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Use of the DICE pulser for High-Pressure Strength Measurements

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Goals

- **Develop technique on the DICE pulser for accurate measurement of compressive strength in aluminum under ramp loading**
  - **Extend previous work developed for ICE on Z**
  - **Apply to several metals and optical materials**

- **Approach**
  - **Demonstrate accurate quasi-isentropic loading data**
  - **Extend to unloading measurements for compressive strength data**

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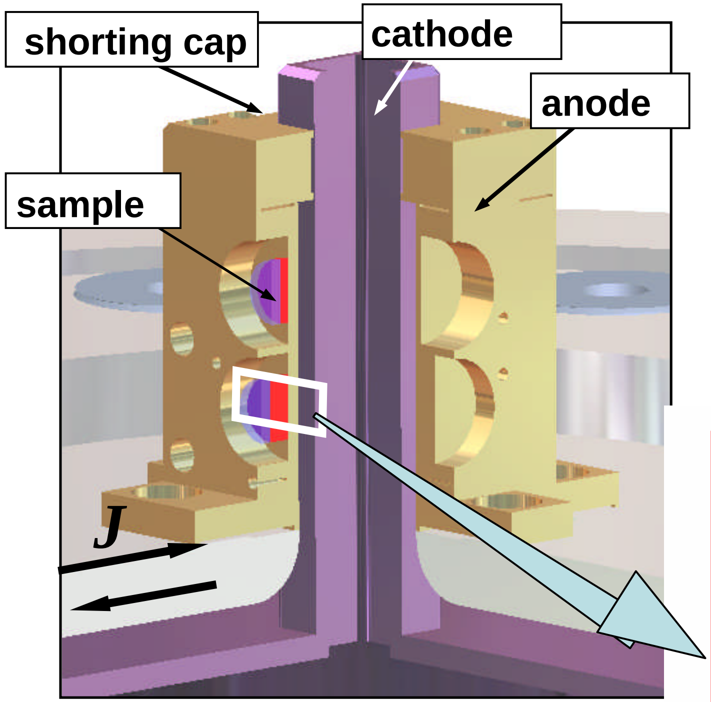
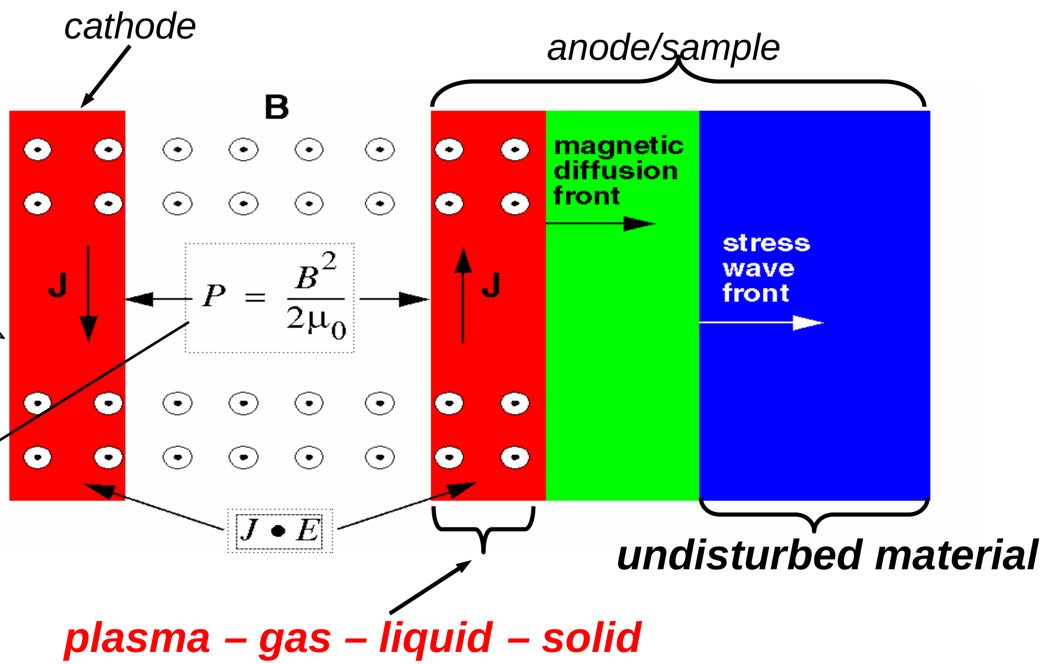
Outline

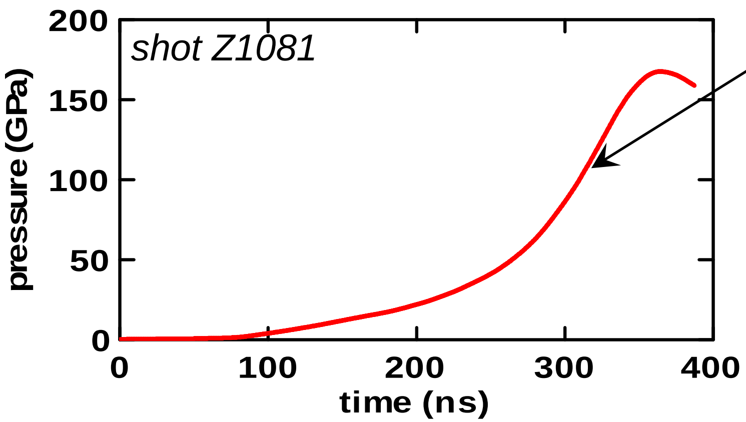
- Background
- Loading technique
- Results
- Work in progress

Magnetic drive developed on Z for producing smooth ramp waves to high pressure



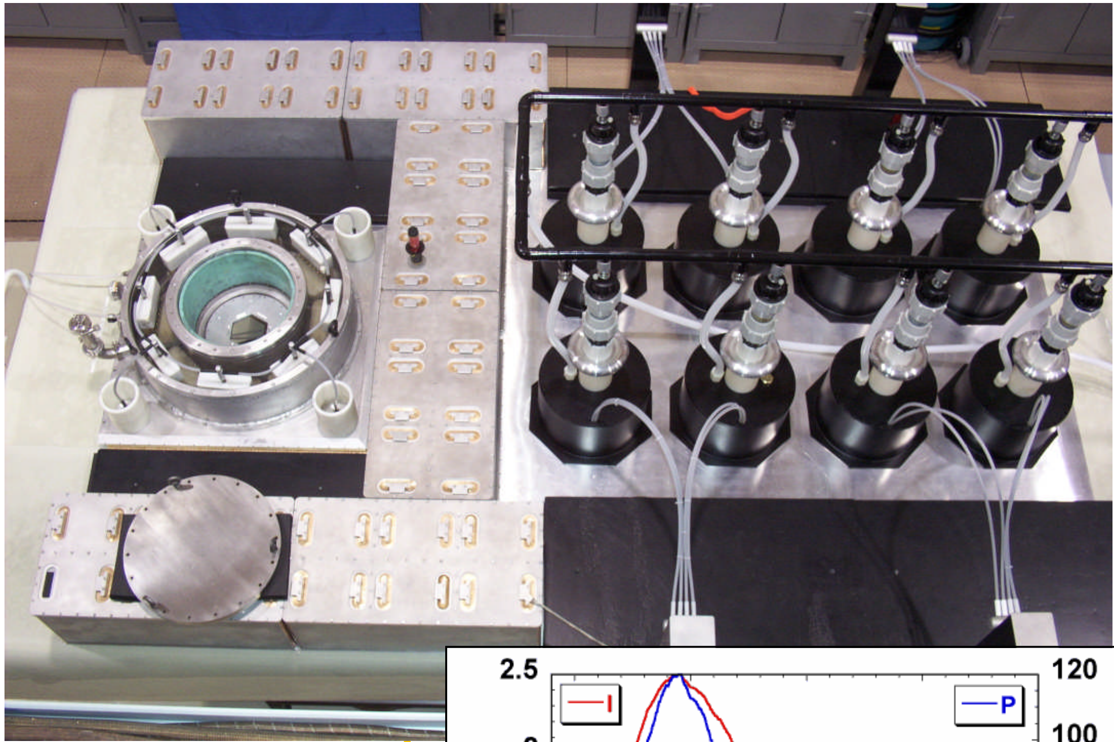
- Electric current induces magnetic field
- $J \times B$ magnetic force transferred to electrode

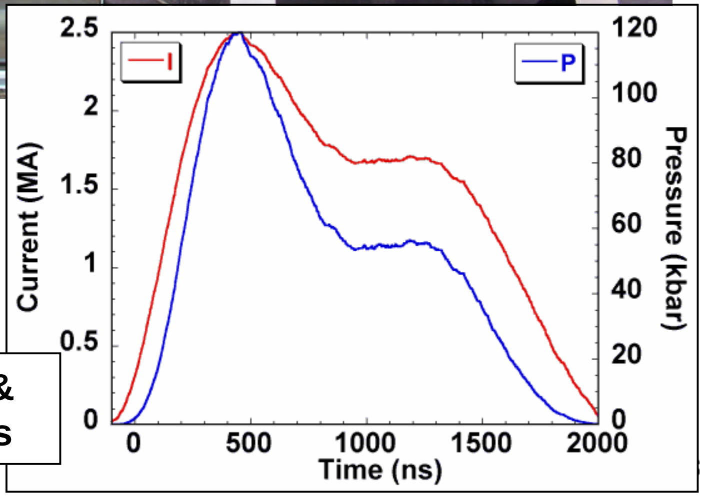




The DICE pulser produces smaller currents over longer times

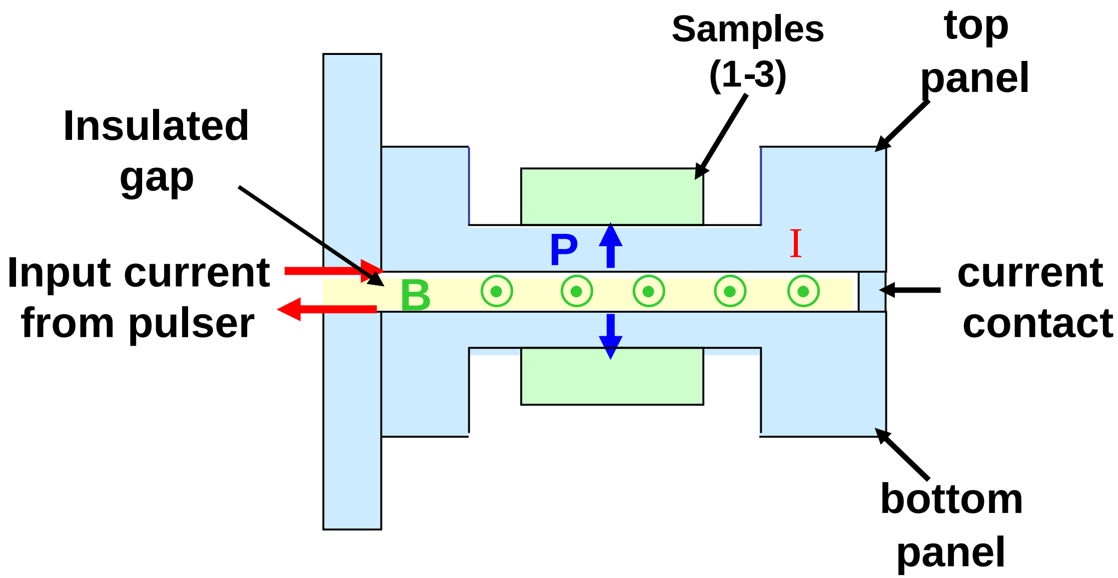
- **Peak current, 3.5 MA;**
  400 - 500 ns risetime;
  peak pressure ~ 200 kbar
- **High-current pulser**
  (~2 shots per day)
- **Energy storage, eight 4-μF capacitors, 80 kV max**
- **Large sample dimensions, ~ 2-3 x 12-18 mm dia.**





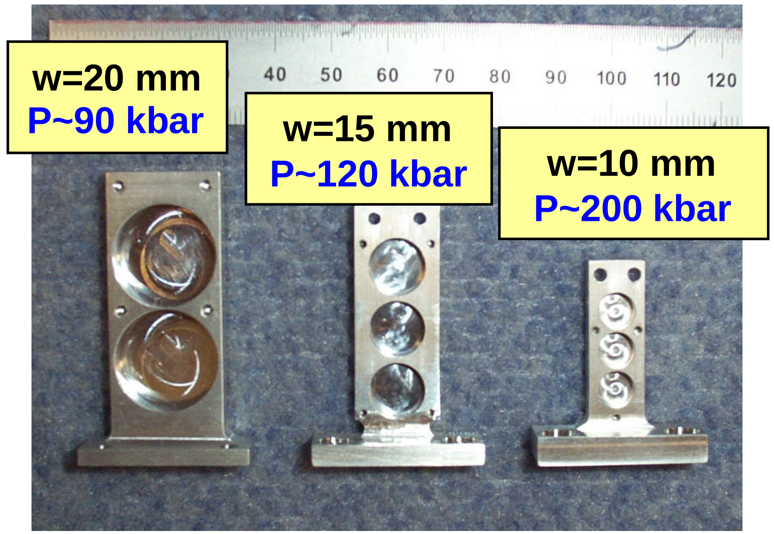
Typical current & pressure profiles

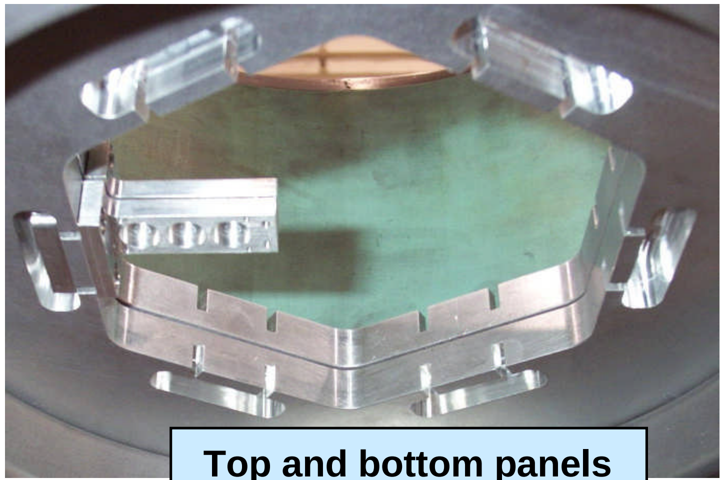
Typical sample test configuration



$$P_{mag} = k_P \frac{B^2}{2\mu_0} = k_P \frac{\mu_0}{2}\left(\frac{I}{w}\right)^2$$

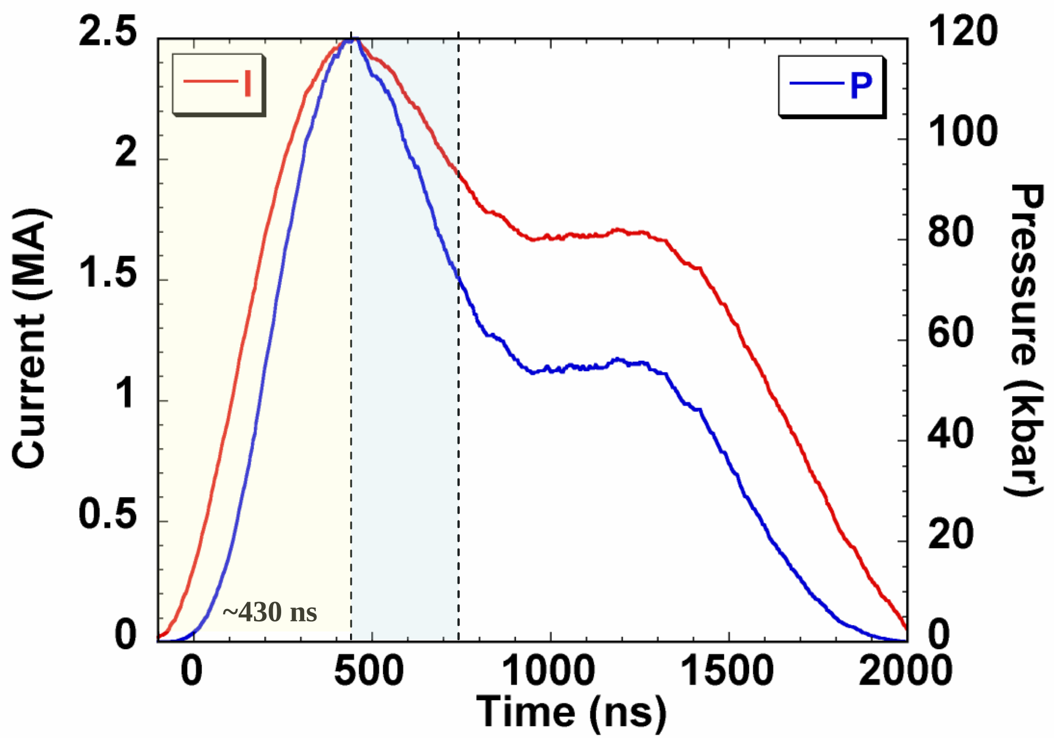
k_p – geometry-dependent scale factor





Top and bottom panels in load chamber

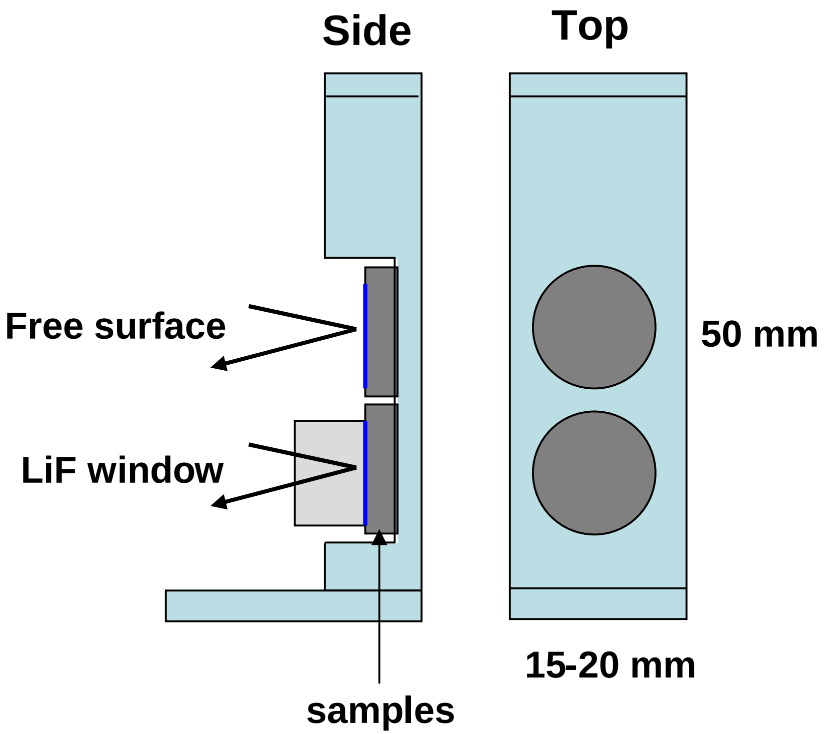
Long pulses on DICE constrain experimental configurations



<u>Design Issues</u>

- **Bottom-top wave interactions**
- **Wave/diffusion front interactions**
- **2-D side rarefactions**
- **Non-constant peak pressure**
- **Drive pressure uniformity**
- **Interface bonds**

A drive configuration is being used that satisfies these requirements on Al experiments



- Panels, 2 x 15 – 20 x 50 mm
- Panel thickness, 2 mm
- σ_{peak} ~ 60-100 kbar
- Drive uniformity ~ 2% central portion
- 200-300 ns of unloading
- Free surface + windows
- Analysis of opposing pairs

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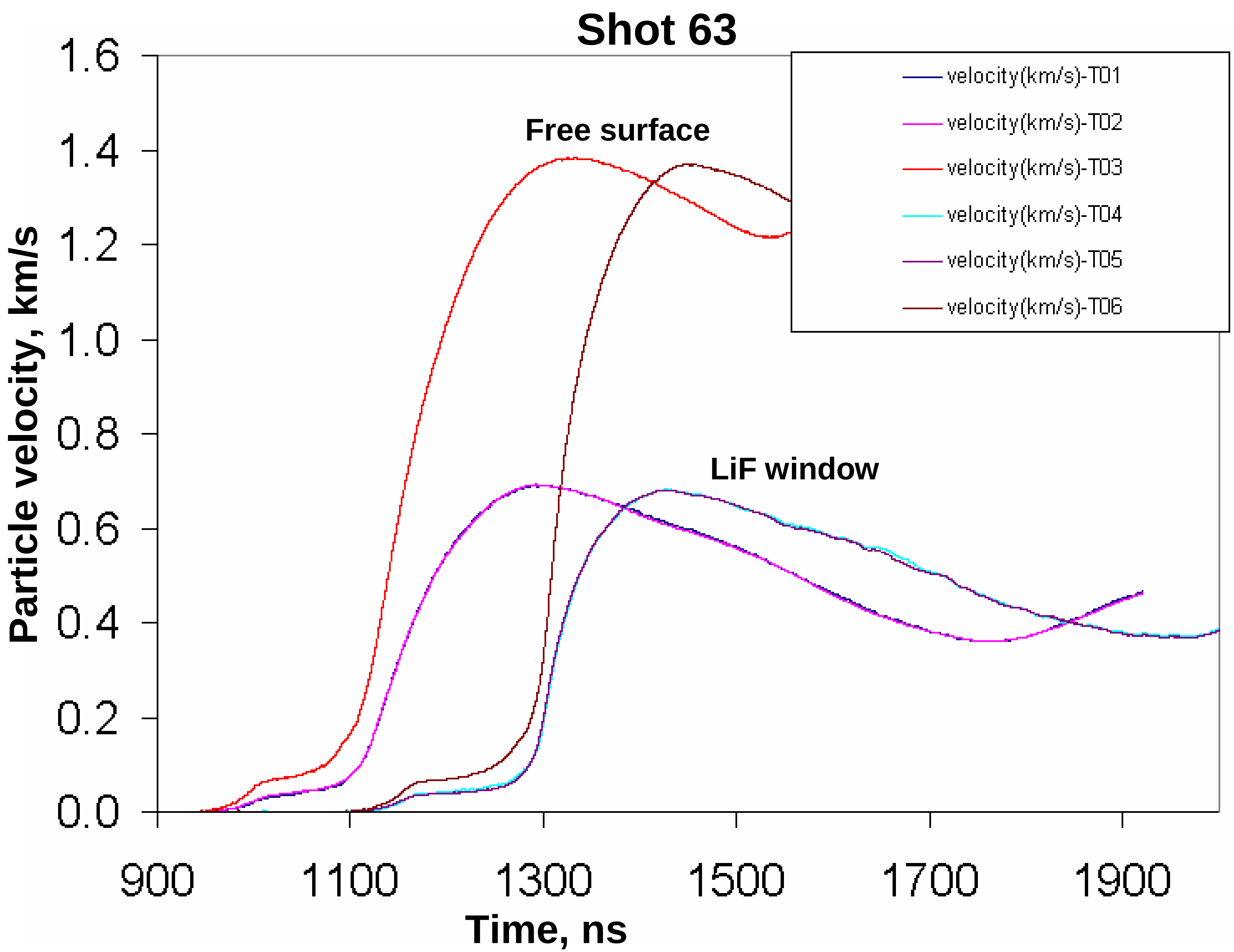
Approach is to first evaluate EOS accuracy, then obtain strength data

- **Demonstrate ability to reproduce EOS data on 6061-T6**
- **Compare to previous Z work, Sesame EOS**
- **Determine compressive strength from loading/unloading data**
- **Compare to ICE studies (GDI, Z, Omega)**
- **Improve method in future experiments**
  - **Evaluation of systematic errors**
  - **Better drive uniformity**
  - **Improved sample preparation methods**
  - **Higher peak pressures**

Recent results from free surface and window experiments on 6061-T6 aluminum



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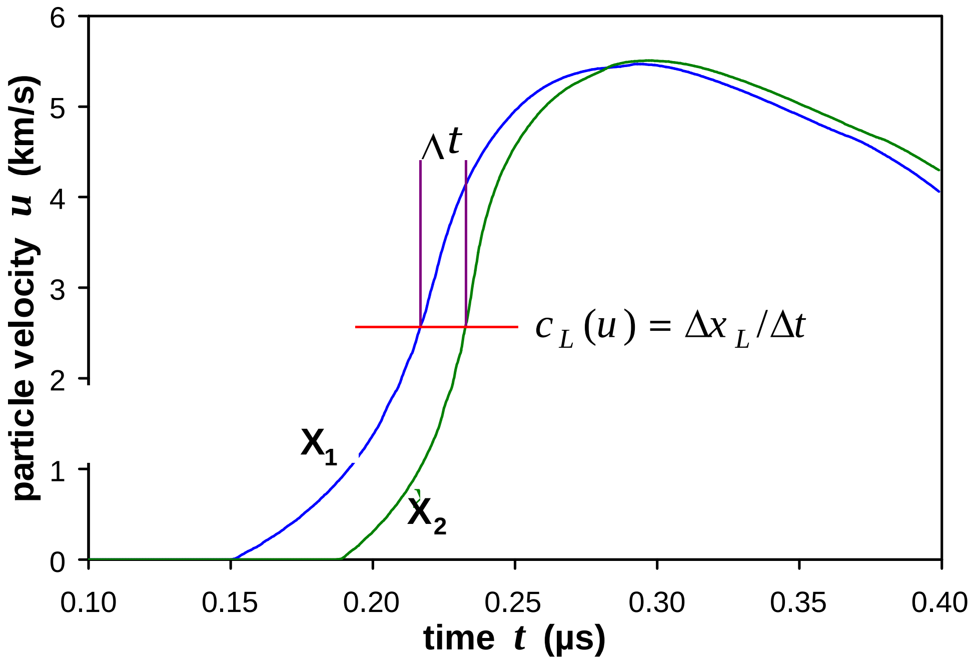
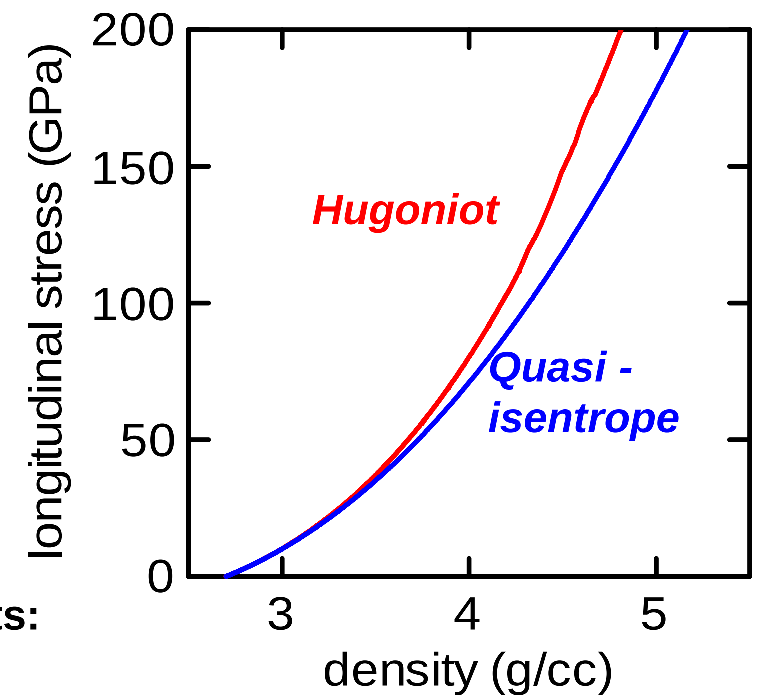
In situ wave profiles can be analyzed to provide continuous σ–ε along the loading path



$$d\sigma_x = \rho_0 c_L du$$

$$\frac{d\rho}{\rho^2} = \frac{du}{\rho_0 c_L}$$



Several methods used to analyze ramp wave results:

- Impedance matching
- Lagrangian wave analysis
- Backward analysis methods (INVICE)

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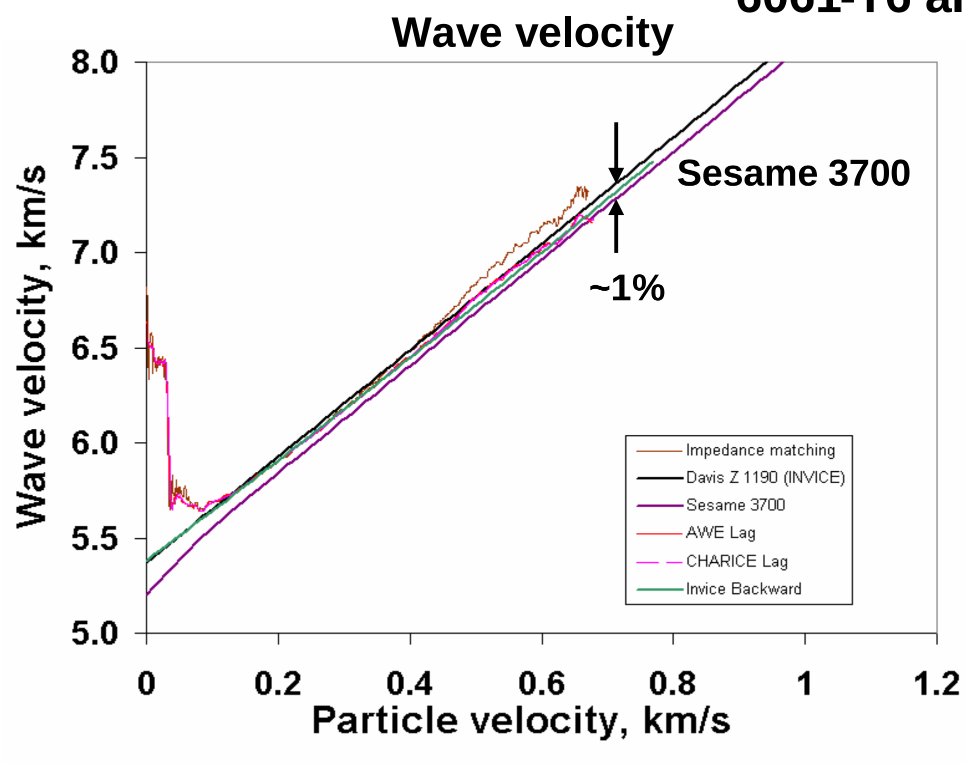
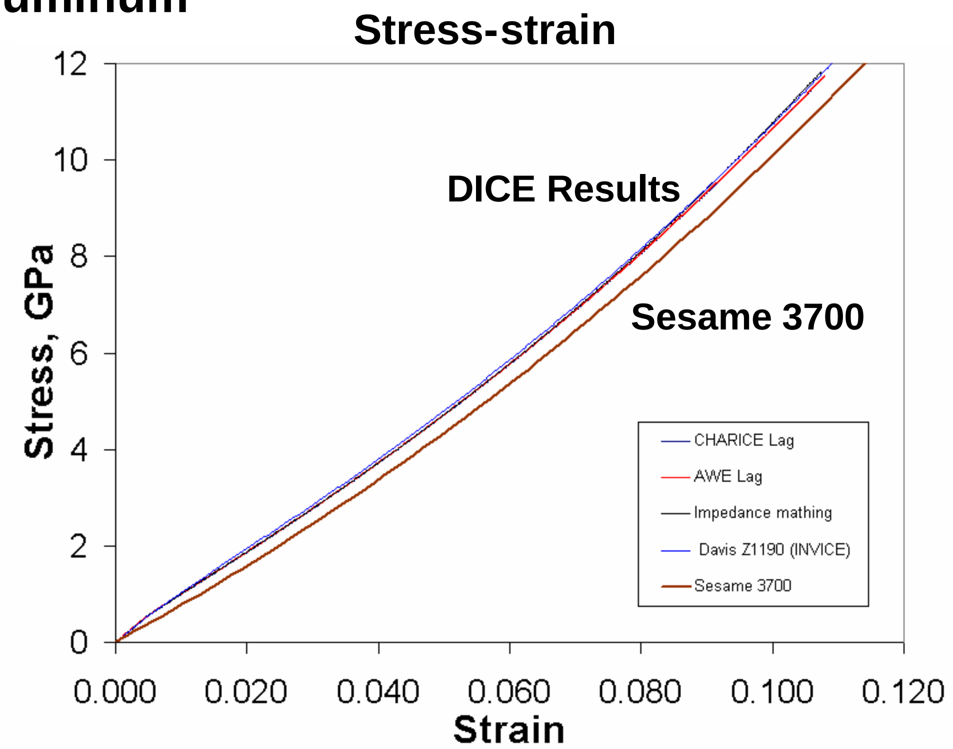
Measured results and comparison to other data

6061-T6 aluminum





- **Agreement with other ICE data to within experimental errors**
- **Major contribution to the difference Sesame 3700 is material strength**
- **Other factors: viscous effects, systematic errors and EOS errors**

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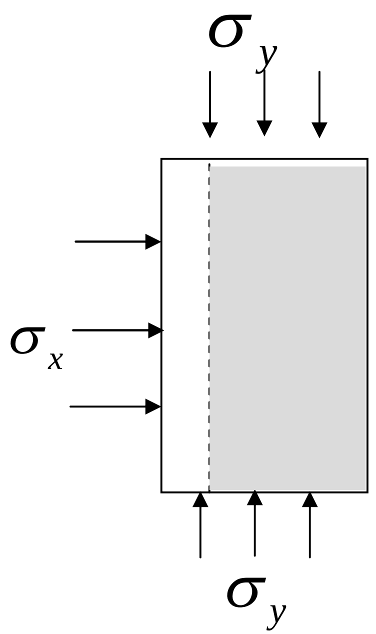
A goal is to estimate shear stresses produced for uniaxial strain ramp loading



Uniaxial strain compression

Strain

$$\varepsilon_{ij} = \varepsilon_{ij}{}^{e} + \varepsilon_{ij}{}^{p}$$

$$\varepsilon_{ii} = 0$$ **(plastic dilatation)**

Stress

$$P = \left(\frac{\sigma_x + 2\sigma_y}{3} \right)$$

$$\tau_c = \frac{1}{2}\left(\sigma_x - \sigma_y\right)$$

$$\sigma_x = P + \frac{4}{3}\tau_c$$

$$\sigma_x = P + \frac{2}{3}Y$$

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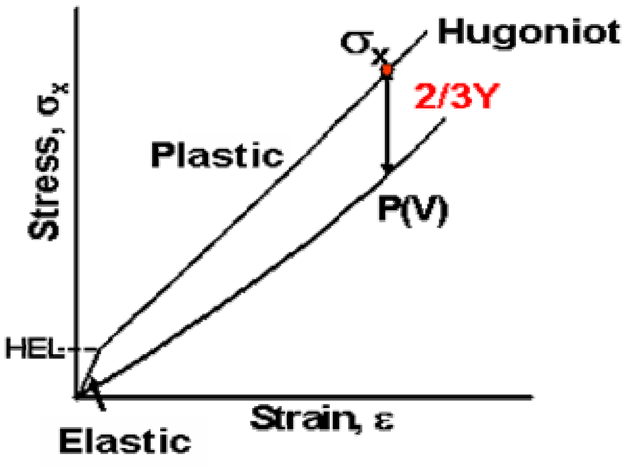
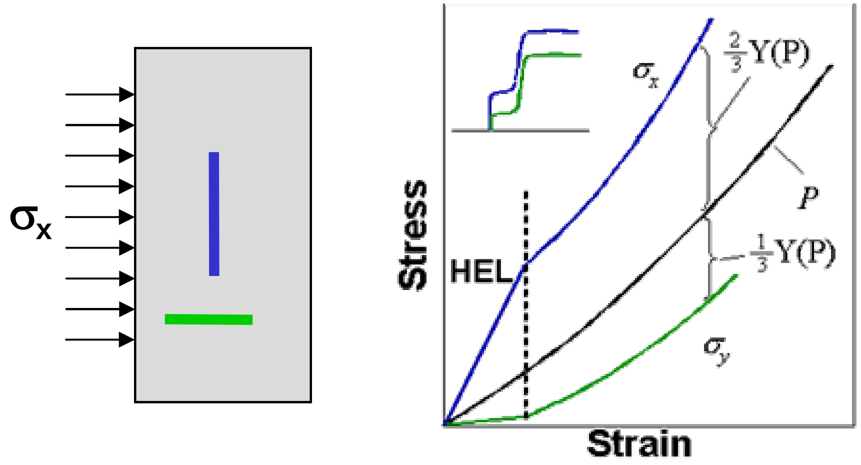
Several techniques have been developed to study strength properties

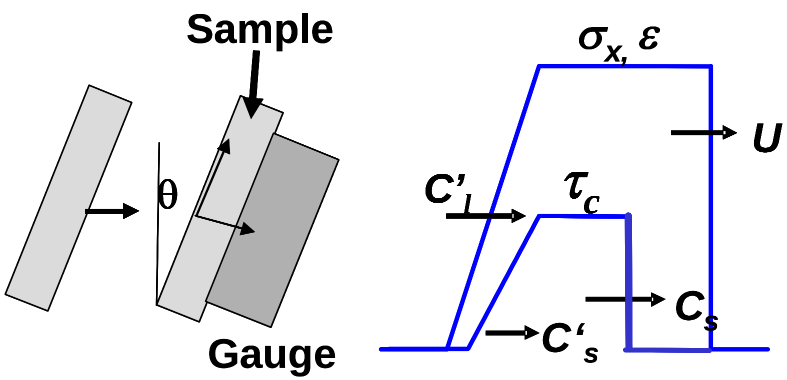
Stress Difference



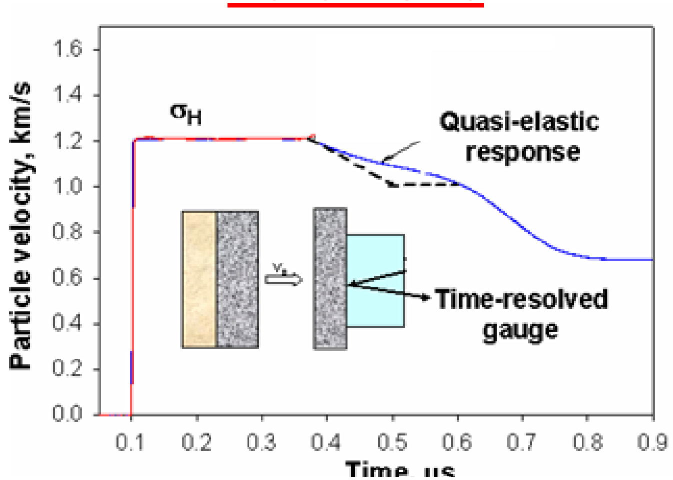
Longitudinal-lateral gauges



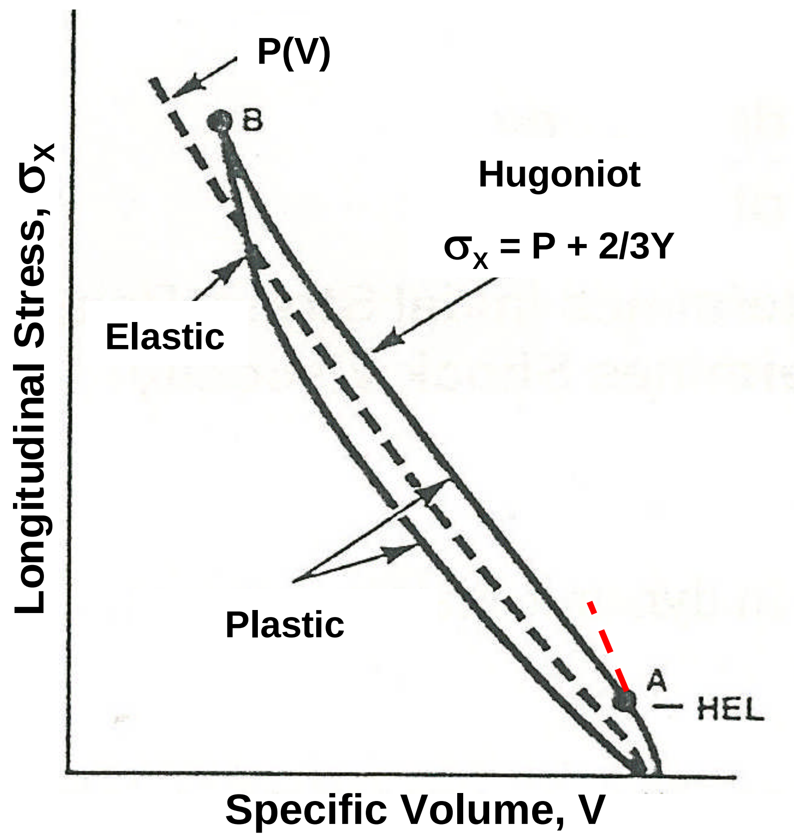
Oblique Impact

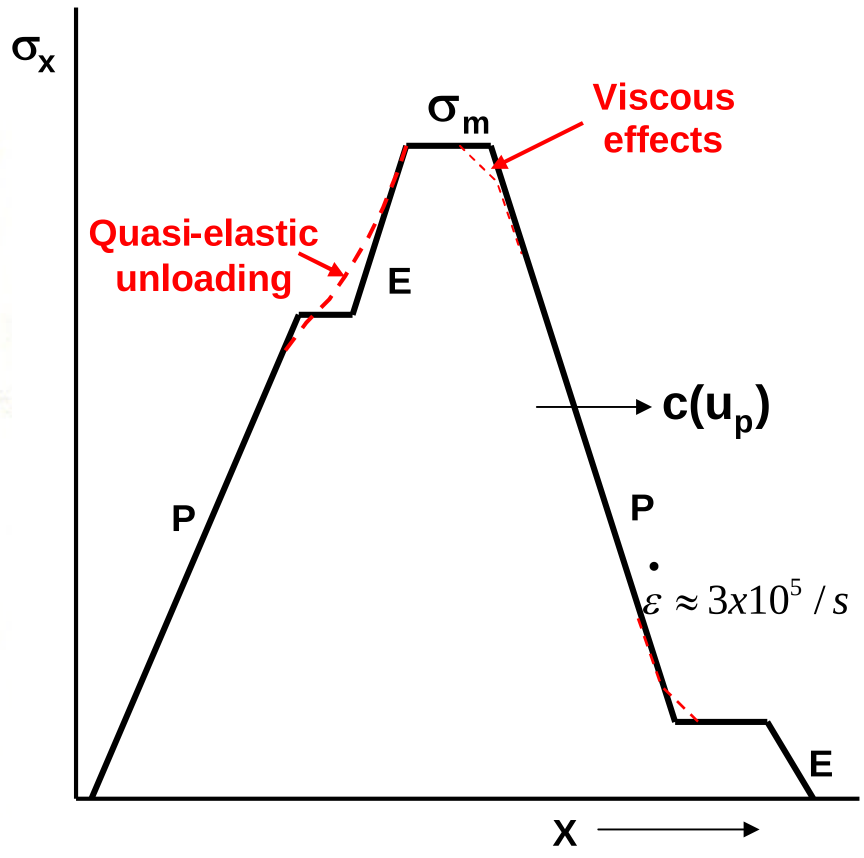


Wave Profile



Elastic-plastic response produces specific signatures in wave structures





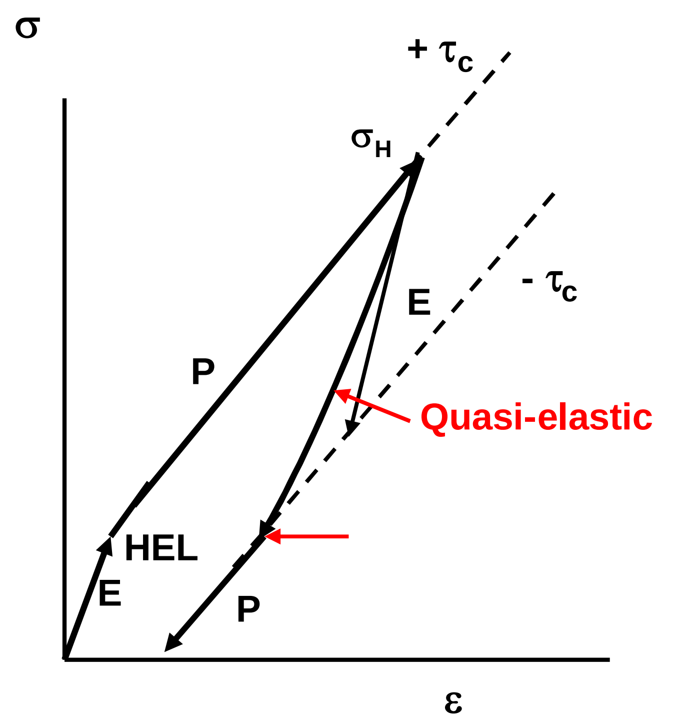
G.R. Fowles, J. Appl. Phys., 1961

Approach

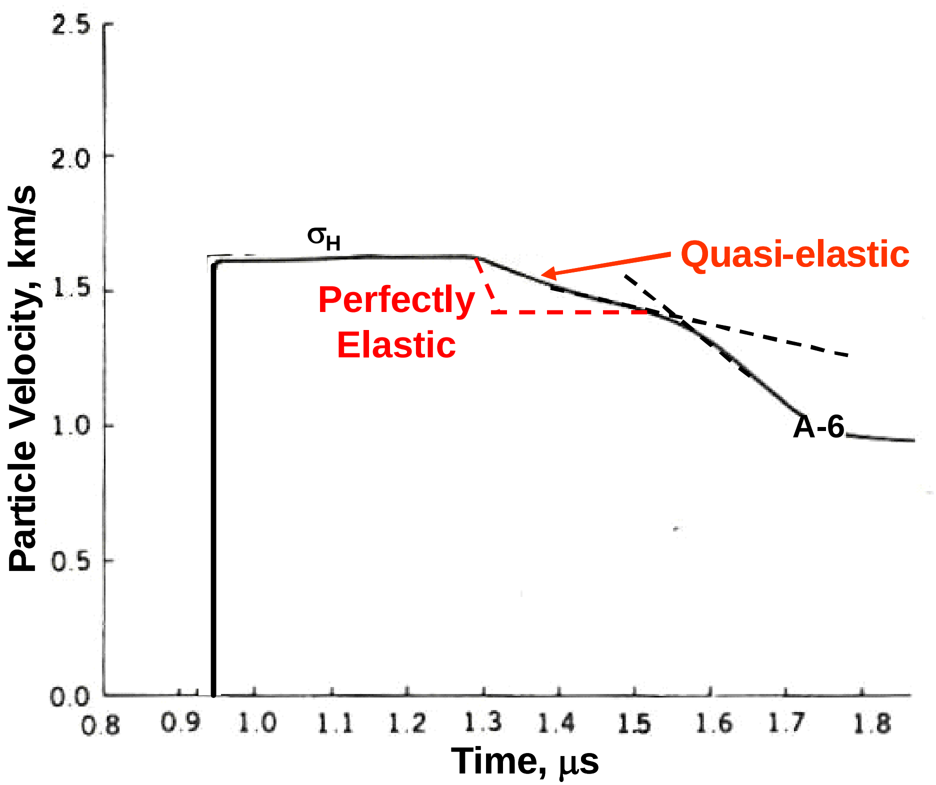
- Develop a configuration for producing uniaxial strain loading and unloading on DICE
- Investigate wave profile techniques for probing strength properties of Al for ramp loading (extension of Z work)
- Compare analysis results using different methods
  - Lagrangian wave analysis
  - Characteristics code approaches (Rothman, Ekert, Davis)
  - Backward analysis
- Investigate effects of window properties
  - E-P effects for unloading
  - Results from different windows (sapphire, LiF, ..)

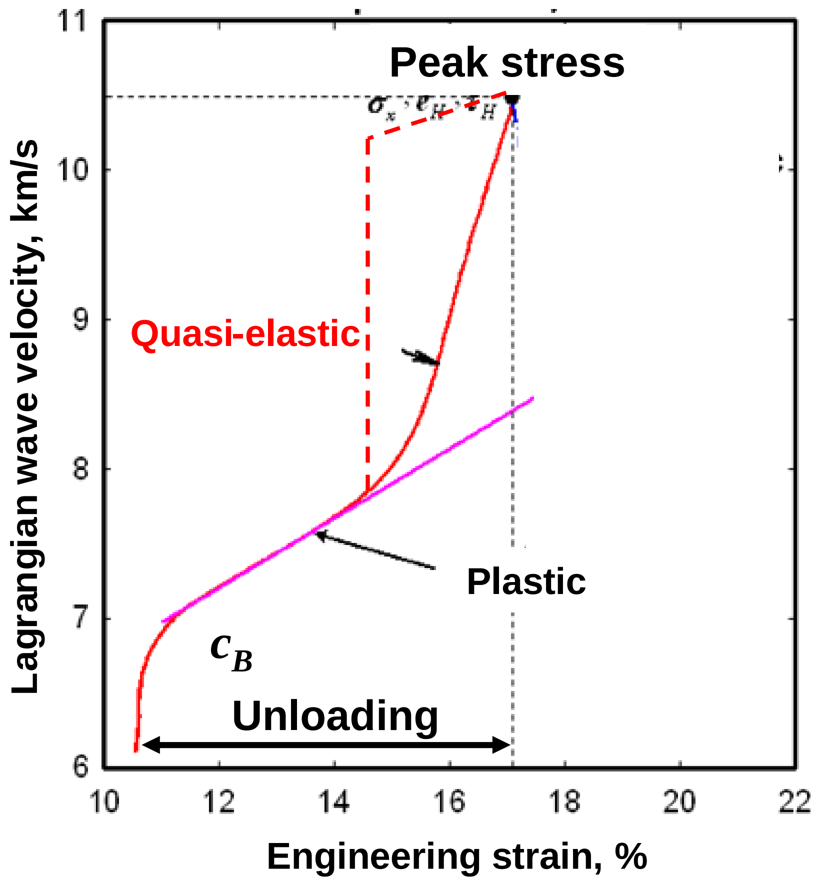
Assumptions used to analyze unloading data

- **Response is rate-independent**
- **A yield surface exists after loading and can be measured as a transition from quasi-elastic to plastic response**
- **The yield function depends on some measure of plastic strain or pressure**
- **Plastic response can be approximated by wave velocities after Q-E transition**



Determination of strength from shock loading/unloading profiles





$$\Delta\sigma = 3/4\rho_0 \int_{e_1}^{e_f} \left(c_L^2 - c_B^2\right) de$$

$= Y$ if Hugoniot state is on the yield surface

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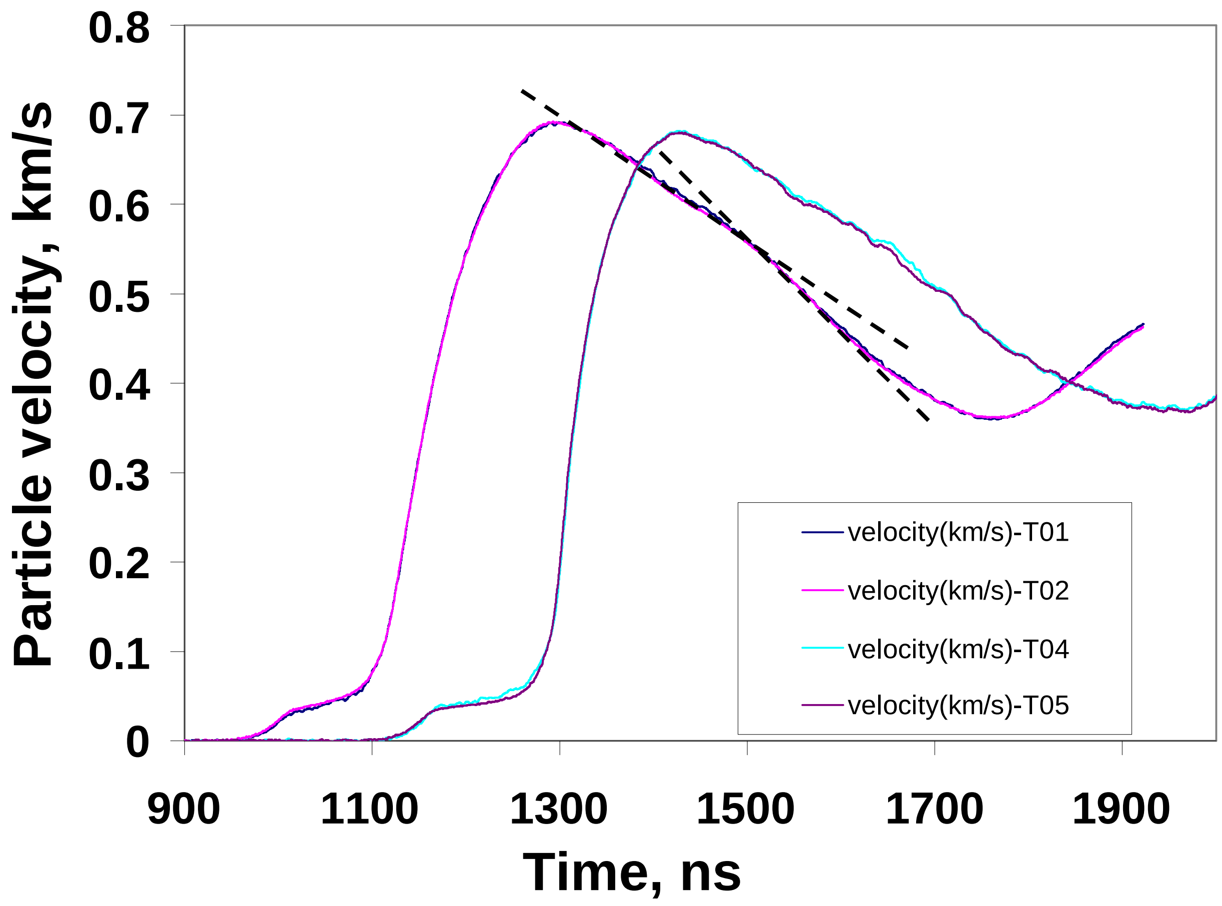
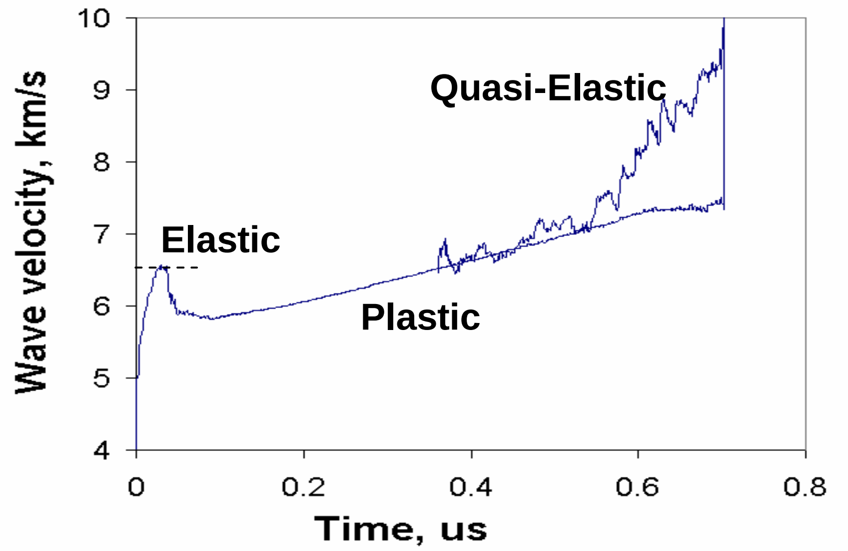
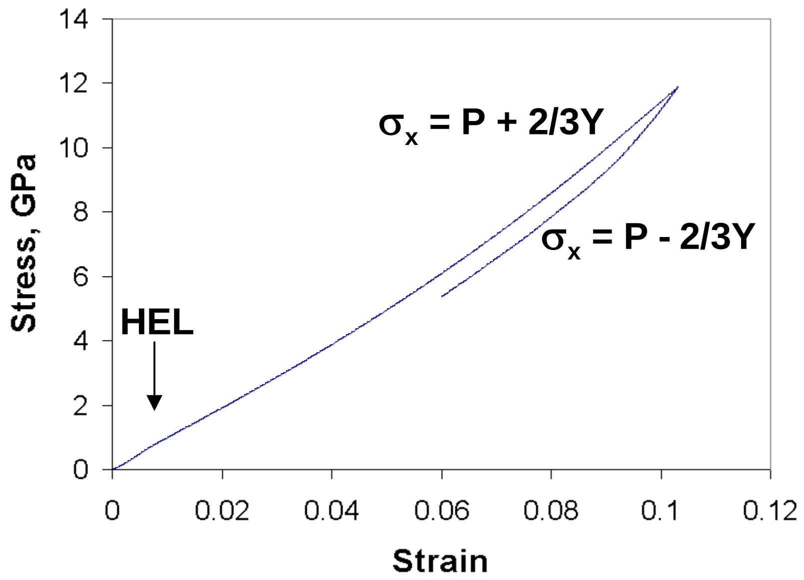
Unloading wave profiles used to estimate strength - redo



- **Good VISAR reproducibility**
- **Quasi-elastic transition detected**
- **~1.5% attenuation**
- **Noisy second unloading signal**

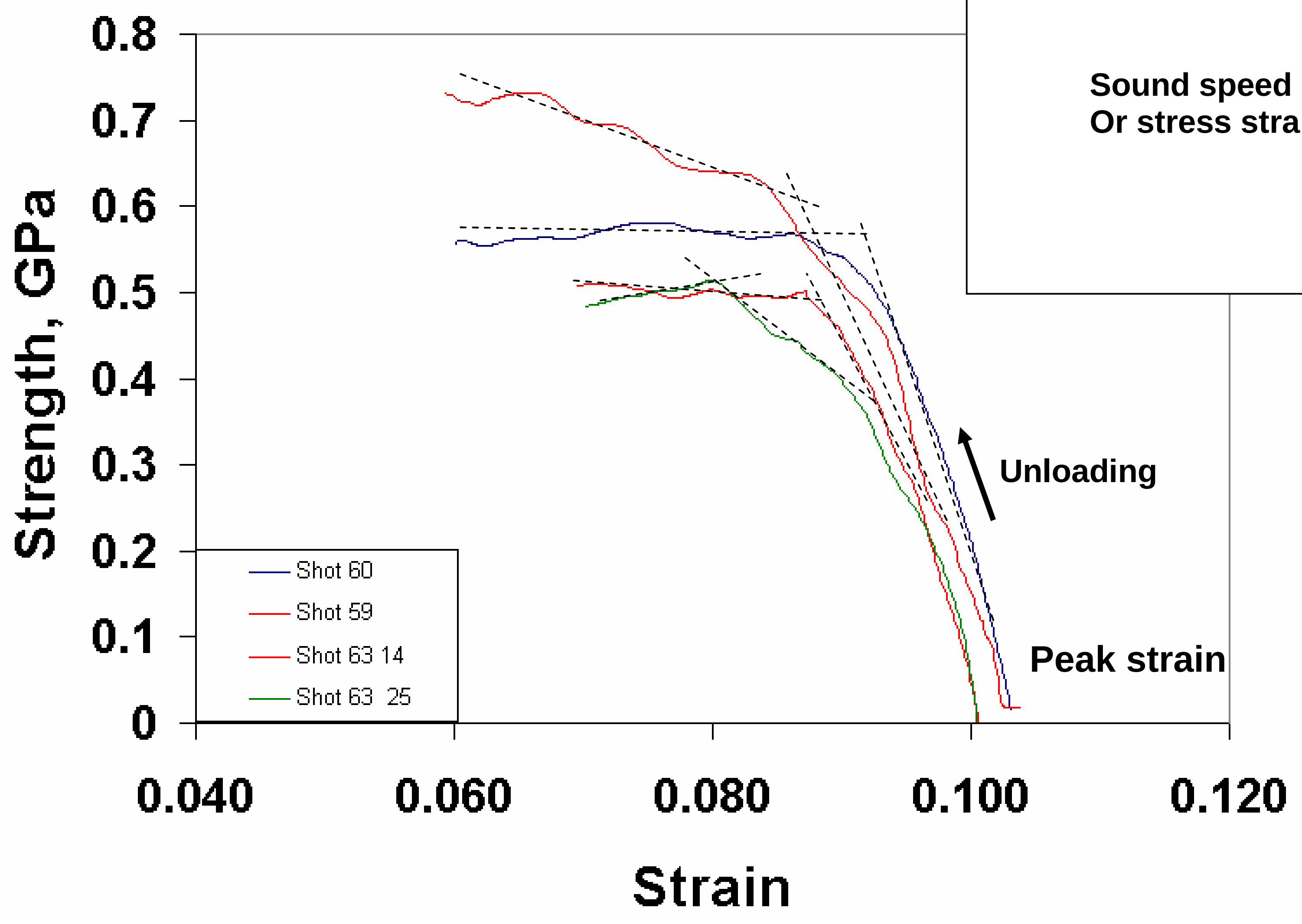
Lagrangian analysis of loading and unloading in ramp experiments





- **Unloading data noisier than for shock experiments**
- **Measurement of loading wave velocity determines bulk response**
- **Softening observed near peak stress in several experiments**

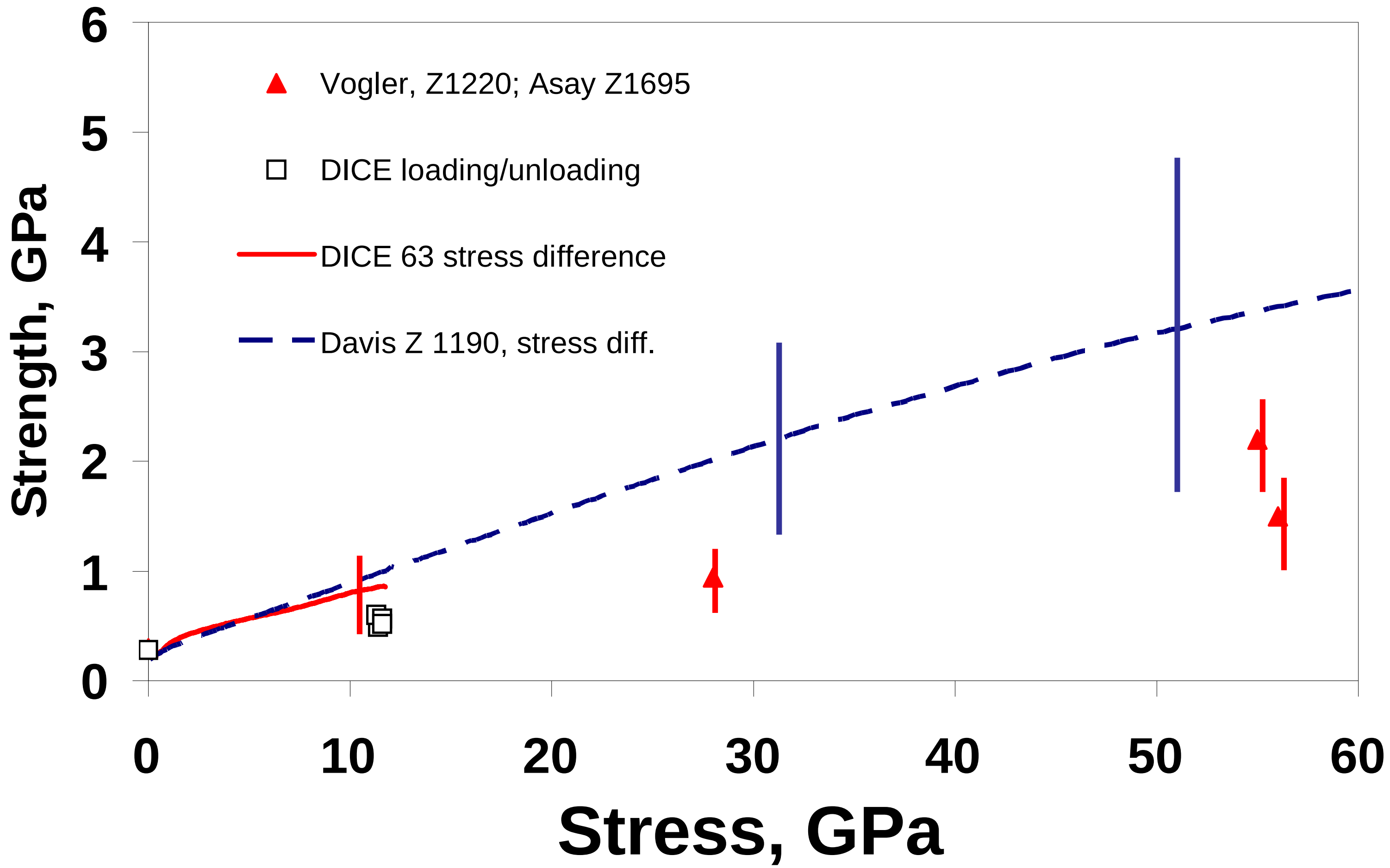
Strength determination



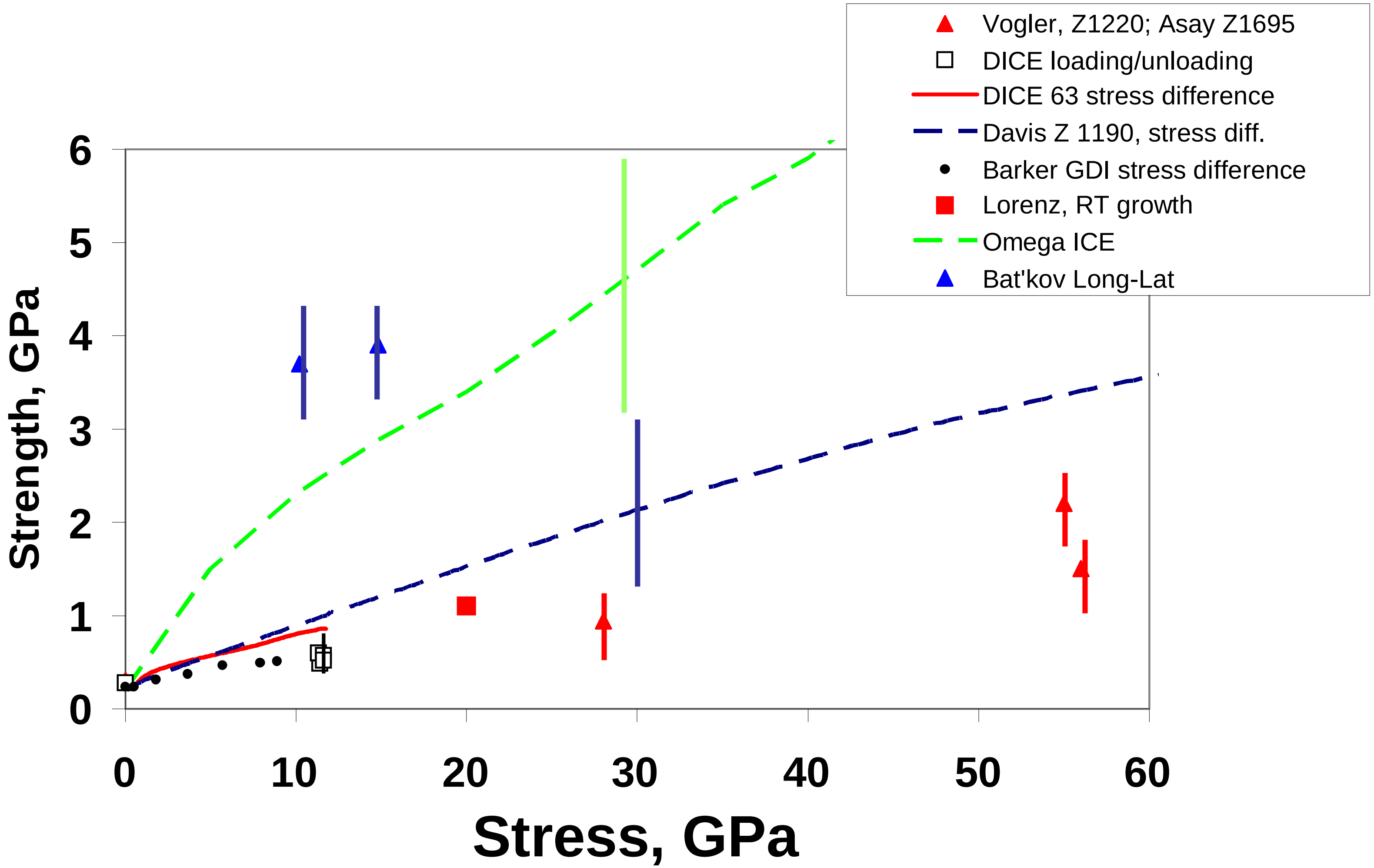
Sound speed
Or stress strain?

Comparison of strength data estimated from stress difference to isentrope and unloading profiles

Strength of 6061-T6 for ramp loading



DICE results are consistent with other strength data for quasi-isentropic loading



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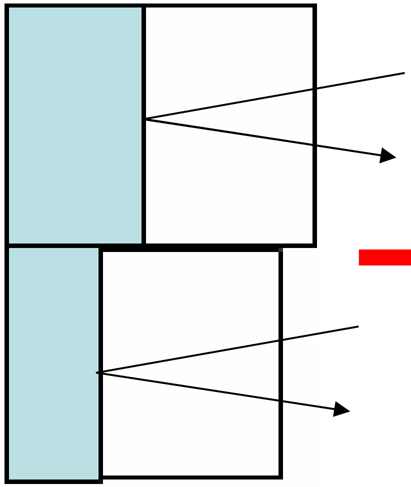
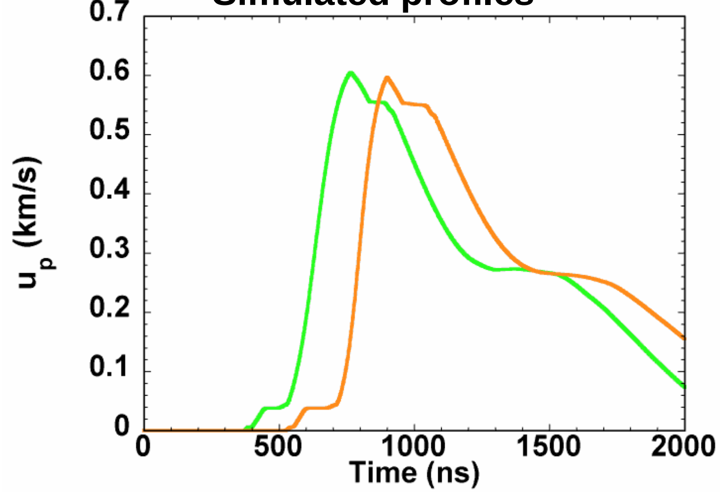
1-D numerical simulations profiles are being used to simulate profiles for Lagrangian analysis

Actual input stress history using E-P with Y_0

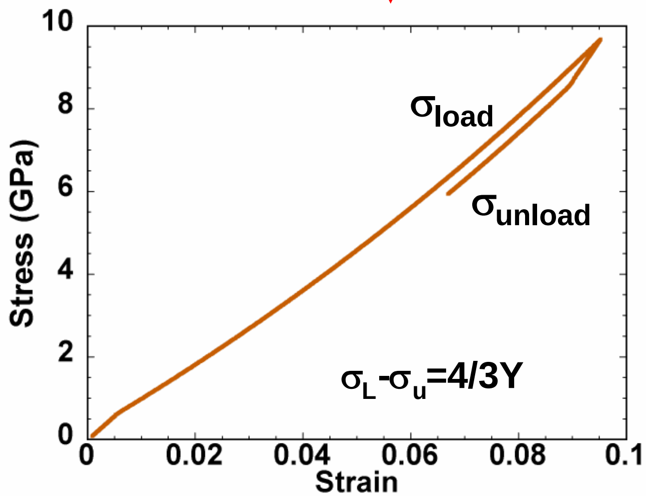
Configuration



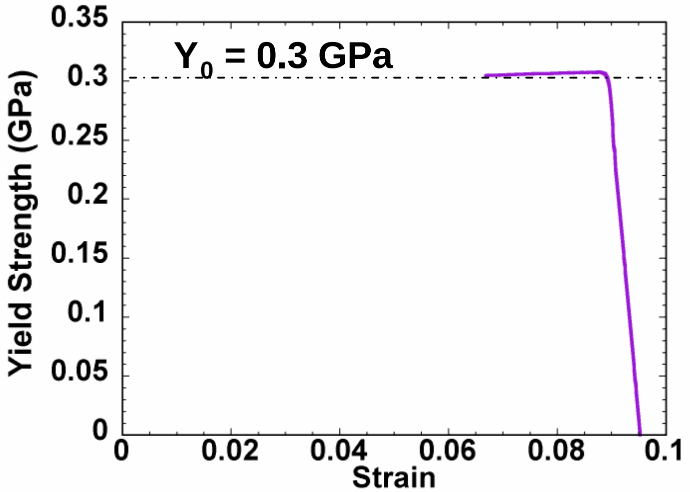
Simulated profiles



Lagrangian Analysis



Estimate Y from Δσ



Summary

- **Loading conditions on DICE are sufficient to obtain loading and unloading and estimates of compressive strength**
- **Compressive stress-strain curves obtained on aluminum are consistent with other data**
- **Estimates of strength are consistent with several other methods, but inconsistent with strength determined from difference to the isentrope**
- **Strength measurements are difficult – coordinated effort with different techniques is necessary to develop consistent models**

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Next steps

- **Improvements in experimental configuration**
  - **Sample preparation techniques (diamond machining, glue bonds)**
  - **Better pressure drive uniformity**
  - **Shorter current risetimes**
  - **Smoother current unloading**
- **Better understanding of unloading response**
  - **Wave attenuation effects**
  - **Effect of LiF properties**
  - **Analysis methods for unfolding perturbed unloading profiles**
- **Studies of strength in several materials**
  - **Effects of initial microstructure in aluminum**
  - **LiF, sapphire (T. Ao)**
  - **High impedance materials (vanadium, tantalum, tungsten)**

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