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Dynamic Interface Instabilities as a Window into Material Behavior

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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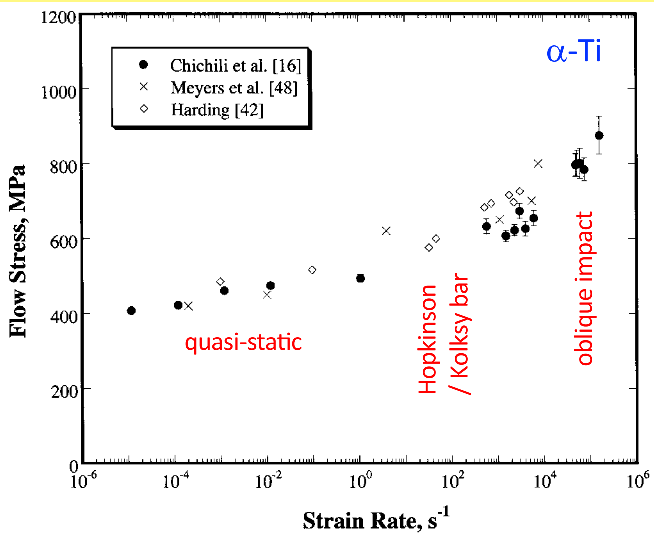
Motivation – Strength under Extreme Conditions

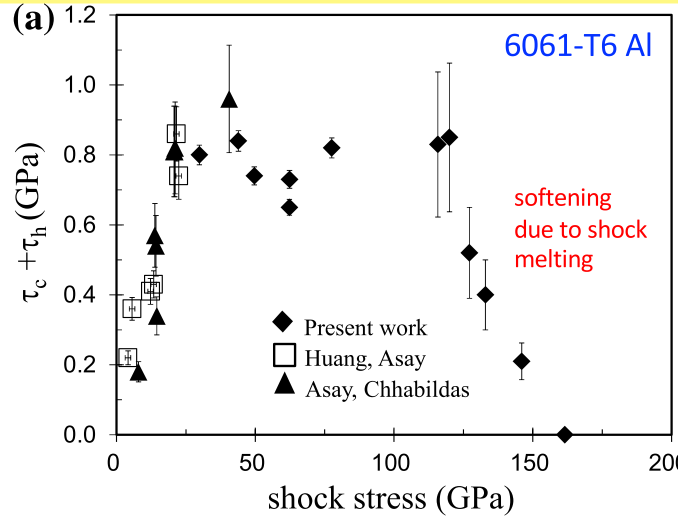
- For many applications involving high pressures and strain rates, the strength of materials cannot be neglected

The mechanics community tends to focus on strain rate dependence



Ramesh et al, MMT 2002

The shock physics community tends to focus on pressure dependence

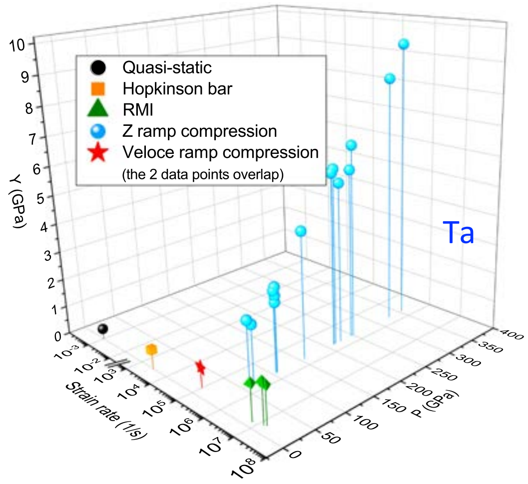


Reinhart et al., JDBM 2015

Motivation – Strength under Extreme Conditions

- Measuring strength in these conditions is challenging, and consistency across techniques difficult to achieve
- Pressure and strain rate cannot always be readily controlled independently
- Picture is further complicated by thermal effects due to shocks and loading path dependence
- Need for techniques to probe material strength in regimes of high pressures (few to 100's of GPa) and strain rates (>10^5 1/s)

Strength dependence on strain rate and pressure



Prime et al., PRE 2019

Dynamic Interface Instabilities

- Arise at interface between dissimilar materials: gases, liquids, solids
- Shear, gravitational, and shock instabilities are most commonly studied; usually occur together in real problems
- Studied because of their importance to a variety of physical phenomena and applications
- Instability stabilized by factors such as surface tension, viscosity, and strength
- Thus, the instability development can be used to probe (not directly measure) these aspects of material behavior

Physical Mesomechanics **10** *5–6 (2007) 265–274*

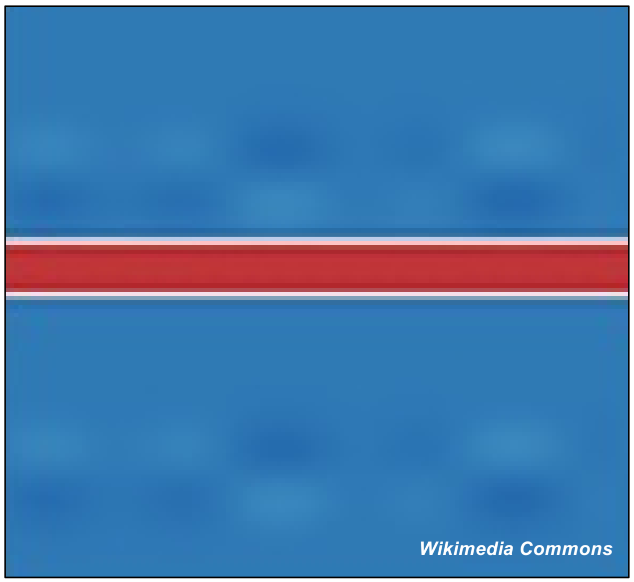
Hydrodynamic instabilities in solid media — from the object of investigation to the investigation tool

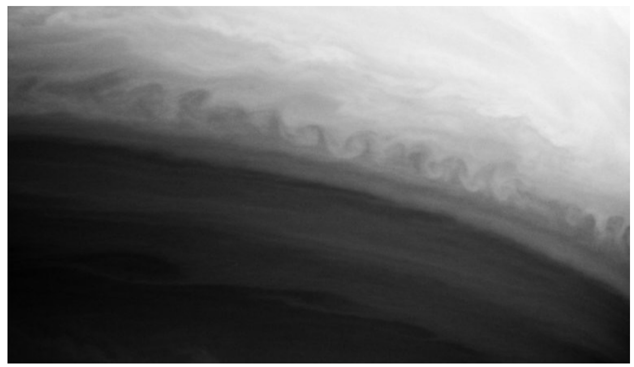
A.L. Mikhailov

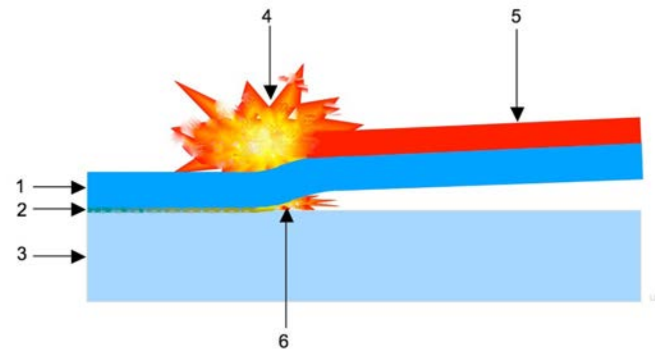
Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics (VNIIEF), Sarov, 607188, Russia

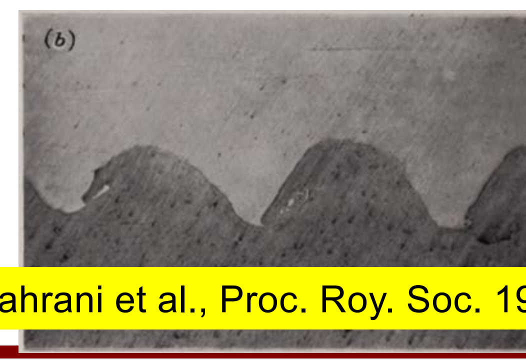
Kelvin-Helmholtz Instability (KHI)

- Shear instability
- Develops at interface between two layers undergoing shearing
- For inviscid fluids, unstable under all conditions







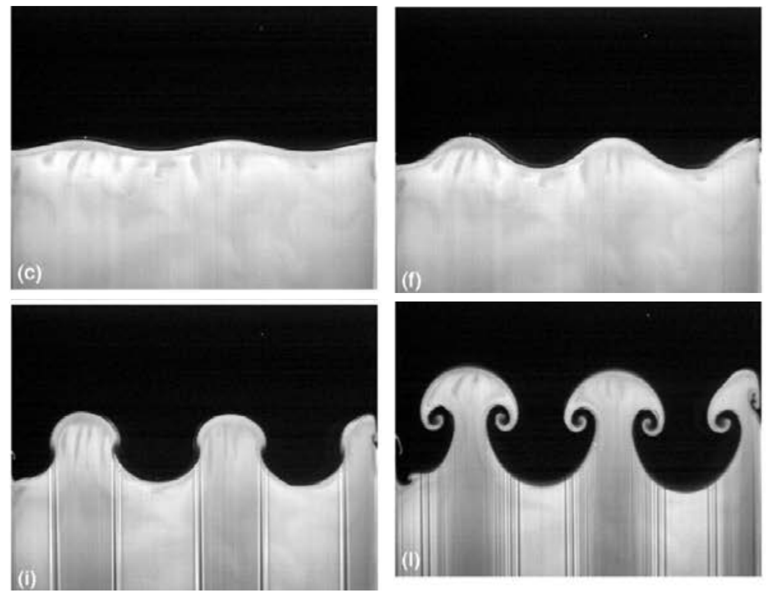


Bahrani et al., Proc. Roy. Soc. 1967

Static Rayleigh-Taylor Instability (RTI)

- **Gravitational** or acceleration instability
- Unstable if dense fluid is above light fluid

$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$



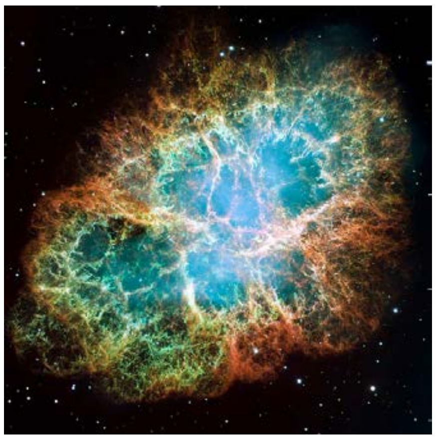
Waddell et al., Phys. Fluids, 2001

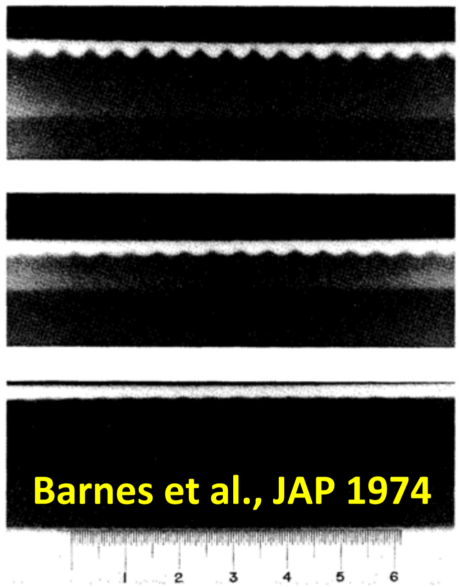
Dynamic Rayleigh-Taylor Instability (RTI)

- Gravitational or **<u>acceleration</u>** instability
- Unstable if light material is pushing on dense material

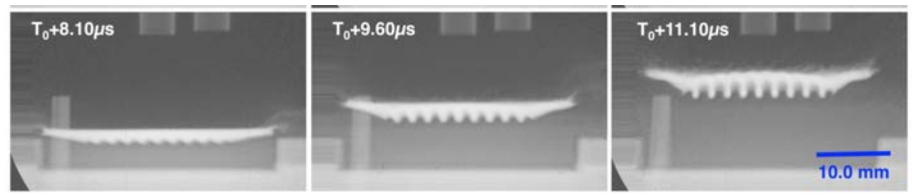
$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

Review: Zhou, *Phys. Rep.*, 2017

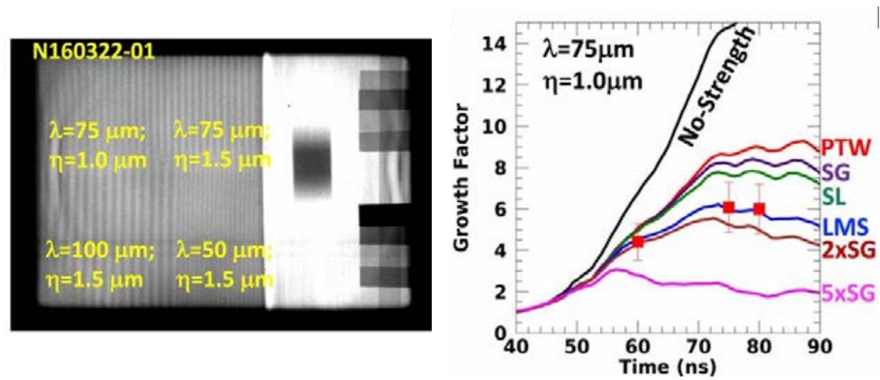




Barnes et al., JAP 1974



Olson et al., SCCM 2014



Remington et al., PNAS 2019

Richtmyer-Meshkov Instability (RMI)

- Shock instability

Richtmyer, R. D. (1960). "Taylor instability in shock acceleration of compressible fluids," *Communications on Pure and Applied Mathematics* **13**, 297-319. (originally published as a LANL report)

Meshkov, E. E. (1969). "Instability of the interface of two gases accelerated by a shock wave," *Soviet Fluid Dynamics* **4**, 101-108.

Robert D. Richtmyer
1910-2003

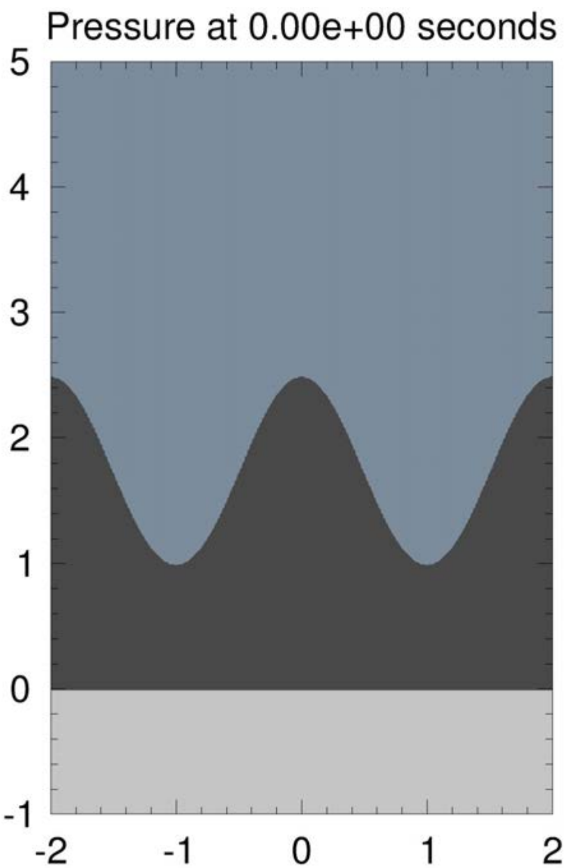
1937-2020

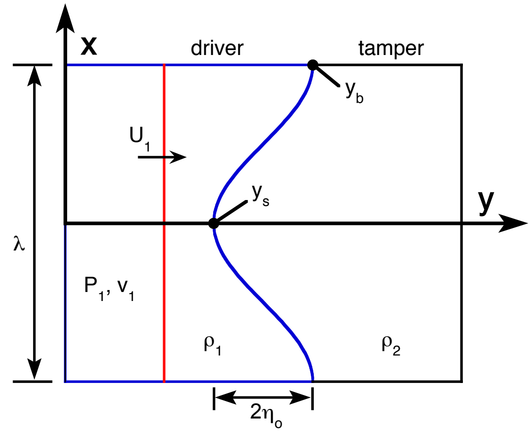
- taught at Stanford 1936-40
- Manhattan Project and LANL
- later taught at NYU and U. of Colorado at Boulder
- with Ulam and von Neumann developed Monte Carlo methods for neutronics
- with von Neumann developed artificial viscosity (1950)

worked at Sarov throughout his career beginning in 1960

Richtmyer-Meshkov Instability (RMI) $1 \geq A > 0$

Review: Brouillette, *Ann. Rev. Fluid Mech.*, 2002





$$k\eta = \frac{2\pi\eta}{\lambda}$$

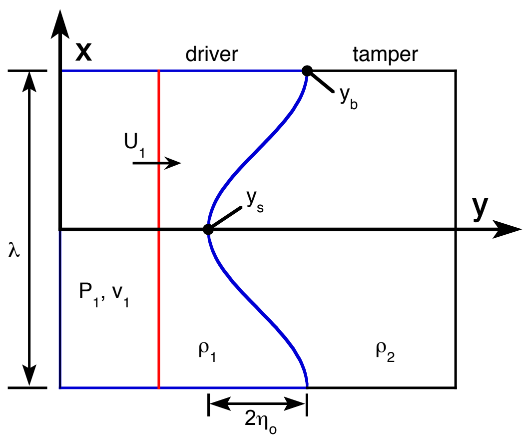
wave number

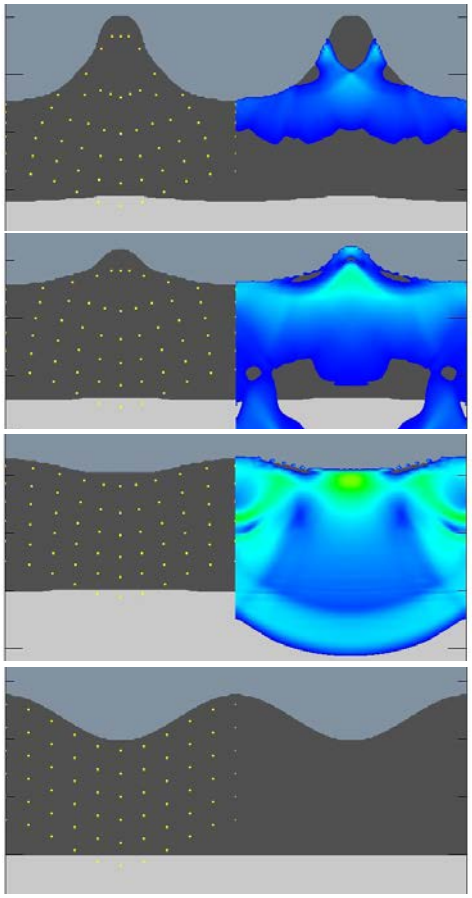
- for A>0 ($\rho_1 < \rho_2$) shock propagates from low- into high-density material
- limiting case of RTI
- perturbation generally grows

Richtmyer-Meshkov Instability (RMI) 0>A≥-1

Review: Brouillette, *Ann. Rev. Fluid Mech.*, 2002

- for 0>A ($\rho_1>\rho_2$) shock propagates from high- into low-density material
- vacuum A=-1 is limiting case
- with sufficient driving force, the perturbation can invert and form a jet (spike)
- jet may arrest or continue growing until it separates (ejecta)
- overdriven cases can also mushroom

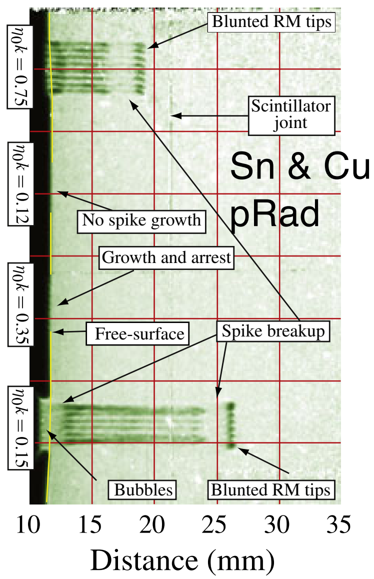


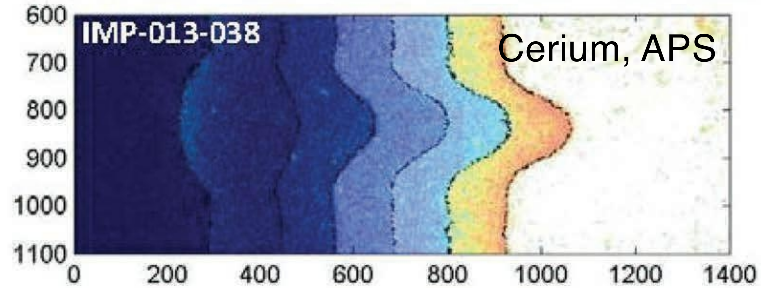


RMI Strength Experiments at *A*=-1

- Backed by vaccum, so ρ_2=0
- Both radiography and velocimetry diagnostics

Dimonte et al. (2011). Phys. Rev. Let.
Buttler et al. (2012). J. Fluid Mech.

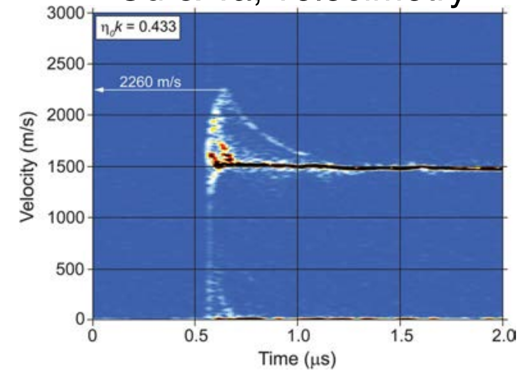




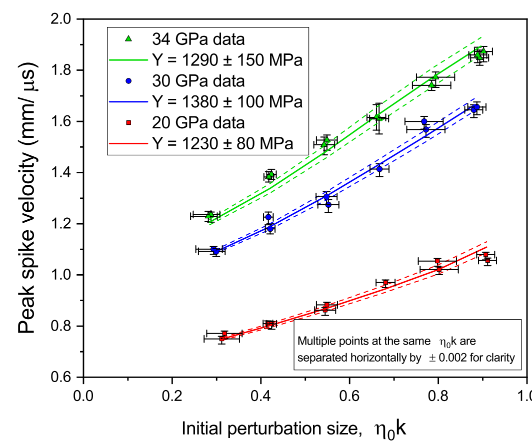
Jensen et al. (2015). J. App. Phys.

$$\frac{\eta_\infty - \eta_o}{\eta_o} = Ck\eta_o \frac{\rho u_{fs}^2}{Y}$$

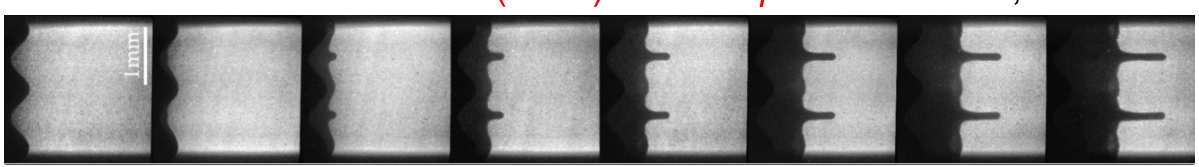
Cu & Ta, velocimetry



Prime et al. (2017). JDBM
Prime et al. (2019). Phys. Rev. E



Olles et al. (2019). *Soc. Exp. Mech.* Cu, DCS



Tamped RMI Strength Experiments ($A\neq$-1)

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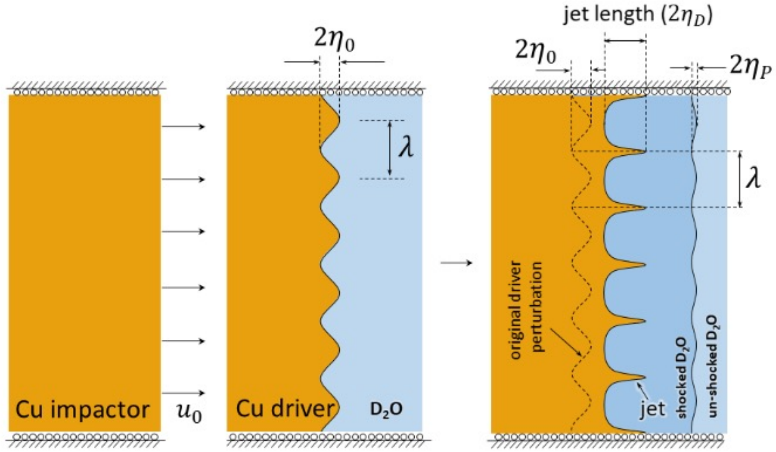
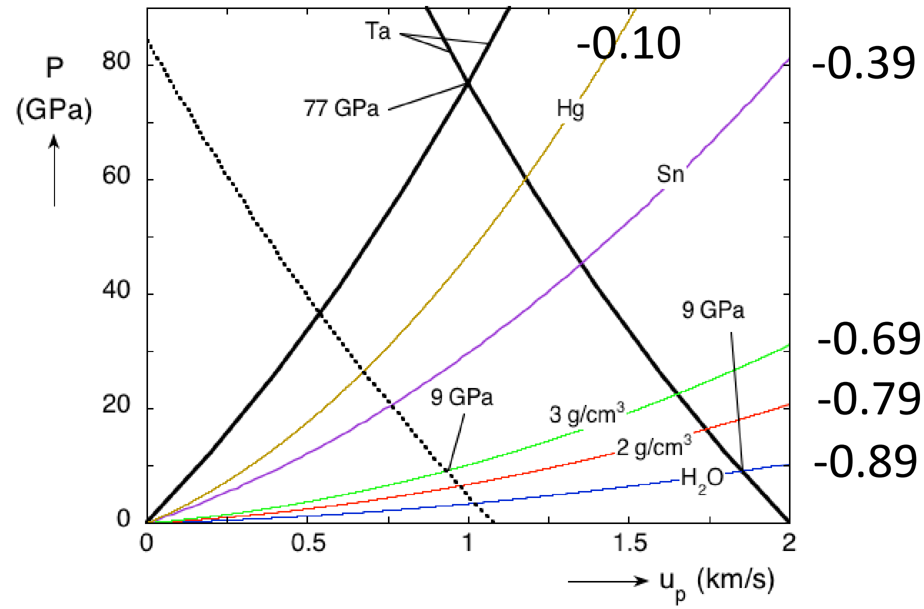
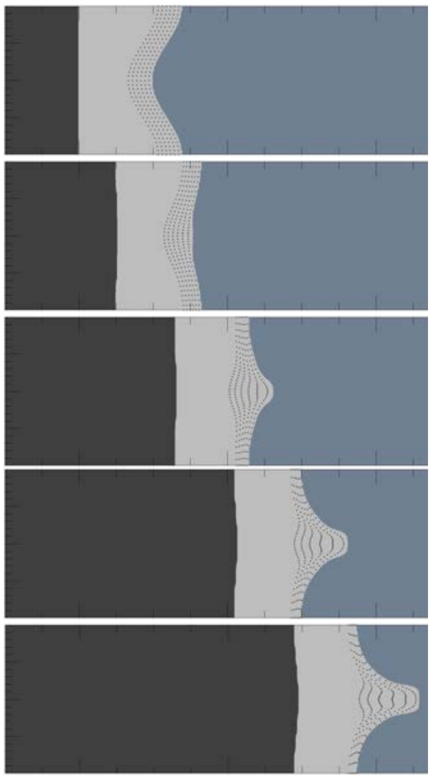


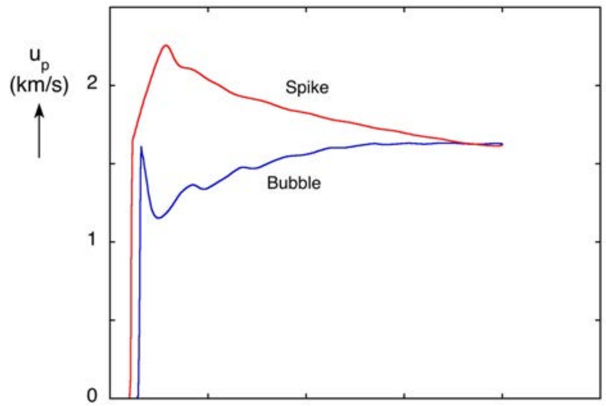


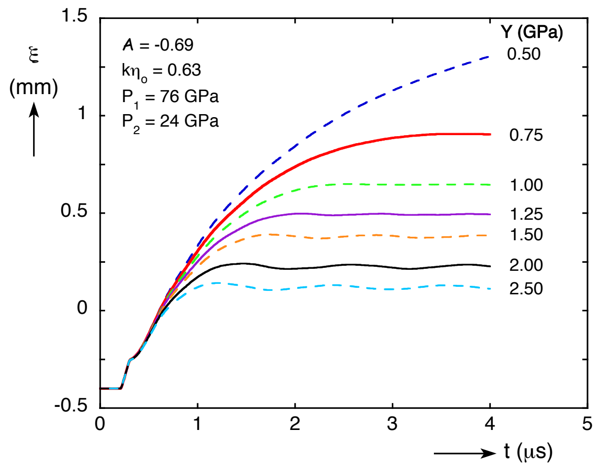
- Adding tamper keeps P above zero, reducing role of damage
- Potential tampers depend upon instrumentation needs/capabilities, but some options available
- For velocimetry, need transparent liquid. With radiography, limited by transmission.
- Liquids: water, perfluorooctane, perflubron, sodium metatungstate solution
- Low melting point metals: Field's metal, Wood's metal, Galinstan, Hg
- Metal powder (Sn, In, Au, etc.)

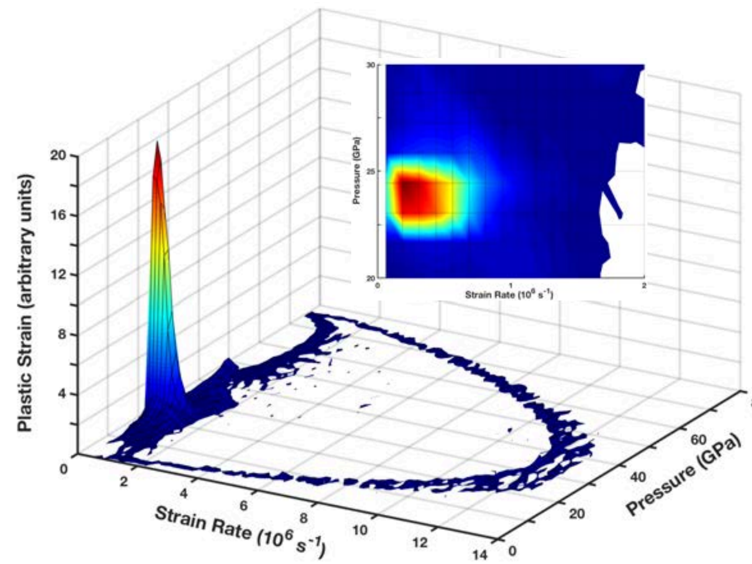
Example: Ta Tamped by Sodium Metatungstate

V = 2 km/s, λ=2 mm, $k\eta_o$=0.63, A=-0.69, P_1=76, P_2=24 GPa, Y_1=0.75 GPa





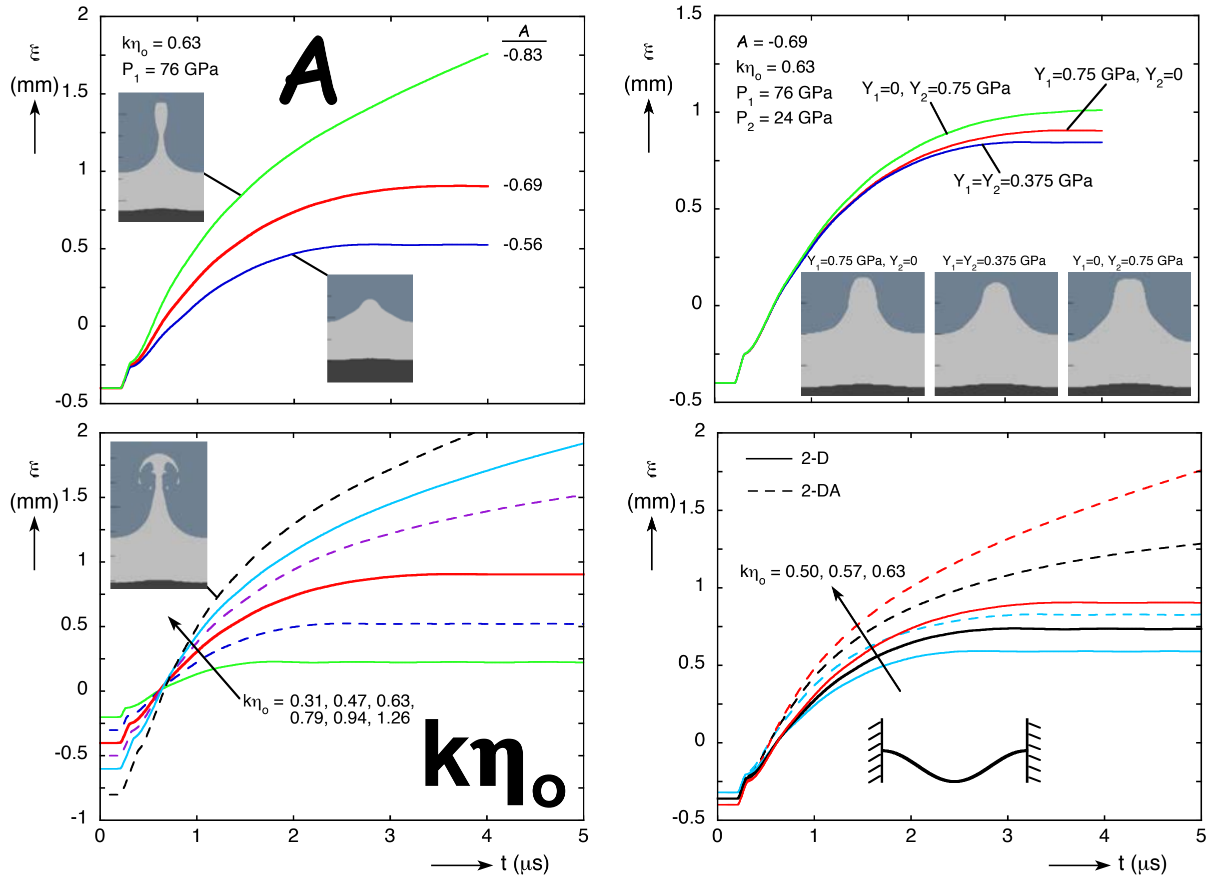




- Though loading is complex, most plastic work occurs near P_2 and 2×10^5 s^{-1}

Tamped RMI Sensitivities

V = 2 km/s, λ=2 mm, kη$_o$=0.63, *A*=-0.69, P$_1$=76, P$_2$=24 GPa, Y$_1$=0.75 GPa

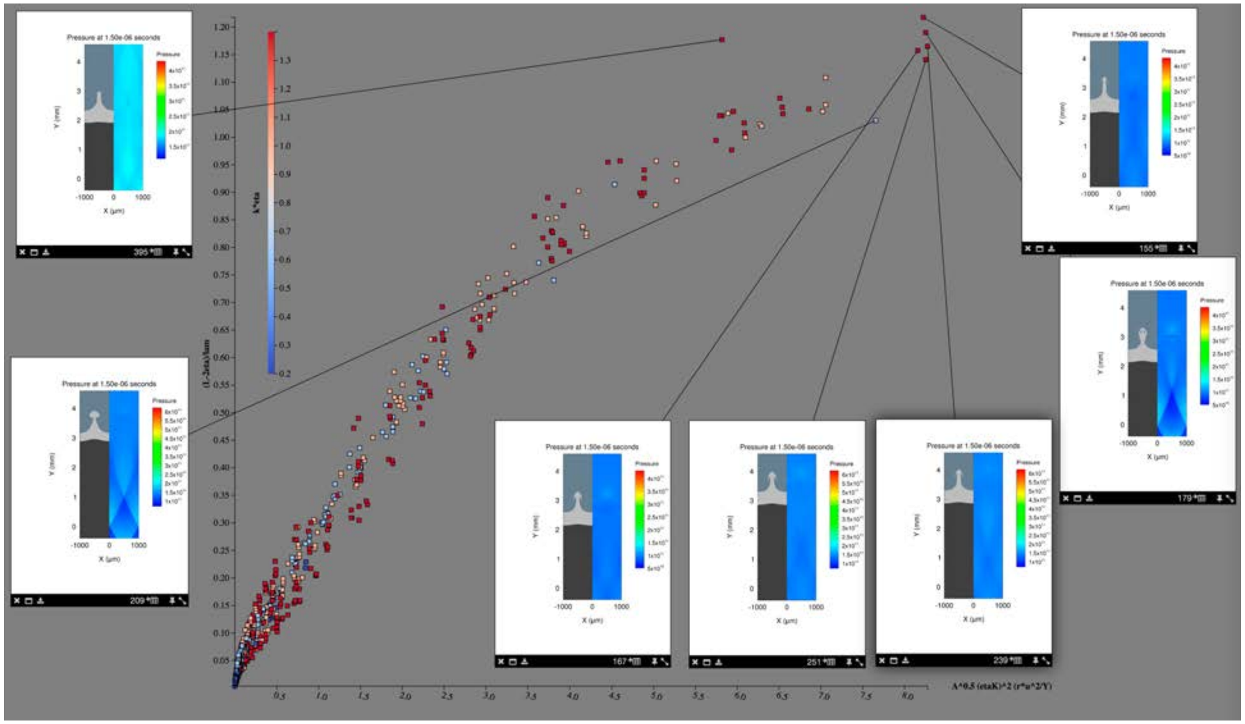


$$\bar{Y} = Y_1 + Y_2 = C$$

- To first order, the sum of the strengths controls jet growth
- Axisymmetric configuration promotes instability

Simulation Ensembles: Dakota & Slycat

- Dakota drives large number (~2000) of simulations for Ta tamped by a fluid, randomly sampling:
  - impact velocity (1-3 km/s)
  - wave parameter (0.25-1.50)
  - tamper density (1.0-7.9 g/cm^3)
  - Ta strength (0.1-3.0 GPa)
- Slycat used for visualizing data on cluster or locally - identify different classes of behavior (e.g. mushrooming) more easily



Non-Dimensionalization of Problem

- A number of different choices possible for RMI experiments, so examine scaling using non-dimensionalized parameters
- Atwood number (*A*) captures relative densities

$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

- Wave number specifies amplitude of the perturbation of the interface

$$k\eta = \frac{2\pi\eta}{\lambda}$$

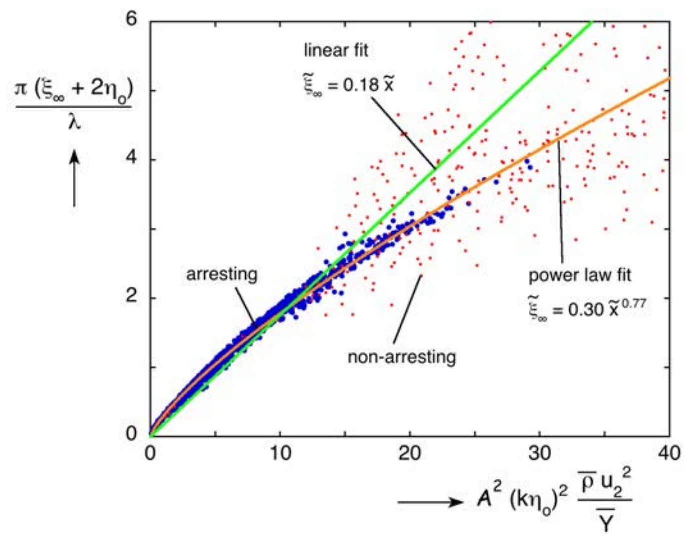
- Strength term quantifies its stabilizing effect

$$\frac{1}{\tilde{\bar{Y}}} = \frac{\bar{\rho} u_2^2}{\bar{Y}}$$

$$\bar{\rho} = \rho_1 + \rho_2$$

$$\bar{Y} = Y_1 + Y_2$$

Scaling for Tamped RMI

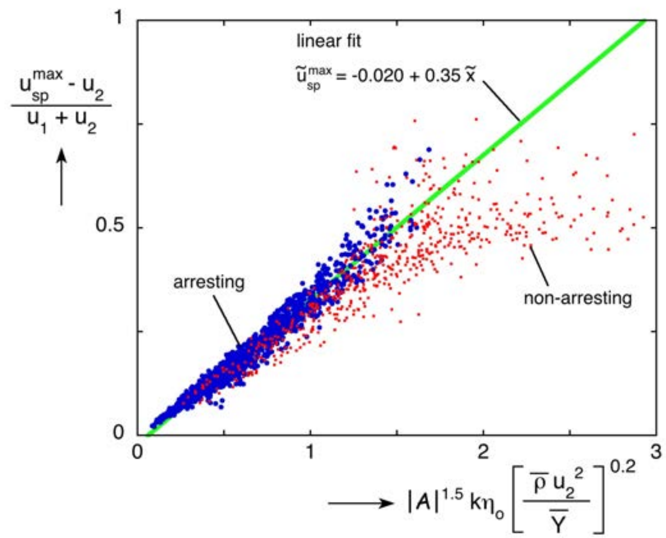


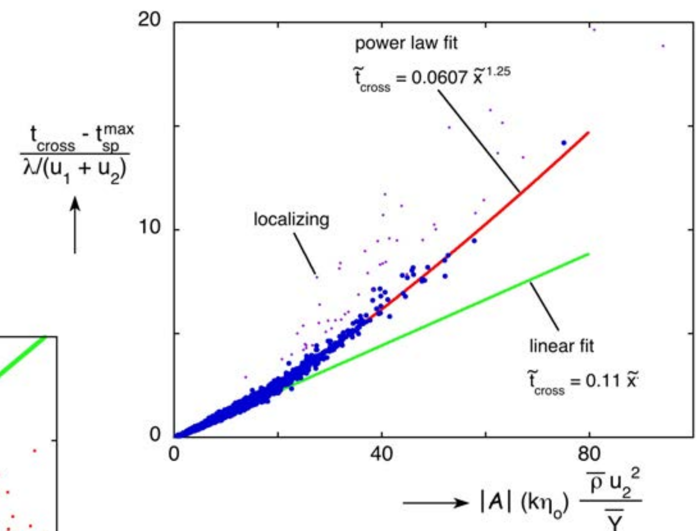
Arrested Length

- probably requires imaging
- scaling agrees with previous work
- proportional to Y^{-1}

Max Spike Velocity

- only need velocimetry
- useful for non-arresting cases
- proportional to $Y^{-0.2}$

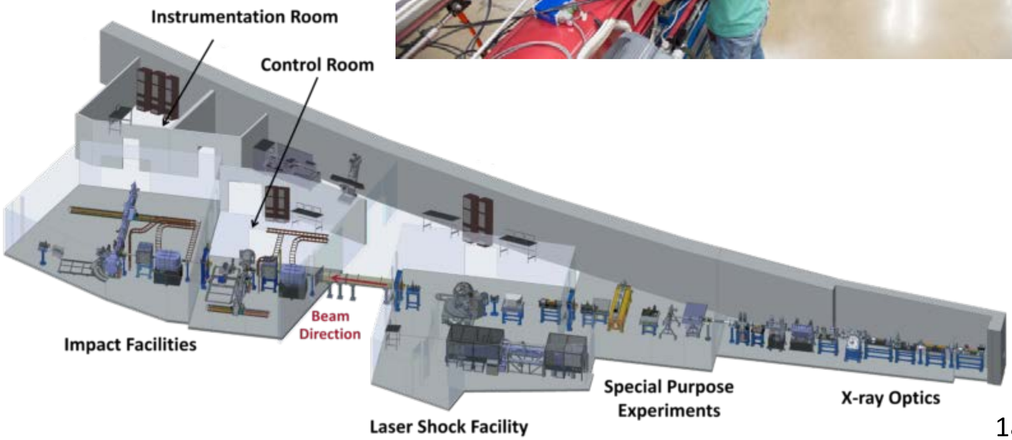




Time when $u_{sp} = u_{bub}$

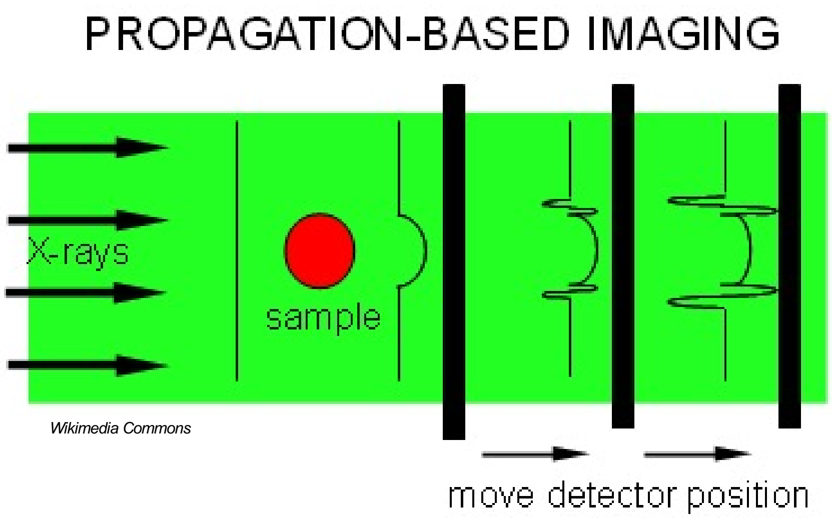
- may be possible for velocimetry
- proportional to Y^{-1}

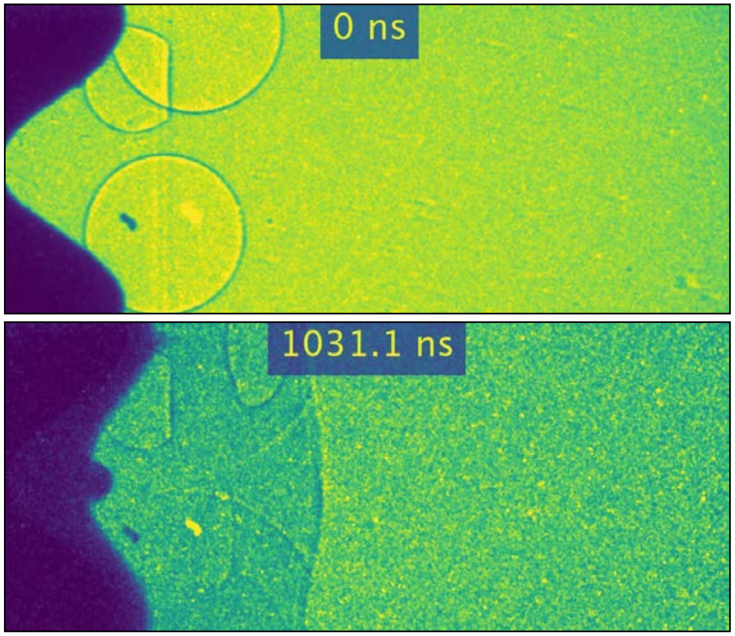
The Dynamic Compression Sector (DCS)
at the Advanced Photon Source at Argonne National Laboratory



- electrons accelerated to high velocities
- bending emits X-rays
- 35 sectors for different uses

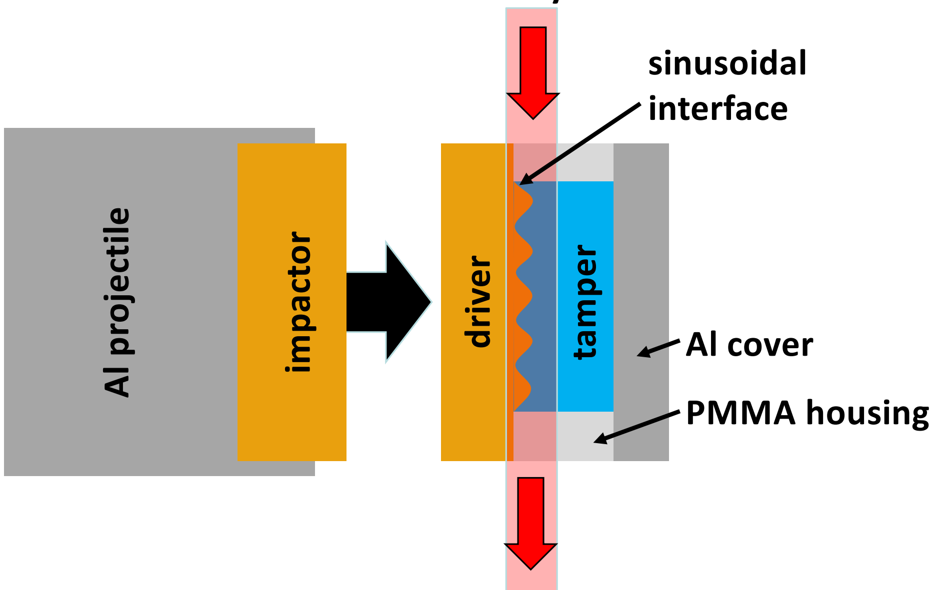
X-ray Phase Contrast Imaging

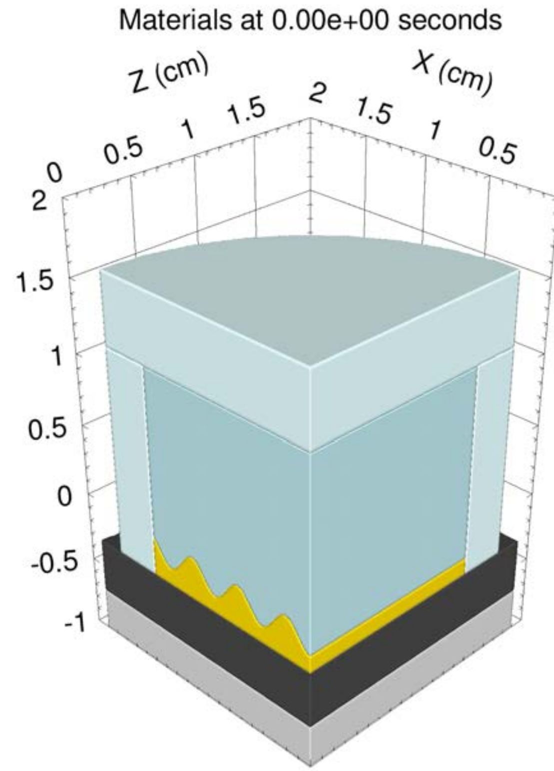




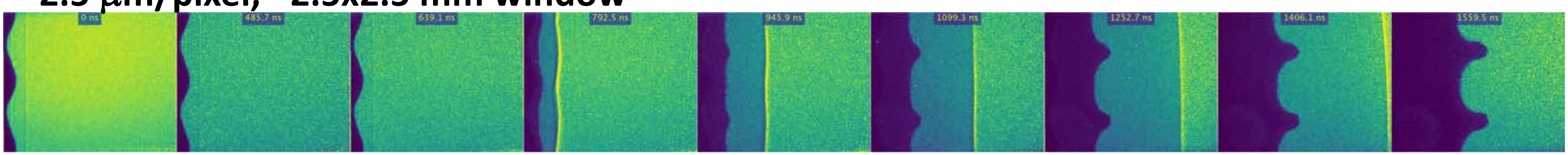
- Detector far from sample
- Tuned to <u>emphasize</u> edges
- Areal density inaccurate if edges are in ROI

Overview of DCS Experiments





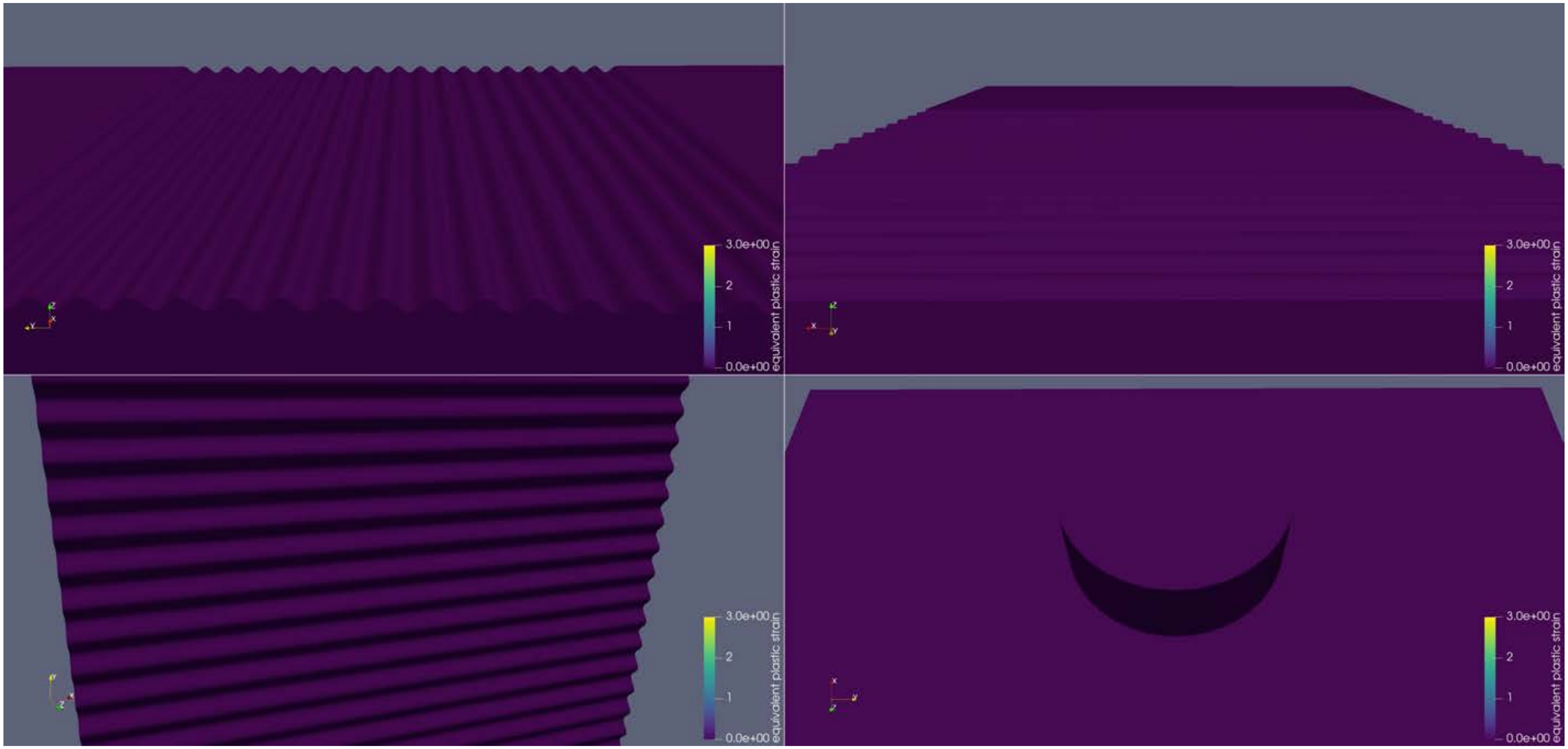
~2.5 µm/pixel, ~2.5x2.5 mm window



static preshot + eight images at 153 ns intervals (33.5 ps FWHM)

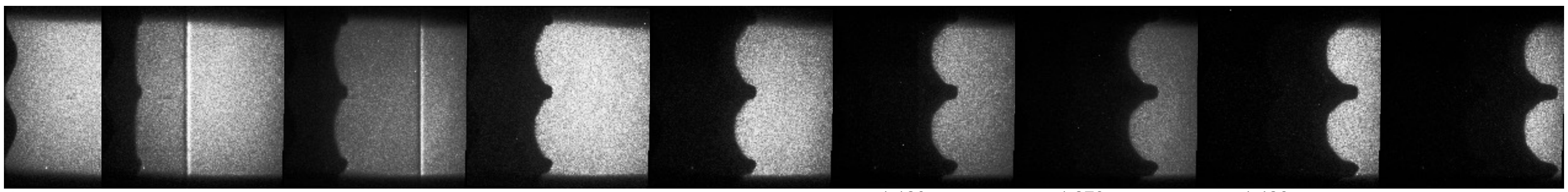
Overview of DCS Experiments

video courtesy of Alejandro Mota (SNL)

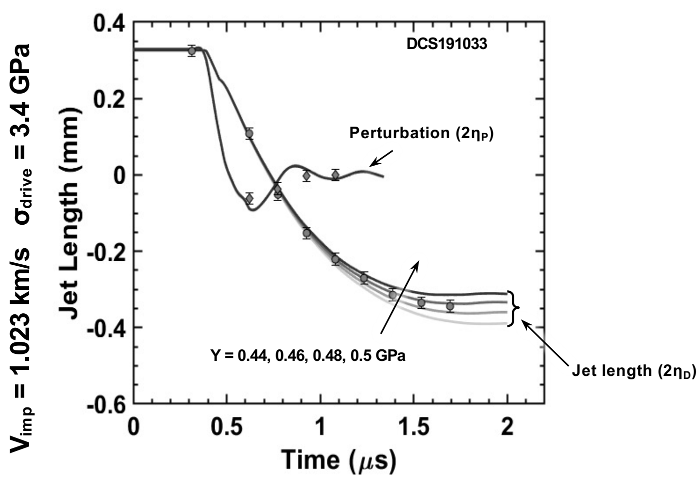


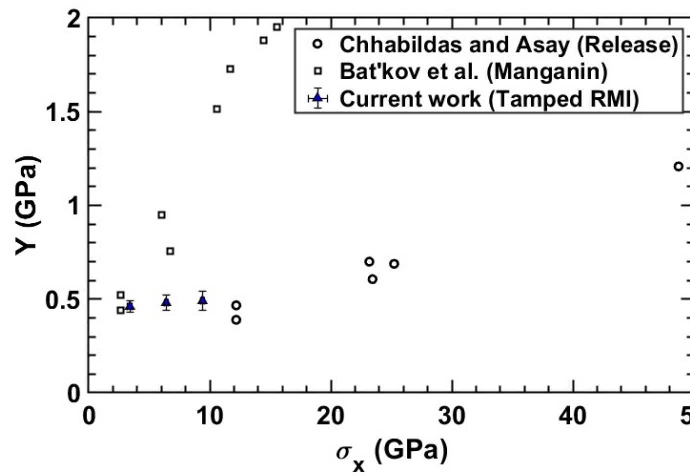
D_2O Tamped RMI Experiments on Cu at DCS

S19-1-036 – Ta/Cu - 1.668kms P1: 47.8 GPa, P2: 9.4 GPa $\eta_o k = 0.5$, $A_o = -0.78$



t_{static} t = 0.353 μs t = 0.660 μs t = 0.813 μs t = 0.966 μs t = 1.120 μs t = 1.273 μs t = 1.426 μs t = 1.580 μs



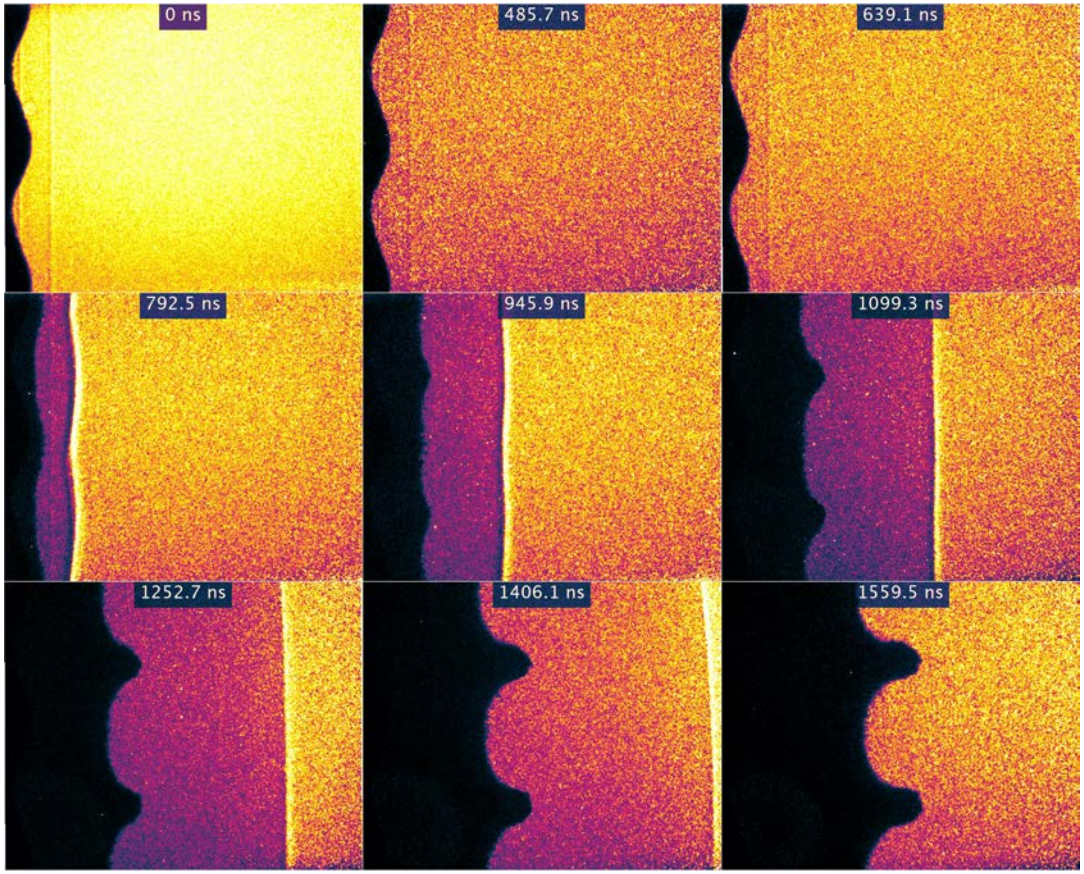


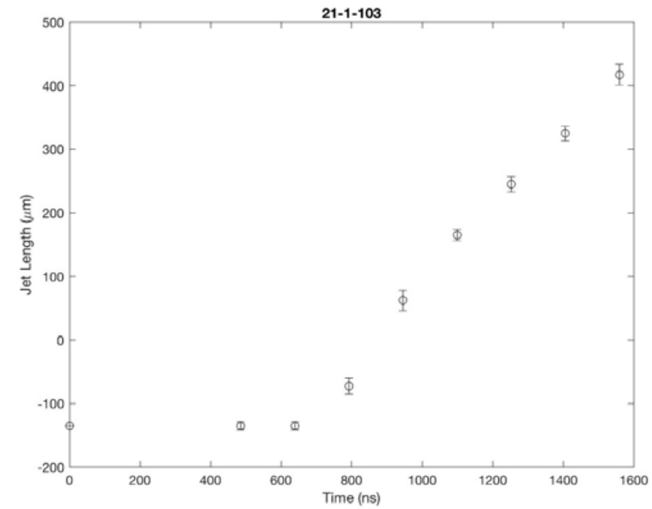
Once calibrated, jetting copper can be used as driver for testing with other materials

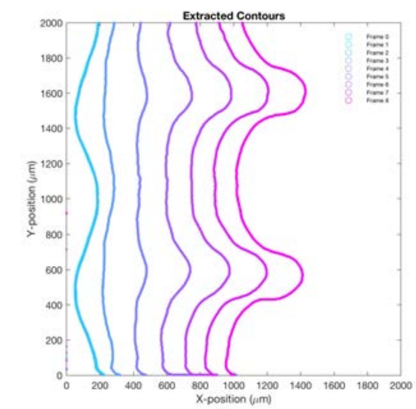
Au Tamped with Fluorooctane (PFO)

V=1.817 km/s, Cu impactor

$\eta_o k = 0.5$, $A_o = -0.83$



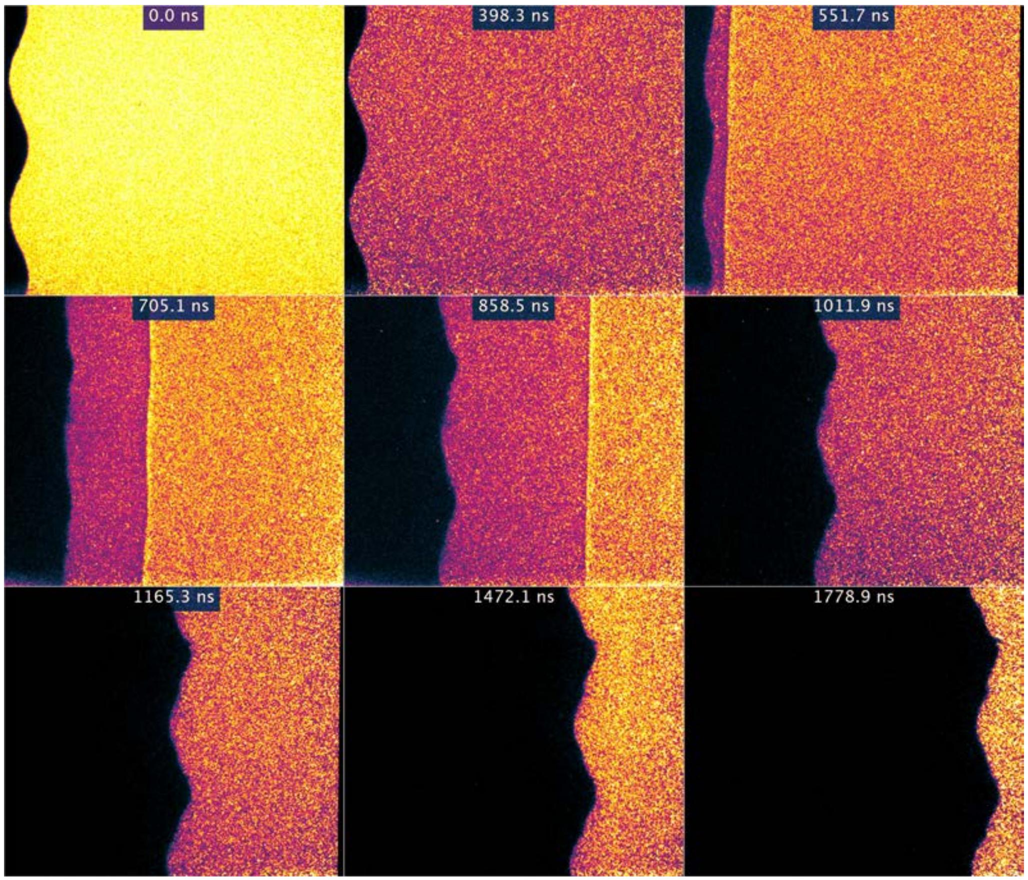


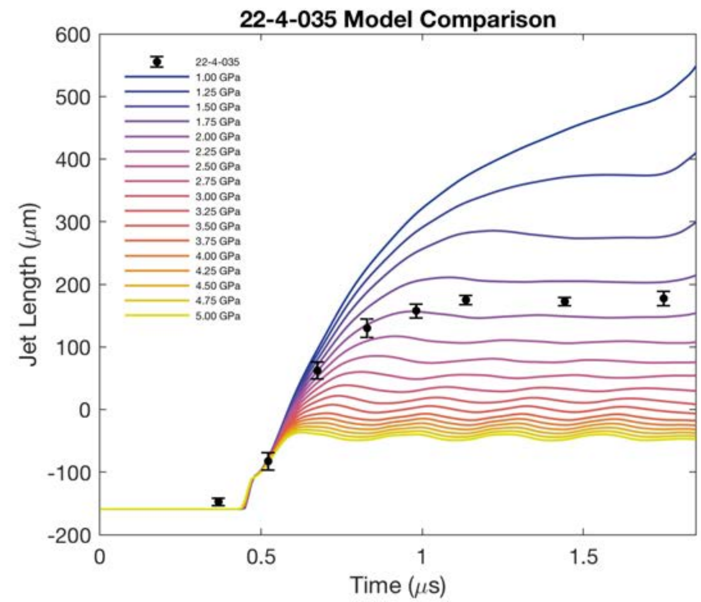


Mo Tamped with D2O

V=2.066 km/s, Ta impactor

$\eta_o k = 0.5$, $A_o = -0.80$

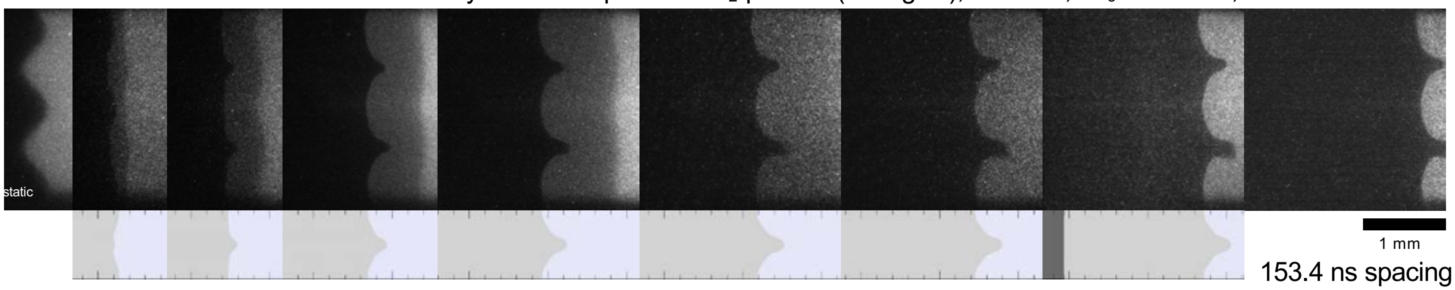




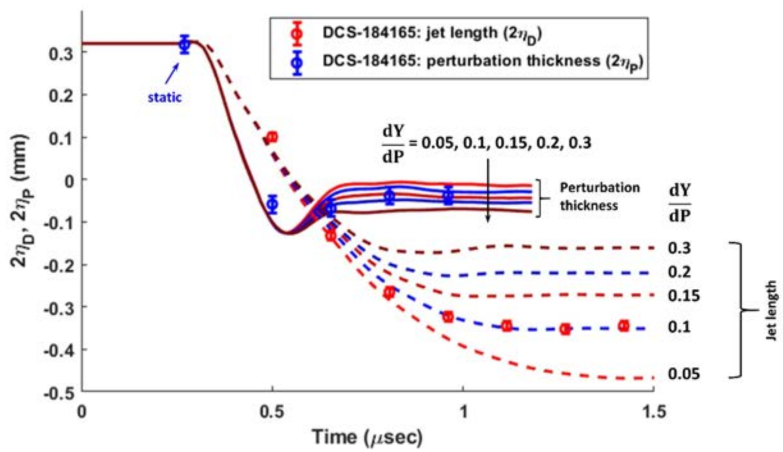
RMI Experiments on Granular SiO_2 at DCS

Sandia National Laboratories

Shot: DCS184165 – V = 2.0 km/s – Cu symmetric impact in SiO_2 powder (1.55 g/cc), λ=1 mm, $2a_o$=0.32 mm, P≈9.5 GPa

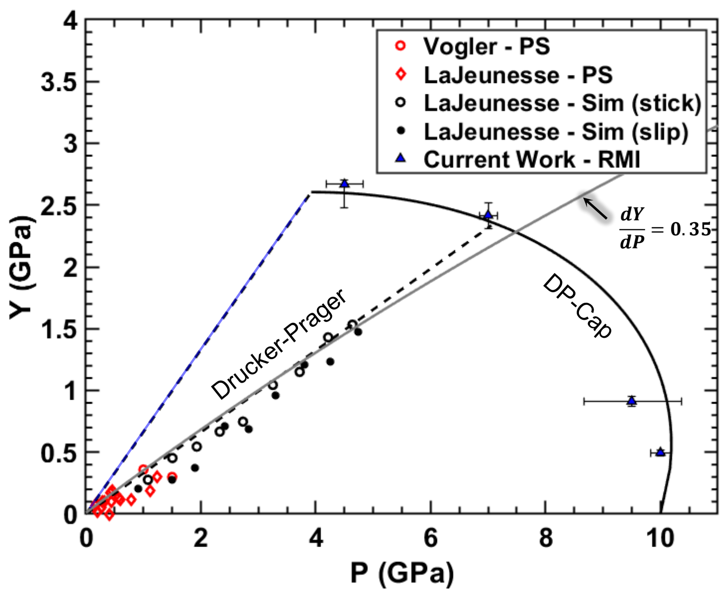


153.4 ns spacing



- RM unstable interface (A ≈-0.7/-0.5) leads to jetting, but jets arrest due to strength of compacted SiO_2
- jet amplitude much more sensitive to strength than shock front perturbation

Granular SiO_2 Strength

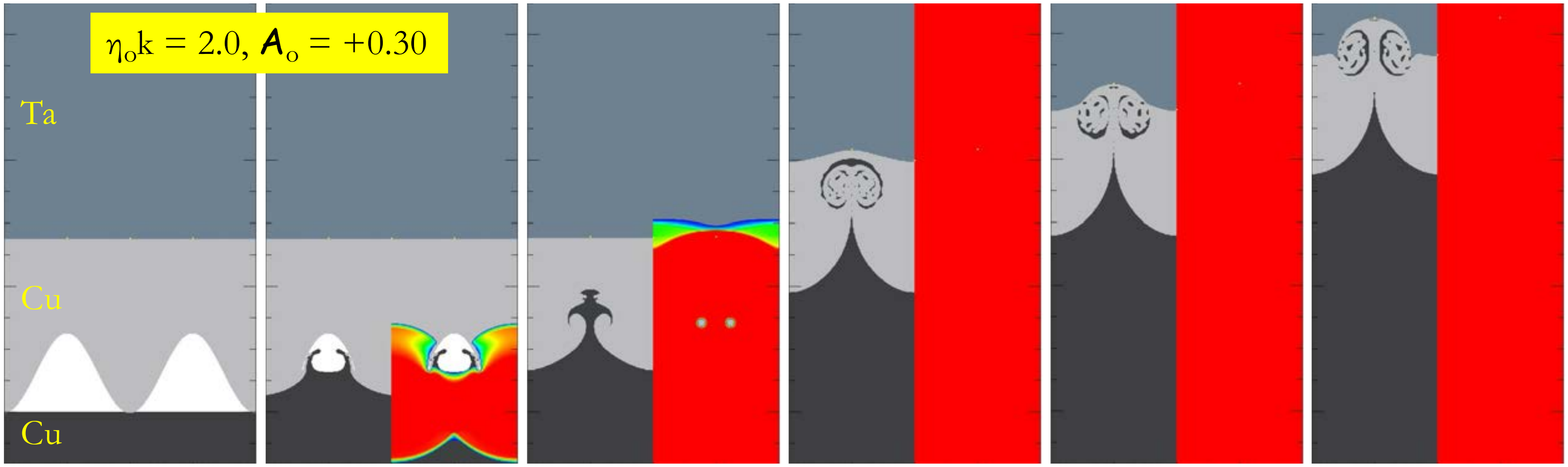


- Strength values obtained at pressures much higher pressures than pressure-shear (elastic-perfectly plastic model used)
- Thermal softening leads to fall-off of strength ~8 GPa
- Data fit with Drucker-Prager type model with a cap
- Strength appears higher than pressure-shear for low pressures, but no direct overlap → future work

Intersection of a non-Planar Shock with a Planar Interface

- Has similar sensitivity to Y but can be used for *A*≈0 or *A*>0
- Non-planar wave generated by a sine wave on the impact surface of the driver – other approaches can be used
- Approach developed by Soviet researchers (Bakhrakh et al., 1997; Mikhailov et al., 1997) using recovery techniques

Mikhailov et al., 2007



Conclusions and References

- Dynamic interface instabilities provide a useful way to probe material behavior
- Tamped RMI experiments can provide strength information at high P and $\dot{\epsilon}$
- Tamper material varied to give desired conditions or can be the subject of study
- Standard jet materials (Cu, Au) being calibrated
- High-speed radiographic imaging provides key information about behavior
- With experience and additional characterization, it should be possible to do some tamped RMI experiments with laser velocimetry only
- Scaling relations useful for design of experiments

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Olles, J.D., Hudspeth, M.C., Tilger, C.F., and ., Vogler, T.J. (2021). "The effect of liquid tamping media on the growth of Richtmyer-Meshkov instability in copper" *Journal of the Dynamic Behavior of Materials* **7**, 338-351.

Hudspeth, M., Olles, J., Mandal, A., Williams, J., Root, S., and Vogler, T. (2020). "Development of a Strength Model for Shocked Porous α-SiO2: Calibration via Richtmyer-Meshkov Instability and Validation via Mach Lens Experiments," *Journal of Applied Physics* **128**, 205901.

Extra Slides

Dense Liquids

Sandia National Laboratories

Wikipedia

Name	Density in g·cm^{-3}
1,2-Dibromoethane	2.180
cis-1,2-Dibromoethene	2.246
trans-1,2-Dibromoethene	2.231
Dibromomethane	2.477
Bromal	2.550
Bromoform	2.890
1,1,2,2-Tetrabromoethane (Muthmanns solution)	2.967
Sodium polytungstate	3.100
Bromine	3.1028
Thoulets solution	3.196
Diiodomethane	3.325
Indiumiodide	3.40
Bariummercuriciodide	3.57
Thallium formate + Thallium malonate (Clerici solution)	4.25
Liquid metal (Gallium/Indium/Tin/Zinc alloy)	6.5
Mercury	13.6

mostly