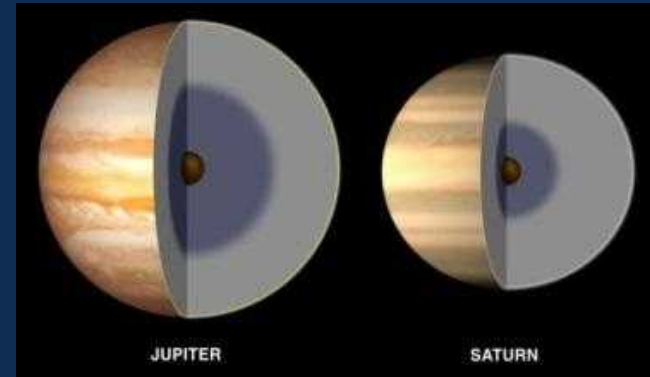
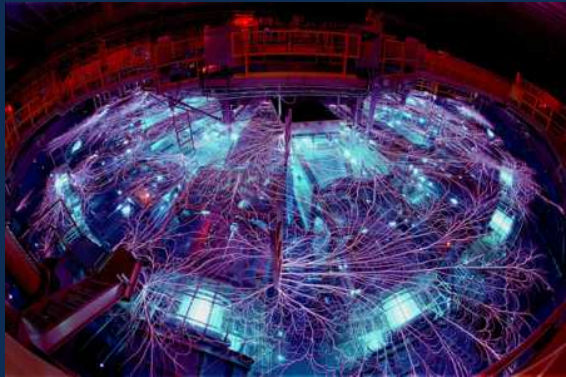


Exceptional service in the national interest



Probing off-Hugoniot states in Ta, Cu, and Al to 10 Mbar compression with magnetically driven liner implosions

SAND2016-NNNN C

T.R. Mattsson, R. W. Lemke, D. H. Dolan, D. G. Dalton, J. L. Brown, G. R. Robertson, M. D. Knudson, E. Harding, A. E. Mattsson, J. H. Carpenter, R. R. Drake, K. Cochran, and A. C. Robinson - Sandia National Laboratories ABQ, NM
K. Tomlinson and B.E. Blue – General Atomics, San Diego CA.



Sandia National Laboratories is a multi-program 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.

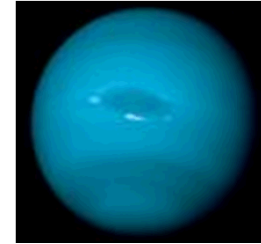
Properties of matter under High Energy Density (HED) conditions are important to geophysical problems

- Planetary science – Jupiter, Saturn, Uranus, Neptune, and exo planets [e.g. hot Neptunes]
 - Water -2005-2012: 2 PRLs and 2 PRBs
 - Metallization of hydrogen/deuterium: SCIENCE 2015

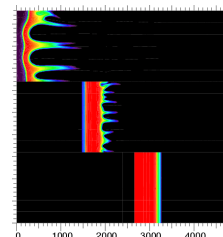
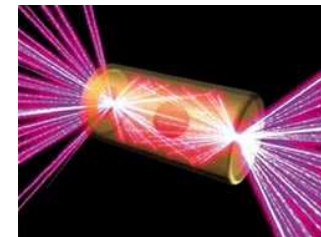
- Planetary science – earths and super-earths
 - Silicates, MgO, and iron/iron alloys
 - Determining the vaporization threshold for iron – and implications for planetary formation, Nature Geoscience 2015

- Materials for Stockpile Stewardship, HED and inertial confinement fusion (ICF)
 - Investigating the periodic table from Aluminum to Zirconium: a broad range of materials are of interest

- **Another breakthrough would be to ramp compress solids to 10 Mbar (MgSiO system for super-earths)**



We turn planetary science *quantitative* by high fidelity modeling and high-precision experiments

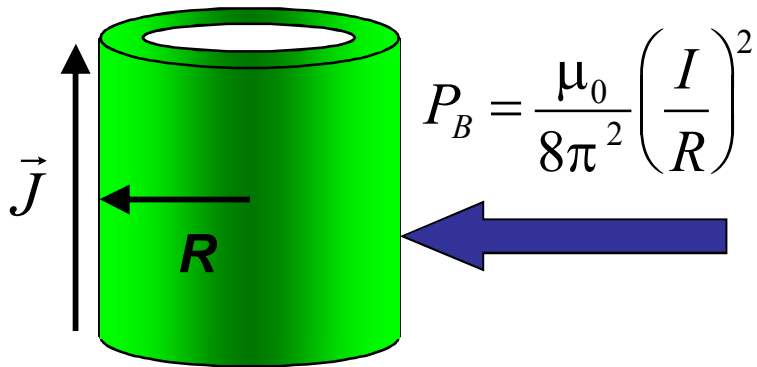


ICF concepts: laser driven hohlraum and MagLIF

How to achieve that?

Quasi-isentropic compression to peak stress of 20 Mbar is possible in cylindrical liner implosions on Z

Liner Z-Pinch Implosion

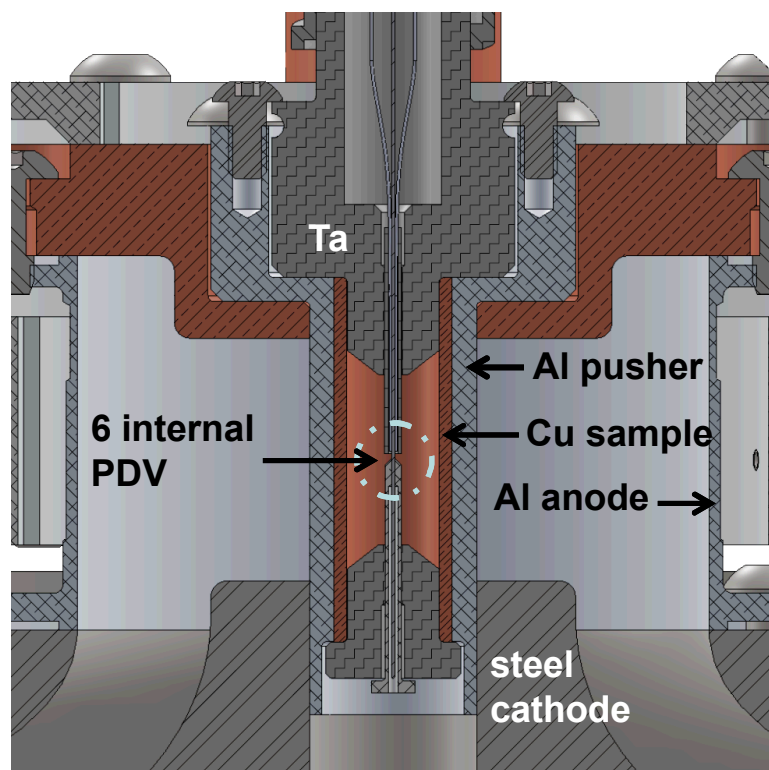


$I=20$ MA; $R=0.1$ cm;
 $P_B \approx 64$ Mbar.

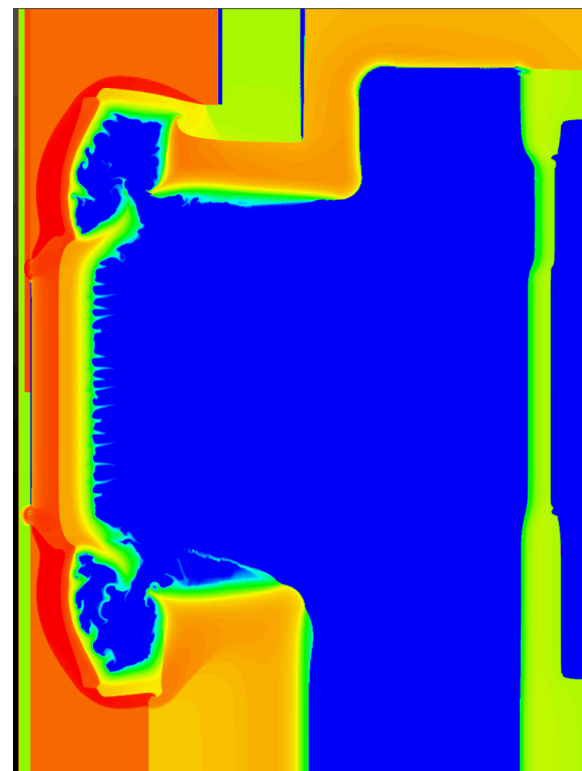
- Magnetic pressure drives stress in the sample.
- Shockless compression achieved by shaping current.
- 3-4 times greater stress than in planar geometry.
- Compressed state of sample diagnosed with Photon Doppler Velocimetry (PDV).
- Principal isentrope of sample inferred using ensemble of velocimetry measurements.
- New optimization based equation of state (EOS) calibration technique used.
- *We have diagnosed compression to ~10 Mbar in Ta, Cu and Al.*

Cylindrical ramp experiment on Z with Cu sample: Six internal PDV probes; 6 external anode can probes, 5 VISAR and 1 PDV

Schematic Al/Cu Cylindrical Experiment



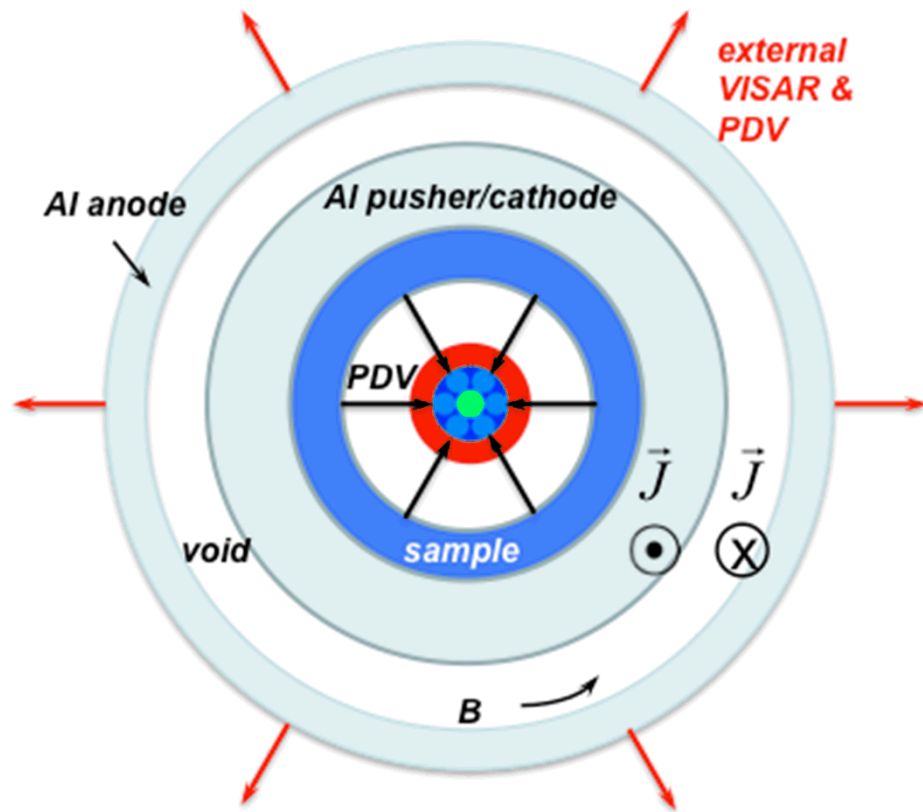
ALEGRA 2D MHD simulation Al/Cu cylindrical ramp experiment: relative density.



Details of PDV diagnostic in D. H. Dolan et al., Rev. Sci. Instrum. **84**, 055102 (2013).

Cylindrical ramp loading experiment: velocimetry data used to infer off-Hugoniot pressure & density

Cylindrical quasi-isentropic compression experiment.



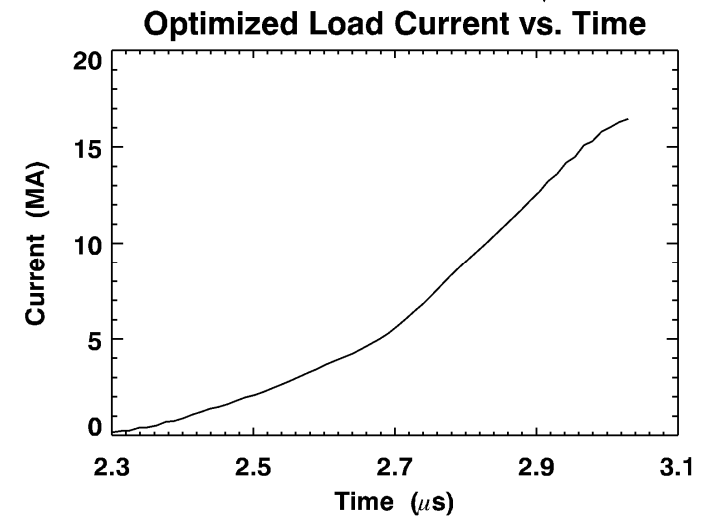
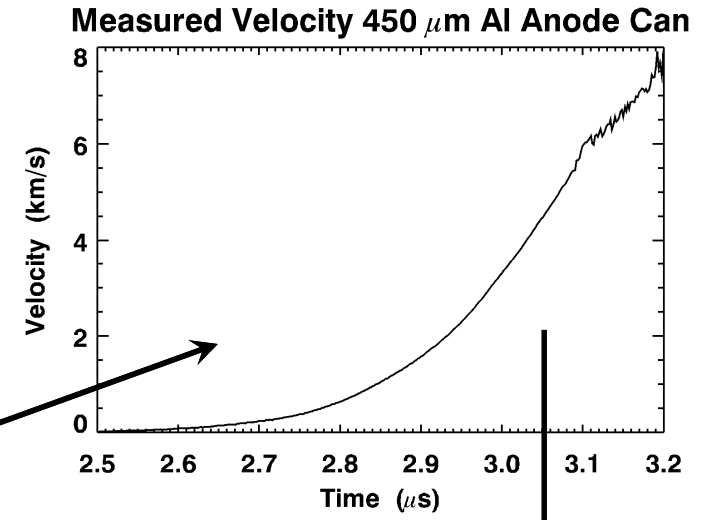
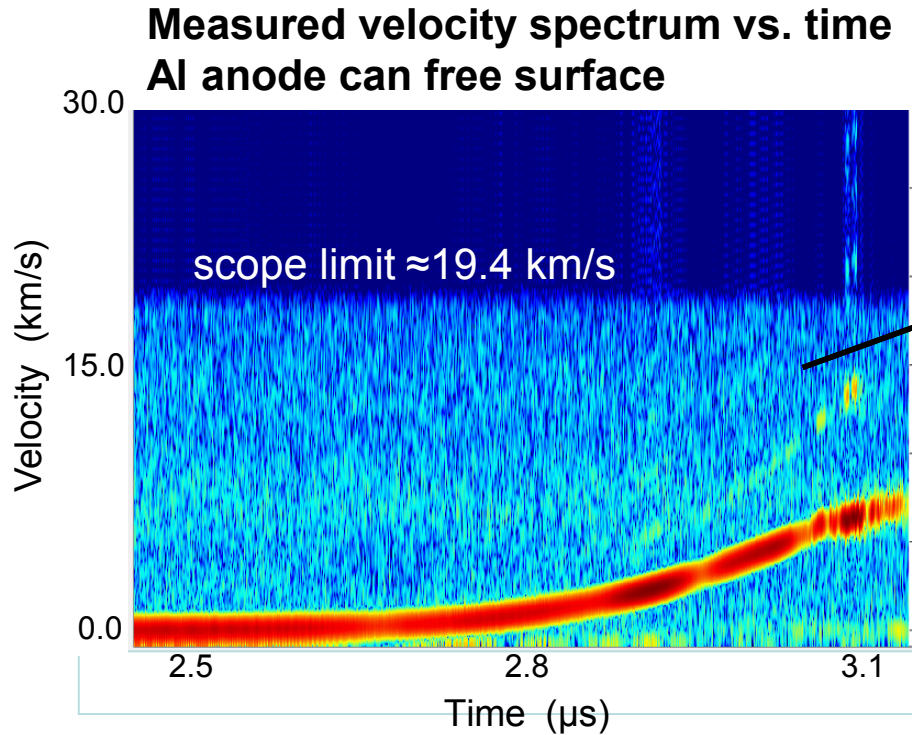
- Pressure and density in sample inferred from velocimetry data + MHD code + mathematical optimization.
 - Precise current drive measurement from *external VISAR* and MHD optimization.
 - *Internal PDV* measures velocity sample free surface.
 - *EOS calibration technique* based on MHD-optimization:
 - 1) *Parameterize sample EOS in MHD simulation;*
 - 2) *Optimization determines EOS parameter values that produce sample free surface velocity.*

ALEGRA MHD and DAKOTA codes central to optimization based EOS calibration method

- **ALEGRA is a 2D/3D arbitrary Lagrangian-Eulerian radiation MHD code developed at SNL (<http://arc.aiaa.org/doi/abs/10.2514/6.2008-1235>).**
 - *Resistive MHD with state-of-the-art electrical conductivity models.*
 - *Large selection of EOS and constitutive models.*
 - *Validated MHD models for Al and Cu flyer plates.*
 - *Demonstrated predictive capability for experiments; flyer plates, planar ICE, strength, solid liner z-pinch.*

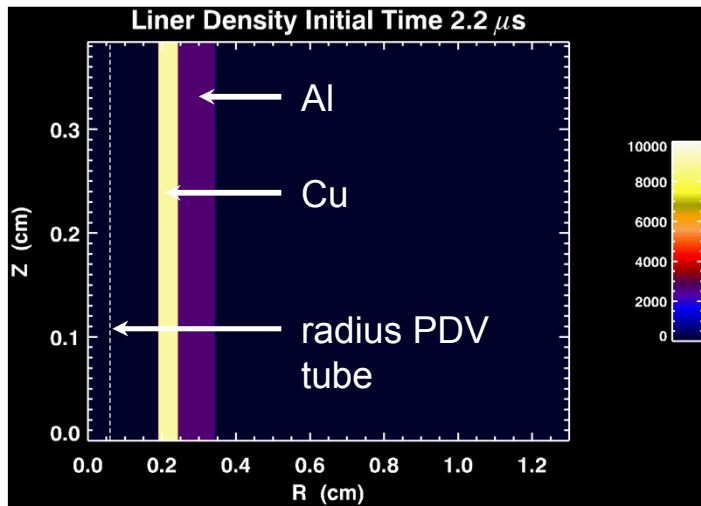
- **DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) developed at SNL (<http://dakota.sandia.gov>).**
 - *Optimization, UQ, parameter estimation and sensitivity analysis.*
 - *Used extensively to design dynamic materials experiments on Z.*

External PDV probe measures free surface velocity Al anode; used with ALEGRA-DAKOTA to obtain load current



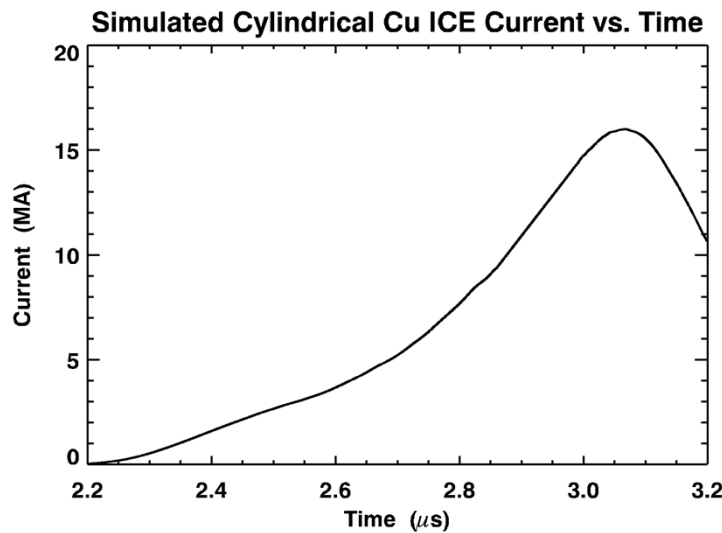
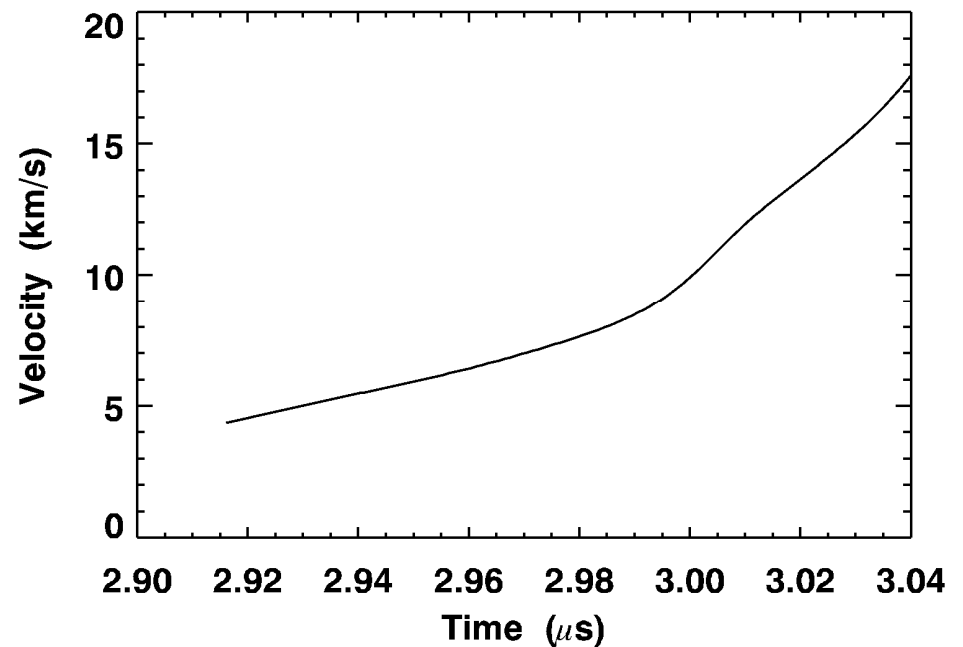
This is a standard way of measuring current – it has a long history on Z.

Simulated cylindrical experiment with Cu sample uses tabular EOS to produce PDV velocity data



Alegra 1D Lagrangian 1 μ m resolution;
Cu inner (outer) radius 1.9 mm (2.43 mm);
Al pusher thickness 1200 μ m.

Simulated PDV Velocity Cu Sample

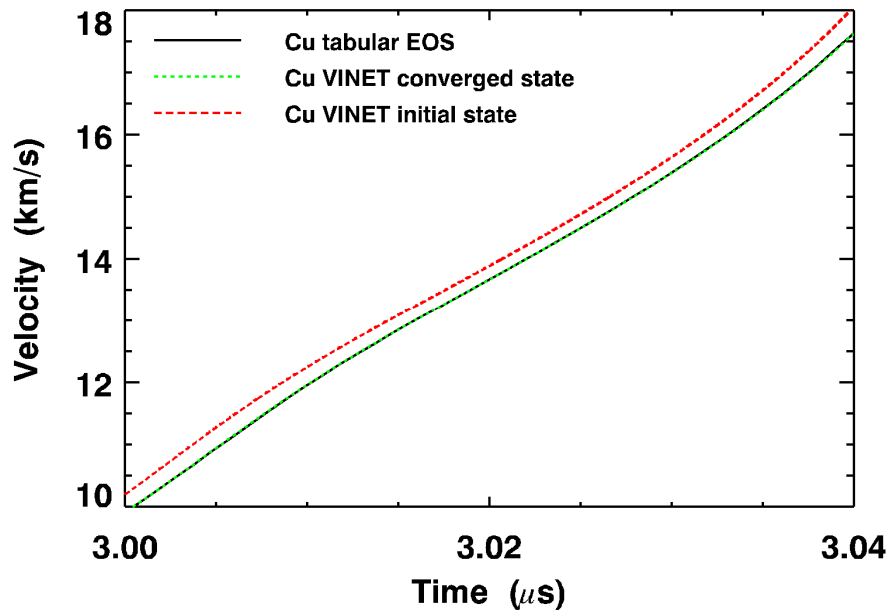


Parameterized Cu EOS converges to tabular EOS when liner velocity converges to data

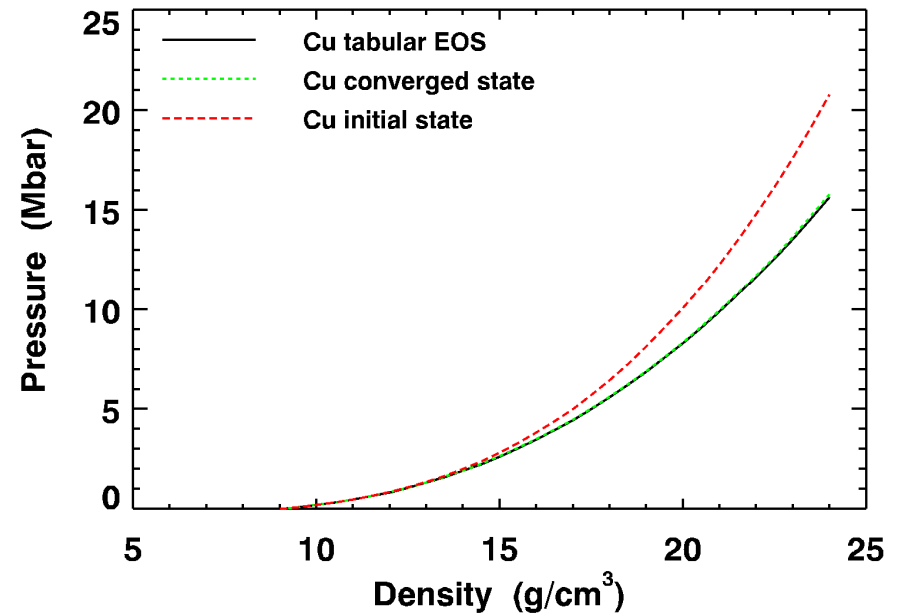
Extended Vinet EOS* with 4 free parameters matches synthetic data very well.

$$P_{ref}^{extvin}(X) = \frac{3B_0}{X^2} Z \exp[\eta_0 Z] \left(1 + \sum_{n=2}^N d_n Z^n \right) \quad X = \left(\frac{\rho_0}{\rho} \right)^{1/3} \quad Z = (1 - X)$$

Simulated PDV Velocity Cu Sample

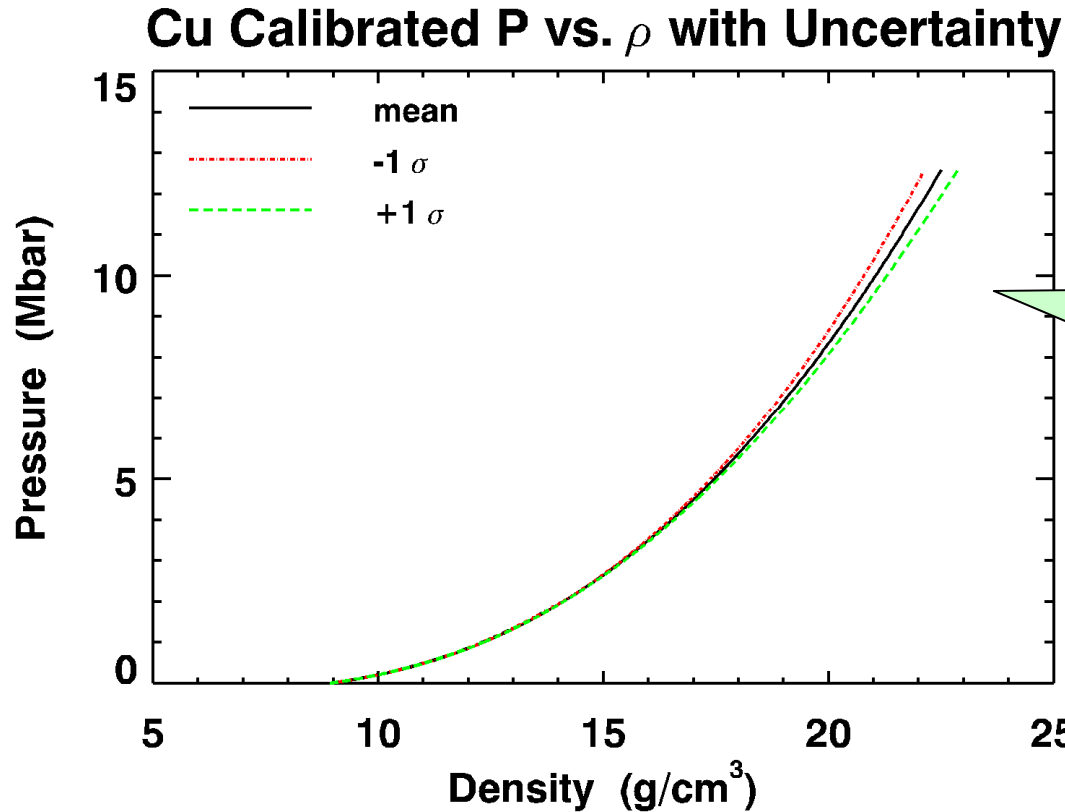


Cu Pressure vs. Density



*Pascal Vinet, et al., Phys. Rev. B 35(4), 1945 (1987).

Monte Carlo analysis of converged EOS quantifies uncertainty; defines convergence criteria for experiment

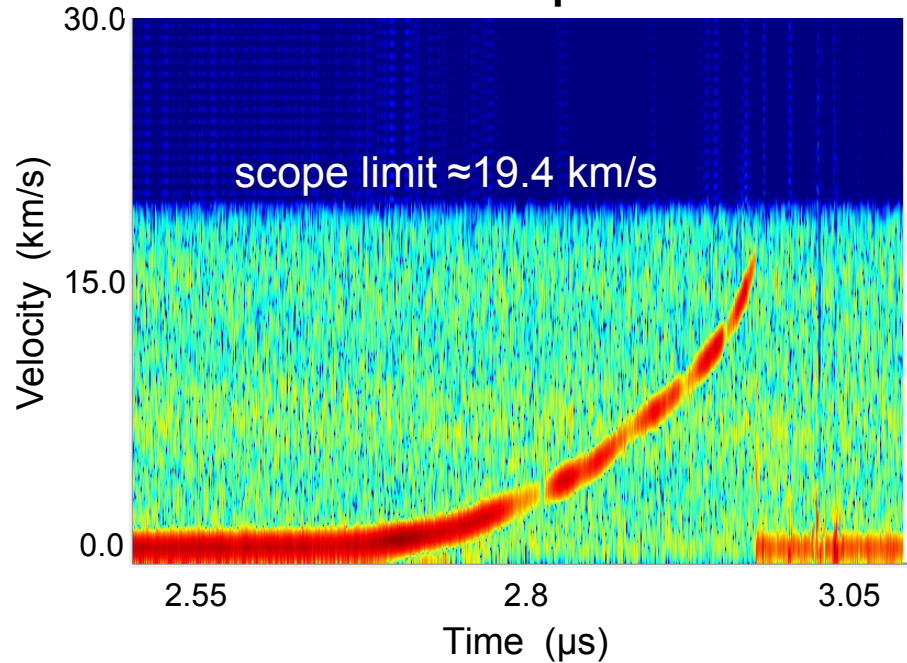


Accounts for 95% confidence interval in calibration run.

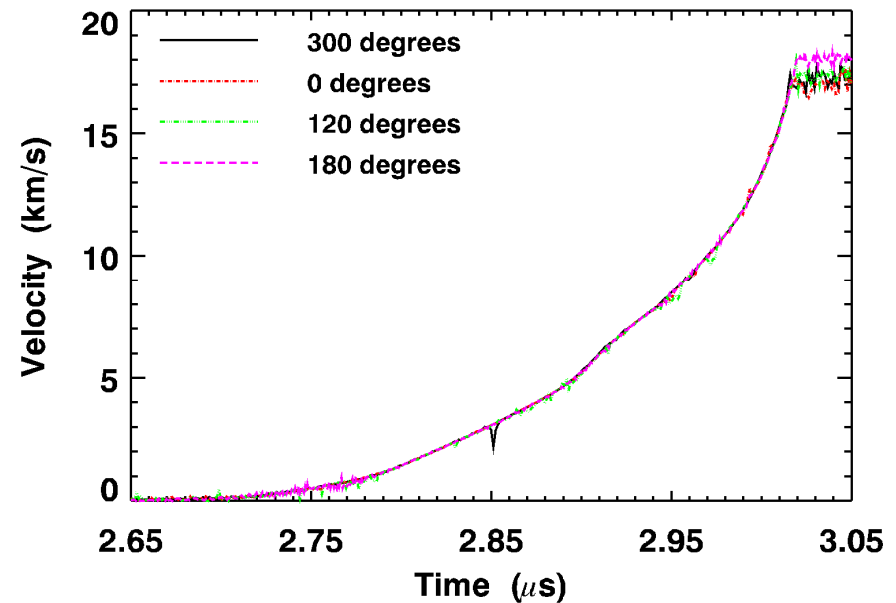
Maximum uncertainty in pressure (density) 5.7% (1.8%) at 11.7 Mbar for residual velocity norm 47 m/s (0.27% of maximum).

Four of 6 liner PDV probes returned data to predicted peak velocity ≈ 18 km/s showing symmetric implosion

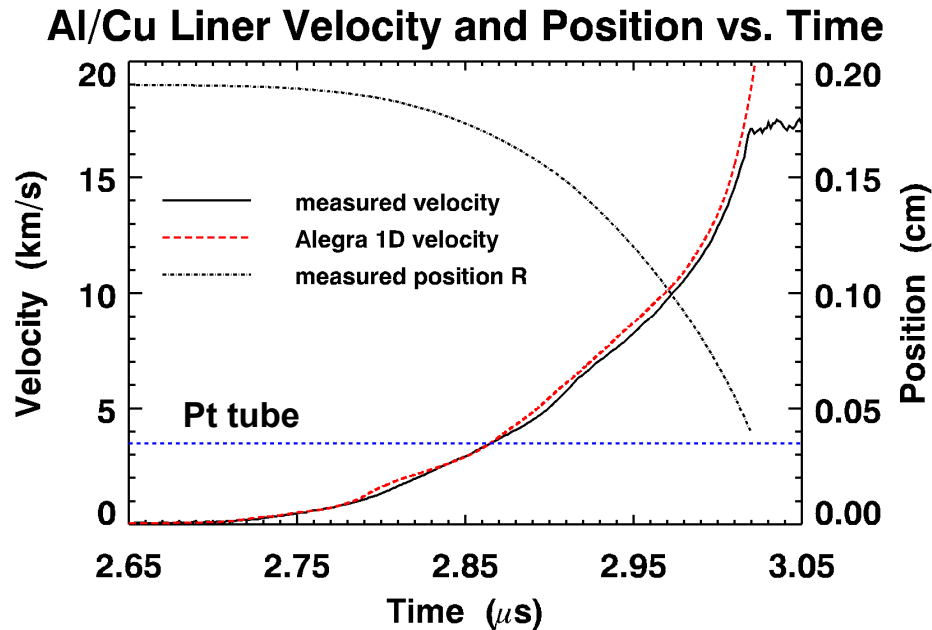
Measured velocity spectrum vs. time
free surface Cu sample



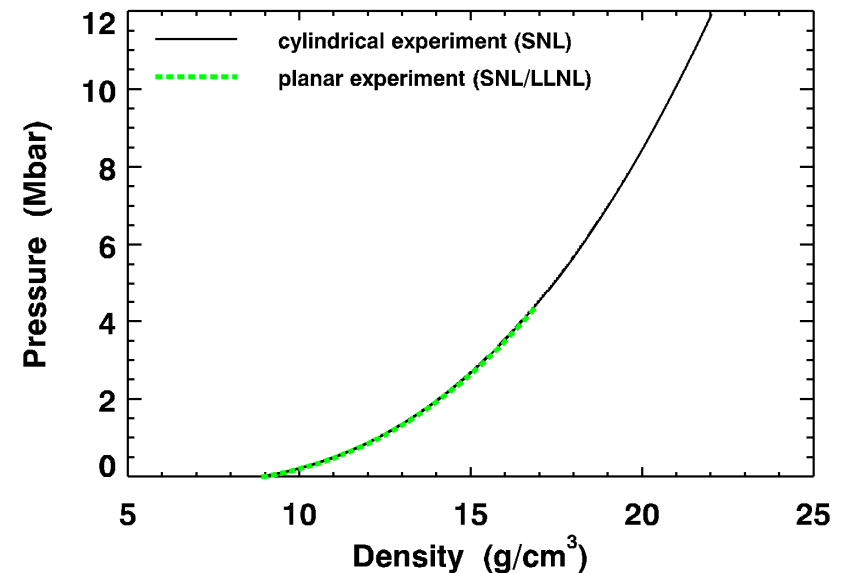
Measured Al/Cu Liner Velocity vs. Time



Copper shocklessly compressed to 12 Mbar: unexpected large difference in simulated & measured velocity



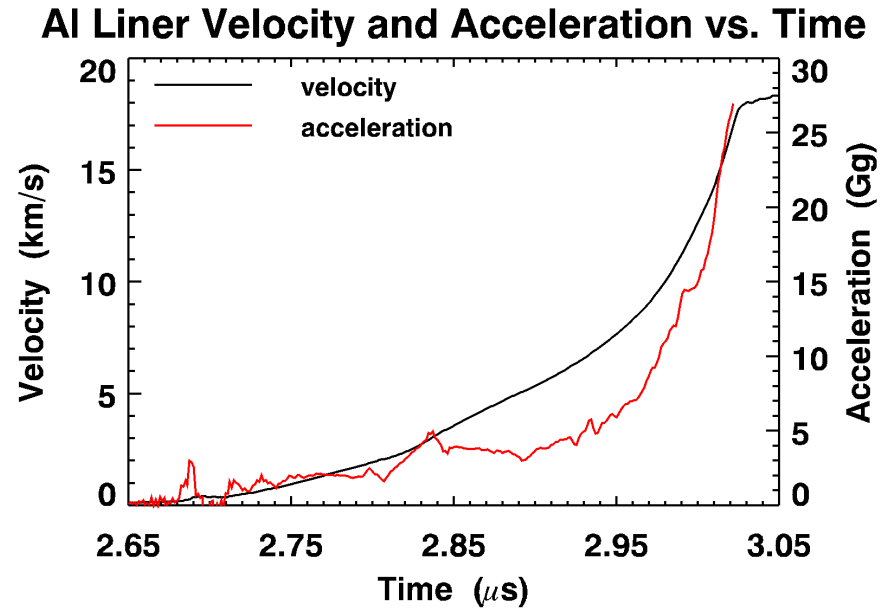
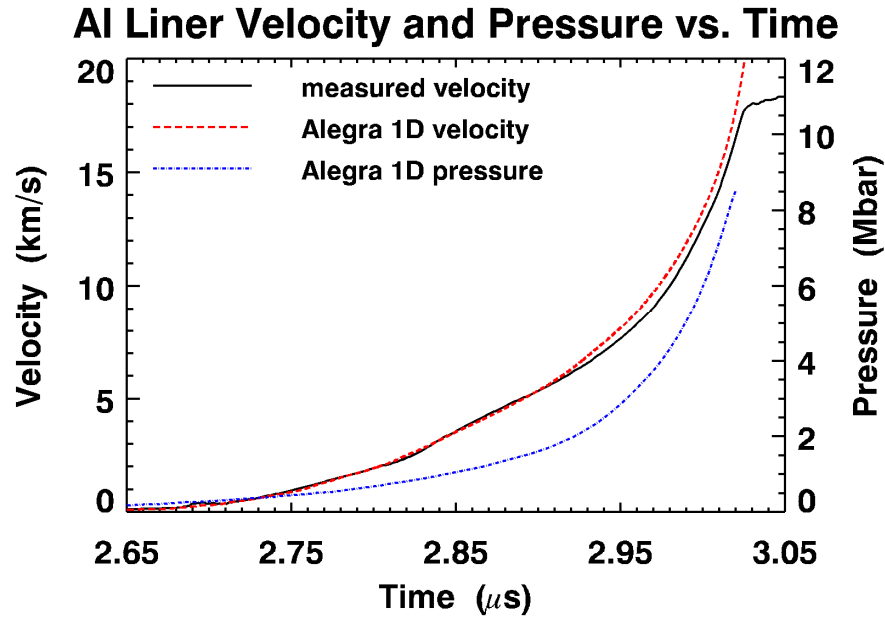
Simulated maximum pressure vs. density in Cu through peak measured velocity



Difference (2-3%) in measured & simulated velocity $t > 2.87 \mu\text{s}$ cannot be attributed to Cu EOS alone.

[Planar experiments on Z and NIF]

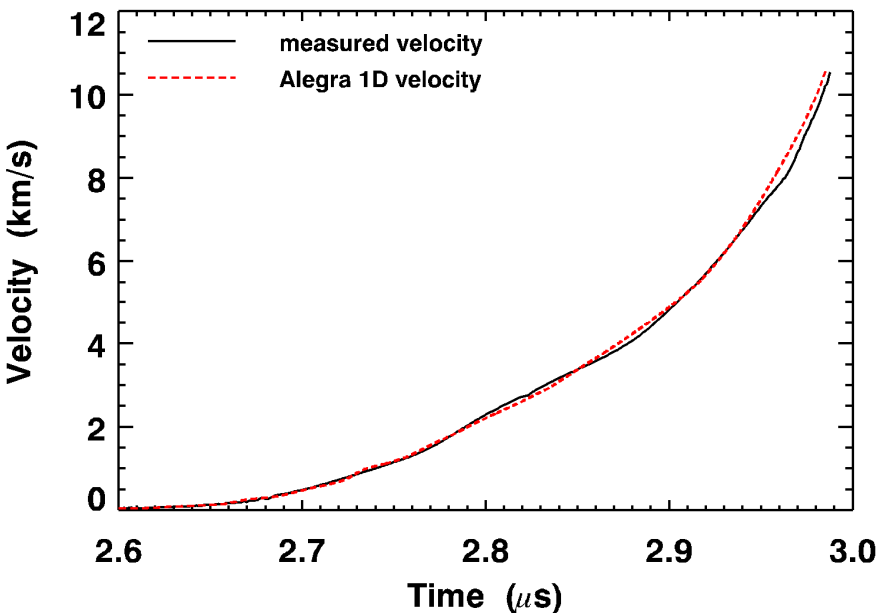
Experiment with Al liner measures compression to 8.4 Mbar; shows similar behavior



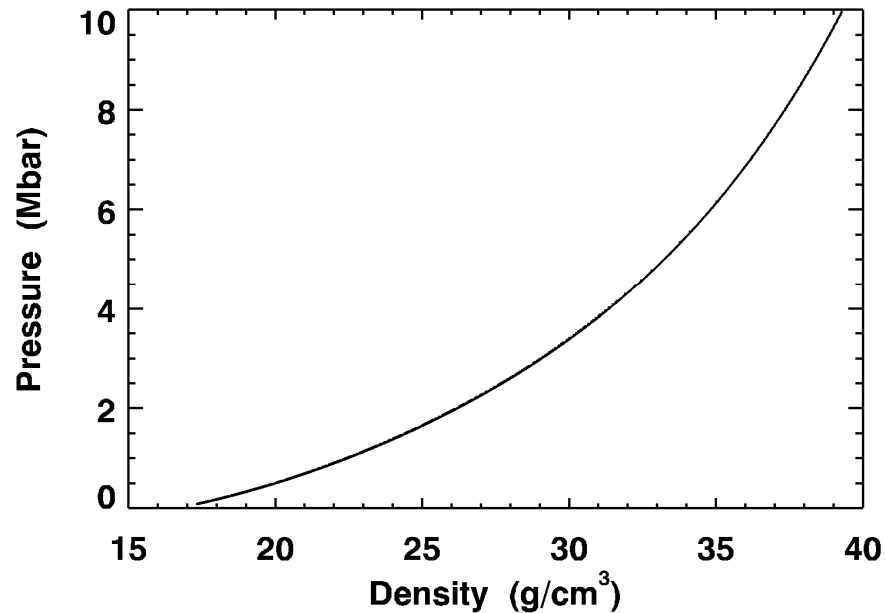
Shockless compression of Ta measured to 10 Mbar: simulated & measured velocity diverge, similar to Cu



Al/Ta Liner Velocity vs. Time



Simulated Pressure vs. Density in Ta



Conclusions

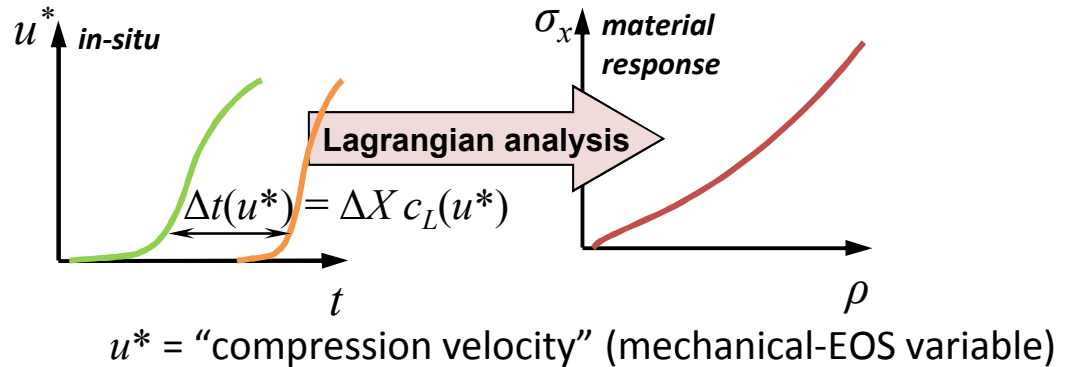
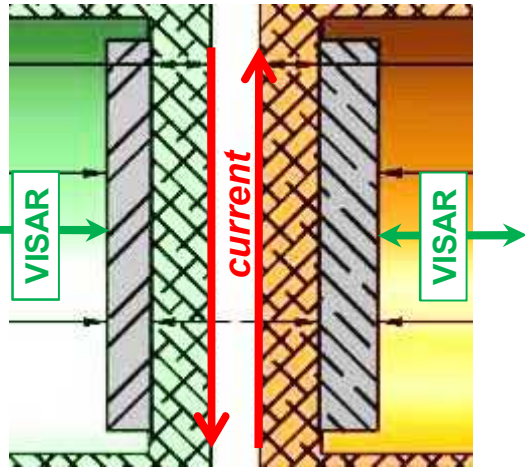
- Cylindrical liner geometry gives off-Hugoniot data on Al, Cu and Ta to ~ 10 Mbar.
- We have done significant development of the platform
 - Matured diagnostics to high precision and reliability
 - Demonstrated a highly symmetric platform
 - We are so far able to invert pressures to about 4-6 Mbar
- A persistent late-time discrepancy in measured and simulated liner PDV suggests a deficiency in our understanding of the drive
 - DAKOTA-ALEGRA EOS calibration depends on accurate knowledge of pusher EOS and the effective magnetic drive
- Path forward
 - Develop a reference-based experiment using stepped targets
 - Improve understanding of current flow/magnetic drive
 - Use radiography to measure density profile (high energy backlighting)

More information – R. W. Lemke et al. Journal of Applied Physics 119, 015904 (2016).

Acknowledgments

- **Dan Dolan and Devon Dalton (SNL):** Photonic Doppler Velocimetry (PDV).
- **Marcus Knudson, Jeff Gluth, Anthony Romero (SNL):** VISAR.
- **Justin Brown (SNL):** post-shot analysis and uncertainty quantification (UQ).
- **Allen Robinson, John Carpenter, Ann Wills, Thomas Mattsson (SNL):** ALEGRA and EOS development.
- **Laura Swiler (SNL):** DAKOTA and UQ.
- **Kurt Tomlinson, Brent Blue, Jerry Taylor (GA):** target fabrication.
- **Eric Harding (SNL):** experiments.

Planar experiments: Lagrangian Analysis extracts quasi-isentropic material response from velocimetry

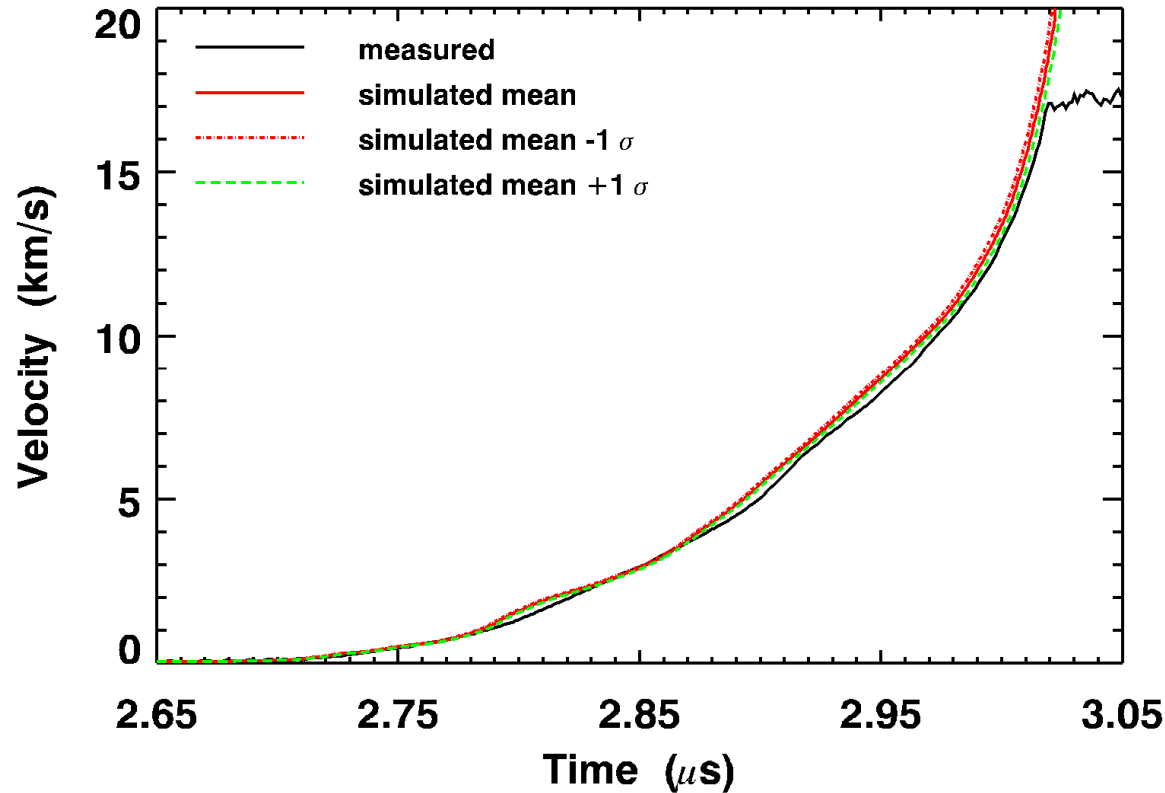


- Inverse Lagrangian Analysis (ILA) accounts for free surface
 - map measured $u(t)$ into in-situ $u^*(t)$, then apply DLA¹
 - assumes single-valued material response
 - assumes identical state at both electrode-sample interfaces
- Single-sample approach uses full sample thickness
 - measure driving $B(t)$ from sample-less electrode
 - simulate in-situ velocity at electrode-sample interface
 - iterate the ILA procedure, recomputing input velocity
 - assumes identical state at both electrode driven surfaces

¹ S. D. Rothman & J. Maw, *J. Physique IV* **134**, p745 (2006)

Monte Carlo UQ: difference in measured & simulated velocity not due to uncertainty in current or dimensions

Al/Cu Liner Velocity vs. Time with Uncertainty



UQ accounts for uncertainties of: 0.4% in current; $\pm 2.5\ \mu\text{m}$ in Al anode thickness; $\pm 5.0\ \mu\text{m}$ in liner inner & outer radii; $\pm 200\ \text{ps}$ timing error in PDV data.