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Molybdenum dynamic yield strength measured via the tamped RMI method

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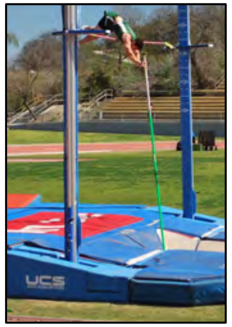
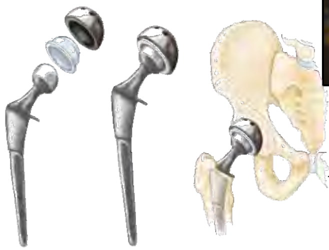
Quick background: how did I get to Sandia?

San Diego, CA





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LRGF Laboratory Residency Graduate Fellowship

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Shock physics experiments
Multi-physics simulations
Compaction modeling
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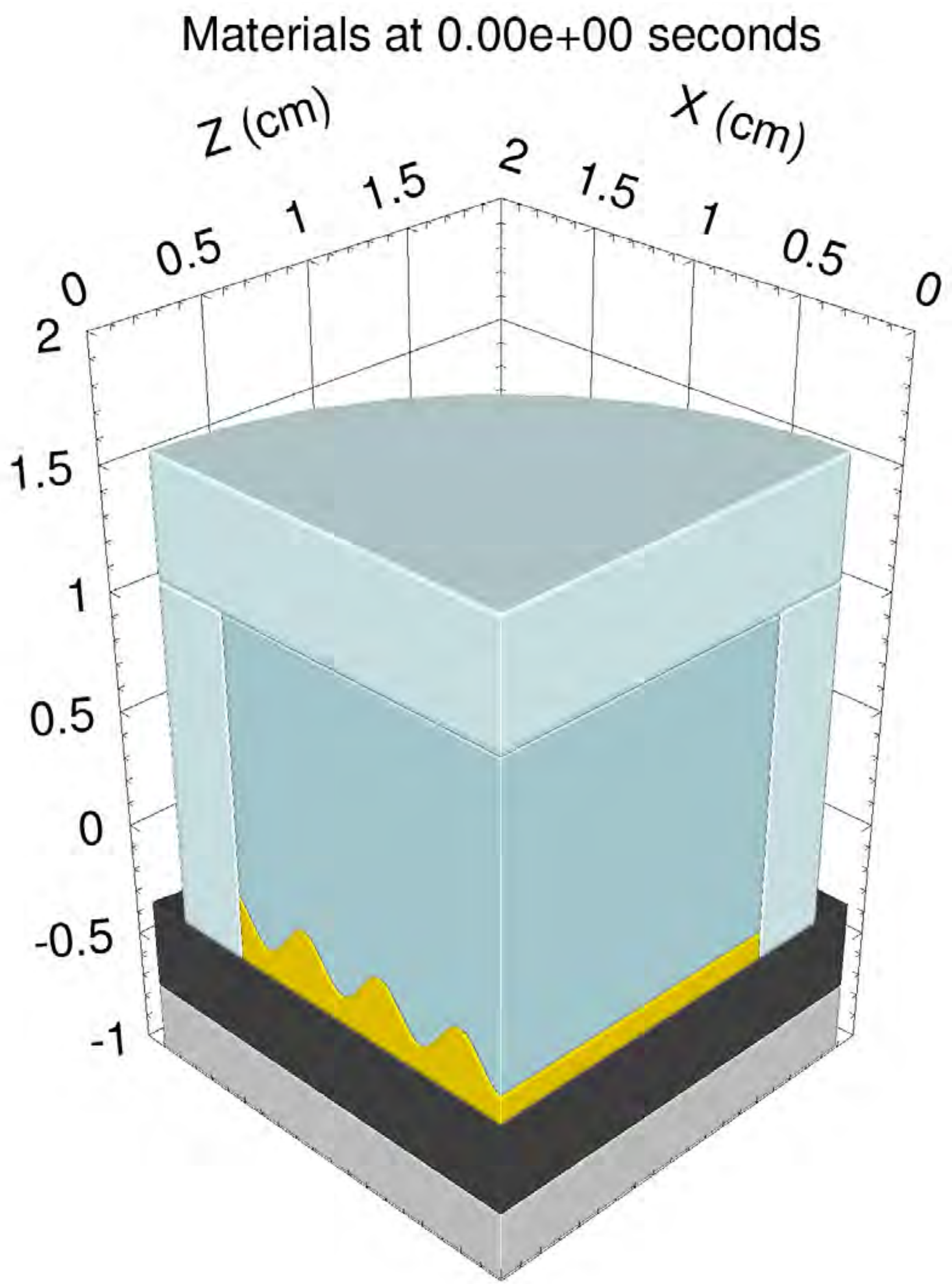
Sandia National Laboratories

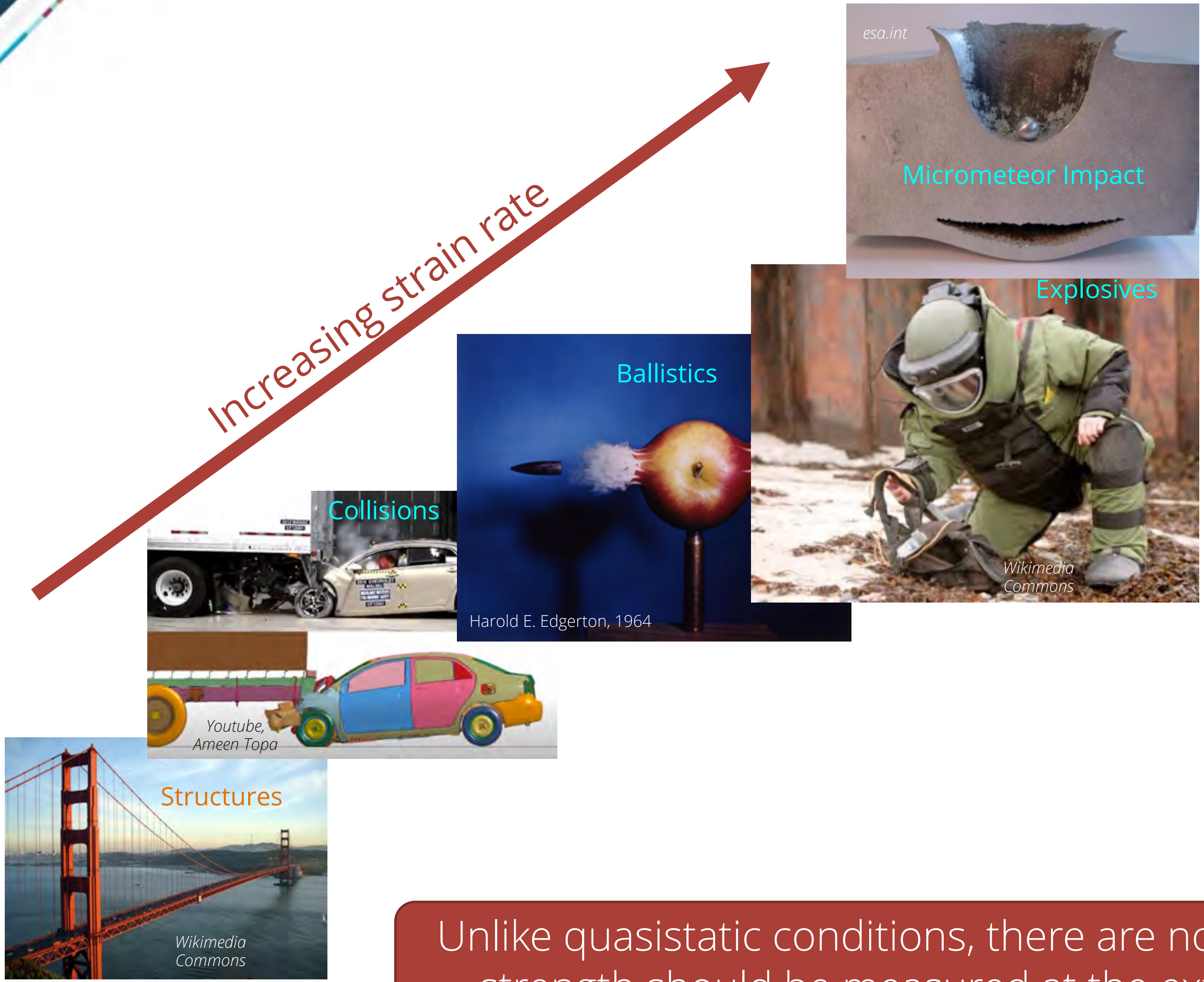
2020-Present
Mech. Engineer
Org. 08363
Impact experiments
Multi-physics simulations
General science & engineering
Dynamic strength research
Mentor: Tracy Vogler

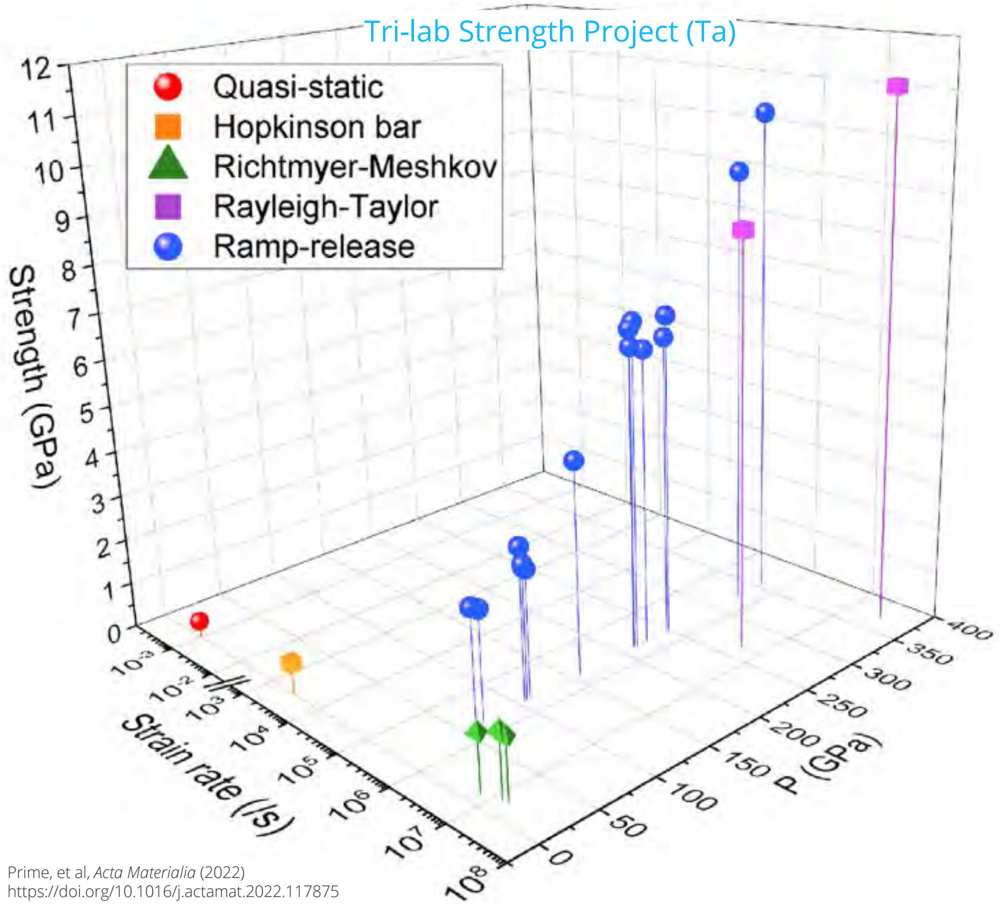
Discussion Overview:

- Why is this research important?
- What is the *Tamped RMI* method?
- Experimental Design and Facility: DCS at APS
- Results & Model Calibration
- Acknowledgements



Strength defines how materials deform. Strength can vary drastically as a function of applied pressure, temperature, and strain rate. Extreme conditions not easily measured.





Prime, et al, *Acta Materialia* (2022)
https://doi.org/10.1016/j.actamat.2022.117875

Fig. 6. The strength values for Ta from five experimental platforms span nearly 11 decades in strain rate, pressures from ambient to over 350 GPa, and show strength increases of almost two orders of magnitude over ambient values, especially at high pressure.

Unlike quasistatic conditions, there are no ASTM standards or similar to define how strength should be measured at the extreme *P*, *T*, and $\dot{\epsilon}$ associated with shock.

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Increasing

Tri-lab Strength Project (Ta)

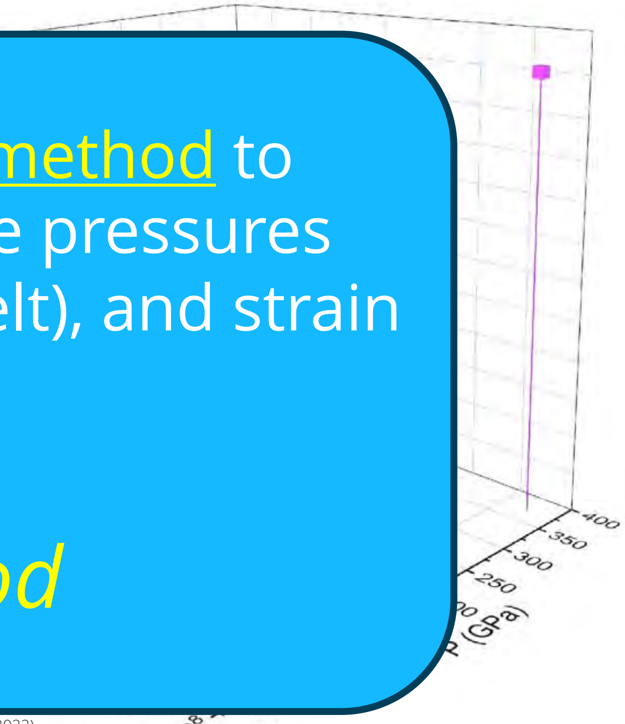

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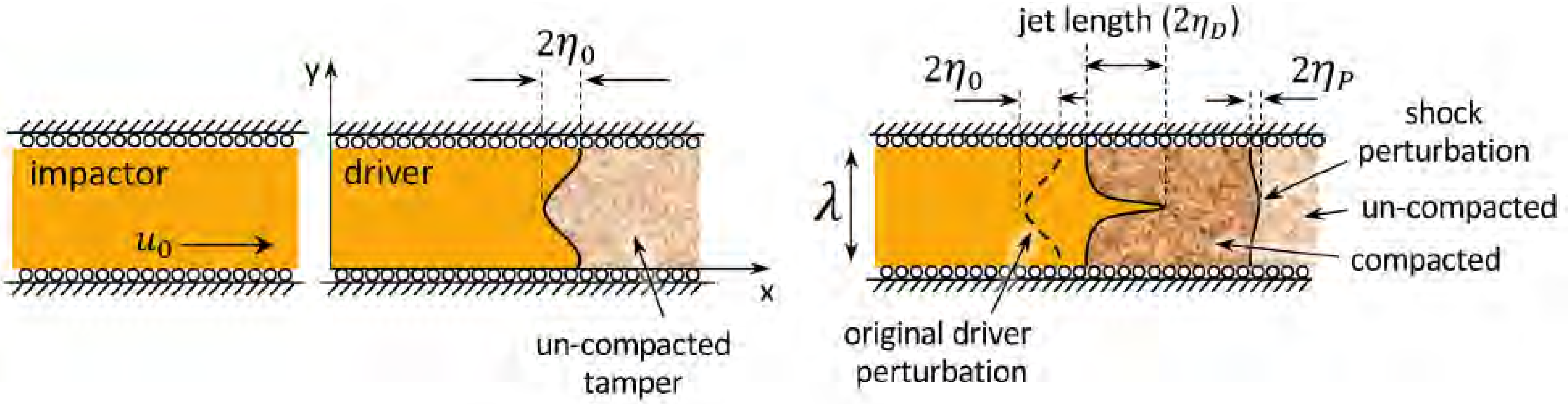
Fig. 6. The strength values for Ta from five experimental platforms span nearly 11 decades in strain rate, pressures from ambient to over 350 GPa, and show strength increases of almost two orders of magnitude over ambient values, especially at high pressure.

At SNL-CA, we are developing a new method to measure material strengths at extreme pressures (~0-100 GPa), temperatures (ambient-melt), and strain rates (~10^5-10^7 /s):

The Tamped RMI method

Unlike quasistatic conditions, there are no ASTM standards or similar to define how strength should be measured at the extreme P, T, and $\dot{\epsilon}$ associated with shock.

The tamped RMI method generates an RMI between two materials, then calibrates material parameters against the interfacial deformation.



Stages of Experiment:

1. Impact drives planar shock through corrugated driver-tamper interface
2. Tamper is shock compressed and corrugation begins inversion. Jet forms.
3. Shocked tamper arrests RMI jet.

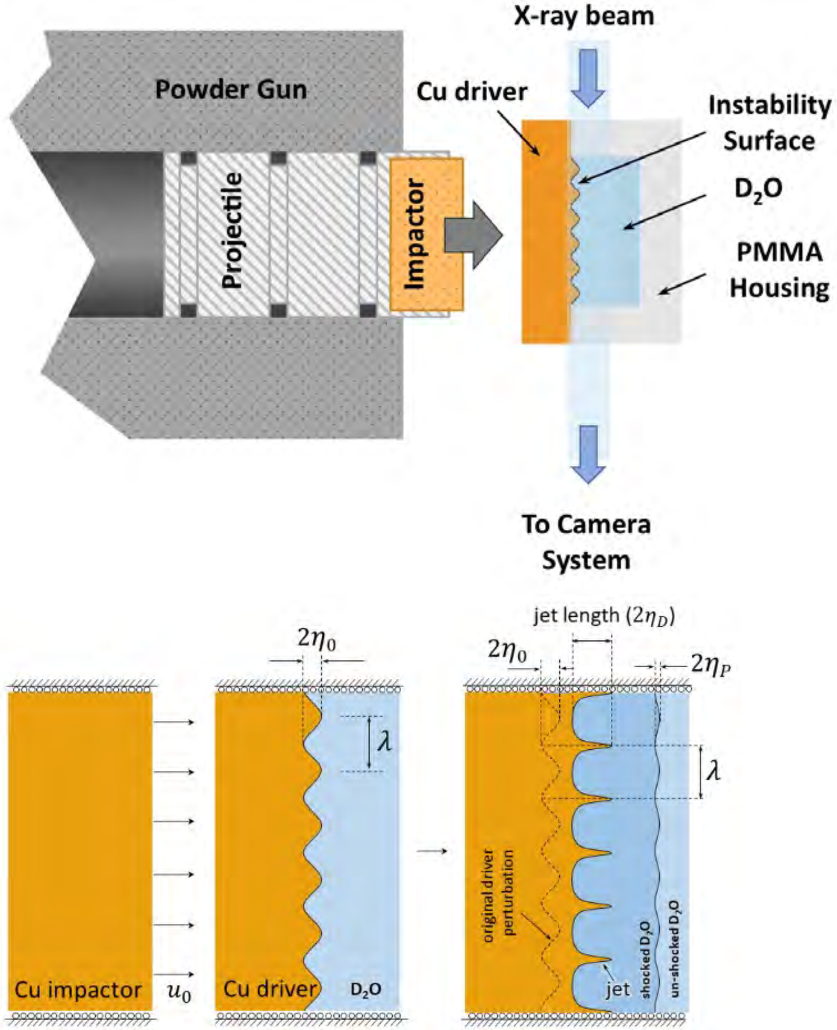
Factors Affecting RMI Inversion Behavior:

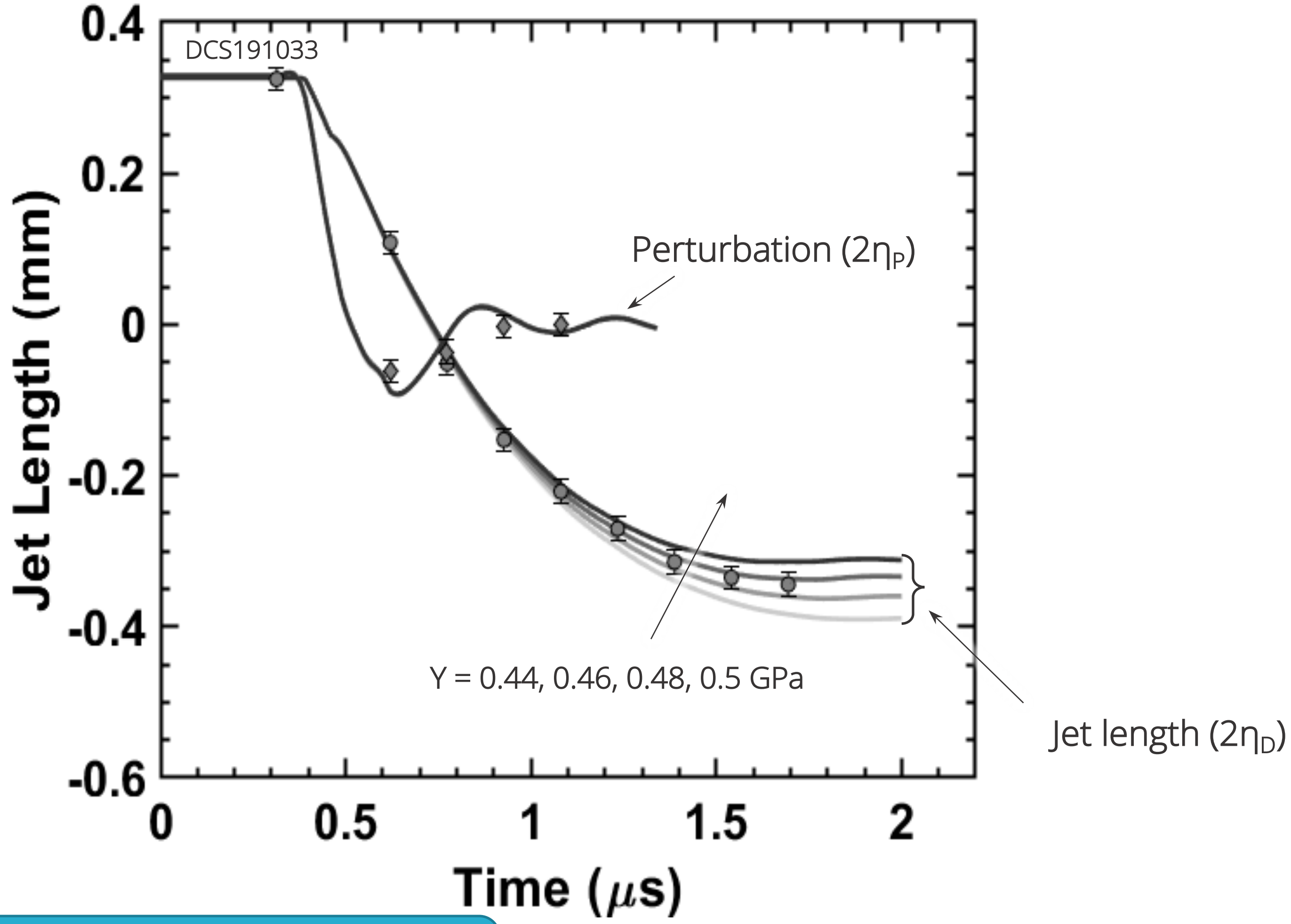
- Driver strength, Y_D
- Tamper strength, Y_T
- Shock stress, σ_1
- Density difference/ratio, $A = \frac{\rho_T - \rho_D}{\rho_T + \rho_D}$
- Corrugation aspect ratio, $k\eta_0$ for sine

By using a liquid tamper, driver strength becomes the only unknown

Hudspeth et al., J. Appl. Phys. 128, 205901 (2020)

Joe Olles and Matt Hudspeth laid the ground work for the current investigation. They calibrated the strength of copper via D_2O-tamped RMI.

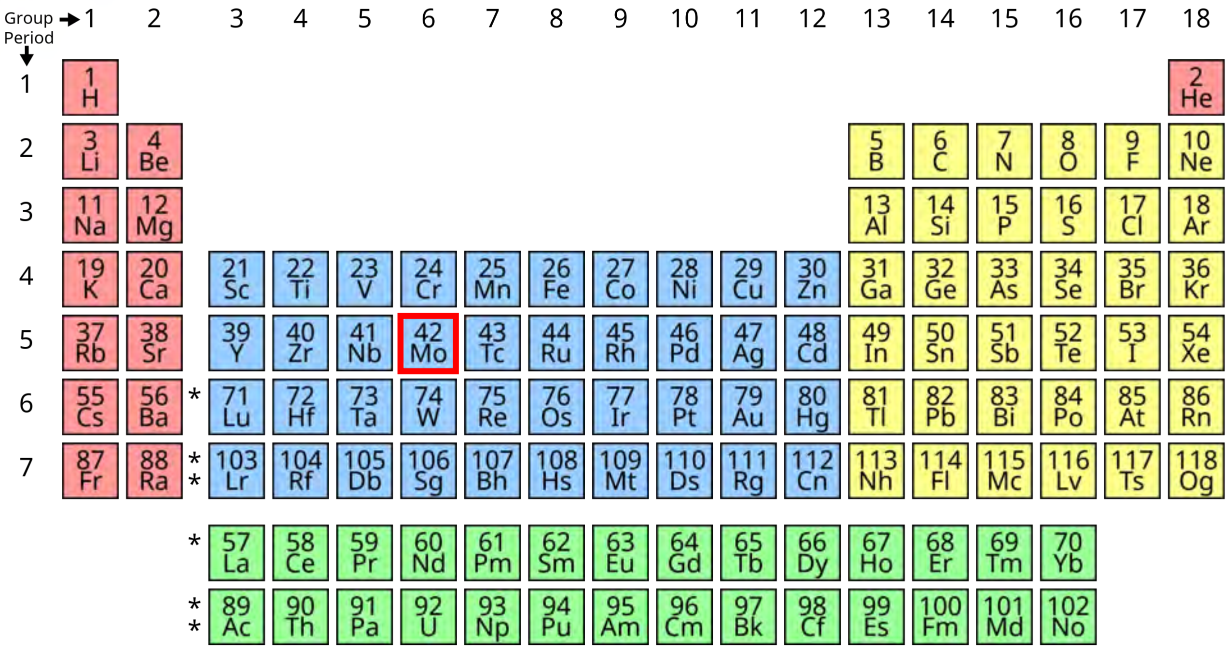


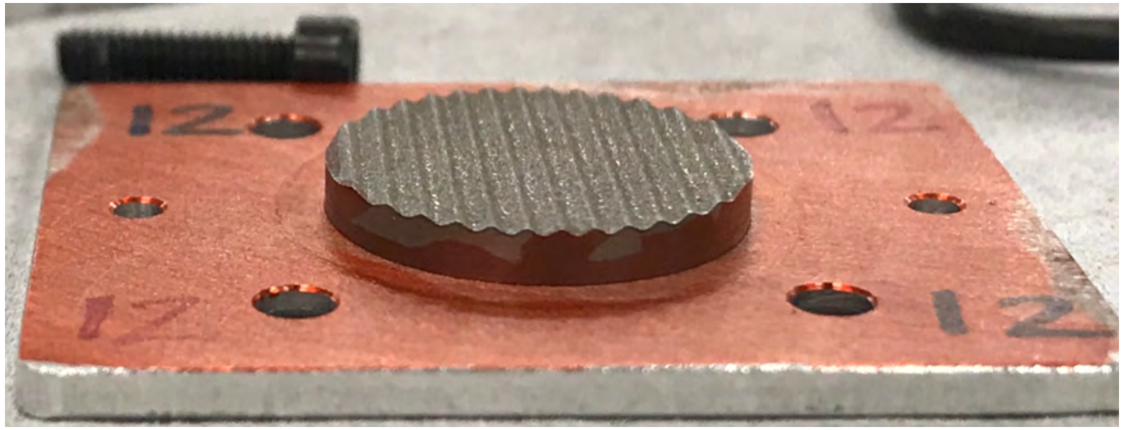


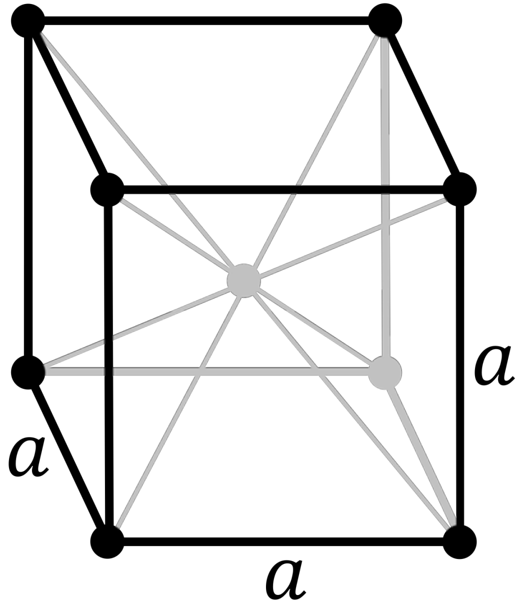
Each experiment yields one $(Y, P, \dot{\epsilon})$ data point on the yield surface

Olles, et al, *JDBM* (2020)
Olles, et al, *APS DFD* (2018)

This study will characterize the dynamic strength of molybdenum (Mo), within the achievable (release) pressure ranges of the DCS powder gun: 0-18 GPa







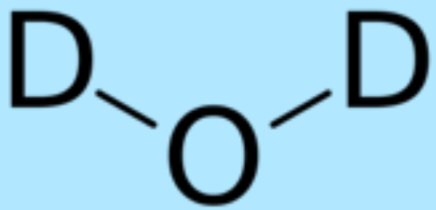
<u>General Properties:</u>
- Refractory
- Brittle
- Strong
- BCC structure

<u>Quantitative Properties:</u>
- ρ=10.21 g/cm3
- $C_L = 6.27$, $C_S = 3.31$ mm/µs
- $\nu = 0.31$
- $T_{melt} = 2896K = 0.250\ eV$

Characterization by Chris Johnson

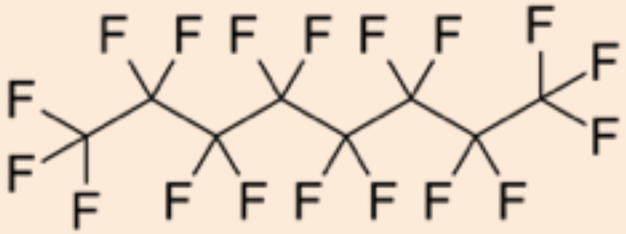
The current study uses D_2O and C_8F_{18} as tamping media to vary Atwood number. Both transmit 1550 nm light and are transparent to the 23-26 kEv X-ray beam.

Heavy Water, 1.11 g/cc

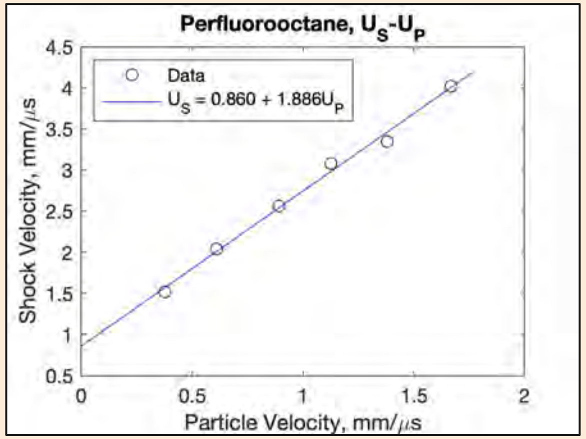


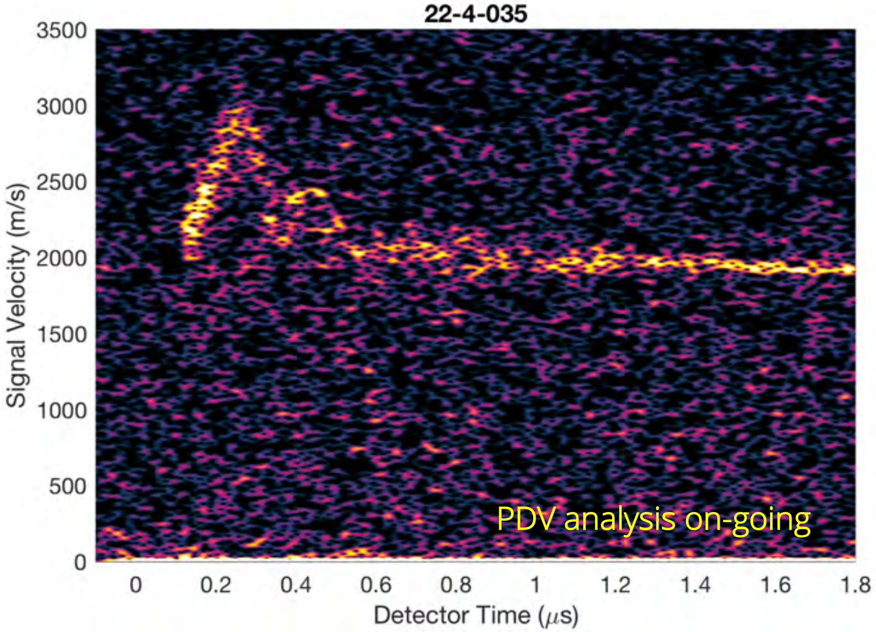
- CTH model is density-scaled version of H_2O
- Previously used in Olles, et al (2020) Cu-D_2O research.

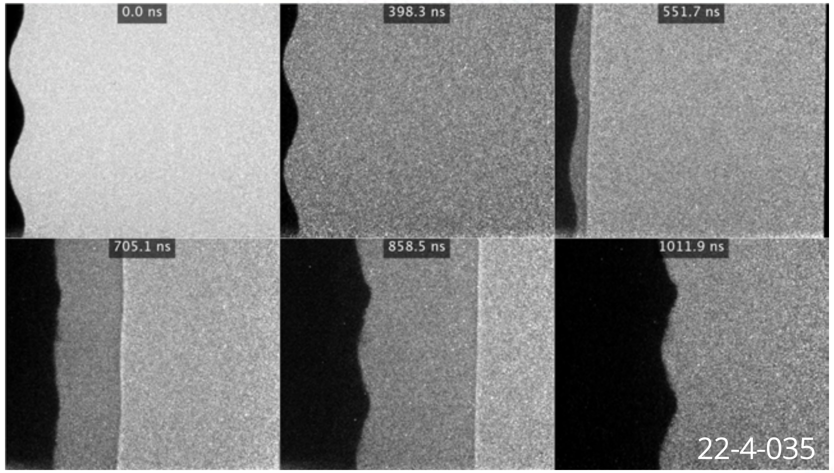
Perfluorooctane, 1.77 g/cc



- Hugoniot and IOR measured by Stacy Guo







The dynamic strength of molybdenum has been investigated in similar pressure regimes, but with alternative techniques. Y=1.1-1.7 GPa.

Dynamic Measurements:

- Furnish and Chhabildas, 1992: Y=~1.4 GPa
  - Shock and release, 6.5-15.0 GPa pressures
- Millett, et al, 2012: Y=1.65 GPa
  - Lateral stress gauge
- Alexander, et al, 2016: Y_0=1.1 GPa
  - MHD compression-shear ramp loading
- C. Johnson, 2021: Y_{HEL}=1.4-1.7, Y_S=1.1 GPa
  - Symmetric oblique experiments
- Some spall experiments showing very low spall strength (brittle behavior)

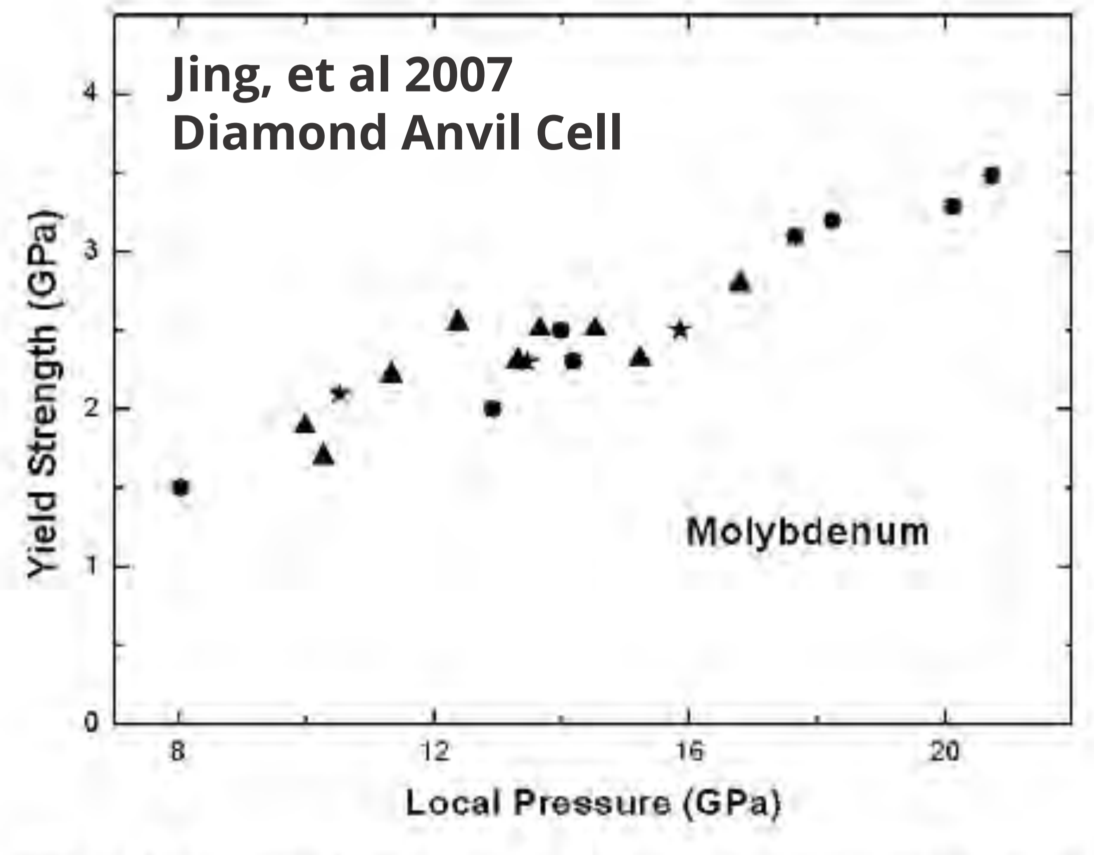
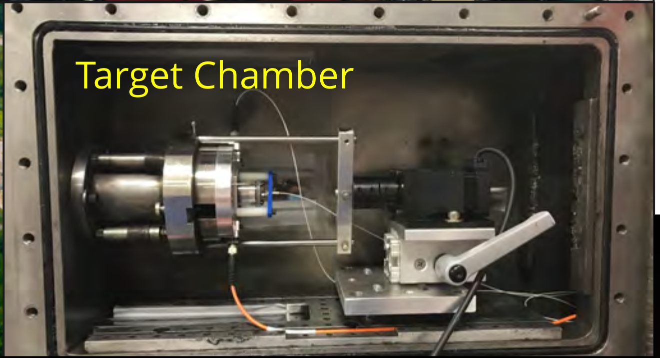
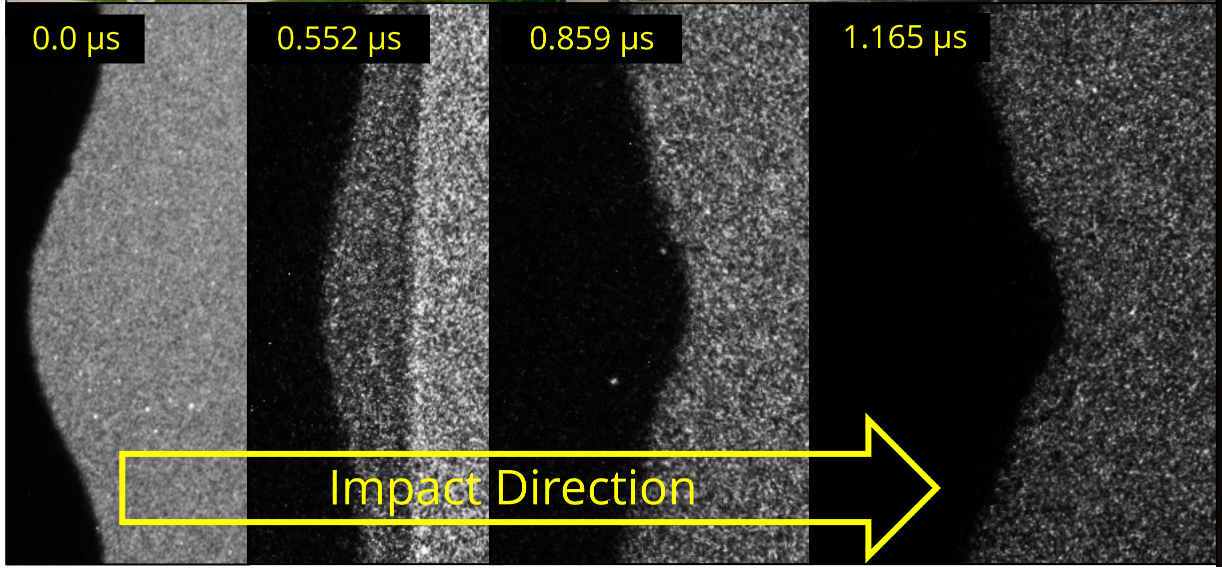
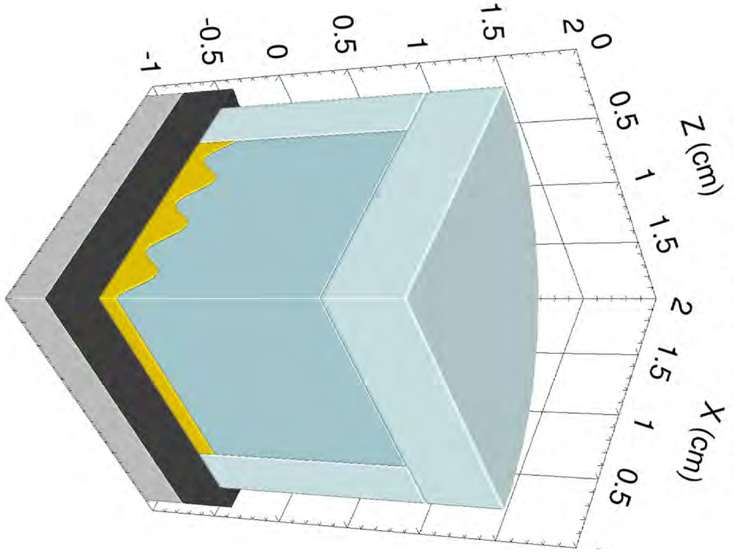


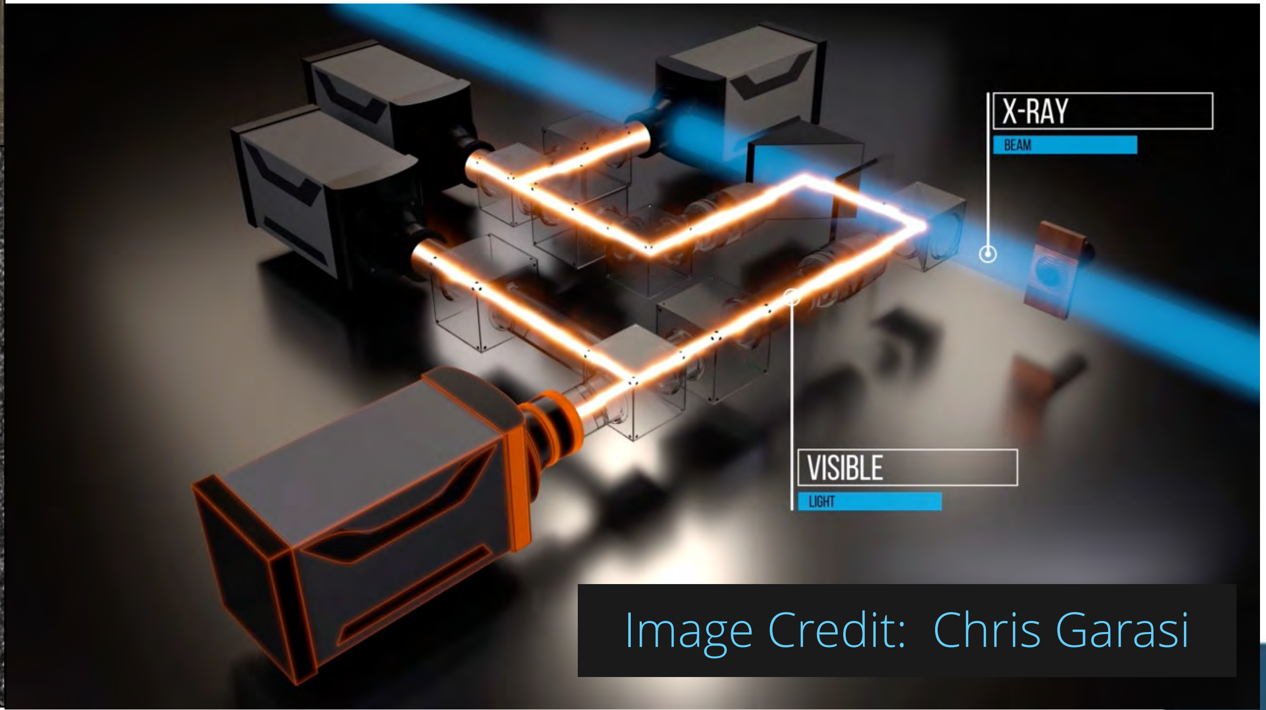
FIG. 6. Yield strength as a function of local pressures obtained in the present experiment: (●) Mo-100, (▲) Mo-250, and (★) Mo-500.

Tamped RMI experiments are performed at ANL/WSU's Dynamic Compression Sector

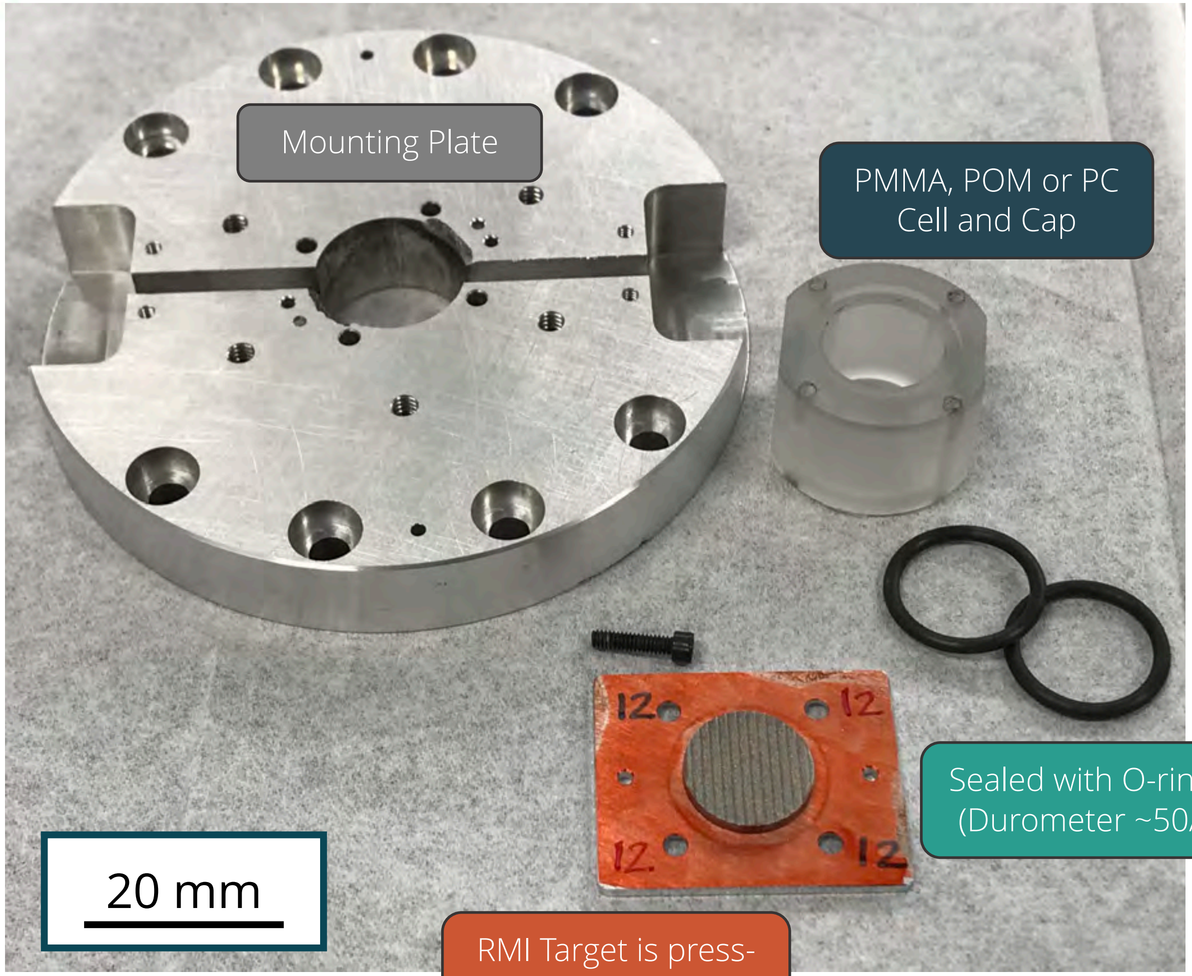


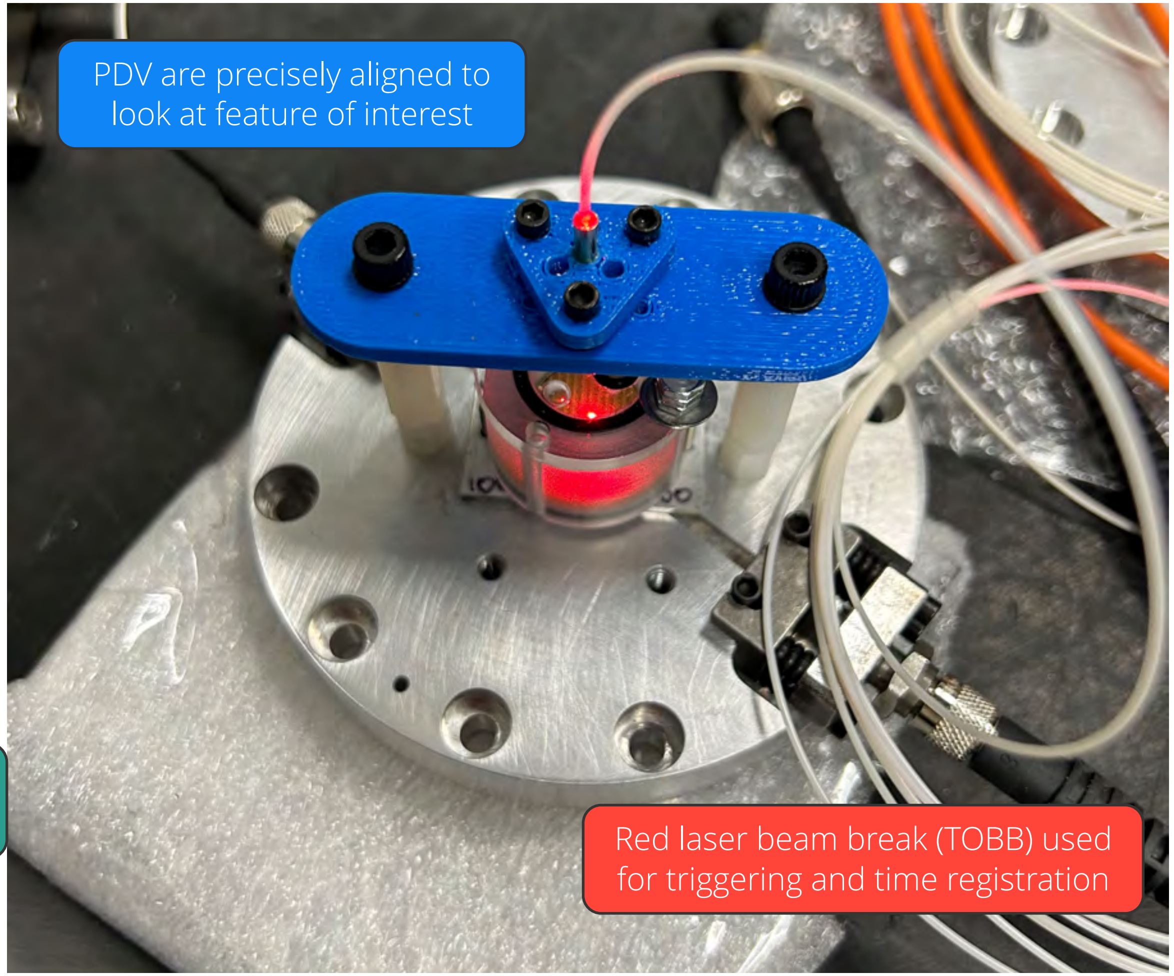






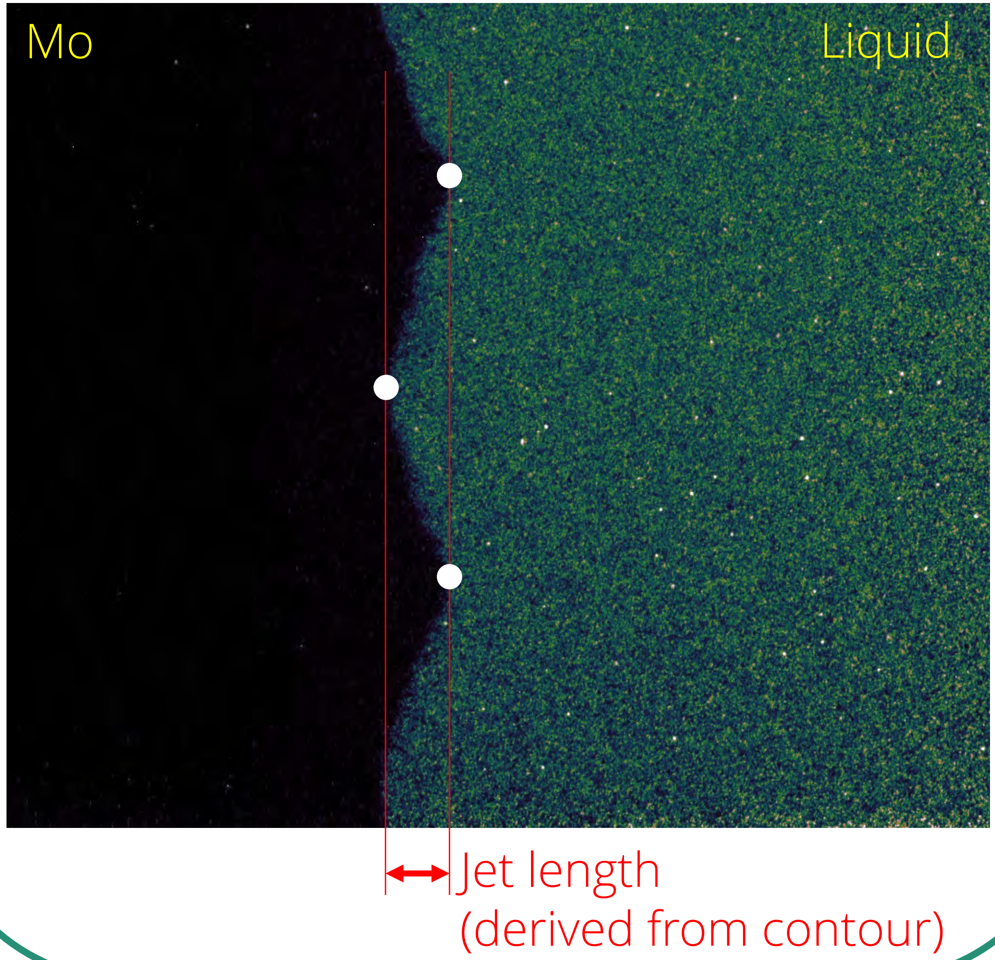
Targets are designed to minimize edge effects, hermetically seal liquid, easily align X-ray and PDV. All critical components machined at SNL-CA machine shop.



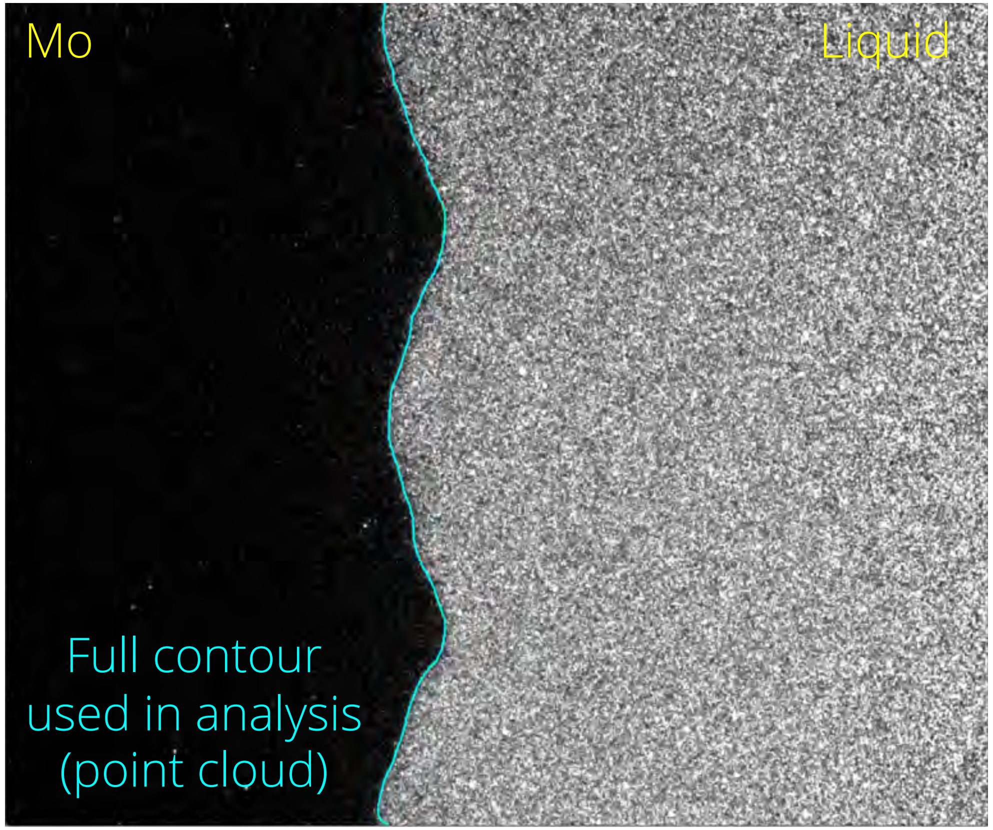


Two forms of data are extracted from XPCI: jet length and contour
Each data type will be used to separately calibrate Mo yield strength.

Jet Length: Proven method, 2-3 points

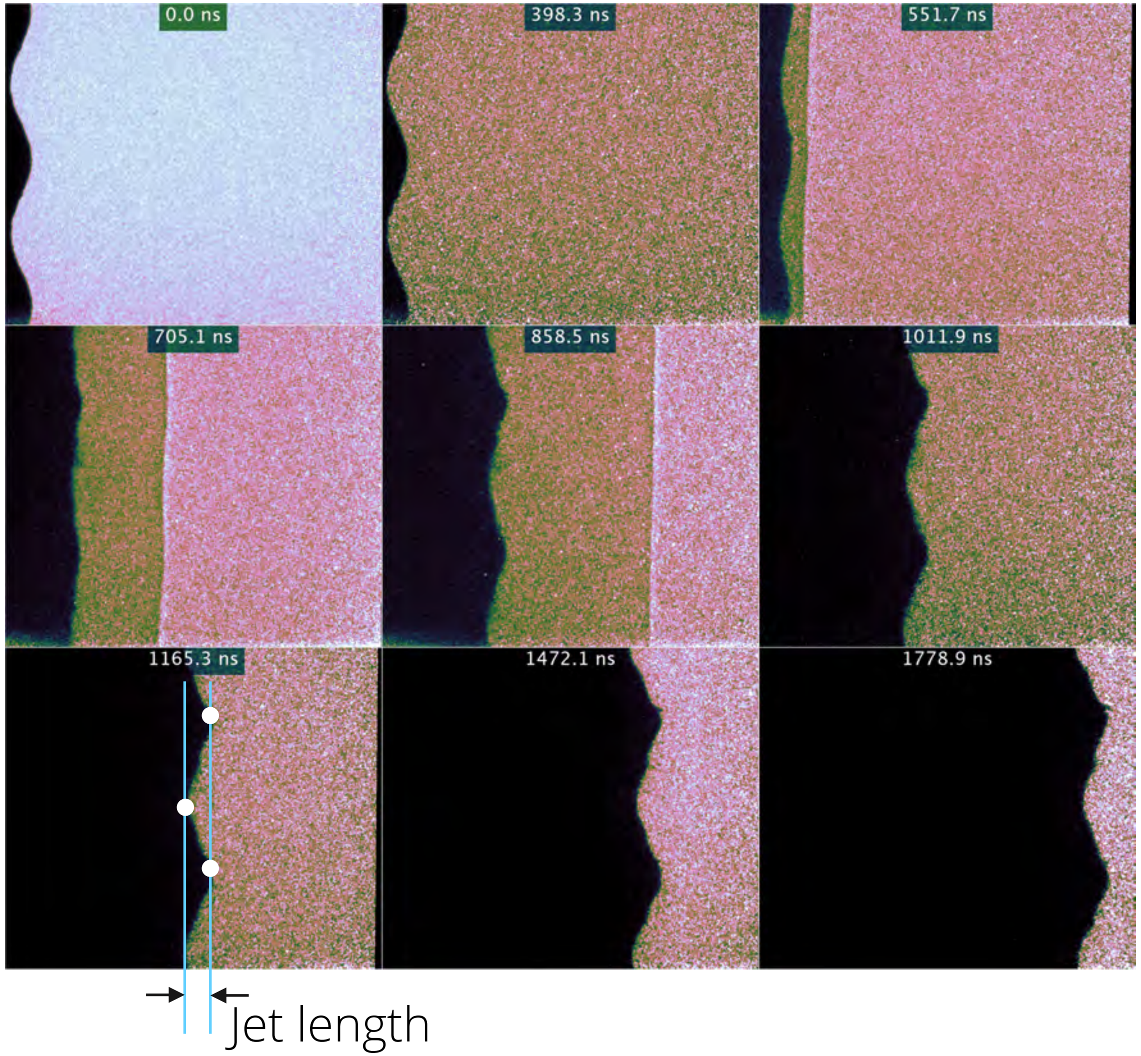


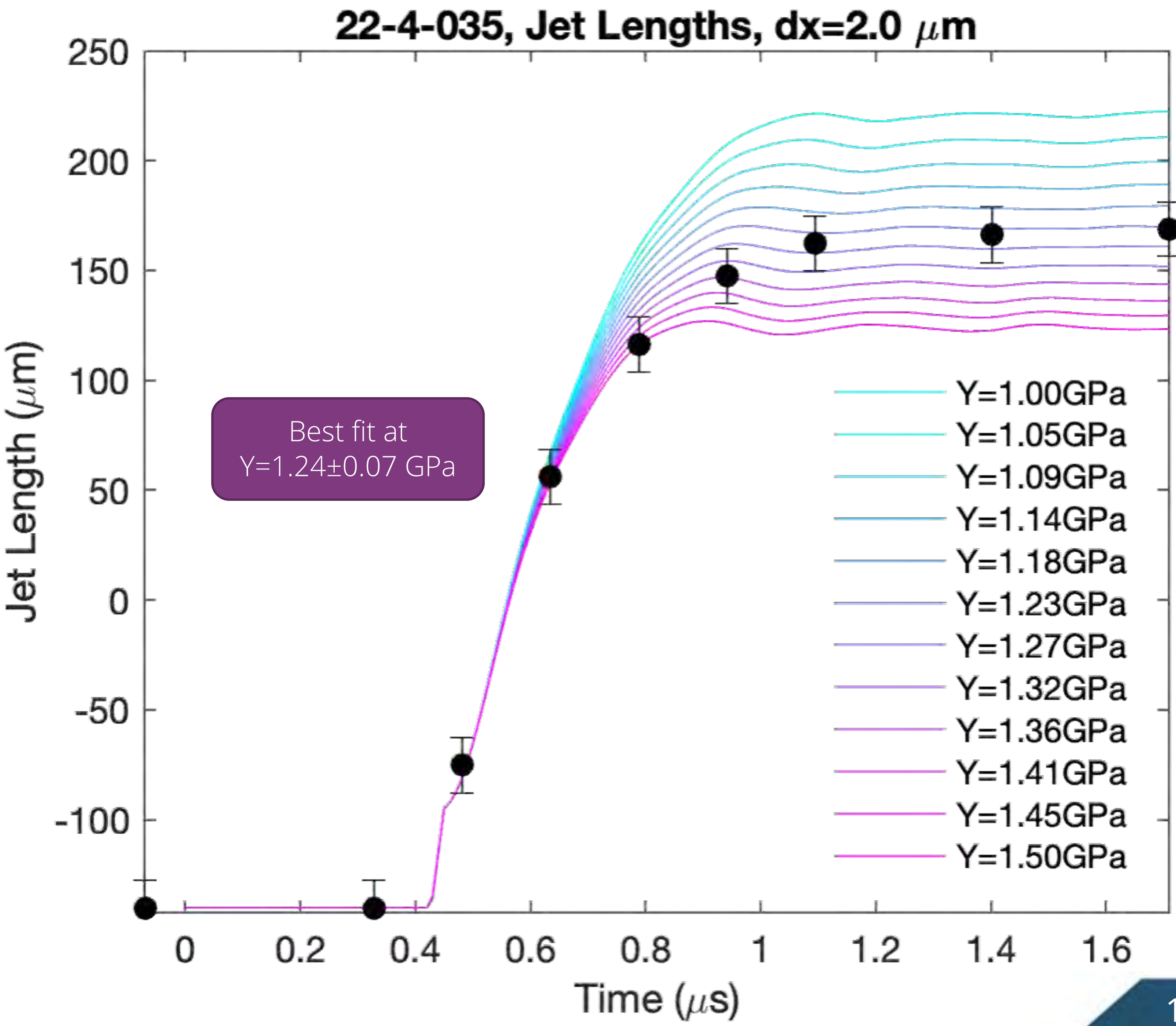
Contour Comparison: New, more robust



Simulations are run with an elastic-perfectly-plastic model, varying yield strength until the experimentally measured (arrested) jet length is reproduced.

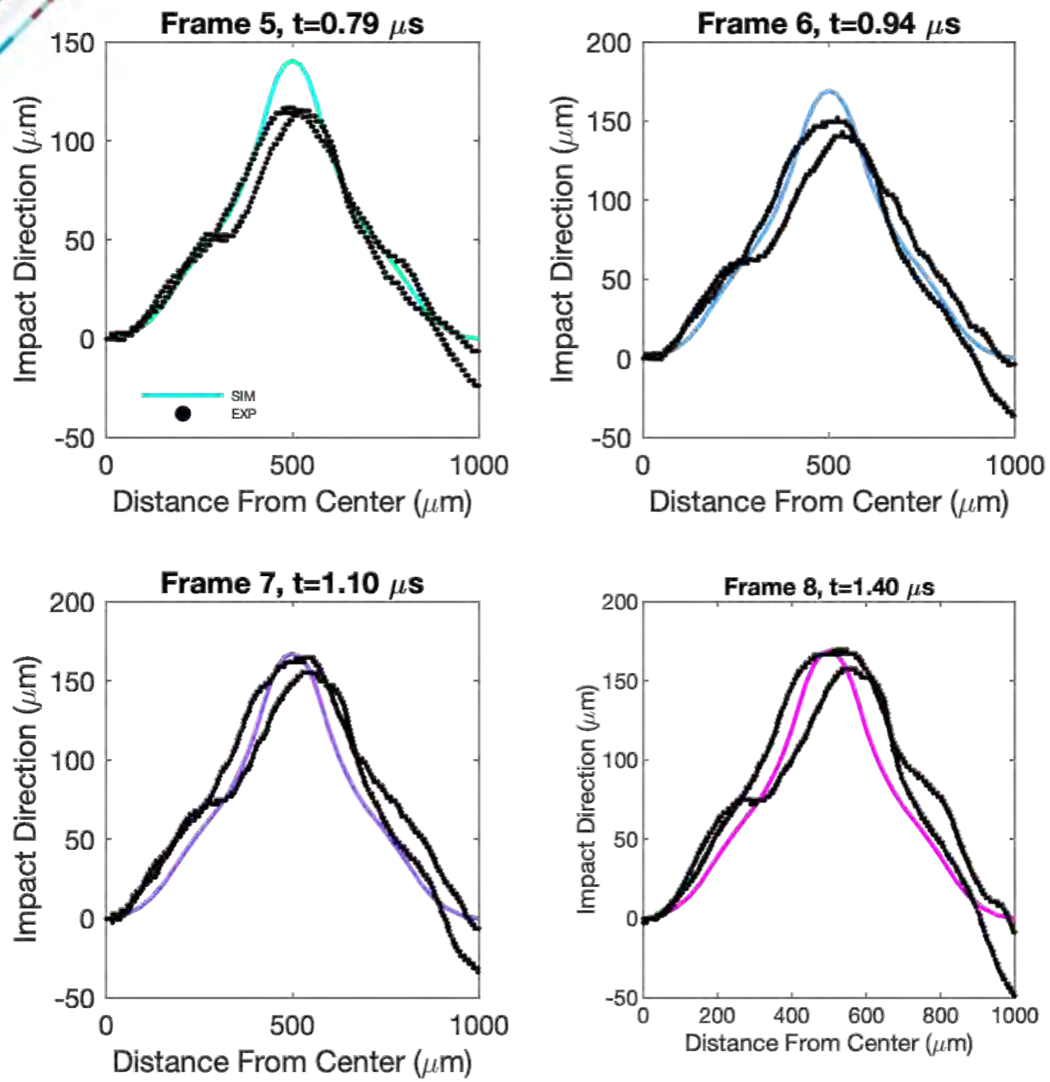
Mo-D_2O, $k\eta_0$=0.50, Ta imp, 2.07 km/s, P_D = 73.2 GPa, P_T = 11.5 GPa

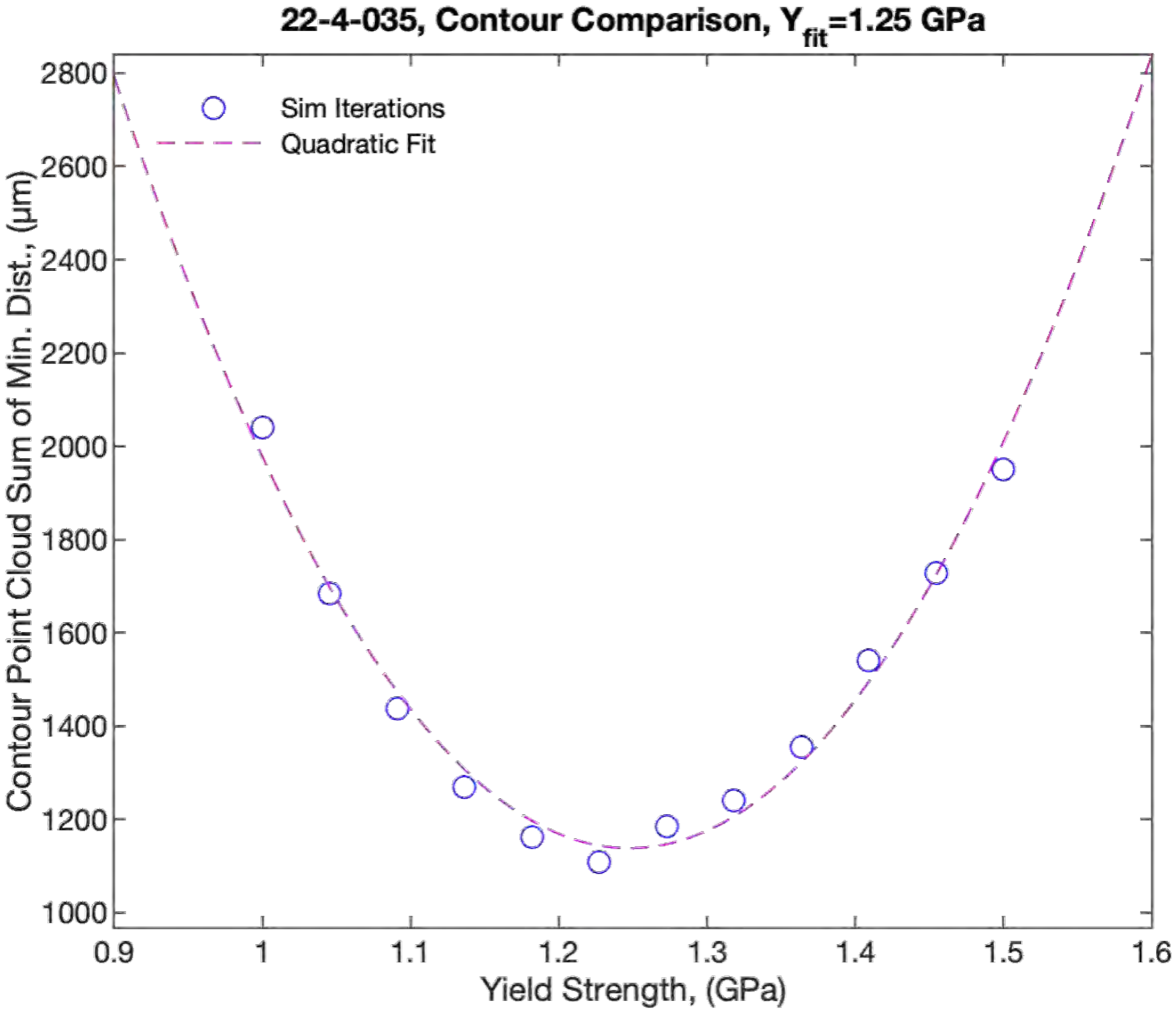




Best fit at
Y=1.24±0.07 GPa

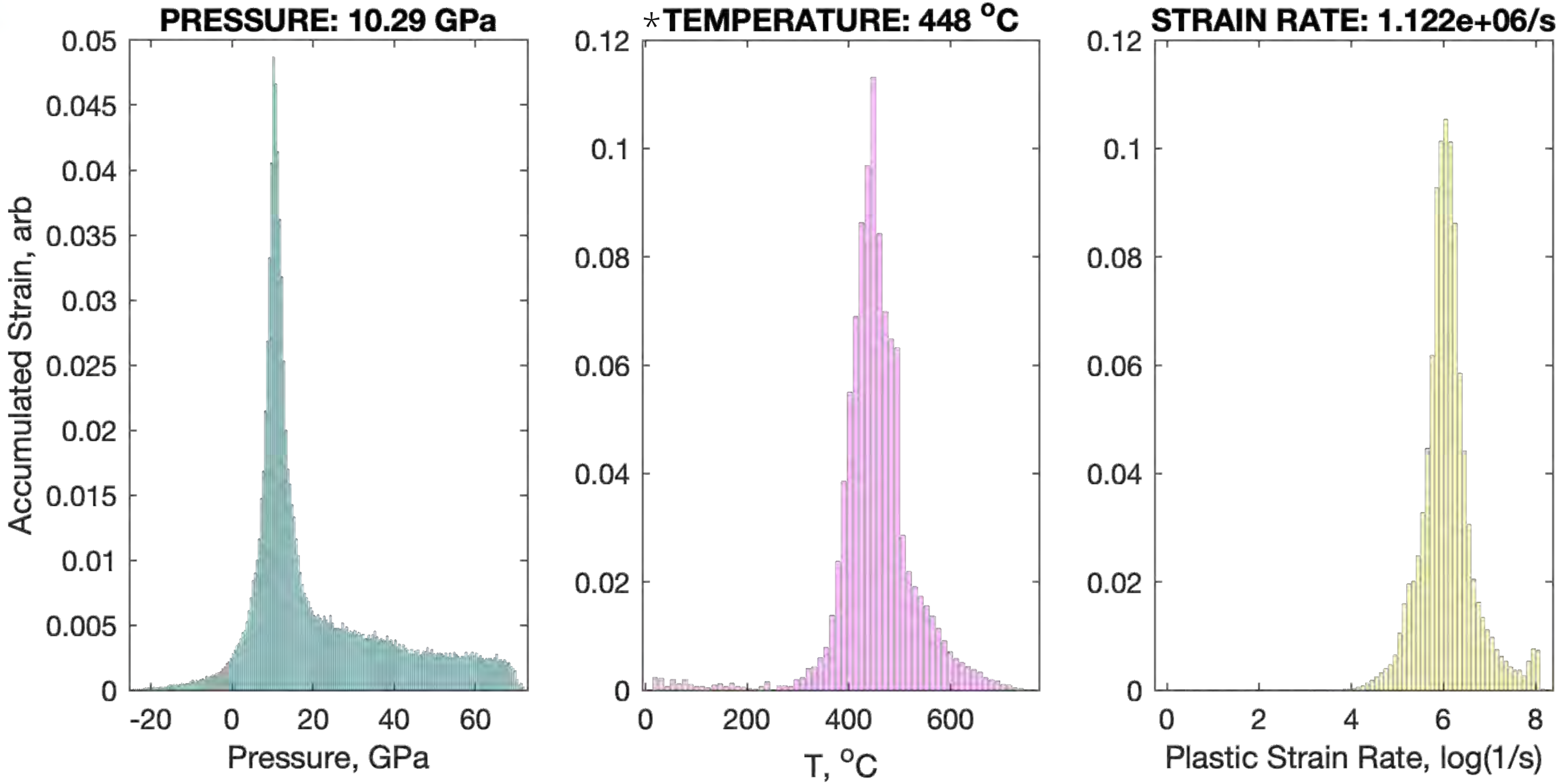
Direct contour comparison is calculated as the sum of minimum distances from sim. to exp. point clouds, i.e., models are fit against total strain.





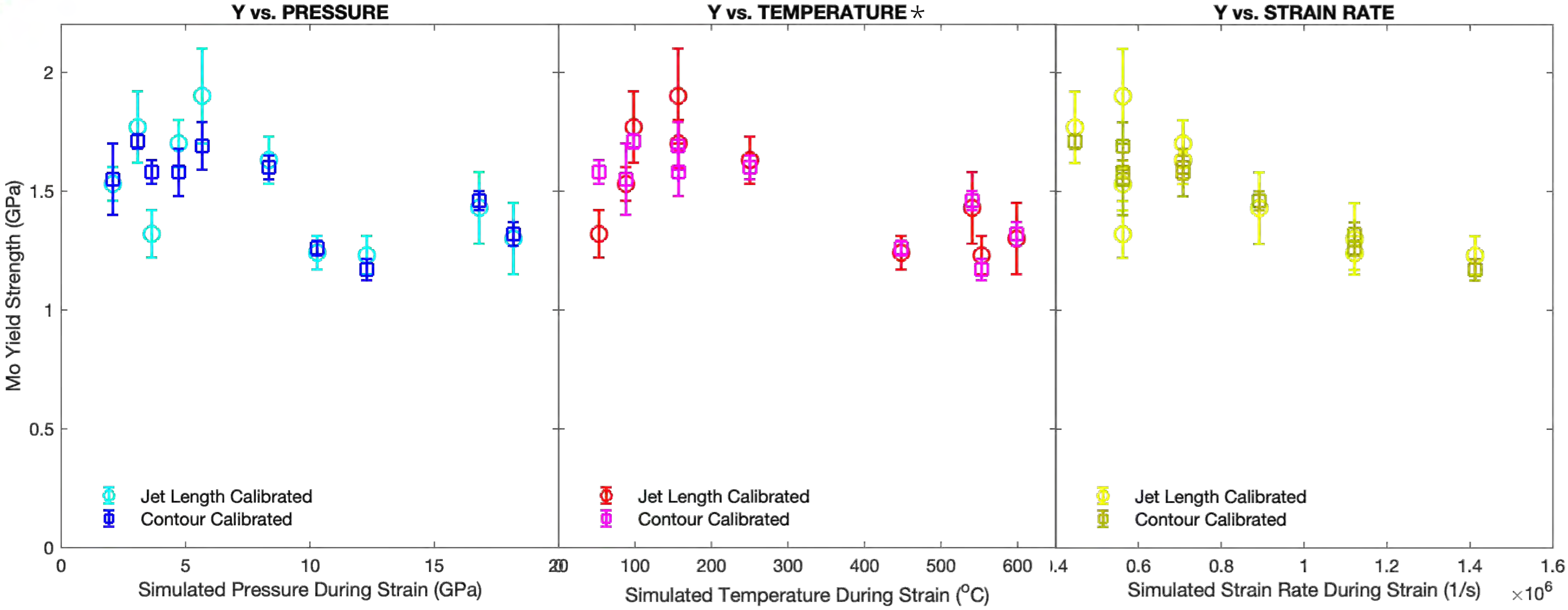
In some cases, only central jet [0,500] is used because of beam edges, etc.

The pressure, temperature, and strain rate associated with calibrated yield strength values are defined by where strain accumulates.



These histograms are generated for <u>each</u> shot to define P, T^*, and $\dot{\epsilon}$

The final product of this investigation is the pressure-, temperature-, and strain rate-dependent yield strength of Mo. Results preliminary, analysis on-going.



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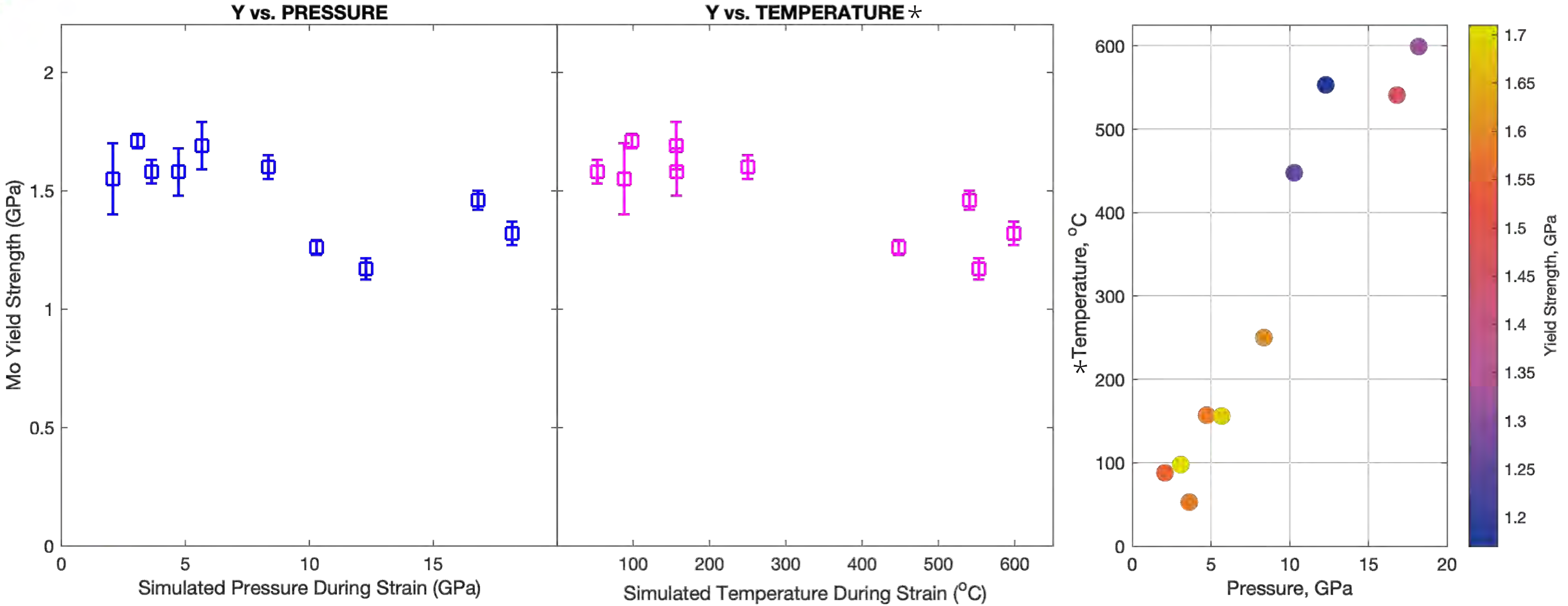
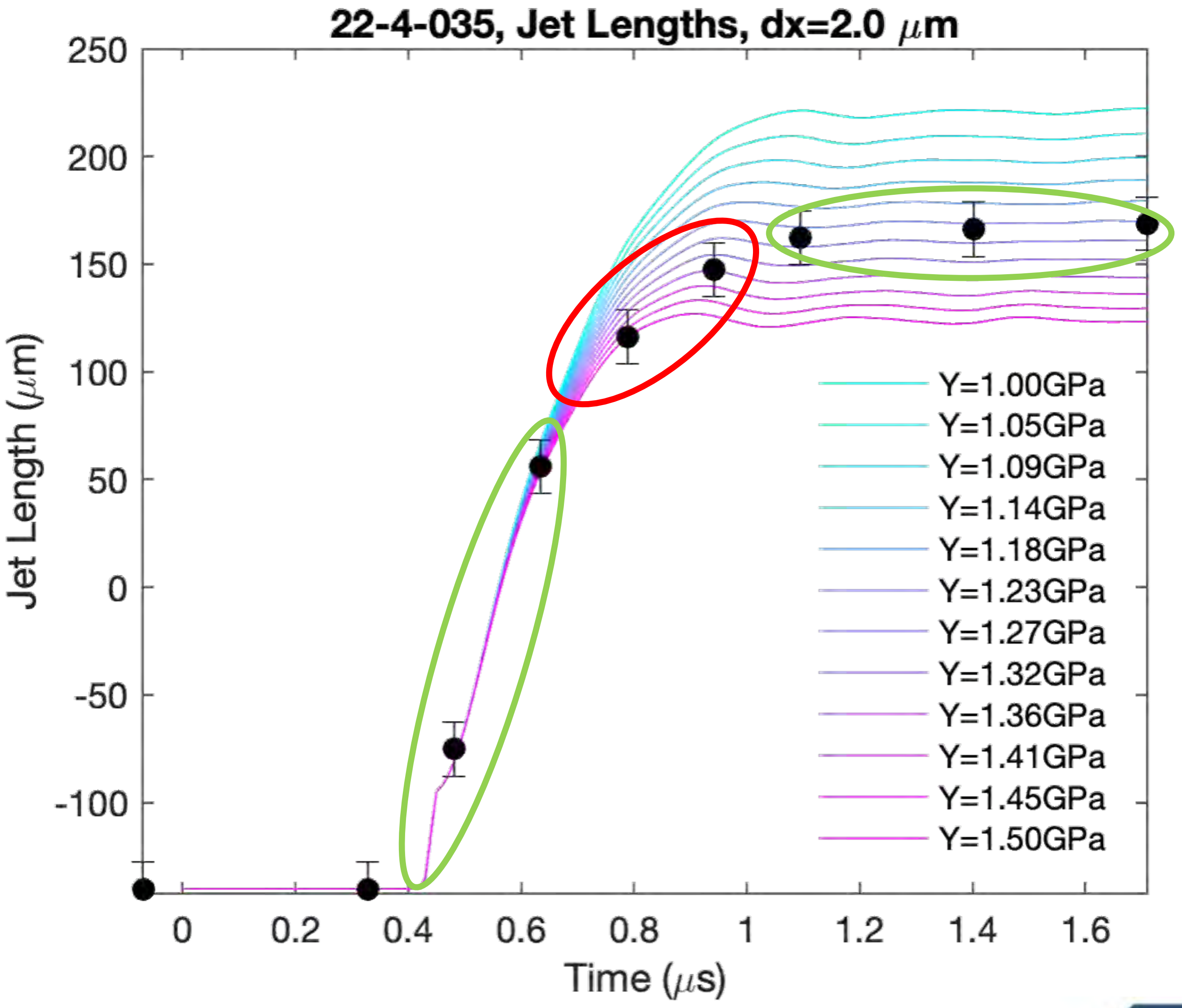


Contour calibrated values indicate competing factors of pressure hardening and thermal softening. Potential for strain or strain rate softening, but all strain rates are similar.

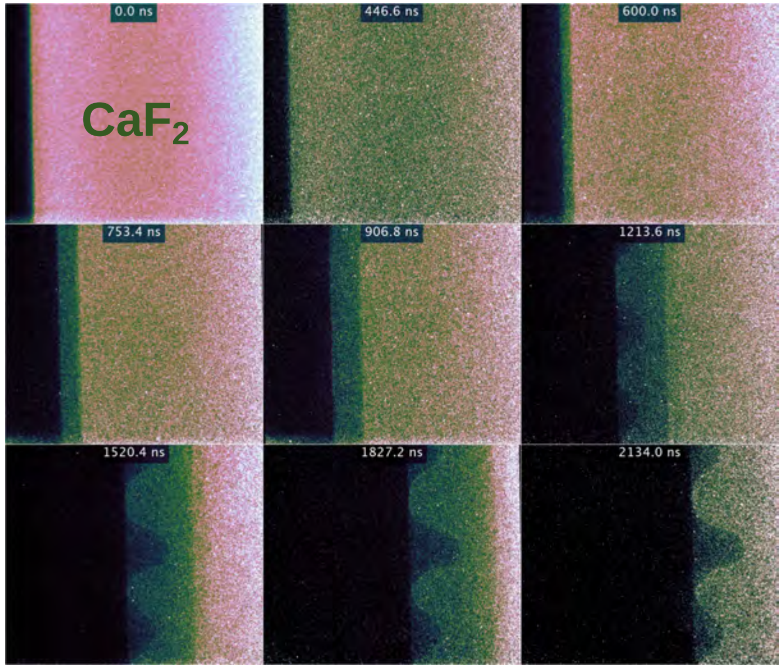
What's left in the analysis steps?

- Uncertainty calculations
- Calibration of more complex models:
  - Johnson cook
  - Steinberg Guinan Lund
- Code-to-code solution verification:
  - ALEGRA
  - SABLE
  - ZAPOTEC
  - FLAG

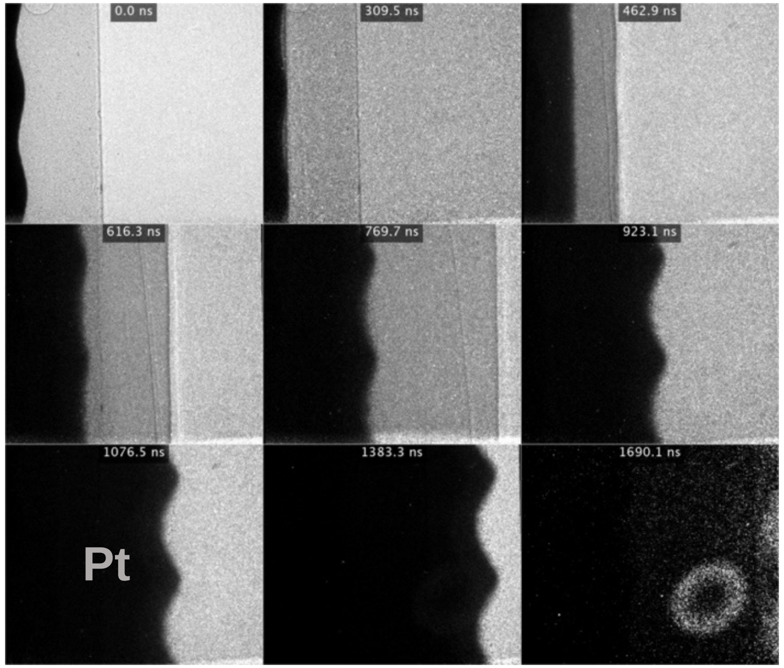


In addition to Mo, we have applied the tamped RMI method to a variety of metals, ceramics, and polymers. 154 shots completed since joining SNL.

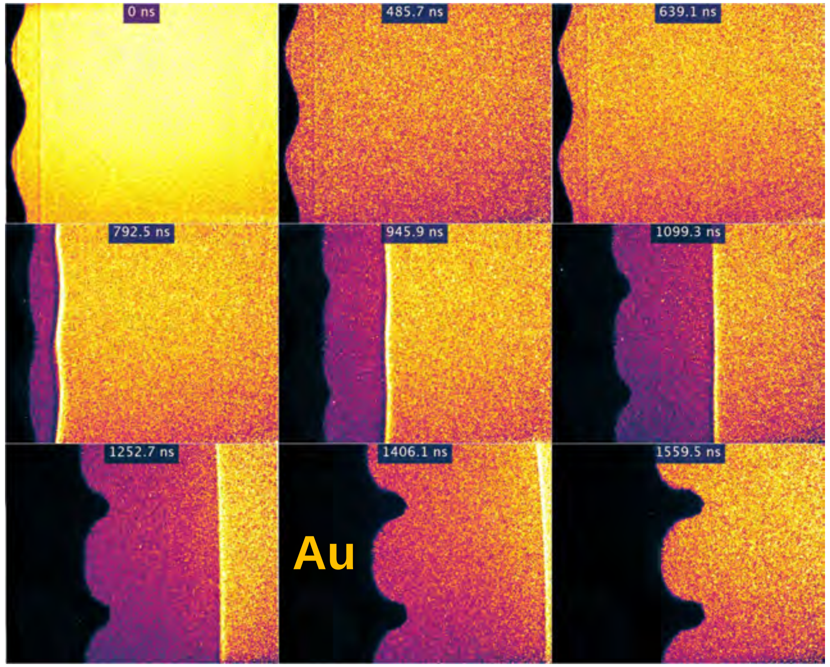
Cu-**CaF_2** powder, 40% TMD, 1035 m/s Cu flyer
37.5-50.0-37.5% multi-hemisphere driver

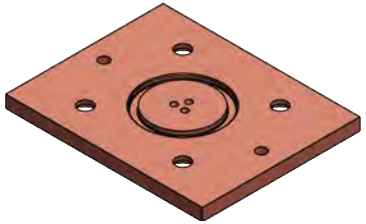


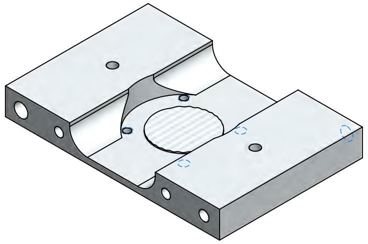
Pt-D_2O, 2147 m/s Ta flyer
sinewave driver, $k\eta_0 = 0.375$



Au-Perfluorooctane, 1817 m/s Cu flyer
sinewave driver, $k\eta_0 = 0.500$







Upcoming releases based on this work:
Dynamic strength of B_4C powder, SiC powder, CaF_2 powder, Al_2O_3 powder, Al_2O_3-Epoxy (ALOX) composites, Epon828, Pt, and Au

Acknowledgements

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- *SNL:* Brittany Branch, Stacy Guo, Seth Root, Tracy Vogler
- *SNL-CA Machine Shop:* Brian Holliday, Bryant Morgan
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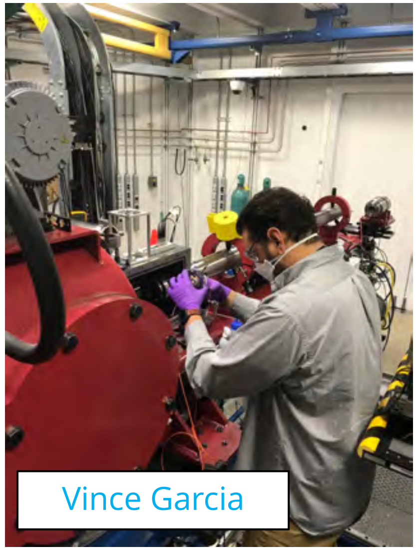
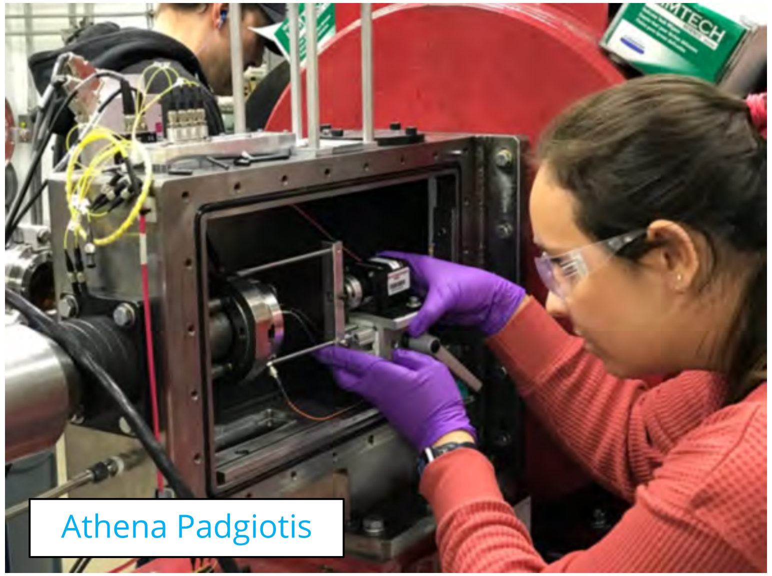
- *LLNL:* Anirban Mandal
- *WSU/DCS:* Robert Zill, Drew Rickerson, Adam Schumann, Nick Sinclair, Kory Green, Pinaki Das, Ray Gunawidjaja, Yuelin Liu, and the whole crew
- *Georgia Tech:* Ben Zusmann, Naresh Thadhani
- *NSWC:* Joe Olles


Ben Zusmann


Brian Holliday


Vince Garcia


Athena Padgiotis

Traveled with me and/or supported DCS experiments hands-on or remote
Machined components or programmed WEDM for every sample
General support and advice

DCS Acknowledgement

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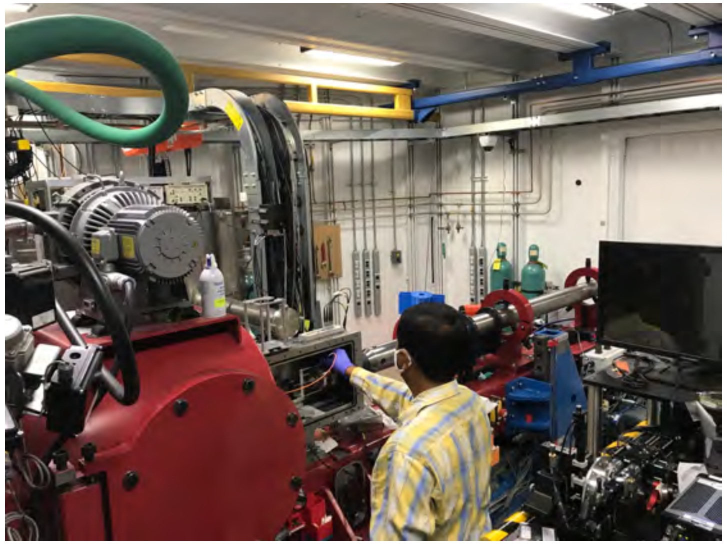

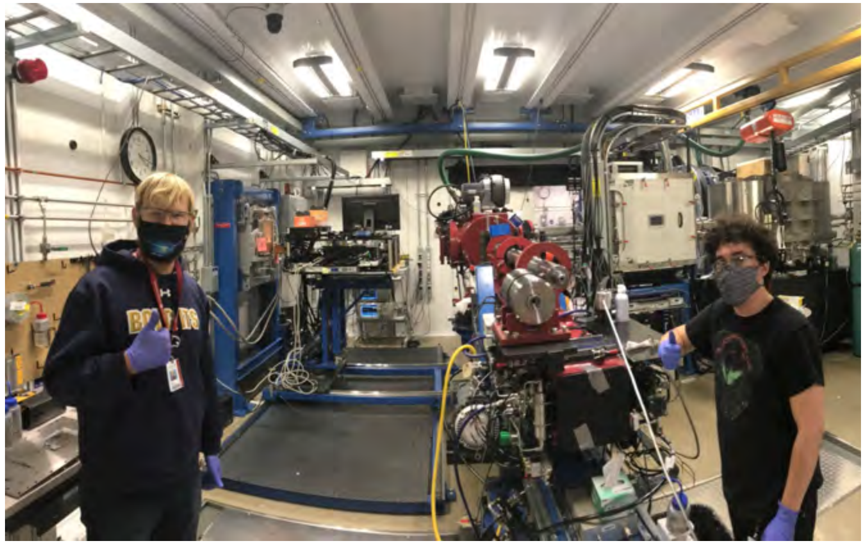

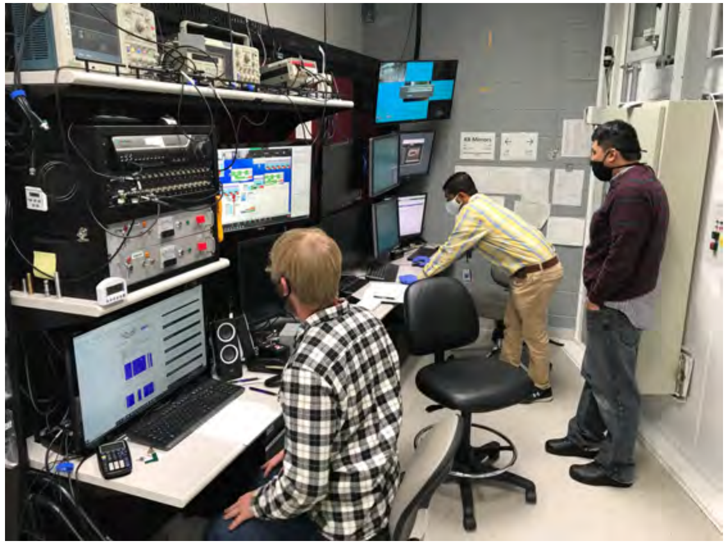

Thank you!

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