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Dynamic Behavior of Granular Ceramics: Experiments and Simulations

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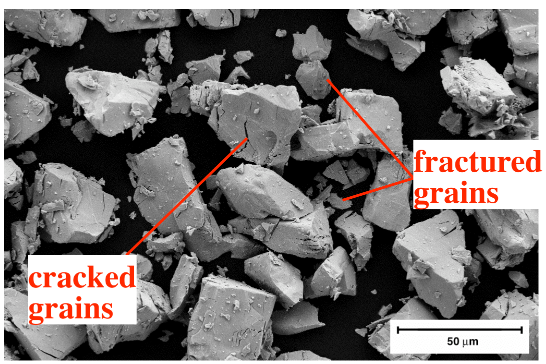

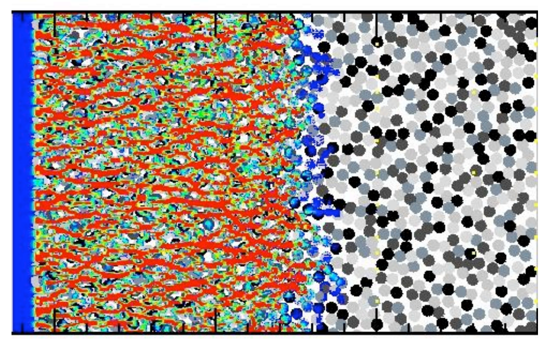

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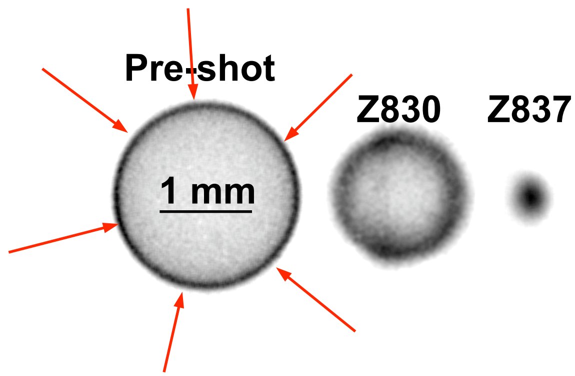
- Introduction to Shock and High-Pressure Physics
- Introduction to Granular Materials
- Planar Impact Experiments
- Mesoscale Modeling
- Other Experimental Work
- Conclusions

Why Do We Need To Know the Behavior of Materials Under Extreme Conditions?

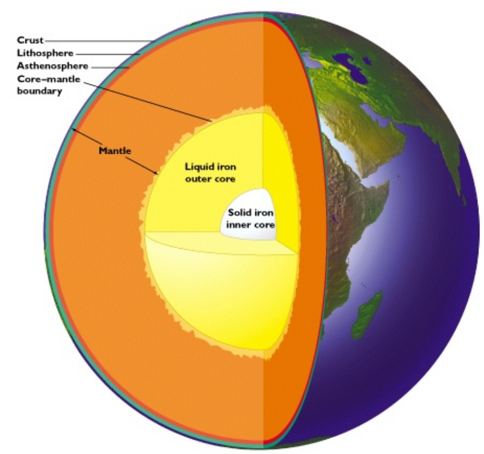
- weapons applications (warheads, armor, etc.)

- explosives behavior and applications

- inertial confinement fusion



- planetary science (P~360 GPa, T~7000 K)

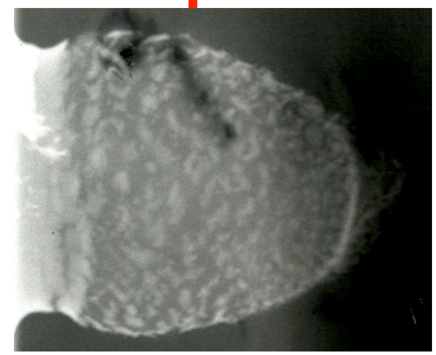


Applications of Shock and Impact Physics in Aerospace Engineering

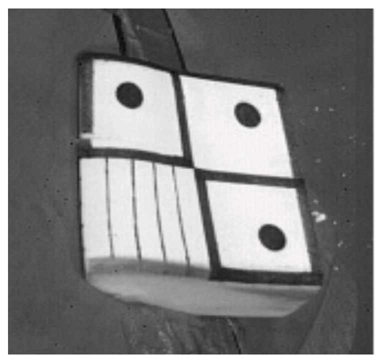
Pluto New Horizons

- impact of asteroids or orbital debris (V=8-15 km/s)
- launch safety for radiological materials (RTG's) or reactors (Prometheus mission)
- launch debris (foam, ice, etc.)

hypervelocity impact



- internal blast
- runway debris & small arms fire
- military aviation and weapons design



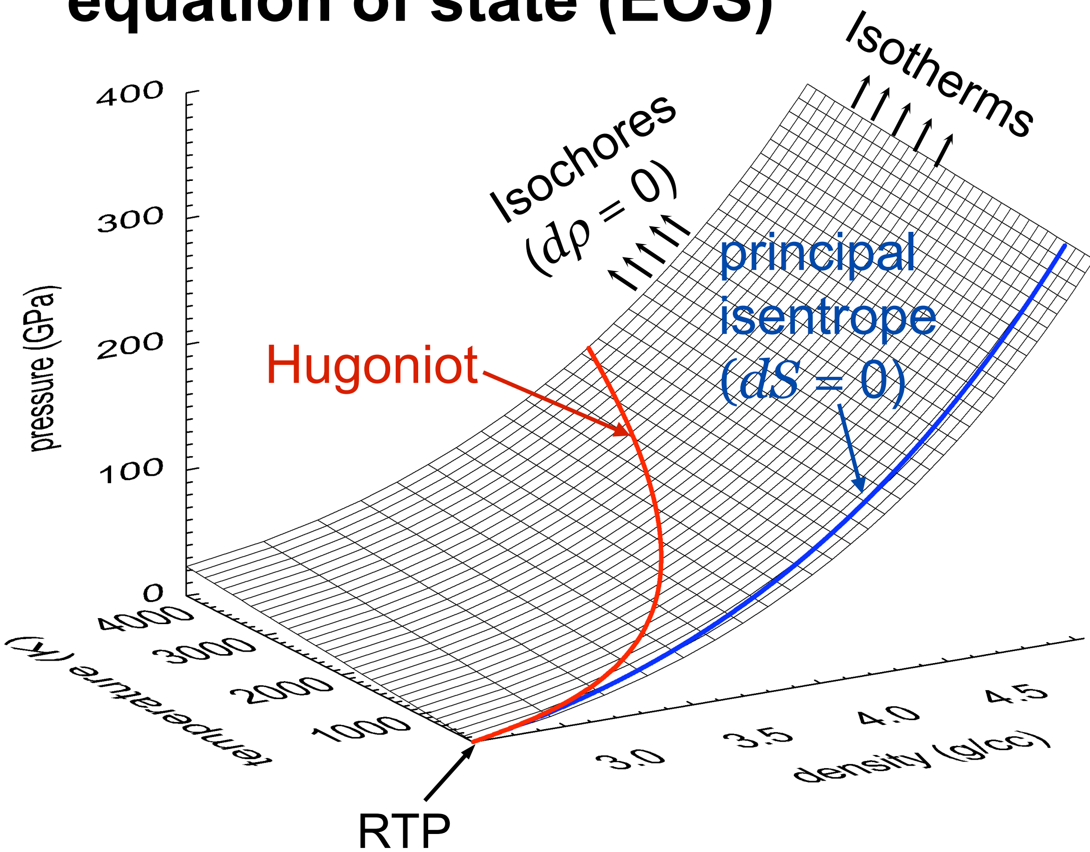
SWRI foam impact expt.

- 100 μm particles
- up to 300 km/s velocities
- P_{max} ~ 100 TPa, T_{max} ~10^6 K

Material Behavior: EOS & Constitutive Aspects

M. Knudson,
M. Desjarlais

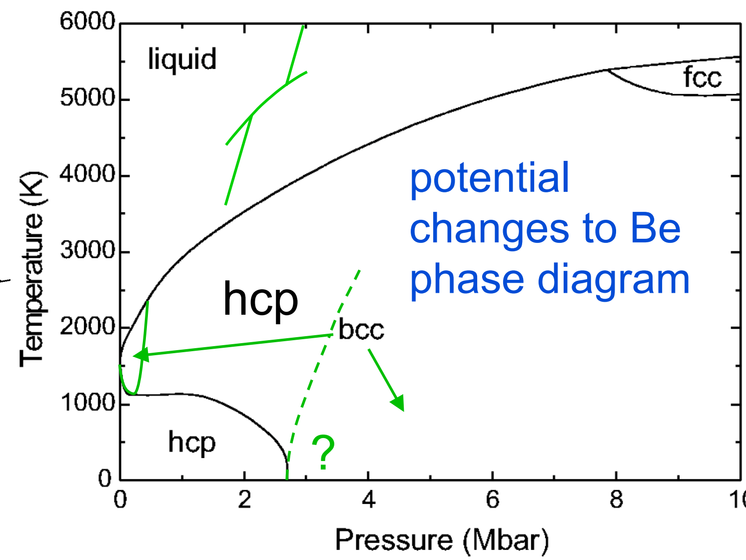
equation of state (EOS)



one thermodynamic state variable as a function of two others:

pressure $P = P(r,T)$

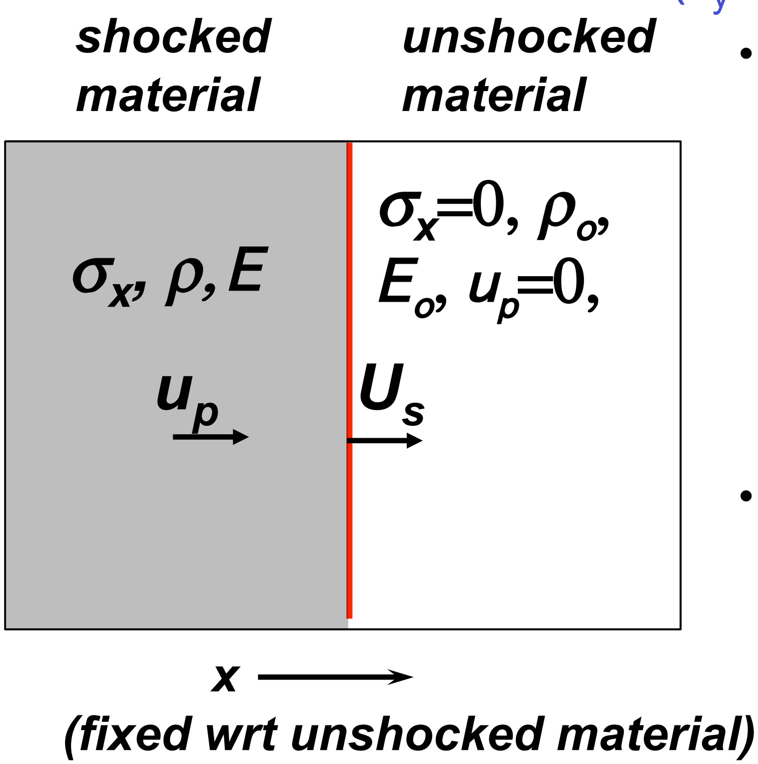
Helmholtz energy $f = f(v,T)$



Also: strength, damage, spall (tensile failure), compaction

What is a Shock Wave?

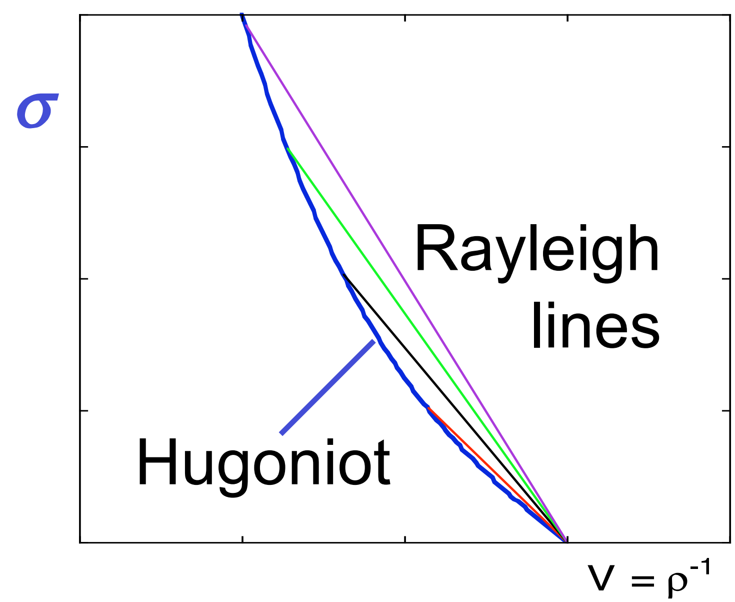
- A “discontinuous” wave that moves at a fixed velocity (if steady)
  - wave front moves at speed U_s *(shock velocity)*
  - shocked material moves at speed u_p *(particle or mass velocity)*
  - uniaxial strain condition ($\varepsilon_y=\varepsilon_z=\varepsilon_{xy}=\varepsilon_{yz}=\varepsilon_{xz}=0$)



- States ahead and behind shock <u>*assumed*</u> to be in thermodynamic equilibrium
  - well defined temperature in each state
  - described by equilibrium thermodynamics
- Shock compression is adiabatic
  - very fast process (< 1 ns)
  - irreversible (i.e. NOT isentropic)
  - temperature *typically* increases

Conservation Equations and the Shock Hugoniot

- Five variables: σ_x, u_p, U_s, ρ, and E
- Three conservation relationships (Rankine-Hugoniot jump conditions)
  - By measuring two variables (typically σ_x, u_p, or U_s), the other three can be determined



<u>conservation of</u>

mass: $\rho_o U_s = \rho (U_s - u_p)$

momentum: $\sigma_x = \rho_o U_s u_p$

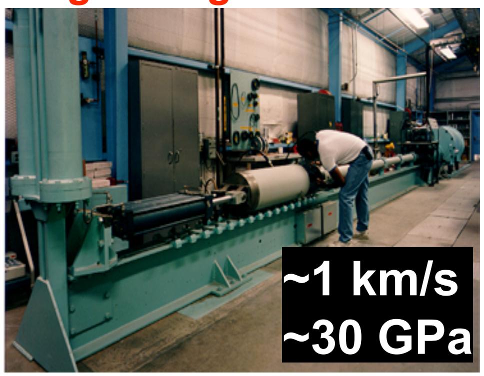
energy: $E - E_o = 0.5\sigma_x (V_o - V)$

material loads along the Rayleigh line, so the Hugoniot is a <u>collection of end states</u>, not a material response curve

the Hugoniot is not a complete equation of state (EOS)!

Gas Guns to Generate Shock Waves

Single Stage Gun 100mm



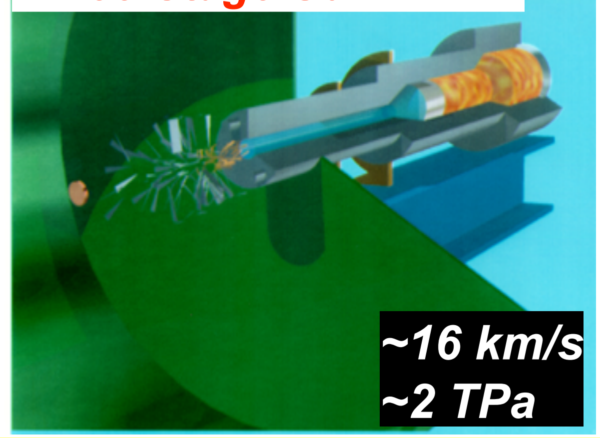
Propellant Gun 89mm

Two-Stage Gun 29mm

gas guns

- launch thin plates (mm's) at high velocities
- well-posed, repeatable initial conditions
- sample is in uniaxial ***strain***
- used to study material behavior at high pressures and strain rates
- usable in laboratory setting

Three-Stage Gun 17mm

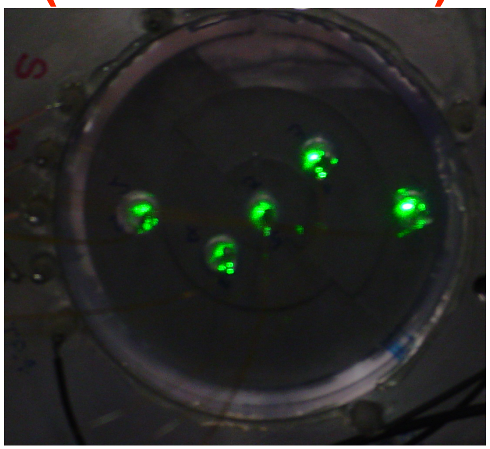


Chhabildas, L. C., Dunn, J. E., Reinhart, W. D., and Miller, J. M. (1993). "An impact technique to accelerate flier plates to velocities over 12 km/s," *Int. J. Impact Eng*. **14**, 121-132.

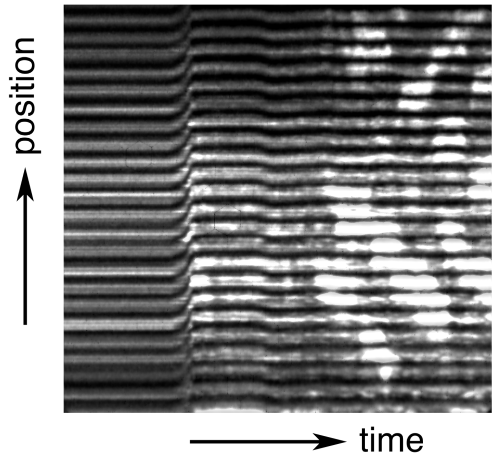
also: explosives, lasers, magnetic loading (Z)

Diagnostics for Dynamic Experiments

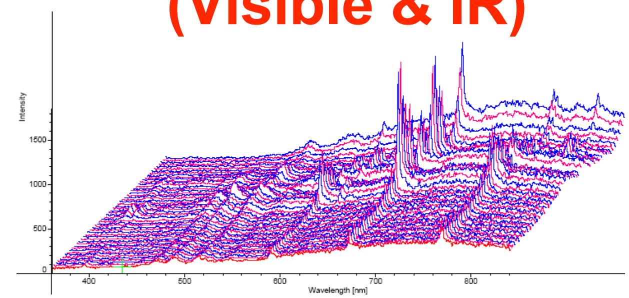
Velocity Interferometry (VISAR & PDV)



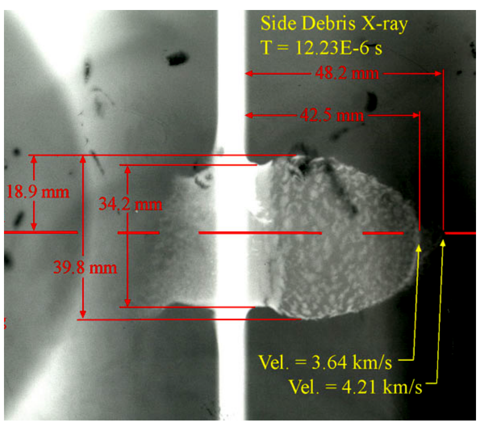
Line-VISAR



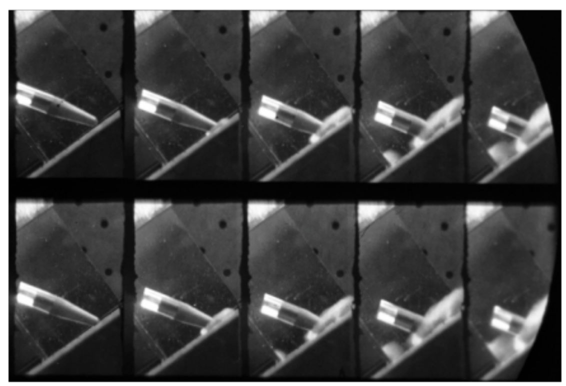
Time-Resolved Spectroscopy (Visible & IR)



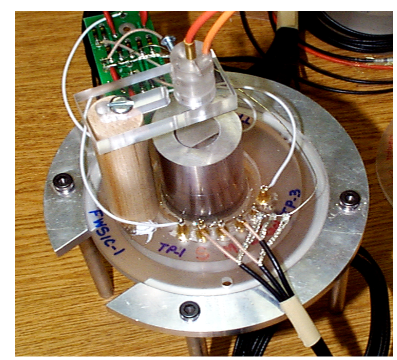
Flash X-rays



High-Speed Photography



Pressure Gauges

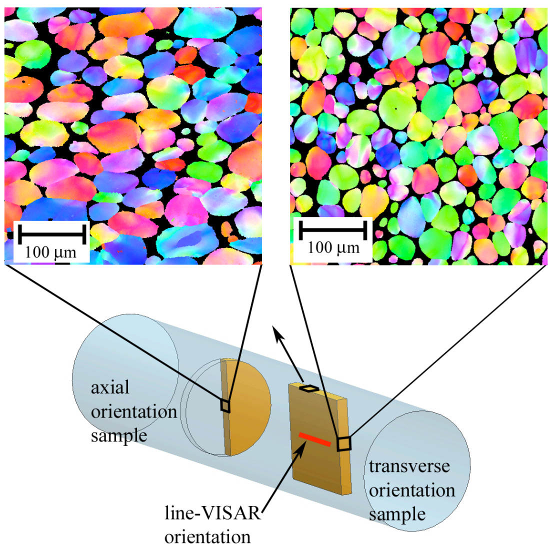


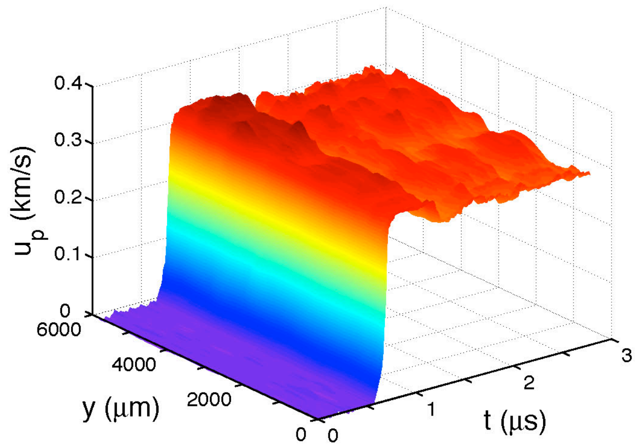
Advanced Diagnostics: pRad, synchrotron, etc.

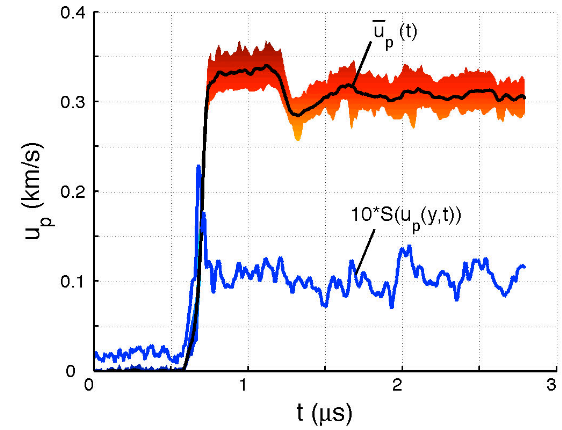
Heterogeneous and Statistical Aspects of Spall

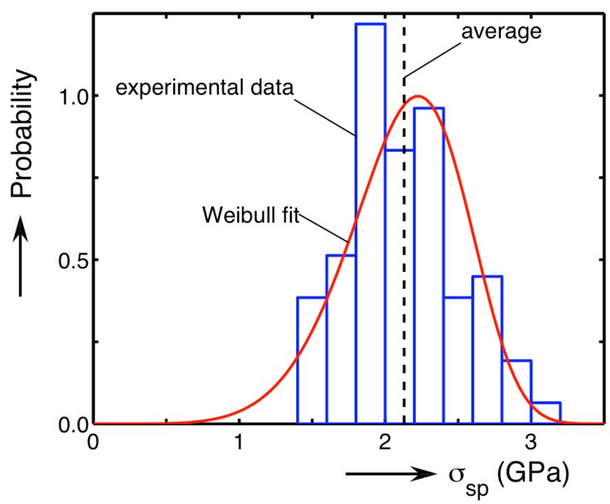
J. Clayton,
T. Vogler

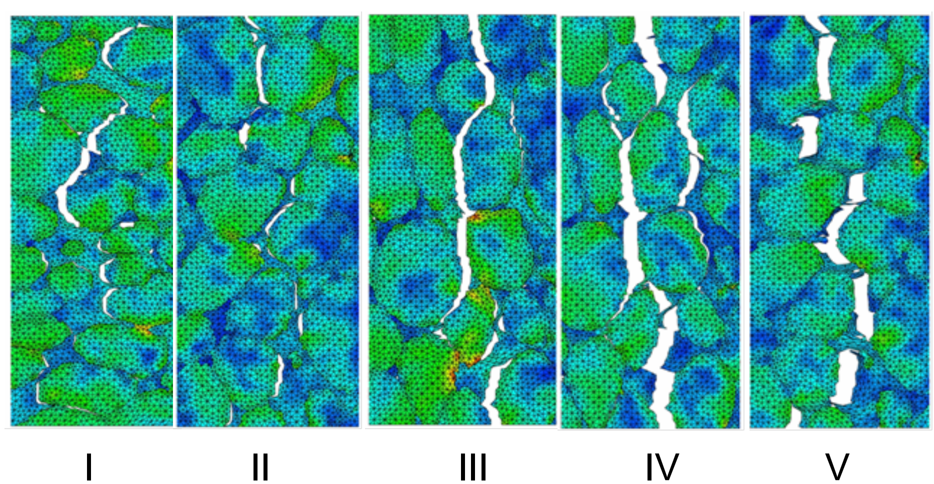
WHA - tungsten heavy alloy











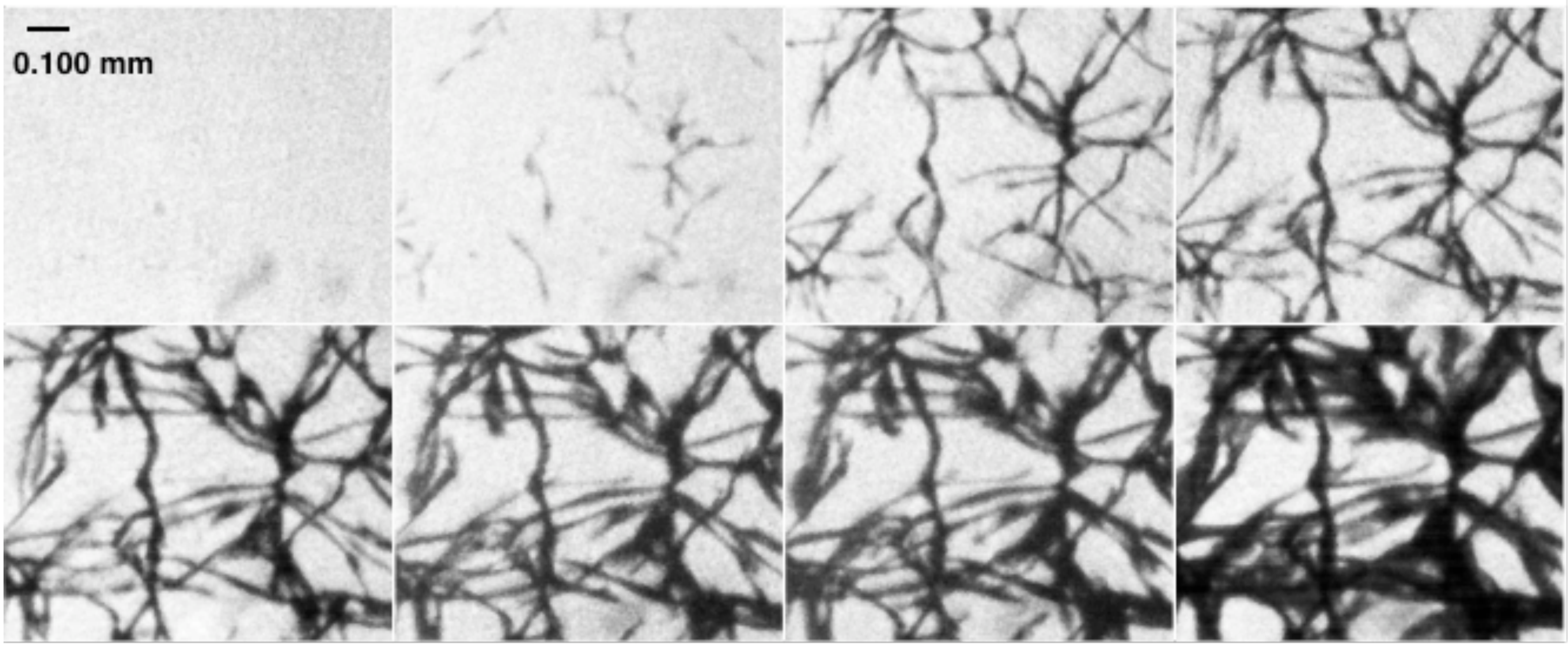
Vogler, T. J., and Clayton, J. D. (2008). "Heterogeneous deformation and spall of an extruded tungsten alloy: plate impact experiments and crystal plasticity modeling," *J. Mech. Phys. Solids* 56, 297-335.

Nanosecond Freezing of Water

- 2.7 GPa (ice VII)
- 25 ns exposure

t(ns) from shock arrival=

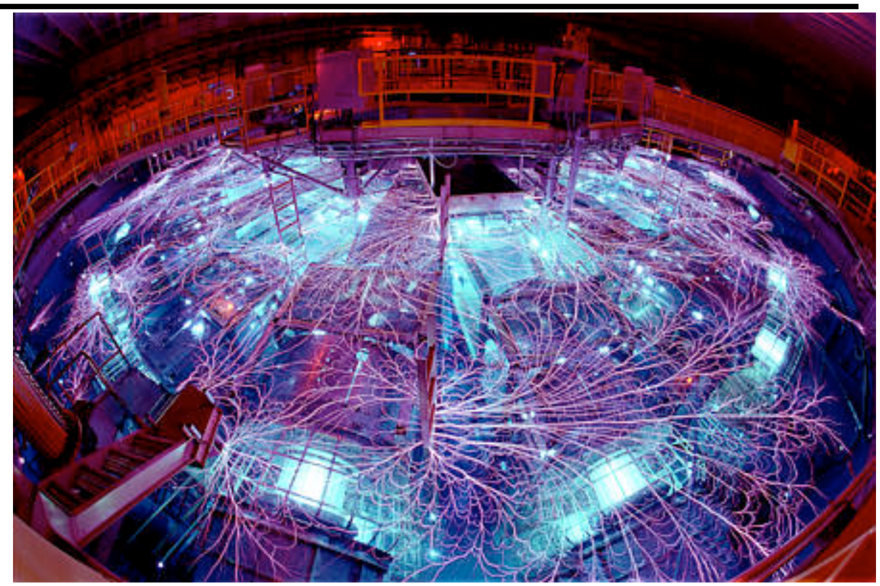
230	330	530	630
730	830	930	1530

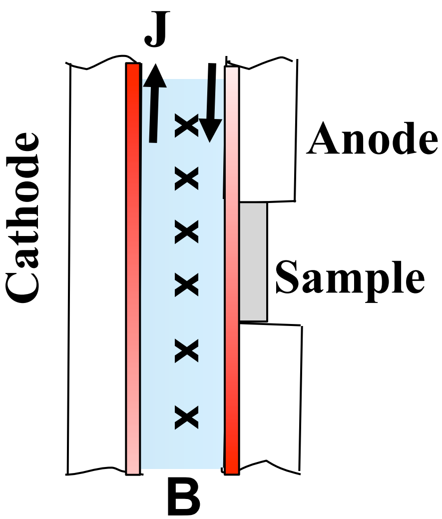


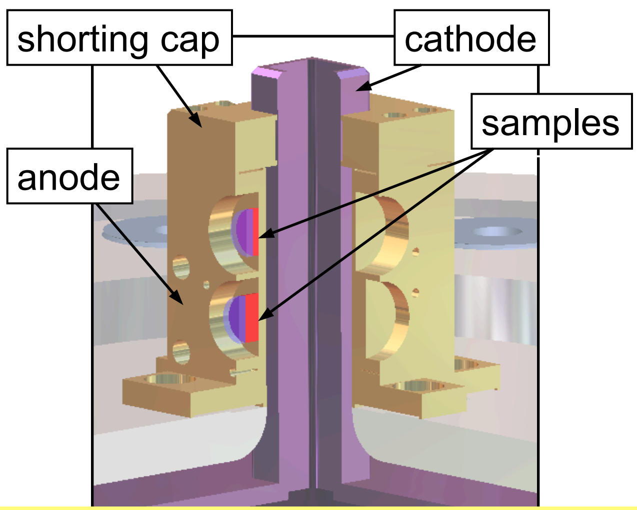
D.H. Dolan and Y.M. Gupta, J. Chem. Phys. **121**, 9050 (2004).

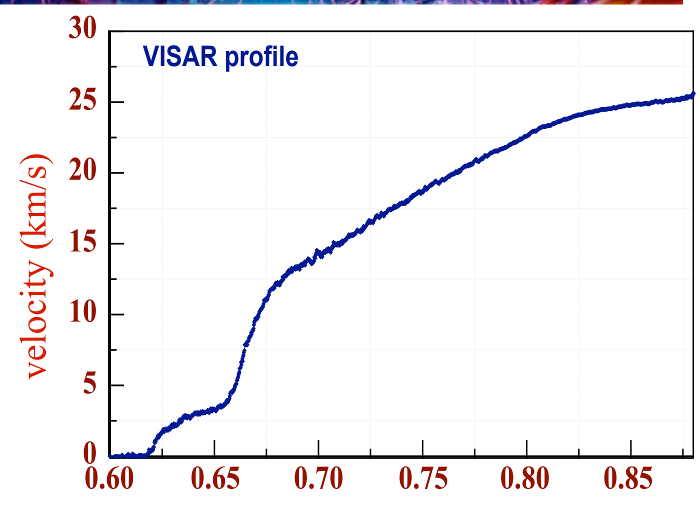
Z Pulsed Power Machine

- **Designed for ICF applications**
- **Generates ~26 MA over 100’s of ns**
- **Utilize current to generate magnetic forces**
- **Magnetic forces create smooth waves in materials**
- **Waves used for isentropic loading (to ~400 GPa) and to launch high-velocity flyer plates (to ~40 km/s)**





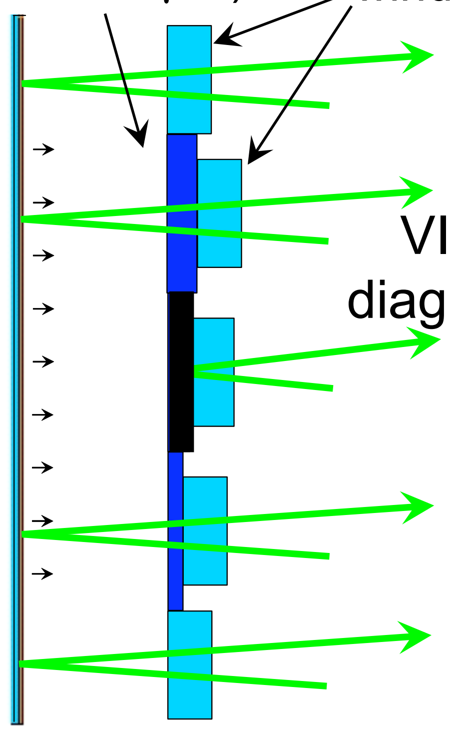


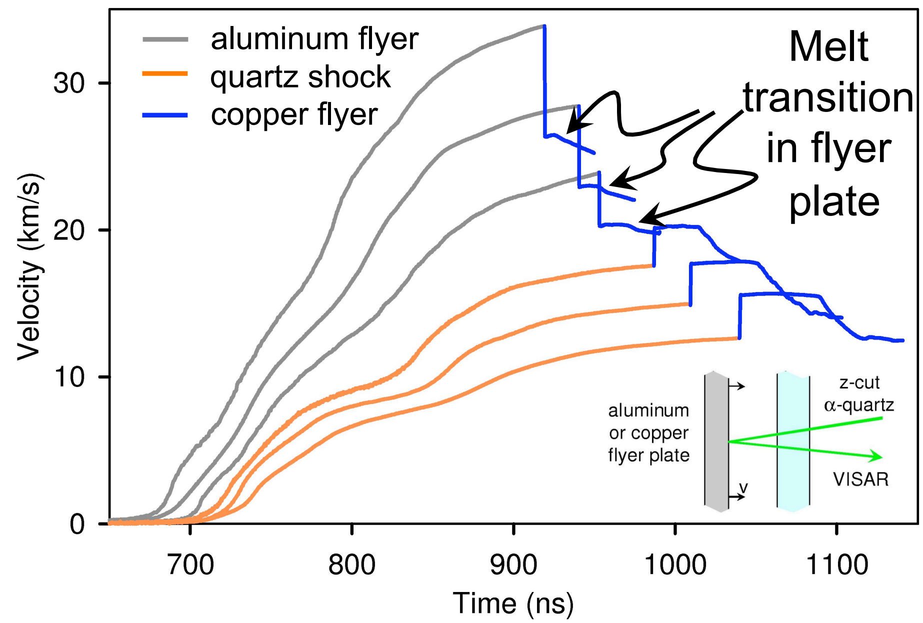


Davis, J.-P., Deeney, C., Knudson, M. D., Lemke, R. L., Pointon, T. D., and Bliss, D. E. (2005). "Magnetically driven isentropic compression to multimegabar pressures using shaped current pulses on the Z accelerator," *Physics of Plasmas* 12, 056310.

Quartz of Interest as Standard - Window in Z Shots

M. Knudson
M. Desjarlais



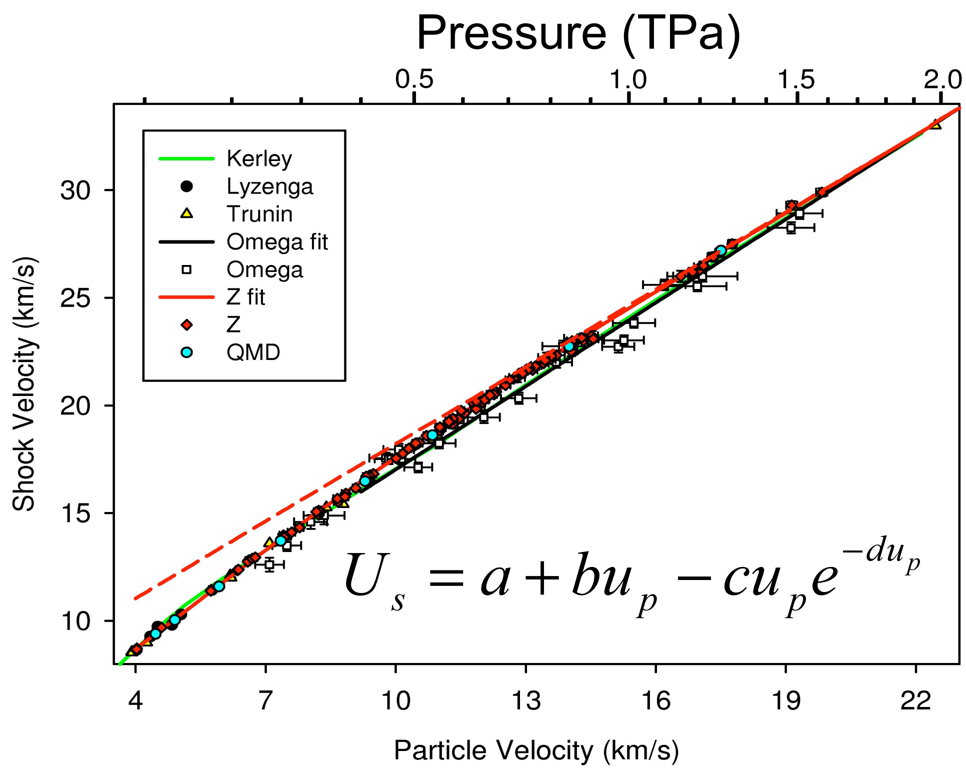


Knudson, M. D., M. P. Desjarlais and D. H. Dolan (2008). "Shock-wave exploration of the high-pressure phases of carbon." *Science* ***322: 1822-1825.***

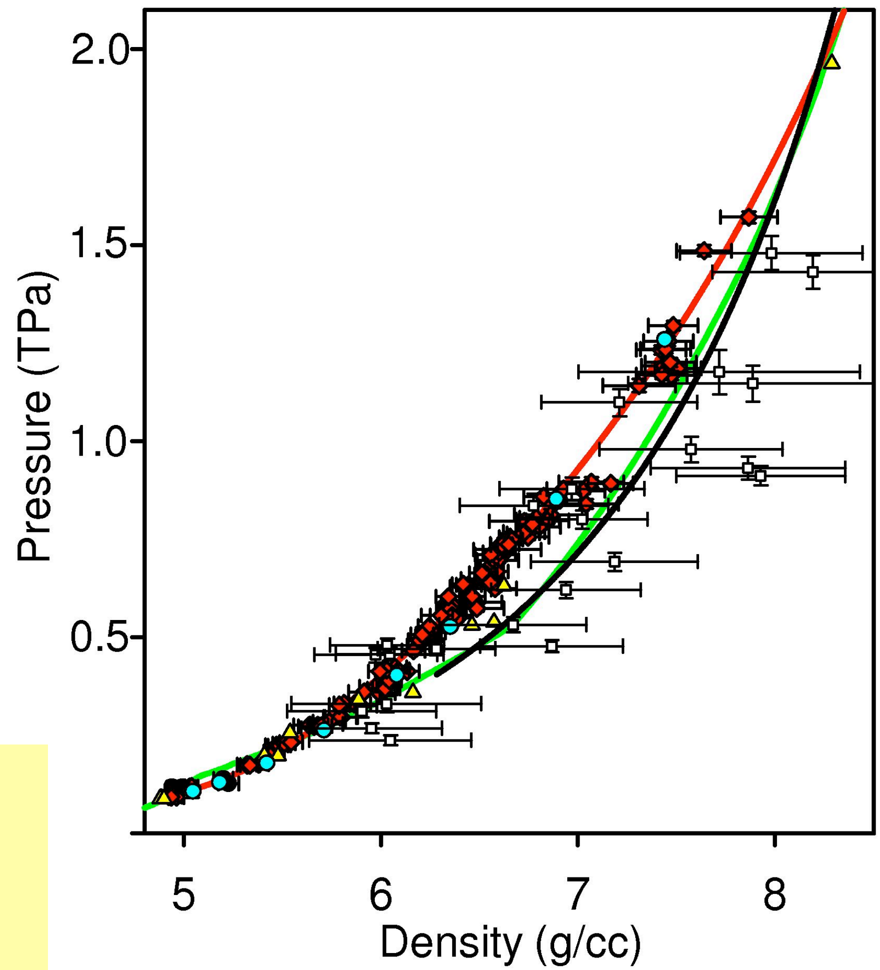
quartz data has large uncertainty and scatter, and U_s-u_p exhibits significant curvature in the several 100 GPa regime; attributed to dissociation

New Hugoniot Data for α-Quartz to 1.5 TPa

M. Knudson
M. Desjarlais



Data set includes ~150 points



Knudson, M. D. and M. P. Desjarlais (2009). "Shock compression of quartz to 1.6 TPa: redefining a pressure standard." *Physical Review Letters* ***103: 225501.***

- Introduction to Shock and High-Pressure Physics
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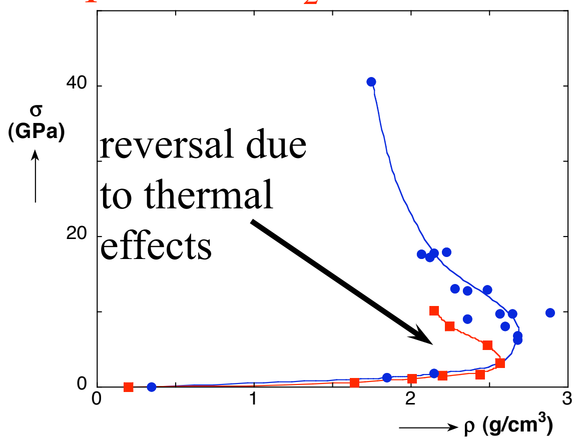
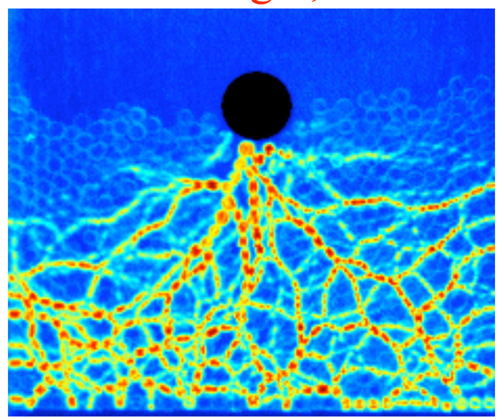
Background on Dynamic Behavior of Granular Materials

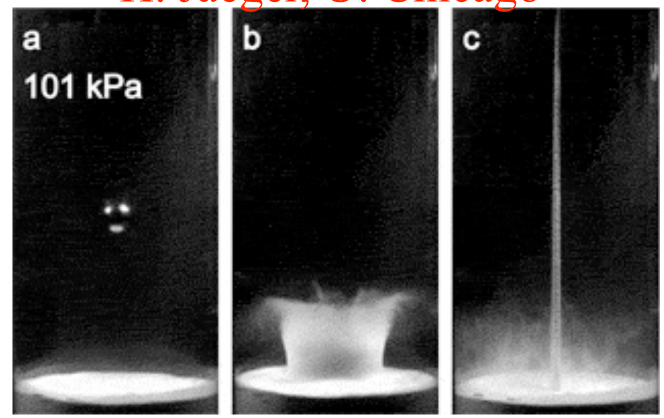
porous SiO_2, Trunin et al.



B. Behringer, Duke



H. Jaeger, U. Chicago

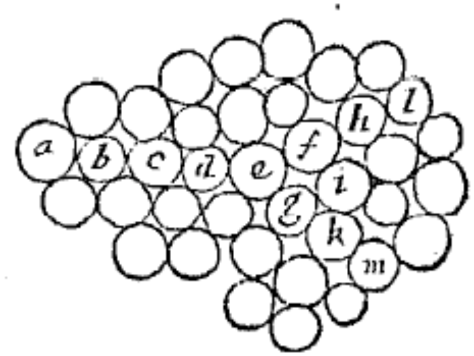


- granular materials display a rich variety of behaviors
- significant experimental and modeling challenges
- extensive quasi-static and low-velocity impact work
- determine thermal behavior through P-V work (Trunin, 2004)
- consolidation studied extensively to optimize loading, etc.
- partial compaction region seldom addressed
- applications: dynamic consolidation, planetary science, energy/blast absorption, ceramic armor

Very Early Thoughts on Particulate Materials

Newton’s *Principia*, Book II, 1687:

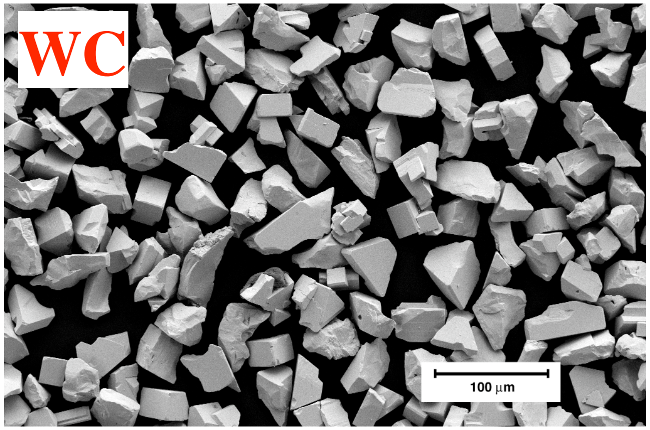
Si jaceant particulæ *a*, *b*, *c*, *d*, *e* in linea recta, poteſt quidem preſſio directe propagari ab *a* ad *e*; at particula *e* urgebit particulas oblique poſitas *f* & *g* oblique, & particulæ illæ *f* & *g* non ſuſtinebunt preſſionem illatam, niſi fulciantur a particulis ulterioribus *h* & *k*; quatenus autem fulciuntur, premunt particulas fulcientes; & hæ non ſuſtinebunt preſſionem niſi fulciantur ab ulterioribus

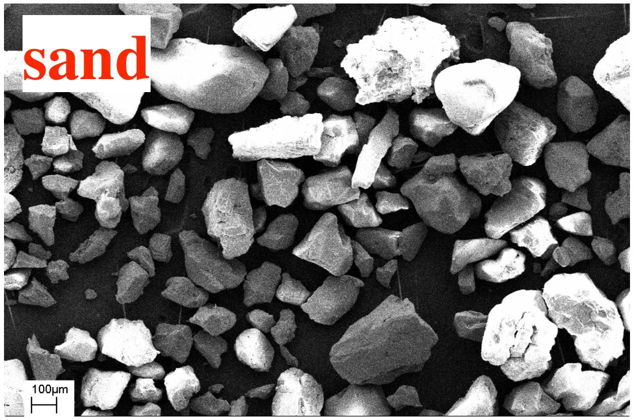


l & *m* eaſque premant, & ſic deinceps in infinitum. Preſſio igitur, quam primum propagatur ad particulas quæ non in directum jacent, divaricare incipiet & oblique propagabitur in infinitum; & poſtquam incipit oblique propagari, ſi inciderit in particulas ulteriores, quæ non in directum jacent, iterum divaricabit; idque toties, quoties in particulas non accurate in directum jacentes inciderit. *Q.E.D.*

Investigation of Dynamic Behavior of Granular Ceramics

- investigate dynamic compaction behavior of ceramic powders (WC, sand, Al_2O_3, etc.)
- develop insight into physics of dynamic behavior of these materials and the parameters that influence it
- explore a variety of techniques (quasi-static experiments, mesoscale simulations, etc.) to predict dynamic results
- determine suitability of current models within Sandia codes for simulating dynamic behavior of powders





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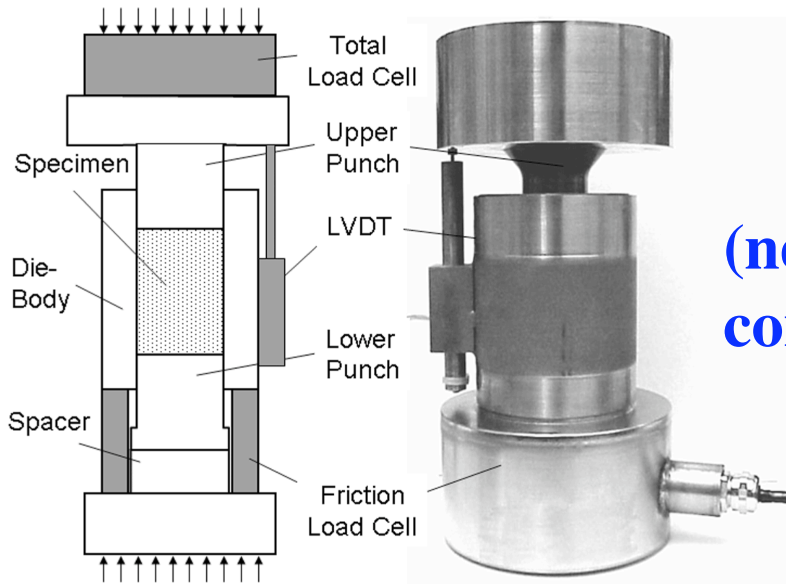
Static Die Compaction Experiments



(nearly) uniaxial strain compaction to ~1.6 GPa

<u>Objectives</u>

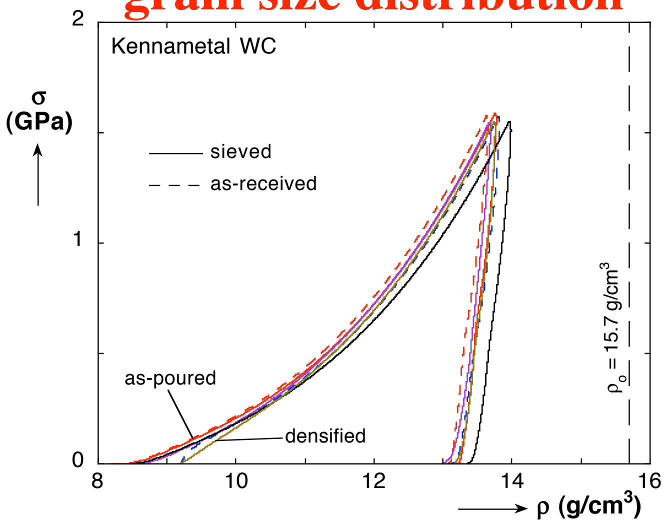
- Determine compaction curve functional form
- Examine effects of experimental parameters (grain size, grain size distribution, grain shape, initial density, loading path, etc.)
- Correlate with dynamic results

Moo Lee, 06711

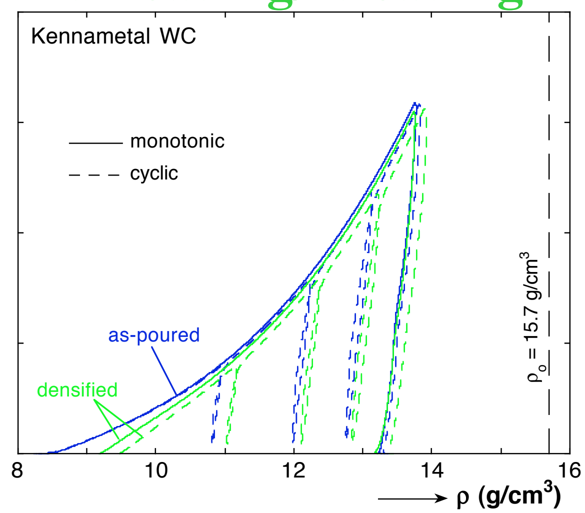
Static Compaction Results

evaluate effects of important variables on loading response

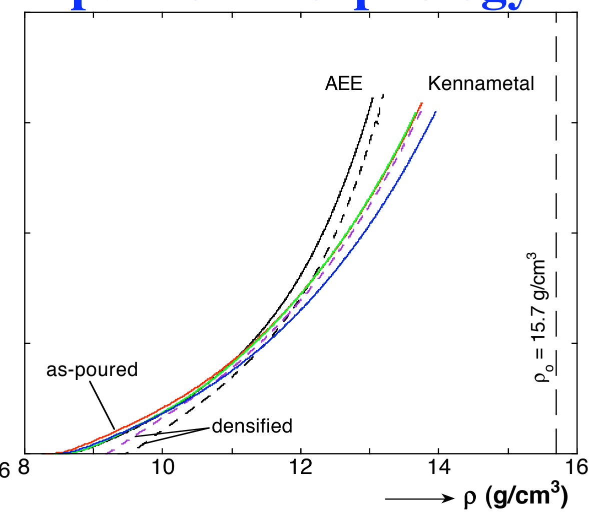
grain size distribution



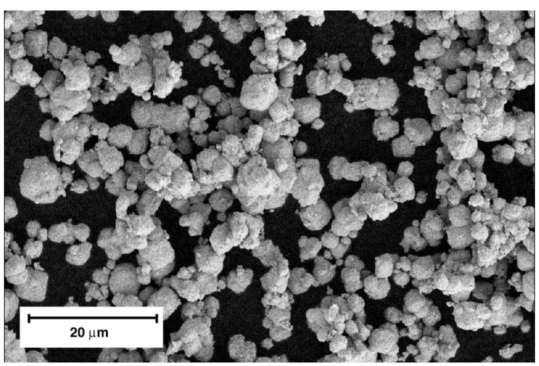
unloading/reloading



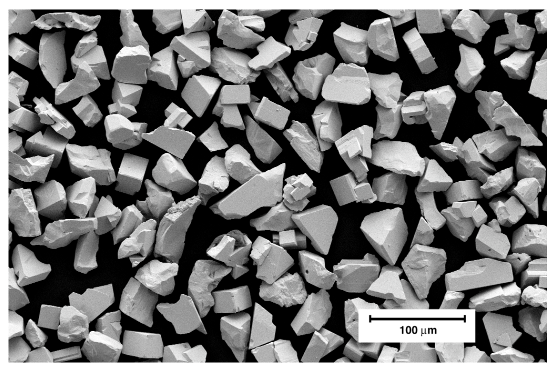
particle morphology



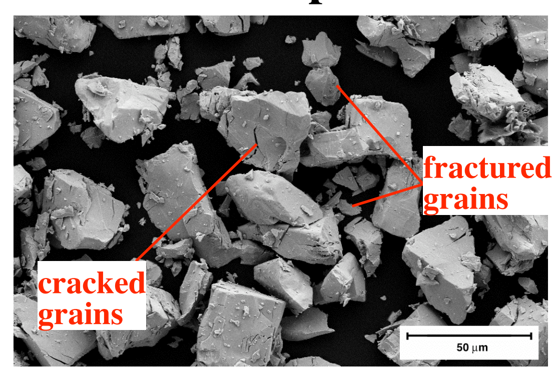
AEE WC



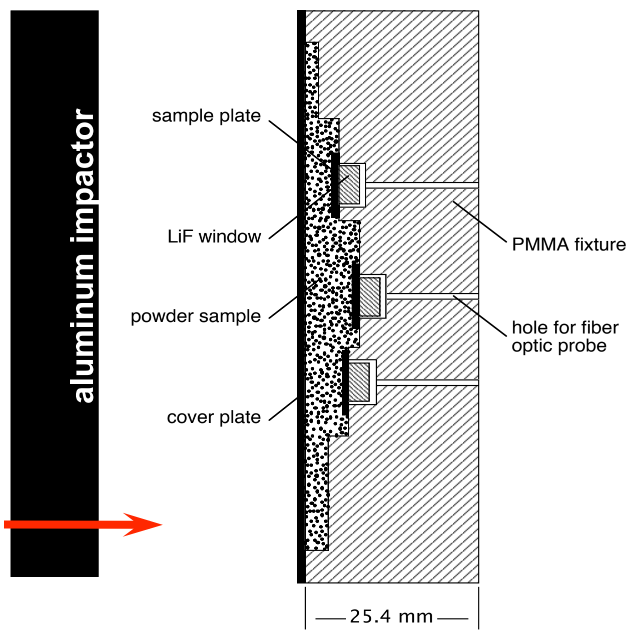
Kennametal WC

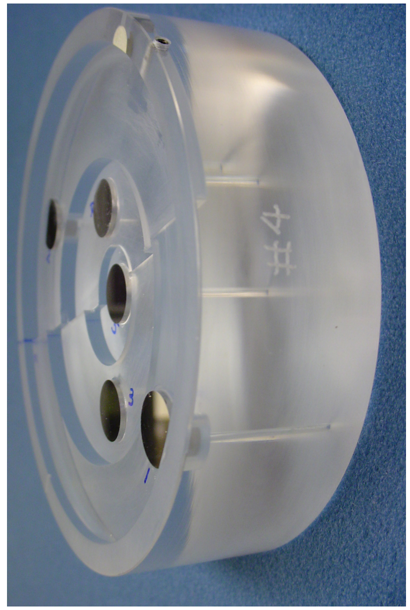


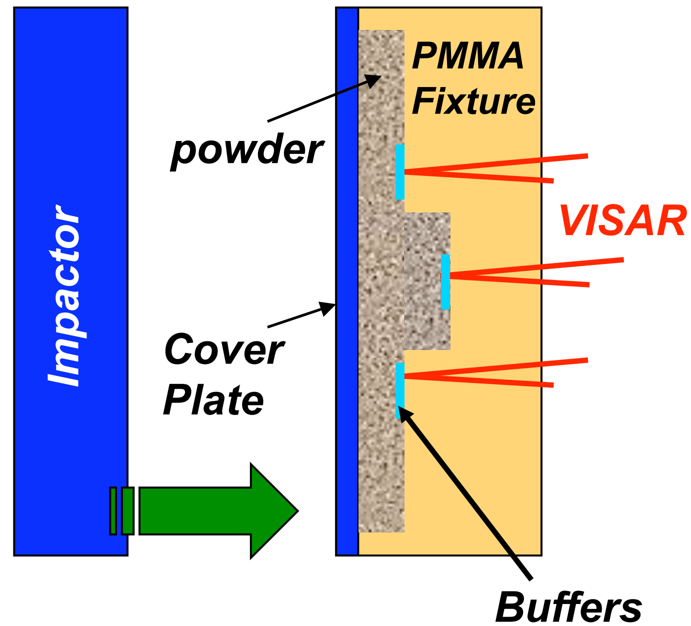
Post-Compaction



Planar Impact Experiments on Granular Materials





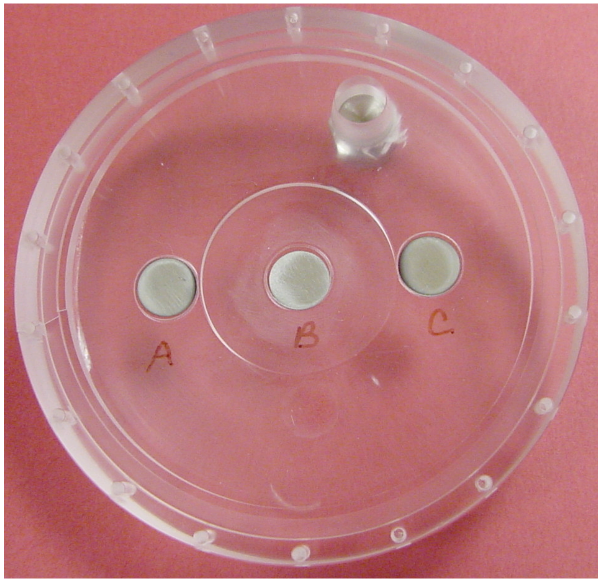


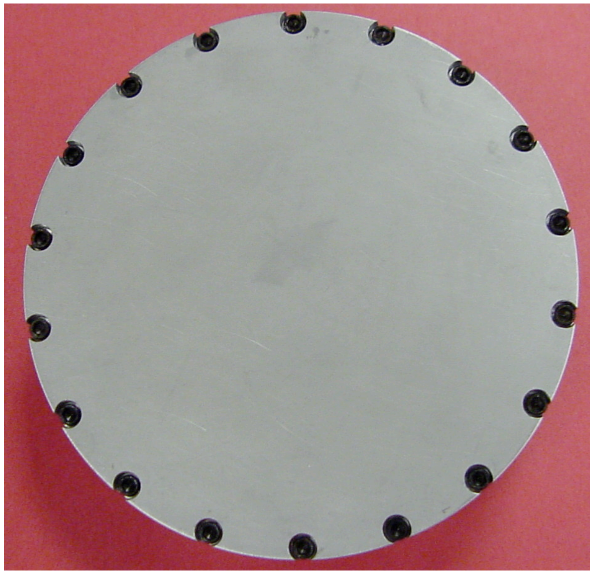
multiple sample thicknesses on the same experiment for accurate shock velocity and uniform powder density; sealed capsule allows fluid / powder mixtures

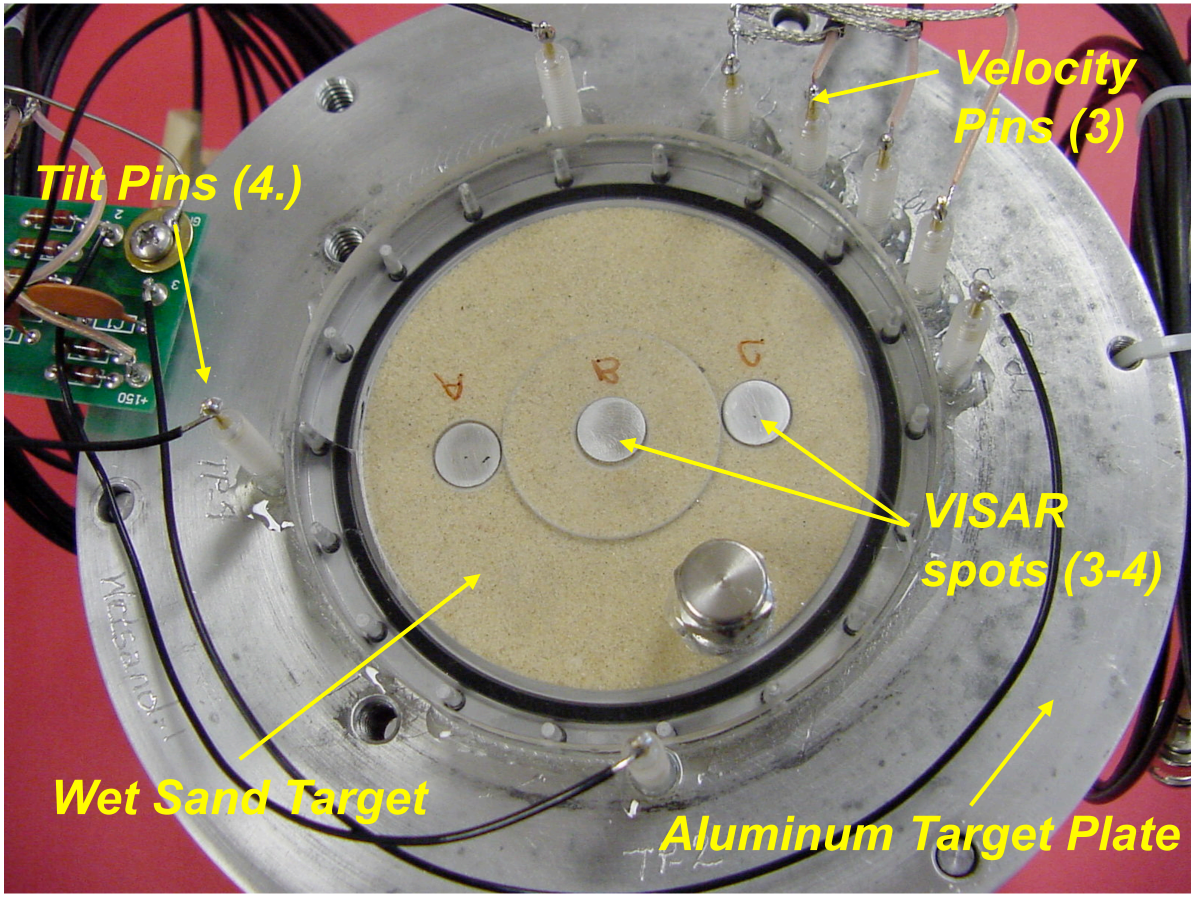
Vogler, T.J., Lee, M.Y., Grady, D.E., 2007. "Static and dynamic compaction of ceramic powders." *International Journal of Solids and Structures* **44**, 636-658.

Brown, J.L., Thornhill, T.F., Reinhart, W.D., Chhabildas,L.C., Vogler, T.J., 2007. "Shock response of dry sand." in Shock Compression of Condensed Matter – 2007, American Institue of Physics, 1363-1366.

Wet Sand Targets

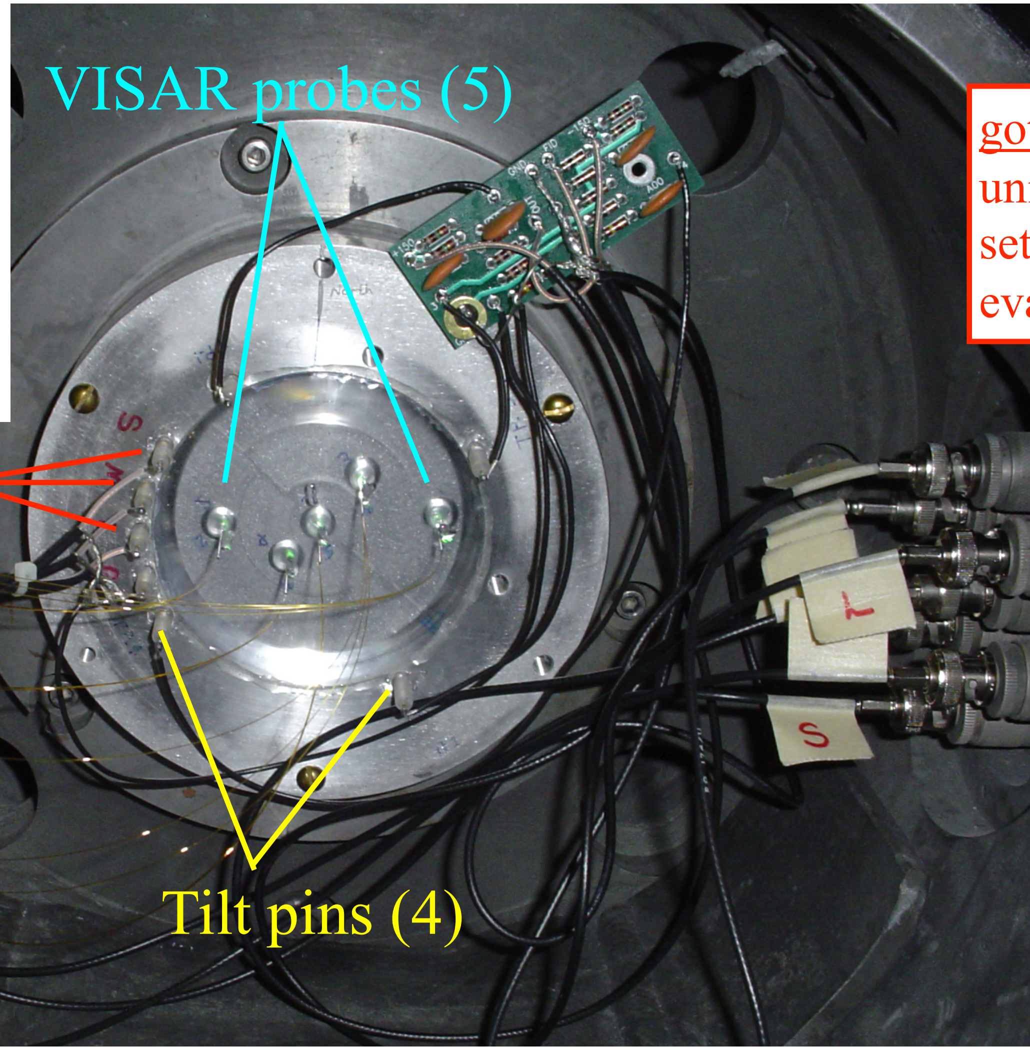






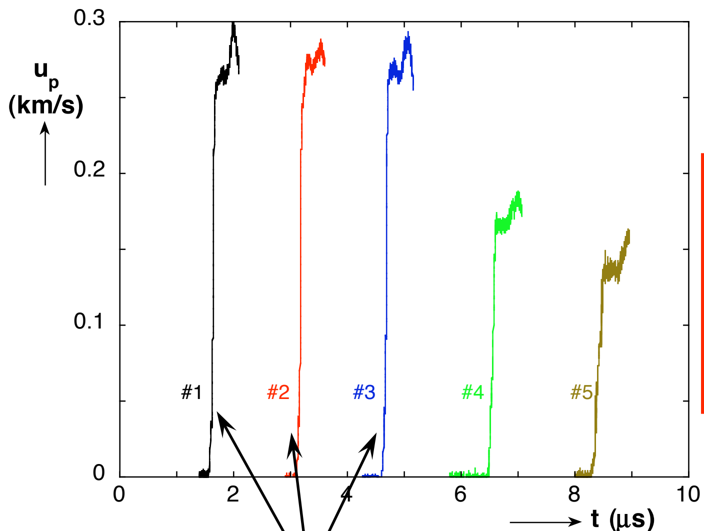
Target Mounted in Gas Gun

Single Stage Gun 100mm

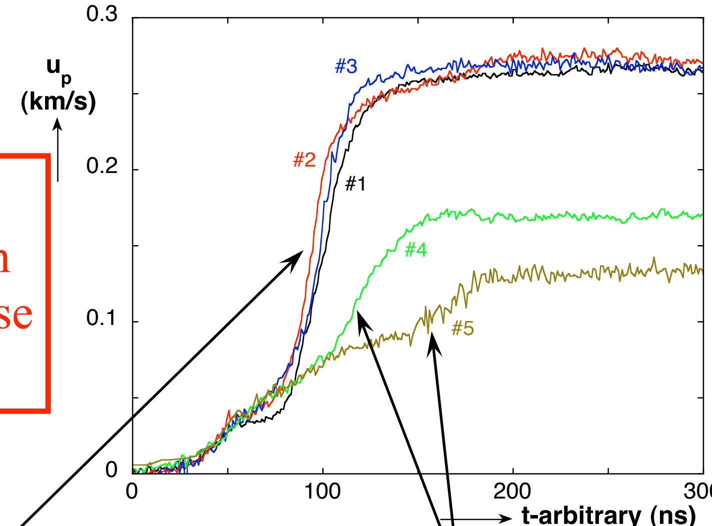


gotcha's:
uniformity
settling
evacuation

Measured Steady Waves



gotcha's:
attenuation
edge release
steadiness



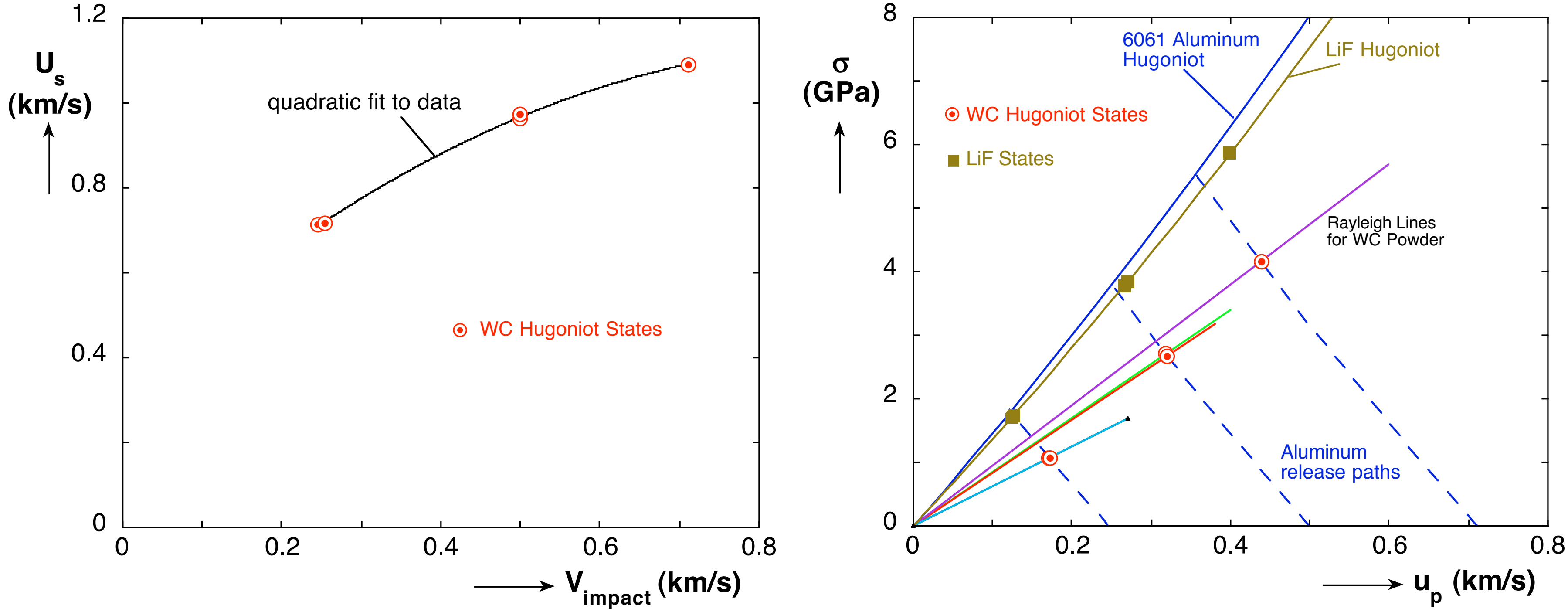
shock velocity calculated based on powder thicknesses and arrival times

steady, structured waves

attenuated waves

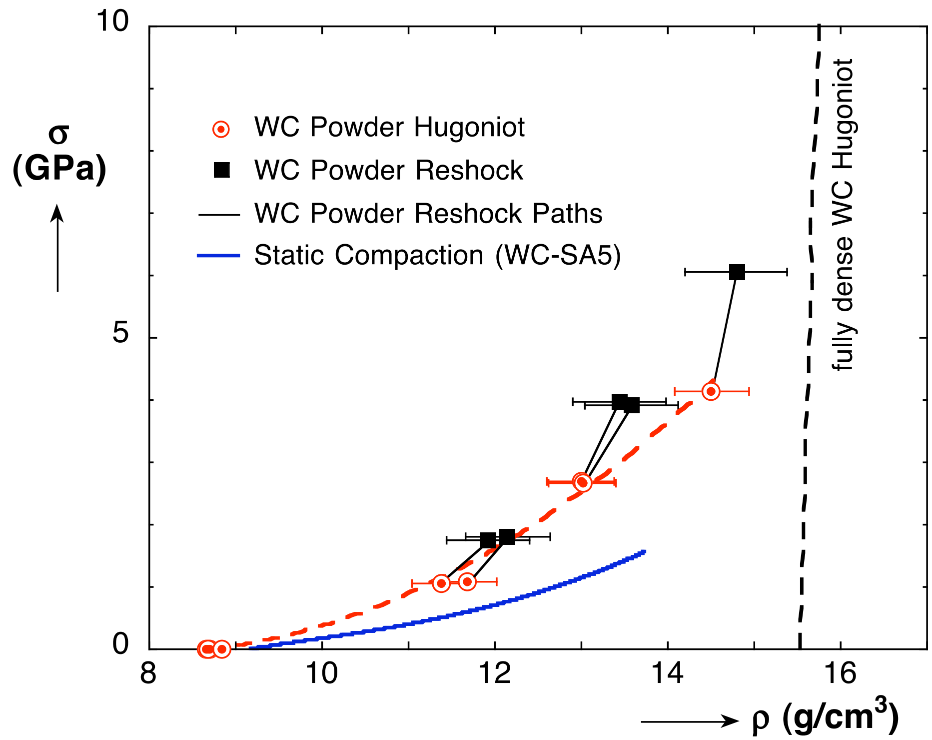
- seem to be first time-resolved measurements of steady waves in granular materials
- since waves are steady, Rankine-Hugoniot jump conditions can be used even though waves have finite rise times

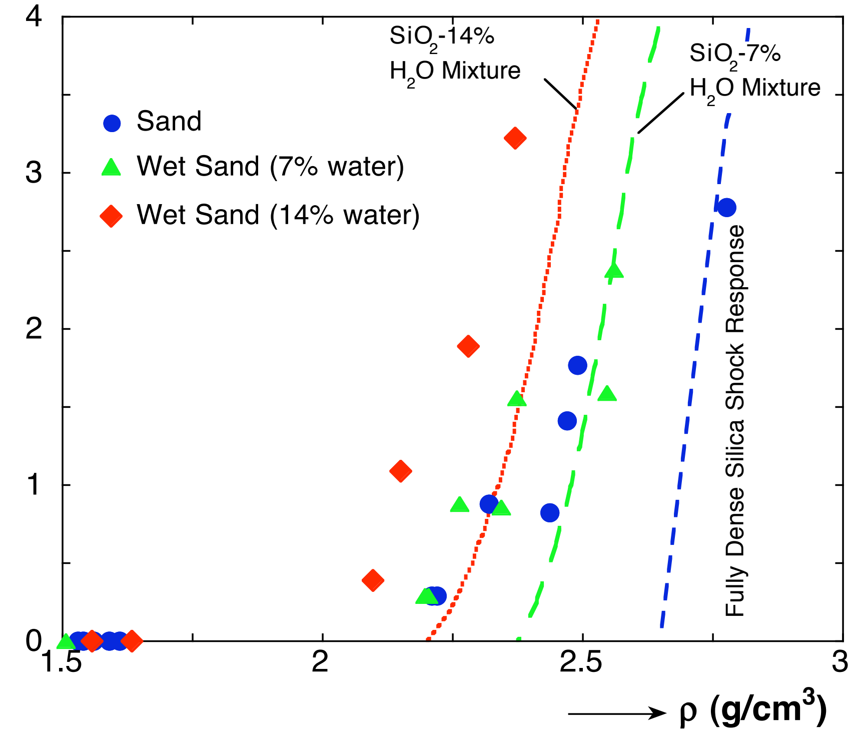
Shock Velocities and Hugoniot States



- impedance matching to aluminum impactor used to determine Hugoniot stress and particle velocity ($\sigma = \rho_{oo} U_s u_p$)
- density then calculated from $\rho = \rho_{oo} U_s / (U_s - u_p)$

Compaction Response for WC and Wet/Dry Sand

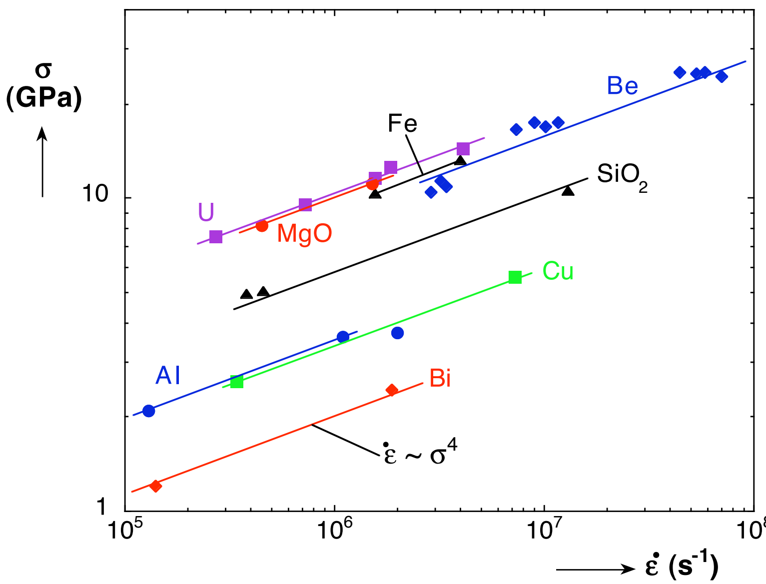


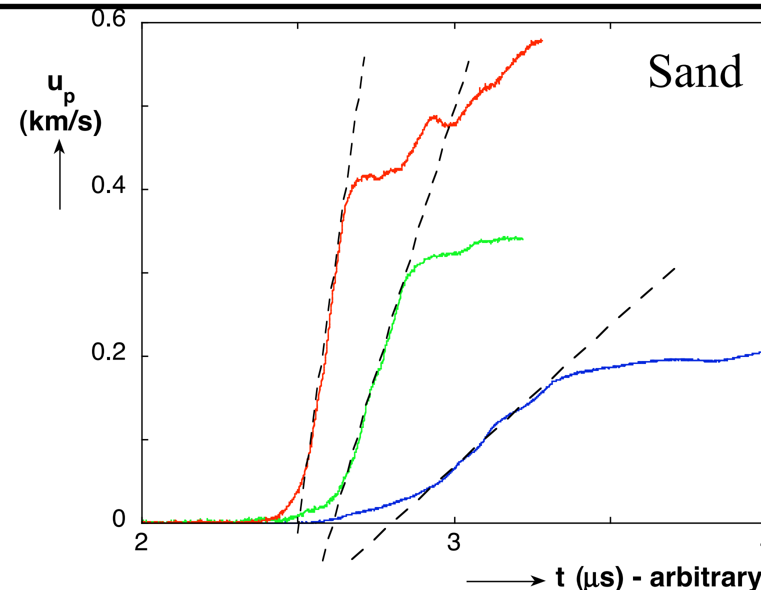


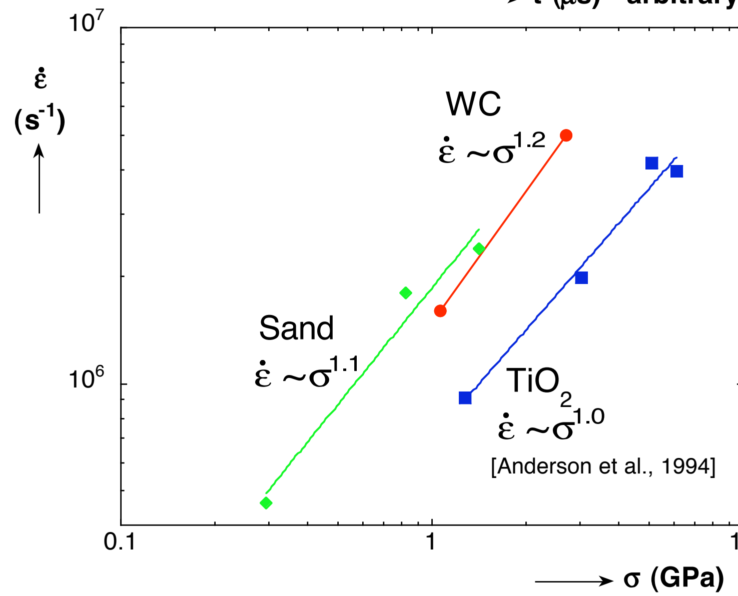
- first reshock state lies above Hugoniot suggesting elastic response of compacted material
- dynamic response is stiffer than static response for WC, about the same for sand

Scaling Between Rise Time of Wave and Stress

for many fully dense materials (Al, Be, Bi, Cu, Fe, MgO, SiO_2, U), rise times of steady waves scale as $\dot{\varepsilon} \sim \sigma^4$ (Swegle & Grady, 1985)

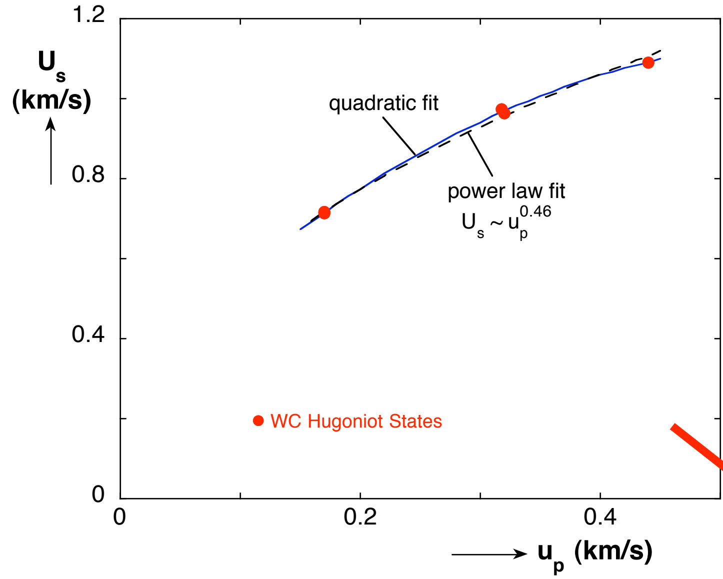


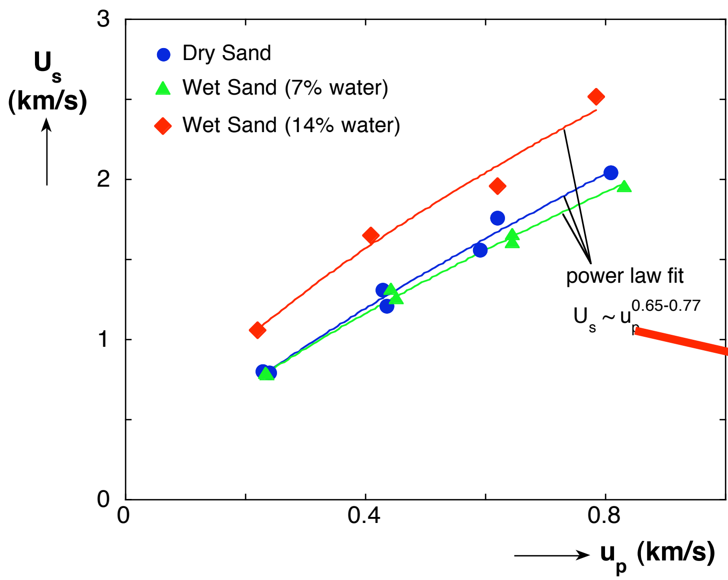




data on three granular ceramics and sugar suggest a linear scaling between stress and strain rate

A Simple Scaling Argument for Granular Materials





$$\sigma = \rho_{oo} U_s u_p$$

$$\varepsilon = \frac{u_p}{U_s}$$

$$\dot{\varepsilon} \propto \frac{\varepsilon}{\Delta t} \propto \frac{u_p / U_s}{d / u_p}$$

mass traversing pores controls width of shock front

$$\dot{\varepsilon} \propto \frac{u_p^2}{d U_s}$$

$$\sigma \propto u_p^{3/2}$$

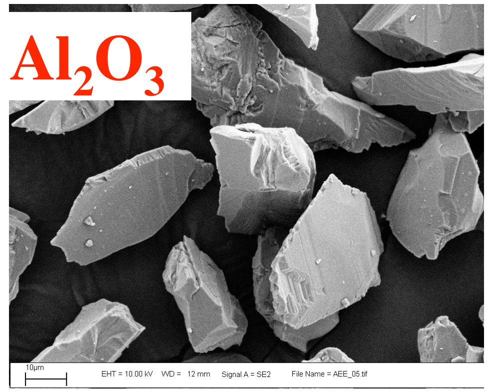
$$\frac{if \quad U_s \propto u_p^{0.5}}{\dot{\varepsilon} \propto u_p^{3/2}}$$

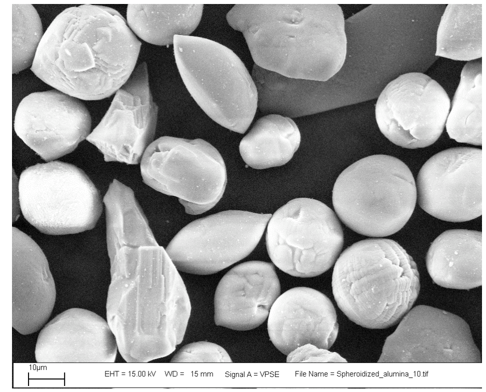
$$\dot{\varepsilon} \propto \sigma$$

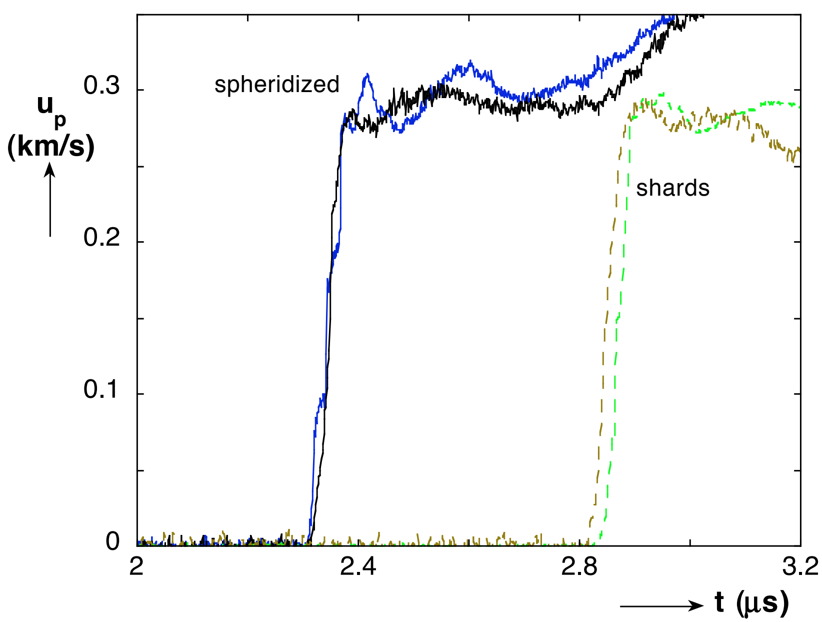
$$\frac{if \quad U_s \propto u_p^{0.75}}{\dot{\varepsilon} \propto \sigma^{0.7}}$$

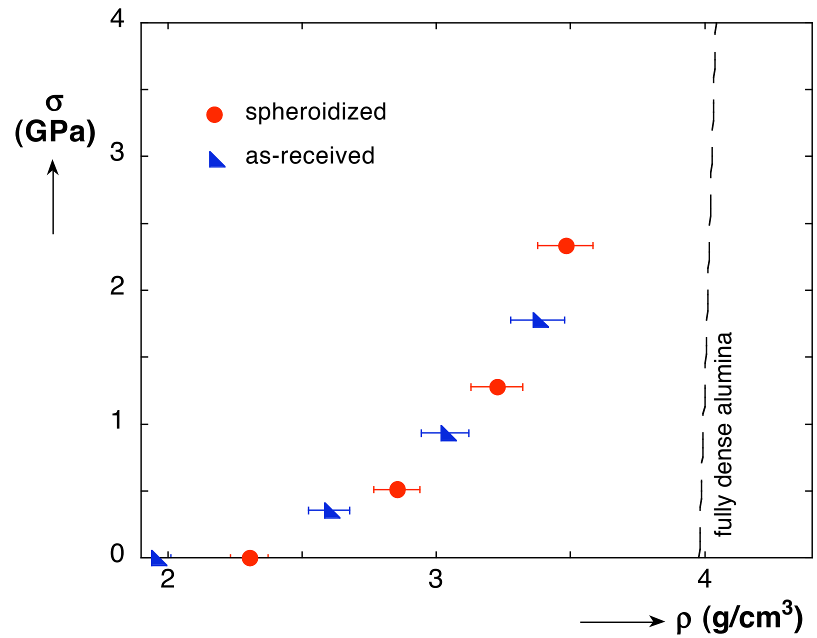
Effect of Particle Morphology

plasma processing used to create spheres, changing particle morphology





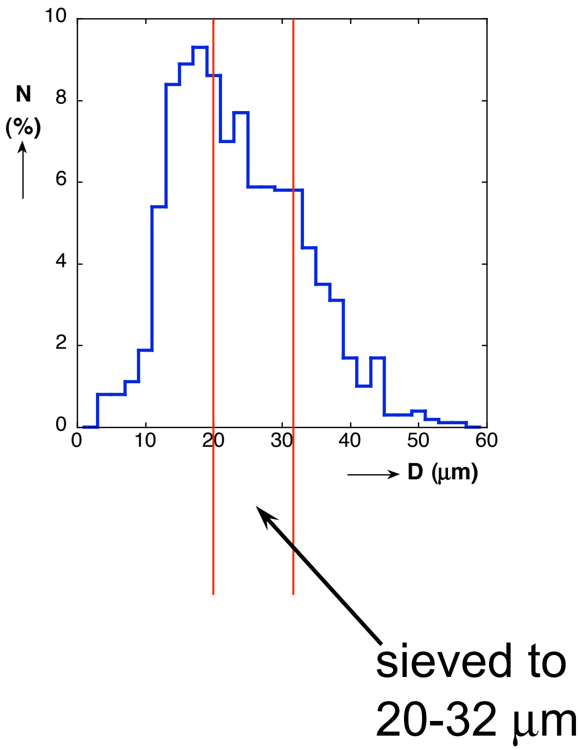


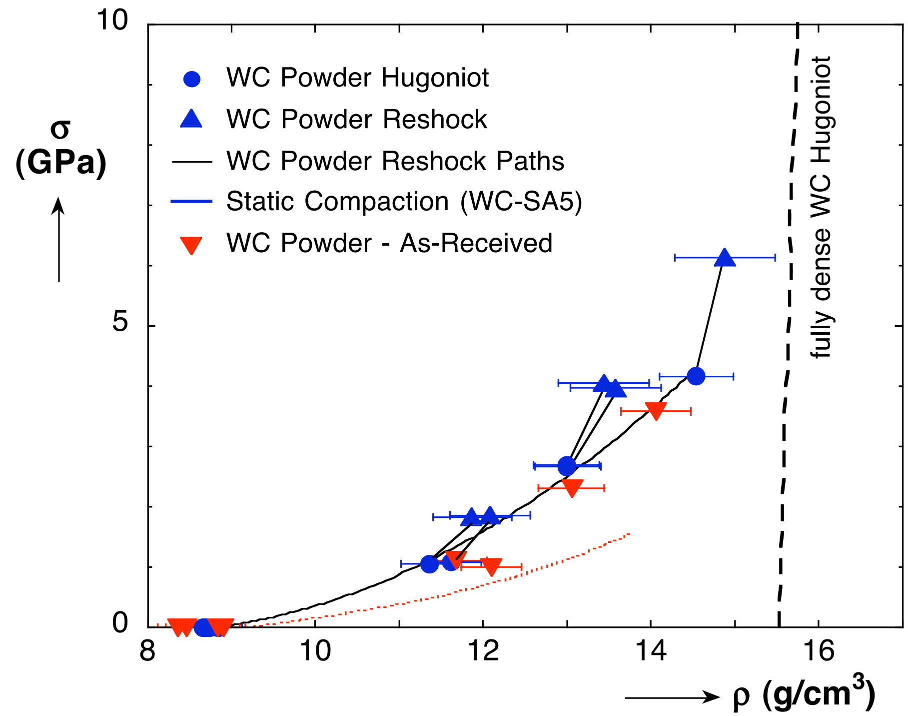


compaction results indistinguishable, but small differences in VISAR records

Particle Size Distribution

as-received particle size distribution





results are insensitive to particle size distribution, at least over the same order of magnitude

- Introduction to Shock and High-Pressure Physics
- Introduction to Granular Materials
- Planar Impact Experiments
- Mesoscale Modeling
- Other Experimental Work
- Conclusions

Mesoscale Modeling of Granular Materials: Past Work

- collapsing ring of material under external pressure (Carroll & Holt, 1972; Nesterenko, 2001; Tong & Ravichandran, 1997)
- Williamson (1990) considered a unit cell in a uniform distribution of particles under dynamic loading
- Benson and coworkers (1994-present) studied compaction of granular materials (primarily metals) using a 2-D Eulerian code for a moderate number of grains
- Baer (2002-present) simulated compation of HMX and sugar (HMX simulant) using a 3-D Eulerian code for a moderate number of particles

- *follow approach of Benson et al. for larger number of grains by exploiting parallel computing platforms*
- *begin with 2-D and determine whether 3-D is necessary*

Mesoscale Modeling of Granular Materials

- particles idealized as circles (rods) for initial work
- constant velocity boundary condition applied
- run in CTH (explicit Eulerian finite difference code)
- Mie-Gruneisen EOS, elastic-perfectly plastic strength for WC

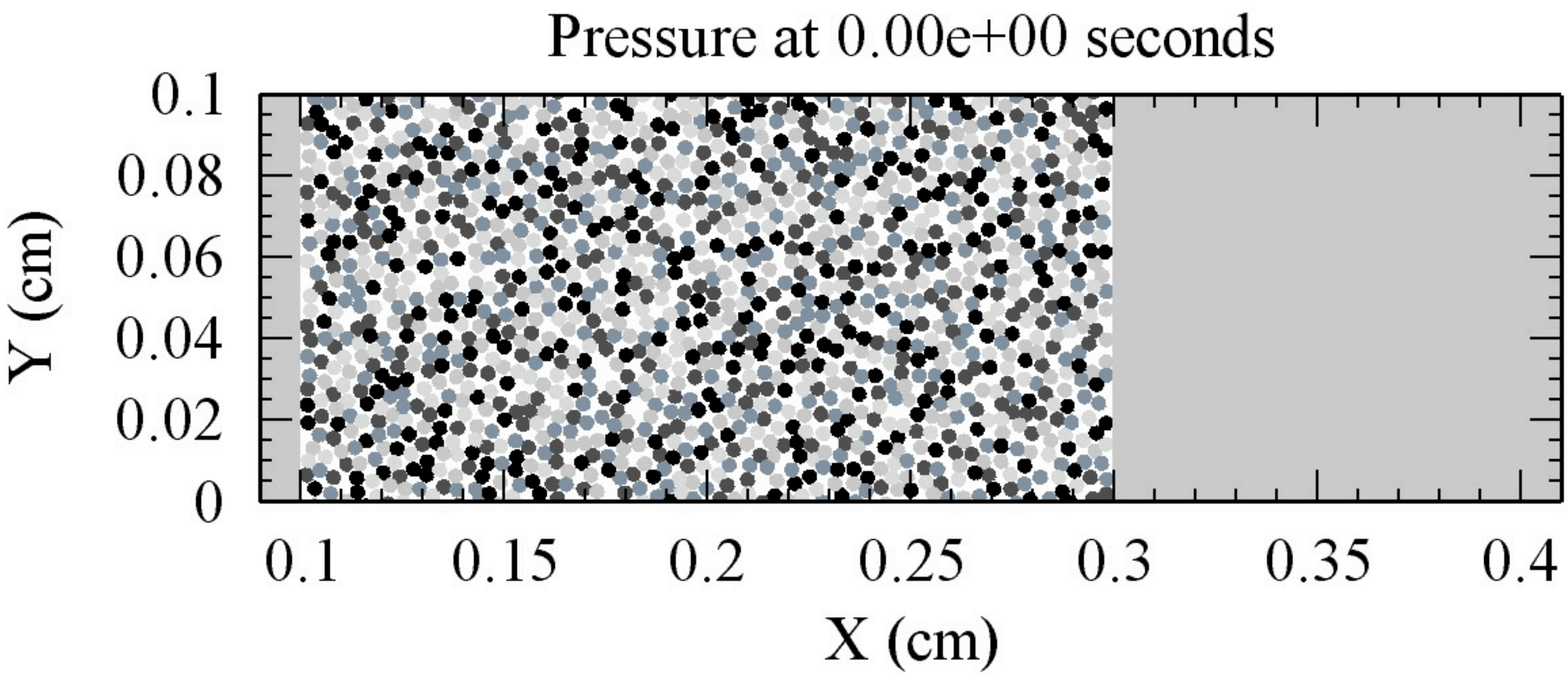
Borg, J.P., Vogler, T.J., (2008). "Mesoscale calculations of the dynamic behavior of a granular ceramic." *International Journal of Solids and Structures* 45, 1676-1696.

Borg, J.P., and Vogler, T.J. (2008). "Mesoscale simulations of a dart penetrating sand," *Int. J. Impact Eng.* (in press).

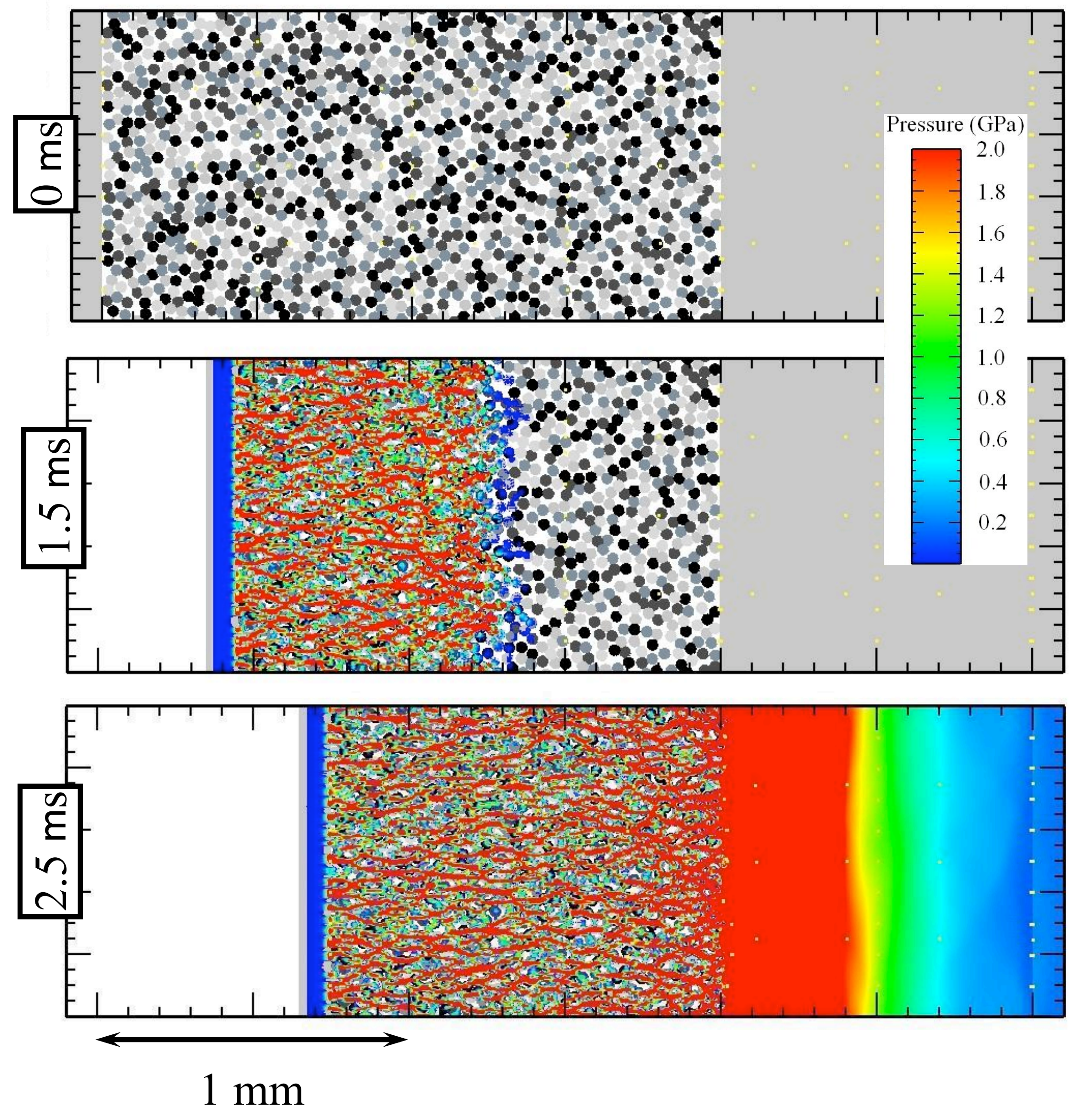
Borg, J.P., and Vogler, T.J. (2007). "Mesoscale calculations of shock loaded granular ceramics," in Shock Compression of Condensed Matter – 2007, American Institue of Physics, 227-230.

get at underlying physics of granular materials

Computational Dynamic Compaction

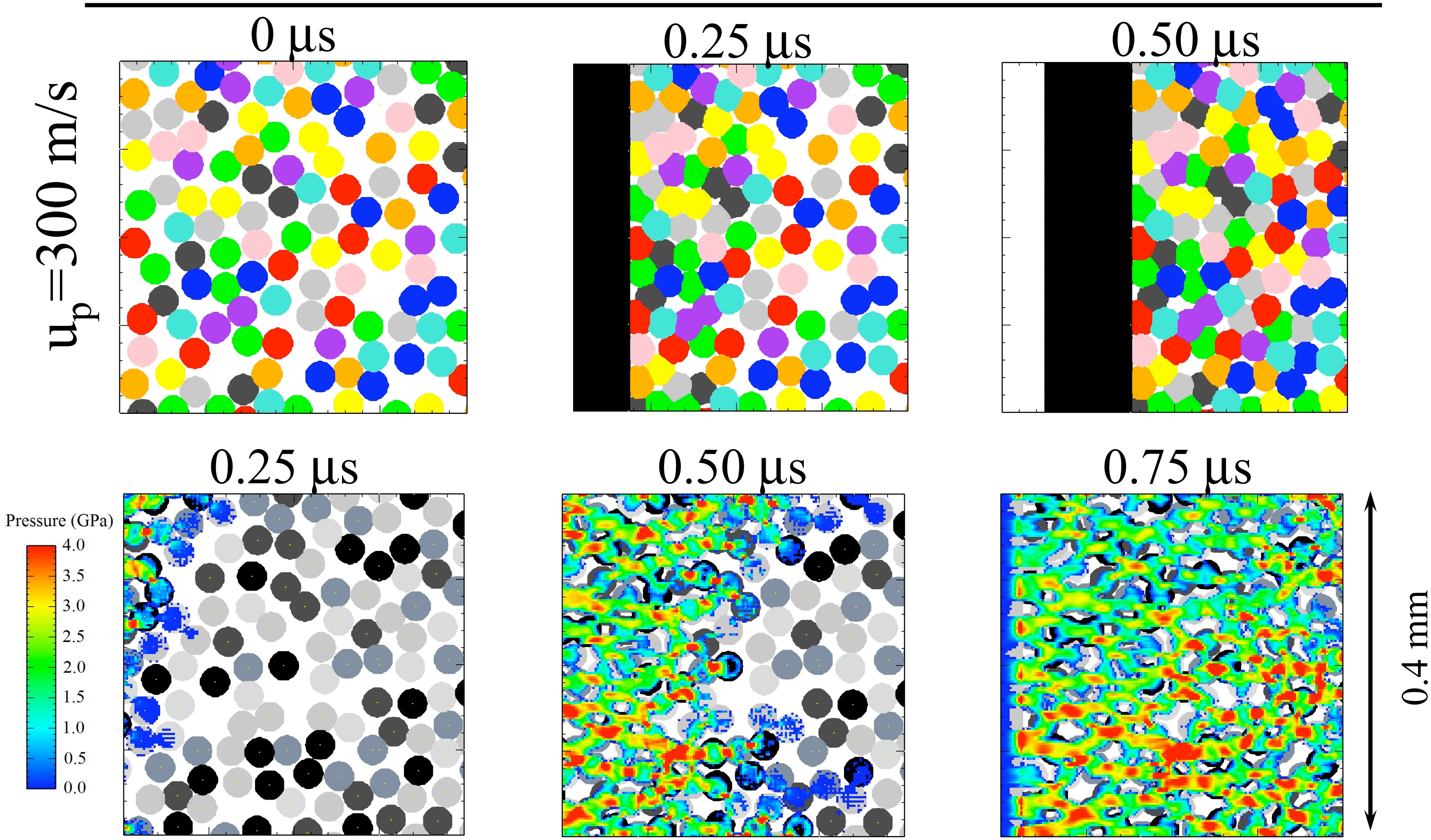


Computational Dynamic Compaction



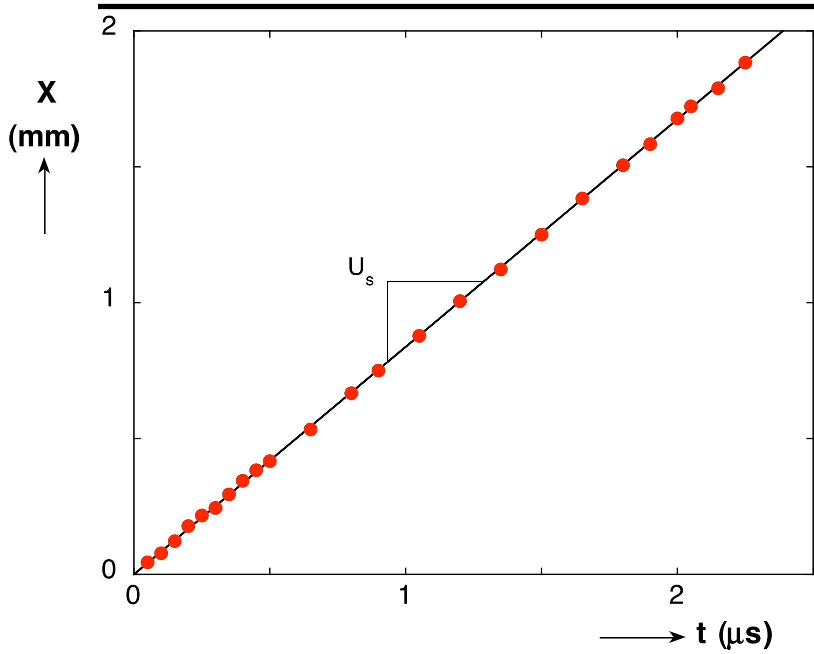
- driver plate velocity u_p=300 m/s
- shock thickness on the order of ~2-5 particles
- strong force chains observed
- wave smooths in aluminum buffer

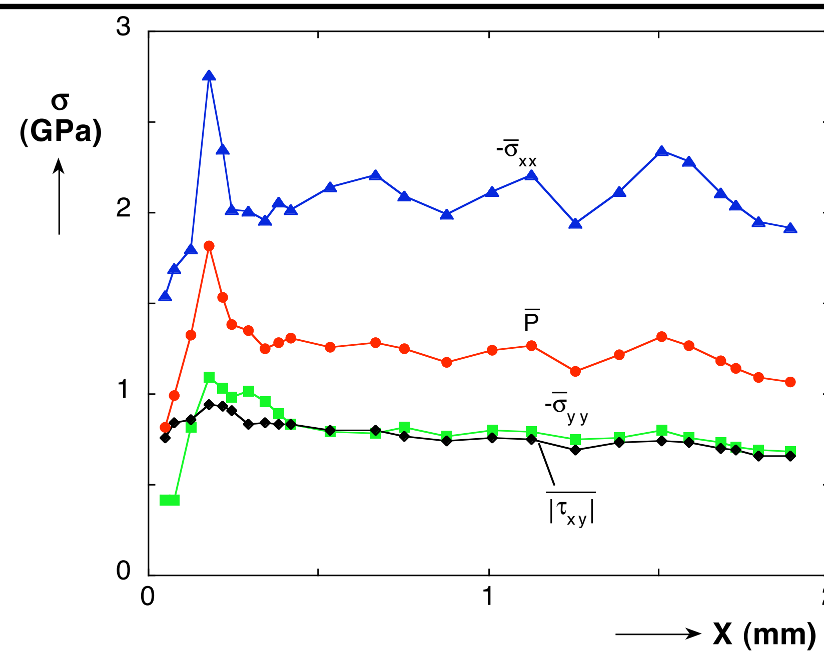
Close-Up of Compaction Process



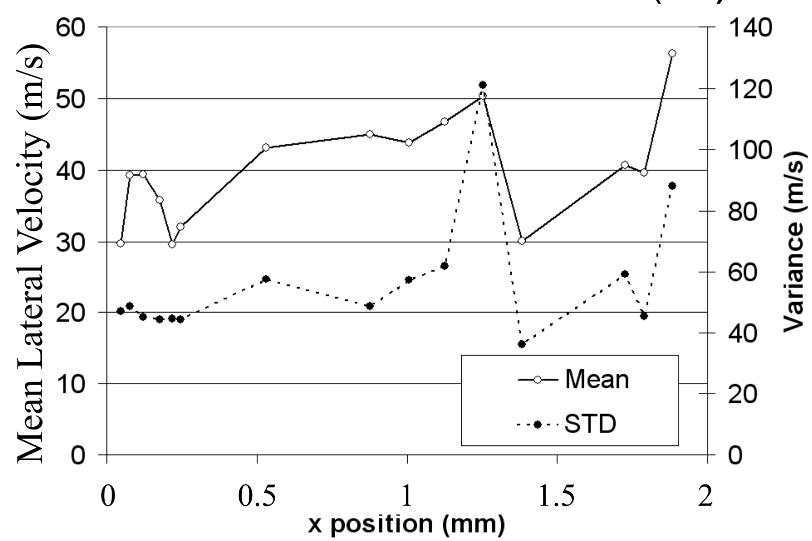
no jetting or vortices so deformation is "*quasi-static*"
(Benson et al., 1997)

Properties of Propagating Wave

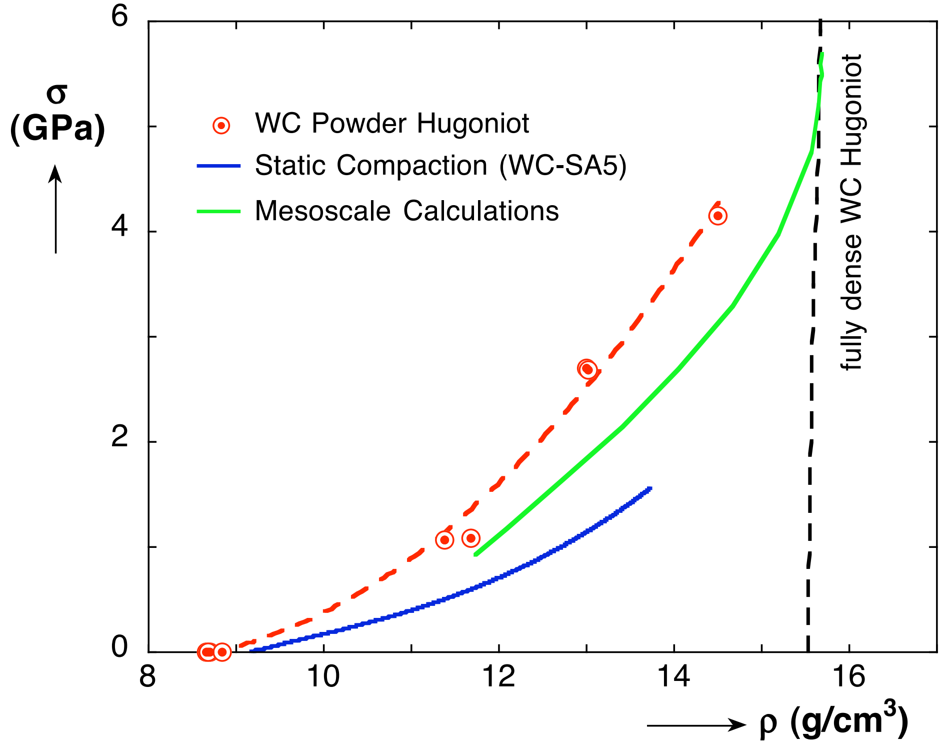




- arrival time of wave suggests steadiness at all times
- stresses in wave front indicate nearly 0.5 mm required to reach steady state
- lateral motion >10% of longitudinal velocity



Calculated Hugoniot from Literature Parameters



$$\sigma = \rho_o U_s u_p$$

$$\rho = \rho_o \frac{U_s}{U_s - u_p}$$

- simulations provide reasonable estimate for Hugoniot
- shortcomings of model:
  - missing physics of granular contact and fracture
  - wrong connectivity in 2-D
  - spherical particles unrealistic
  - inaccurate strength for small particles

Sensitivity to Simulation Parameters

Material Properties

- Particle size distribution (negligible effect)
- Dynamic yield strength (strong effect)
- Material EOS (negligible effect)
- Spall strength (strong effect but threshold)

Two-Dimensional Properties

- Material distribution (strong effect)
- Variations in boundary conditions (small effect)

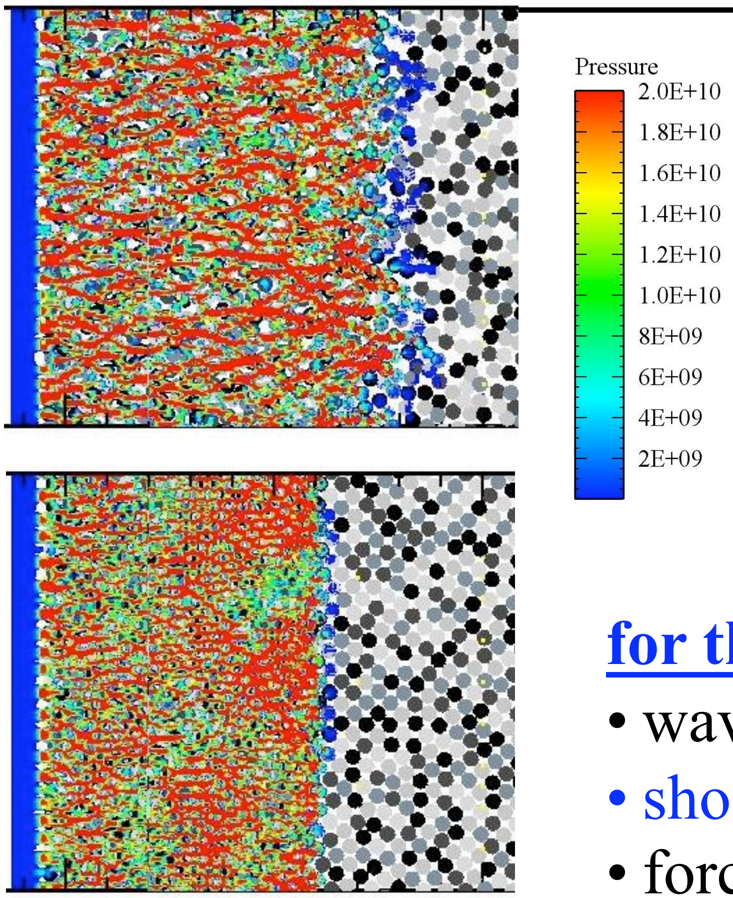
Hydrocode Behavior

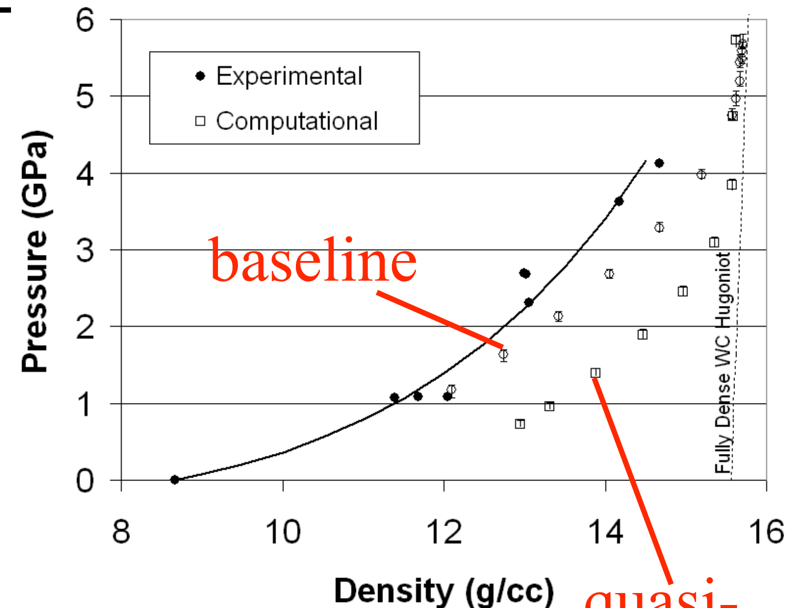
- Mixed cell strength (very strong effect)

Effect of Order on Shock Structure

Baseline

Quasi-Crystalline





quasi-crystalline

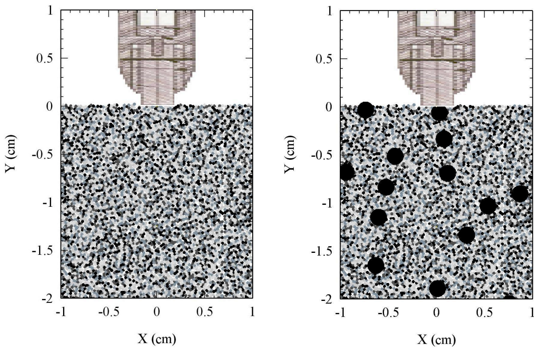
<u>for the quasi-crystalline case:</u>

- wave much slower
- shock front less diffuse
- force chains less pronounced

- shock propagation must rely on momentum (i.e. particle motion) to transport shock information
- lateral motion minimized
- material becomes anisotropic (slow and fast directions)

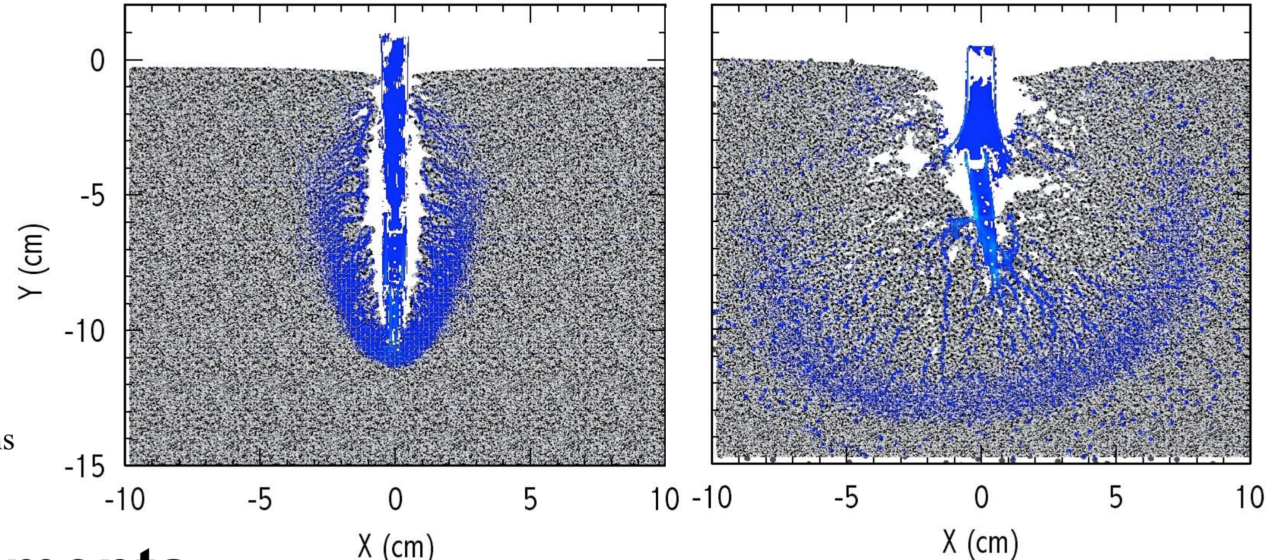
"System Level" Work
providing insight into nonuniform targets

Borg and Vogler, Int. J. Impact Engineering (in press)

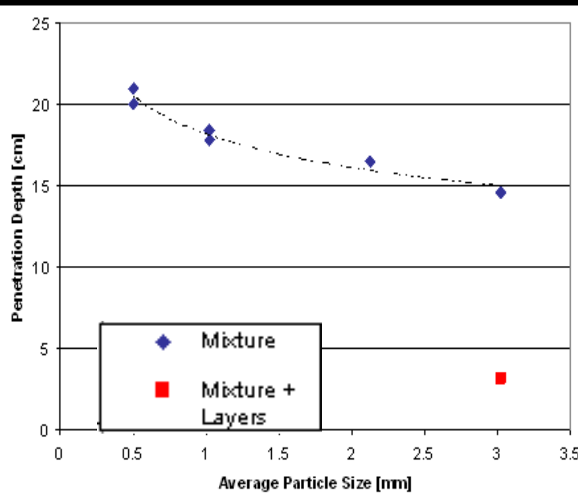


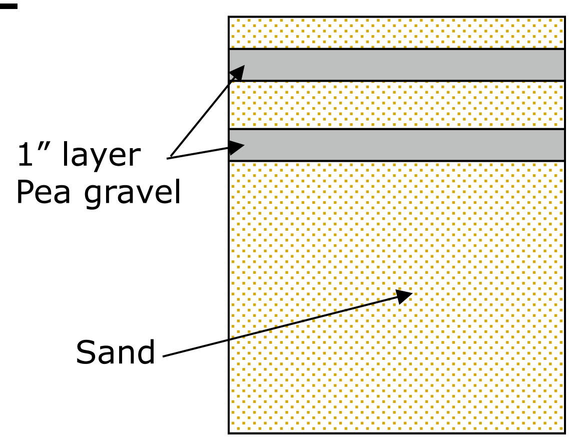
224 mm Sand with 1.6 mm grains

224 mm uniform sand | 224 mm sand with 1.6 mm



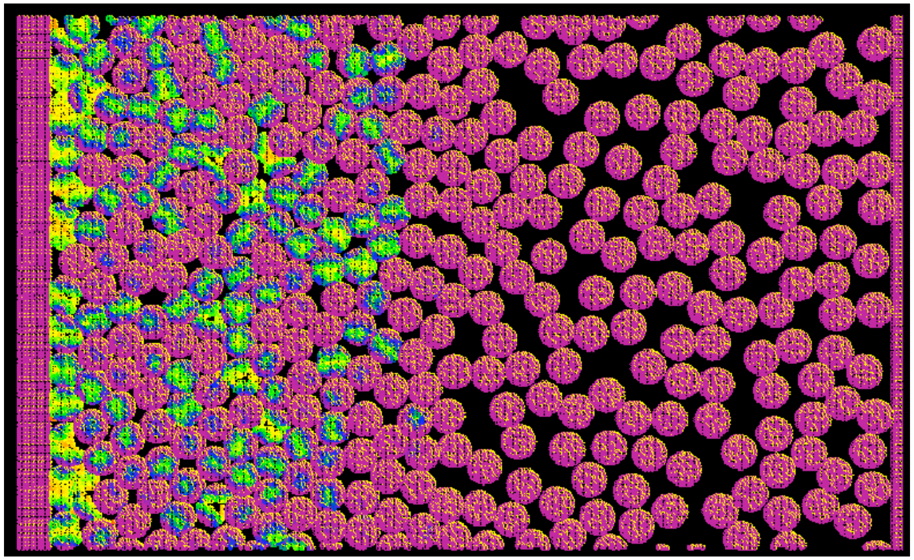
small-scale experiments

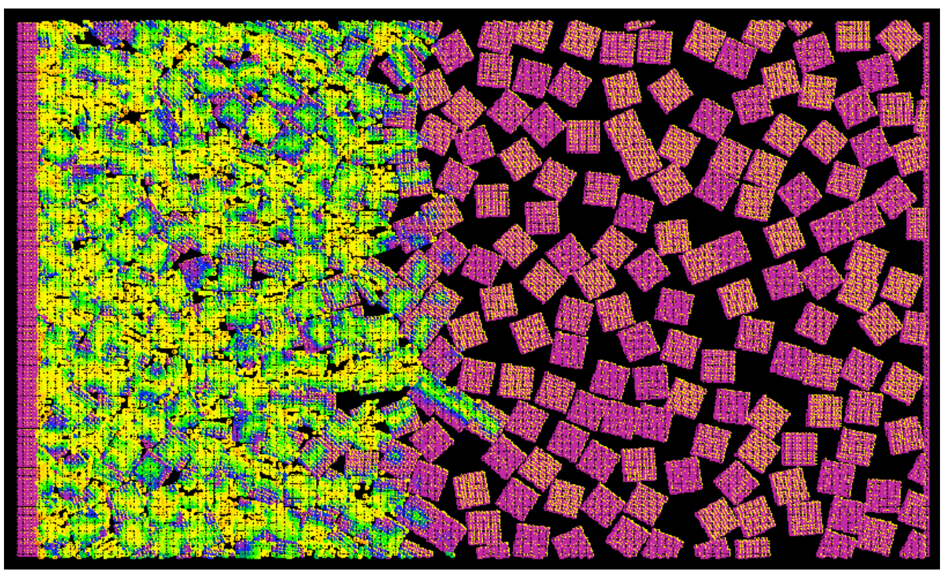




mesoscale simulations in progress to understand deflection mechanism

Initial Mesoscale Calculations with Peridynamics





- non-local method based on reformulation of governing equations in integral form (Silling, JMPS 2000)
- model framework still under development
- includes fracture and contact missing from CTH
- response insensitive to particle shape despite large differences in particle fracture (dissipation due to fracture is small)

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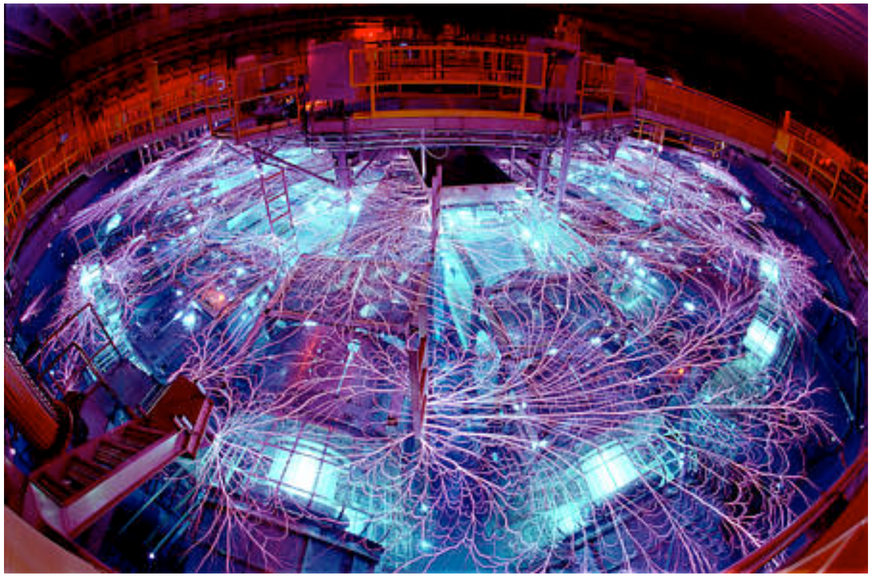
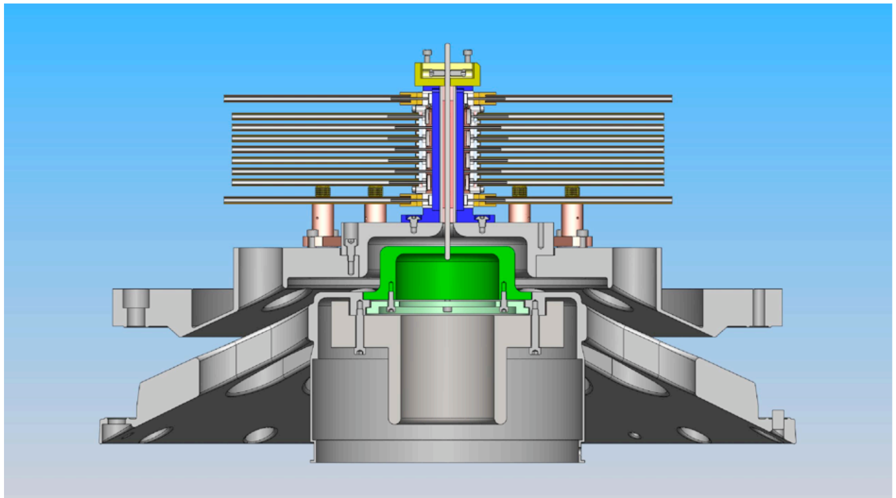
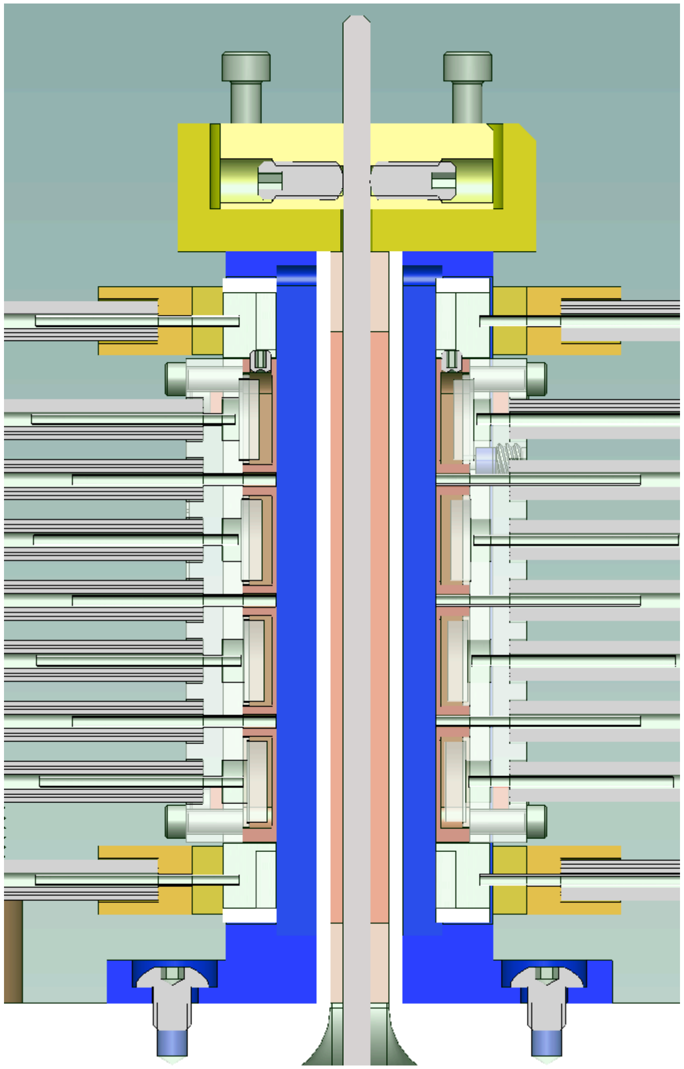
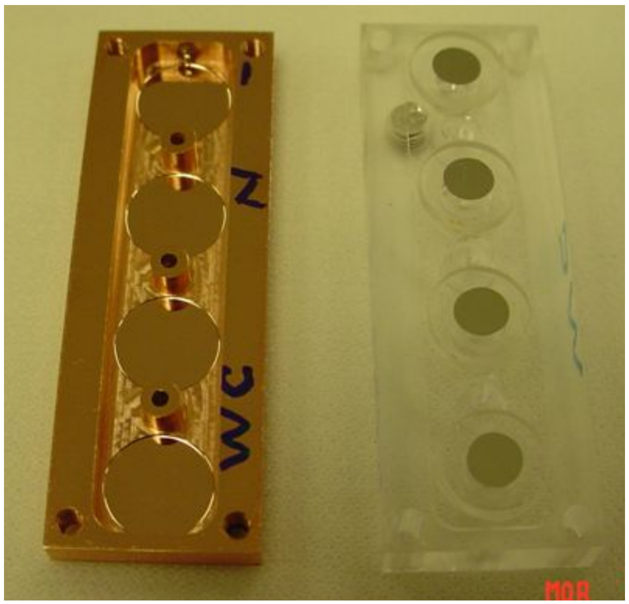
Ultra-High Pressure
Z Experiments

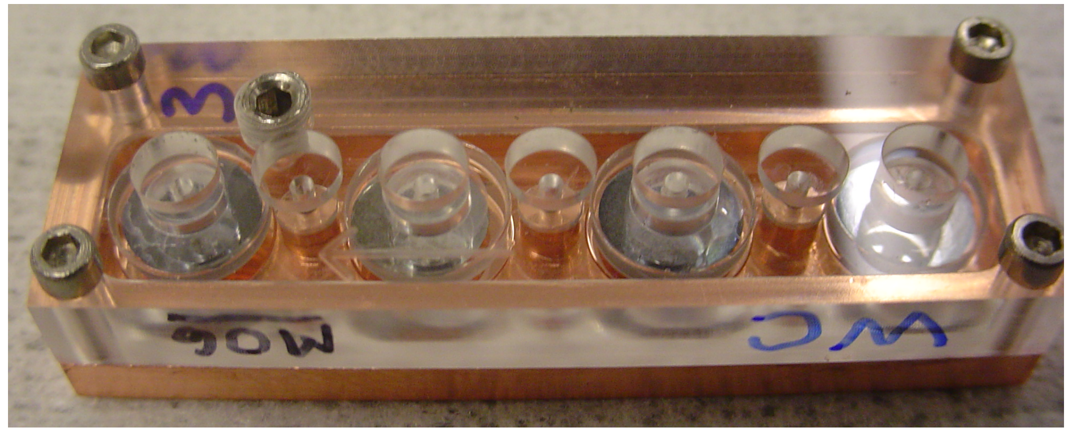






Z Powder Capsule



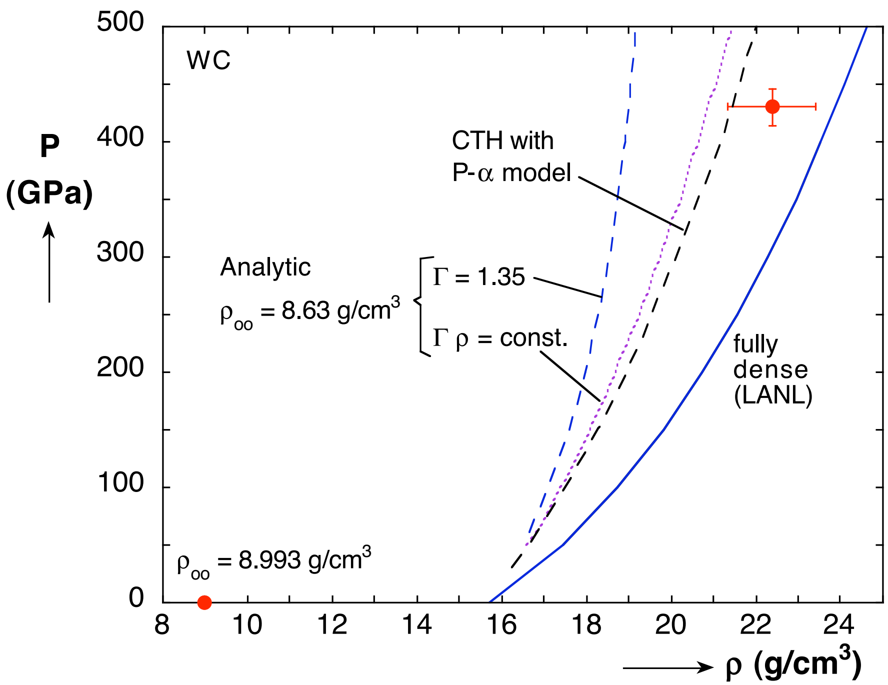


each target consists of:

- 300 µm Cu flyer on 700 µm Al
- 300 µm Cu driver
- four WC thicknesses of 400, 600, 800, and 1000 µm
- quartz windows.

VISAR measurements made at each sample/window interface and above, below, and between the samples

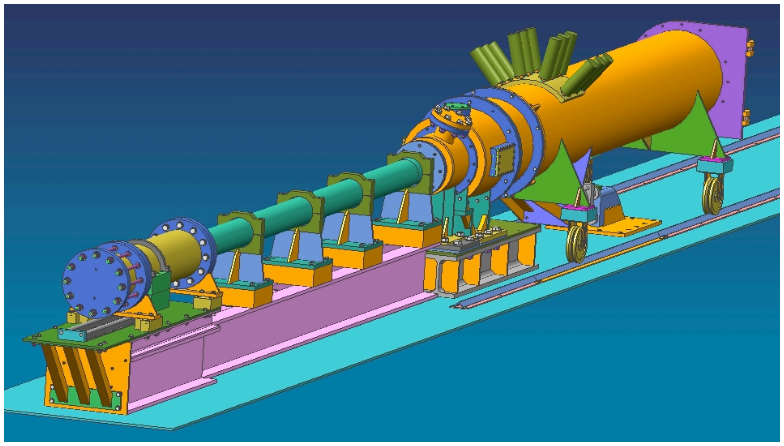
Z Experiment - Granular WC

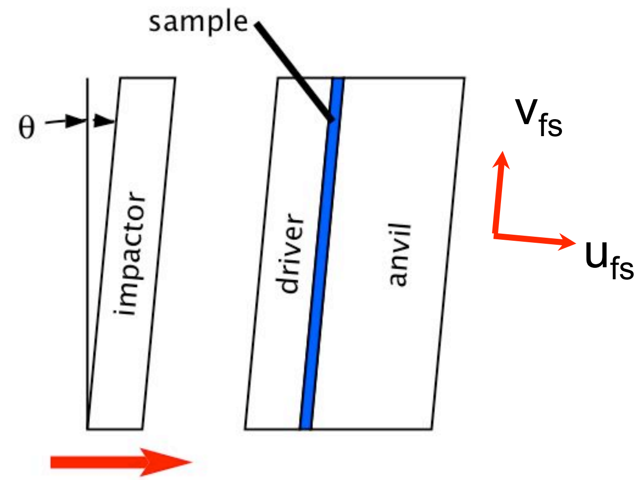


- Fully dense WC Hugoniot from LASL shock compendium
- Porous Hugoniot calculated analytically for Γ=1.35 and Γρ=constant with initial density of 8.63 g/cc; melting neglected
- Calculations with CTH utilizing a Mie-Gruneisen EOS and the P-α model; melting neglected

- Data point shown is for Z-2096, impact of a copper flyer into the copper driver at 9.85 km/s. Initial sample density was 8.993 g/cc.
- Porous material melts at 45-50 GPa vs. 390-440 GPa
- Preliminary error bars based on uncertainty in shock velocity, EOS of copper, impact velocity, and initial density.

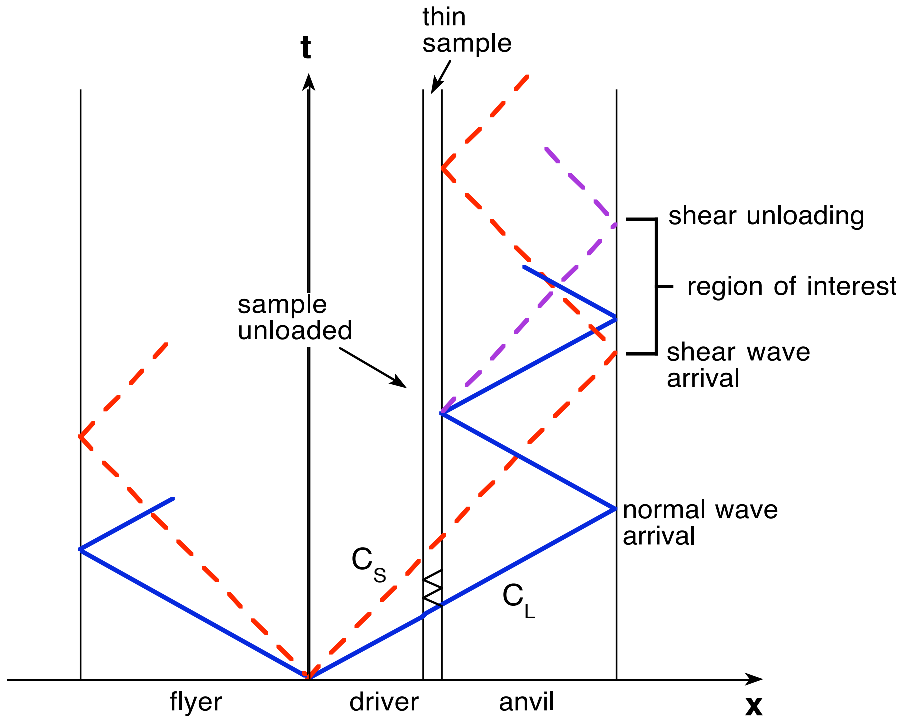
Pressure-Shear Loading of Granular Materials

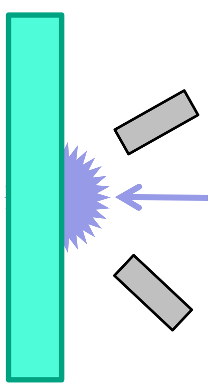




- slotted barrel prevents rotation and ensures planar impact at angle θ
- elastic impactor, driver, and anvil simplify analysis (steel, WC, etc.)
- angle θ must be small enough to prevent slipping (less than ~30°)
- variation of impact velocity, angle, and sample thickness allow control of pressure and strain rate
- capable of strain rates of 10^5 - 10^6 s^{-1}

Basics of Pressure-Shear Experiments





$$v_{12}^* = \frac{\cos(17)+1}{2} v_x + \frac{\sin(17)}{2} v_y$$

$$v_{13}^* = \frac{\cos(25)+1}{2} v_x - \frac{\sin(25)}{2} v_y$$

- normal stress (pressure) defined by flyer/driver/anvil material and impact velocity

$$\sigma = \tfrac{1}{2}\cos(\theta) V_{impact} \rho_o^{anvil} c_o^{anvil}$$

- shear stress given by:

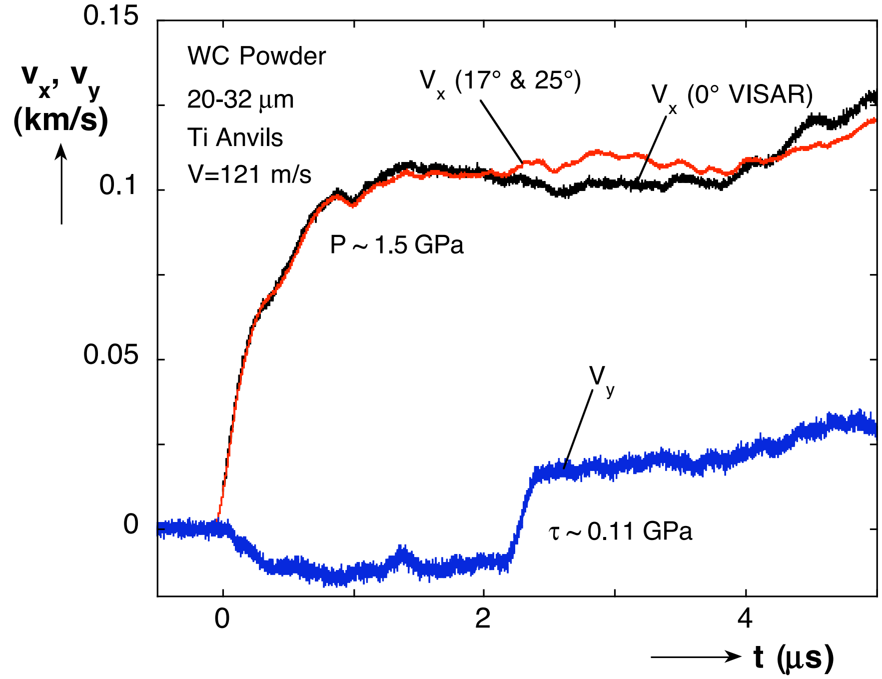
$$\tau(t) = \tfrac{1}{2} \rho_o^{anvil} c_o^{anvil} v_{fs}(t)$$

- strain rate given by:

$$\dot{\gamma} = \frac{V \sin\theta - v_{fs}}{h}$$

Experiment WC-1

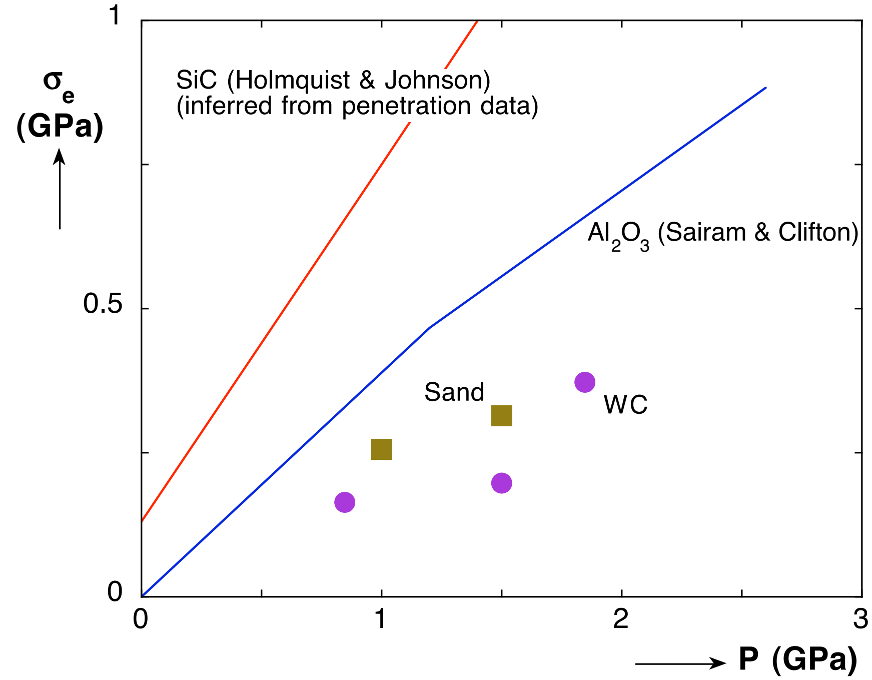
- 250 µm sample thickness, 20-30 µm grains
- Ti-6-4 plates
- V=121 m/s, θ=20°
- resolve velocities to normal (v_x) and transverse (v_y) components - check against 0° probe
- tilt causes initial transverse velocity
- nearly steady-state shearing observed after about 2.2 µs



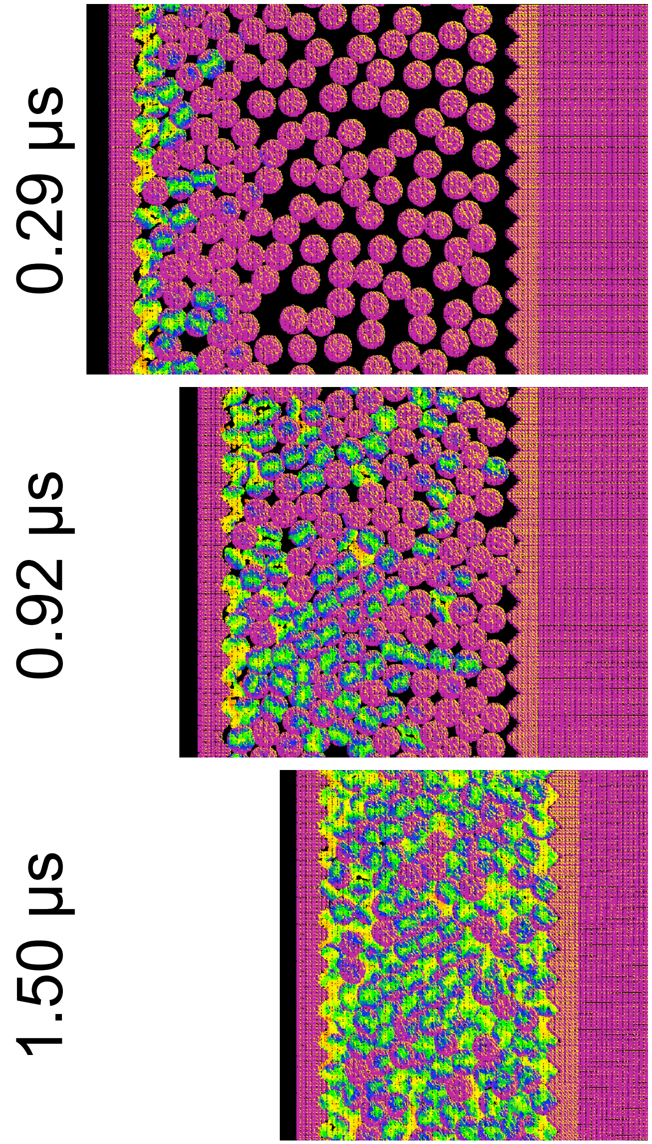
$$\dot{\gamma} = \frac{V \sin\theta - v_y}{h} \approx 1 \times 10^5 \ s^{-1}$$

Ceramic Powder Strength

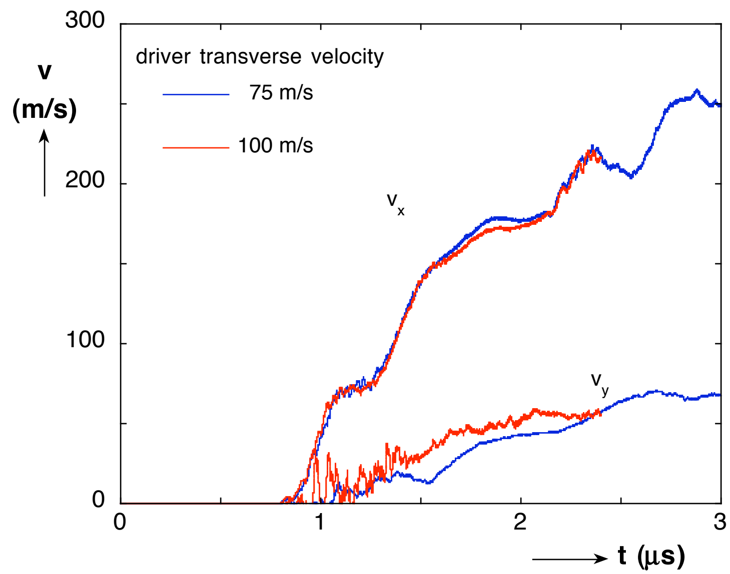
- Holmquist & Johnson inferred strength of granular SiC through high-velocity penetration experiments
- Sairam & Clifton performed pressure-shear experiments on Al_2O_3
- current results appear plausible, but more work needed:
  - ensure slippage not occurring (alternate anvil materials, surface finishes, angles, etc.)
  - increase impact velocities/pressures
  - examination of recovered plates / particles



Mesoscale Simulations of Pressure-Shear Loading



CTH mesoscale simulations of pressure-shear loading are qualitatively wrong

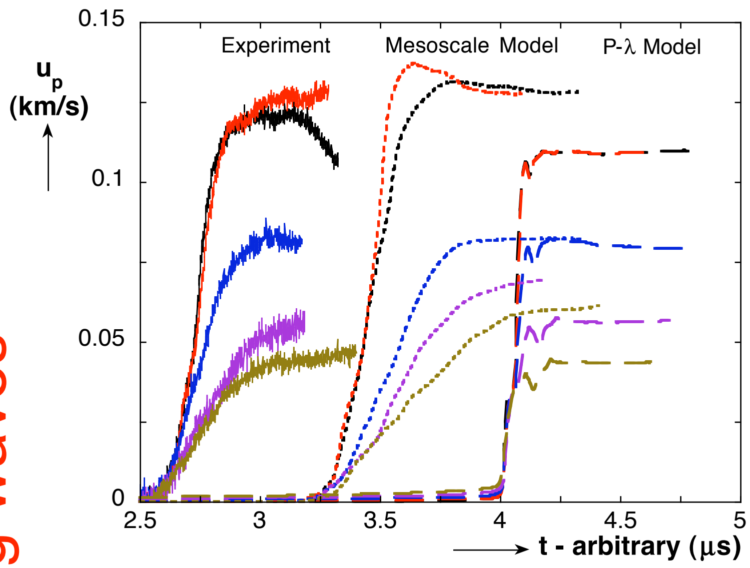


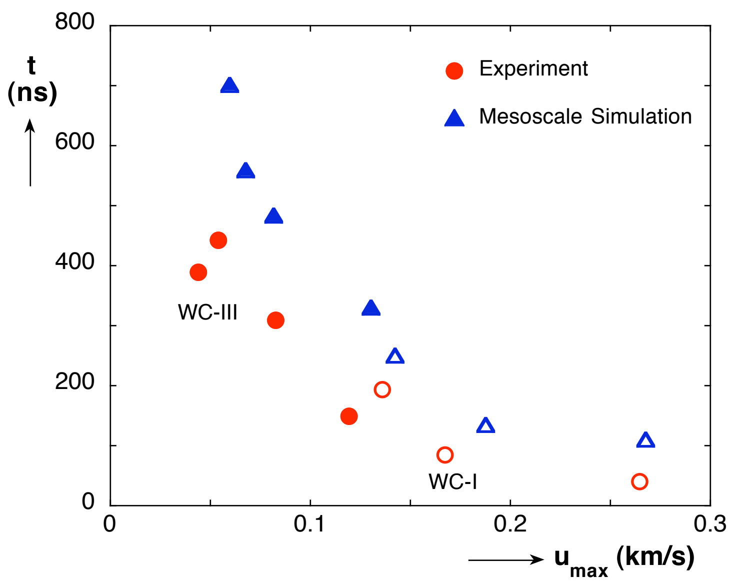
initial pressure-shear simulations with EMU promising, but additional work needed

Dynamic Validation Experiments:
necessary to build confidence in models

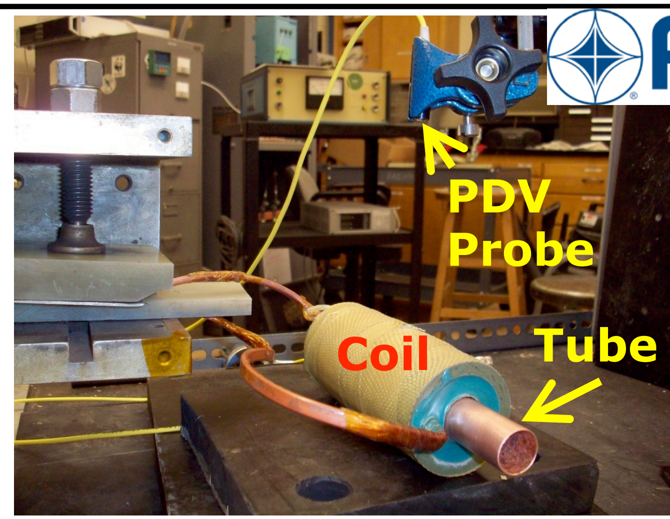
G. Daehn,
G. Fenton

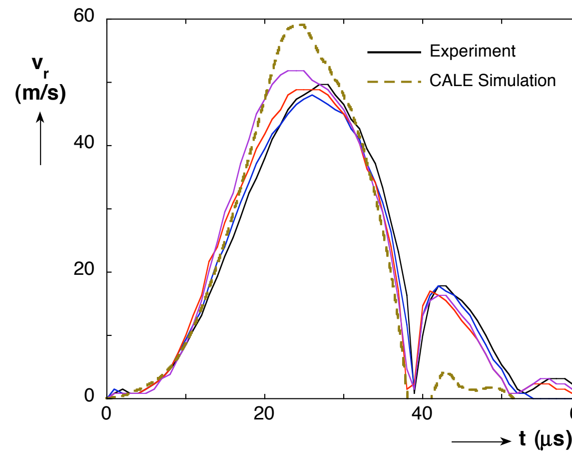
attenuating waves

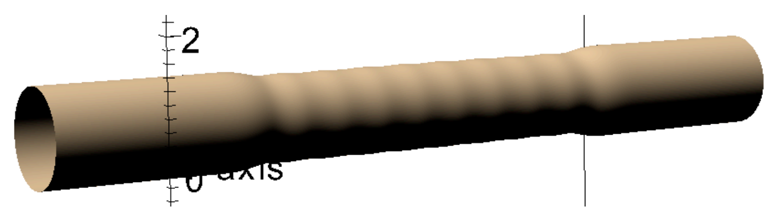




magnetically driven cylinders

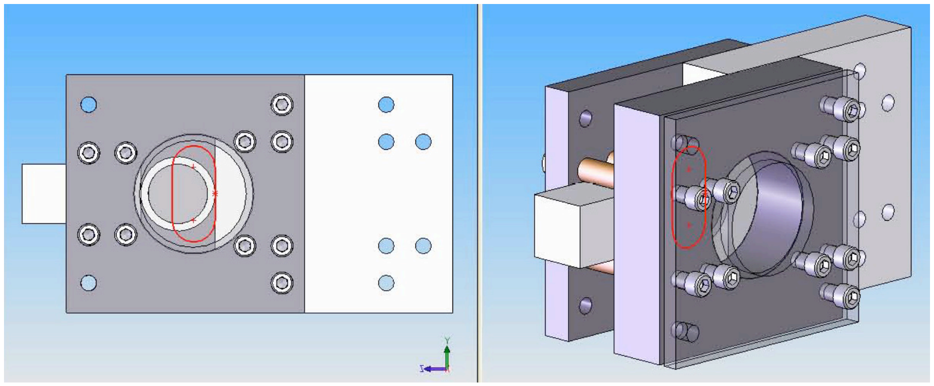


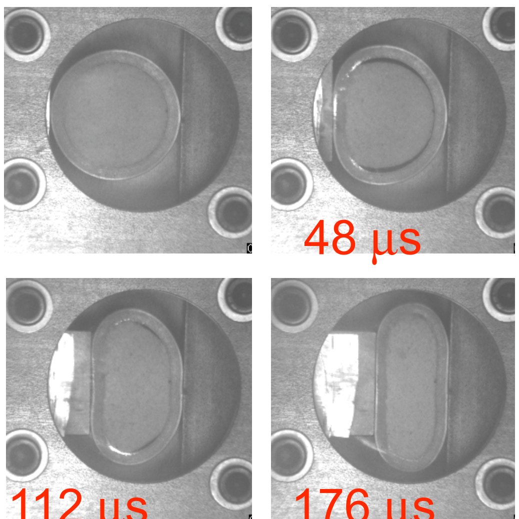


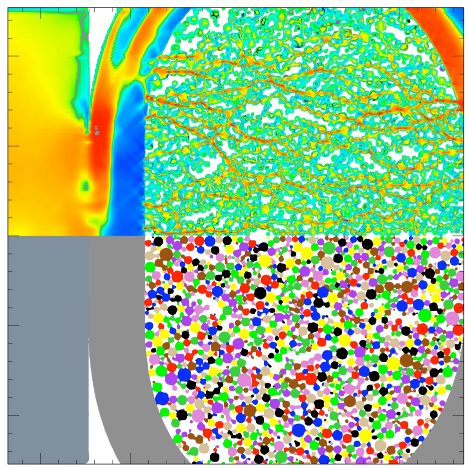


Validation Experiments for Granular Materials

D. Sandoval

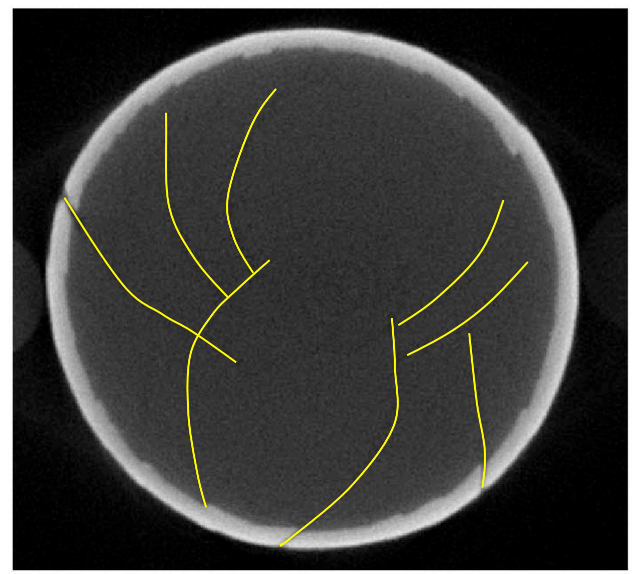






a good validation experiment is simple, instrumentable, in a relevant regime, well posed, repeatable, and sensitive to the relevant material behavior

K. Lappo



- Introduction to Shock and High-Pressure Physics
- Introduction to Granular Materials
- Planar Impact Experiments
- Mesoscale Modeling
- Other Experimental Work
- Conclusions

Conclusions

- **planar waves in granular ceramics:**
  - steady waves observed with very low wave speeds observed
  - waves have finite rise times; strain rate ~σ
  - dynamic response significantly stiffer than static response for WC; about the same for sand
- **mesoscale simulations:**
  - nonuniform stress distribution (force chains)
  - significant lateral motion and distance to reach steady state
  - particle methods or other techniques needed for missing physics
  - may be suitable for some macroscopic simulations
- **high pressure experiments on Z:**
  - attain pressure levels that cannot readily be reached
  - probe thermal aspects of high pressure EOS
- **pressure-shear experiments:**
  - directly measure deviatoric response of granular materials
  - additional work needed to verify and understand results

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T. Buchheit - nanoindentation

D.E. Grady, L.C. Chhabildas - decades of shock physics experience

numerous technicians and support staff are <u>essential</u> to facility operations