SAND2011-4359C

# Magnetically Applied Pressure-Shear (MAPS):

## A Novel Technique for Strength Measurement


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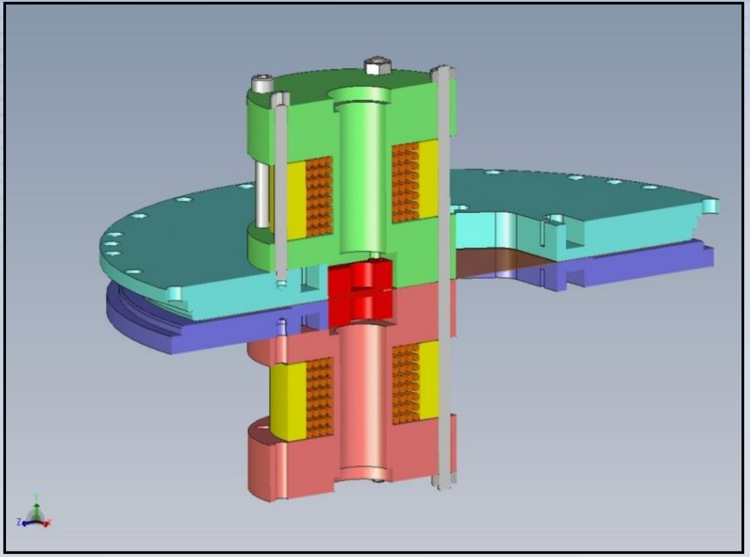

**SEM Annual Conference & Exposition on Experimental and Applied Mechanics**

***Mohegan Sun, Uncasville, Connecticut***

***June 13 - 16, 2011***

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# Outline

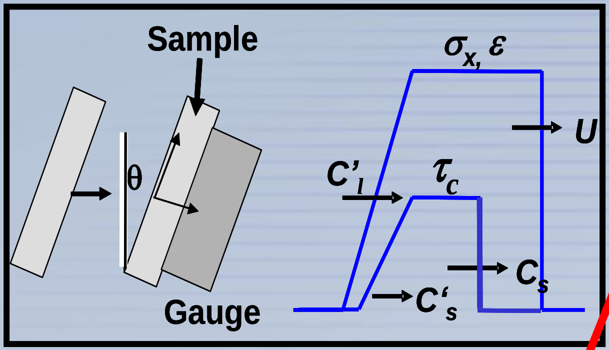
- **Motivation**
  - Why do we need a new measurement technique?
- **Overview of the MAPS approach to strength measurement**
  - Principles of operation
  - Implementation on the Veloce Small Pulser
  - Design considerations
- **Experimental results**
  - Initial measurements on aluminum
  - 2D material response of zirconia
- **Summary**

For further details:

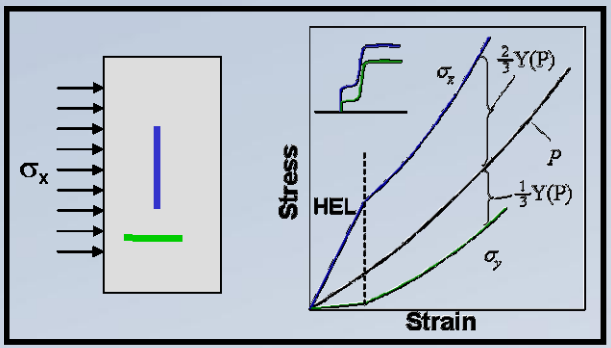
C.S. Alexander, J.R. Asay and T.A. Haill, *JAP*, **108**, 126101 (2010).

# Motivation: Existing strength measurement techniques have limitations at high pressure

Oblique impact




Lateral gauges



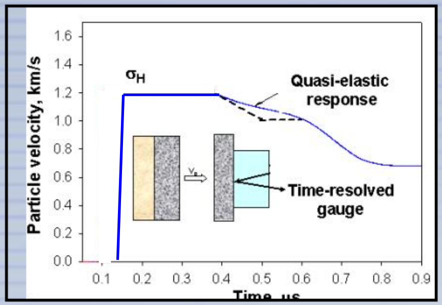

Limited to low P (<200 kbar)

Requires assumptions

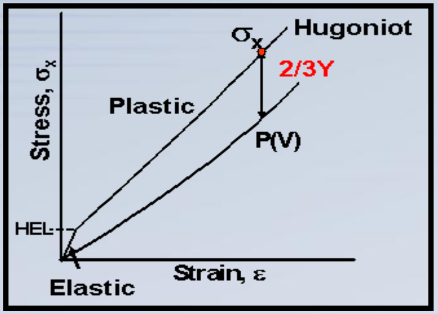
Large uncertainties

Requires accurate models which are unknown

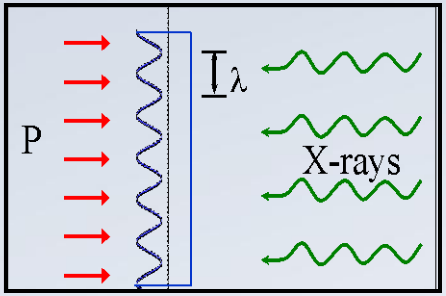
Wave Profile




Stress Difference

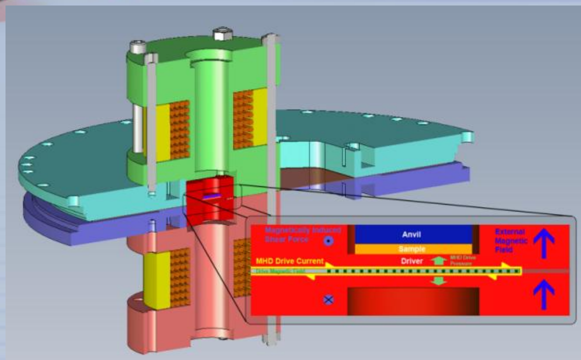


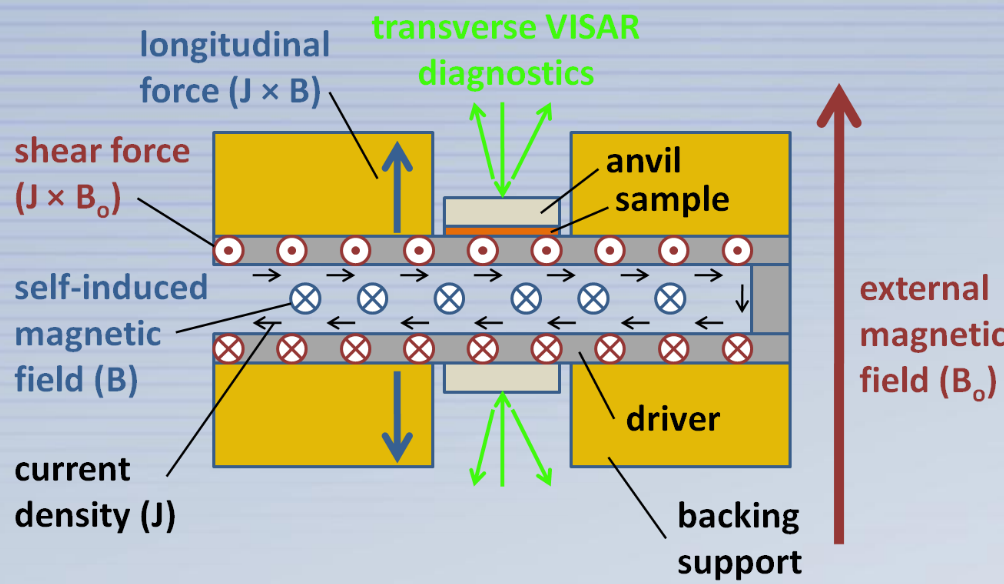

Rayleigh-Taylor




There is a need for improved strength measurement capability at high pressures

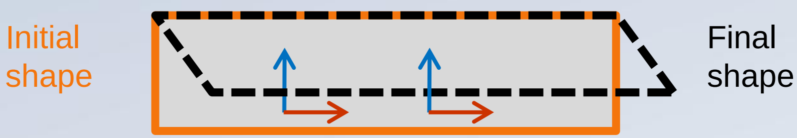
# Operating principles behind the MAPS technique




1. A pulsed power drive generates current (J) in parallel panels and induces a magnetic field (B) between the panels
2. The interaction J×B produces a pressure wave which compresses the material
3. A large (10T, ~$10^5$ times Earth's field) external magnetic field ($B_o$) is applied
4. The interaction $J \times B_o$ produces a shear wave in the driver (panel)
5. The generated shear wave propagates through the sample material where it is truncated to a level determined by the sample strength
6. Specialized VISAR interferometry is used to record both longitudinal and transverse particle velocities (NOTE: probe orientation is transverse to plane of page)
7. Pressure and strength are calculated from the measured particle velocities

end view of sample




Sample is compressed by the longitudinal force and then sheared by the shear force

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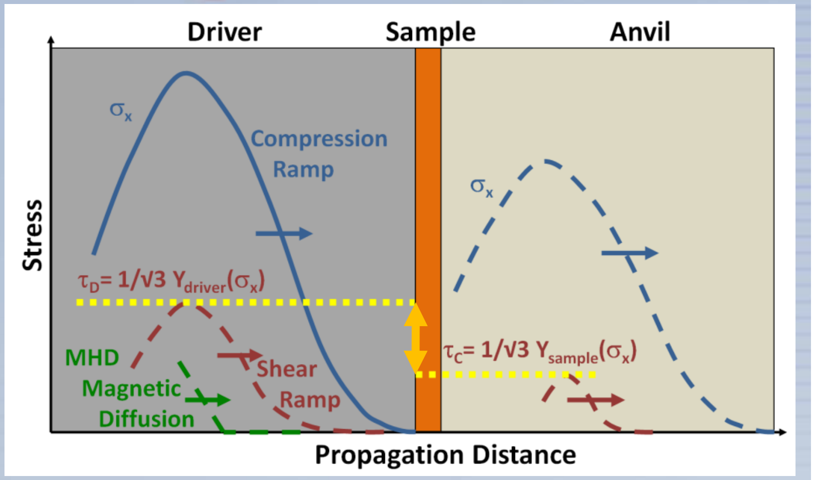
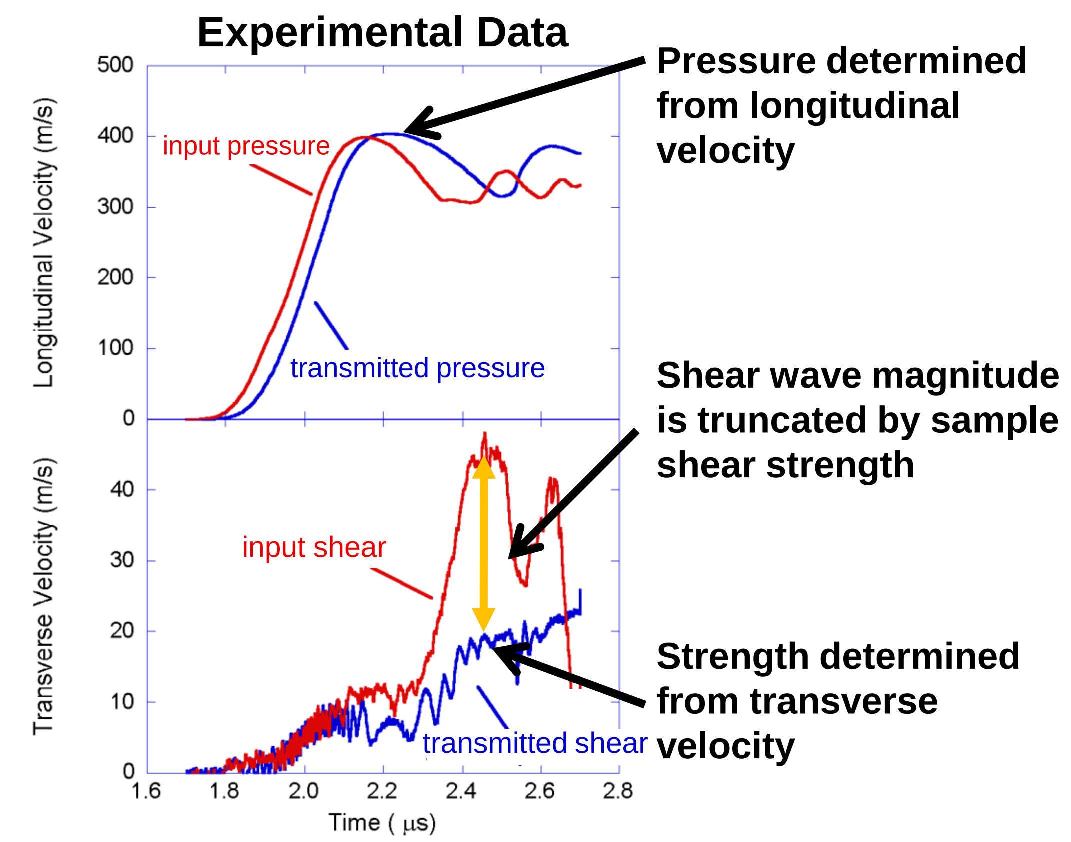
# MAPS: a novel method to measure shear strength at high pressure




- Sample is compressed by longitudinal wave to high pressure
- Shear wave is produced in driver by interaction of drive current and an external magnetic field
- Maximum shear that can be transmitted through sample limited by von Mises yield criterion

$$\tau \leq 1 / \sqrt{3}\, Y(\sigma_x)$$




- Strength determined directly from longitudinal and shear particle velocities measured at anvil free surface using VISAR

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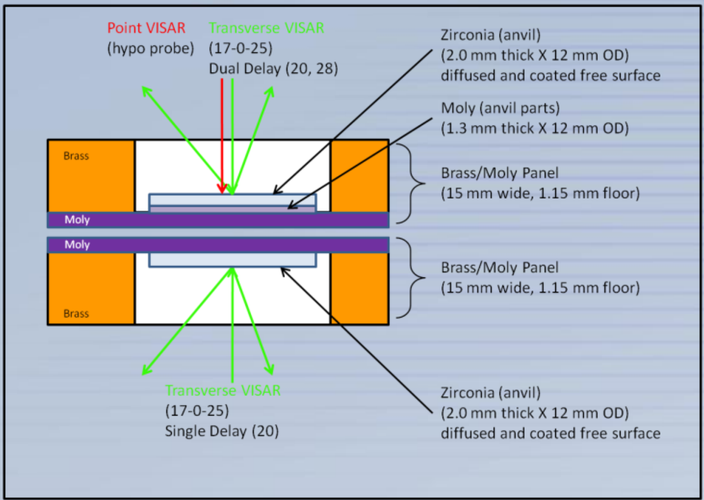
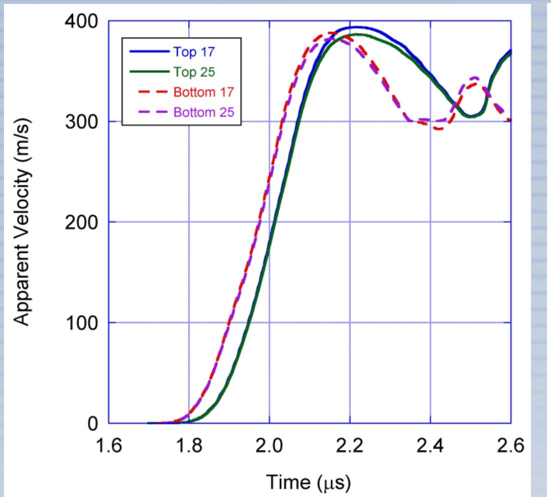
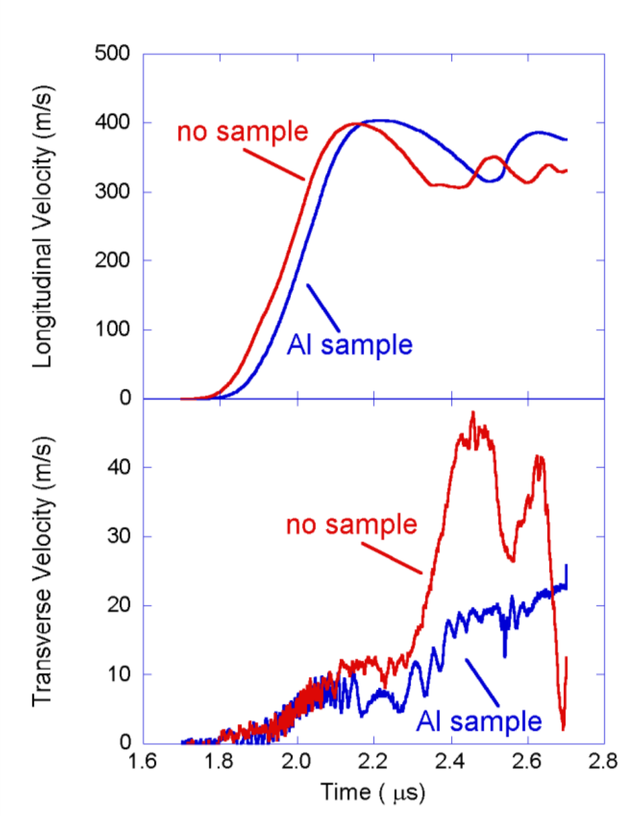
# Initial MAPS experiments measure aluminum strength at 8.85 GPa

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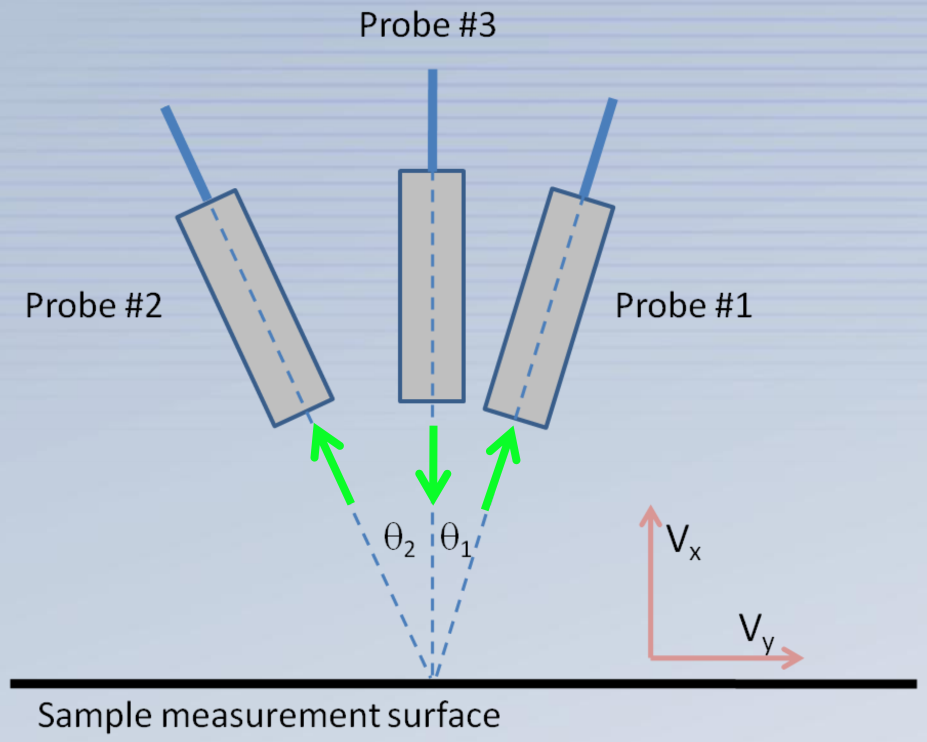
# Transverse VISAR velocity determination




$$v_1^* = \frac{\cos(\theta_1)+1}{2} v_x - \frac{\sin(\theta_1)}{2} v_y$$

$$v_2^* = \frac{\cos(\theta_2)+1}{2} v_x + \frac{\sin(\theta_2)}{2} v_y$$

$$G_1 = \frac{1}{2}(\cos\theta_1 + 1)$$

$$G_2 = \frac{1}{2}(\sin\theta_1)$$

$$G_3 = \frac{1}{2}(\cos\theta_2 + 1)$$

$$G_4 = -\frac{1}{2}(\sin\theta_2)$$

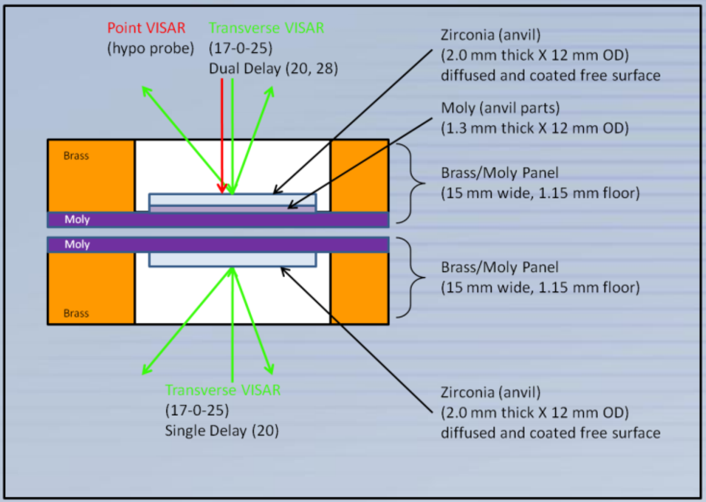
$$F_1 = G_1 - \left(\frac{G_1 G_2}{G_4}\right)$$

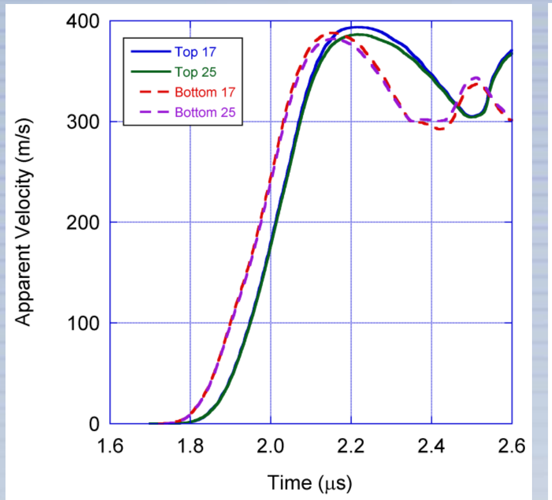
$$F_2 = \left(\frac{G_2}{G_1 G_4 - G_2 G_3}\right)$$

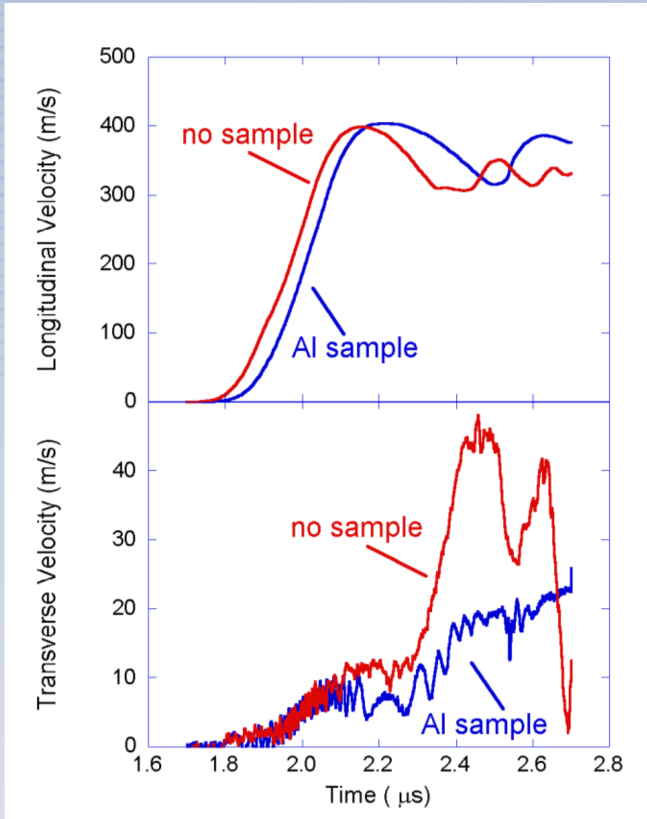
$$v_x = \left(\frac{v_1^* - F_2 v_2}{F_1}\right)$$

$$v_y = \left(\frac{v_2^* - F_3 v_x}{G_4}\right)$$

# Initial MAPS experiments measure aluminum strength at 8.85 GPa



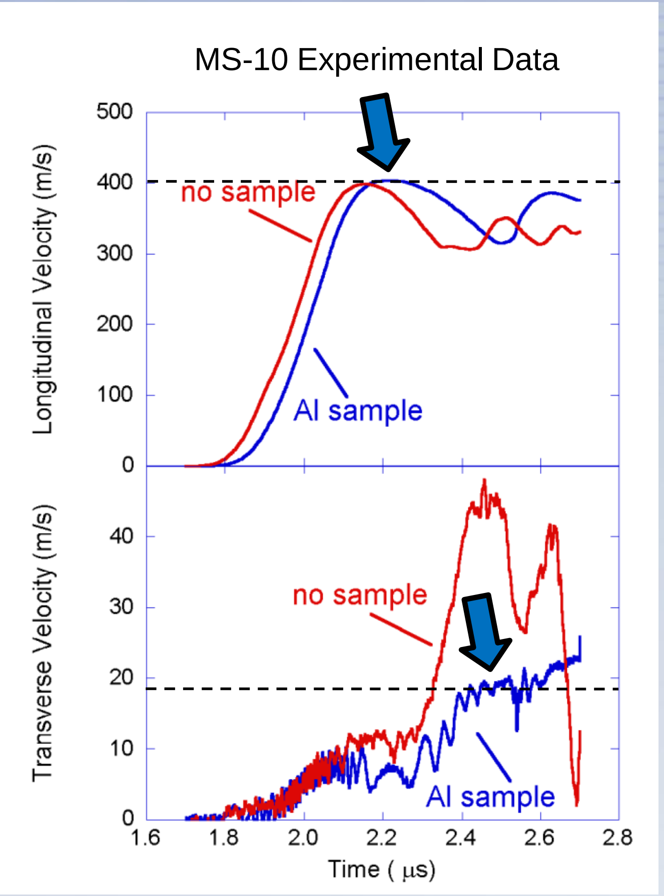




# Pressure and shear are calculated directly from measured free surface velocities

$\sigma = \rho_o C_L u_p$

$\sigma$ = (6.07 g/cc) (7.33 km/s) ½(0.398 km/s)

$\sigma$ = 8.85 GPa




$\tau = \rho_o C_\tau u_p$

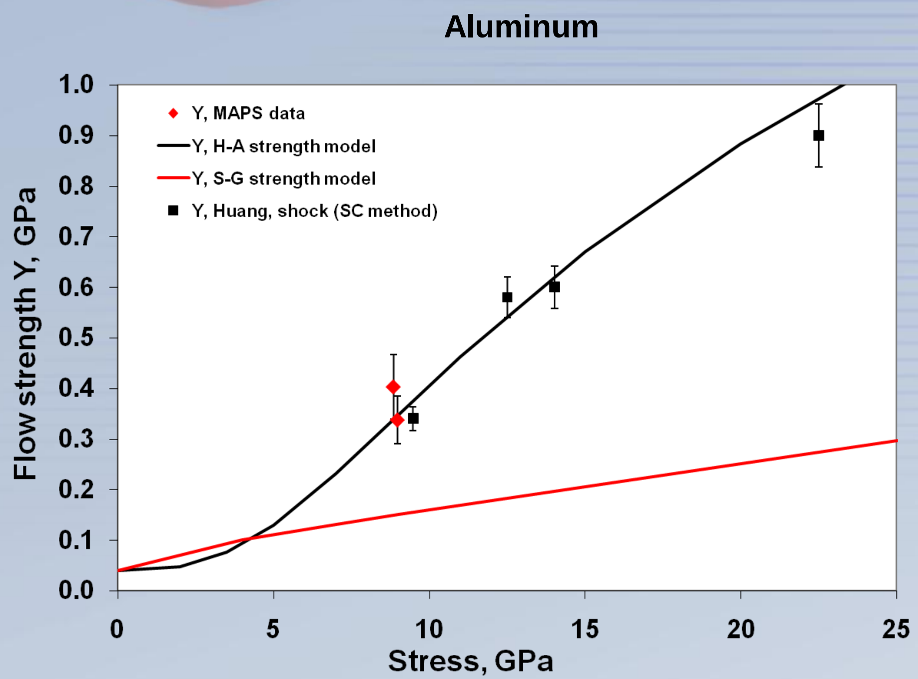
$\tau$ = (6.07 g/cc) (4.105 km/s) ½(0.0187 km/s)

$\tau$ = 0.233 GPa

$Y = \sqrt{3}\,\tau$ = 0.404 GPa

±0.065 (16%)

# Initial MAPS data comparison with established strength data is excellent



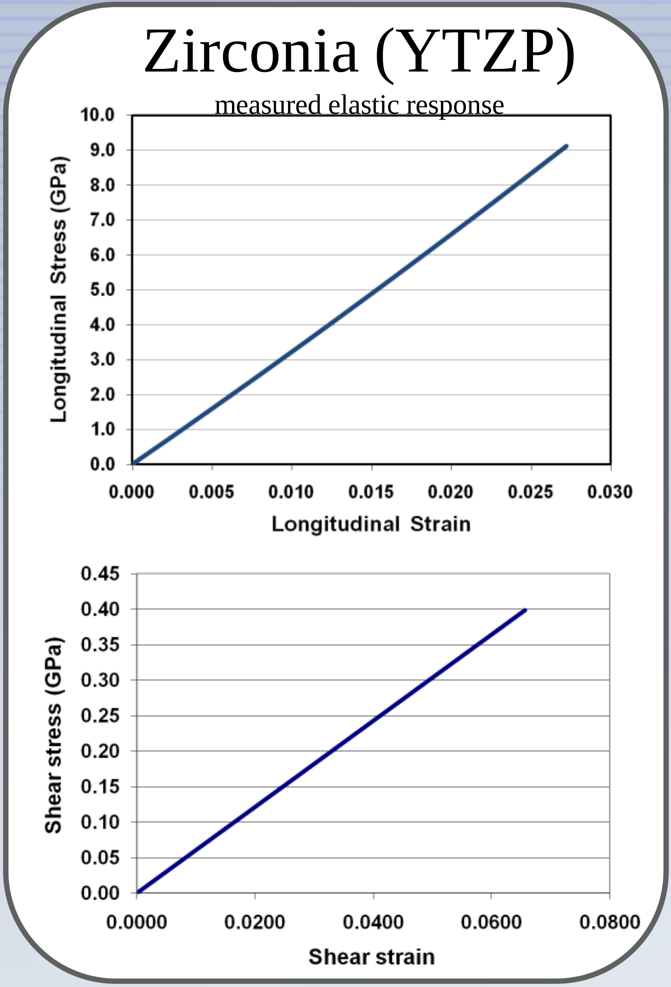

H. Huang and J.R. Asay, *J. Appl. Phys.* **98**, 033524 (2005)
D.J. Steinberg, S.G. Cochran, and M.W. Guinan, *J. Appl. Phys.* **51**, 1498 (1980)

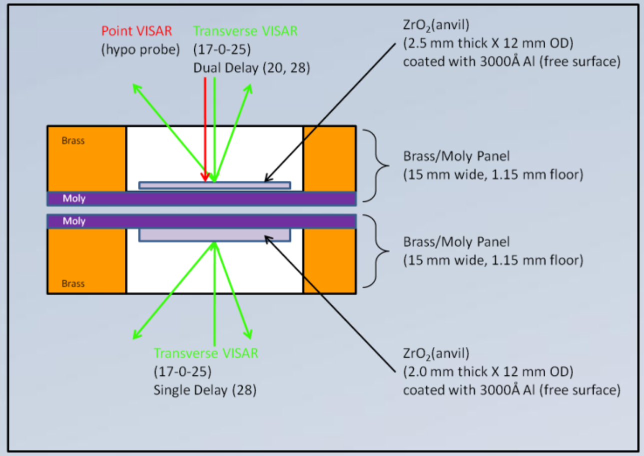
- **Accuracy and configuration being improved – goal is δY ≤ 5% at Mbar pressures**
- **Technique easily discriminates between strength models**

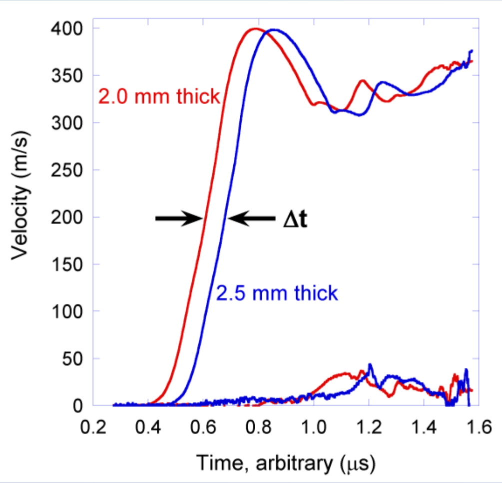
# Additional utility of the MAPS experimental configuration: 2D model validation data

New multi-dimensional capability for enhanced model validation!

•Has been applied to verify elastic response of zirconia anvil material  to ~9 GPa

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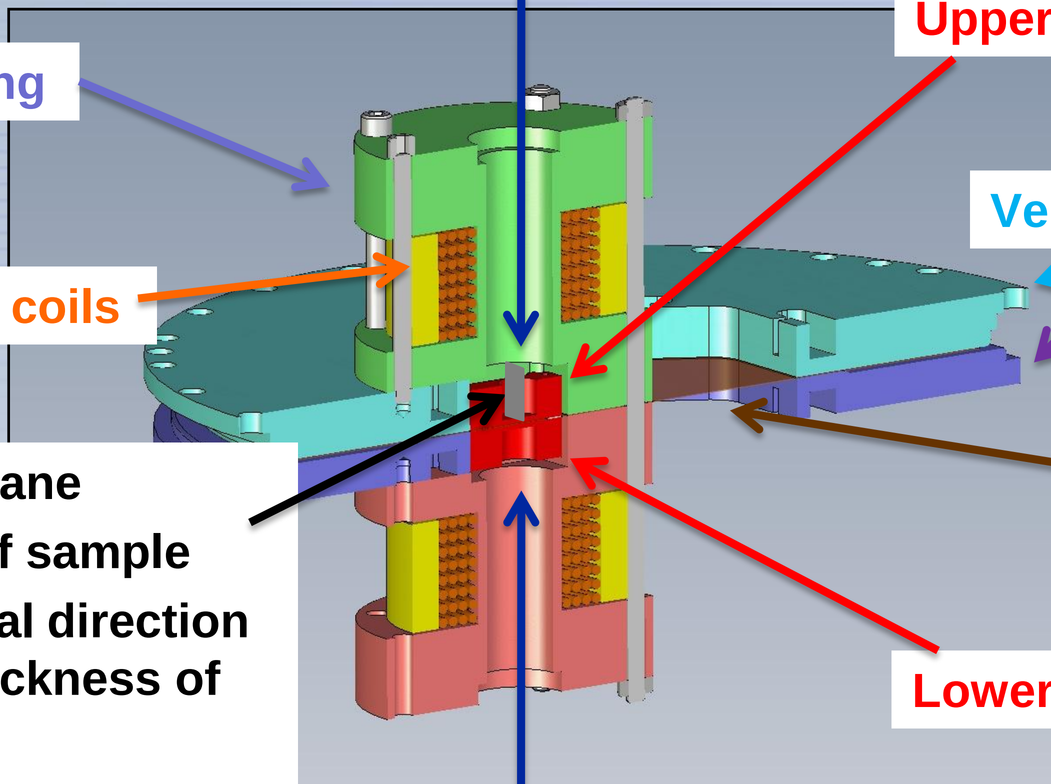
# Summary

- MAPS is a novel technique to directly measure material strength at high pressure
- MAPS capability has been demonstrated
    - 2 Al strength shots
    - 1 $ZrO_2$ shot
- Work is ongoing to demonstrate MAPS on additional materials at modest pressures
- Transition to Z is in progress (expected CY2012) to extend to higher pressures

End of show

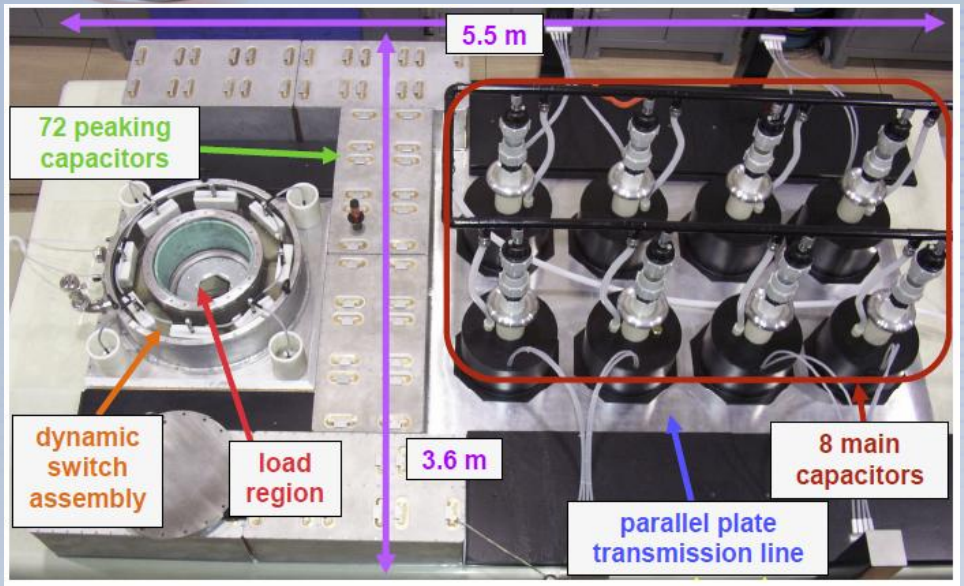
- **Back-up Slides**

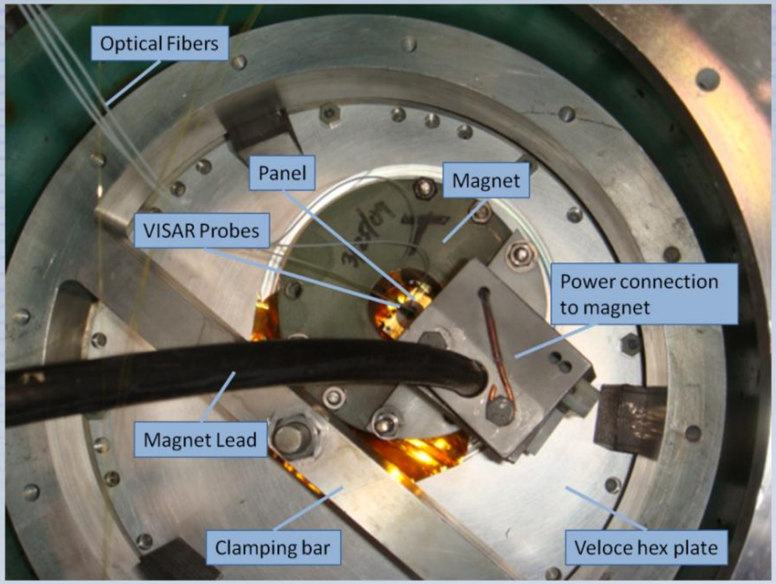
# Notional View of the MAPS Experimental Implementation



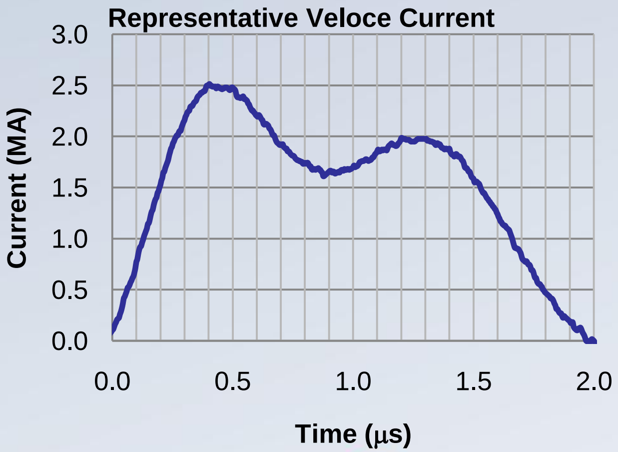

- Simulation plane
  - At center of sample
  - Longitudinal direction through thickness of panel (x)
  - Shear direction across width of panel (y)

# MAPS Experiments on the Veloce Small Pulser




- **MAPS developed on SNL's Veloce pulser**
  - 2.5 MA, 2 μs current pulse
  - ~10 GPa sample pressures
  - 10 mm diameter, 50-100 μm thick sample sizes




T. Ao, et al., A compact strip-line pulse power generator for isentropic compression experiments, RSI, 79, 013903 (2008).

# Design of Driver Panel: Desired Properties of Driver Material

- **High Yield Stress**
  - Shear stress generated by $J \times B_o$ limited by driver yield stress
- **High Melt Temperature**
  - Remain solid
  - Efficiently couple magnetic forces into driver
- **High Conductivity (Low Resistivity)**
  - Increase drive current for given capacitor bank charge
  - Inhibit magnetic diffusion (MHD drive) into driver
- **Low Density**
  - Magnetic forces able to accelerate panels

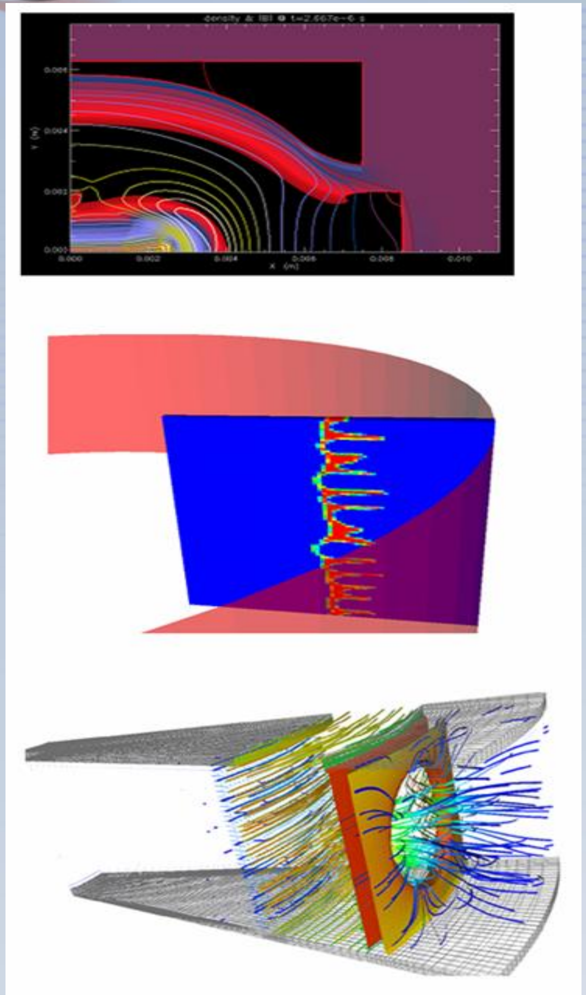
# Design of Anvil Panel: Desired Properties of Anvil Material

- **High Yield Stress**
  - Do not limit material stresses received from test sample
    - Anvil strength must exceed sample strength at measurement pressures
  - Propagate high longitudinal and shear stresses (velocities) to free surface with little attenuation
  - Avoid spall
- **High Melt Temperature**
  - Remain solid
- **Low Conductivity (High Resistivity)**
  - Allow faster permeation of external $B_o$ field
  - Inhibit current flow into anvil

# Materials of Interest:
# Initial Material Parameters

| | Z | Material | Density (g/cm$^3$) | Melt Temperature (K) | Yield Stress (GPa) | Poisson Ratio | Conductivity ($\mu\Omega$*cm)$^{-1}$ |
|---|---|---|---|---|---|---|---|
| sample | **13** | **Aluminum** | **2.7** | **933** | **0.29** | **0.33** | **0.377** |
| | 22 | Titanium | 4.54 | 1933 | 0.85 | 0.30 | 0.024 |
| | 26 | Iron (304 SS)<br>(V-250 SS) | 7.87 | 1808 | (0.34)<br>(1.56) | (0.283)<br>(0.283) | 0.103 |
| driver | 29 | Copper | 8.96 | 1356 | 0.12 | 0.33 | 0.598 |
| | **42** | **Molybdenum** | **10.22** | **2890** | **1.6** | **0.375** | **0.192** |
| | 47 | Silver | 10.50 | 1235 | 0.05 | 0.37 | 0.629 |
| | 73 | Tantalum | 16.65 | 3269 | 0.77 | 0.30 | 0.080 |
| | 74 | Tungsten | 19.3 | 3683 | 2.20 | 0.30 | 0.177 |
| | 79 | Gold (Cu) | 19.32 | 1338 | 0.02 (0.63) | 0.42 | 0.425 |
| | 92 | Uranium | 18.95 | 1405 | 0.40 | 0.30 | 0.033 |
| anvils | | **Diamond** | **3.52** | **~ 3820** | **35 - 91** | **0.104** | **< $10^{-8}$** |
| | | Sapphire | 3.97 | ~ 2326 | 14 - 18 | 0.18 – 0.29 | < $10^{-1}$ |
| | | **Zirconia (YTZP)** | **6.026** | **~ 2988** | **8.5** | **0.3124** | **< $10^{-8}$** |

# Physics Models in ALEGRA - a 3D/2D Radiation Magneto-Hydrodyanmics code



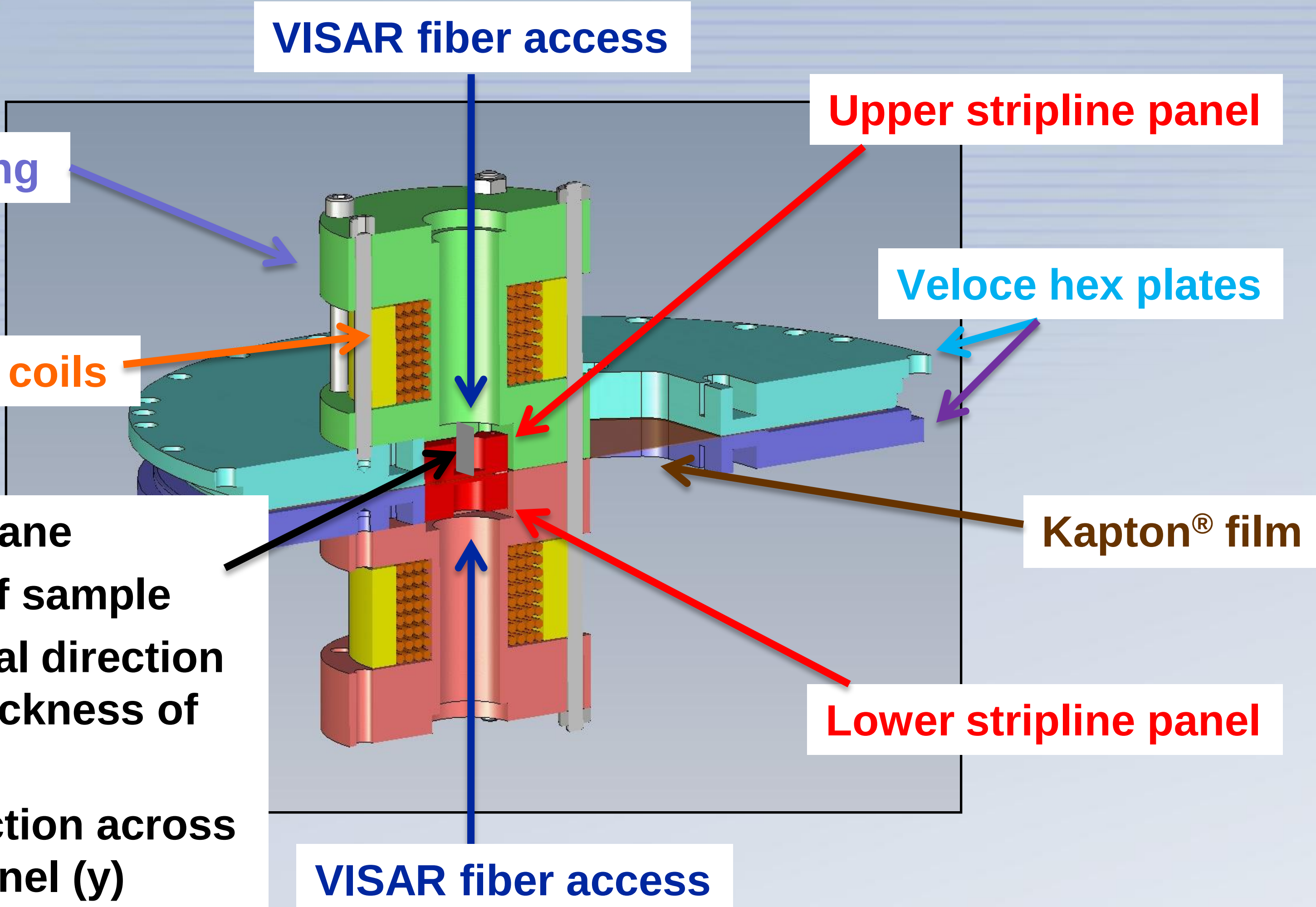
- **2D (RZ & XY) and 3D (XYZ)**
- **Unstructured Finite-Element Based**
- **Eulerian/Lagrangian/ALE**
- **Object Oriented**
- **Massively Parallel**
- **Isentropic Multi-Material**
- **Coupled Physics**
  - Hydrodynamics
  - Magnetics
  - Thermal Conduction
  - Radiation (Multi-Group Diffusion & IMC)
- **Material Models**
  - LANL Sesame & other EOS
  - Lee-More-Desjarlais (LMD) Conductivity
  - XSN & Propaceos Opacities

A. C. Robinson, et al., “ALEGRA: An Arbitrary Lagrangian-Eulerian Multimaterial, Multiphysics Code,” AIAA 2008-1235, 46th AIAA aerospace Science Meeting and Exhibit, Reno, NV, Jan. 2008.

# ALEGRA Material Models

| Material | Equation of State | Strength Model | Conductivity Model |
|---|---|---|---|
| Molybdenum | KEOS Sesame<br>ANEOS 2984 | CTH<br>Elastic-Plastic<br>Steinberg-Guinan | Lee-More-<br>Desjarlais<br>(LMD) |
| Aluminum | SNL Sesame 3720 | CTH<br>Elastic-Plastic<br>Steinberg-Guinan | Lee-More-<br>Deslarlais<br>(LMD) |
| Zirconia | Mie-Gruneisen<br>Us-Up EOS | CTH<br>Elastic-Plastic<br>High Yield Strength | Constant<br>Electric & Thermal<br>Conductivity |

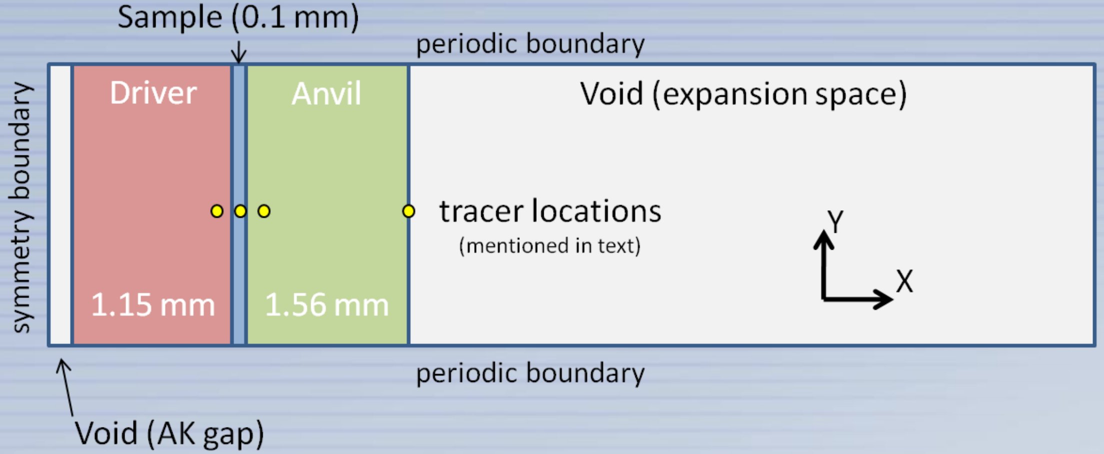
# Notional View of the MAPS Experimental Implementation




- Simulation plane
  - At center of sample
  - Longitudinal direction through thickness of panel (x)
  - Shear direction across width of panel (y)

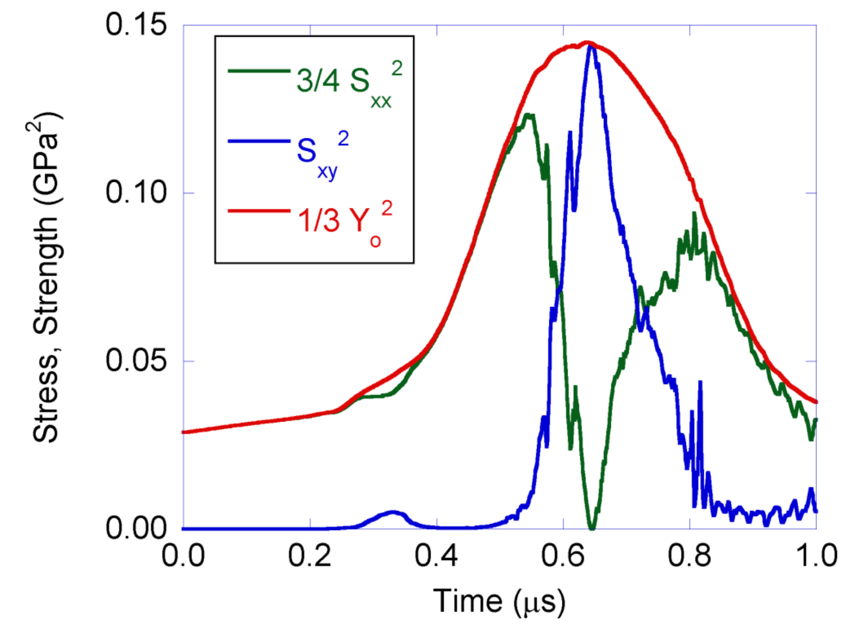
# ALEGRA Modeling of MAPS Experiments

$$B(t) = f(t)\,\frac{\mu_0\, I(t)}{W + G}$$




- **Assume sufficient uniformity near center of sample**
- **2D Cartesian Eulerian mesh**
  - **5 - 10 μm cell size**
- **Periodic mesh in transverse or shear direction (Y)**
- **Uniform, static $B_0$ magnetic field in longitudinal direction (X)**
- **Current driven tangent magnetic field applied at AK gap**
- **Stripline BC**
  - ***W* = panel width**
  - ***G* = AK gap**
- **Current density out of the plane of mesh**
- **Lagrangian tracers throughout**
  - **Most significant tracers shown**

# Stress Coupling




$$\frac{1}{3} Y_0^2 = \frac{3}{4} S_{xx}^2 + S_{xy}^2$$

$Y_0$ = Yield Stress

$S_{xx}$ = Longitudinal stress deviator

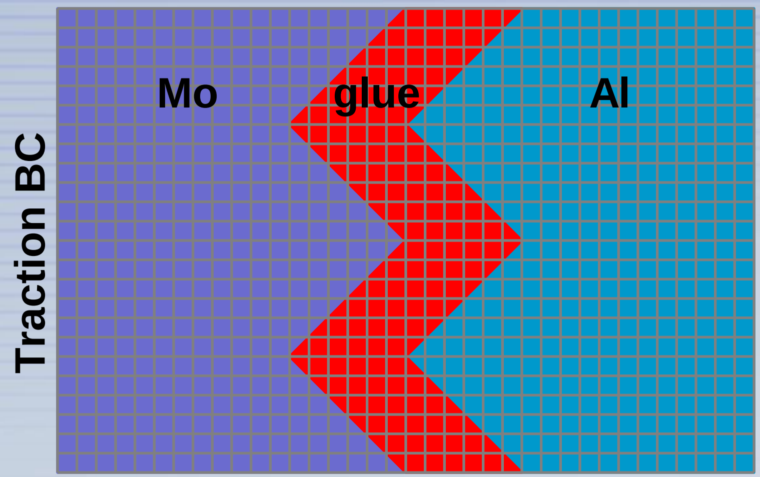
$S_{xy}$ = Shear stress deviator

- **For inelastic materials, deviatoric longitudinal and shear stress are:**
  - Coupled through yield function
  - Limited by maximum yield stress
- **Sample probed at peak yield stress**
  - – Forward shear wave arrives at sample during peak compression
- **Due to coupling, $S_{xx}$ reduced to zero at yielding**


J.W. Swegle and L.C. Chhabildas, "Chapter 25: A Technique for the Generation of Pressure-Shear Loading Using Anisotropic Crystalls," pp. 401-415, in M.A. Meyers and L.E. Murr, Shock Waves and High Strain Rate Phenomena in Metals, Plenum Press, NY, 1981.

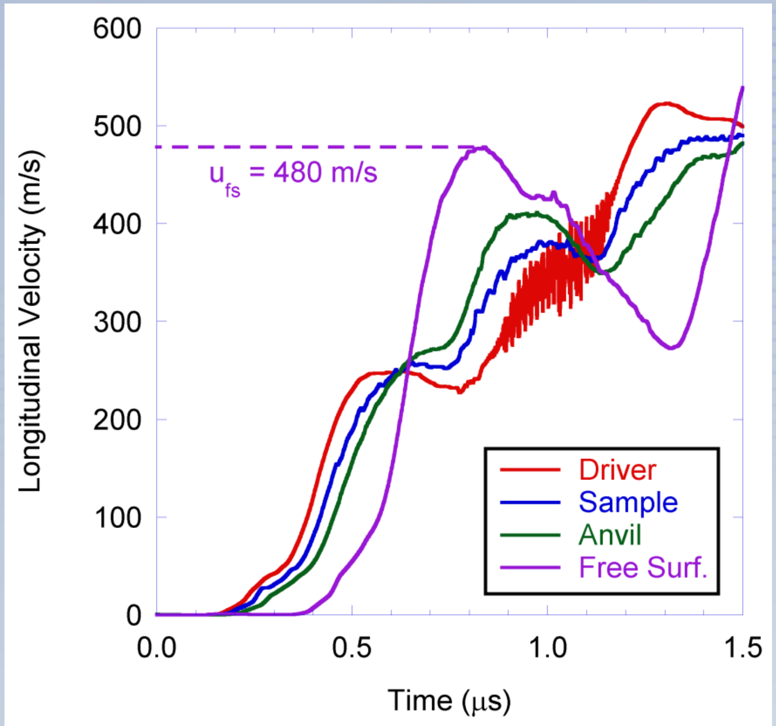
# Transmission of shear at interface

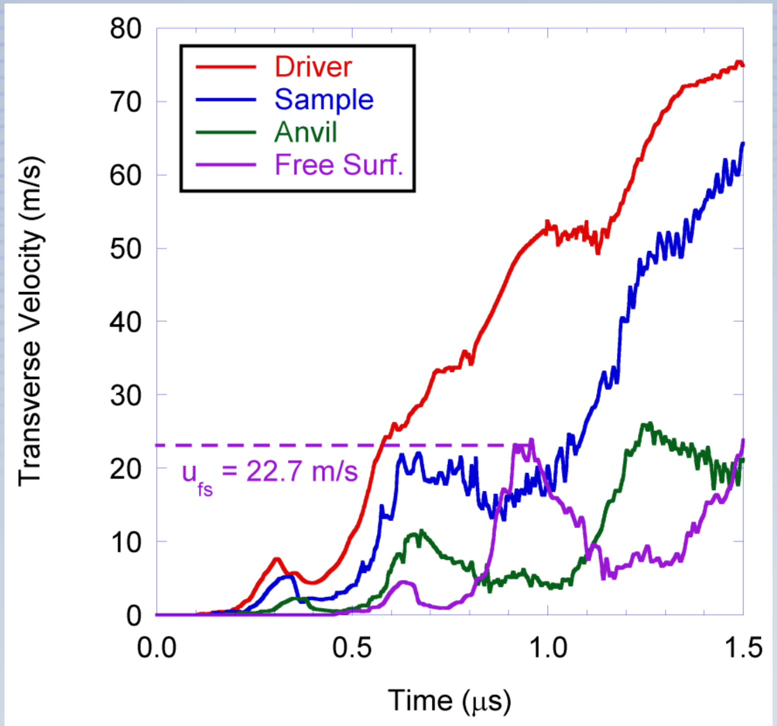
- **We conducted an investigation of surface roughness on shear transmission at a boundary**
- **Geometry**
  - Molybdenum driver – (partial)
  - Glue layer – 1 μm thick
  - Aluminum sample – (partial)
  - Mesh cell size – 0.05 μm
- **Interface**
  - 1, 2 or 3 μm peak-to-valley roughness
  - 2 μm wavelength
- **Traction boundary condition**
  - Determined from MHD simulation




- **Results**
  - No reduction in shear through this range of parameters
  - Glue compressed by longitudinal stress
  - Shear transmitted by interlocking peaks and valleys of surface roughness

# MHD Simulation Results: Free Surface Velocity




**Longitudinal Free Surface Velocity**

$u_L$ = 0.480 km/s

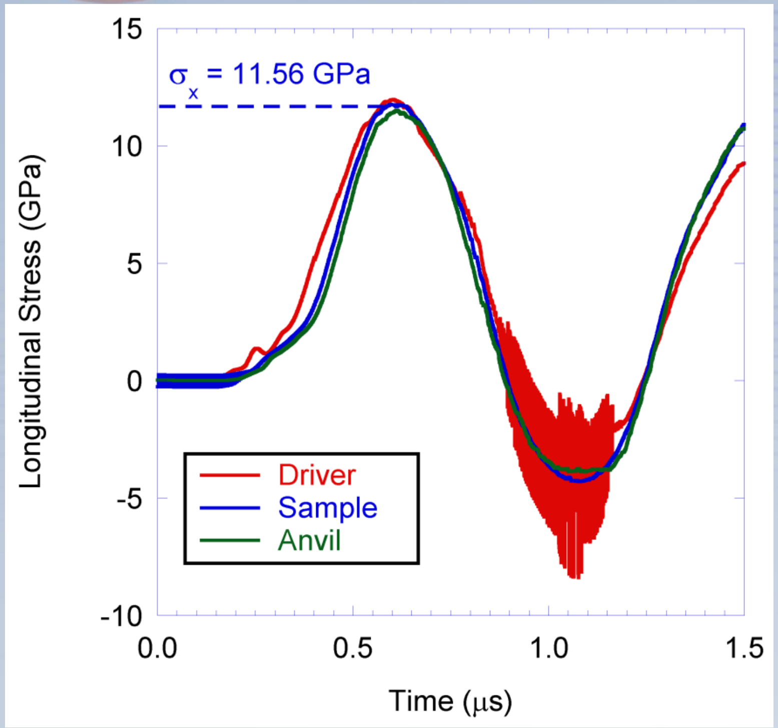
$C_L$ = 7.99 km/s

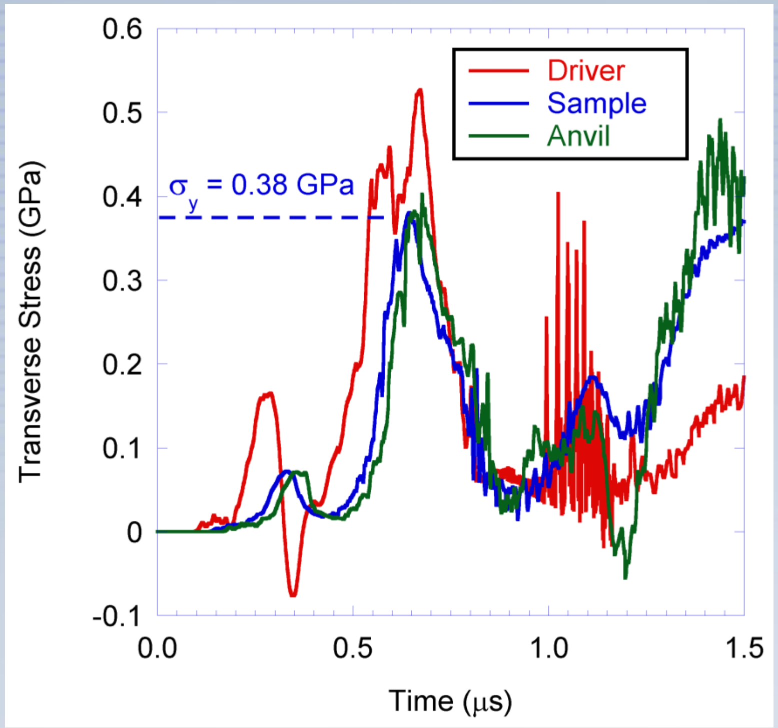
**Shear Free Surface Velocity**

$u_S$ = 0.0227 km/s

$C_S$ = 5.56 km/s

# MHD Simulation Results: Tracer Longitudinal and Shear Stresses




**Simulated Longitudinal Stress**

$$\sigma = \rho C_L U_{PL} = \tfrac{1}{2} \rho C_L V_L$$

$$\sigma = 11.56 \text{ GPa}$$

**Simulated Shear Stress**

$$\tau = \rho C_S U_{PS} = \tfrac{1}{2} \rho C_S V_S$$

$$\tau = 0.38 \text{ GPa}$$

$Y = \sqrt{3}\,\tau = 0.661$ GPa
$Y_{SGL} = 0.660$ GPa

Self-consistent