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High Pressure Strength of Metals Under Isentropic Loading

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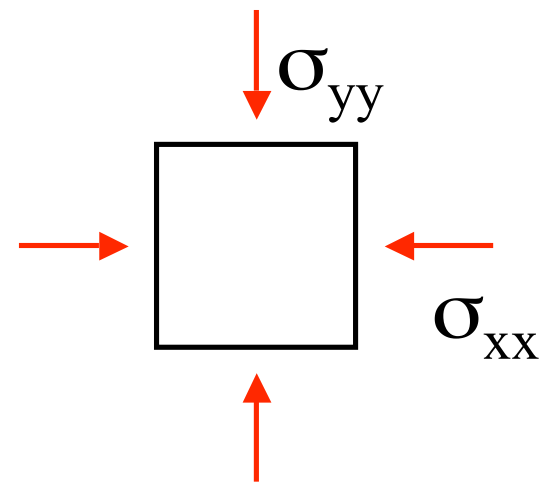
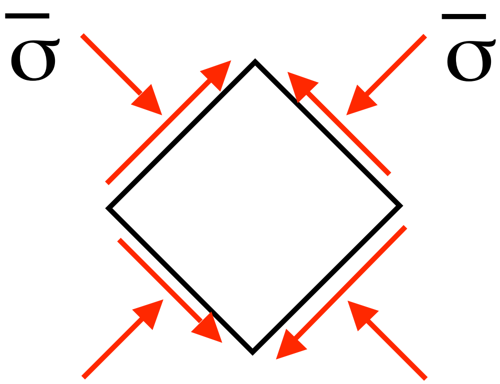
Motivation

- increases uncertainties in EOS models
- can be important in impedance matching
- strength affects stress state in diamond anvil cell (Chijioke et al., J6-2)
- understanding of strength needed for accurate computational results
- weapons and armor applications (ceramic armor, etc.) influenced by strength
- Rayleigh-Taylor instabilities inhibited by strength

What is Strength?

- strength is the ability of a material to sustain $\tau_{ij} \neq 0$ or $\sigma_{xx} \neq \sigma_{yy}$
- for a 1-D shock or isentropic experiment, this is means $\sigma_{yy} = \sigma_{zz} \neq \sigma_{xx}$
- conservation equations provide no information about σ_{yy}





$$\tau = 0.5(\sigma_{xx} - \sigma_{yy})$$

By a simple tensor transformation (45° rotation), the stress state can be expressed as a mean stress (mechanical pressure) and a shear stress

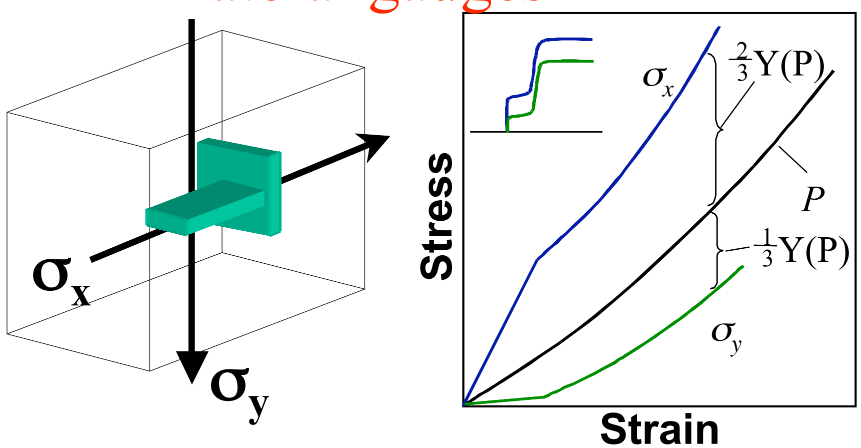
By analogy with uniaxial tension, $Y = 2\tau_c$

What is Strength? (cont.)

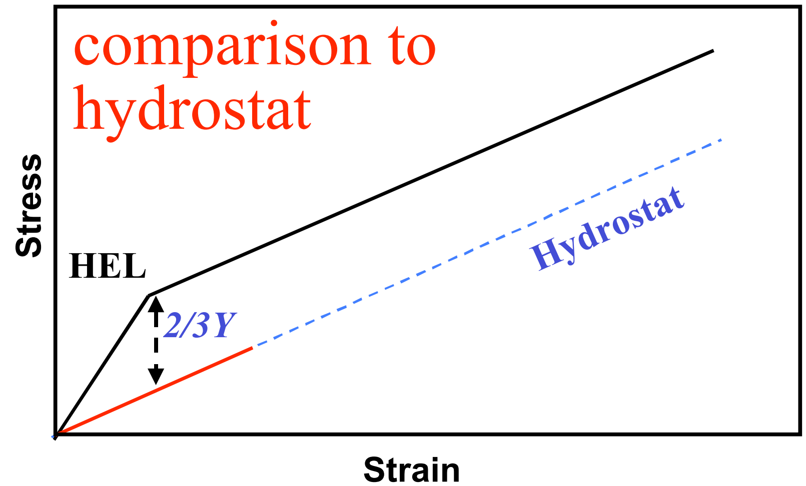
- Within the context of metals, strength is controlled by dislocation formation, motion, and annihilation (plastic deformation) and mechanisms such as twinning
- Other mechanisms may be relevant for different classes of materials; e.g. chain untangling and sliding in polymers, microcracking for brittle materials
- Deformation mechanisms are typically irreversible and path-dependent

Techniques to Determine Strength at High Pressures

lateral gauges



comparison to hydrostat



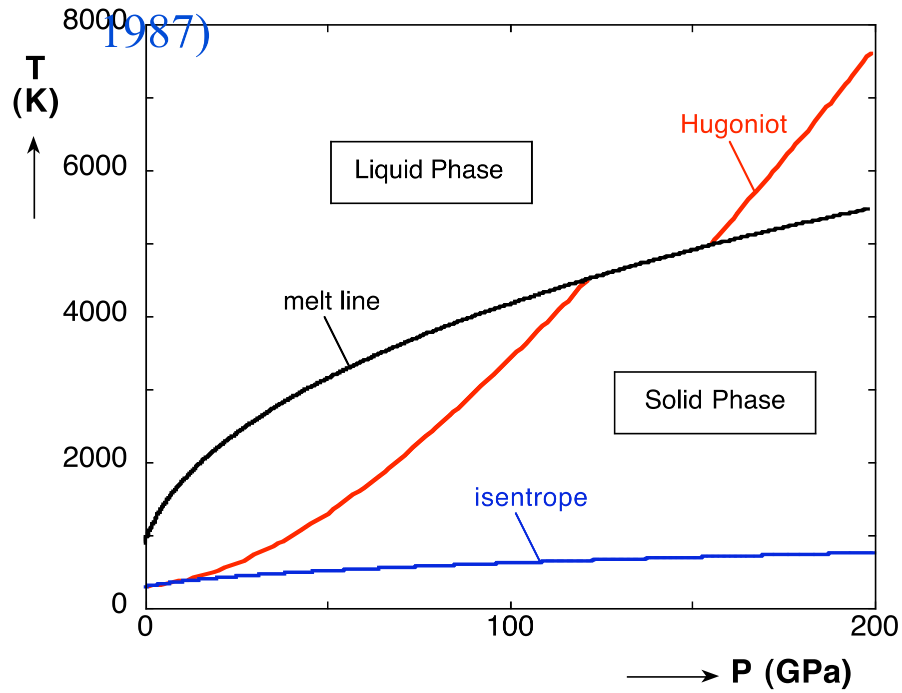
- *stress gauges can provide independent measures of σ_x and σ_y to determine dynamic strength*
- *calibration of gauges difficult*
- *gauges only function to ~20 GPa due to shorting of insulation*

- *most common method: compare with hydrostatic data*
- *hydrostat from ultrasonic sound speed data (C vs. P) or diamond anvil cell (P - V)*
- *uncertainties can be very large*

also: X-ray diffraction, pressure-shear loading, growth of Rayleigh-Taylor instabilities, within diamond anvil cells

Isentropic Loading Accesses Cool Regimes Where Strength Is More Important

Aluminum - Sesame 3700 (Kerley, 1987)



- Hugoniot passes into liquid phase at ~120 GPa
- Isentrope remains in solid phase, rise of T minimal

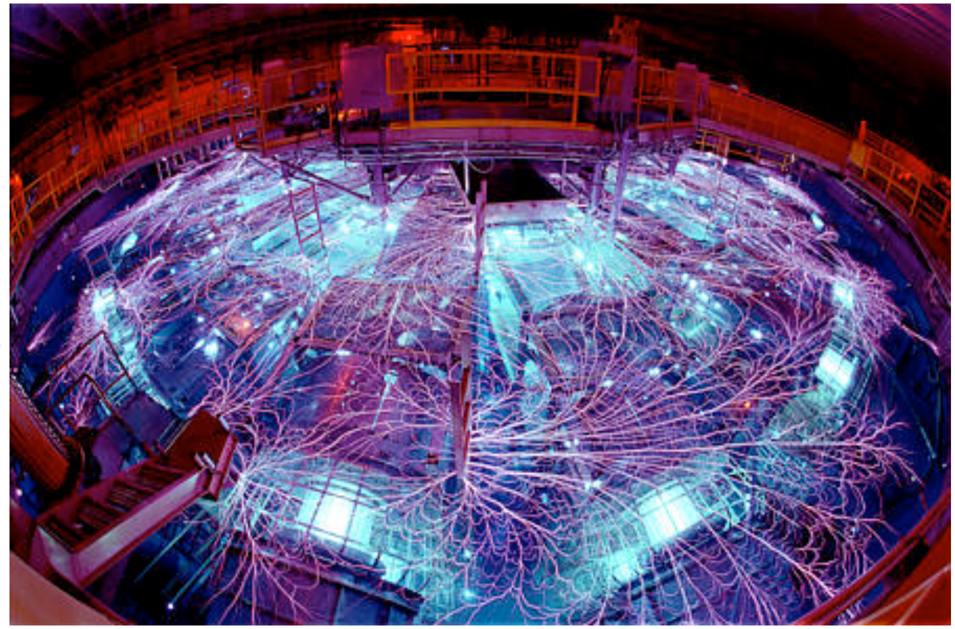
<u>Steinberg-Guinan Strength Model (rate-independent version):</u>

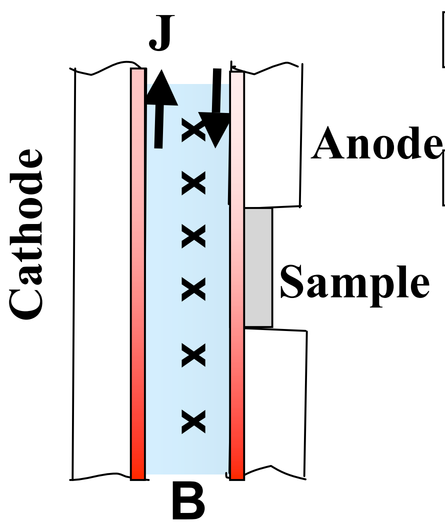
$$\frac{Y}{Y_o} = \left(1 + \beta(\varepsilon_p + \varepsilon_i)\right)^n \frac{G(P,T)}{G_o} \qquad G(P,T) = G_o + \frac{\partial G}{\partial P}\frac{P}{\eta^{1/3}} + \frac{\partial G}{\partial T}(T - T_o)$$

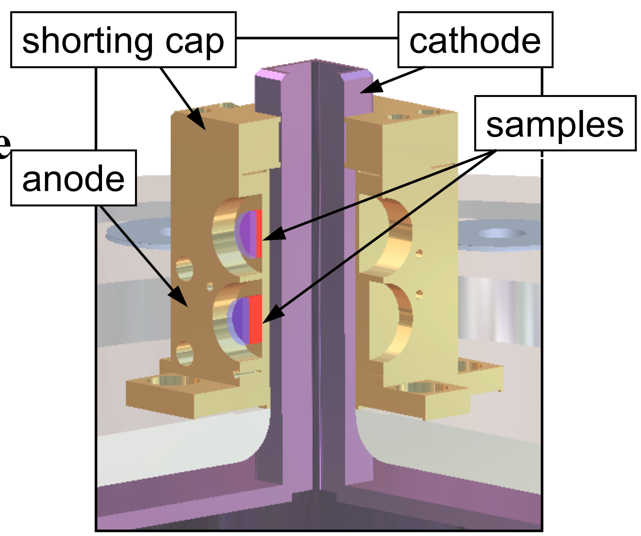
strength larger under isentropic loading due to smaller ΔT
strain rate orders of magnitude lower than shock case

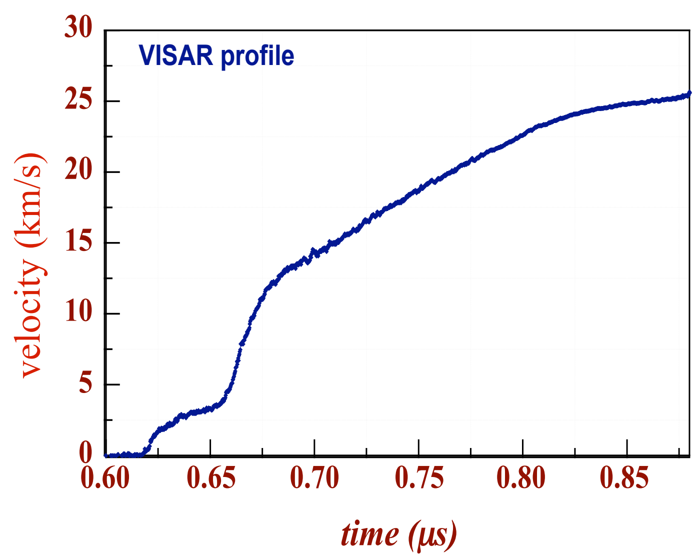
Z Machine Provides New Capabilities for Isentropic Loading

- Designed for ICF applications
- Generates >20 MA over 100's of ns, 11.5 MJ of stored energy
- Current generate magnetic forces
- Magnetic forces create smooth waves in materials
- Waves used for isentropic loading to stresses >250 GPa









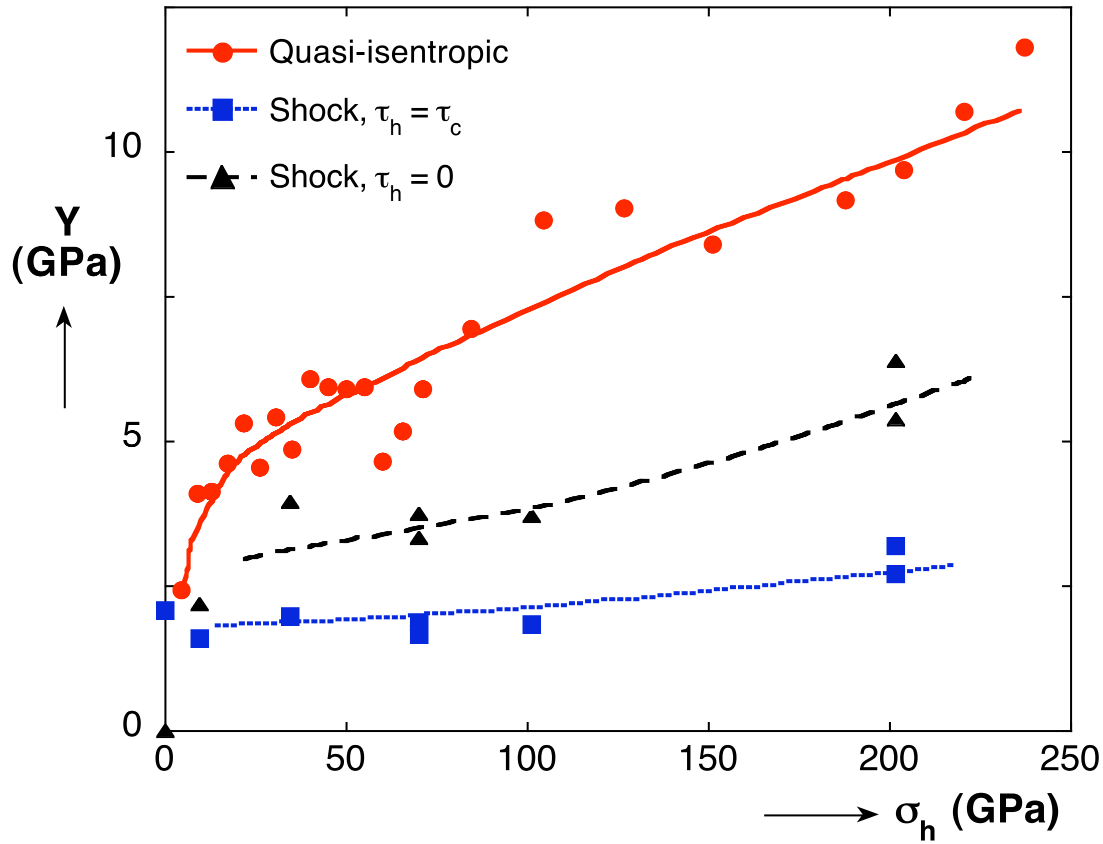
Strength Under Quasi-Isentropic Loading: Previous Work

aluminum - isentrope stiffer
than Hugoniot to 9 GPa
(Barker-SNL)

tungsten - isentrope from
graded-density impactor
lies above Hugoniot up to
140 GPa due to strength

molybdenum - isentrope from
Z compared with hydrostat
to estimate strength
(Reisman-LLNL/SNL)

Chhabildas & Barker, 1988



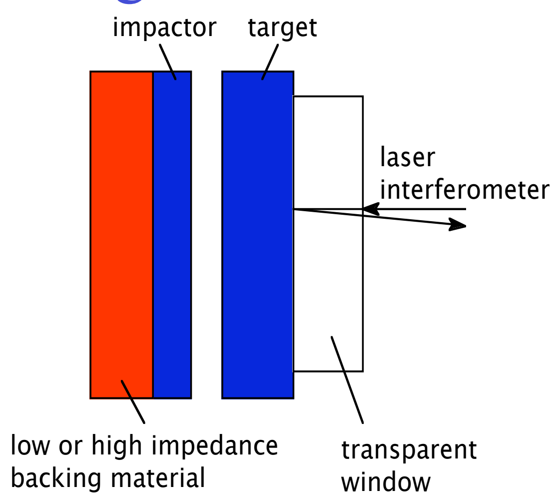
lateral gauges

- AD-1 aluminum and copper (Bat'kov *et al.*)
- copper, iron, steel (Rosenberg *et al.*)

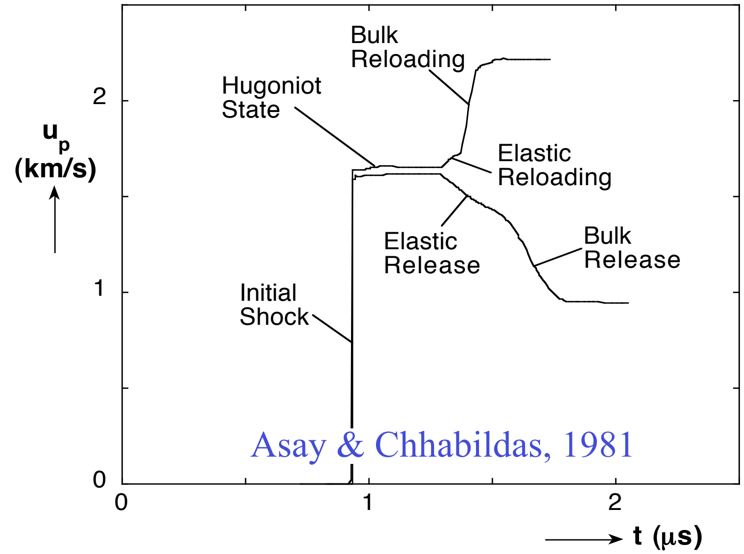
growth of Rayleigh-Taylor instabilities - aluminum and vanadium (LLNL)

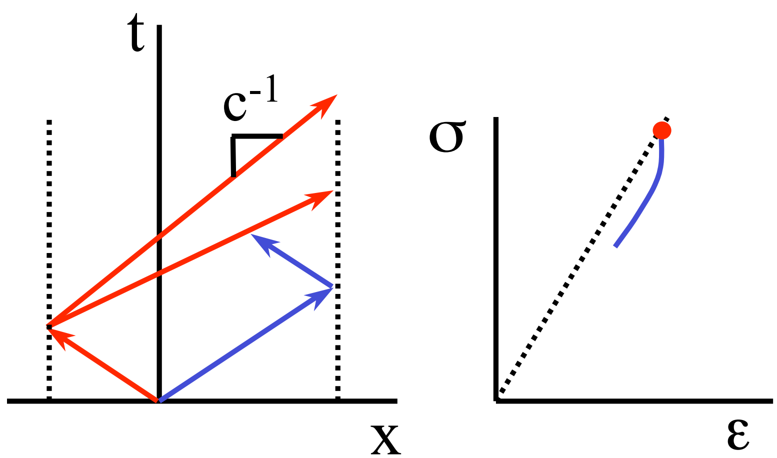
Self Consistent Method
(Asay, Lipkin, Chhabildas, *et al.*)

reshock & release configuration



results for 6061-T6 Al

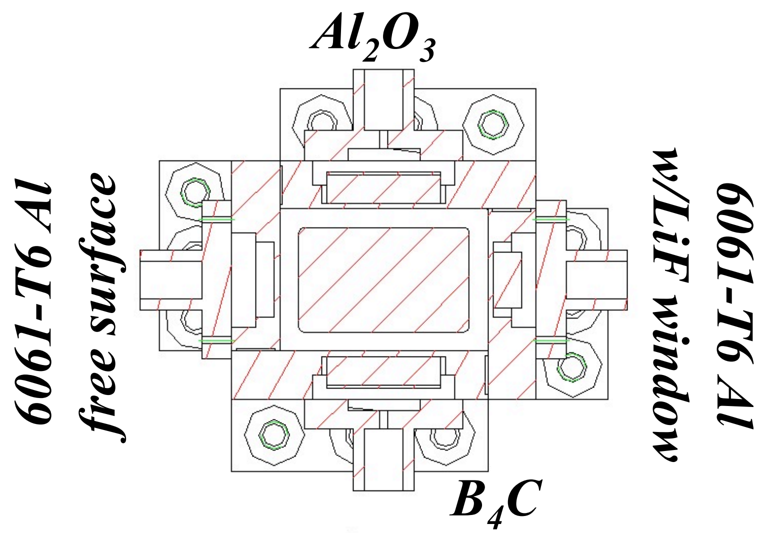


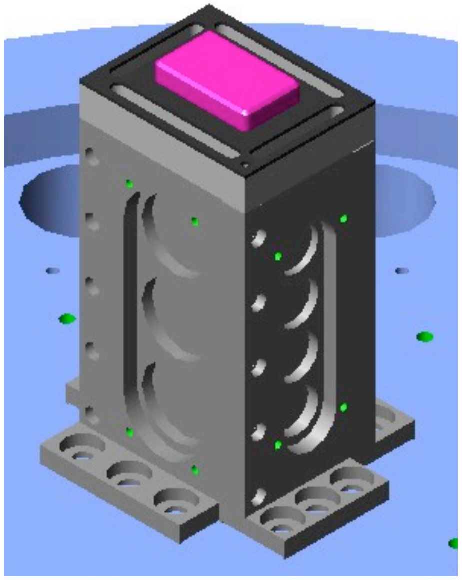


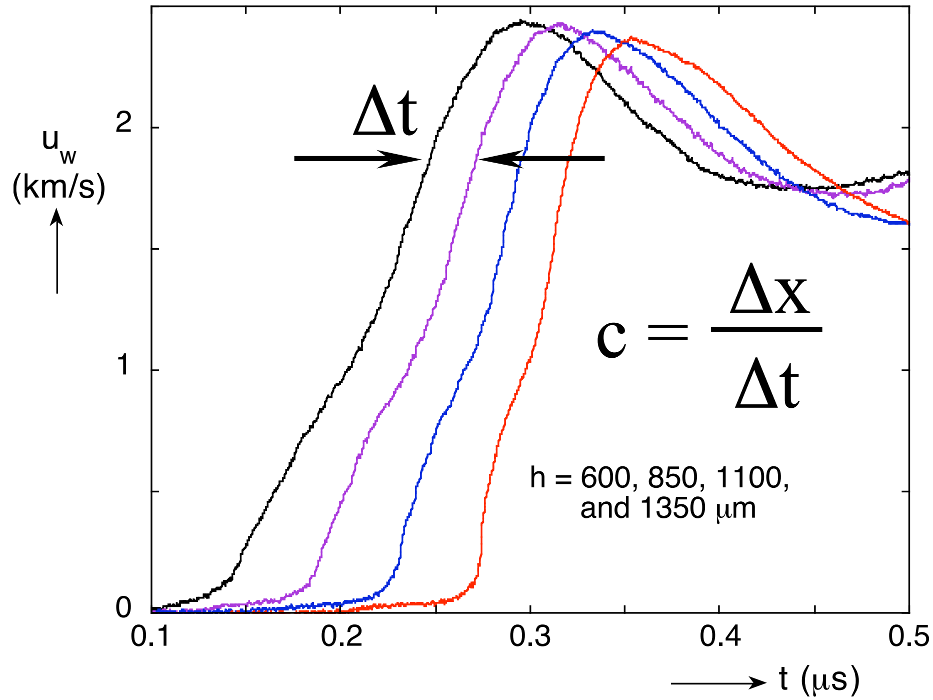
- wave speed determined from VISAR release or reloading profiles
- unloading path calculated from incremental relations

strength based on relative difference from Hugoniot state

Results for 6061-T6 Aluminum, Z1220





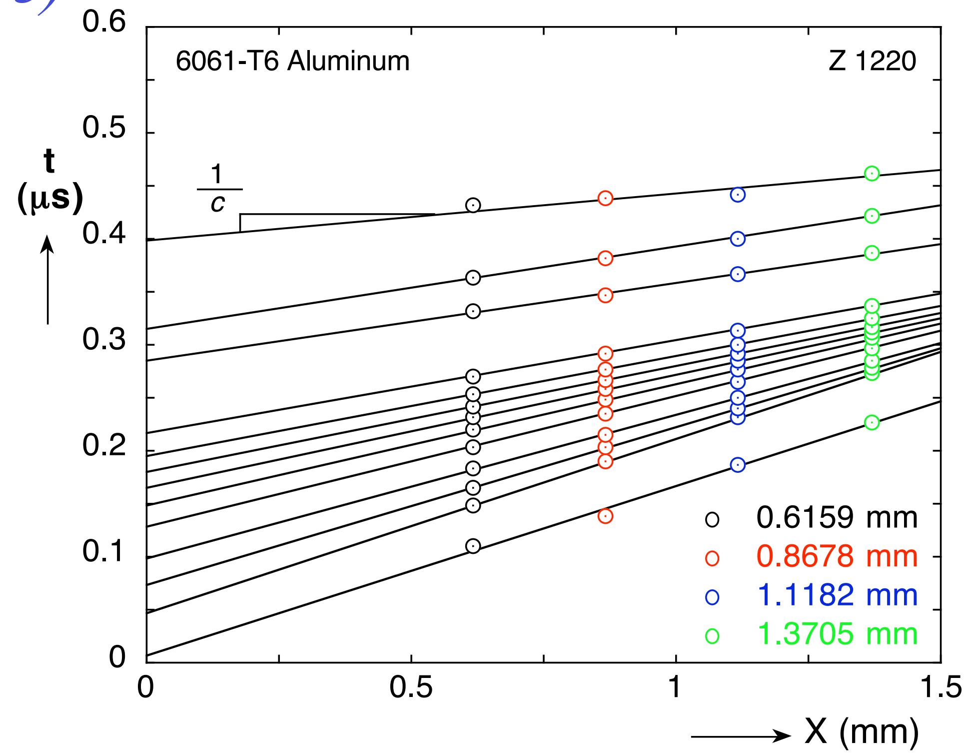


- four profiles, both loading and unloading histories
- peak attenuation evident
- unloading structure develops in thicker samples

Lagrangian Analysis Technique

- *backwards integration technique of Dennis Hayes is non-unique for elastic-plastic materials*
- *Lagrangian analysis technique follows previous work by Grady and others (Anderson, H6-3)*

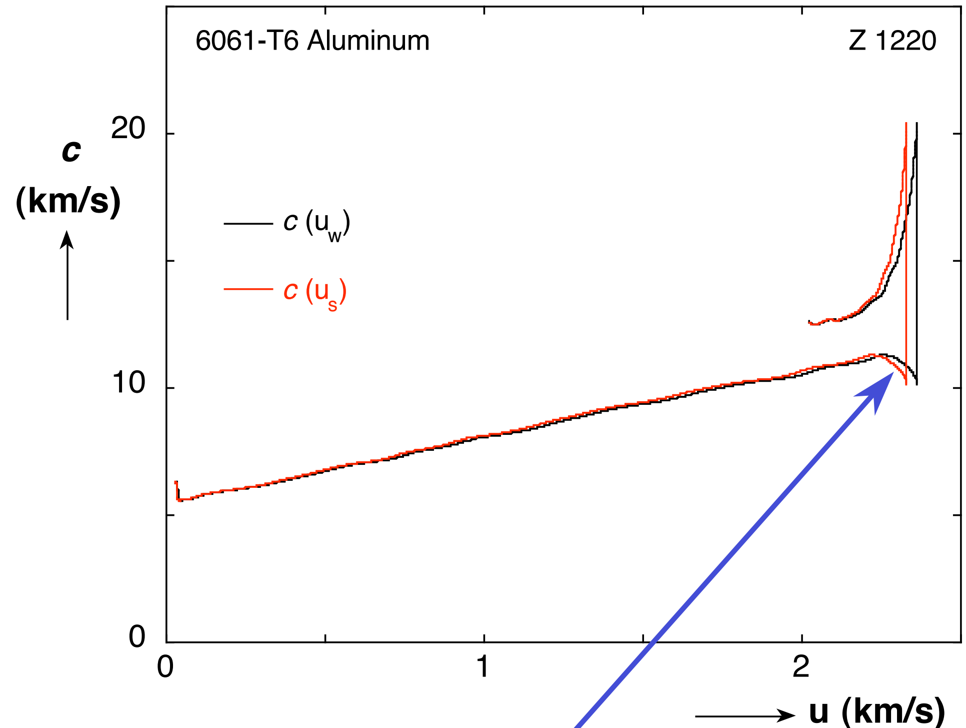
1) determine $c(u_w)$ by least-squares fit to VISAR data



Lagrangian Analysis Technique (2)

2) correct $c(u_w)$ to $c(u_p)$ by impedance matching of window and sample

$$\Delta u_s = \frac{Z_s + Z_w}{2Z_s} \Delta u_w$$



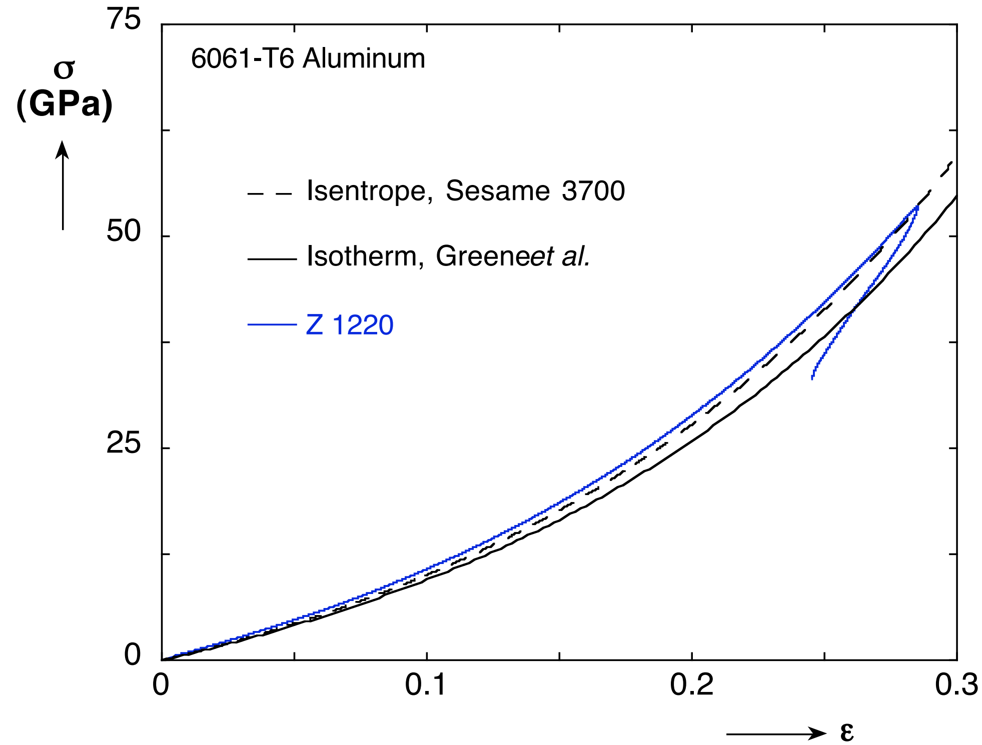
relaxation due to drop in strain rate?

Lagrangian Analysis Technique (3)

3) integrate stress and strain using incremental relations:

$$\Delta\sigma = \rho_o c \, \Delta u_p$$
$$\Delta\varepsilon = \Delta u_p / c$$

for unloading, ignore attenuation by beginning at lowest peak u_p



Assumptions in Lagrangian Analysis Technique

- characteristics not bent by window interactions
- rate-independent material
- all points experience same loading history
- window behavior known
- window loads along its principal isentrope

none of assumptions fully met!

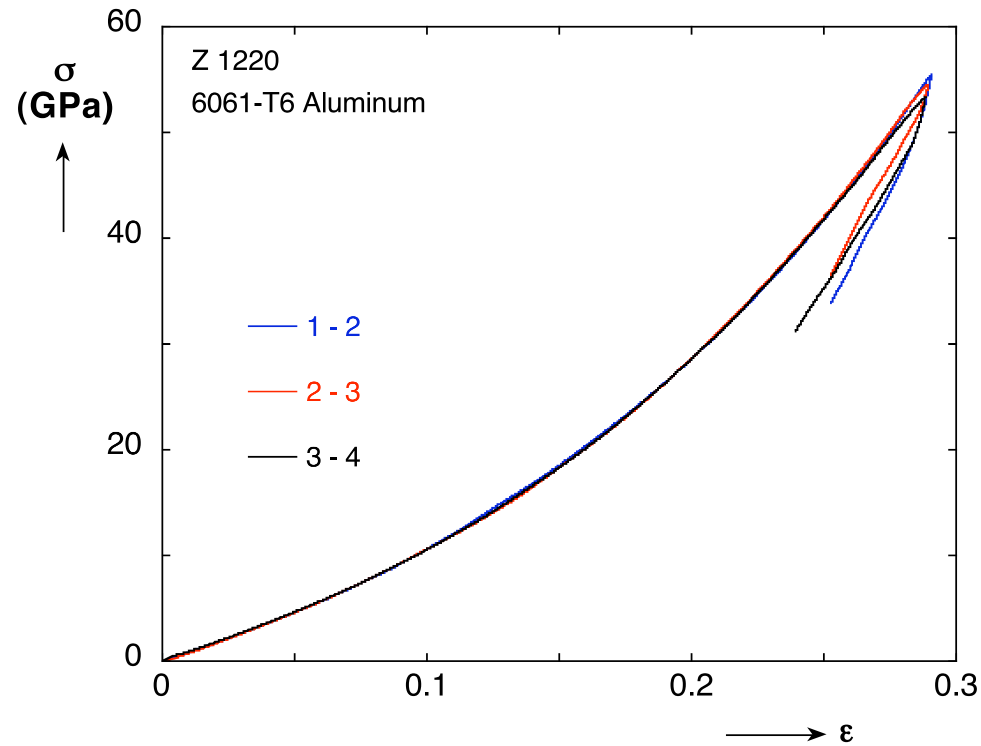
none is too bad, either!

Strength Measurement

Since stress-strain histories are somewhat different for each material point, VISAR results are analyzed in a pairwise fashion.

Loading responses are very similar for the three pairs.

Difference between loading and unloading curves is a measure of the strength.



$$Y = \frac{3}{4}\left(\sigma_L - \sigma_U\right)$$

$= \sout{3.1}$, 2.2, 1.5 GPa

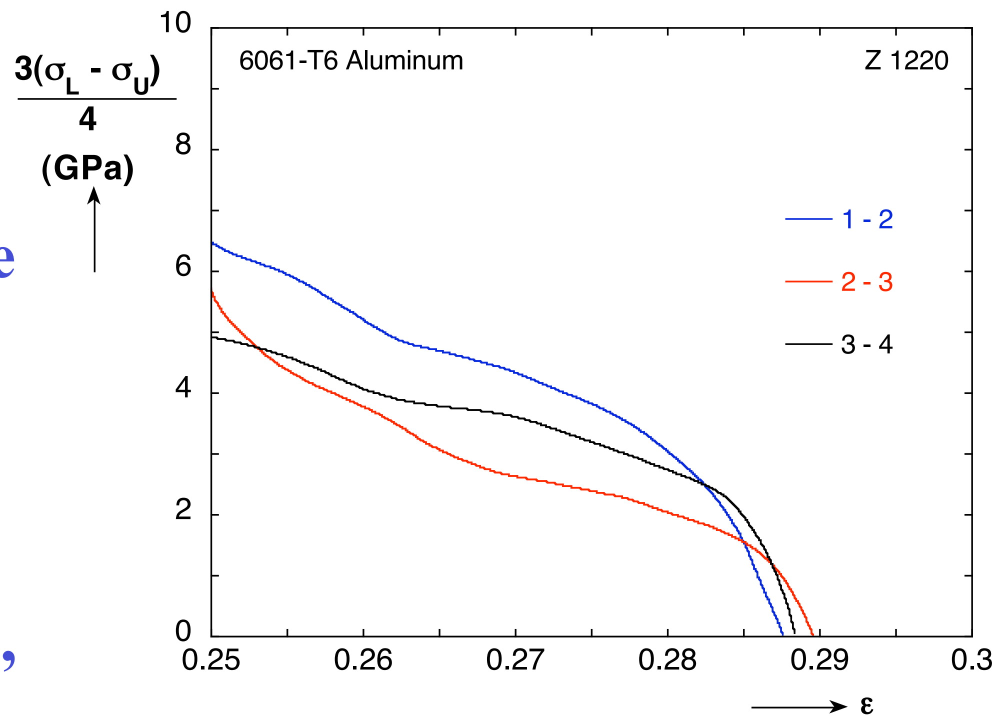
results suspect due to wave interactions

Strength Measurement (2)

Difference increases rapidly due to elastic unloading.

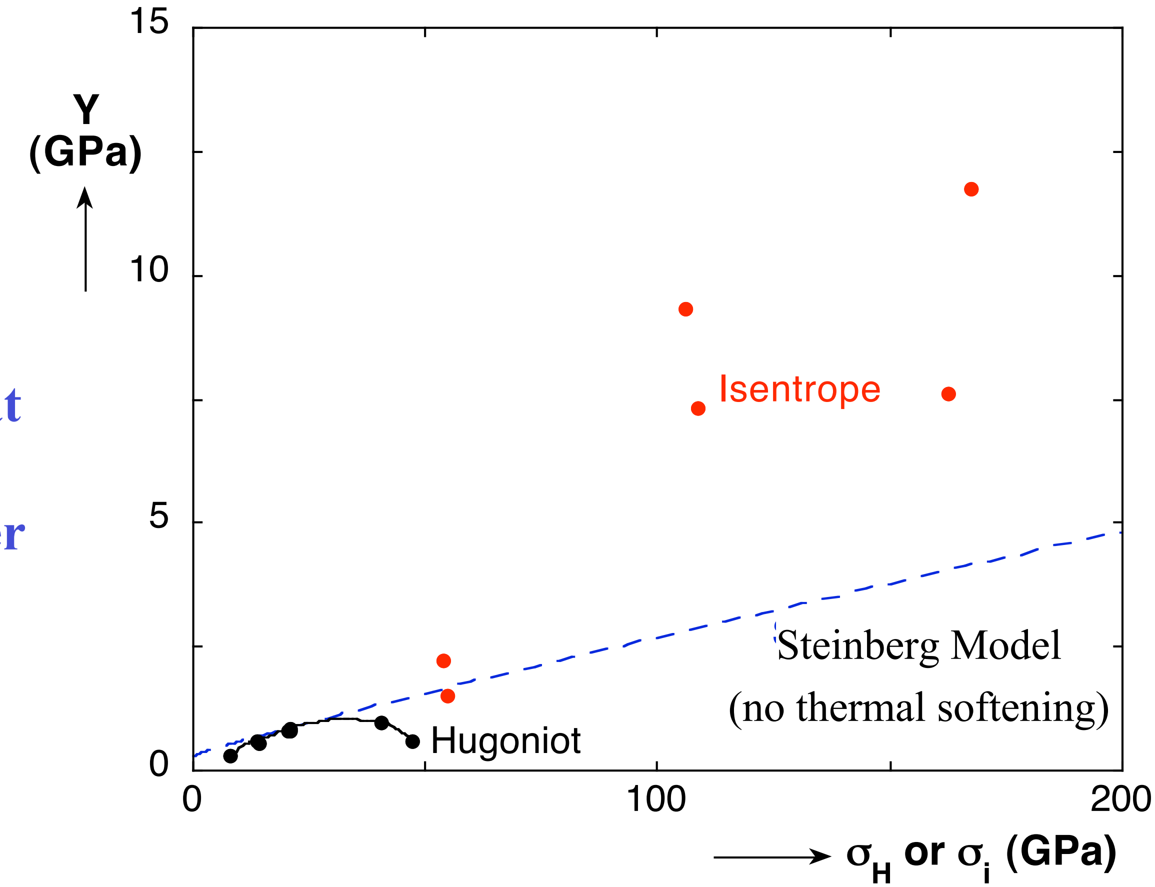
Slope decrease but difference continues to increase, either due to work hardening or analysis artifacts.

Effective values for *Y* are 3.1, 2.2, and 1.5 GPa (ambient value was 0.3 GPa).



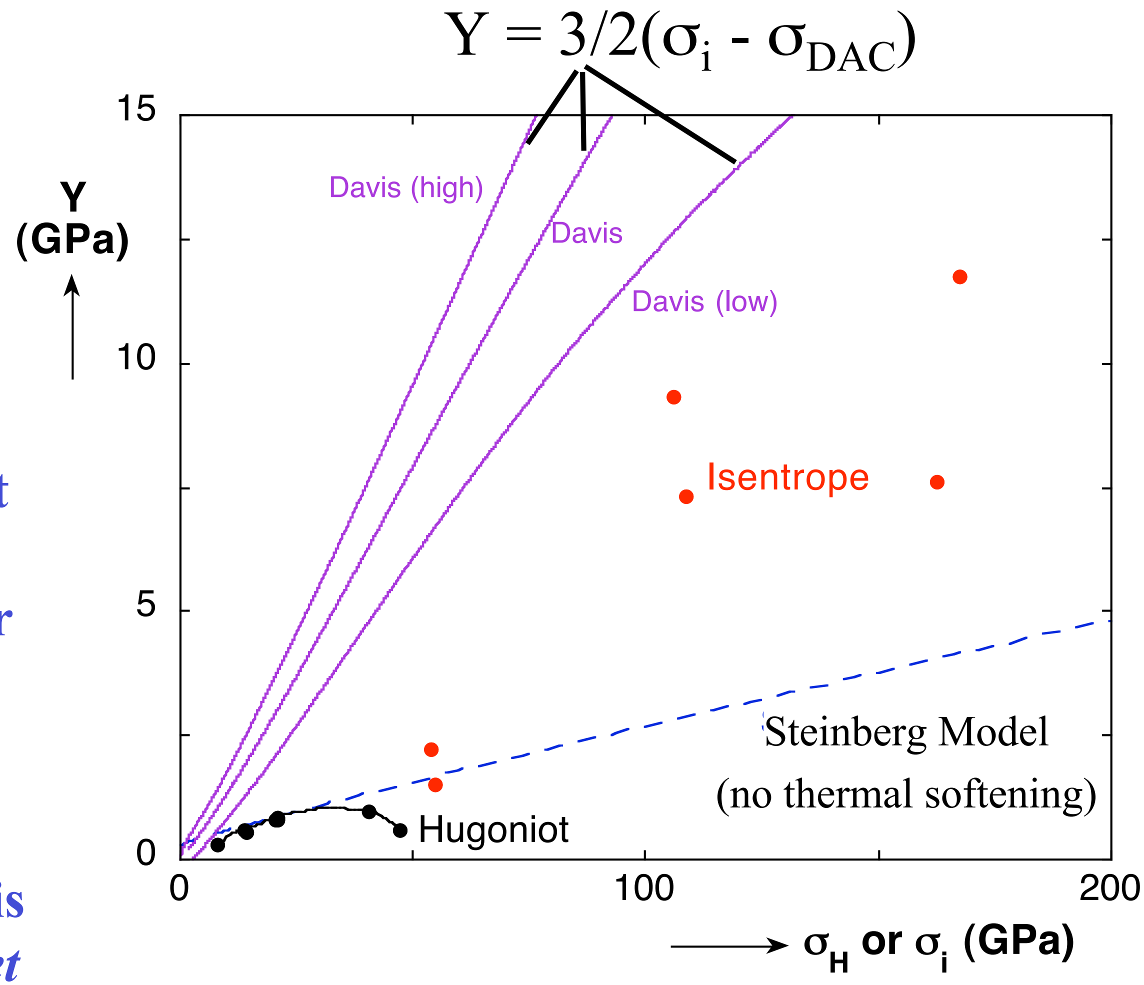
Strength Values

- strength under isentropic loading continues to increase with increased stress (due to pressure and/or work hardening)
- current experimental results agree with Steinberg model at low stresses but deviate at higher stresses (though higher stress have lower confidence)



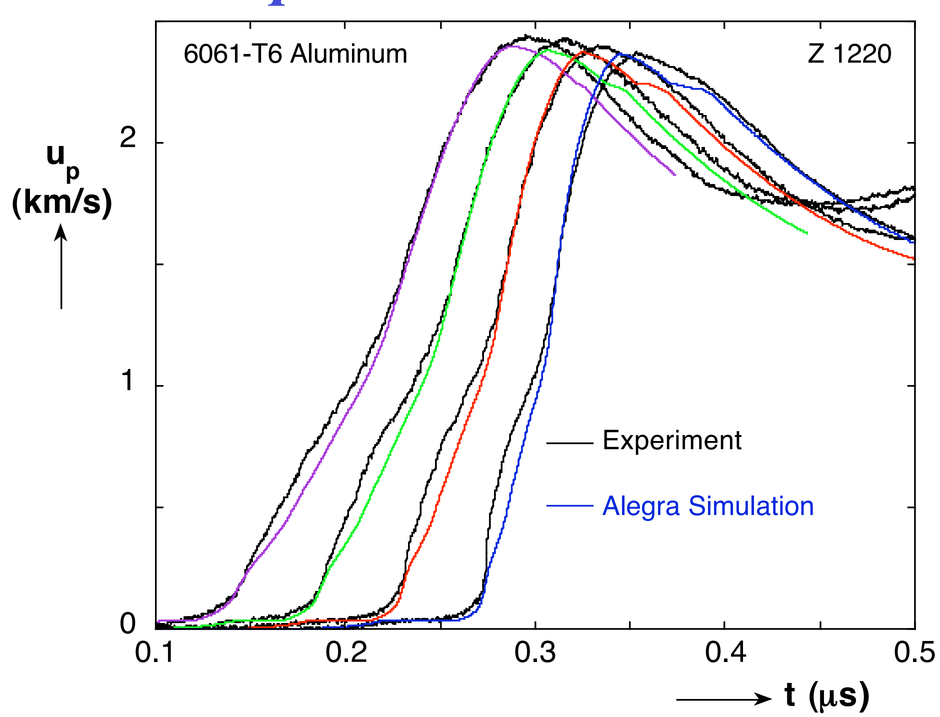
Strength Values

- strength under isentropic loading continues to increase with increased stress (due to pressure and/or work hardening)
- current experimental results agree with Steinberg model at low stresses but deviate at higher stresses (though higher stress have lower confidence)
- comparison with isotherm unreliable for calculating strength (isentrope from Davis 2005, isotherm from Greene *et al.* 1994)



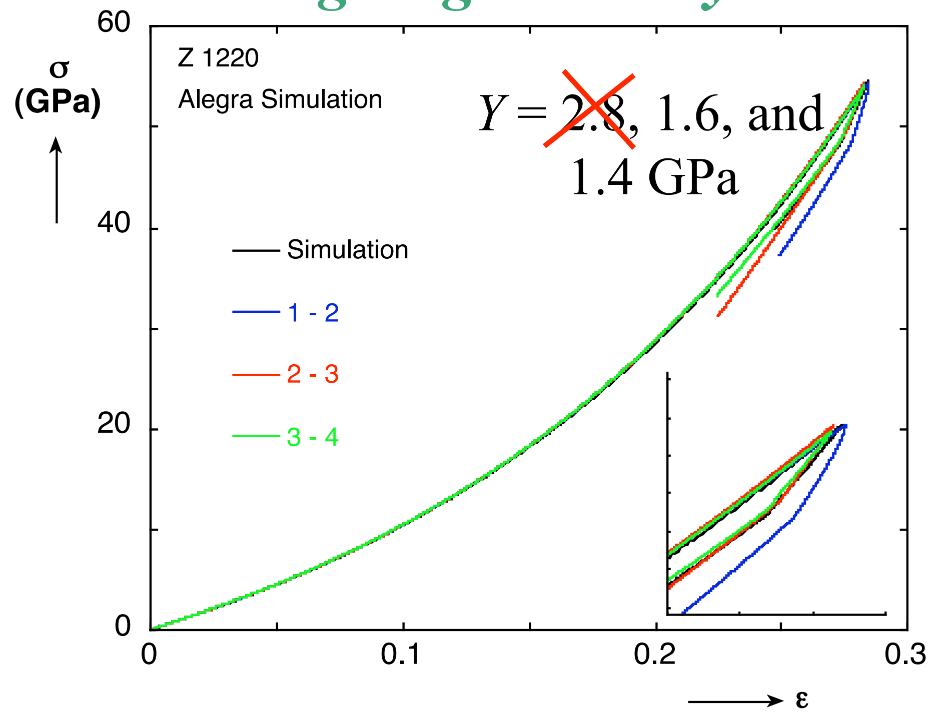
Simulated Data for Z 1220

Experiment & Simulation



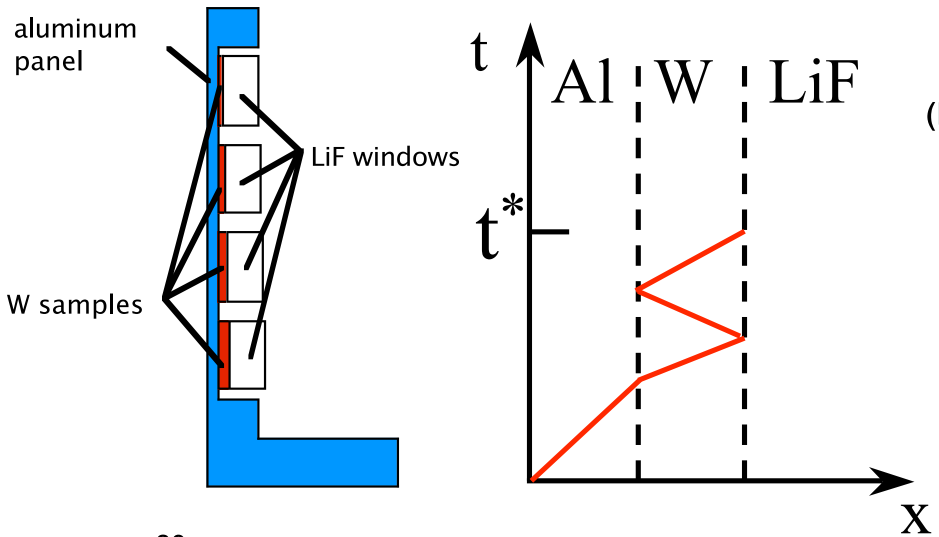
- 1-D Alegra simulation (explicit arbitrary Lagrangian-Eulerian magneto-hydrodynamics code, Steinberg-Guinan-Lund strength model)
- current input somewhat off on loading, too much structure in unloading wave

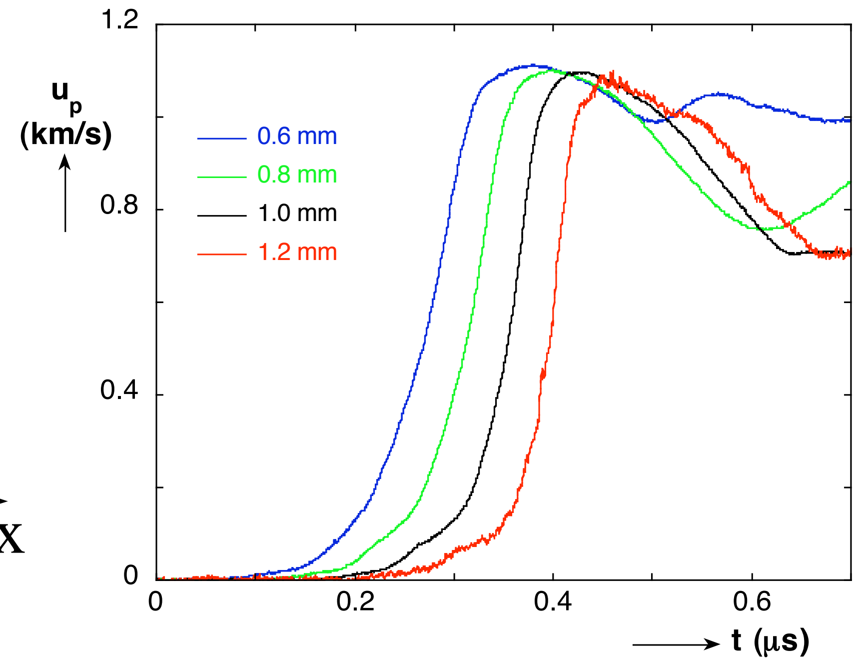
Lagrangian Analysis

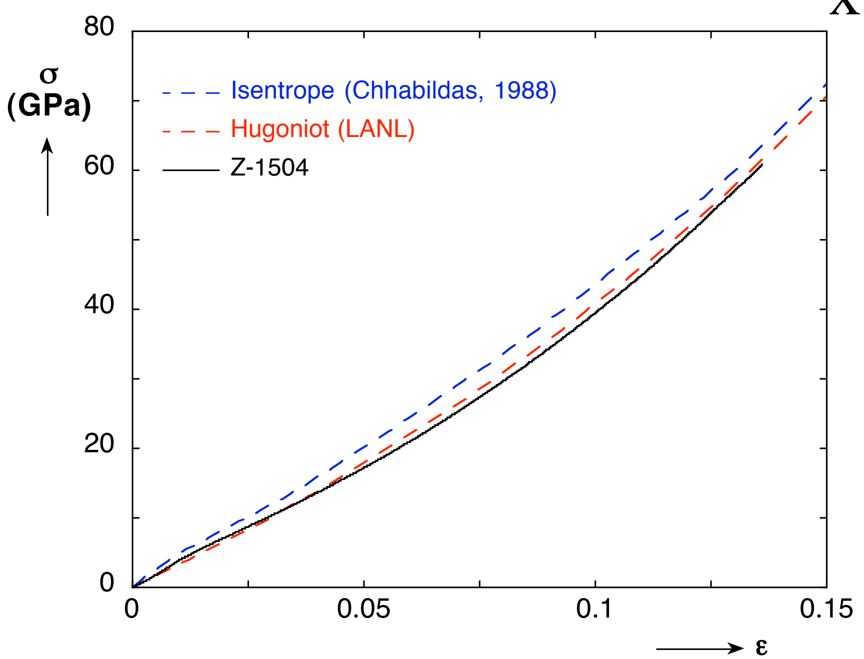


- loading captured extremely well
- first pair affected by window perturbations reaching drive surface, but others accurate measurements of *Y (1.48 GPa)*

Z-1504 Tungsten to 61 GPa

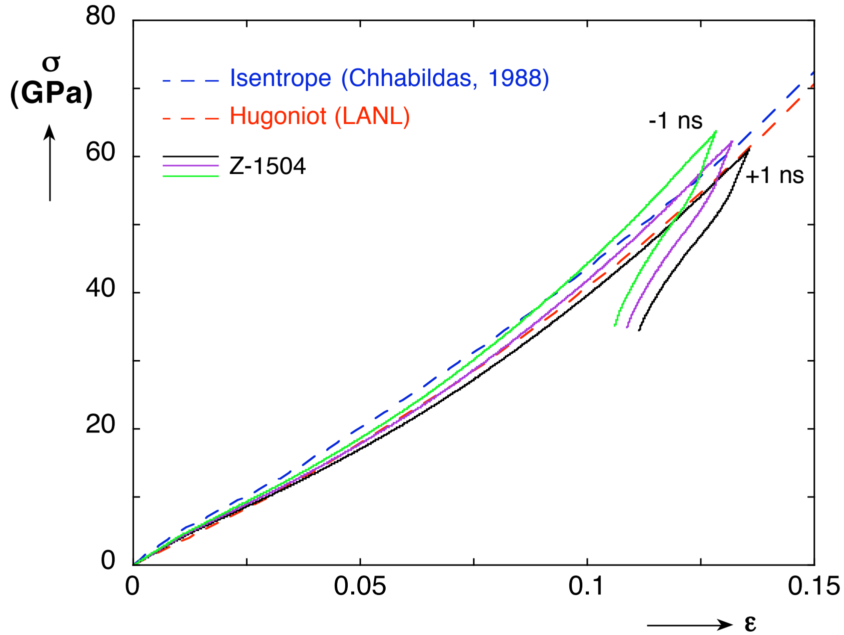


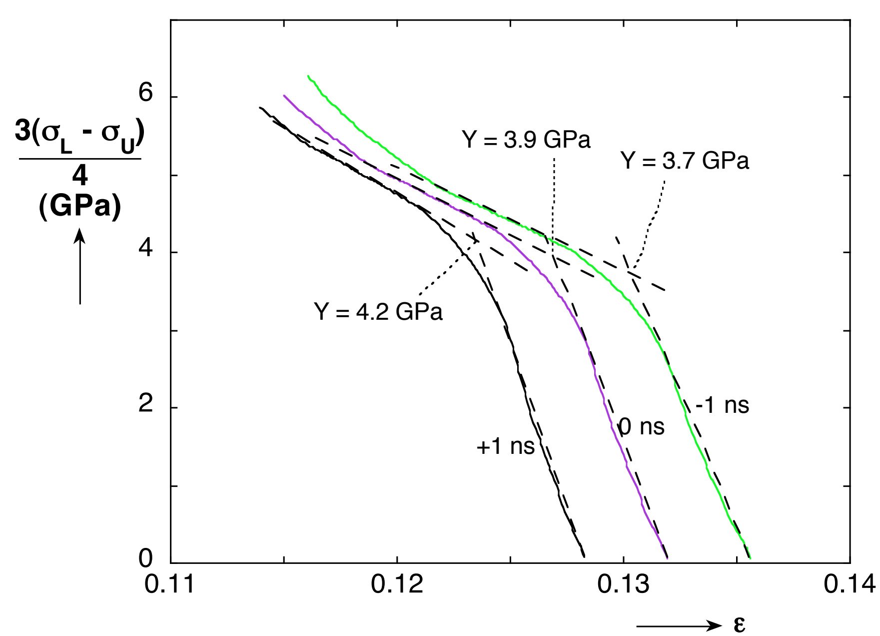




- **thinnest sample obviously affected by wave interactions, spall signature**
- **fourth thickness noisy**
- **Lagrangian analysis gives results that agree well with Hugoniot but are softer than previous isentrope**

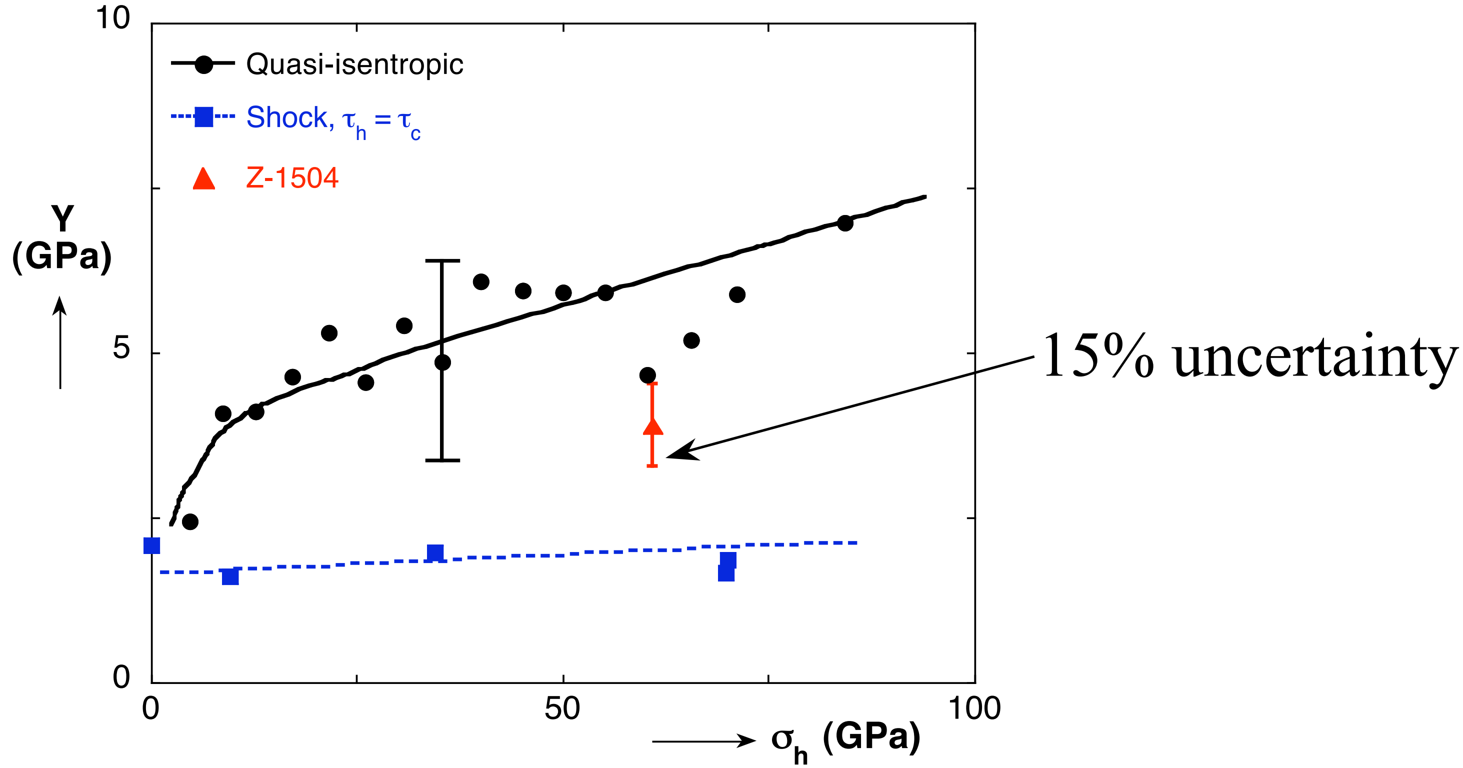
Unloading Paths and Strength





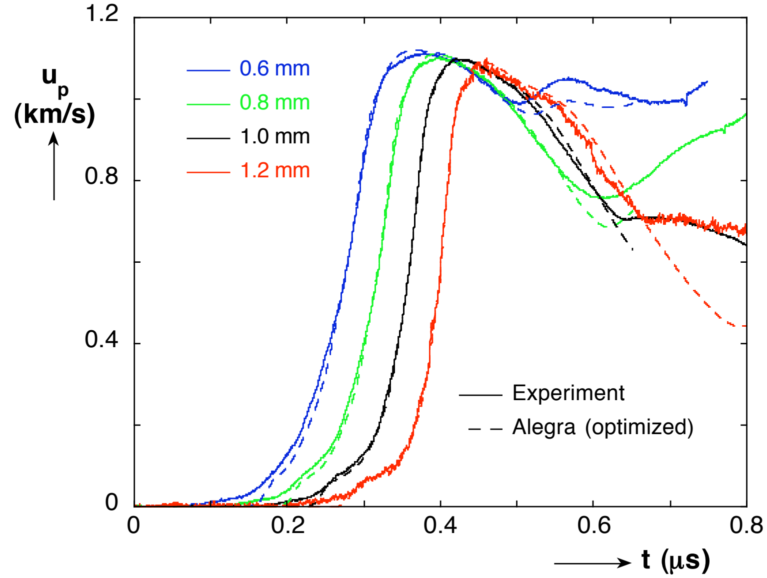
- shifting profile #2 by -1 ns brings responses calculated for 1-3, 1-2, and 2-3 into agreement
- ±1 ns shift changes Y only by about 8%, so strength is relatively insensitive to small timing errors

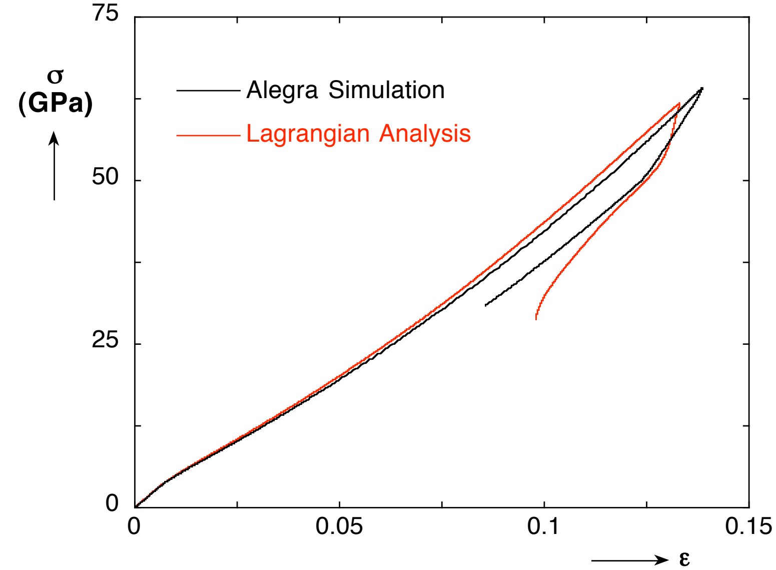
Strength Under Isentropic and Shock Loading

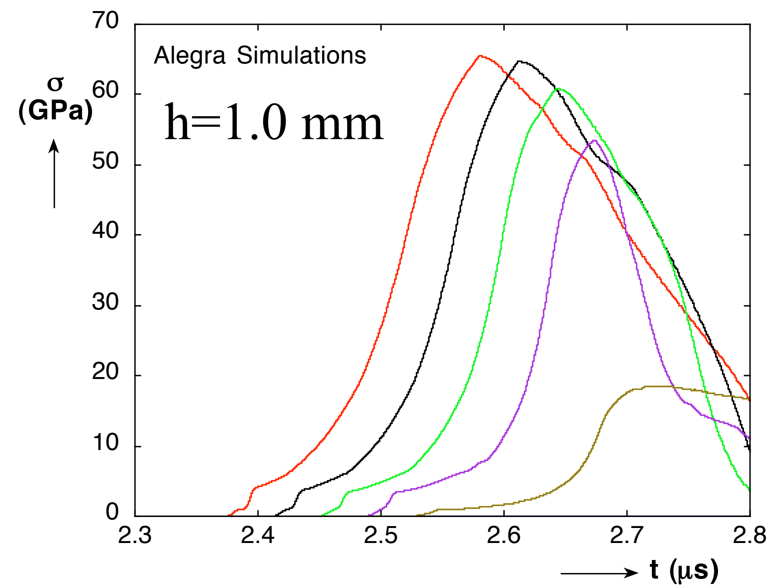


- **strength at 61 GPa somewhat lower than previous results but overlap within uncertainty**
- **uncertainty of current measurements seems to be lower than previous method; uncertainties more easily quantifiable**

Alegra Simulations of Experiment

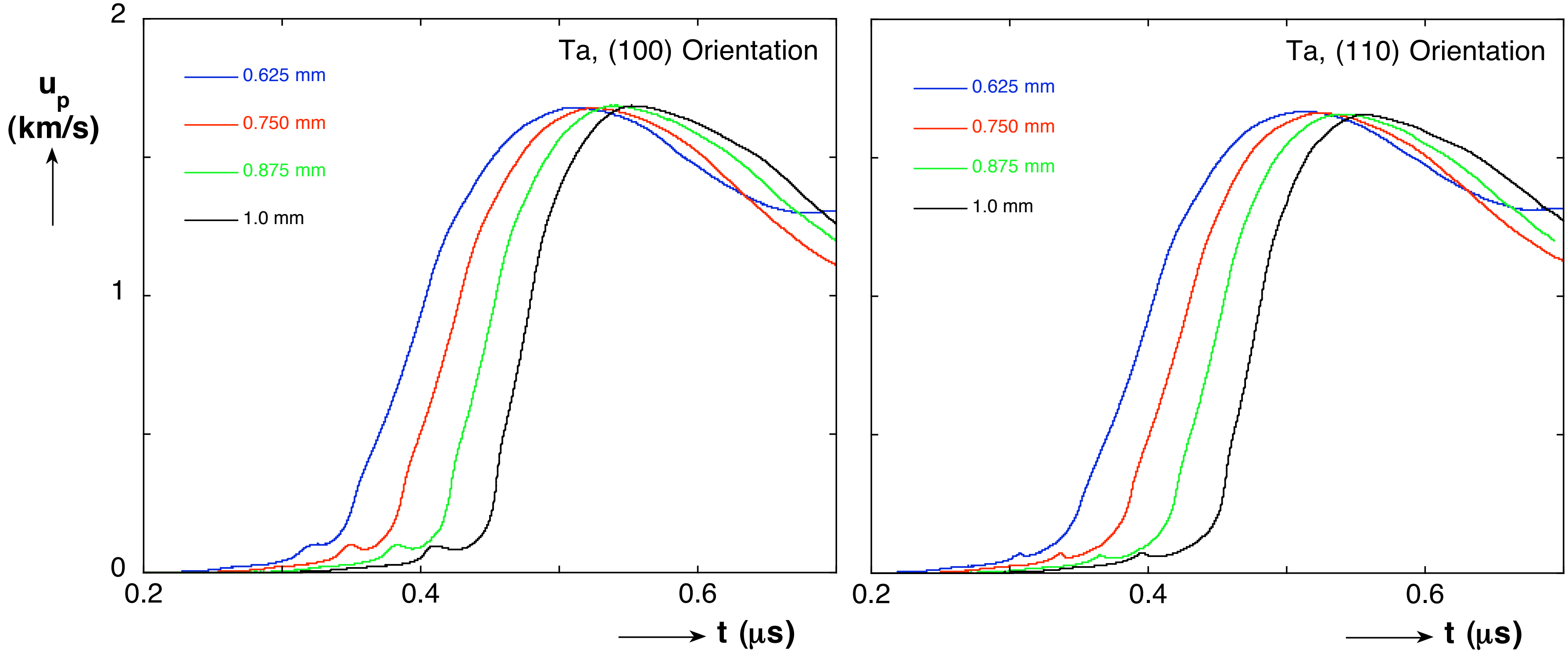






- initial Alegra simulations match VISAR profiles well
- Lagrangian analysis gives a 20% high strength value
- loading path within material nonuniform

Ta Single Crystal Results



- higher elastic limit for (100)
- strength at 80 GPa approximately 2.4 GPa for both orientations

Conclusions

- first strength measurements made with the self-consistent technique for isentropic loading
- strength measurements made on Z to 160 GPa for Al and 60 GPa for W
- results suggest surprisingly high strength for aluminum
- strength results are relatively insensitive to timing errors (1 ns shift gives ~8% error in *Y* at 60 GPa)
- experiment must meet restrictions to avoid reverberations and shock formation in window
- conservative estimate of 20-30% uncertainty on *Y* at 50 GPa for Al, 15% for W; error for higher pressure results not yet quantified

Future Work

- gas gun experiments with graded-density impactors to remove complications of magnetic loading and wave attenuation
- improved Lagrangian analysis technique to account for attenuation (e.g. Aidun & Gupta)
- better establish error bars due to experimental uncertainty and analysis technique
- strength model which more accurately matches VISAR histories needed
- iterative MHD modeling may be needed for high stress levels
- comparison of different techniques (e.g. Rayleigh-Taylor, DAC, and self-consistent) for same materials
- direct comparison of experiments with molecular dynamics
- investigate effect of solid-solid phase transformations on strength and vice-versa