SAND2008-3107C

Strength Properties of Beryllium and Diamond

JOWOG32 materials meeting
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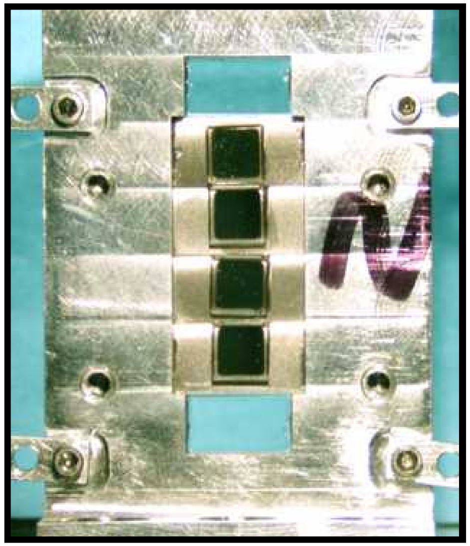

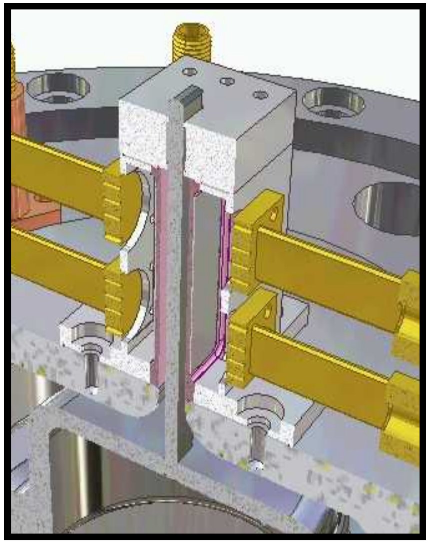

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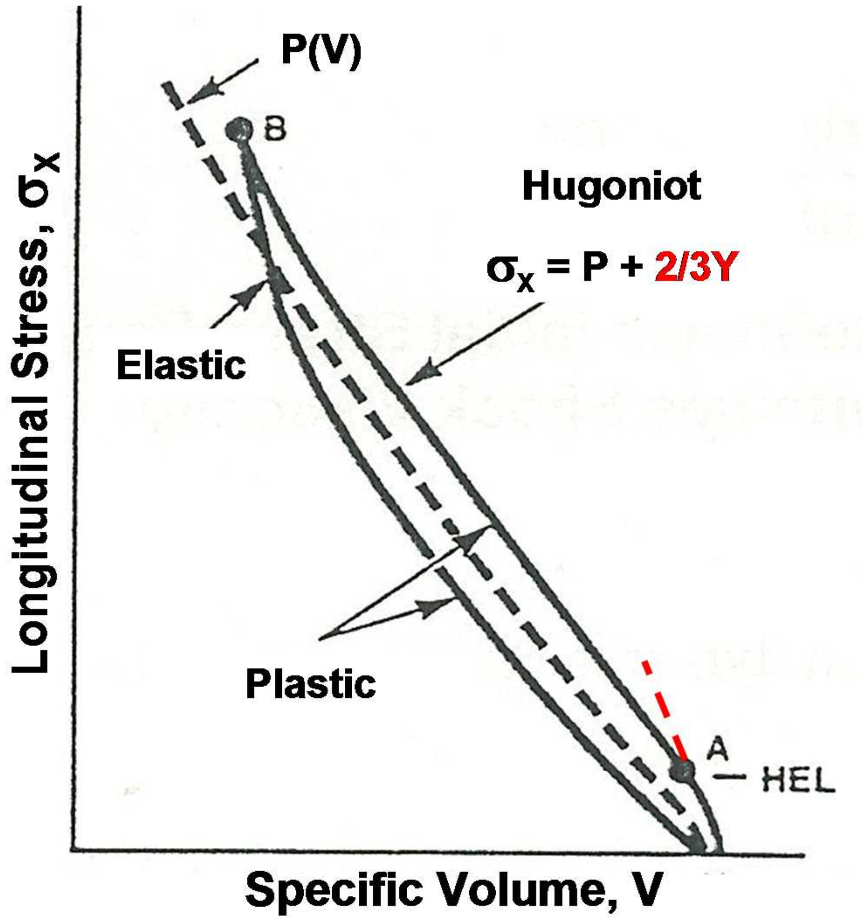
Outline

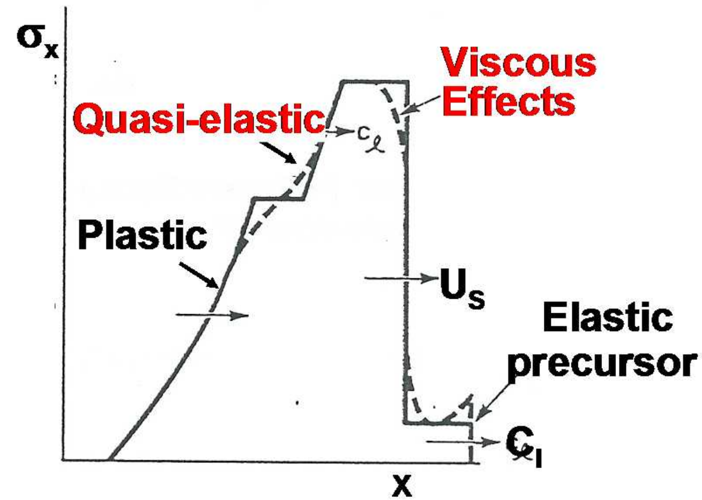
- Be strength results
  - Hugoniot experiments
  - Preliminary isentropic compression experiments
- Diamond strength results
  - Hugoniot experiments

A wave profile technique is used to estimate high pressure compressive strength

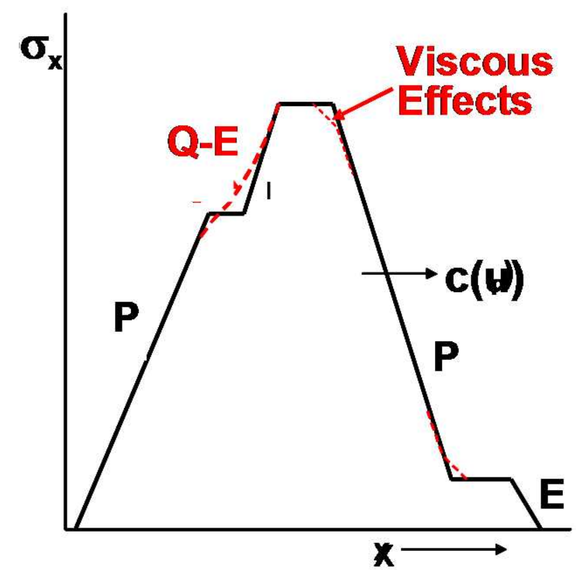


G.R. Fowles, 1961

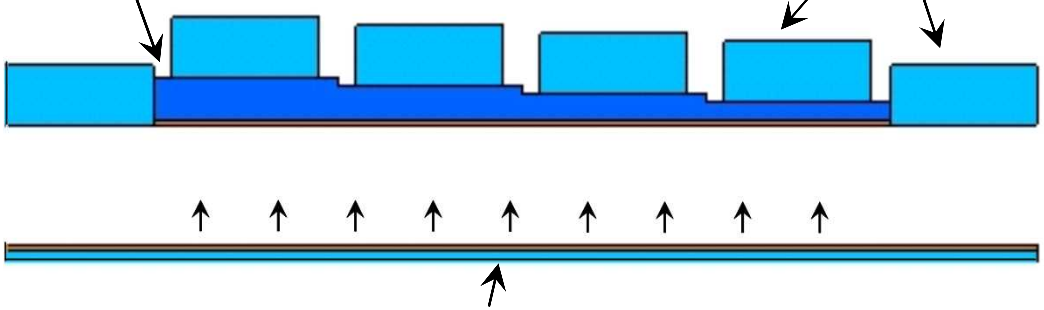
Shock/unloading

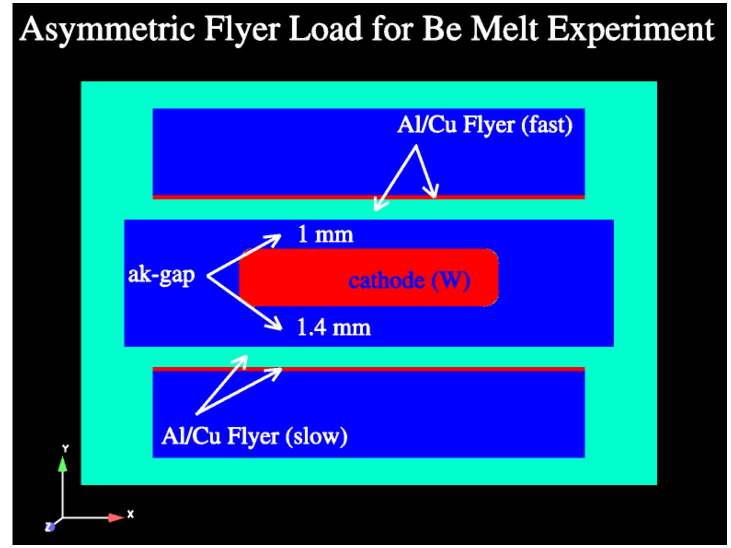


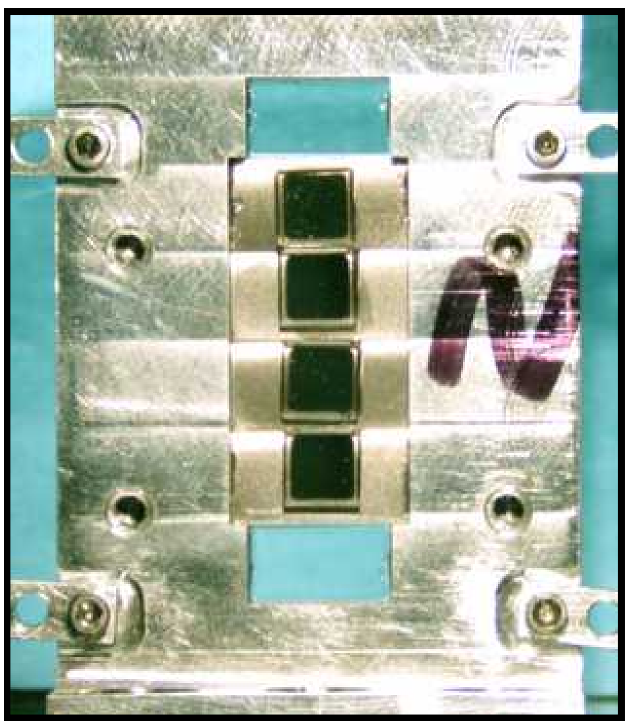
Ramp loading/unloading



MHD simulations were critical in providing load geometries to achieve desired flyer velocities







- Experiments required an Al/Cu flyer with peak velocities in the range of 7-14 km/s
- Three asymmetric loads were designed to produce 2 flyers per shot with ~10% difference in peak velocity
- ALEGRA 2D MHD was used to set flight distances and to set charge voltages on Z

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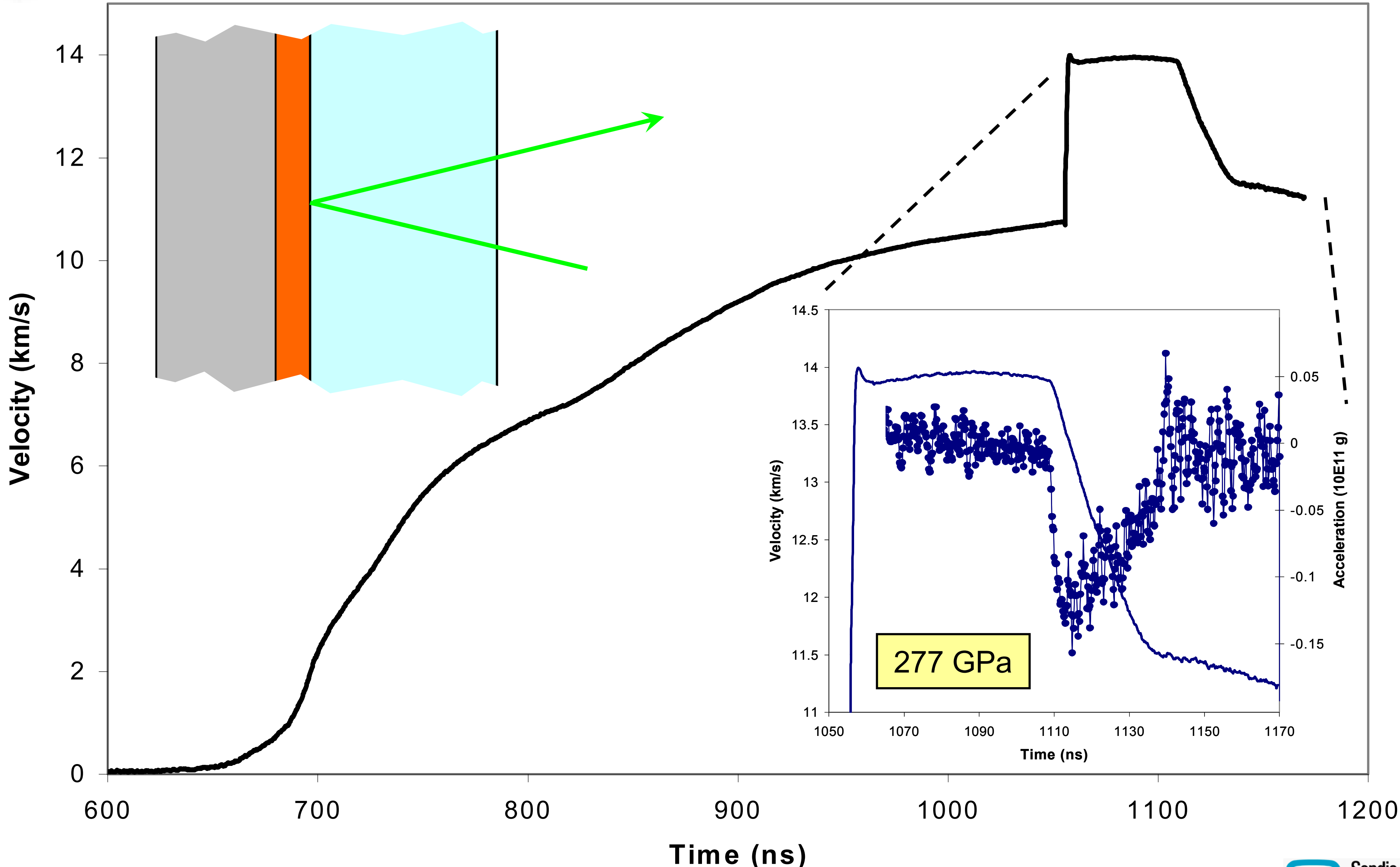
Impact experiments provide a very controlled, well defined loading at high velocity



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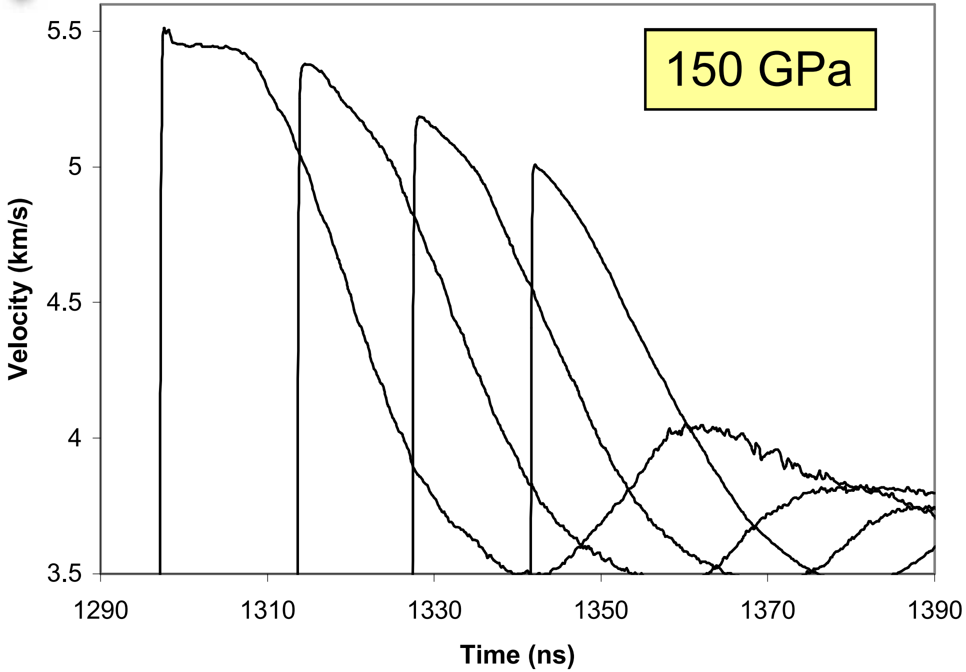
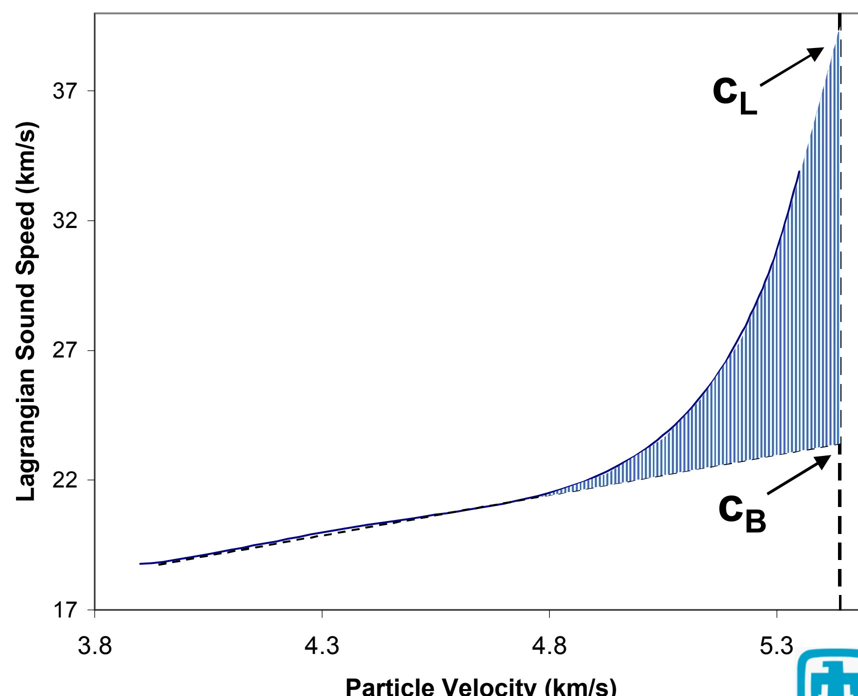
Multiple profiles allow for analysis of wave speeds and estimation of strength on the Hugoniot



- Multiple profiles provides evolution of the wave enabling estimation of wave speed
- Enabled by the multiple diagnostics and the large area flyer plates on Z
- Similar experiments will be performed on Be obtained from LANL towards the level 2 milestone for FY08

- Both c_L and c_B can be obtained from the Lagrangian analysis
- "Area under curve" provides an estimation of strength on the Hugoniot
- A similar analysis can be performed with the data with quartz windows by backward integrating to the Be/quartz interface



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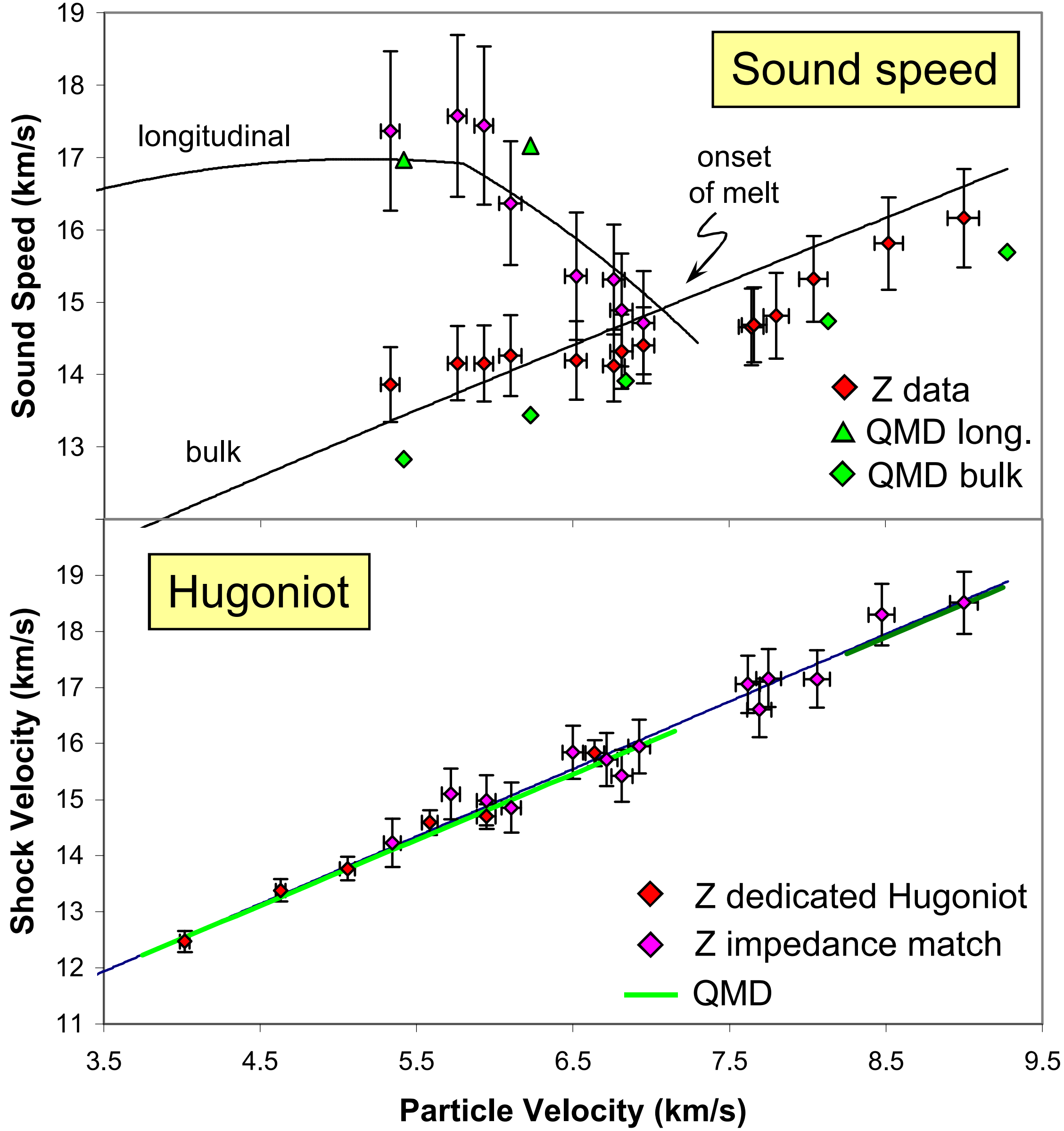
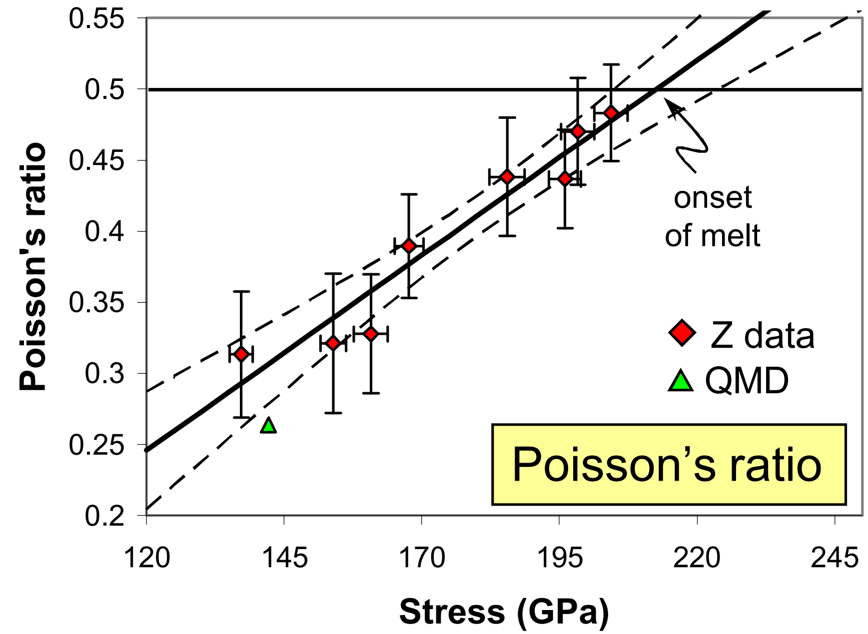
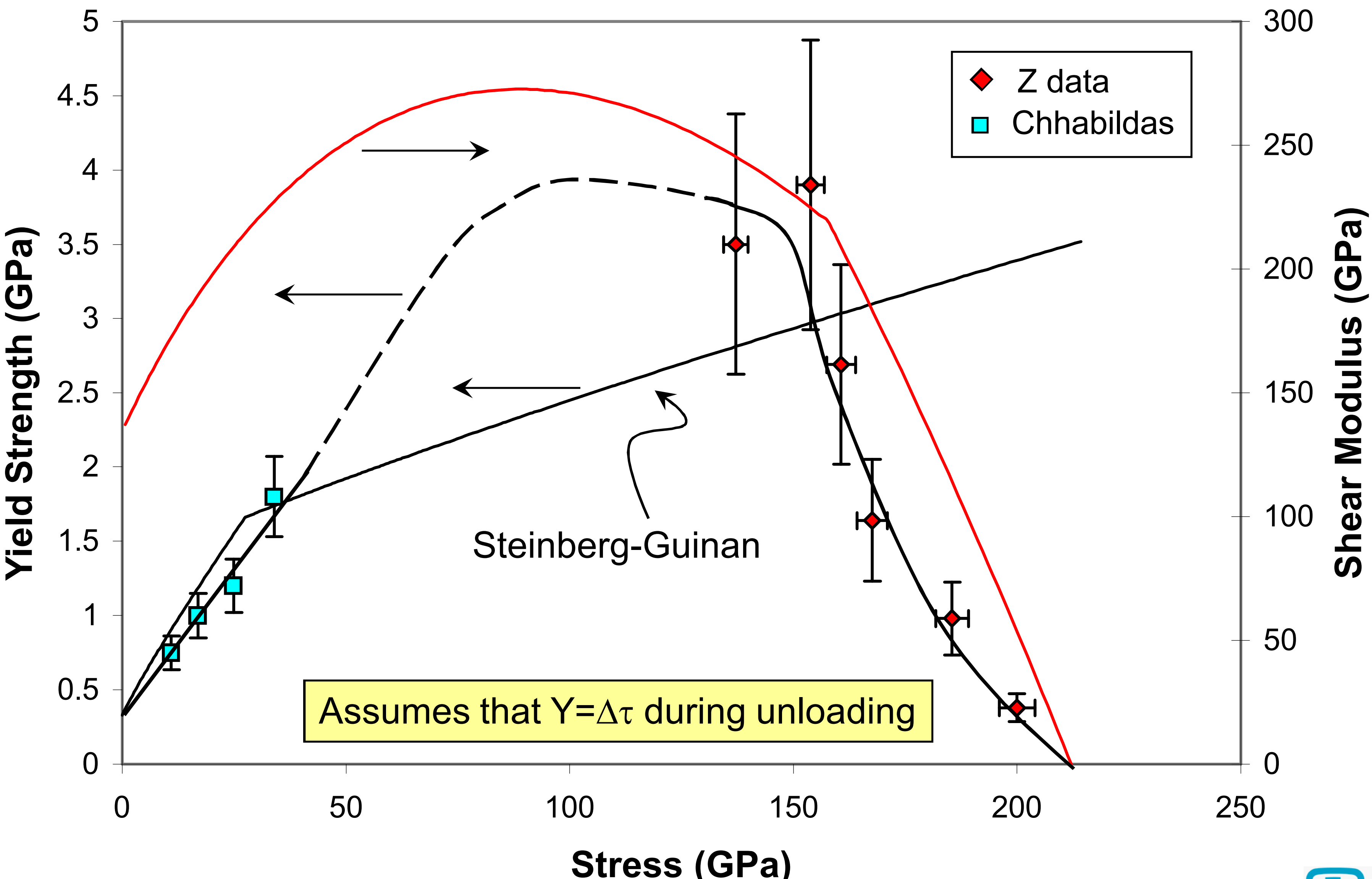
Comparison of Hugoniot and sound speed measurements with QMD calculations for hcp Be



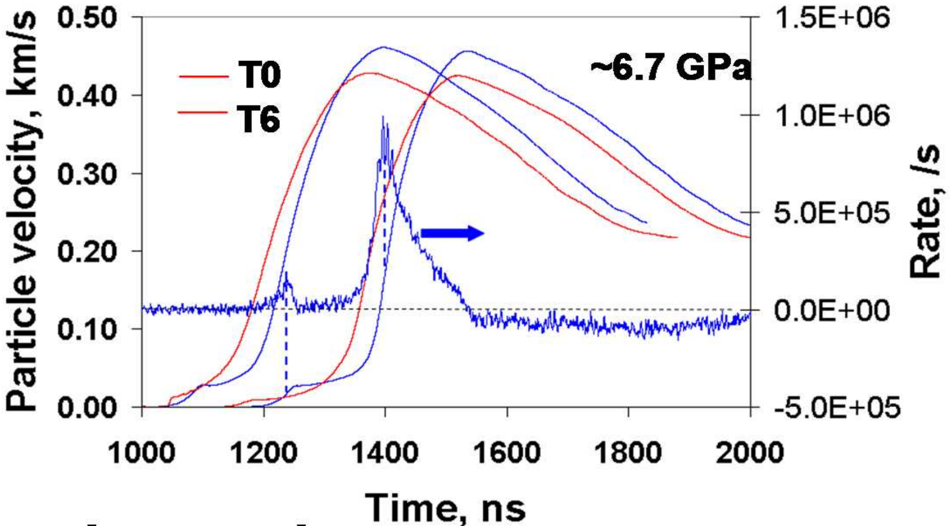


- Mie-Grüneisen equation of state fit to the Hugoniot data
- Piecewise linear fit to the Poisson's ratio
- QMD calculations in good agreement with experiment for the hcp phase of Be

The release data is providing an estimate of the yield strength of Be below melt

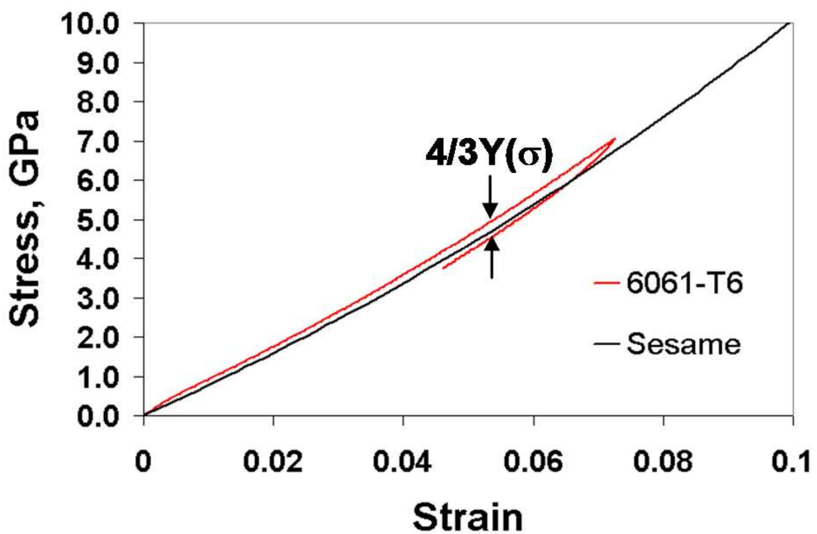


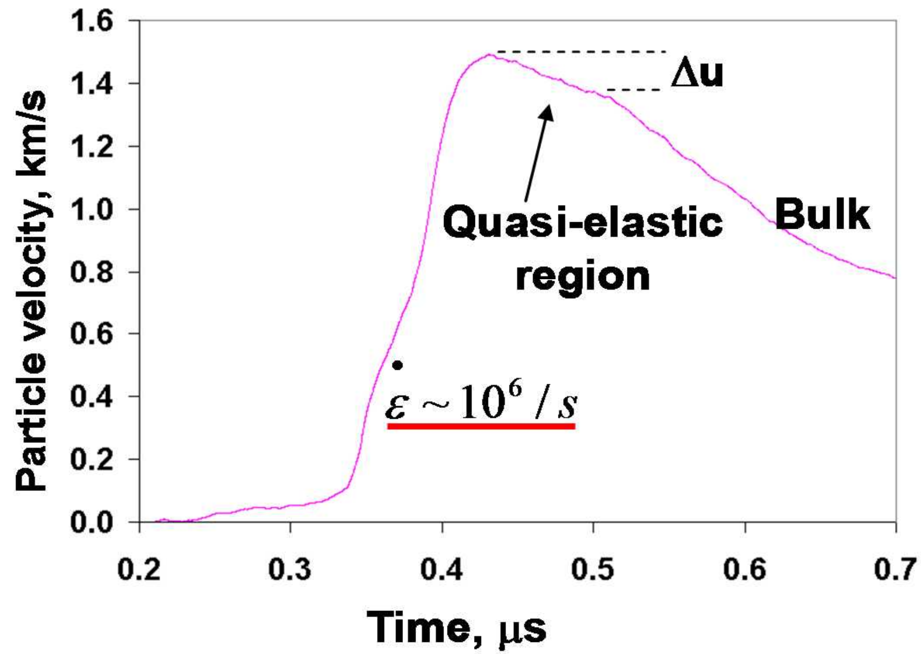
Different techniques are being evaluated to infer compressive strength from wave profile measurements



$$d\sigma = \rho_0 c\, du$$

$$d\varepsilon_e = du/c$$





Q-E strength : $$\Delta\tau \sim Y = \frac{3}{4}\rho_0 \int \left(c^2 - c_B^2\right) d\varepsilon_e \sim \frac{1}{2} G(\varepsilon_m)\Delta\varepsilon_T$$

Q-E true strain: $$\Delta\varepsilon_T \sim \frac{\rho}{\rho_0}\frac{\Delta u}{\bar{c}}$$

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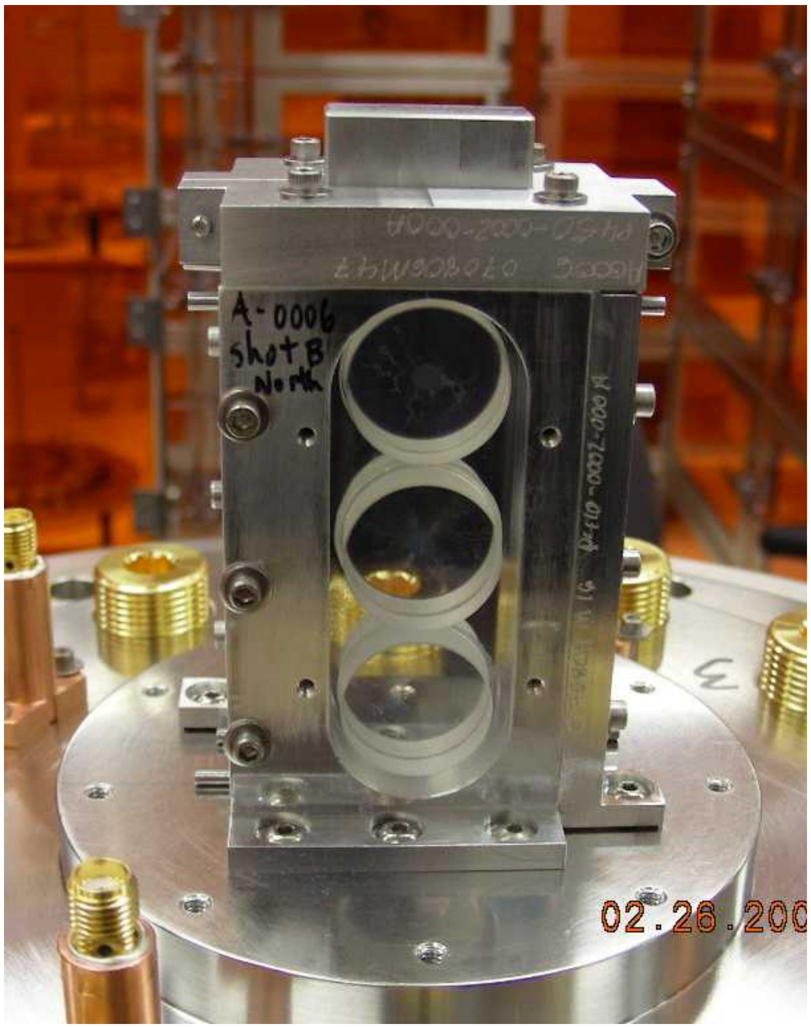
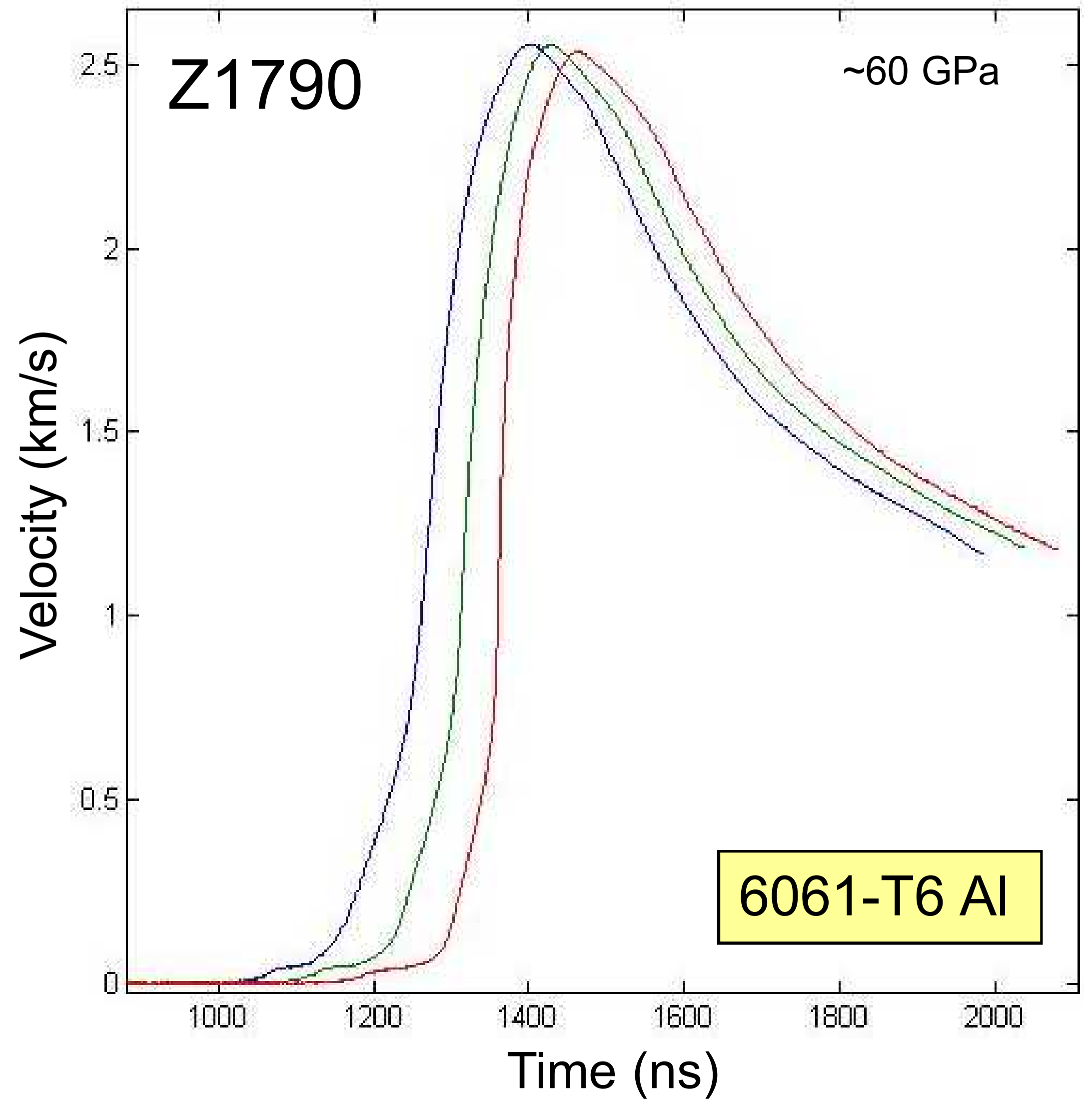
We have obtained useful wave profile data to infer strength in several materials

Coax strength load hardware





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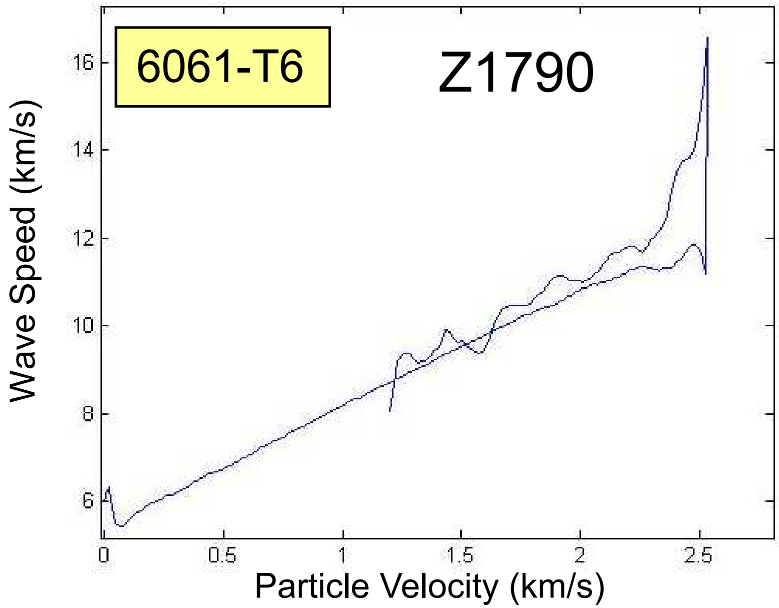
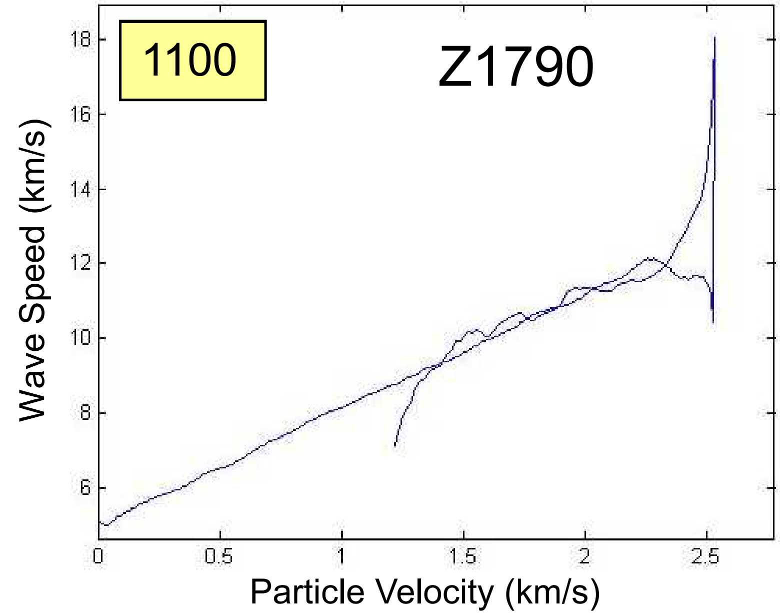
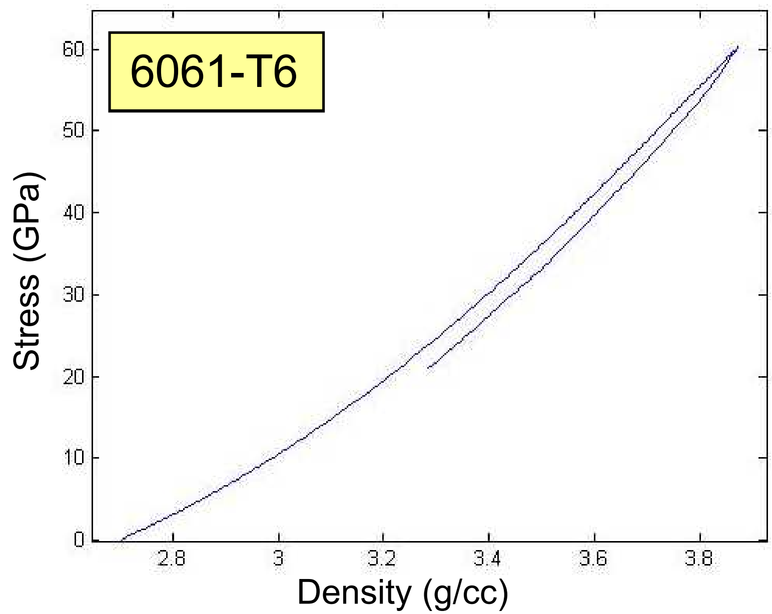
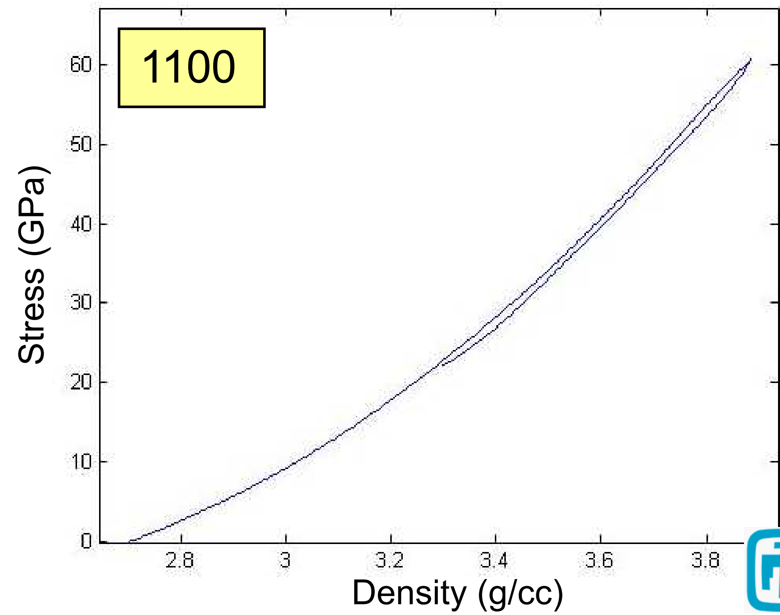
Analysis of wave profiles is providing reasonable estimates of strength at high pressure









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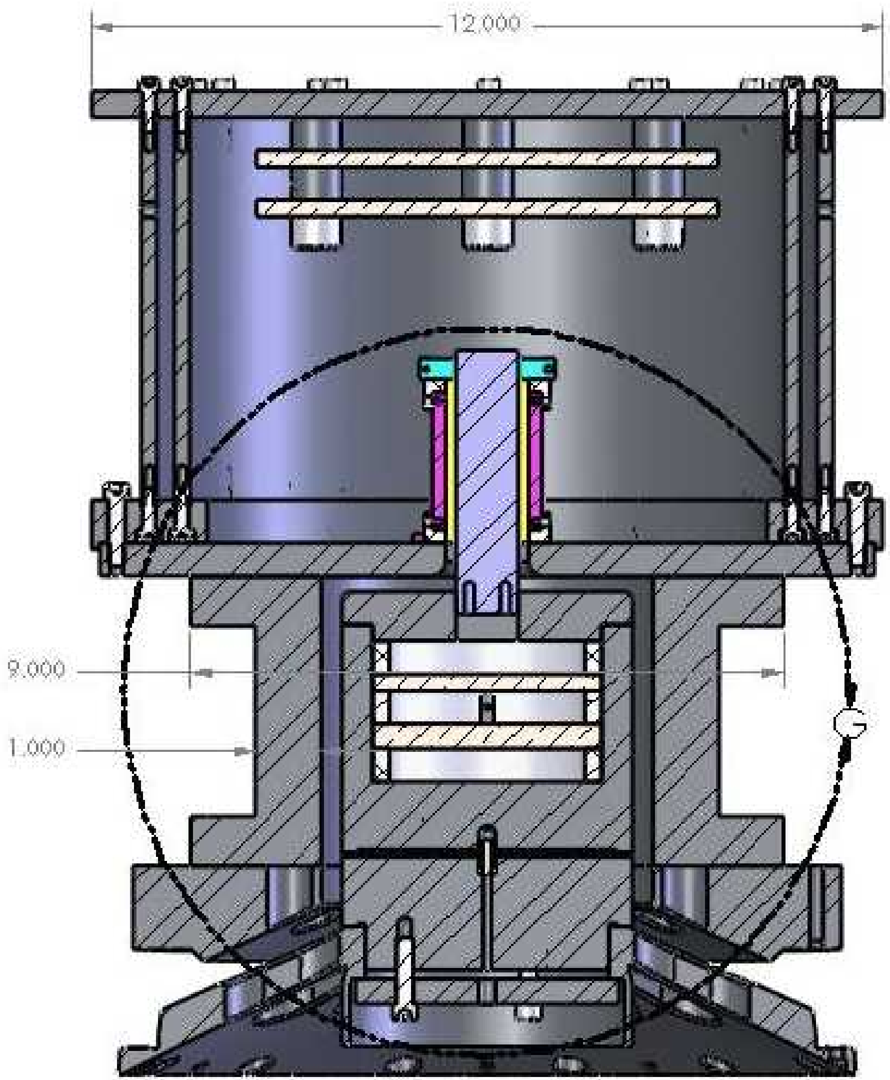
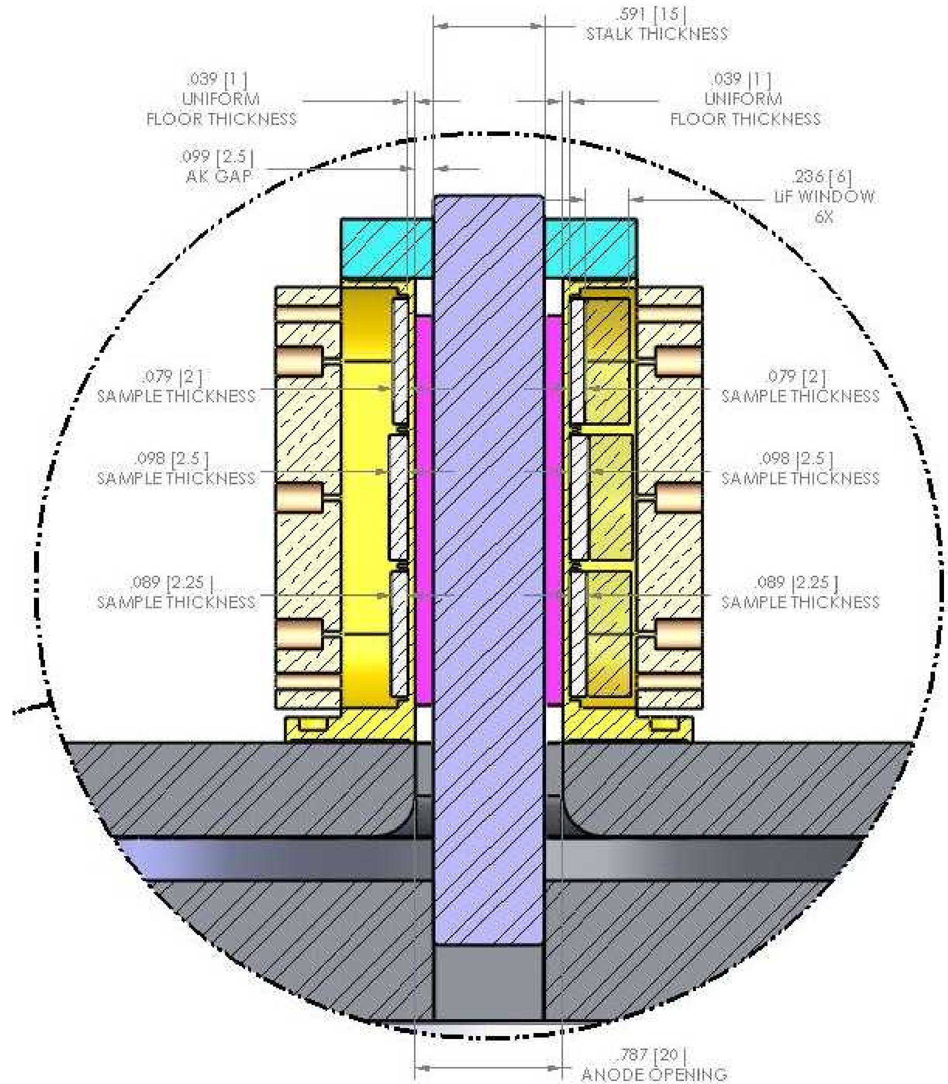
These same techniques will now be applied to Be samples provided by LANL





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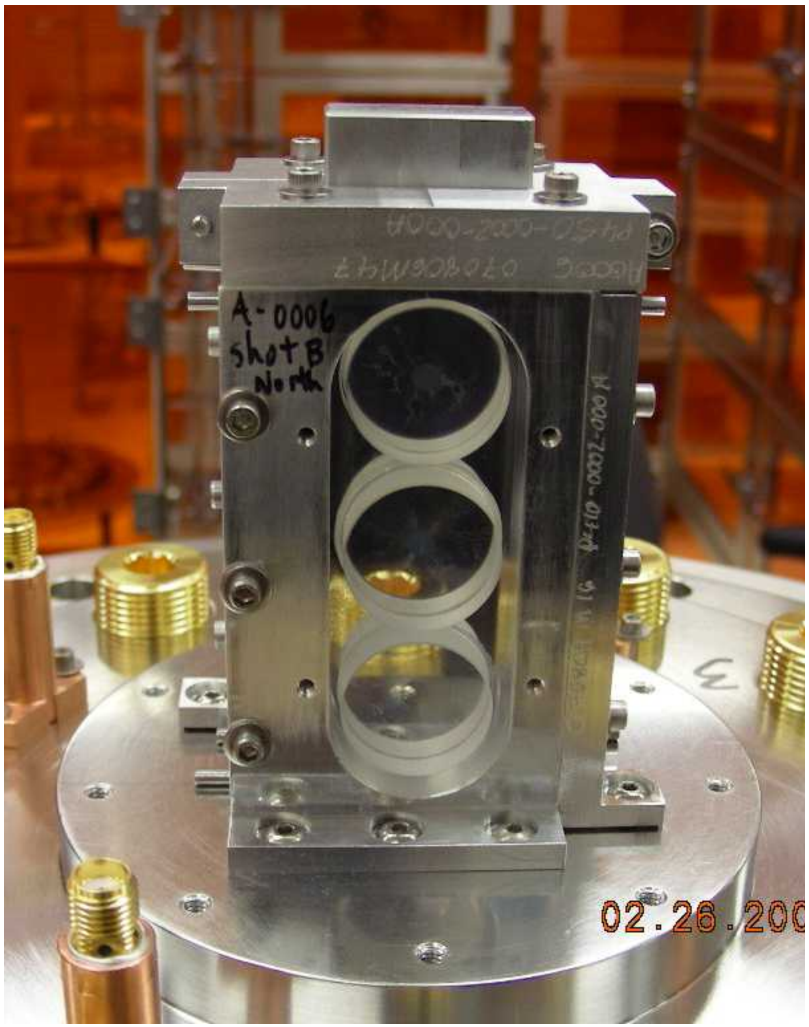
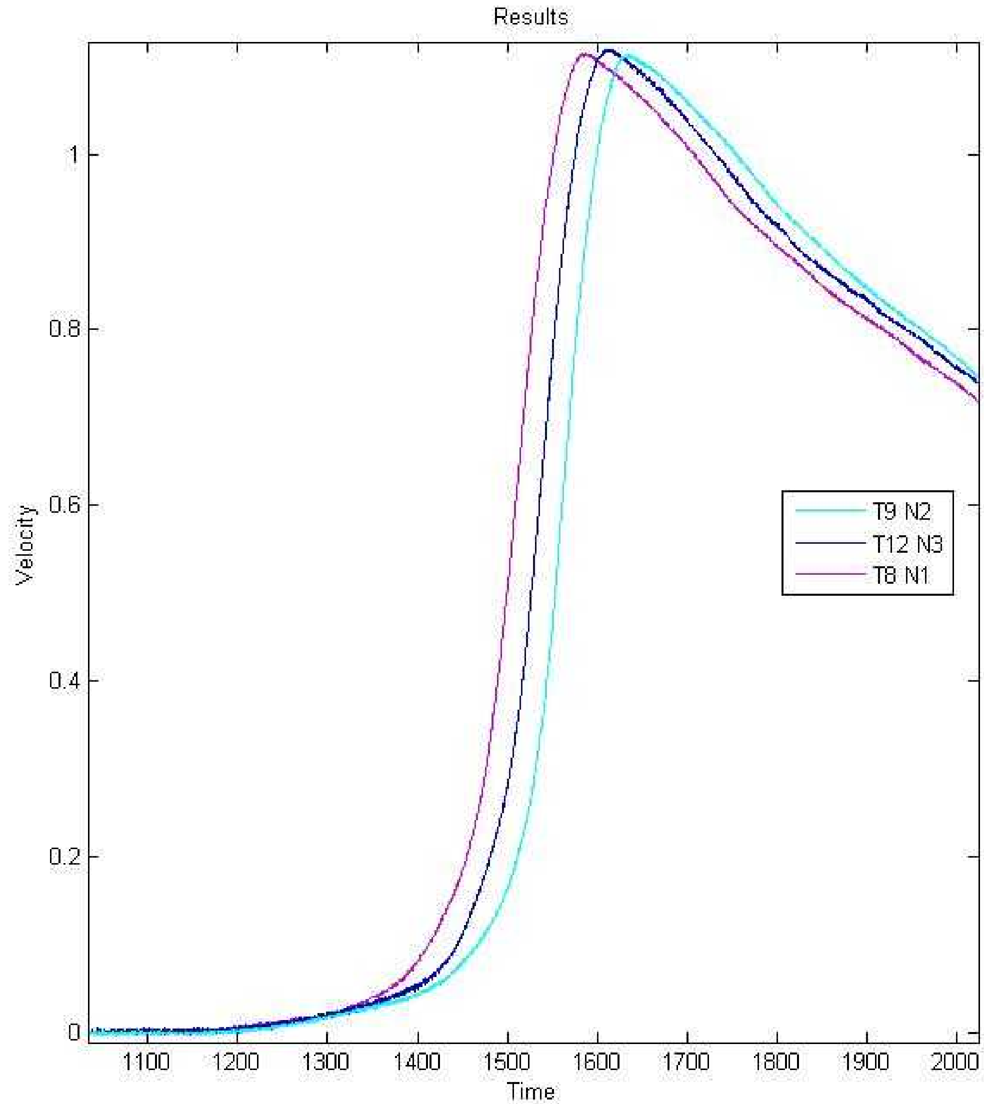
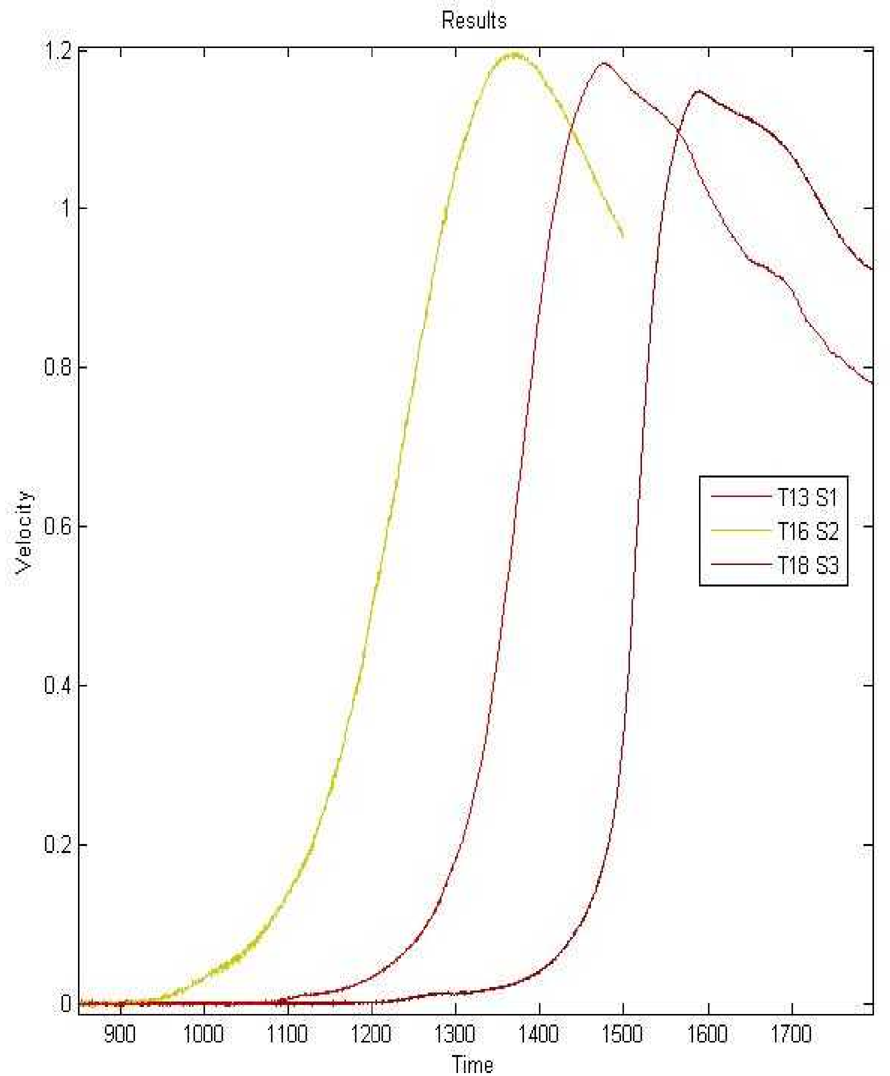
Preliminary results on Be have been recently obtained on Z

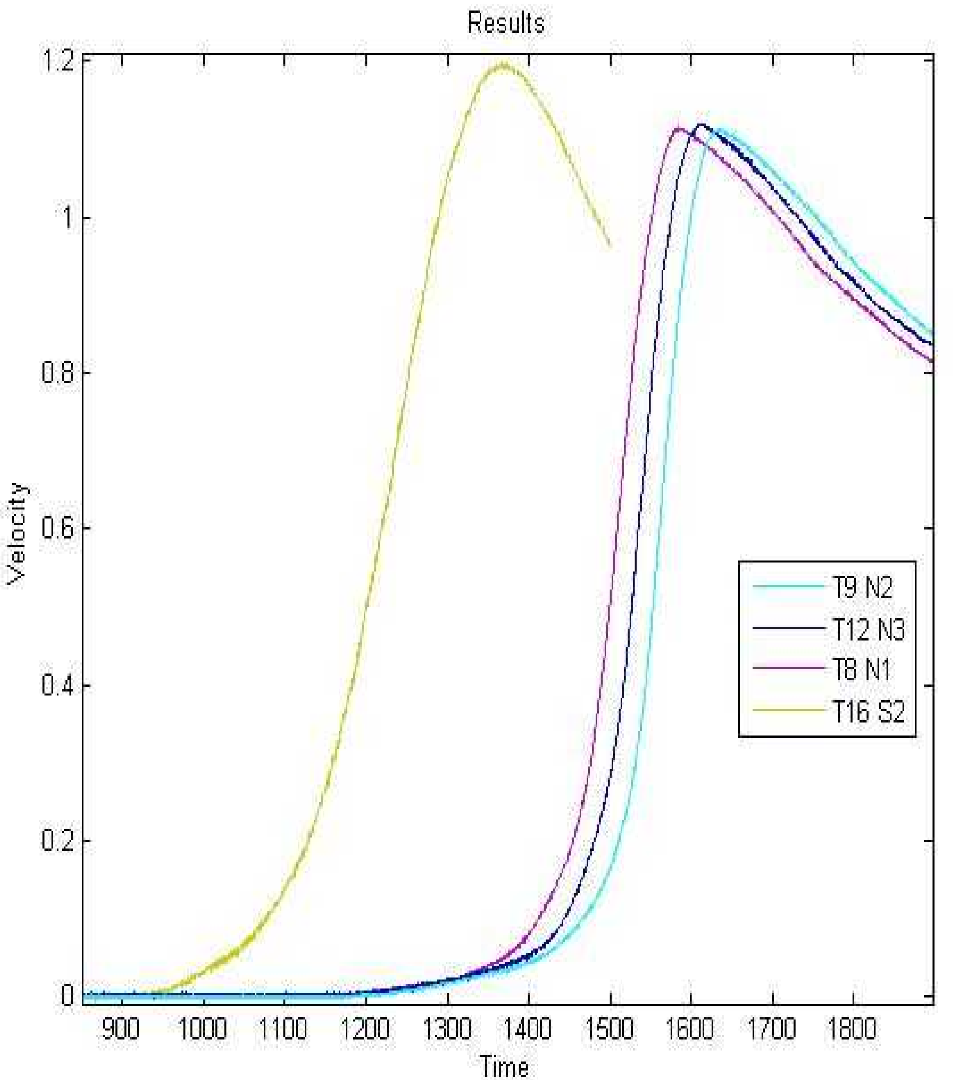
Coax strength load hardware





Preliminary results suggest the strength effect is not as clean as in a single crystal material





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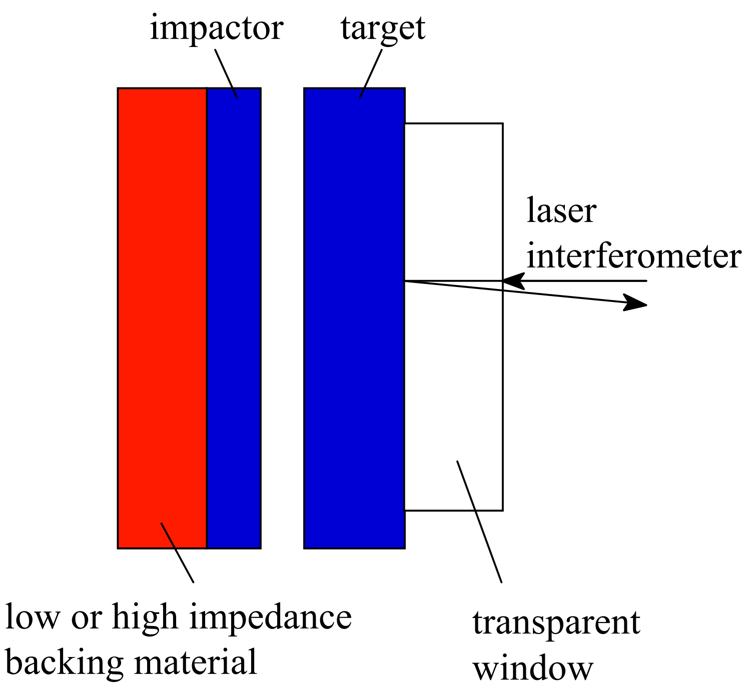
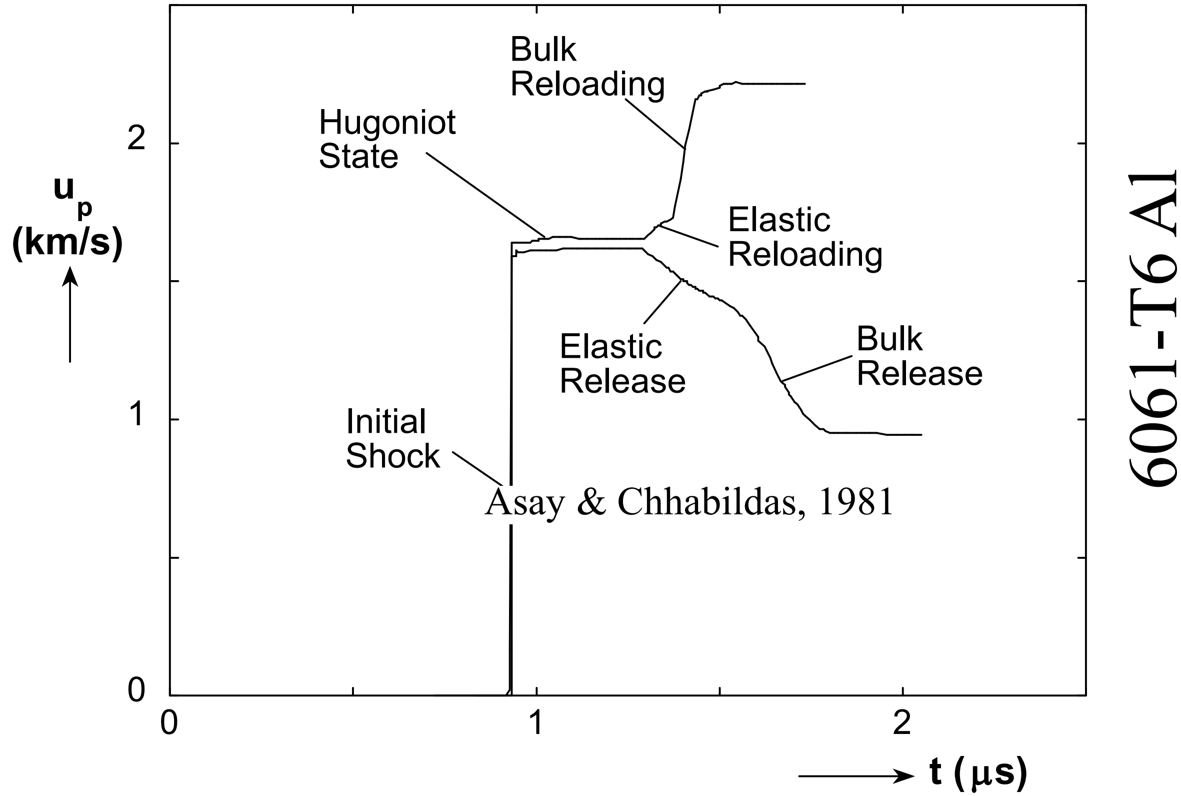
Outline

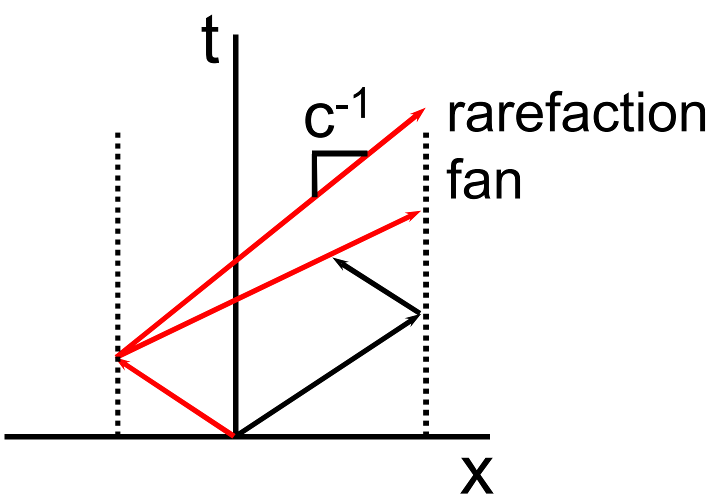
- Be strength results
  - Hugoniot experiments
  - Preliminary isentropic compression experiments

- Diamond strength results
  - Hugoniot experiments

Shock-release and shock-reshock data indicate that the material may not be on yield surface







- Wave speed determined from VISAR release or reloading profiles
- Elastic response on reloading indicates material not on current yield surface in shocked state
- τ_h for aluminum non-zero, approximately zero for tungsten

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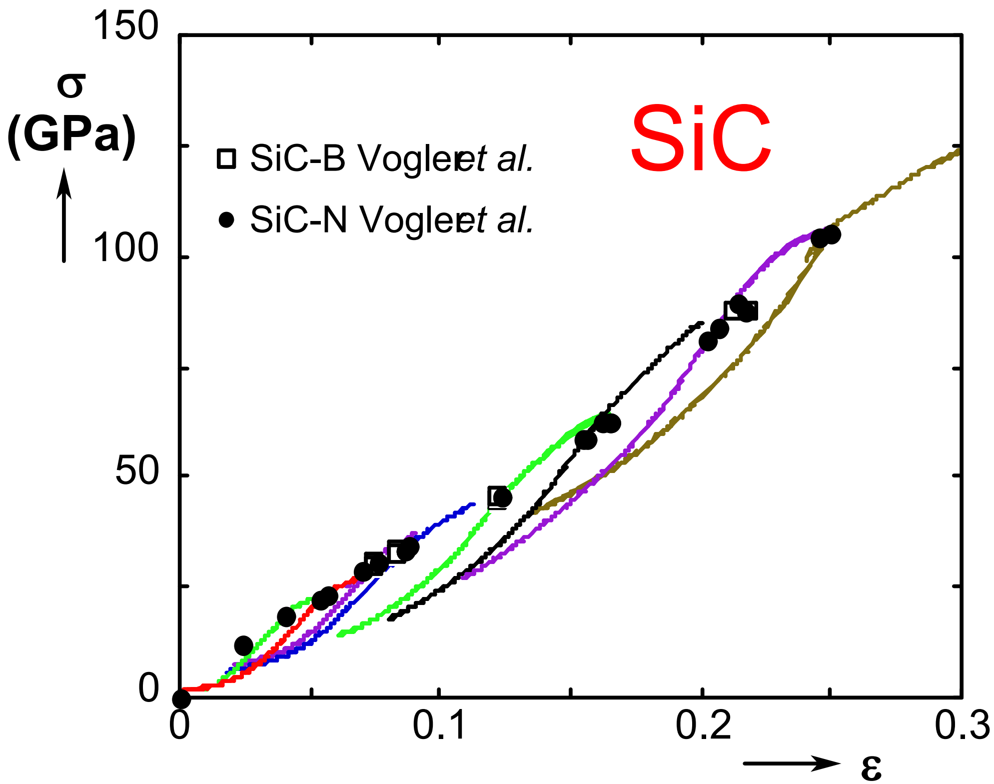
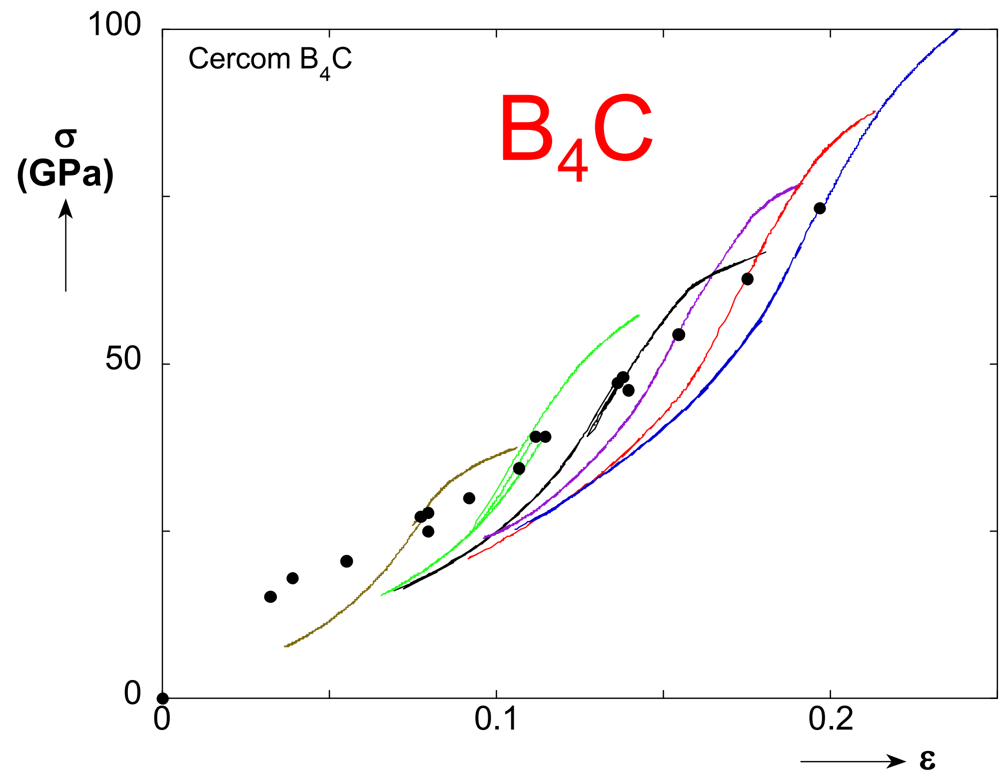
In some cases the deviation from the yield surface can be significant, suggesting negligible shear stress





- Release paths below Hugoniot
- Reshock paths slightly above Hugoniot
- Suggests slight relaxation of shear stress

- Release paths below Hugoniot
- Reshock paths significantly above Hugoniot
- Suggests significant relaxation of shear stress

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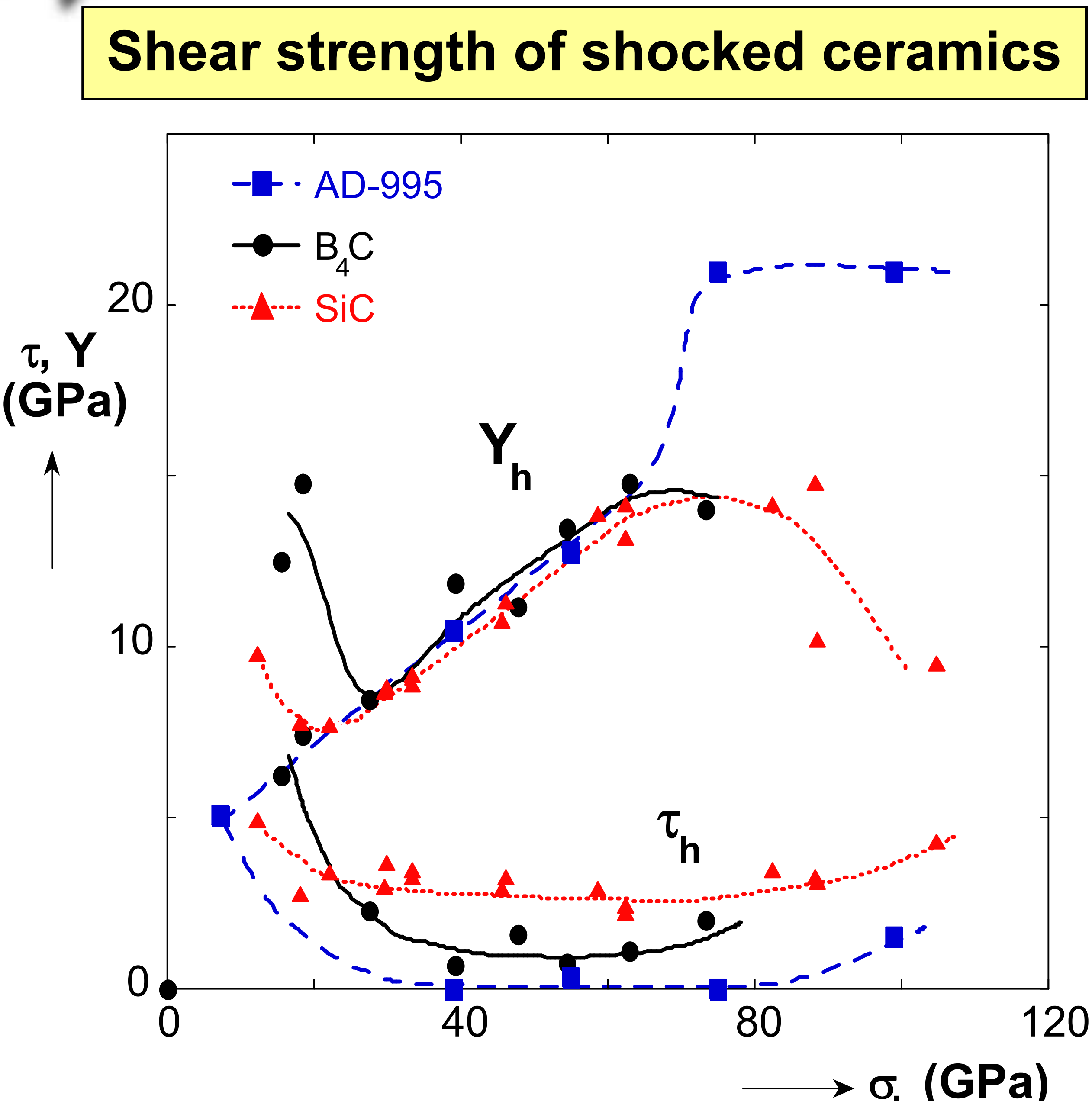
Strength results for some ceramics



- Ceramics have very high strength in the shocked state
- Same value of *Y* from 30-65 GPa
- Different values of τ_h seen
  - AD-995 in hydrostatic state
  - SiC most metal-like
- Damage mechanisms may play a role similar to that of thermal trapping or heterogeneous deformation in metals

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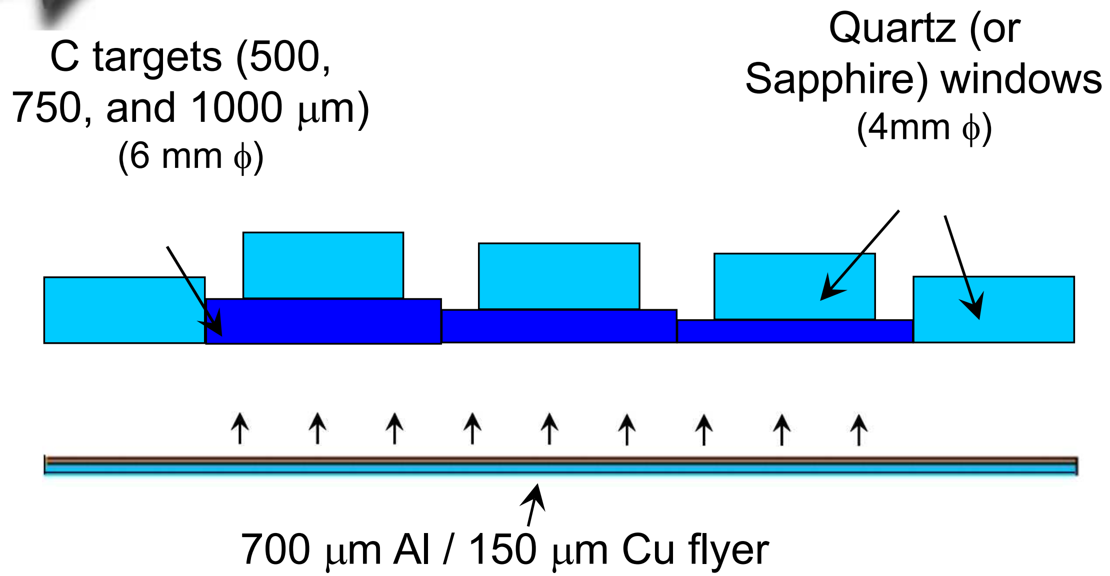
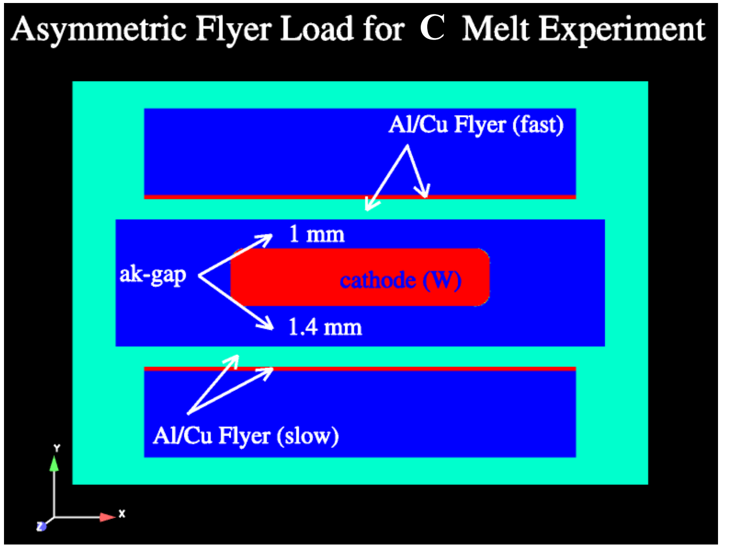
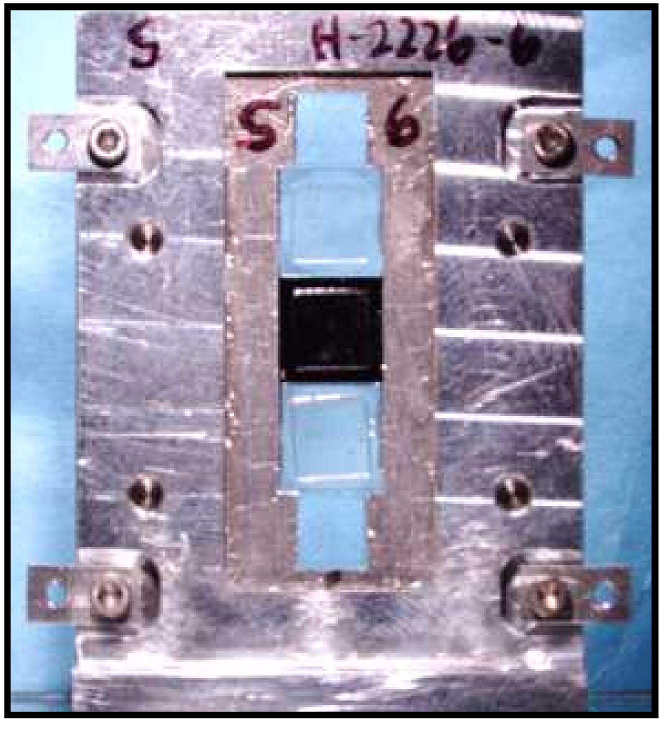
MHD simulations were critical in providing load geometries to achieve desired flyer velocities







- Experiments required an Al/Cu flyer with peak velocities in the range of 13-24 km/s
- Three asymmetric loads were designed to produce 2 flyers per shot with ~10% difference in peak velocity
- ALEGRA 2D MHD was used to set flight distances and to set charge voltages on Z

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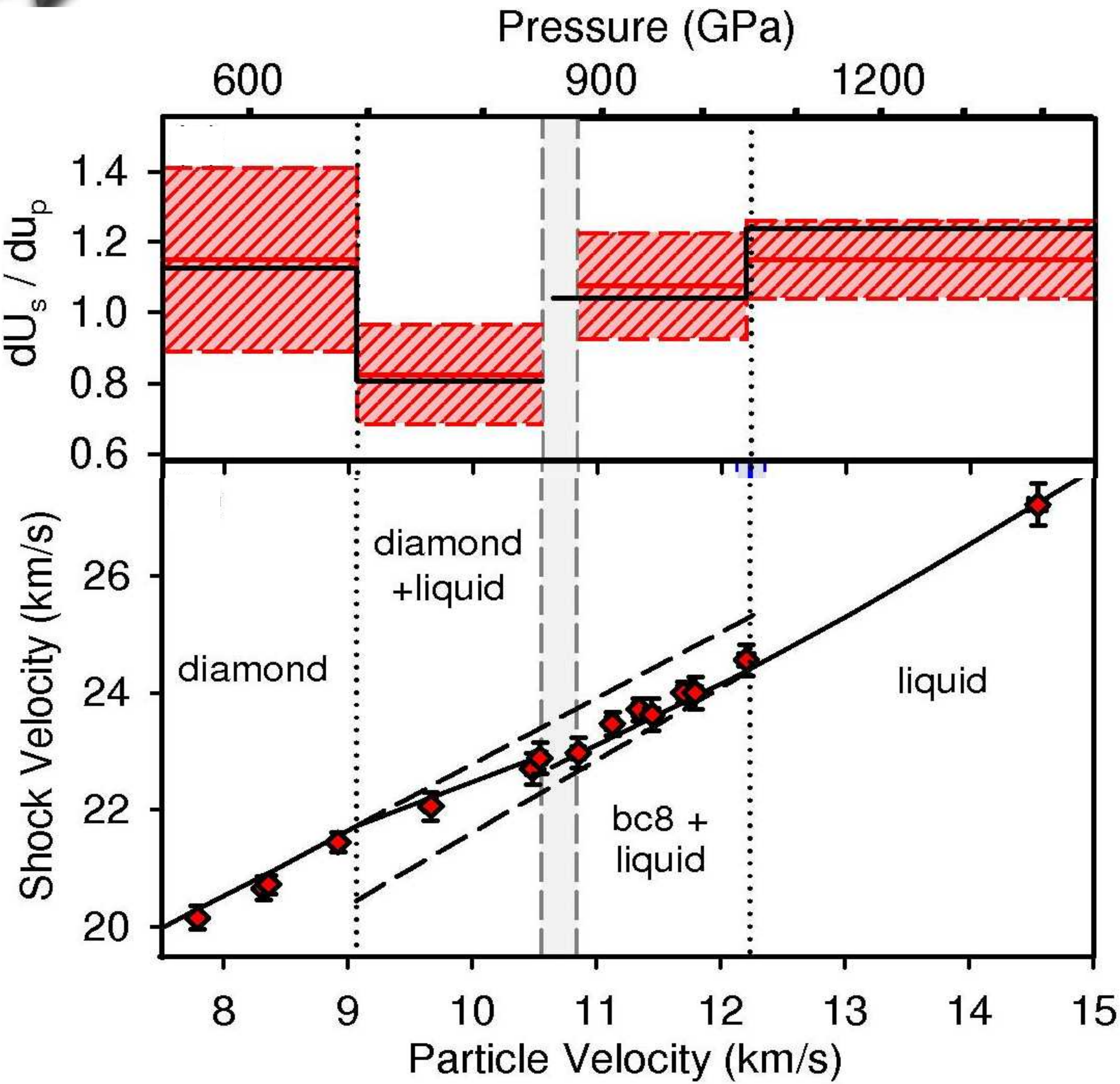
Z Hugoniot data provides evidence for a triple point in the diamond melt curve



- Piecewise weighted least squares linear fits to the Z data
- Breakpoints for linear segments determined through minimization of Chi-square in non-linear optimization
- Same trends in the magnitude of slope changes observed in experiment
- Experimental results consistent with QMD predictions regarding diamond-liquid-bc8 triple point

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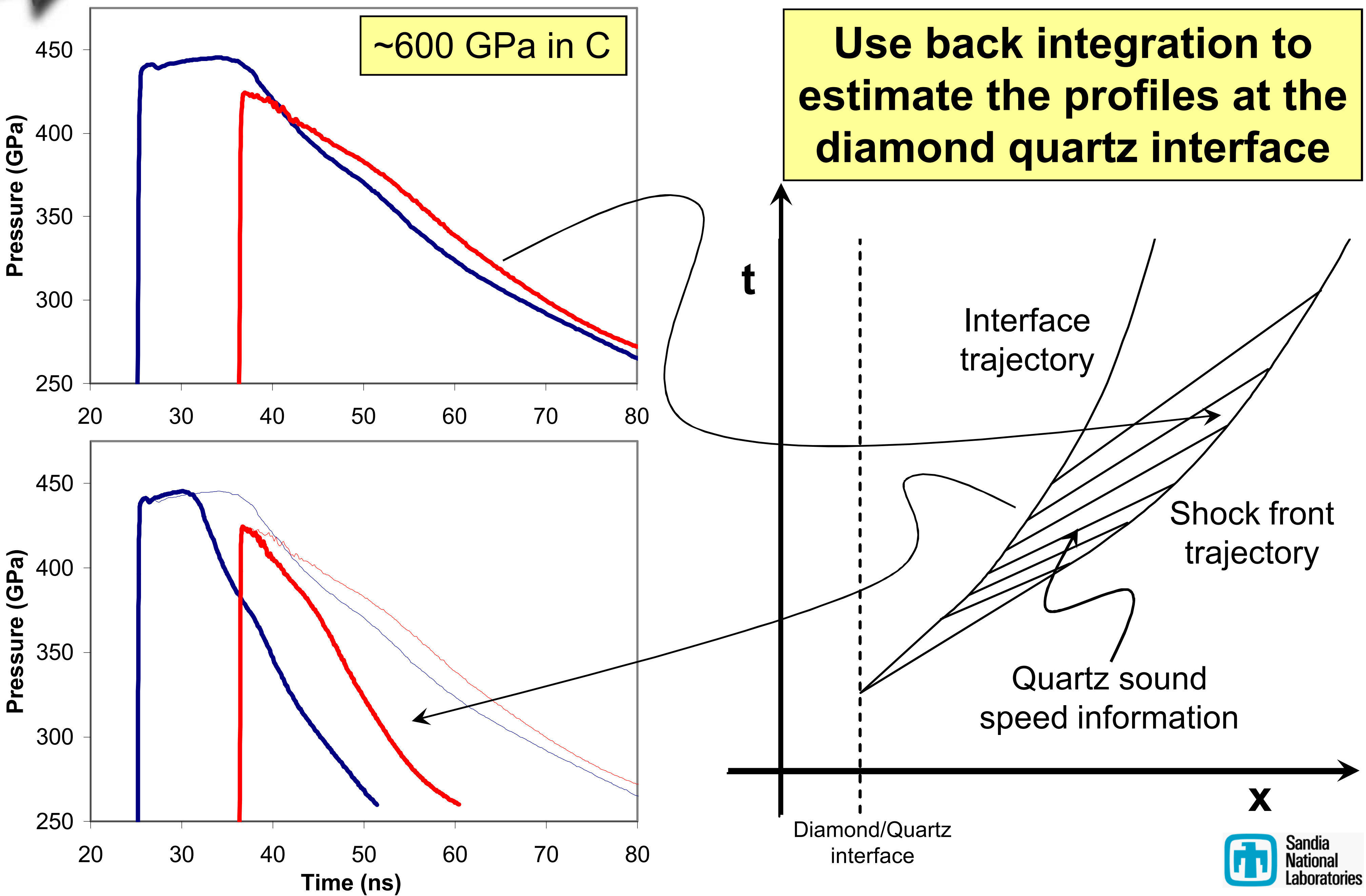
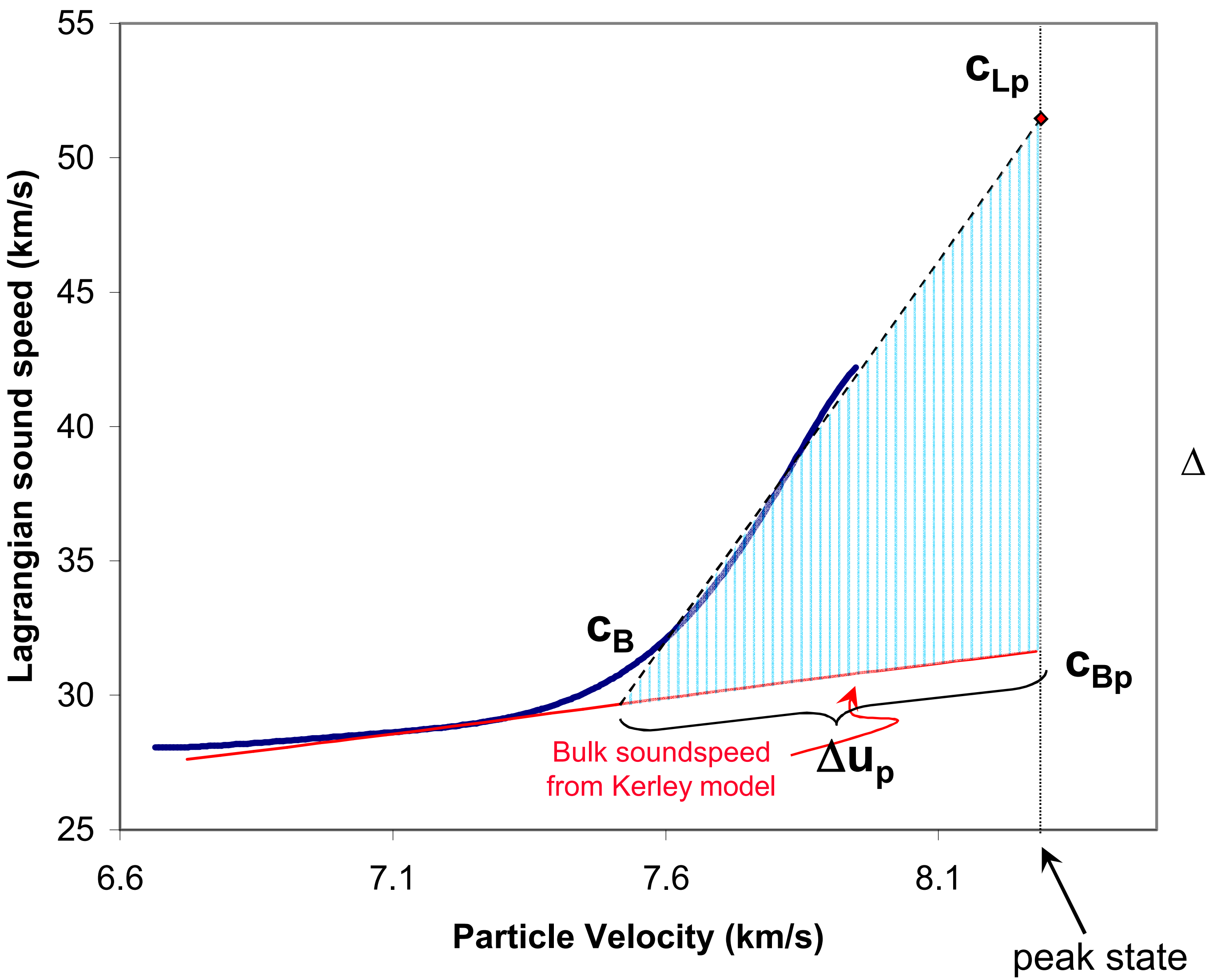
Multiple profiles allows for analysis of wave speeds and estimation of strength on the Hugoniot



Multiple profiles allow for analysis of wave speeds and estimation of strength on the Hugoniot

Estimated soundspeed for diamond



If we assume soundspeed is linear in strain then:

$$\Delta\tau = \frac{3}{4}\rho_0 \int \left(c^2 - c_B^2\right) d\varepsilon$$

leads to:

$$\Delta\tau = \frac{\rho_0}{2}\frac{\left(c_{Lp} - c_{Bp}\right)}{\left(c_{Lp} + c_B\right)}\left[c_{Lp} + c_{Bp} + c_B\right]\Delta u_p$$

which for this case gives:

$$\Delta\tau = 36 \text{ GPa}$$

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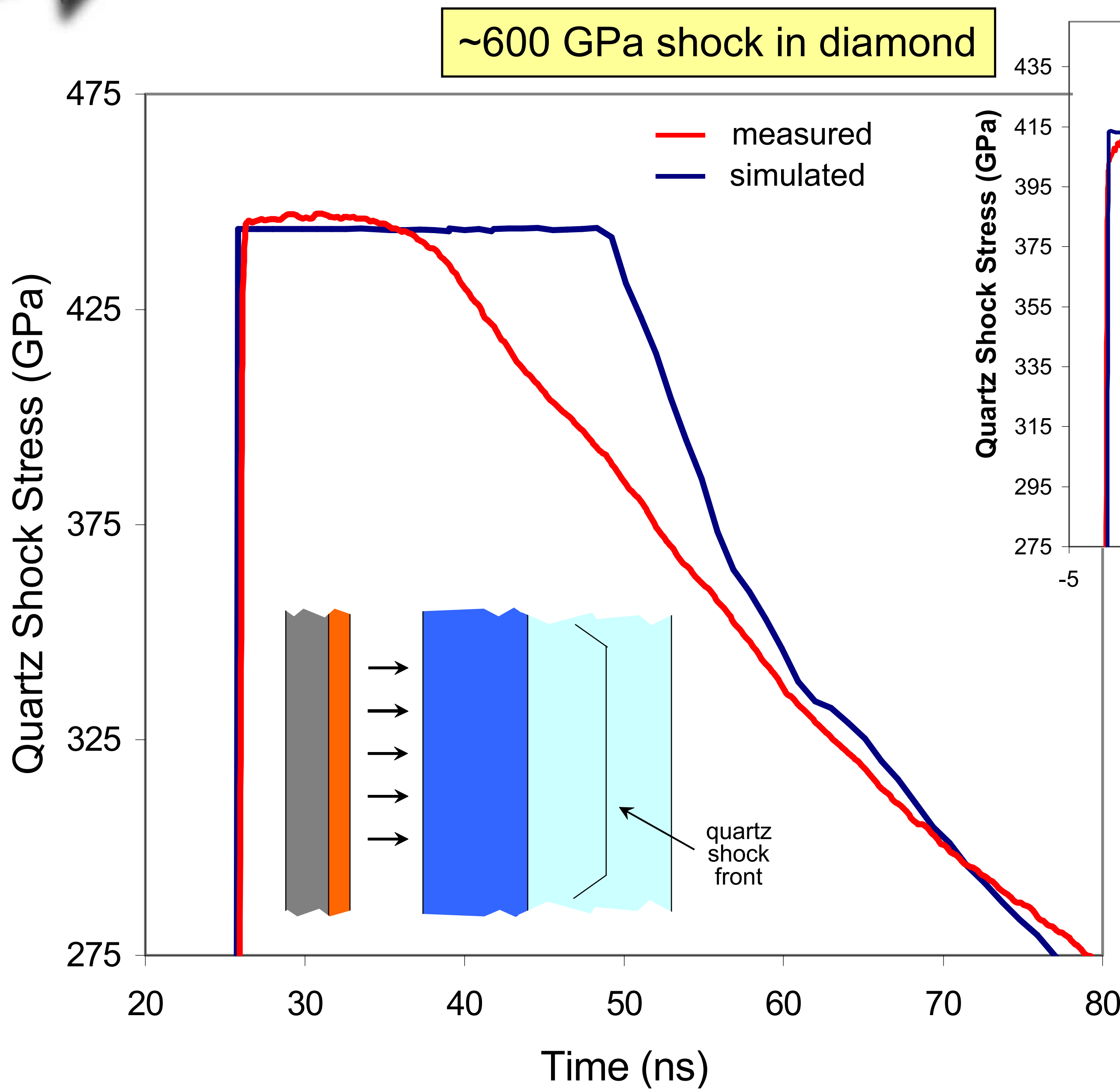
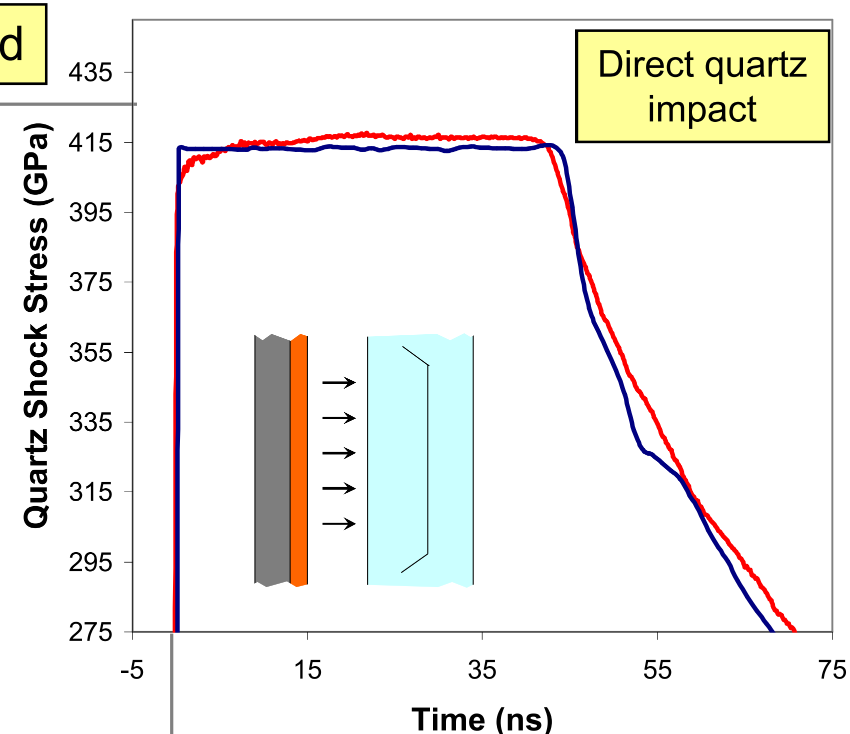
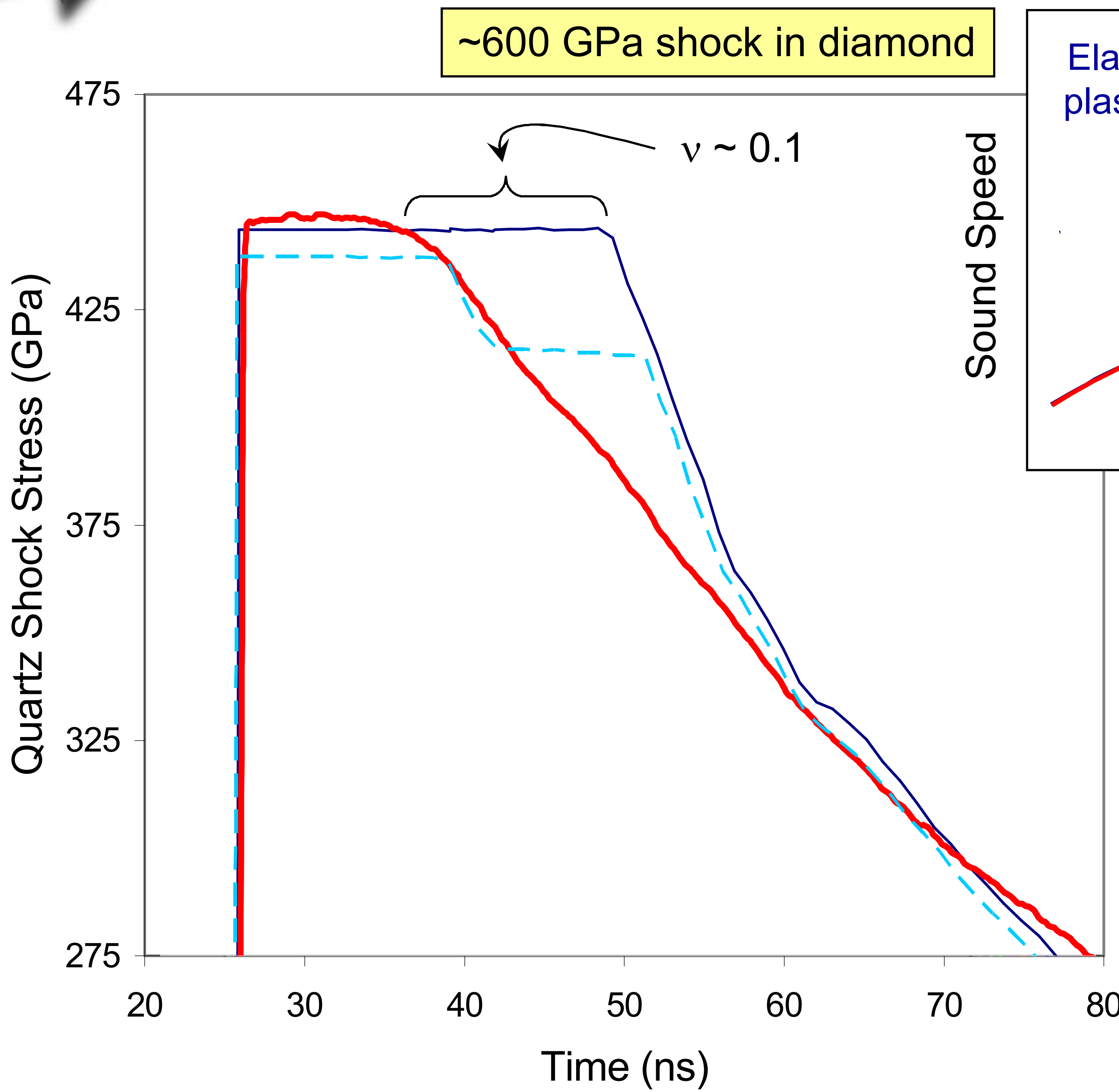
Release wave profiles corroborate significant yield strength in the Hugoniot state

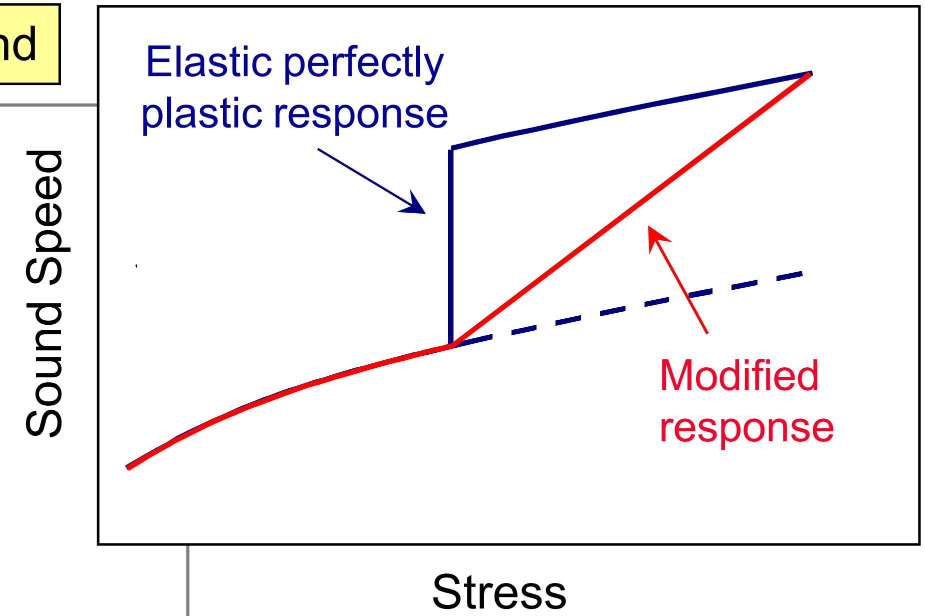




- Reasonable agreement for direct impact into quartz window
- Significant difference between measured and simulated profiles with inclusion of diamond

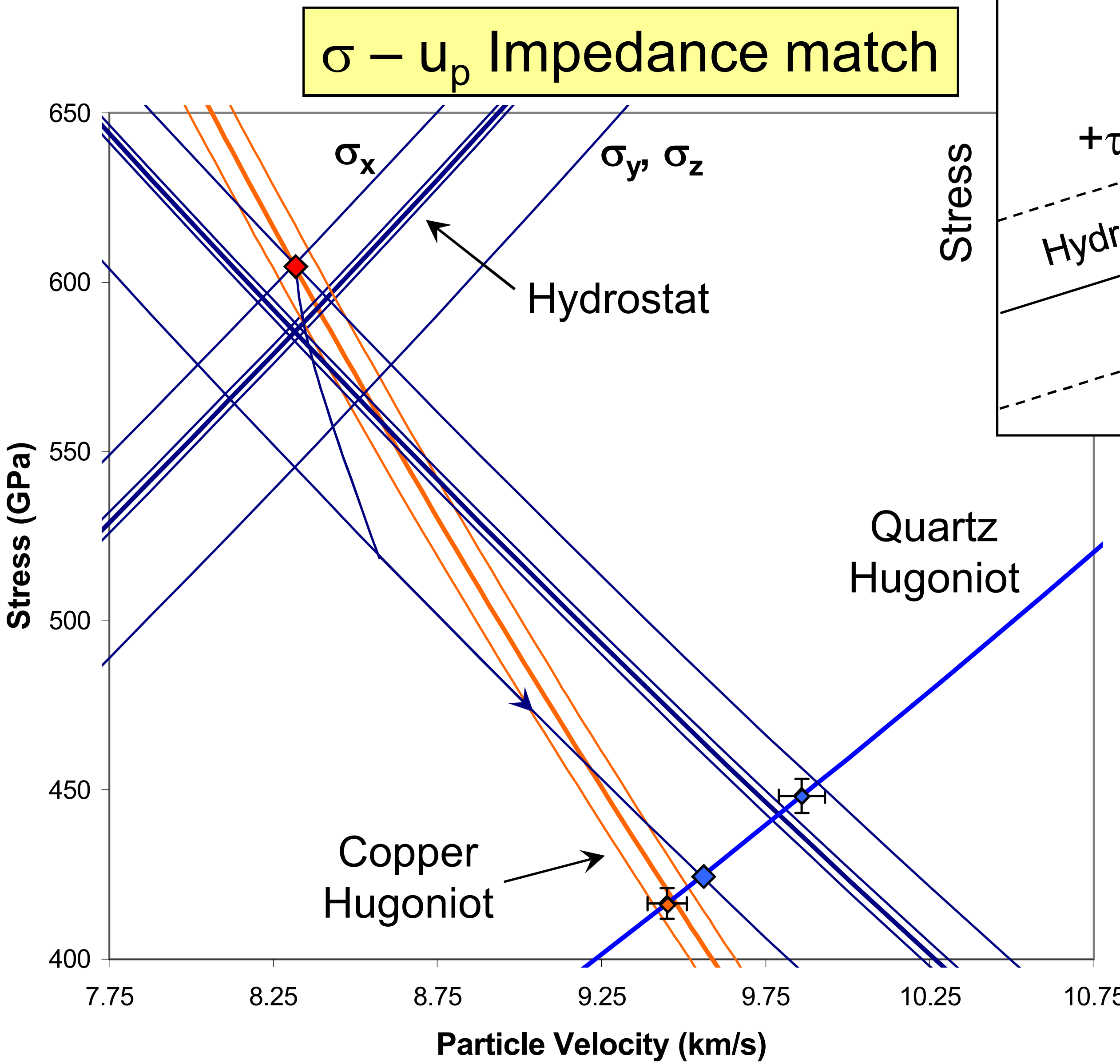
Preliminary inference of Δ shear stress suggest values in the range of ~25-40 GPa

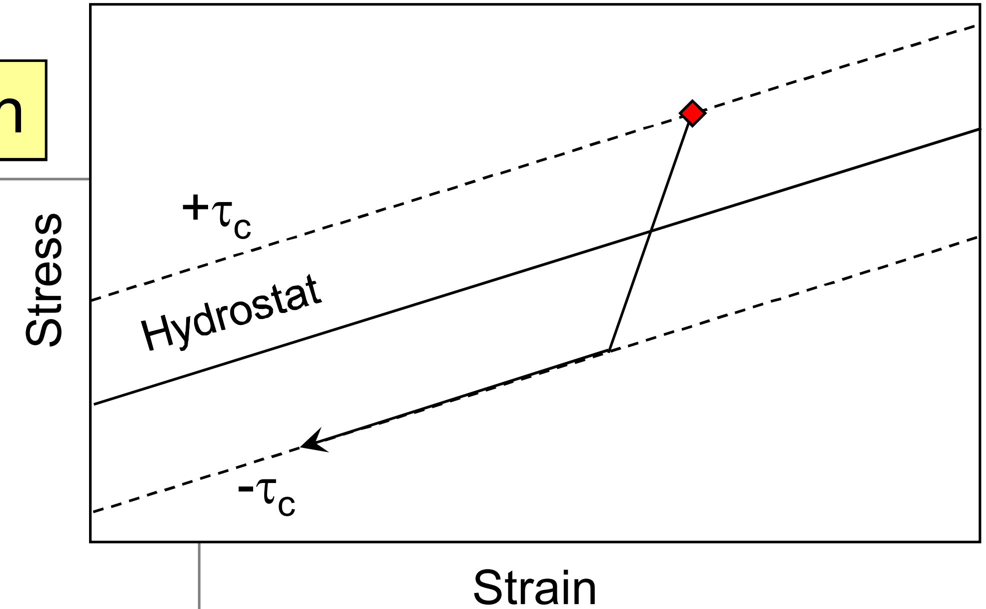




- Hydrocode simulations provide insight into the yield strength
- Poisson's ratio is quite low, of order $\nu = 0.1$
- Reasonable agreement with measured profiles suggests $\Delta\tau \sim 25\text{-}40$ GPa

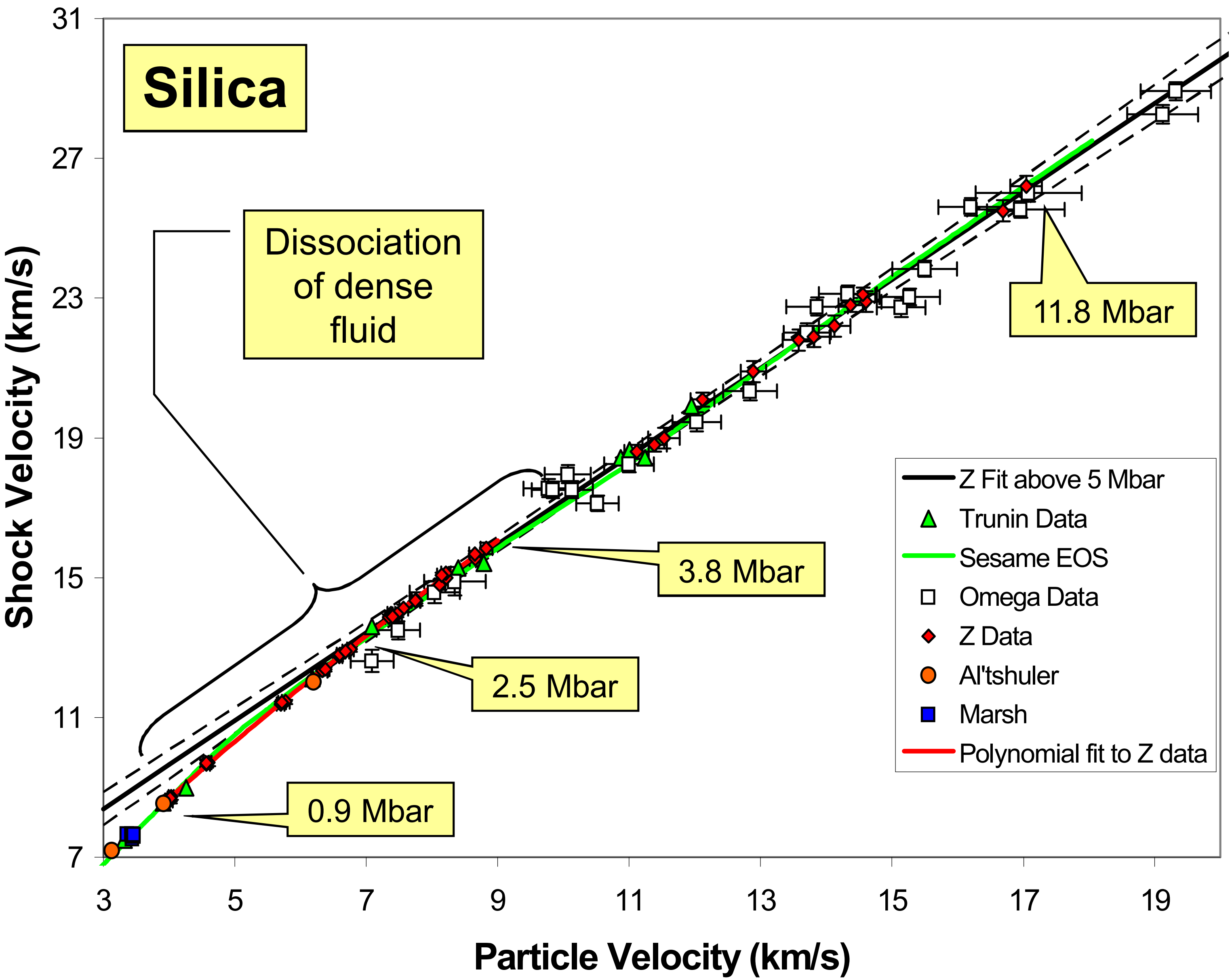
Impedance matching at window suggests negligible shear stress in the Hugoniot state





- Difference in impedance match state in Quartz is statistically significant, ~2.7% in U_s
- Uncertainty in the measured Quartz shock velocity is <1%
- Incompatible with the release data

Very precise Hugoniot data for silica have been obtained on the Z accelerator



High pressure response of Silica is of fundamental importance to geophysics

Quartz is becoming the standard of choice for high pressure laser Hugoniot measurements

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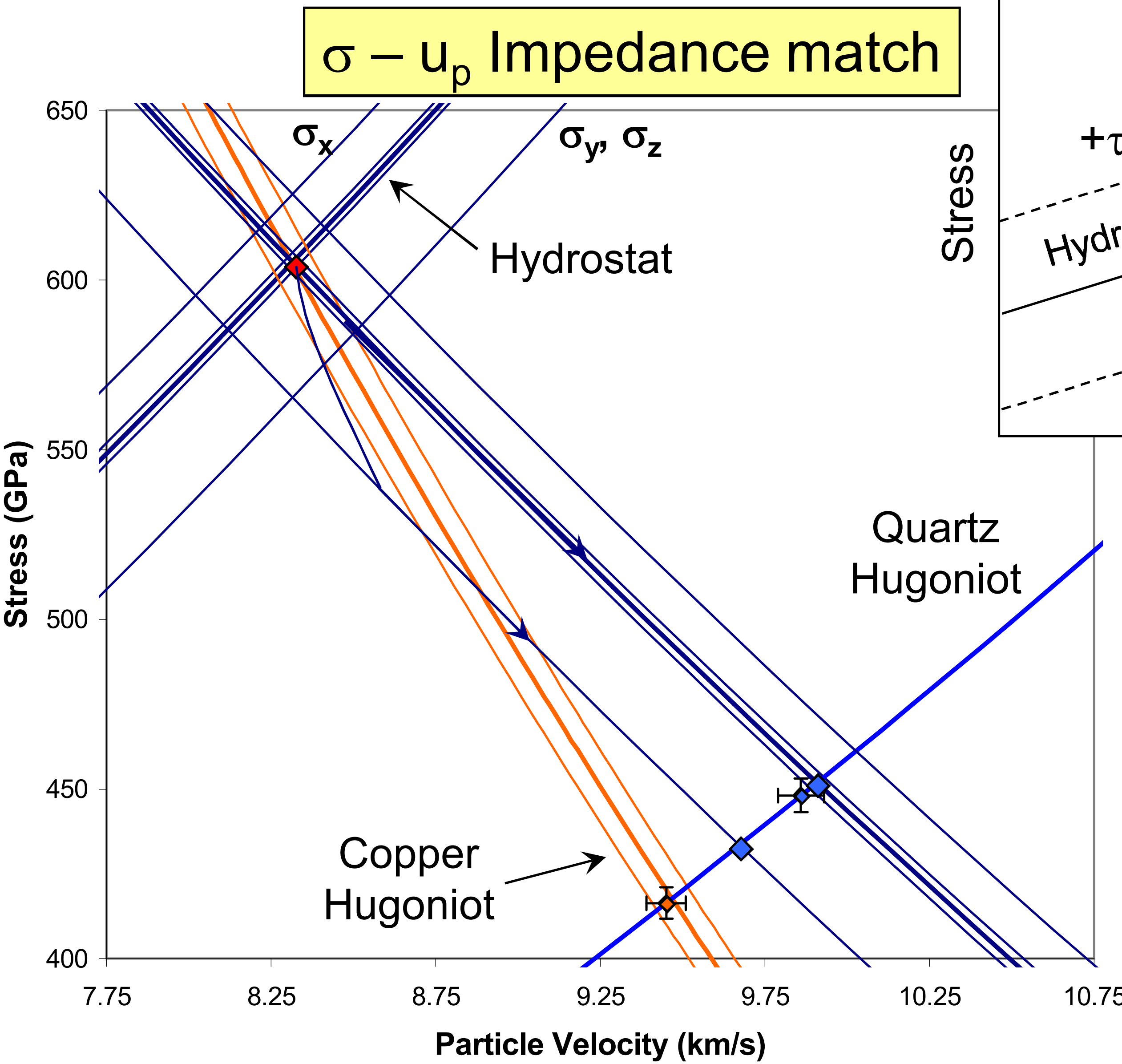
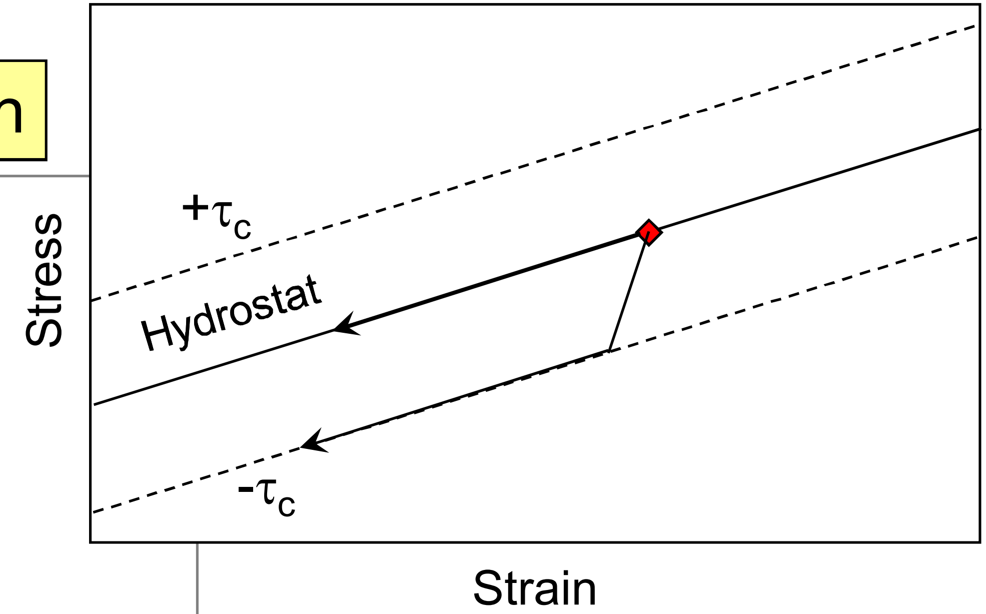
Impedance matching at window suggests negligible shear stress in the Hugoniot state





- Better agreement between impedance match and experimental measurement
- Strong case for negligible shear stress in Hugoniot state
- Difference in impedance match state in Quartz may be statistically significant, ~1.7% in U_s

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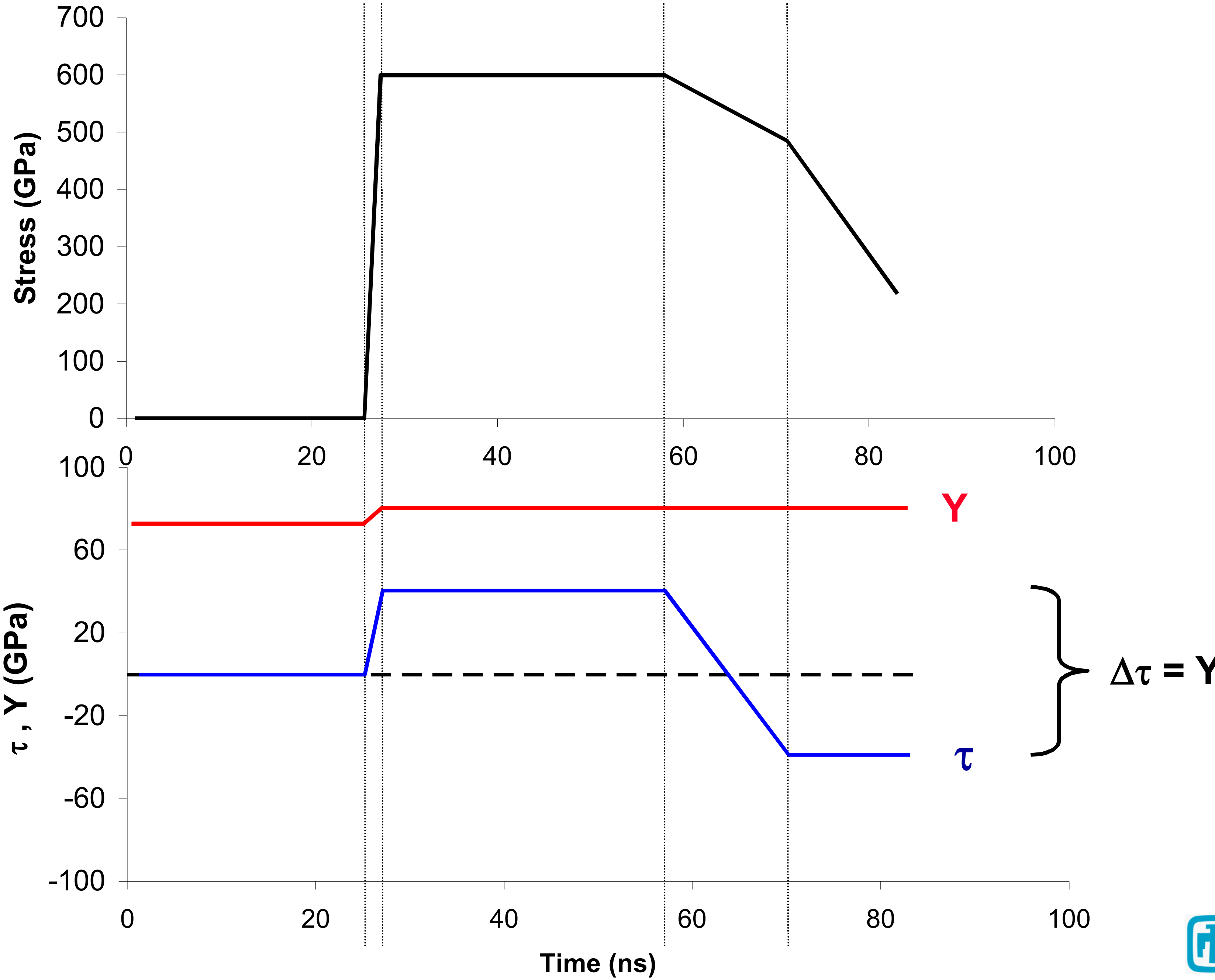
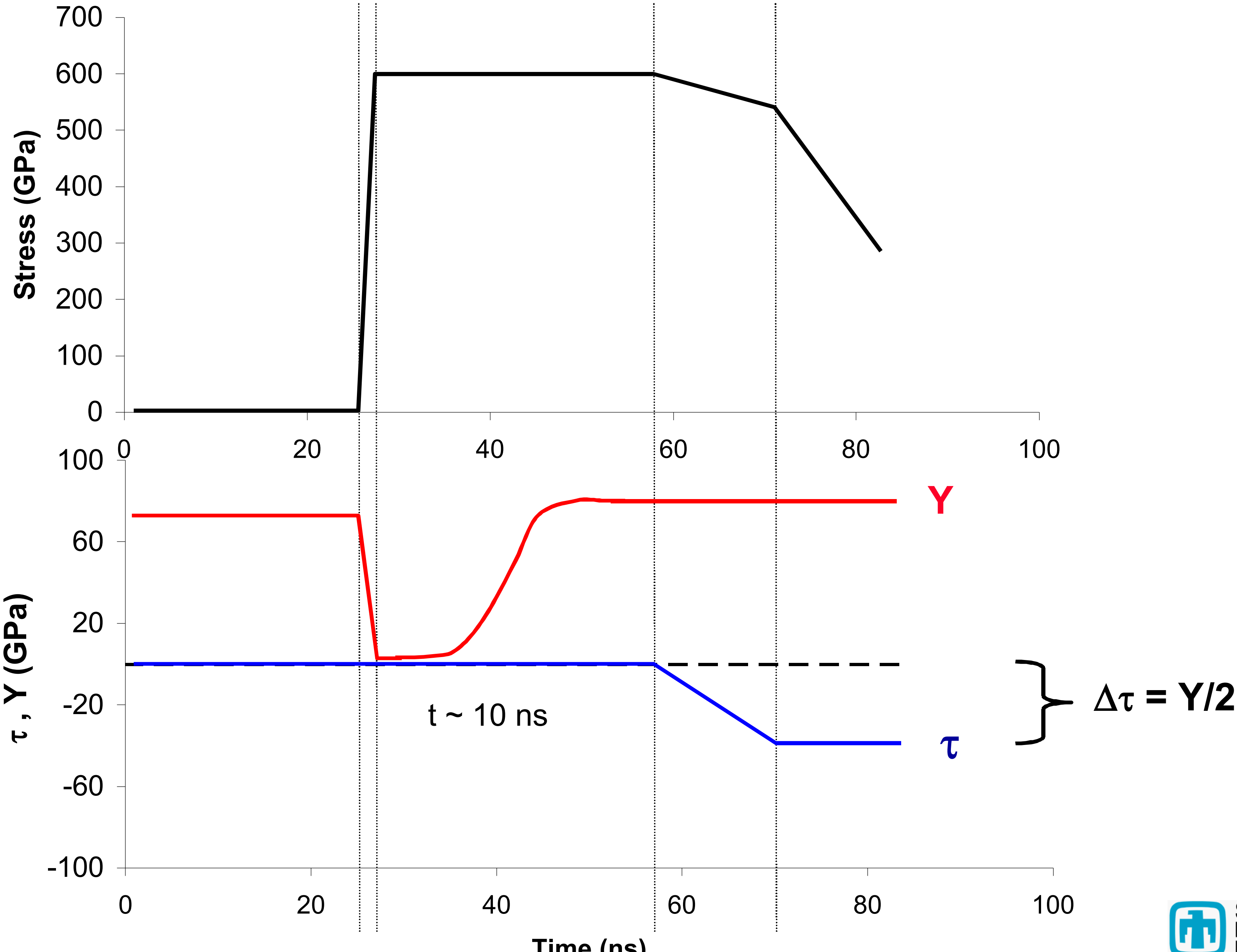
These results suggest that the simplistic picture of strength is grossly inadequate



A picture for diamond consistent with present measurements has strength recovering



Summary

Beryllium Conclusions

- Be melts on the Hugoniot at ~210 GPa
- Be coexistence ~50 GPa
- Be melts directly from hcp (not bcc)
  - Caused us to revisit the phase diagram
- Be exhibits significant yield strength near melt, ~3.5 GPa

Diamond Conclusions

- Extremely precise Hugoniot measurements obtained for diamond at multi-Mbar pressures
- Diamond melts on the Hugoniot at ~700 GPa
- Diamond coexistence is large, ~350-400 GPa
- There appears to be a diamond-liquid-bc8 triple point along the coexistence curve at ~880 GPa
- Diamond exhibits an extremely large yield strength near melt, ~50-80 GPa
  - It appears there is negligible shear stress in the shocked state
- Nano- and Micro-crystalline samples appear to behave similarly