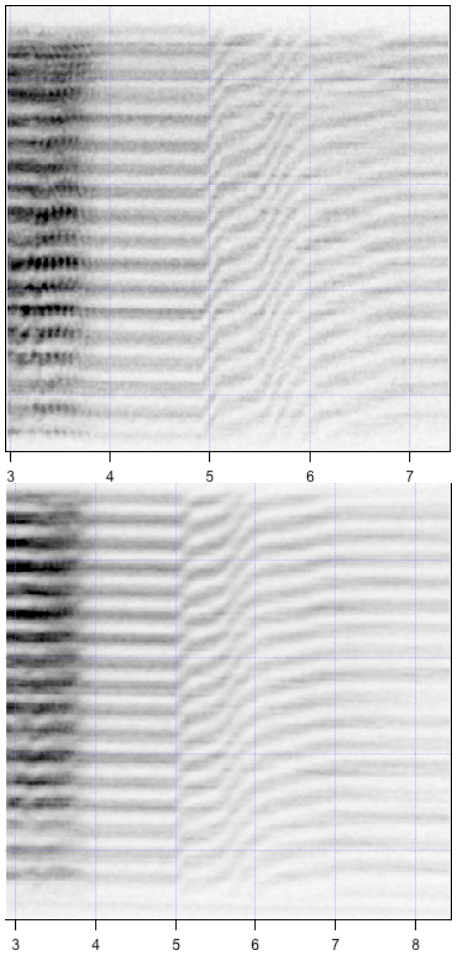
If we know the EOS of LiF or Diamond we can find the Pressure in the sample using the VISAR diagnostic

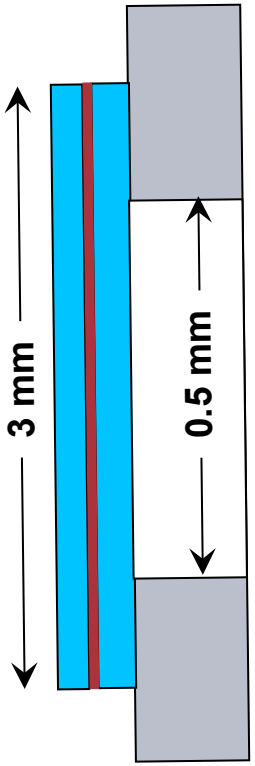
Proof of principle already demonstrated for XRD and XAFS on iron

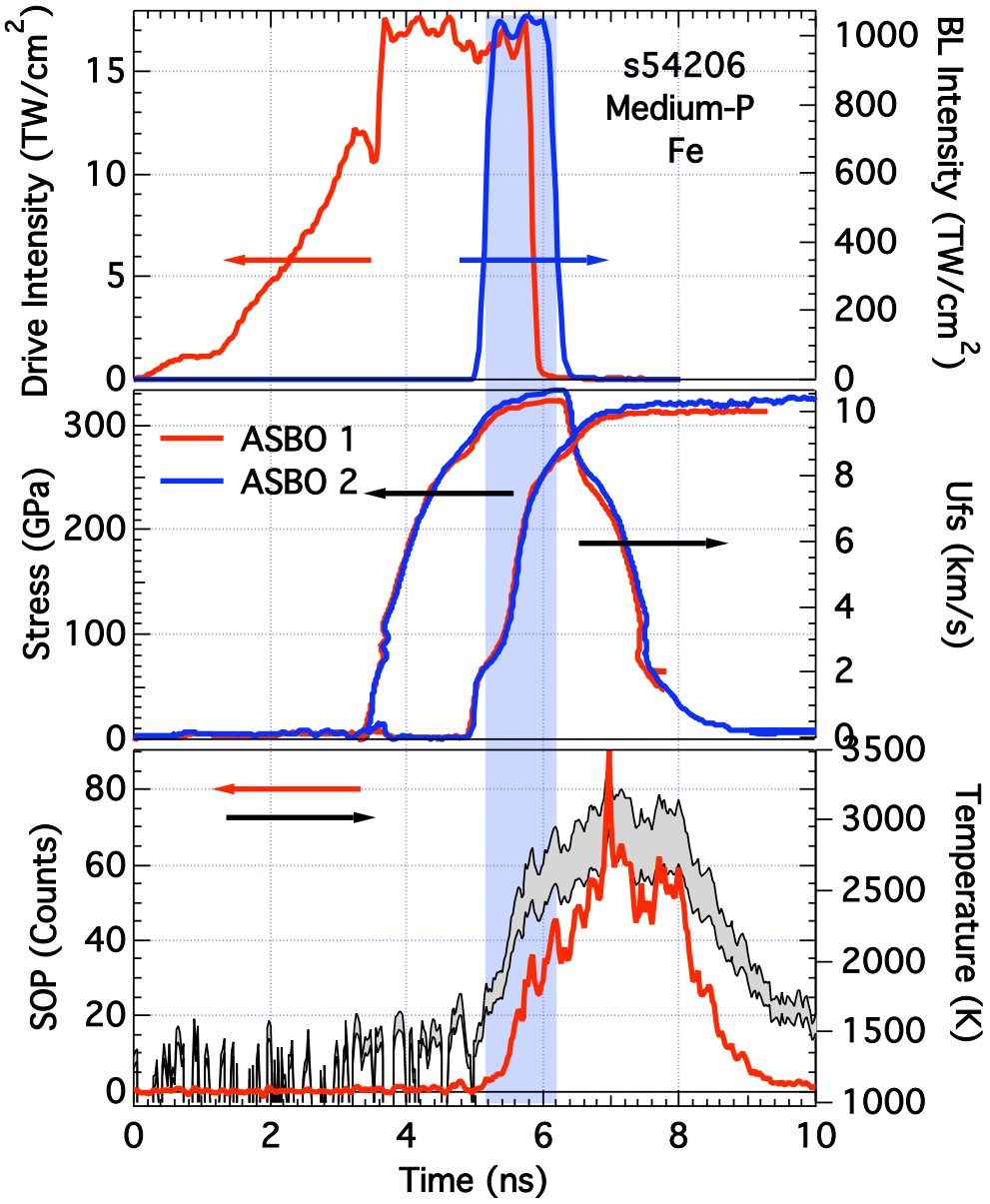
Using this target design, we believe we can ramp compress samples to ~30 Mbar, Hold the state for several ns, Determine the pressure, and Make a measurement.

XRD, XAFS, XANES, Reflectivity, ...
Temperature remains the most important parameter that we do not know how to measure.

s54206, Fe



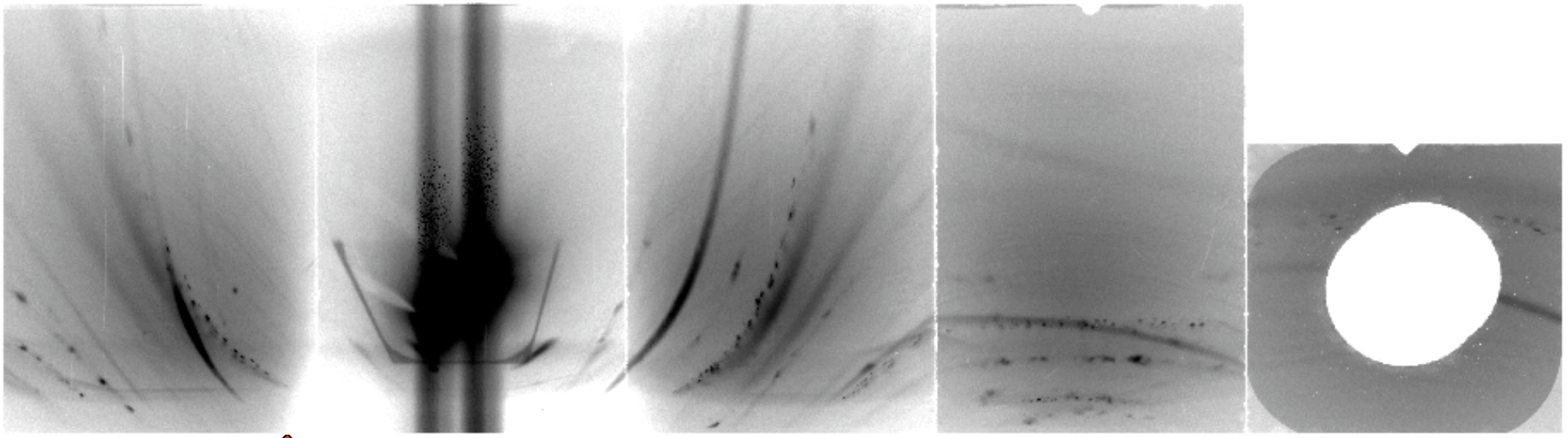




Strain rate is very high, ~10^8 s^{-1}.
Looks like temperature is low.
What does diffraction look like?

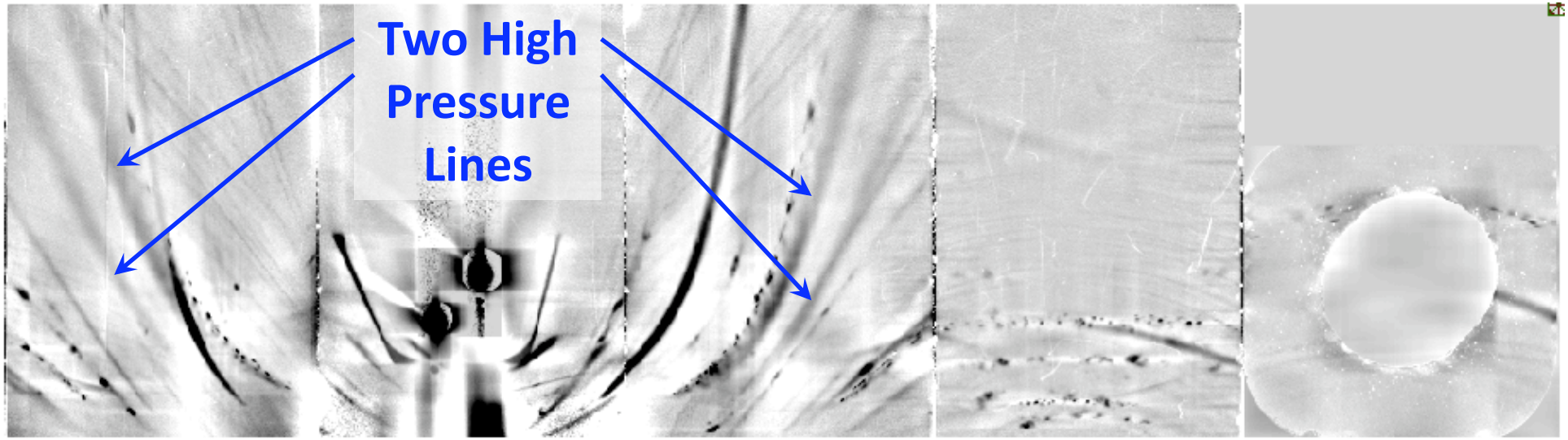
Shot 54203

$$P = 185^{+6}_{-17}\ \text{GPa}$$

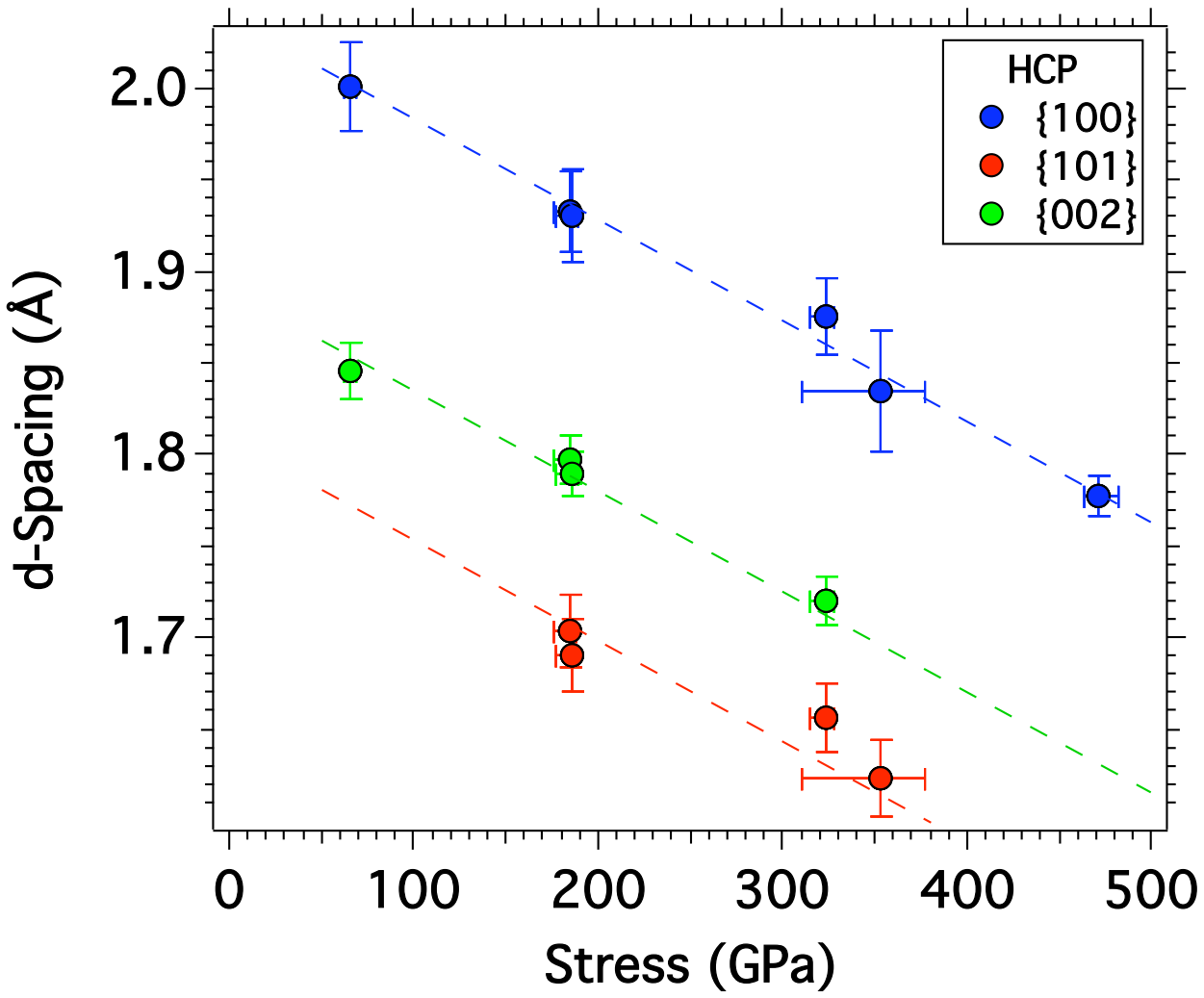


Raw Data

Wavelet-FT Background Subtraction

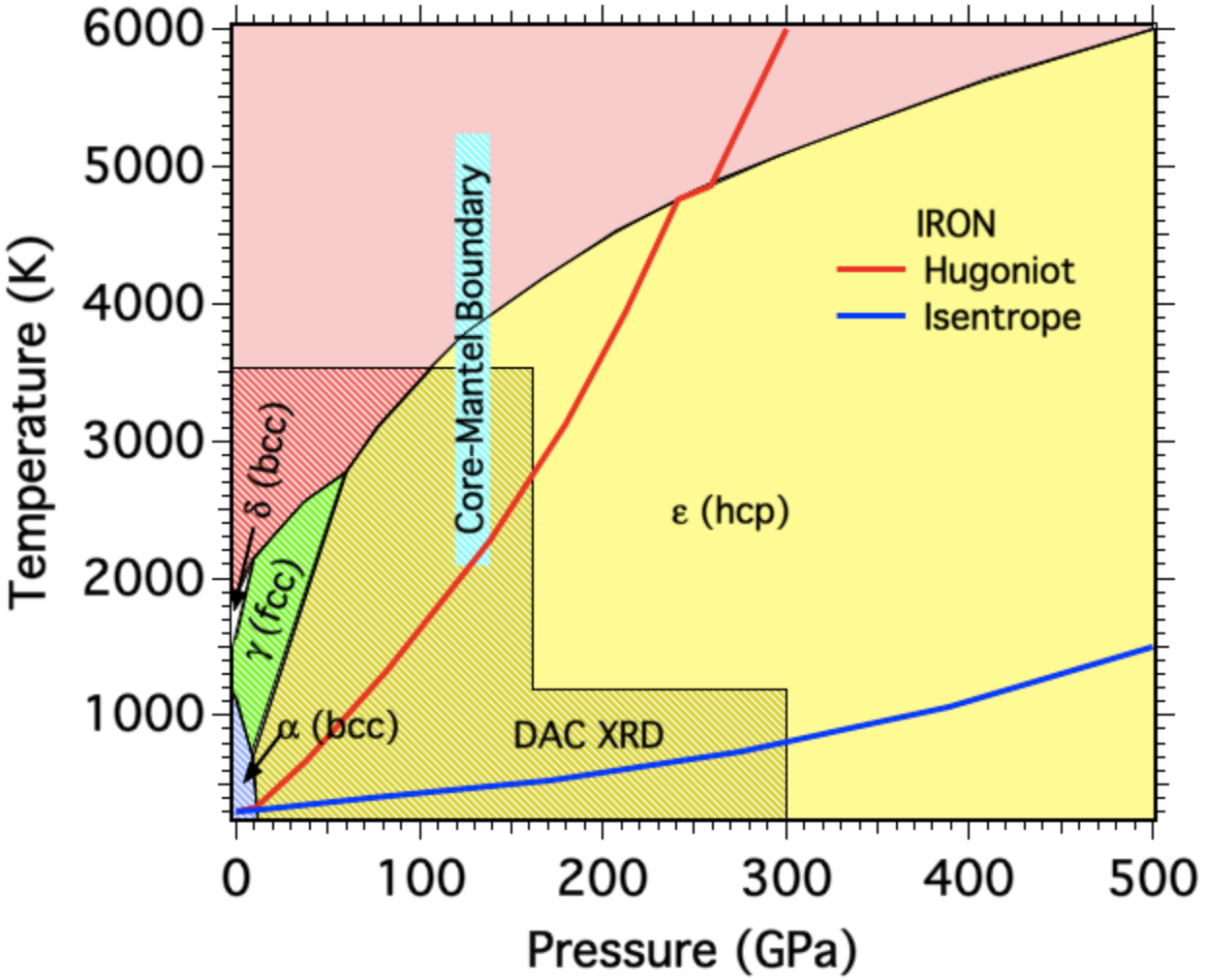


We see 2 strong, 1 weak reflections.



We will *assume* a structure and fit.

Likely Structures: HCP (variable *c/a*), FCC

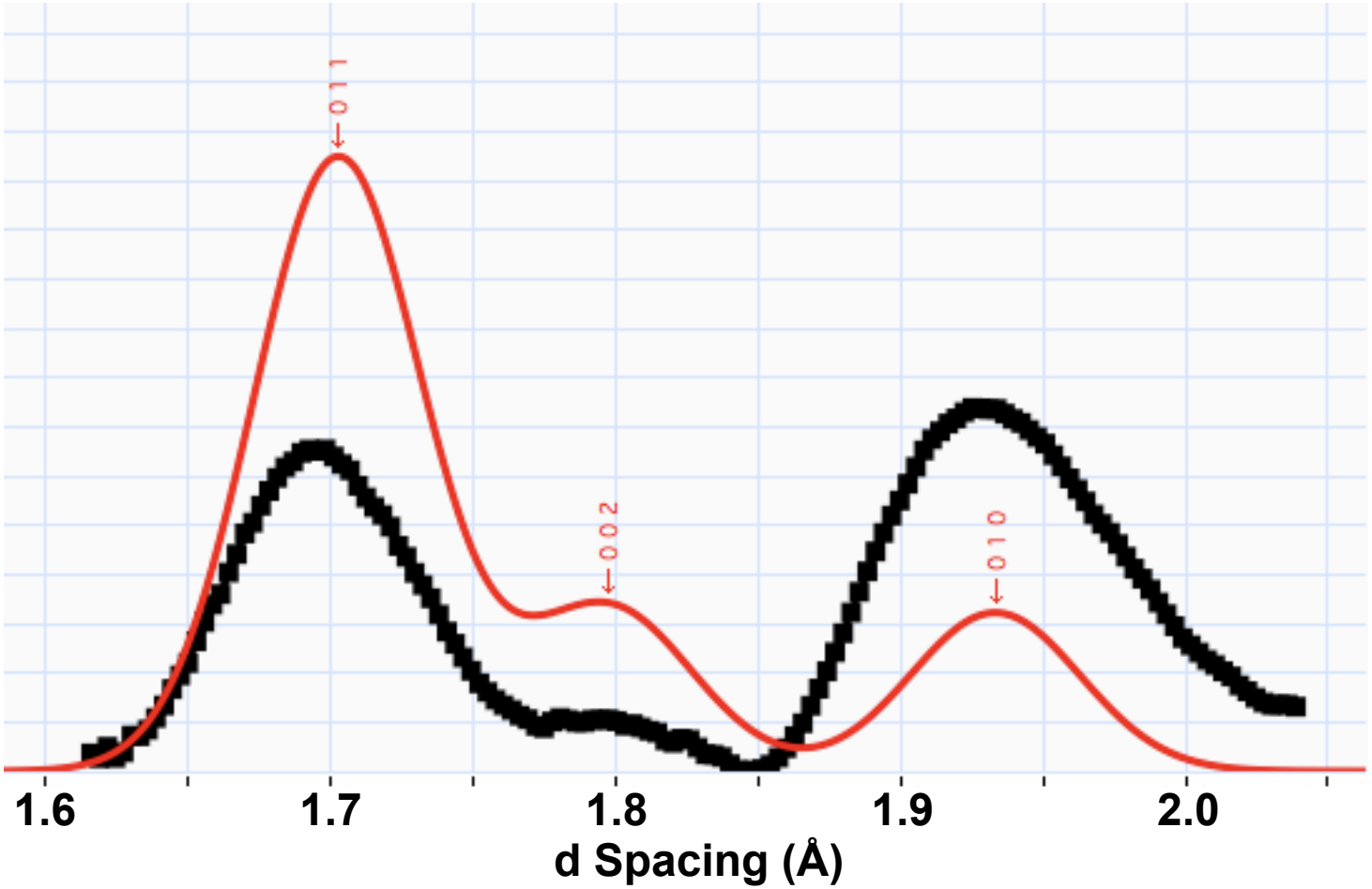


Guided by static experiments, potential structures are hcp with *c/a*=1.61 and fcc. (Ma, et al. 2004)

Previous shock experiments on single crystals found hcp (c/a=1.73) (Kalantar, et al. 2005)

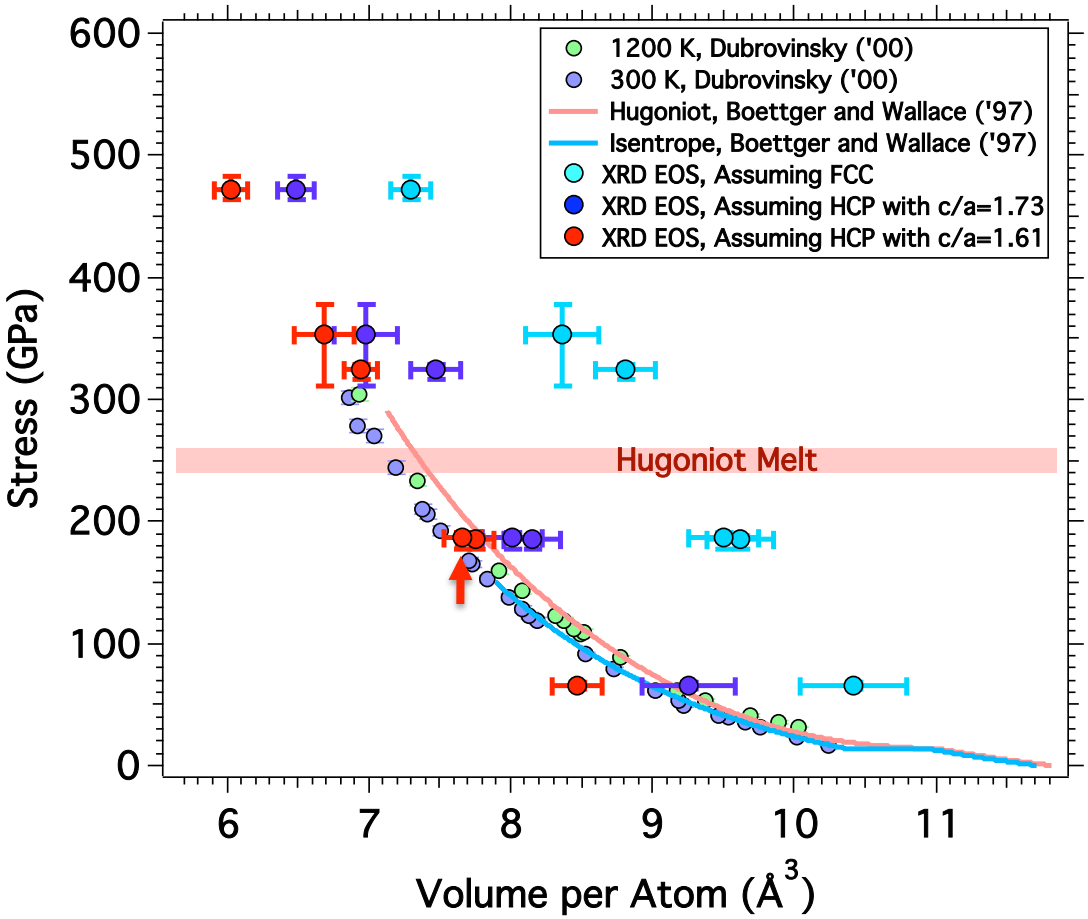
Best Fit Assuming HCP, c/a = 1.61

As observed in DAC experiments



Triplet, peak positions fit well for this shot, but significant basal texture required to get agreement with doublet structure observed.

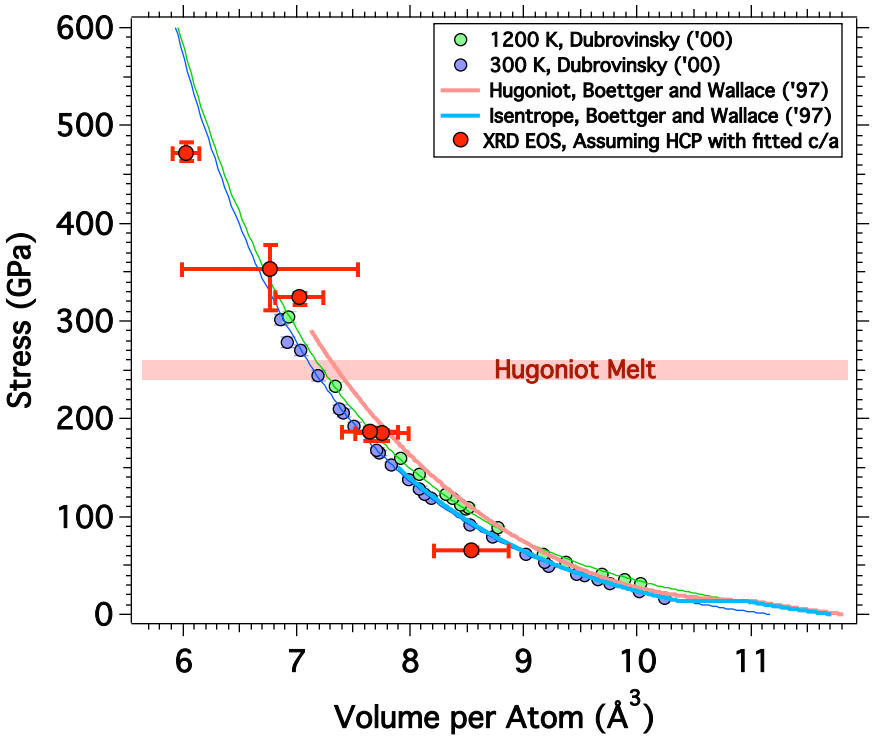
Results and Comparison

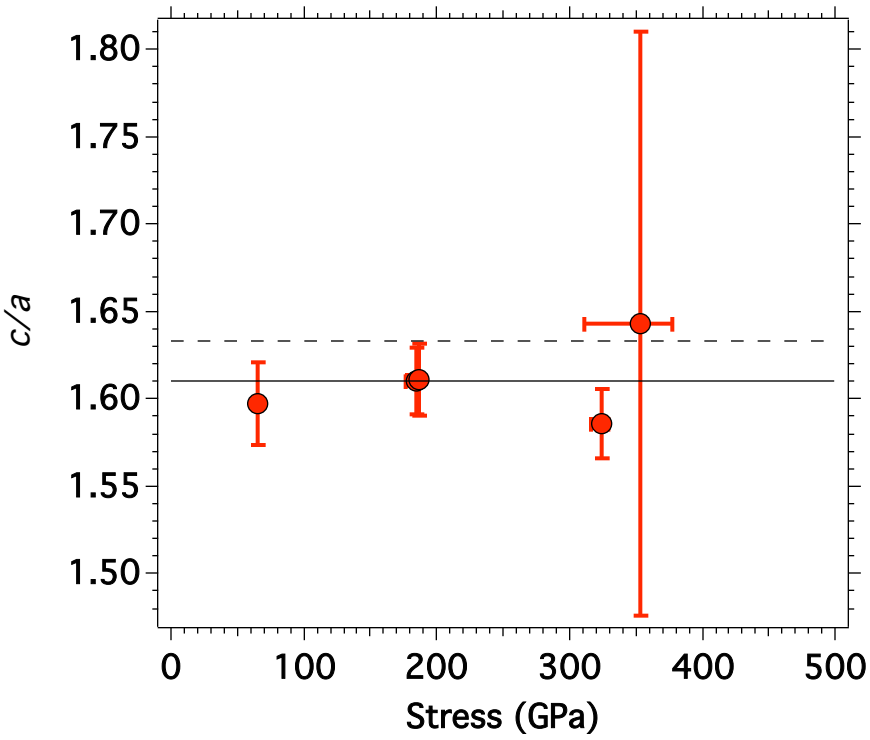


Diffraction on *solid* Fe to 472 GPa

- **Highest pressure X-ray diffraction ever.**
- **Far above Hugoniot melt (~250 GPa).**
- **Structure appears to be HCP with *c/a*~1.61.**
- **More analyses / experiments still needed.**

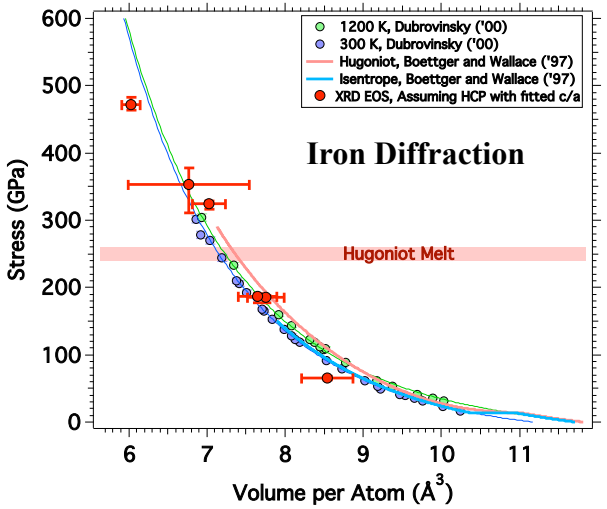
We can also fit *c/a* ratio

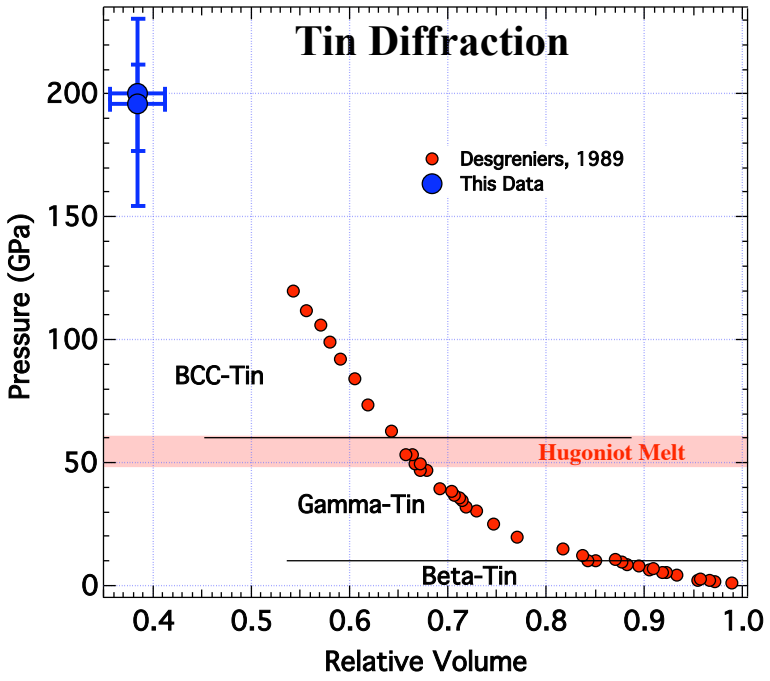


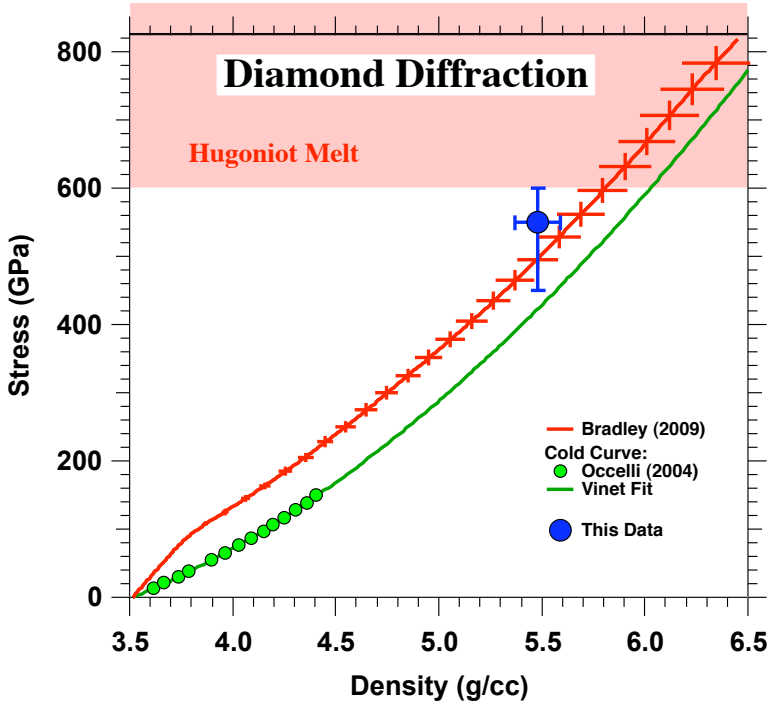


Our data is in good agreement with previous static data: *c/a* = 1.61 (Ma, et al. 2004).

We have also measured Tin and Diamond







X-ray Diffraction

- **Highest pressure diffraction data ever recorded.**
- **Far above Hugoniot melt for Irong (250 GPa).**

Future Directions

- **Higher pressure.**
- **More diffraction lines.**
- **More accurate temperature determination.**

DACs in the ’80s ⟺ Laser Compression in the 00’s

DACs	Lasers
Ruby Calibration (Pressure, Temperature)	Quartz Calibration (Pressure, Temperature, Reflectivity)
Raman and Visible Spectroscopy	VISAR
X-ray Diffraction (energy dispersive)	X-ray Diffraction (angle dispersive)

The last 20 years have seen fantastic advances in DAC techniques, measurements, and diagnostics.

Our biggest challenge is to make similar progress in the next 20 years on laser-compression experiments.

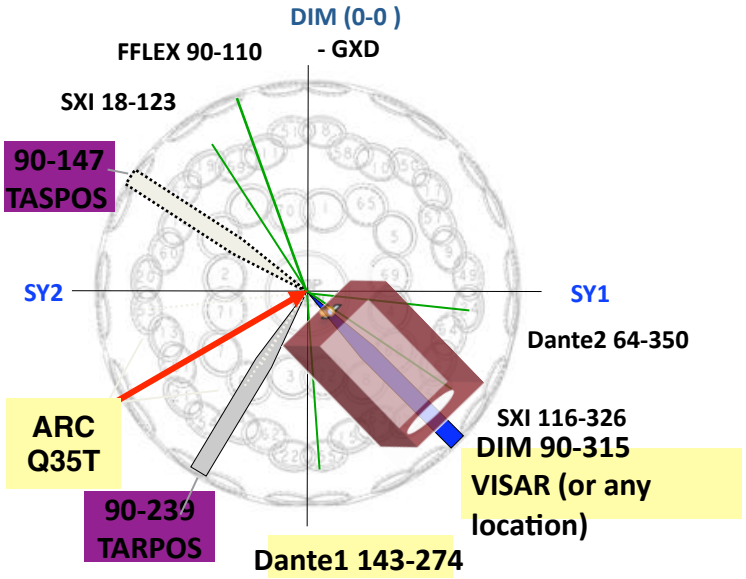
The most important experimental advance will be the ability to produce a uniform sample state and perform in-situ measurments.

Unfortunately, transparent windows are needed (although LiF is transparent to at least 900 GPa under ramp compression).

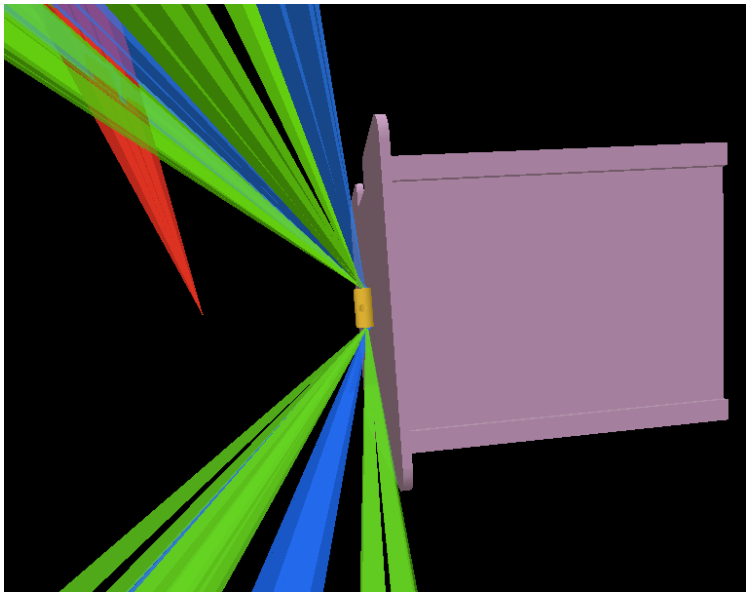
Temperature diagnostics are critically needed (EXAFS?).

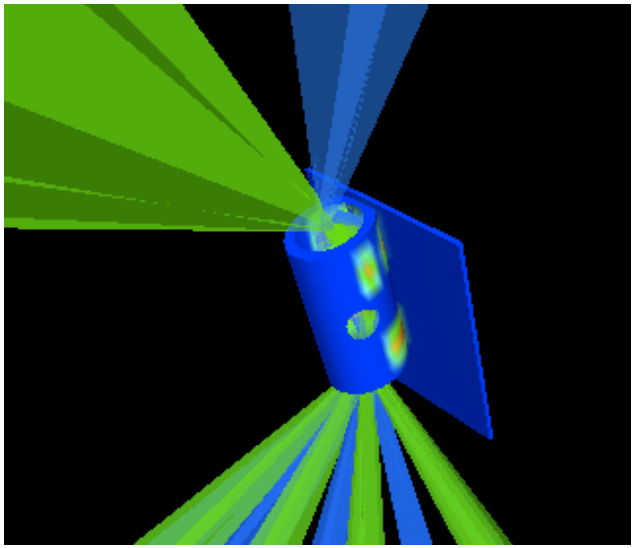
On to the NIF

We Have a Concept for Xray Diffraction on the NIF



Experiment Layout - Target Chamber (Top View)





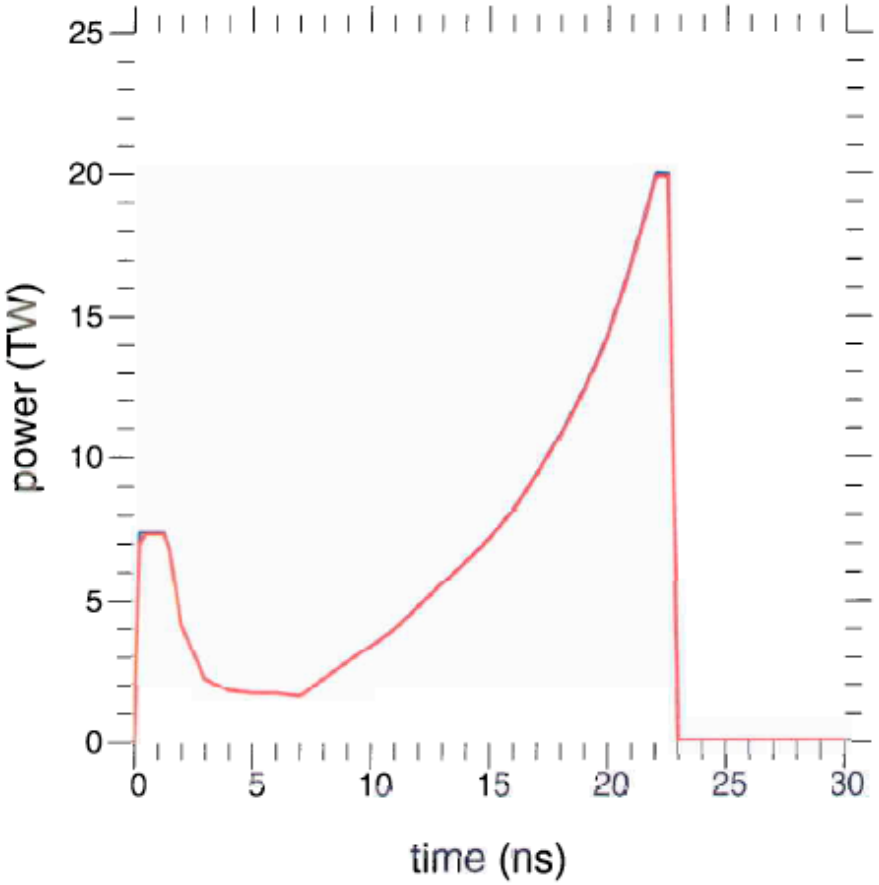
Hohlraum: 60 beams from top and bottom using quads, Q12T, Q16T, Q34T, Q43T, Q44T, Q45T, Q46T, Q11B, Q12B, Q35B, Q36B, Q41B, Q43B, Q45B, Q46B.

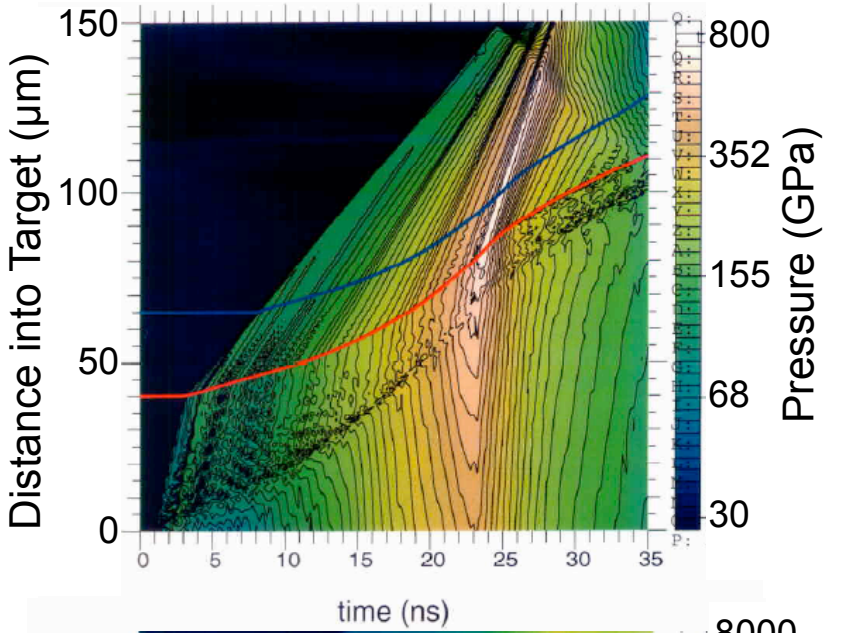
Plus ARC, Q35T

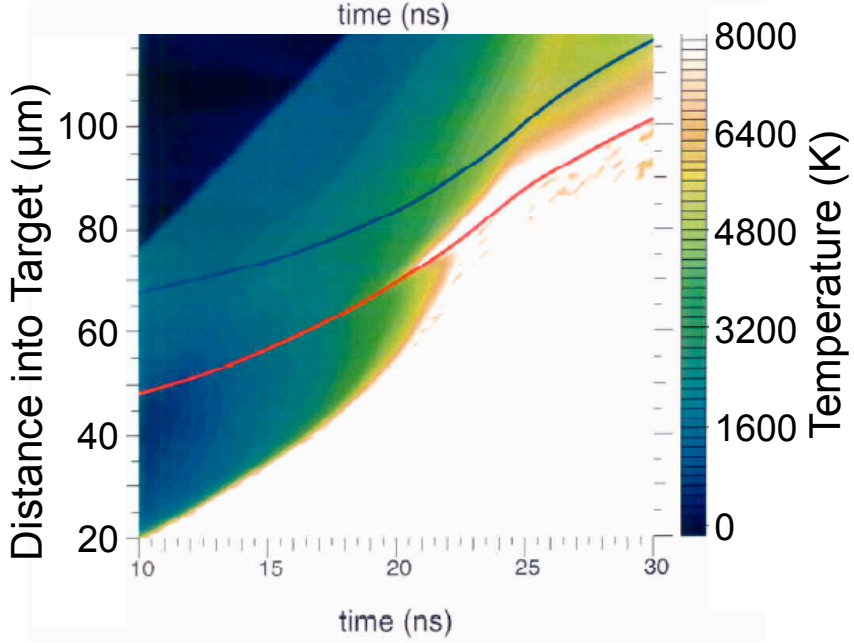
Visar is pointed at TCC.

8 Mbar Ta EOS Point Design for the NIF

Designer: Dave Braun

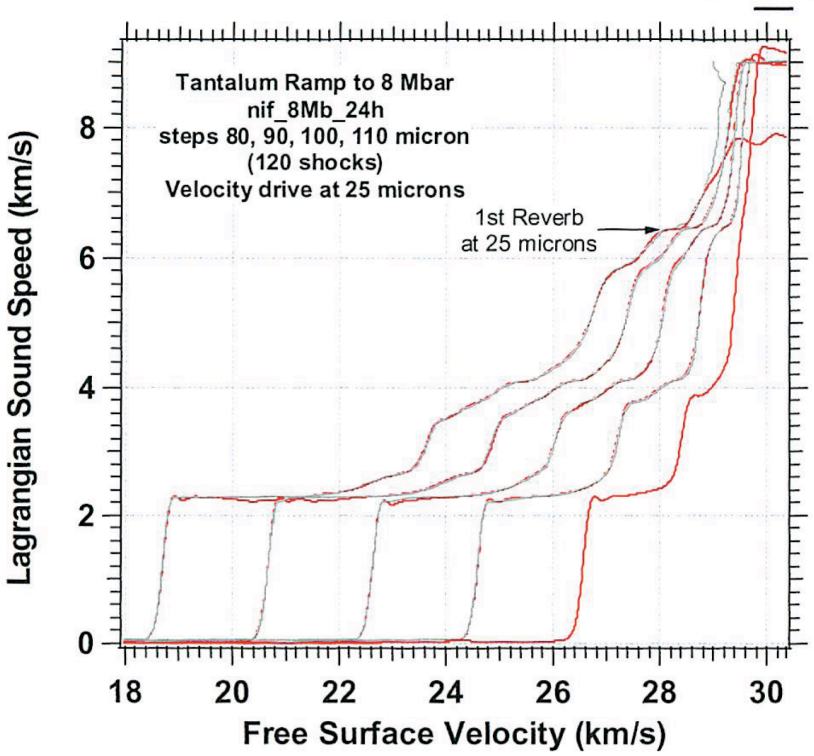


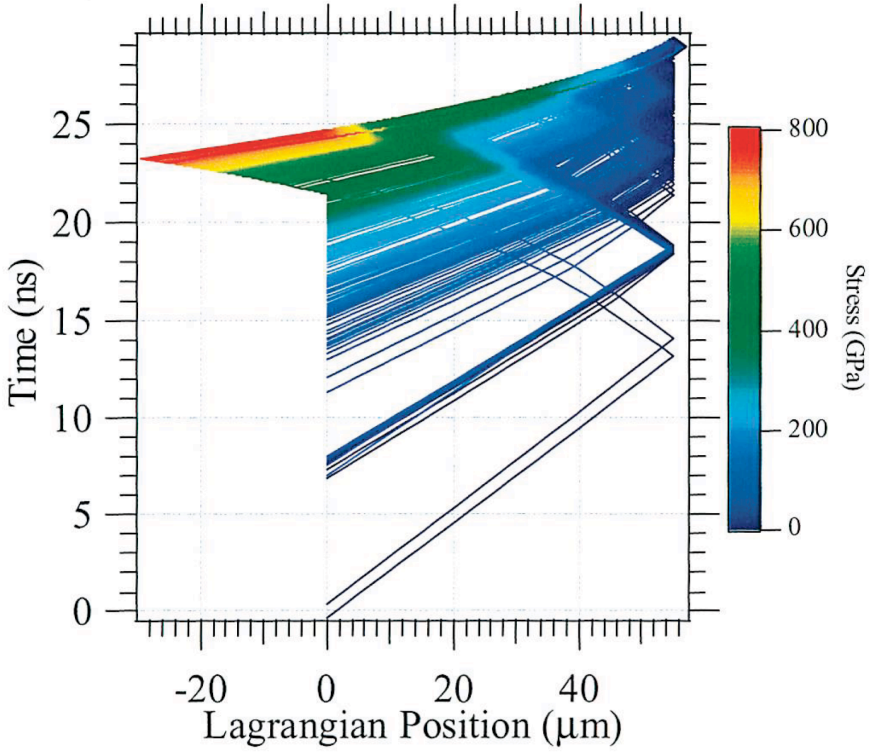




We have a design for an 8Mbar drive for tantalum on NIF using less than 200 kJ of power. We will use this design this spring.

Tantalum Ramp to 8 Mbar
nif_8Mb24h

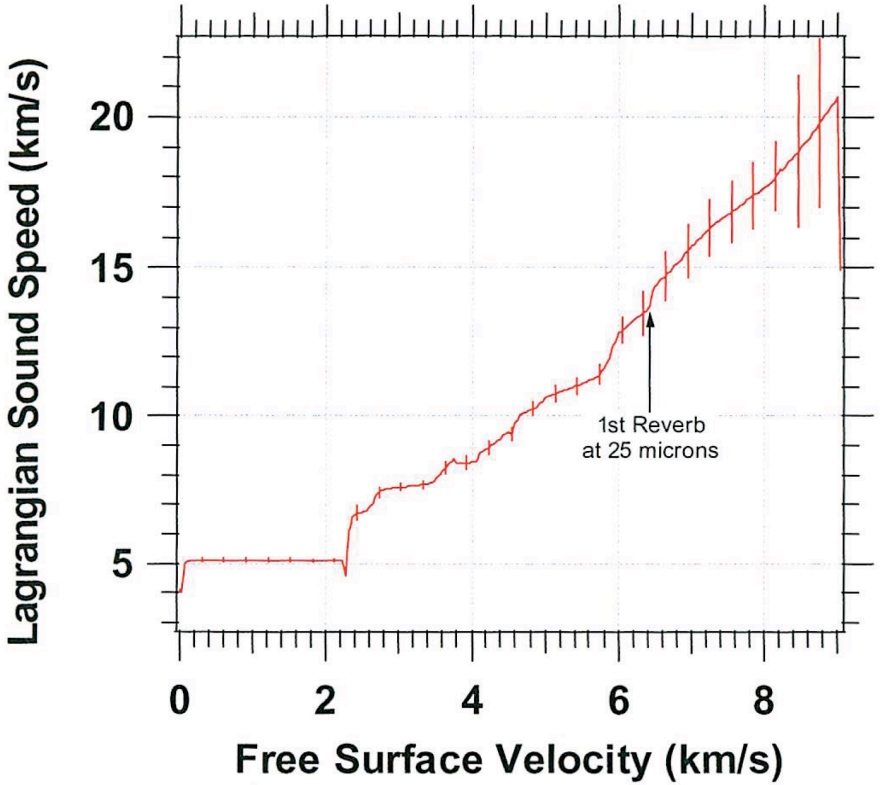


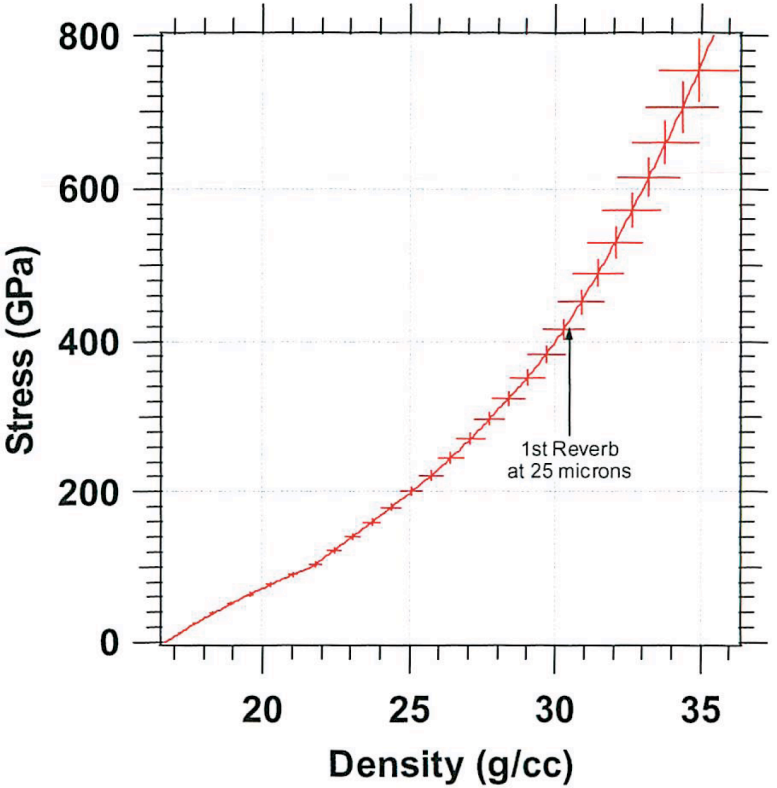


Velocity drive is at 25 microns so 80 micron step has reverb at 55. Note that the 80 reverb goes back to –25 microns so that only the 90 micron thick step will avoid reverbs.

Thus, we should use this drive with 80, 90, 100, and 110 micron steps. These are the steps I used in the analysis.

Tantalum Ramp to 8 Mbar
nif_8Mb24h





Red curve is this analysis using errors of 0.03 km/s, 50 ps, and 100 nm. Reverberations are marked at the 25 micron position, Steps used are 80, 90, 100, and 110 microns.

We believe that we can achieve better than 6% uncertainty in a single NIF shot to 800 GPa.

Conclusions

Ramp Compression Tantalum Equation of State

- **Stress-density on 8 shots to over 300 GPa.**
- **Very consistent with previous Z shots.**

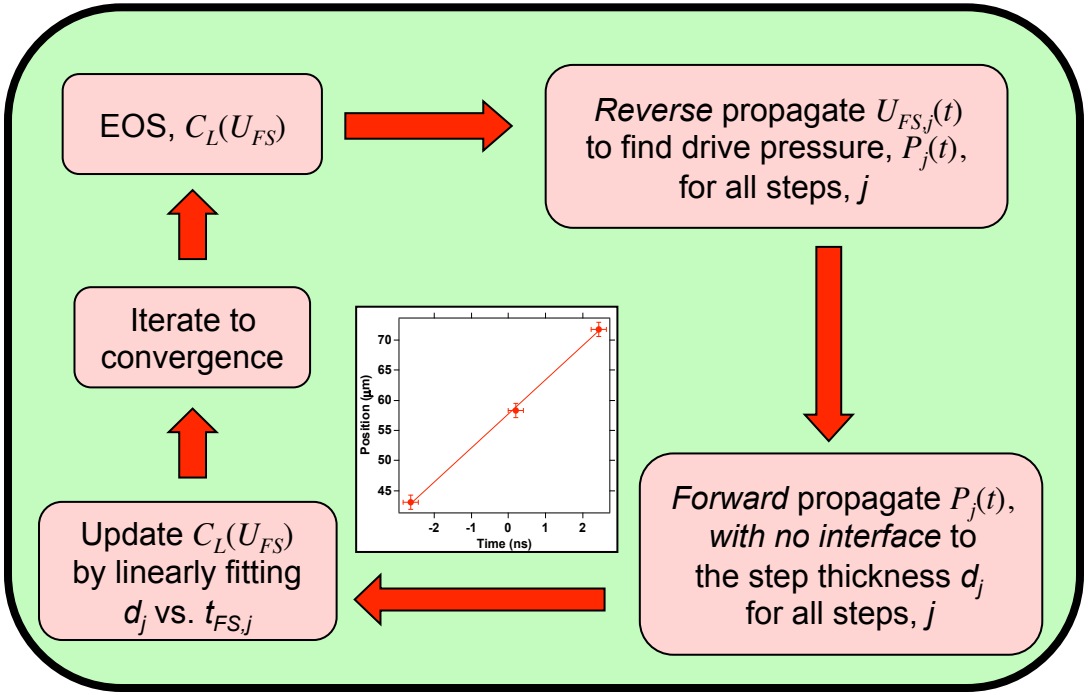
Next Year: NIF experiments to 500 GPa and more . . .

Diffraction on *solid* Fe to 470 GPa

- **Highest pressure X-ray diffraction ever.**
- **Far above Hugoniot melt (~250 GPa).**
- **Structure appears to be HCP.**
- **More analyses / experiments still needed.**

No obvious limit on pressure

Shortcomings of current analyses



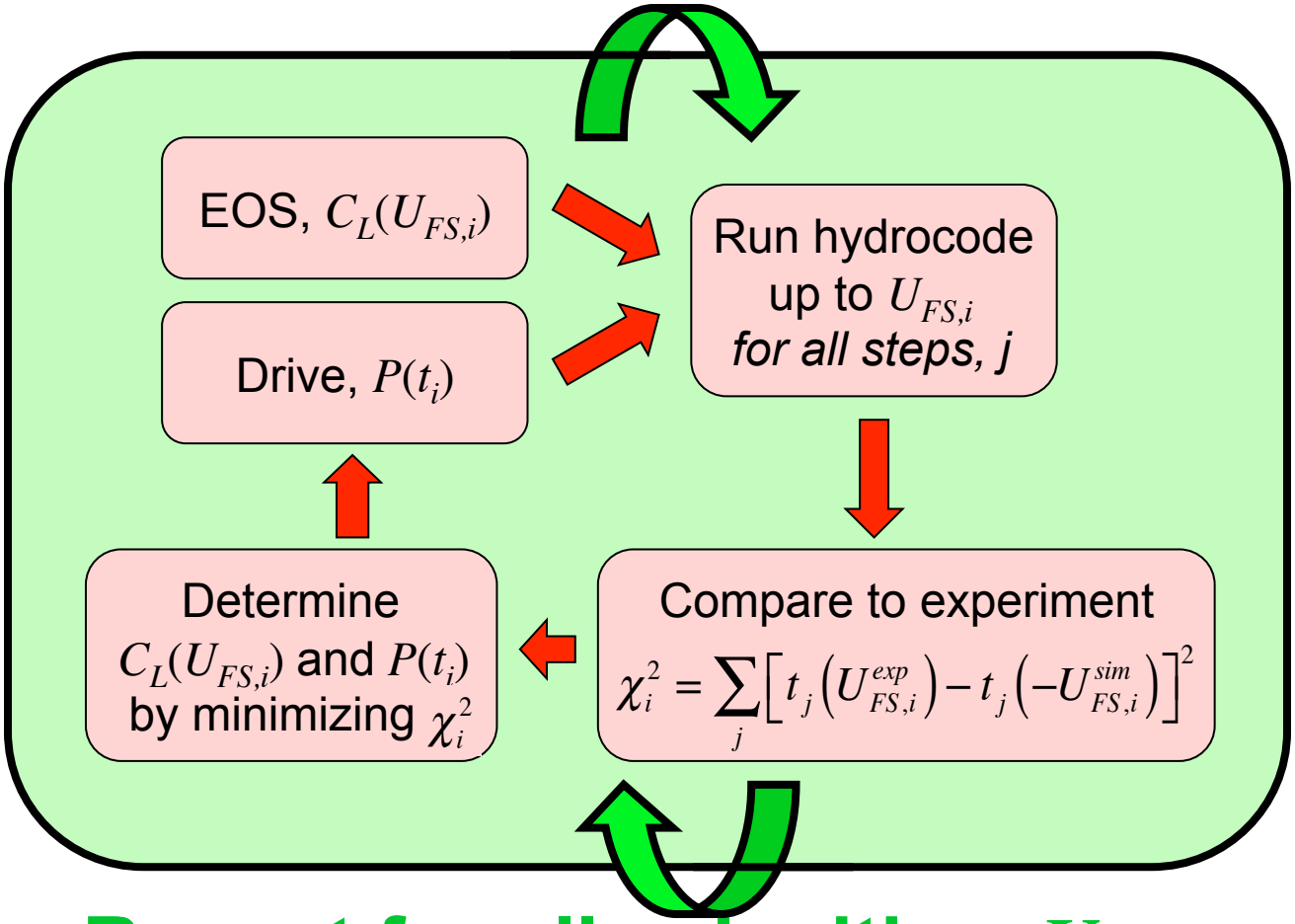
Current method requires *both* reverse and forward propagation steps.

Shocks are created by phase transitions.

Phase transtions and EP transitions both require time-dependent analysis.

We need to develop a forward only analysis method

We are developing a Forward-Only Analysis Method



Repeat for all velocities, $U_{FS,i}$

- **This method still requires a model for time-dependent phase transitions.**
- **Exact methods being developed by Evan Reed and by Bryan Reed potentially offer a very attractive alternative.**

Iterative Analysis:
Correction for free-surface wave interactions.

Rothman, et al. J. Phys. D (2005)

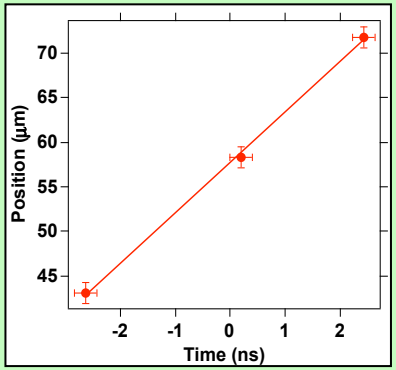
EOS, $C_L(U_{FS})$

Reverse propagate $U_{FS,j}(t)$ to find drive pressure, $P_j(t)$, for all steps, *j*

Forward propagate $P_j(t)$, *with no interface* to the step thickness d_j for all steps, *j*

Update $C_L(U_{FS})$ by linearly fitting d_j vs. $t_{FS,j}$

Iterate to convergence



Absolute Stress-Density Measurement