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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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Dynamic Interface Instabilities

- Arise at interface between dissimilar materials: gases, liquids, solids
- Shear, gravitational, and shock instabilities are most commonly studied
- 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*

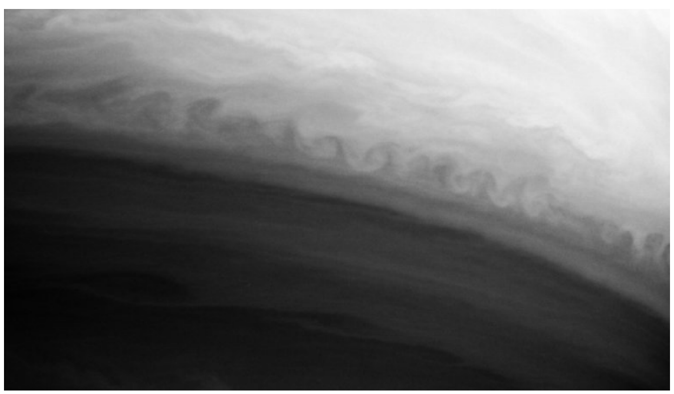
Hydrodynamic instabilities in solid media — from the object of investigation to the investigation tool

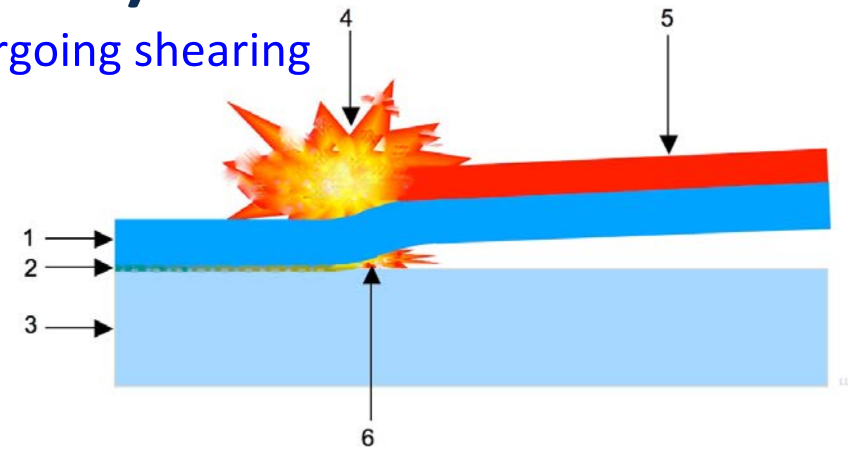
A.L. Mikhailov

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

Kelvin-Helmholtz Instability (KHI)

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





Findik, Mat. & Design, 2011

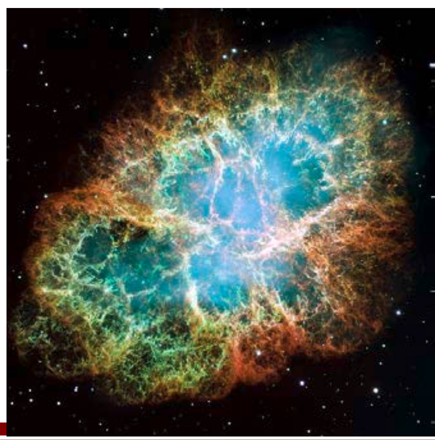
Bahrani et al., Proc. Roy. Soc. 1967

Rayleigh-Taylor Instability (RTI)

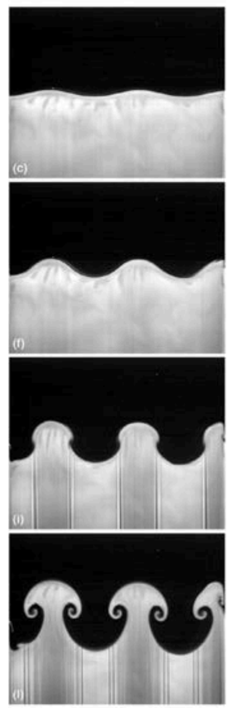
Review: Zhou, *Phys. Rep.*, 2017

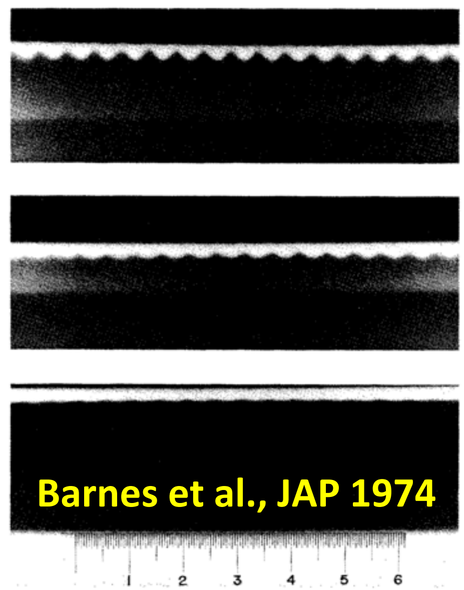
- Gravitational instability
- Unstable if acceleration from light to dense material

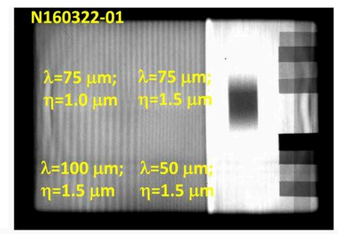
$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

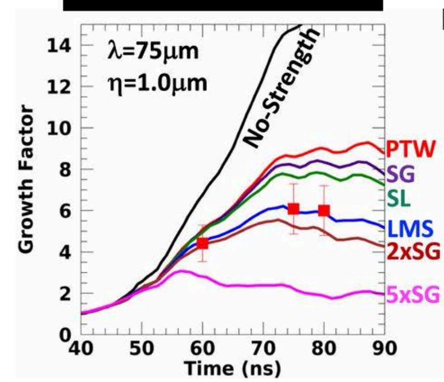


Waddell et al., Phys. Fluids, 2001







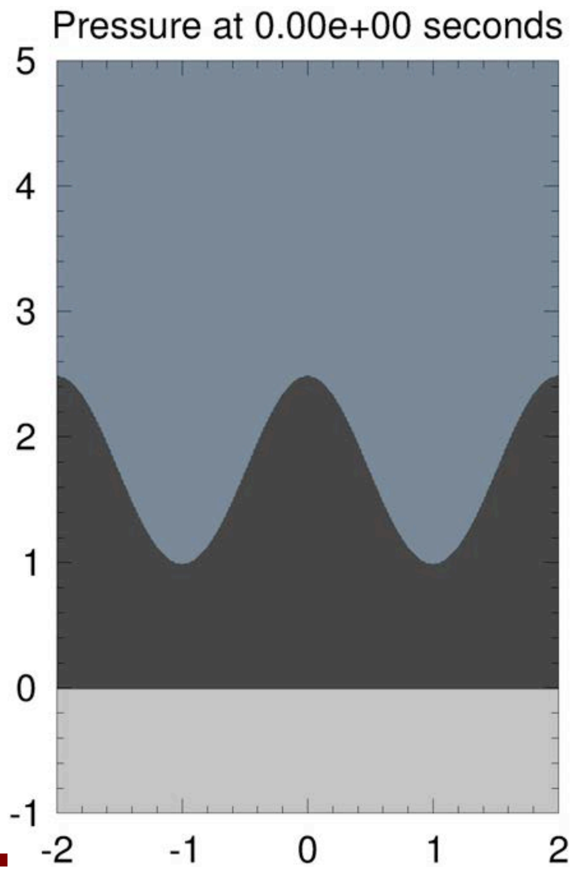


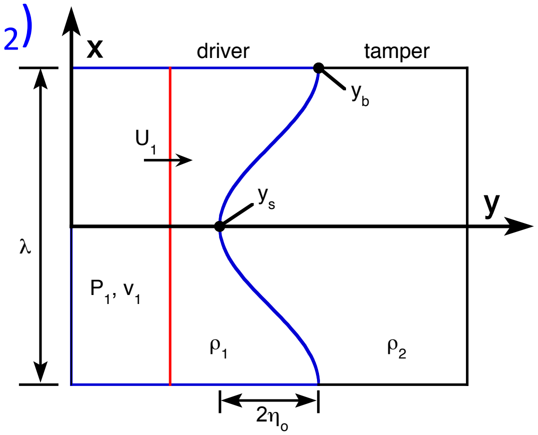
Remington et al., PNAS 2019

Richtmyer-Meshkov Instability (RMI)

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

Limiting case of RTI for A>0 ($\rho_1<\rho_2$)

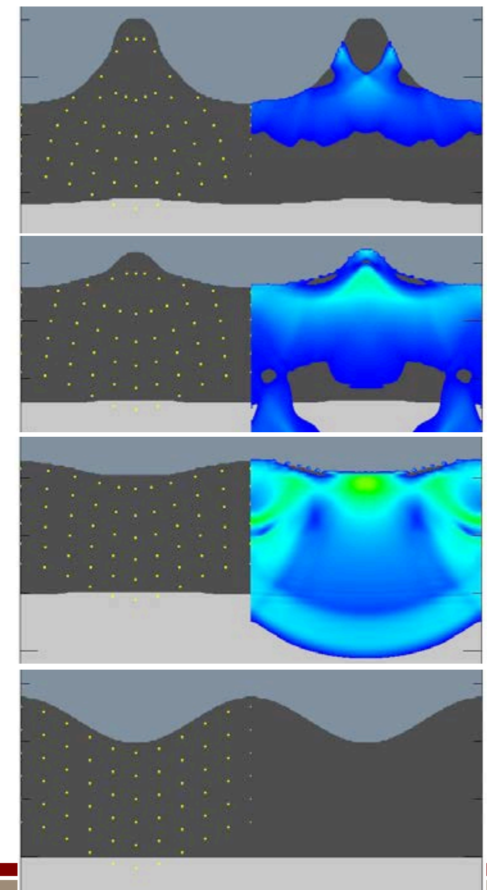




Bakhrakh et al., 1997

- doesn't invert
- arrests
- can separate
- can mushroom

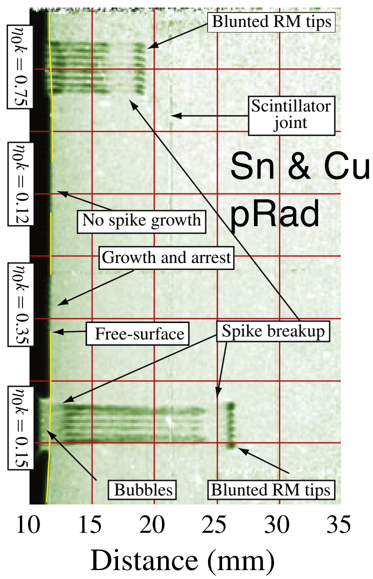
For A<0 ($\rho_1>\rho_2$), can invert

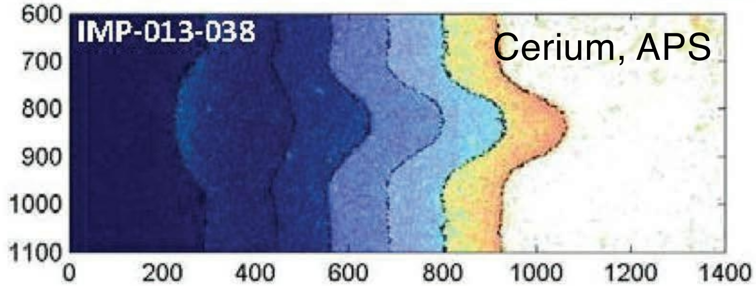


RMI Strength Experiments at *A*=-1

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

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

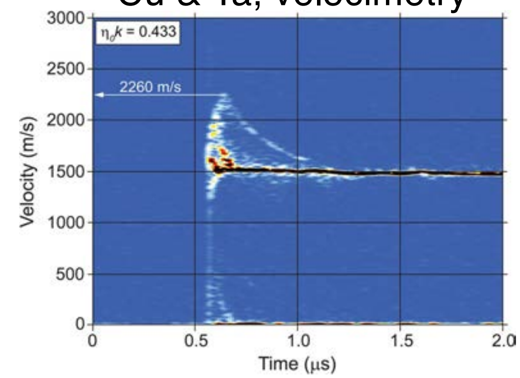




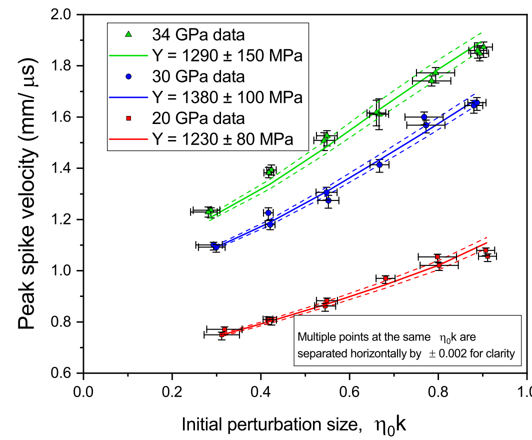
Jensen et al. (2015). J. App. Phys.

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

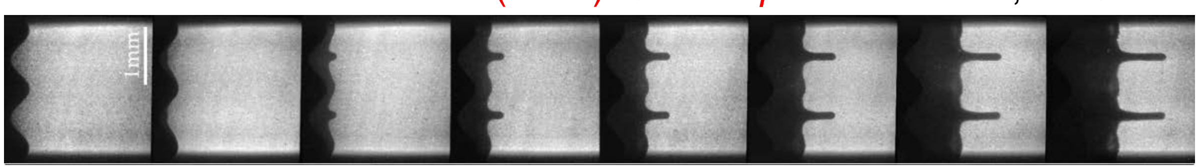
Cu & Ta, velocimetry



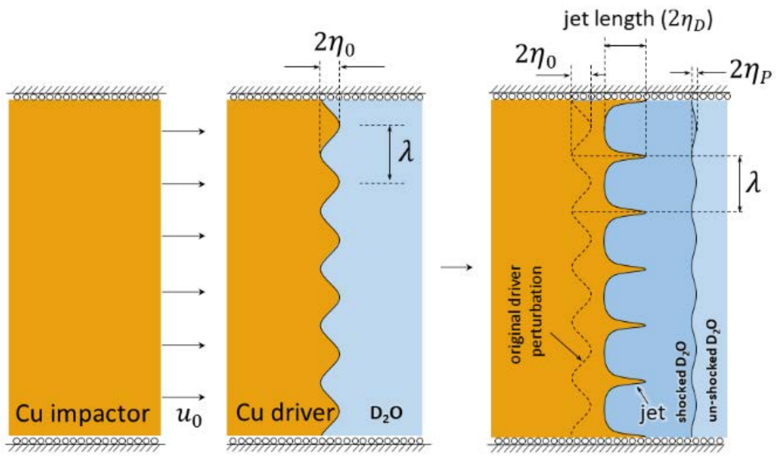
Prime et al. (2017). JDBM
Prime et al. (2019). Phys. Rev. E

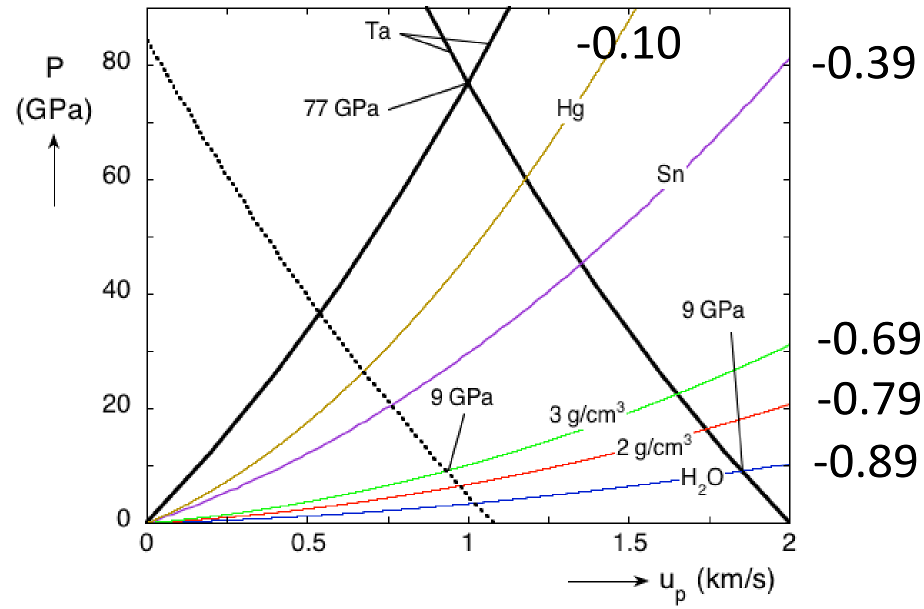


Olles et al. (2019). *Soc. Exp. Mech.* Cu, DCS



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

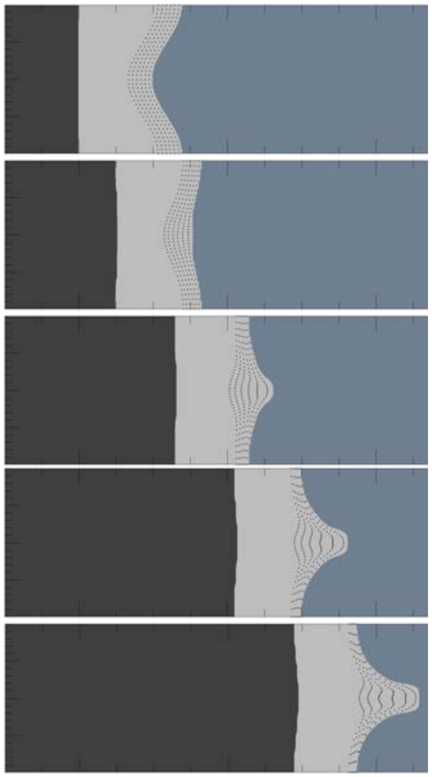


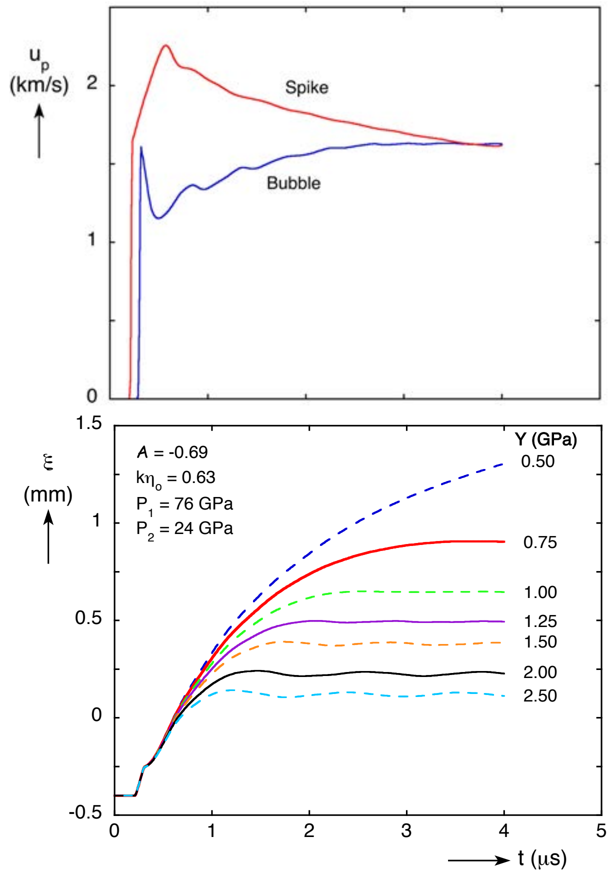


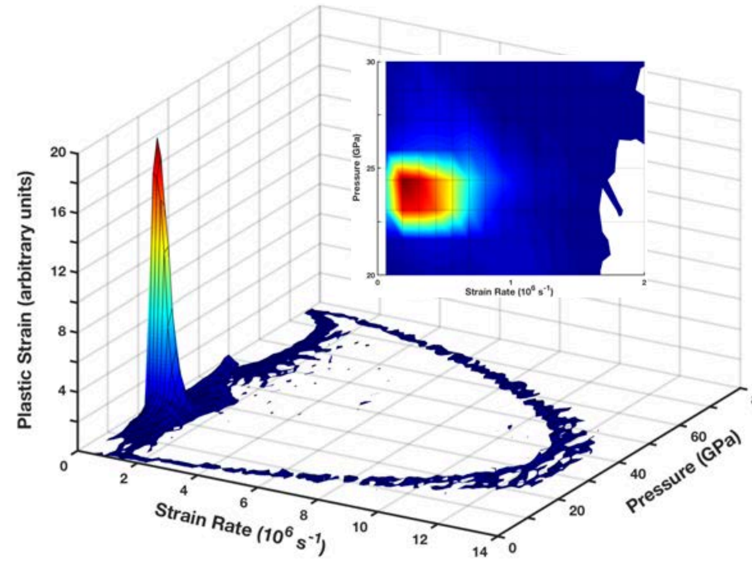
- Adding tamper keeps P above zero, reducing role of damage
- Potential tampers depend upon instrumentation needs/capabilities, but some options available
- For velocimetry, need transparent liquid. With radiography, limited by transmission.
- Liquids: water, perfluorooctane, perflubron, sodium polytungstate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

Example: Ta Tamped by Sodium Pertungstate

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



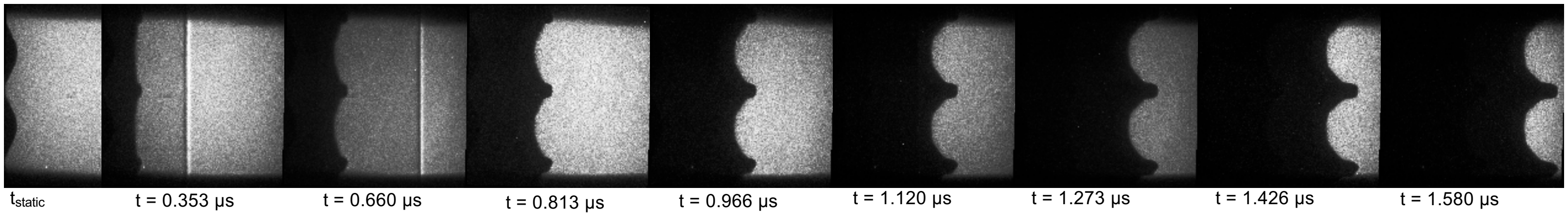


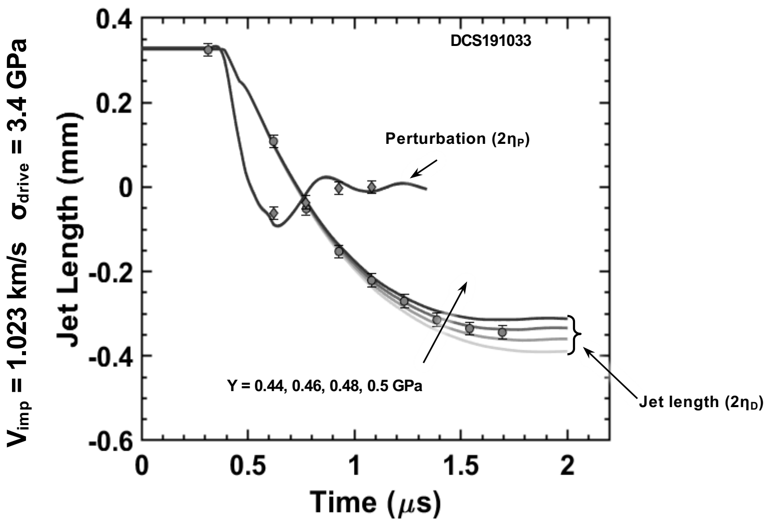


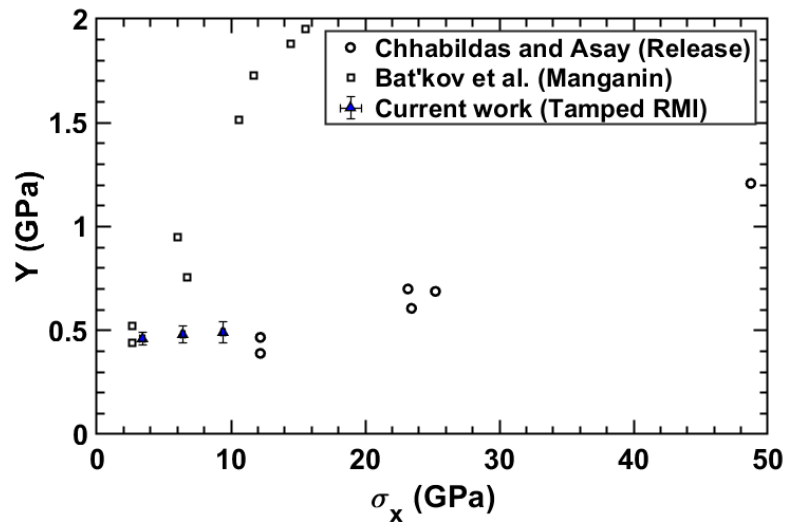
- Though loading is complex, most plastic work occurs near P_2 and $2x10^5\ s^{-1}$

D_2O Tamped RMI Experiments on Cu at DCS

S19-1-036 – Ta/Cu - 1.668kms   P1: 47.8 GPa, P2: 9.4 GPa $\eta_0 k = 0.5$, $A = -0.78$



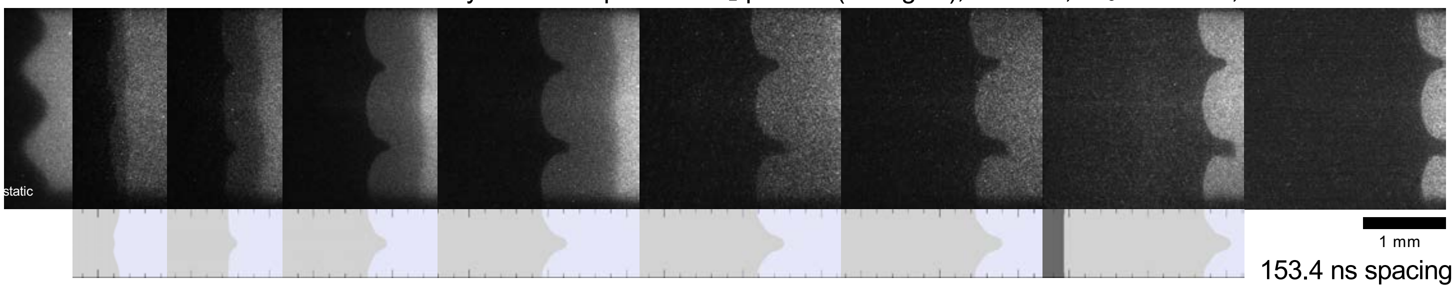




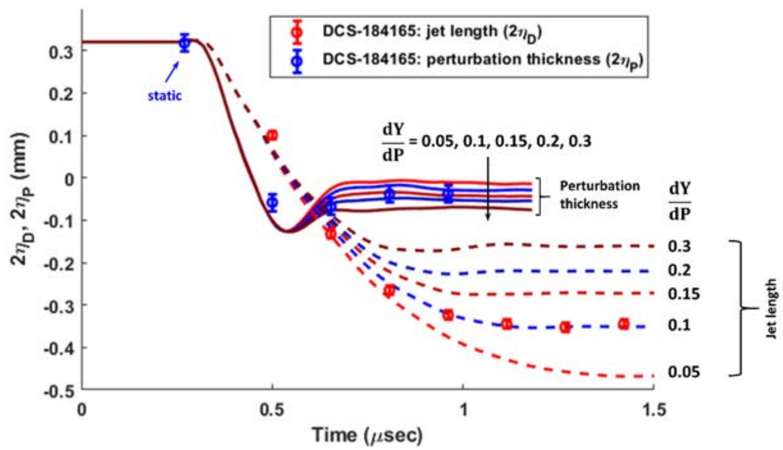
Once calibrated, jetting copper can be used in RMI experiments into other materials

RMI Experiments on Granular SiO_2 at DCS

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

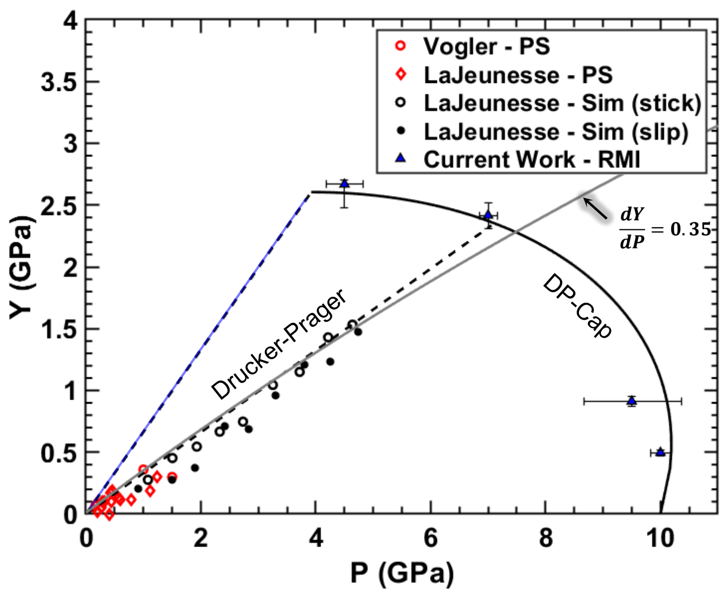


153.4 ns spacing



- 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

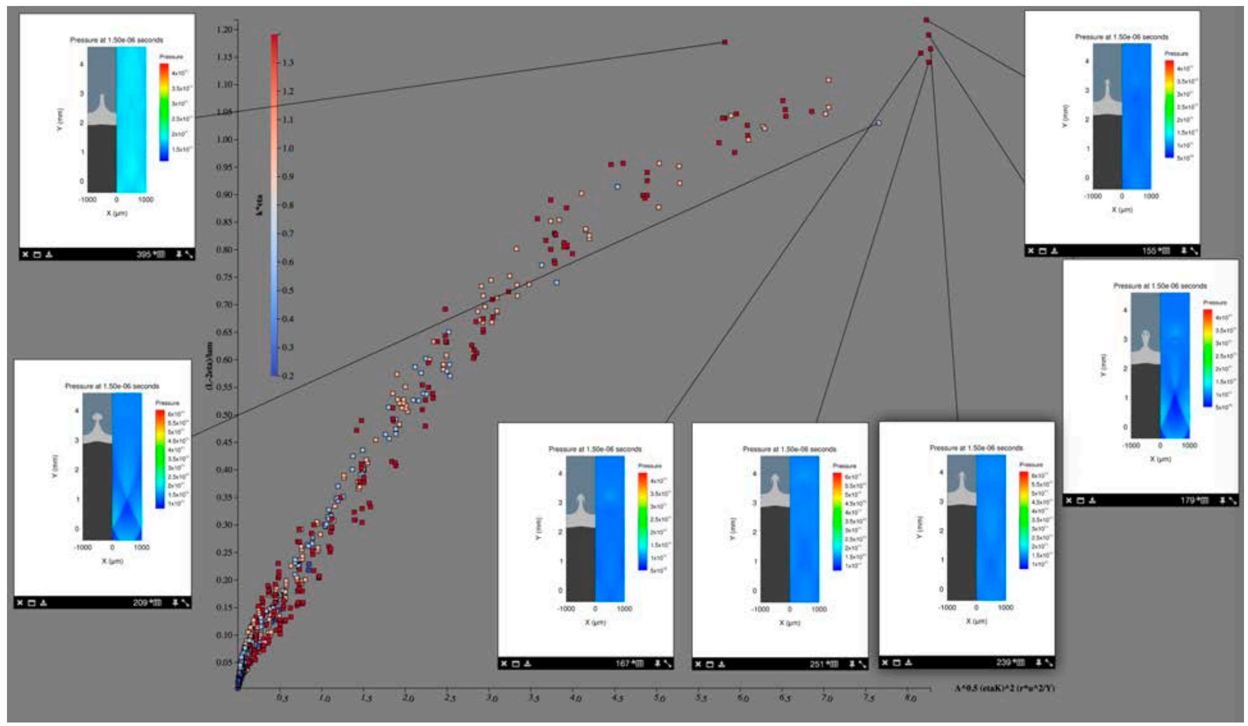
Granular SiO_2 Strength



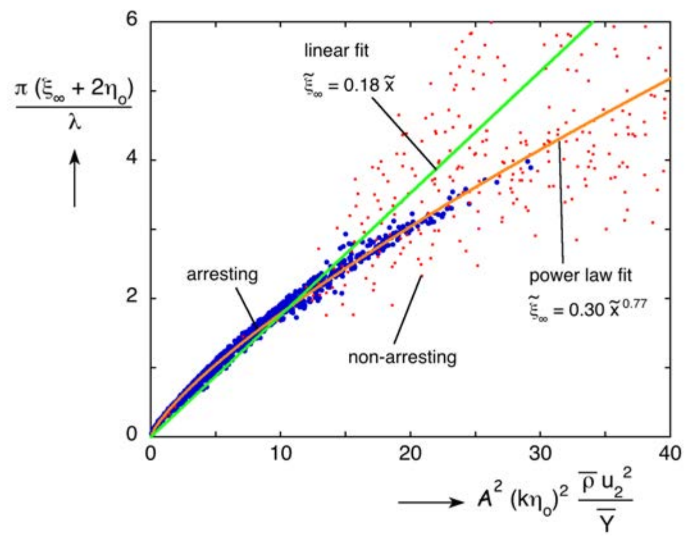
- Strength values obtained at pressures much higher pressures than pressure-shear (elastic-perfectly plastic model used)
- Thermal softening leads to fall-off of strength ~8 GPa
- Data fit with Drucker-Prager type model with a cap
- Strength appears higher than pressure-shear for low pressures, but no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

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



Scaling for Tamped RMI

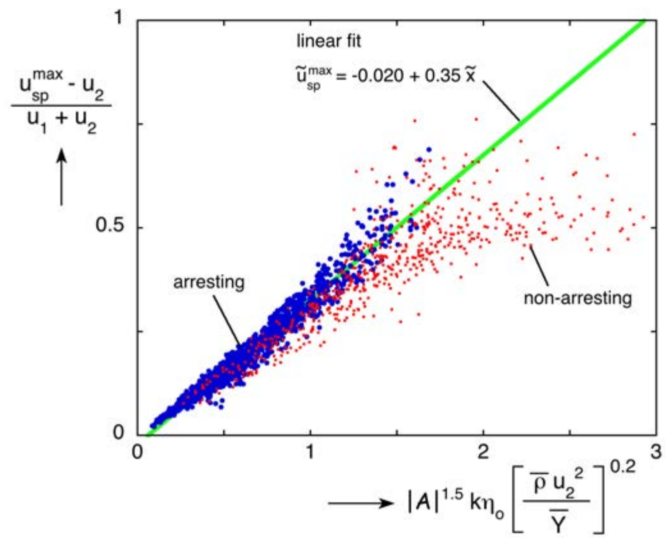


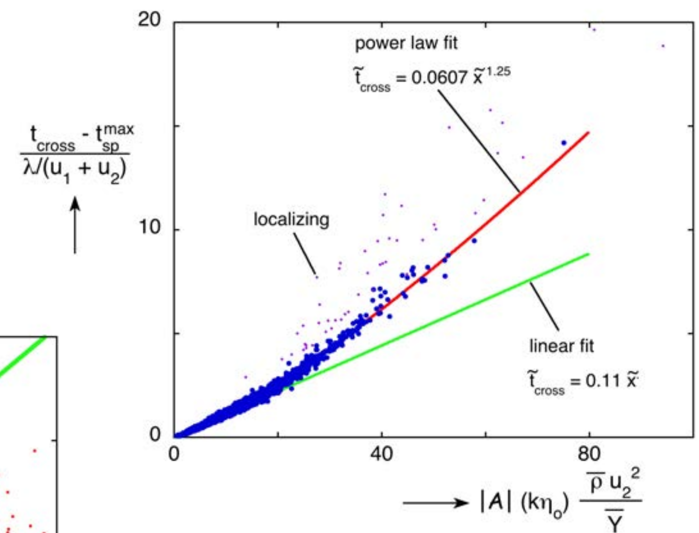
Arrested Length

- 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}

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
- More study needed for tamper materials and standard jet materials (Cu, Au)
- 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 velocimetry only
- Scaling relations useful for design of experiments

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* (submitted).

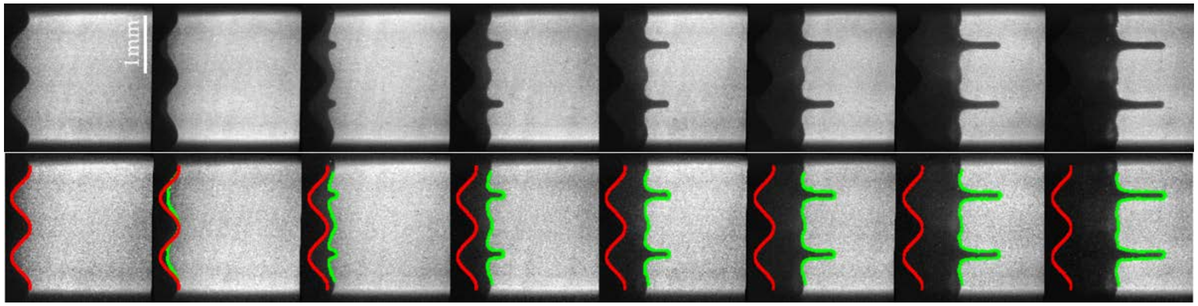
Olles, J.D., Hudspeth, M.C., Vogler, T.J., and Tilger, C.F. (2021). "The effect of liquid tamping media on the growth of Richtmyer-Meshkov instability in copper" (in preparation).

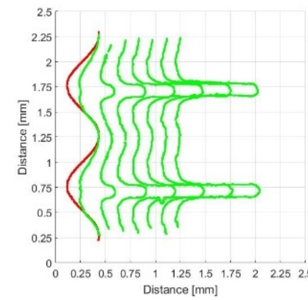
Vogler, T.J. and Hudspeth, M.C. (2021). "Tamped Richtmyer-Meshkov Instability Experiments to Probe High-Pressure Material Strength," *Journal of the Dynamic Behavior of Materials* (submitted).

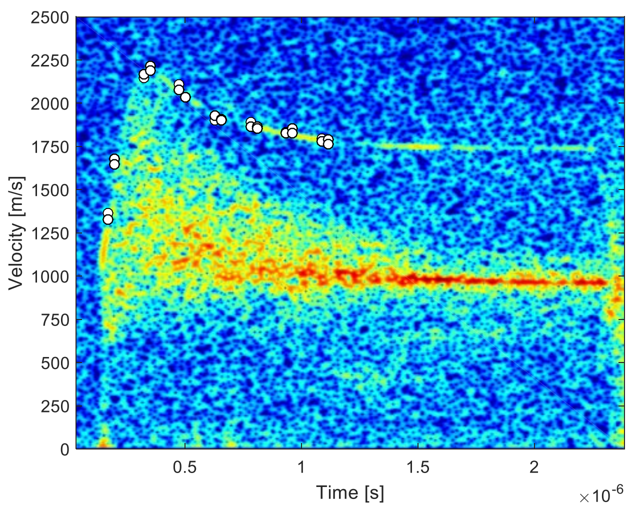
Extra Slides

>>>>Improved Imaging at the Dynamic Compression Sector at APS

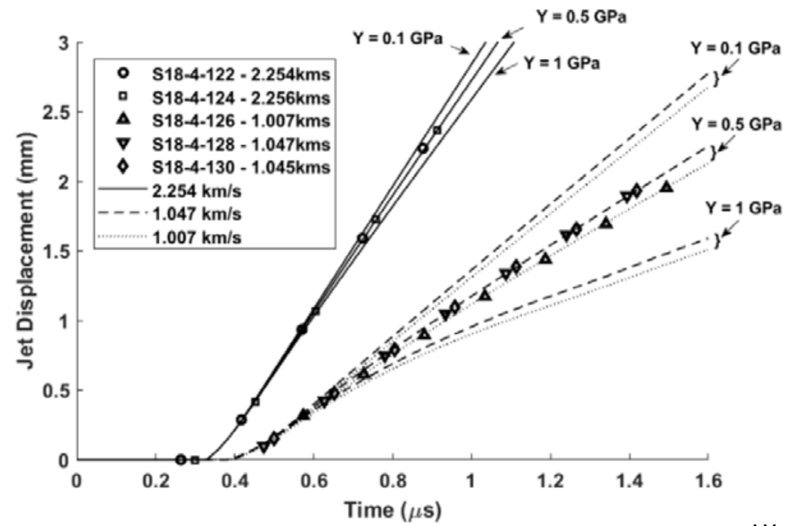
Olles et al. (2021). *JDBM*





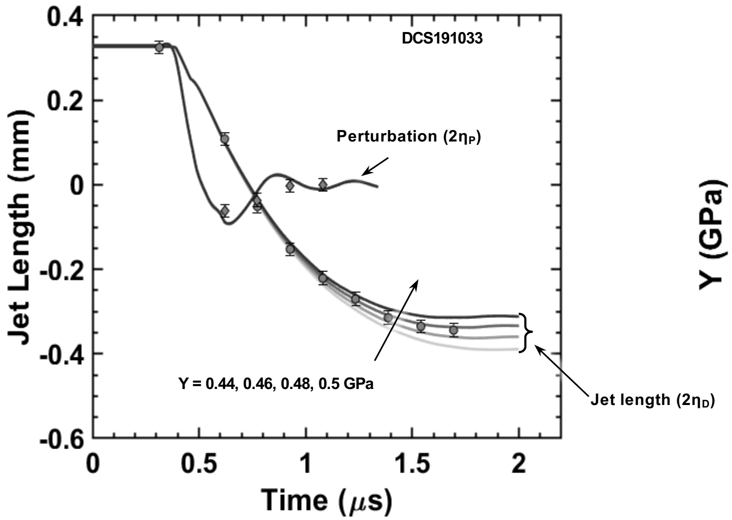


Spatial resolution: ~2.5 μm
Window size: ~2.5 x 2.5 mm
Temporal resolution: 33.5 ps
Min interframe time: 153.4 ns
Number of frames: 8

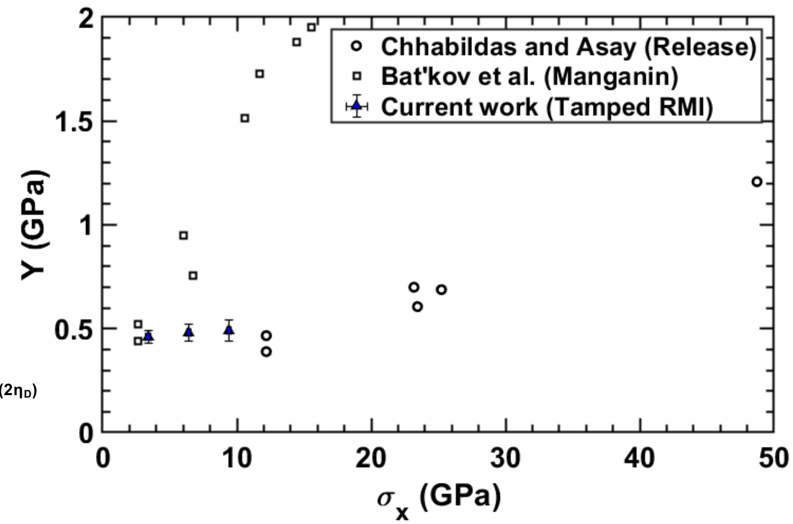


D_2O Tamped RMI Experiments on Cu at DCS

Jet Length Evolution



Strength vs Long. Stress



Material	EoS	ρ_0 (g/cc)	C_s (km/s)	s
Copper	M-G	8.93	3.94	1.49
D_2O	M-G	1.107	1.48	1.984

Material	Model	Y_{inf} (GPa)	ν
Copper	EPP	0.48	0.36

Once calibrated, jetting copper can be used in RMI experiments into other materials

Dense Liquids

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