Modeling Laser Material Strength Experiments

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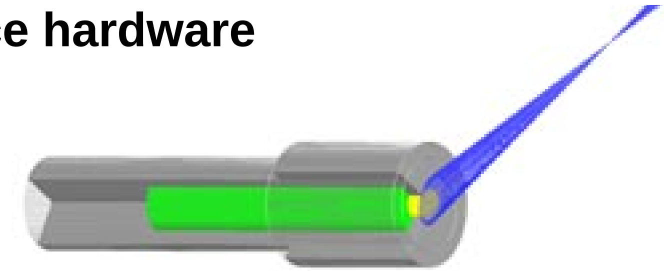
Outline of poster

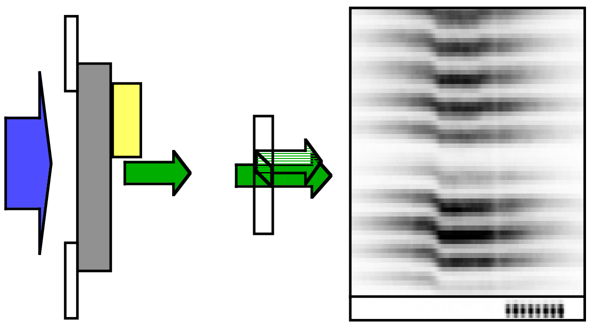
- Material strength model
    - Elastic-plastic flow
    - Steinberg-Guinan and Steinberg-Lund models
- VISAR velocity measurement
    - Experiment
    - Model
- Diffraction
    - Experiment
    - Model
- Sample recovery
    - Experiment
    - Decay of shock strength
- Summary and future developments

The constituitive properties of metals is of general scientific interest

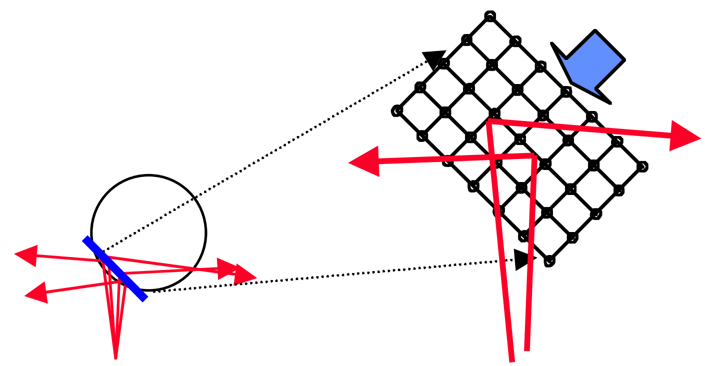
- Laser experiments give us access to new regimes
  - High pressures
  - High strain rates
- How materials deform at strain rates > 10^8/s is unknown
- Relevant for impact of micrometeorites on space hardware
- Diagnostics
  - VISAR
  - X-ray diffraction
  - Recovery
- Infer properties such as EOS, K, G, Y



Recovery

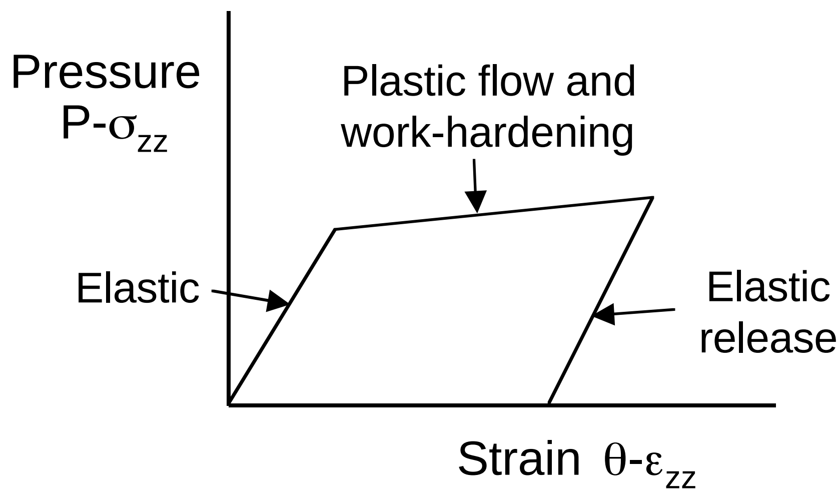


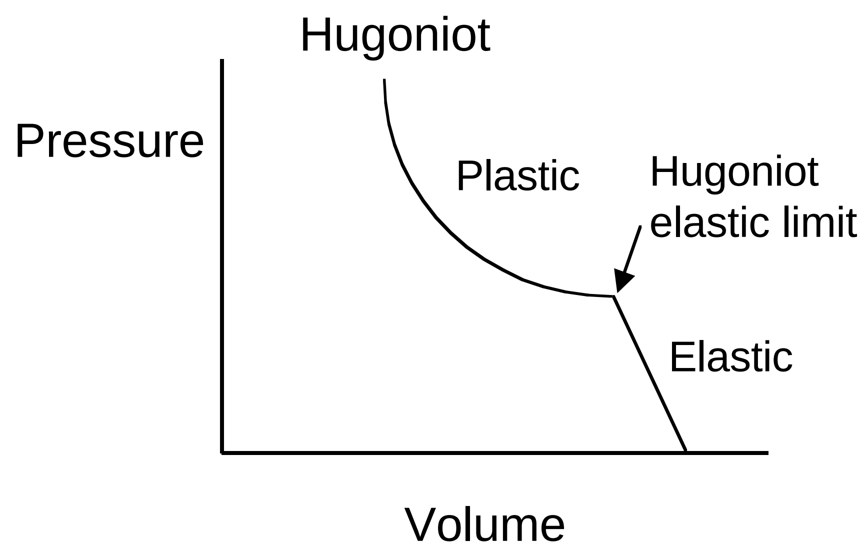
VISAR

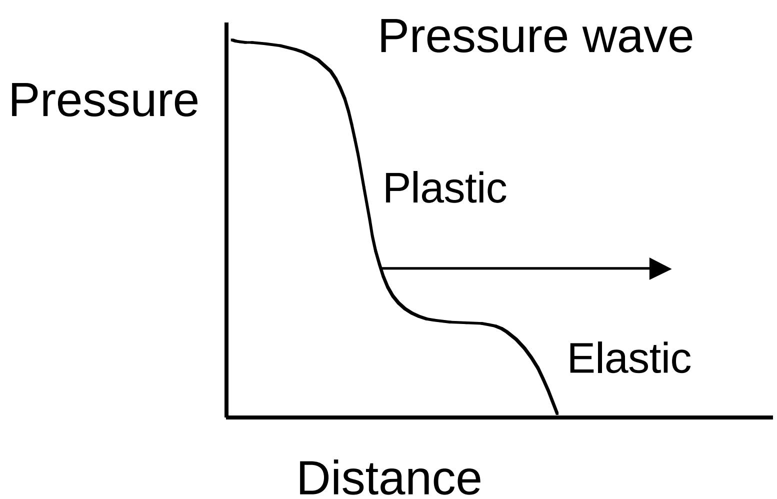


X-ray diffraction

Moderate shocks show both elastic and plastic waves







We use a material strength package in our code

Newton's law

$$\rho\dot{v}_r = -\frac{\partial}{\partial r}\left(P - \sigma_{rr}\right) + \frac{\partial}{\partial z}\sigma_{rz} + \frac{1}{r}\left(2\sigma_{rr} + \sigma_{zz}\right)$$

$$\rho\dot{v}_z = -\frac{\partial}{\partial z}\left(P - \sigma_{zz}\right) + \frac{\partial}{\partial r}\sigma_{rz} + \frac{1}{r}\sigma_{rz}$$

ρ= density
v= velocity
P= hydrodynamic pressure
σ= deviatoric stress
θ= hydrodynamic strain
ε= deviatoric strain
K= bulk modulus
G=shear modulus

Definition of strain

$$\dot{\theta} = \frac{\partial v_r}{\partial r} + \frac{\partial v_z}{\partial z} + \frac{v_r}{r}$$

$$\dot{\varepsilon}_{rr} = \frac{1}{3}\left(2\frac{\partial v_r}{\partial r} - \frac{\partial v_z}{\partial z} - \frac{v_r}{r}\right)$$

$$\dot{\varepsilon}_{zz} = \frac{1}{3}\left(2\frac{\partial v_z}{\partial z} - \frac{\partial v_r}{\partial r} - \frac{v_r}{r}\right)$$

$$\dot{\varepsilon}_{rz} = \frac{1}{2}\left(\frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r}\right)$$

EOS with strain

$$\dot{P} = -K\dot{\theta} - \dot{P}^{inelastic}$$

$$\dot{\sigma}_{rr} = 2G\dot{\varepsilon}_{rr} - \dot{\sigma}_{rr}^{inelastic} + 2\sigma_{rz}\omega + (\sigma_{zz} - \sigma_{rr})\omega^2$$

$$\dot{\sigma}_{zz} = 2G\dot{\varepsilon}_{zz} - \dot{\sigma}_{zz}^{inelastic} - 2\sigma_{rz}\omega - (\sigma_{zz} - \sigma_{rr})\omega^2$$

$$\dot{\sigma}_{rz} = 2G\dot{\varepsilon}_{rz} - \dot{\sigma}_{rz}^{inelastic} + 2(\sigma_{rz} - \sigma_{rr})\omega - 2\sigma_{rz}\omega^2$$

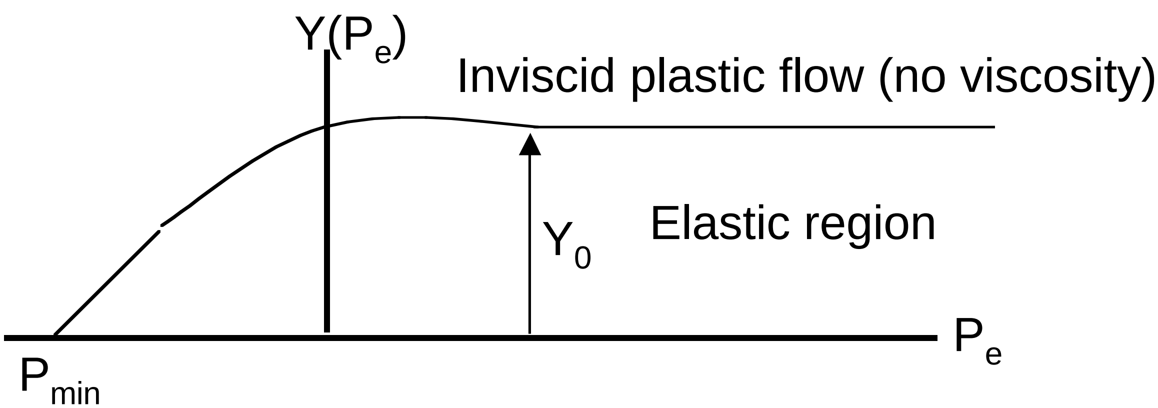
$$\omega = \frac{1}{2}\left(\frac{\partial v_r}{\partial z} - \frac{\partial v_z}{\partial r}\right)$$

We use a von Mises yield criterion for the onset of plastic flow

Deviatoric strain invariant $J = \sqrt{\frac{4}{3}\left(\sigma_{rr}^2 + \sigma_{zz}^2 + \sigma_{rz}^2 + \sigma_{rr}\sigma_{zz}\right)}$

Effective pressure $P_e = P - \sqrt[3]{\left(\sigma_{rr} + \sigma_{zz}\right)(\sigma_{rz}^2 - \sigma_{rr}\sigma_{zz})/16}$

When J > Y(P_e), the elastic limit is exceeded and plastic flow begins



von Mises, Z. Angew. Math. U. Mech. **8** (1928), translated in UCRL Trans. 872

Uniaxial strain equations

$$\rho \dot{v}_z = \frac{\partial}{\partial z}\left(-P + \sigma_{zz}\right)$$

$$\dot{\theta} = \frac{\partial v_z}{\partial z}$$

$$\dot{\varepsilon}_{zz} = \frac{2}{3}\frac{\partial v_z}{\partial z}$$

$$\dot{P} = -K\dot{\theta} - \dot{P}^{inelastic}$$

$$\dot{\sigma}_{zz} = 2G\dot{\varepsilon}_{zz} - \dot{\sigma}_{zz}^{inelastic}$$

$$P_e = P - \tfrac{1}{4}\sigma_{zz}$$

$$J = \left|\sigma_{zz}\right|$$

$$\text{Sound speed } c_{11} = \sqrt{\left(K + \tfrac{4}{3}G\right)/\rho}$$

Steinberg-Guinan Model

$$G(P,T) = G_0\left(1 + \frac{1}{G_0}\frac{\partial G}{\partial P}\frac{P}{\eta^{1/3}} - \frac{1}{G_0}\frac{\partial G}{\partial T}(T-300)\right)$$

$$Y = Y_0 f(\varepsilon_p)\, G(P,T)/G_0$$

$$Y_0 f(\varepsilon_p) = Y_0\left(1 + \beta(\varepsilon_p + \varepsilon_i)\right)^n \leq Y_{\max}$$

$$T_{melt} = T_0 \exp\left(2a(1-\tfrac{1}{\eta})\eta^{2(\gamma_0 - a - 1/3)}\right), \quad \eta = \frac{\rho}{\rho_0}$$

D.J. Stenberg, S.G. Cochran and M. W. Guinan, J. Appl. Phys. **51**, 1498 (1980)
D.J. Steinberg, UCRL-MA-106439 (1991)

Steinberg-Lund Model

$$Y = \{Y_T(\dot{\varepsilon}_p, T) + Y_A f(\varepsilon_p)\} G(P,T)/G_0$$

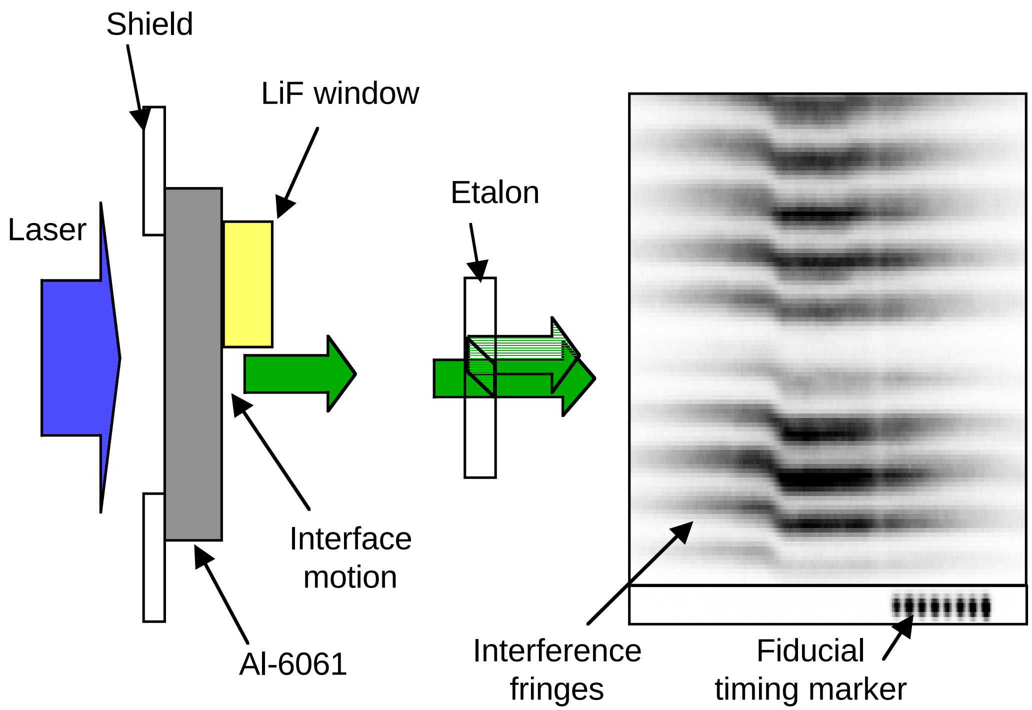
$$\dot{\varepsilon}_p = \{\frac{1}{C_1}\exp[\frac{2U_K}{kT}(1-\frac{Y_T}{Y_P})^2] + \frac{C_2}{Y_T}\}^{-1}$$

$$Y_A f(\varepsilon_p) = Y_A\left(1+\beta(\varepsilon_p+\varepsilon_i)\right)^n \leq Y_{\max}$$

$$Y_T \leq Y_P$$

D.J. Stenberg and C.M. Lund, J. Appl. Phys. **65**, 1528 (1989)

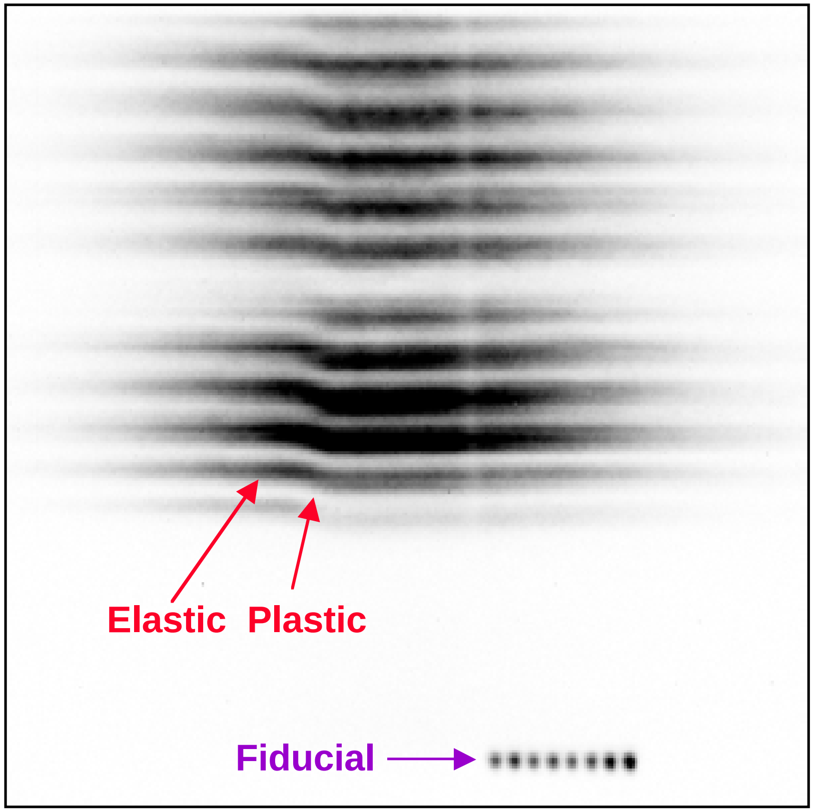
VISAR measures the surface velocity history

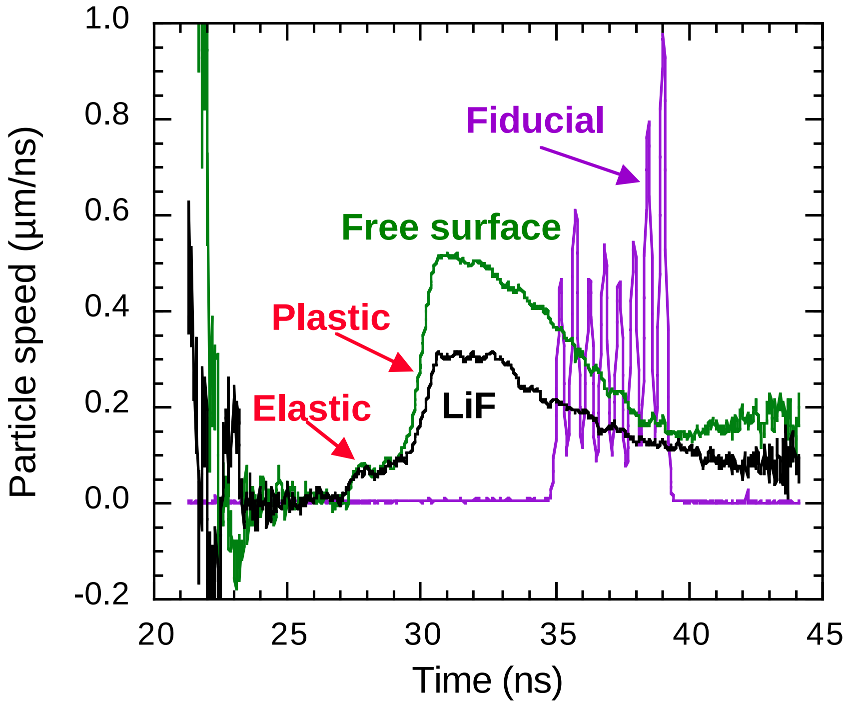


- An optical laser pulse is reflected from the free surface of the foil and injected into an interferometer
- The phase of the fringe is proportional to the velocity of the free surface
- Spatial resolution of the VISAR system provides data on the rear-surface motion with and without the LiF window

VISAR measurement of elastic-plastic wave breakout in Al-6061

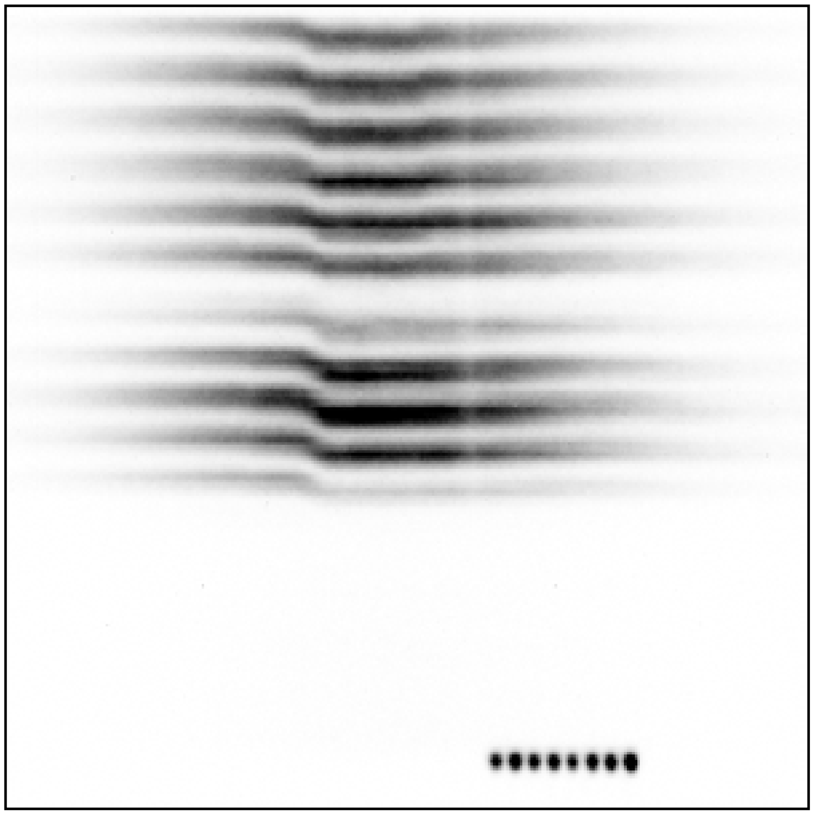
- 195 µm Al-6061, LiF over half of the rear surface
- Omega shot #21382 - 19 J on target

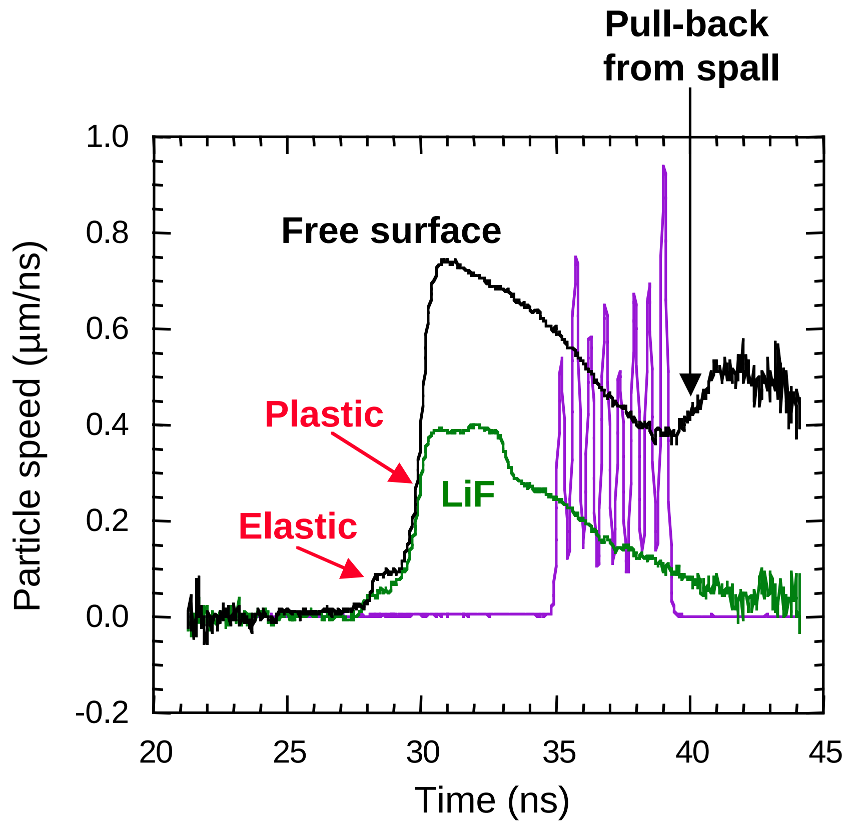




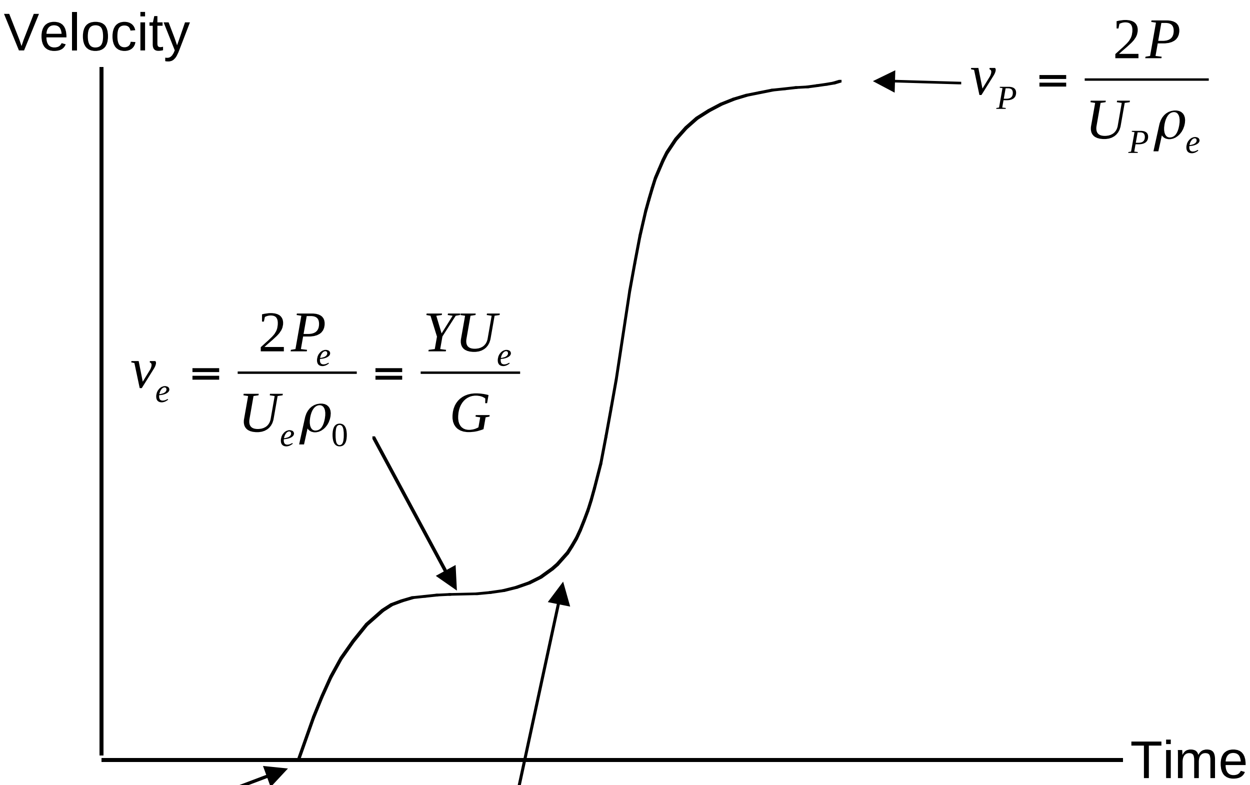
The wave profile shows a pull-back at higher drive pressure

- 195 µm Al-6061, LiF over half of the rear surface
- Omega shot #21384 - 33 J on target





We use VISAR data to determine the shear modulus, bulk modulus and yield strength



$$v_P = \frac{2P}{U_P\rho_e}$$

$$v_e = \frac{2P_e}{U_e\rho_0} = \frac{YU_e}{G}$$

$t_e = L_1/u_e + t_1$

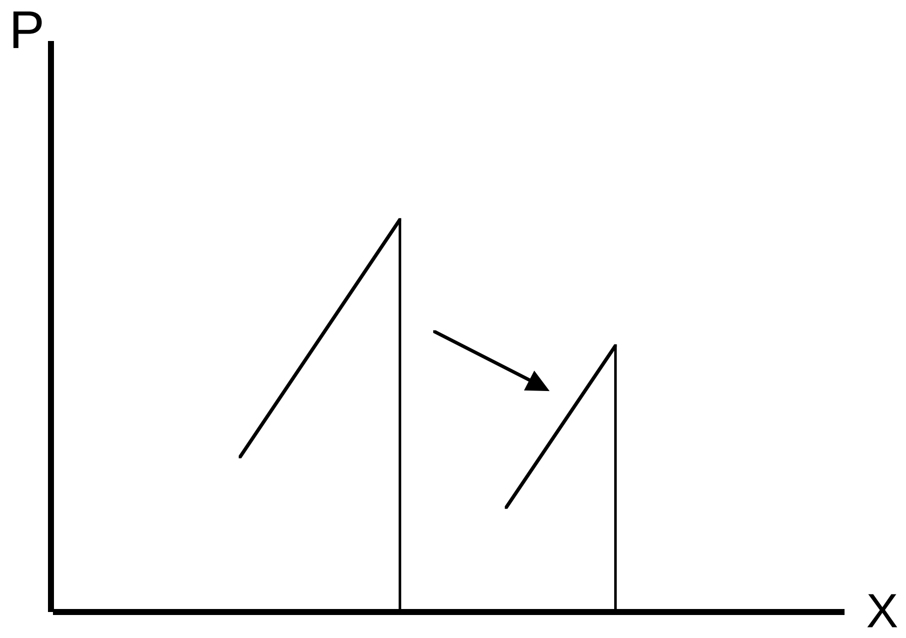
$t_p = L_2/u_p + t_2$

$$U_e^2 = \frac{K + \frac{4}{3}G}{\rho_0}$$

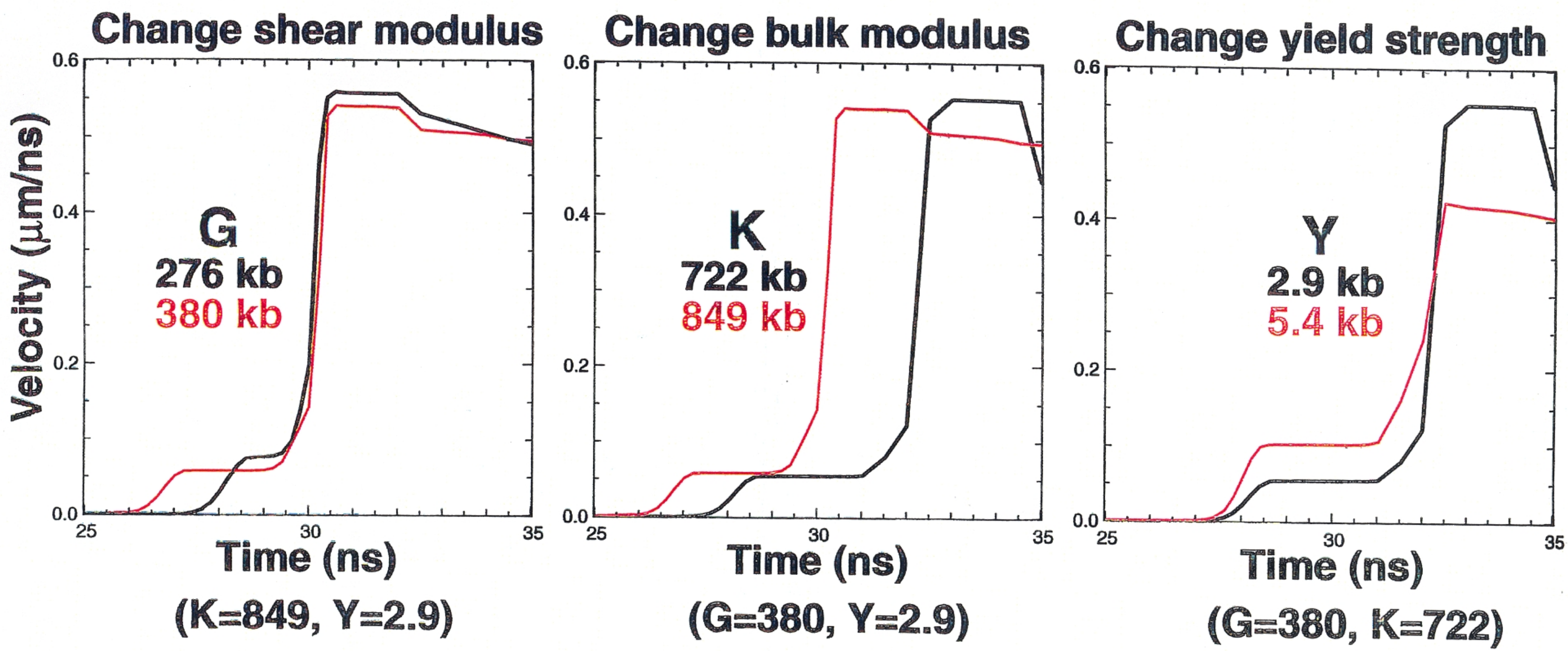
$$U_p^2 = \frac{K}{\rho_e}$$

Shocks lose strength as they propagate

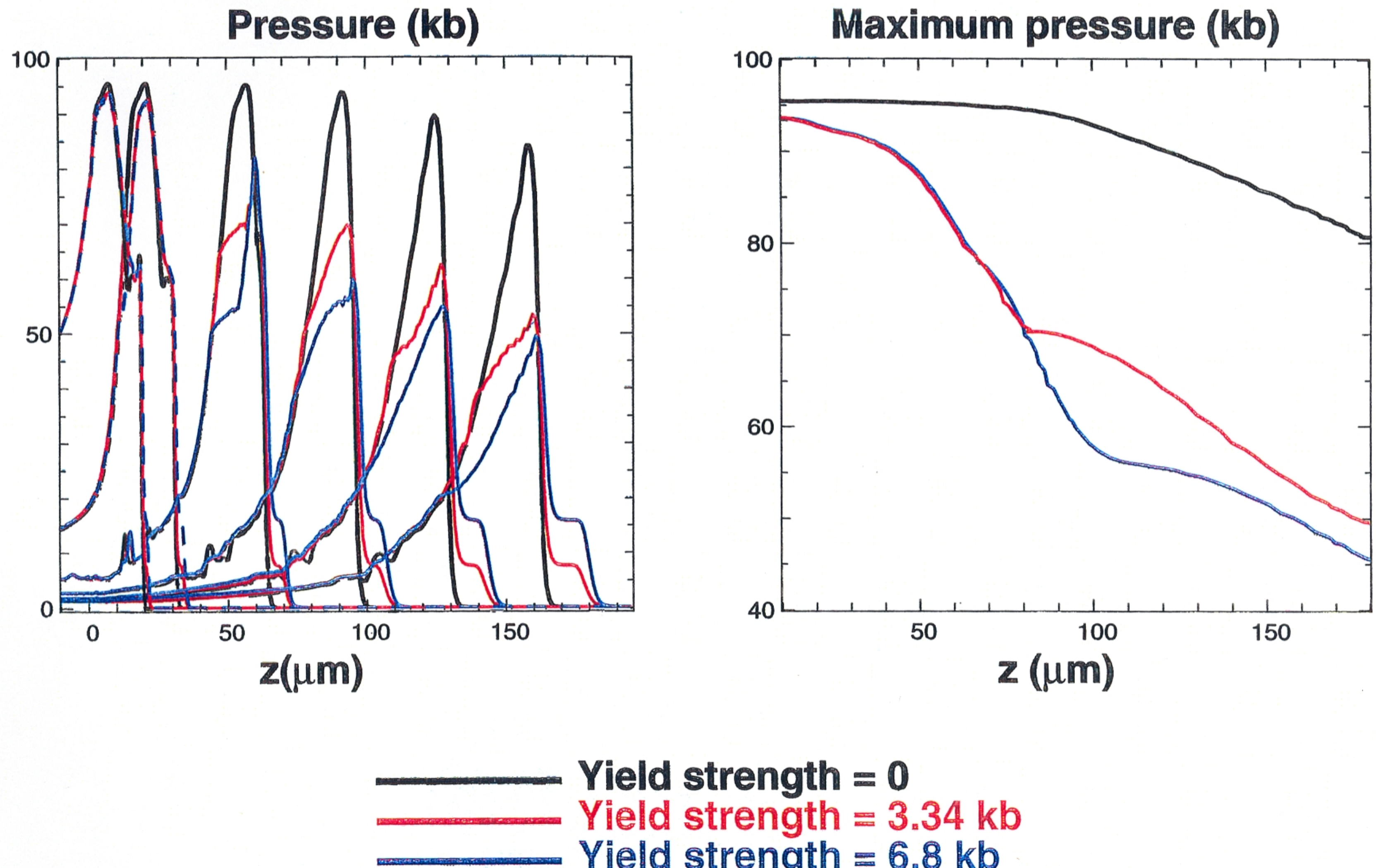
$$\left.\frac{dP}{dx}\right)_{shock} = -\left.\frac{dP}{dx}\right)_{rarefaction}\left(\frac{u_{material}+c_s}{U_{shock}}-1\right)$$



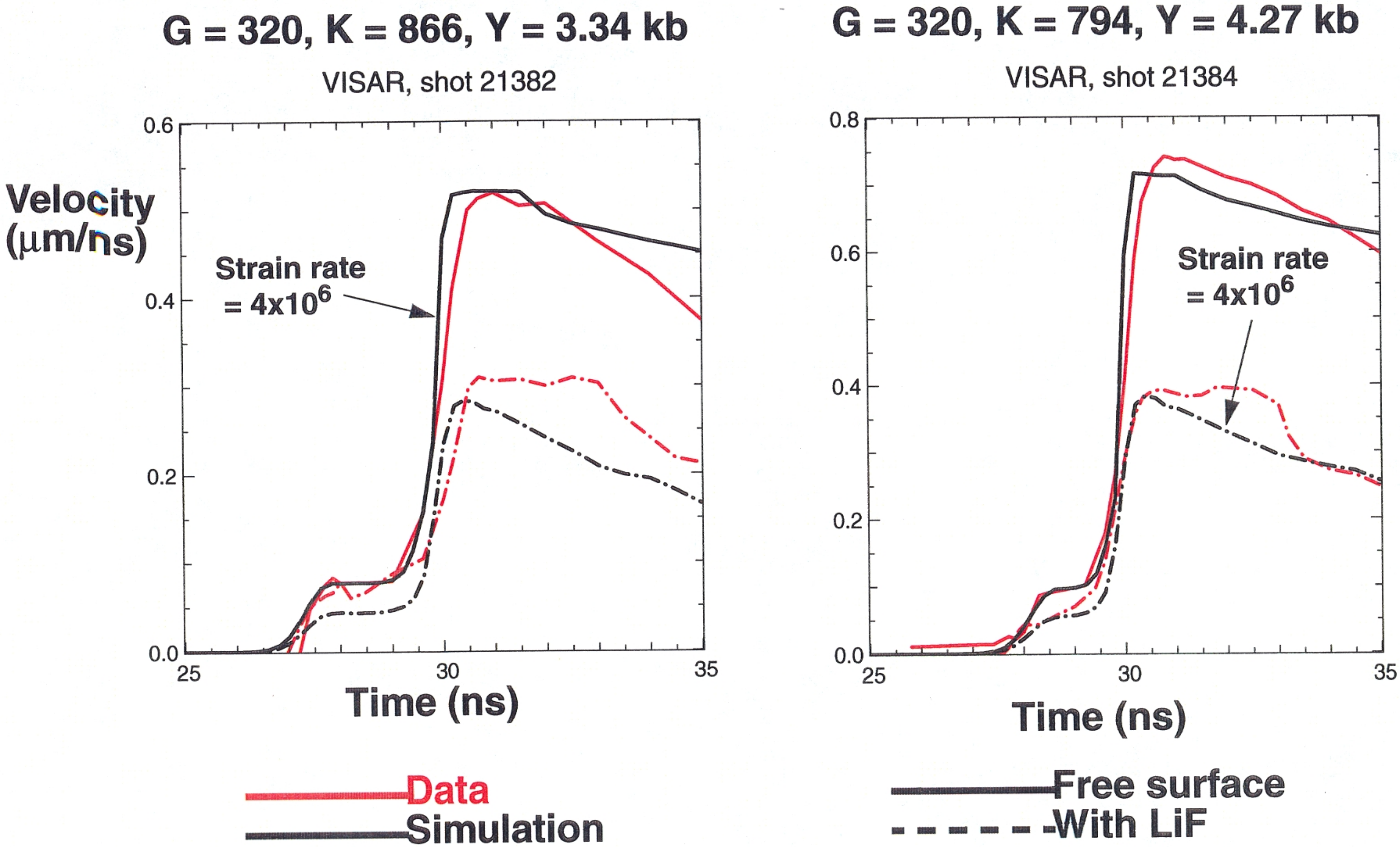
The shear modulus, bulk modulus and yield strength affect the rise time and velocity of the VISAR data



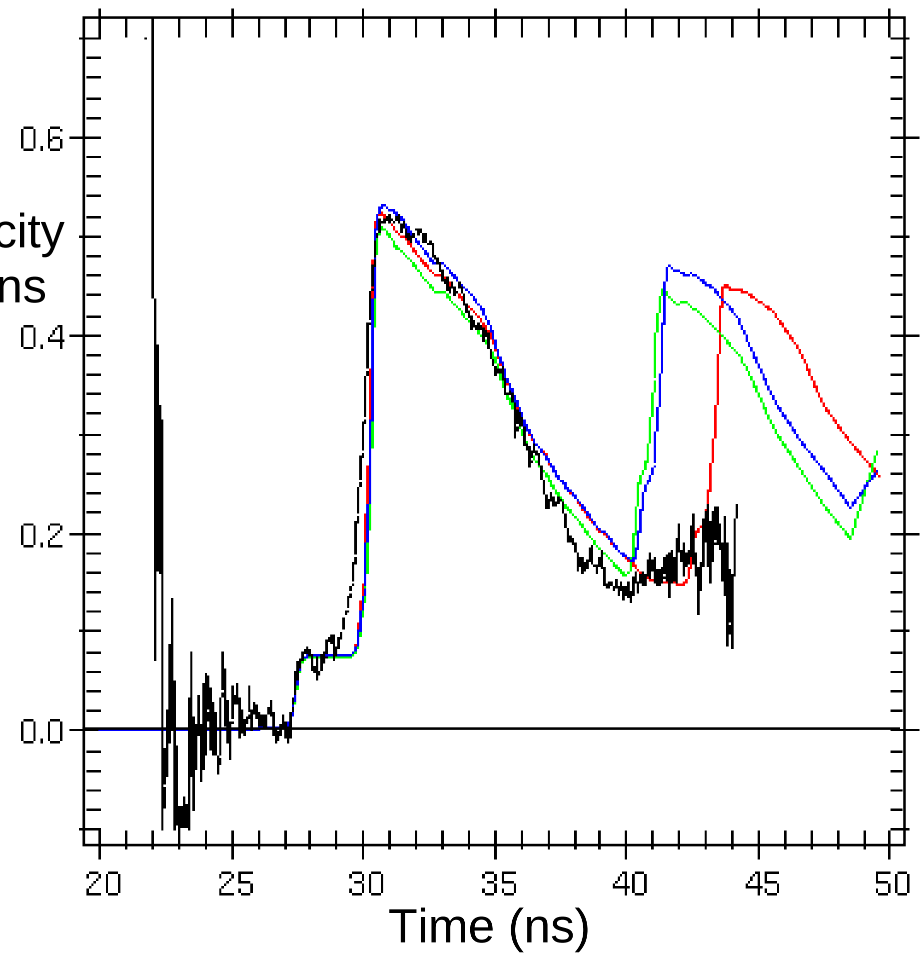
The shock strength decreases more rapidly with increasing yield strength



We can match rise times and velocities by varying bulk modulus, shear modulus and yield strength



The Steinberg-Guinan model by itself gives a spall time that is too late compared to the data



Data
Steinberg-Guinan
Steinberg-Lund
SG+Steinberg-Tipton failure model
$eps_{max} = 0.25$, $(\rho/\rho_0)_{min} = 0.9665$

Steinberg-Tipton Failure Model

Damage ranges from 0 to 1

Broken material: $Y_b < P$, $G_b/G_0 = Y_b/Y_0$

$\{P,G,Y\} = \text{damage}*\{P_0,G_0,Y_0\} + (1-\text{damage})*\{P_b,G_b,Y_b\}$

$$\frac{d}{dt}\text{Damage} = \begin{cases} \dfrac{RC_s}{\Delta X_{zone}} & \sum_i \max(0, \dfrac{f_i}{fmax_i})^2 > 1 \\ 0 & \sum_i \max(0, \dfrac{f_i}{fmax_i})^2 < 1 \end{cases}$$

$$C_s = \sqrt{\frac{4G_0}{3\rho}}$$

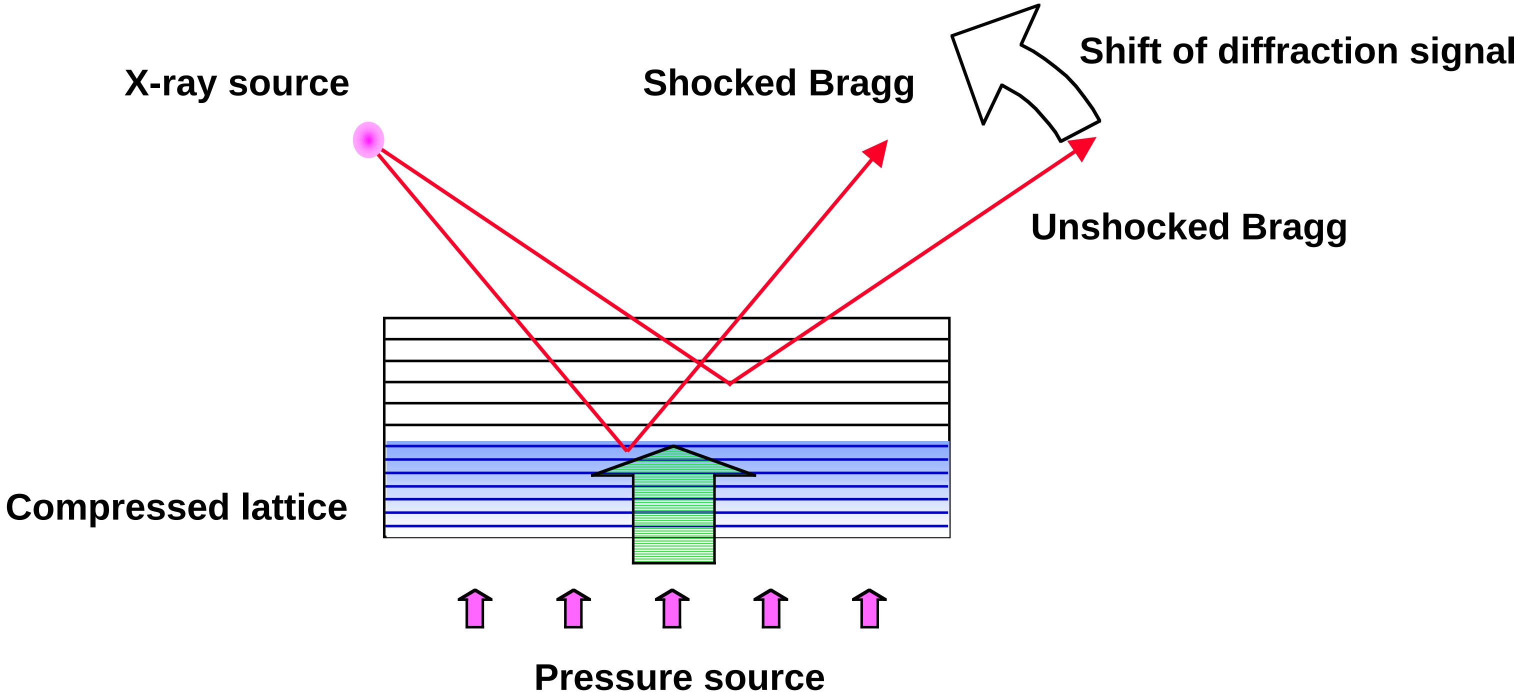
$f_i = \{\text{eps}, \rho/\rho_0 - 1, P, \sigma, \Delta\sigma\}$

Parameters

- Steinberg-Guinan
  - p_{min} = -30 kb
  - ρ/ρ_0 = 0.9665
  - K= 940 kb
  - G_0 = 325 kb
  - Y = 3.335 kb
  - eps_{max} = 2.0
- Steinberg-Tipton
  - $\rho/\rho_0 - 1$ = -.0335
  - eps = .25
  - R = 10^{20}
- Steinberg-Lund
  - Y = 1.5 kb
  - c_1 = .71
  - c_2 = .12
  - u_k = .31
  - y_{prl} = 1.9 kb

Dynamic x-ray diffraction measures density and crystal structure

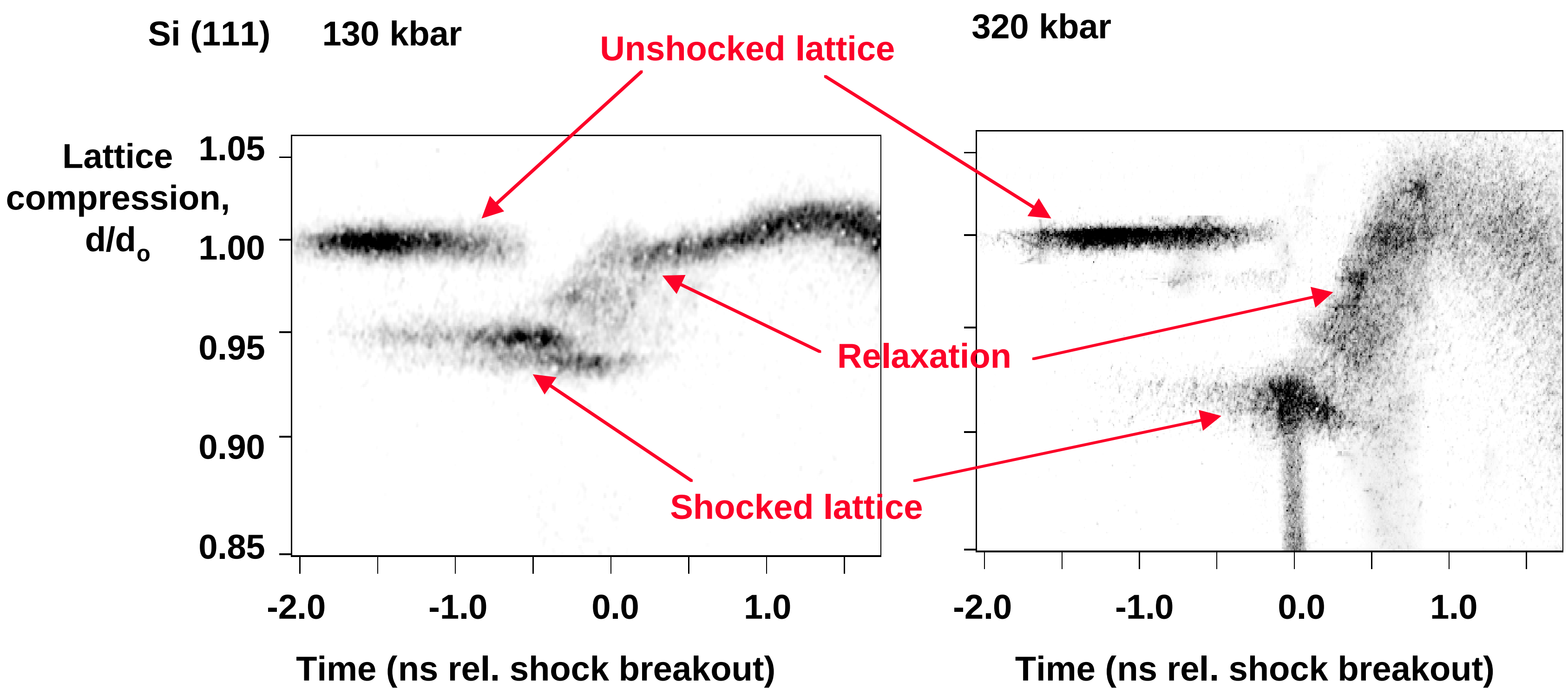
- **In situ x-ray diffraction allows us to probe the material state by providing information on the lattice under compression**
- **Technique applied on laser experiments at Nova and elsewhere (Janus, Vulcan, Trident, OMEGA) and powder and gas gun facilities**



Q. Johnson, A. Mitchell, R.N. Keeler, L. Evans, *Phys Rev Lett* **25**, 1099 (1970)
J..S Wark, R.R. Whitlock, A.A. Hauer, J.E. Swain, P.J. Solone, *Phys Rev B* **40**, 5705 (1989)

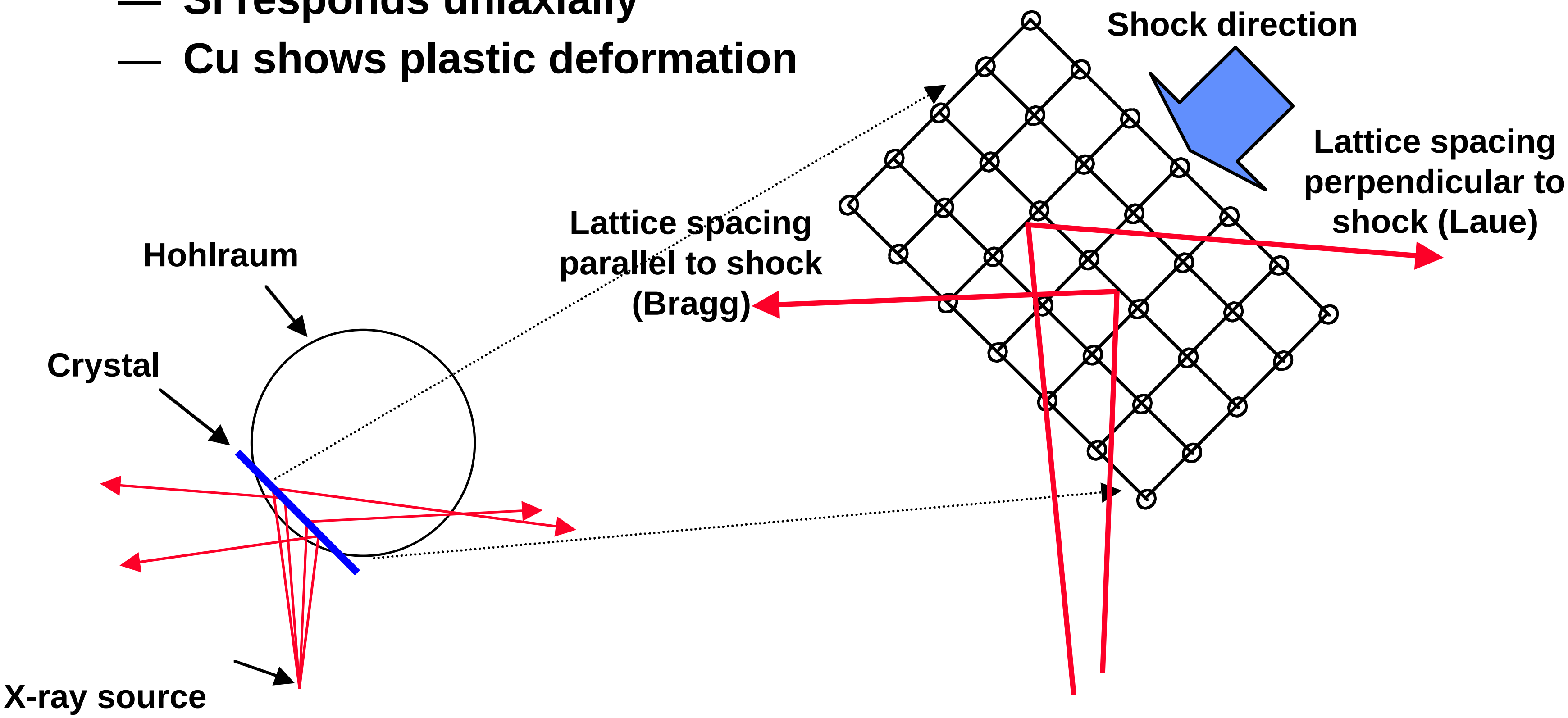
Diffraction from shock compressed Si has been demonstrated on Nova

- Low intensity square laser pulse generates a single shock drive
- Displacement of the diffraction signal indicates a compression of the lattice spacing



Diffraction from orthogonal lattice planes provides information on the transition to plasticity

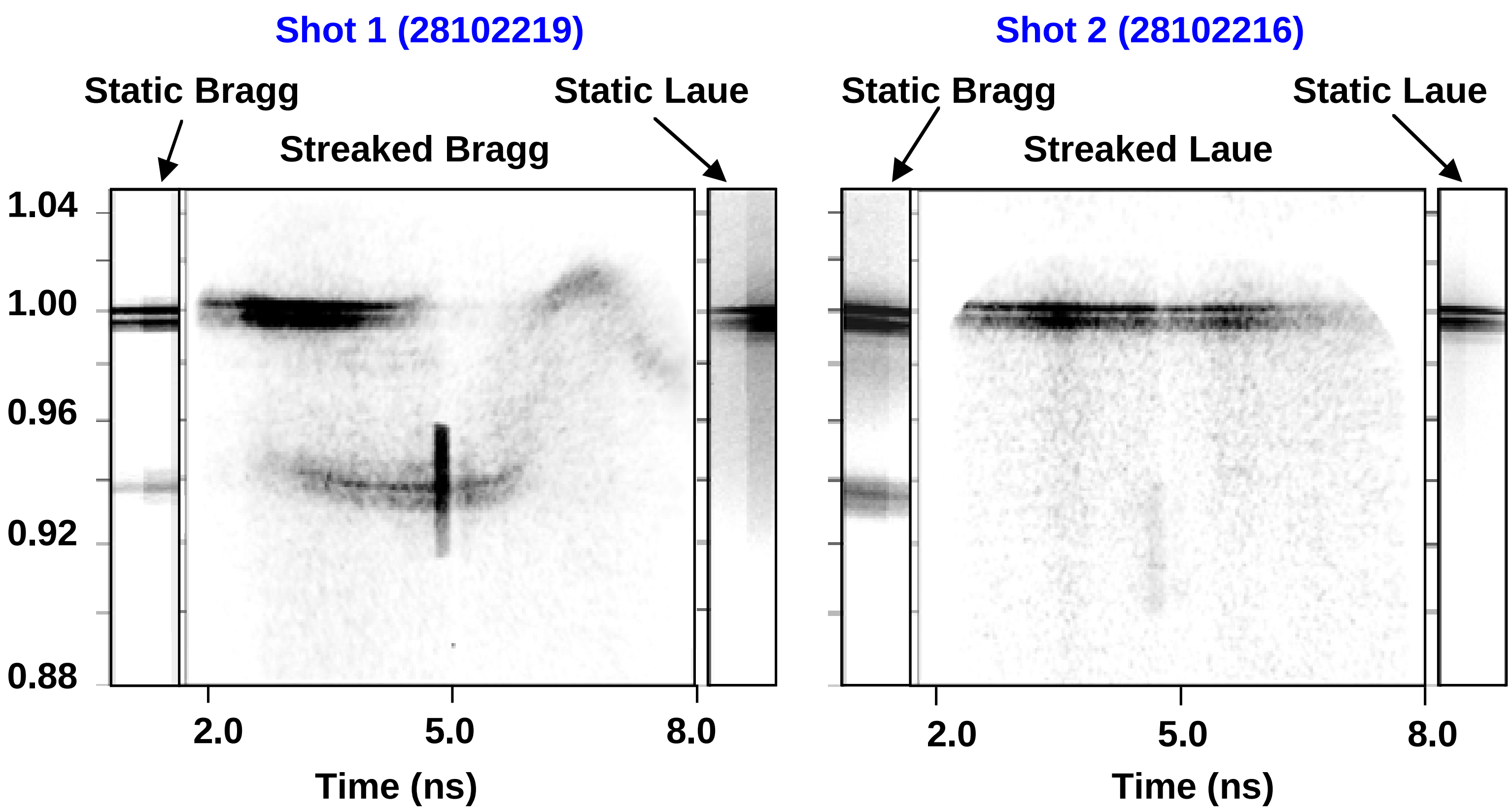
- Simultaneous measurements are made of compression of orthogonal lattice planes
- Shock compression above the HEL for Si and Cu show very different behavior on the ns time scale[1]
  - Si responds uniaxially
  - Cu shows plastic deformation



[1] A. Loveridge et al, *"Anomalous elastic response of silicon to uniaxial shock compression on nanosecond timescales"*, Phys. Rev. Letters **86**, 2349 (2001)

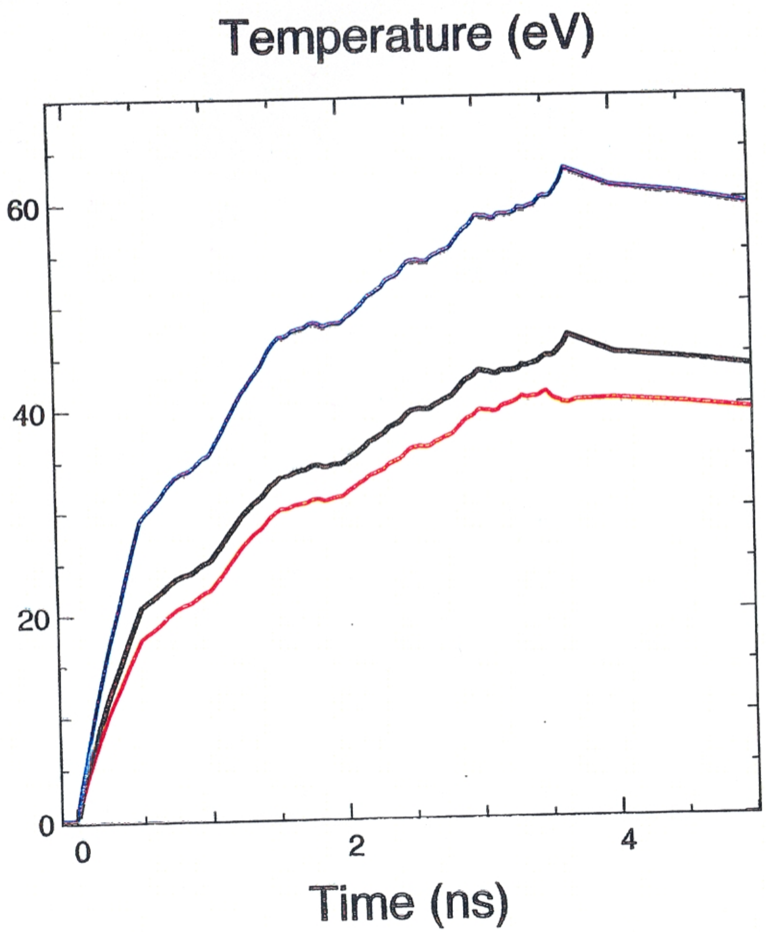
Simultaneous measurements of orthogonal planes indicate Si responds uniaxially on a ns time scale

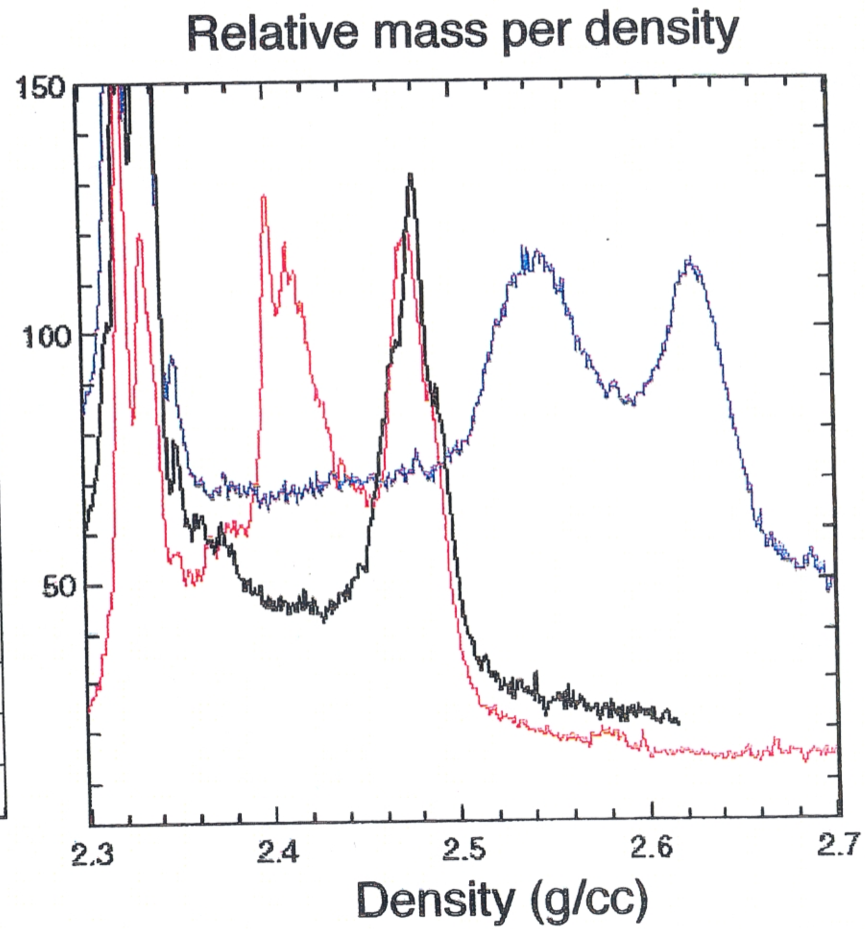
- Si shock compressed along (400); probed along (400), (040)
- P = 115-135 kbar; HEL = 84 kbar, 40 μm thick Si
- Simultaneous measurements of Bragg and Laue diffraction



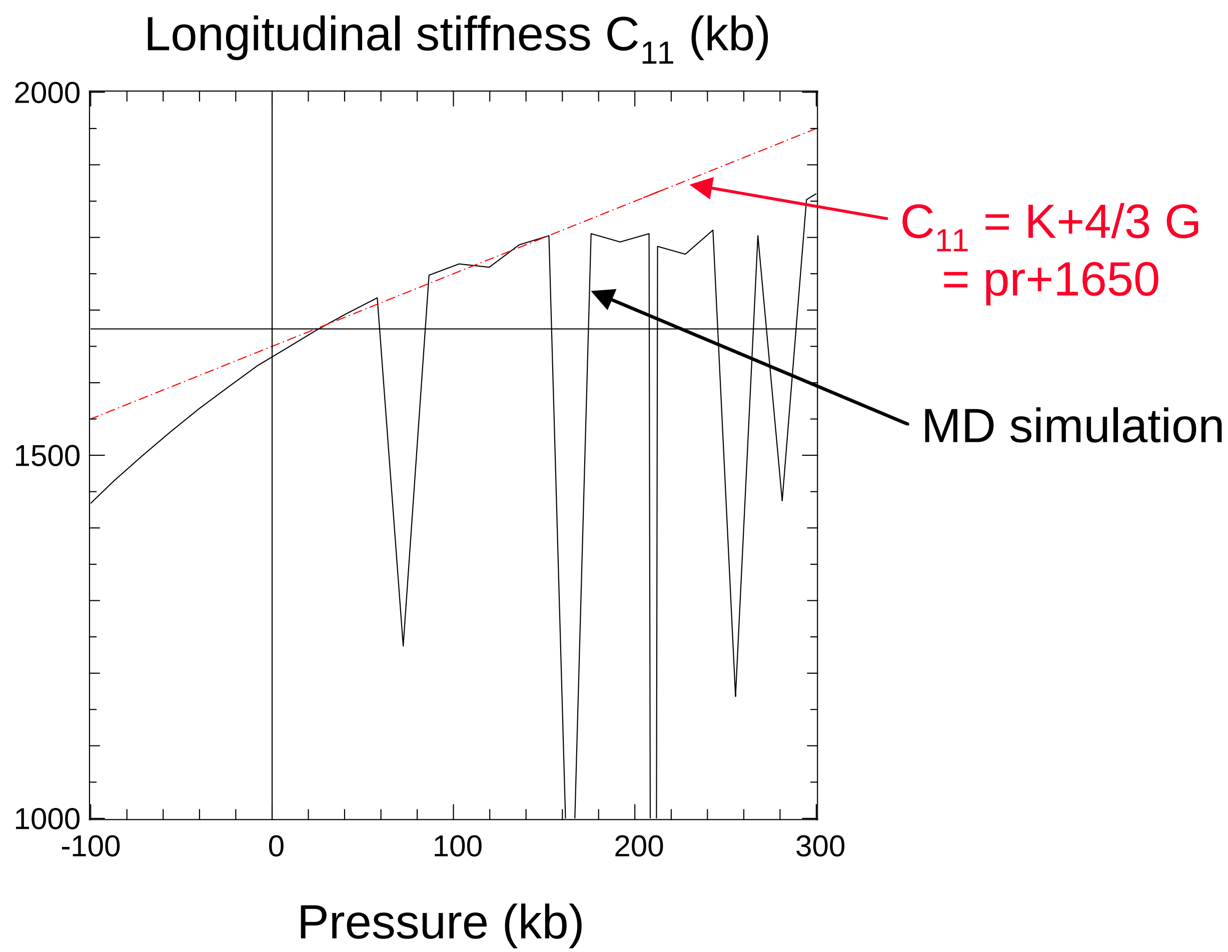
1-D compression in Si is due to high Peierls barrier

X-ray diffraction of 40 μm Si shows density features that vary with drive temperature



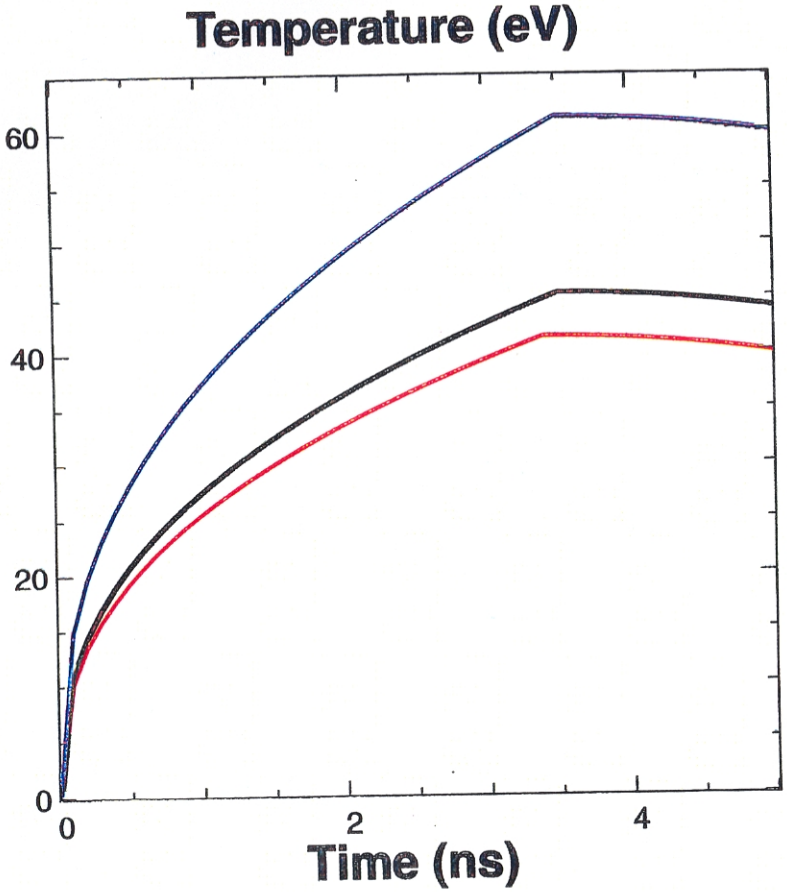


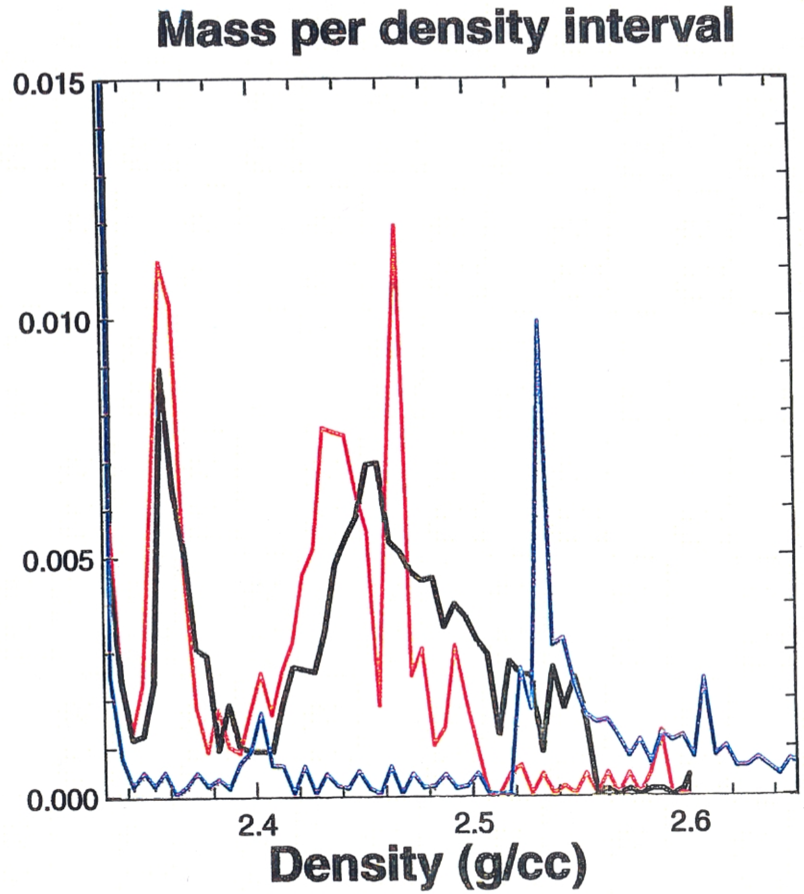
Molecular dynamic simulations show that the Si longitudinal stiffness increases with pressure



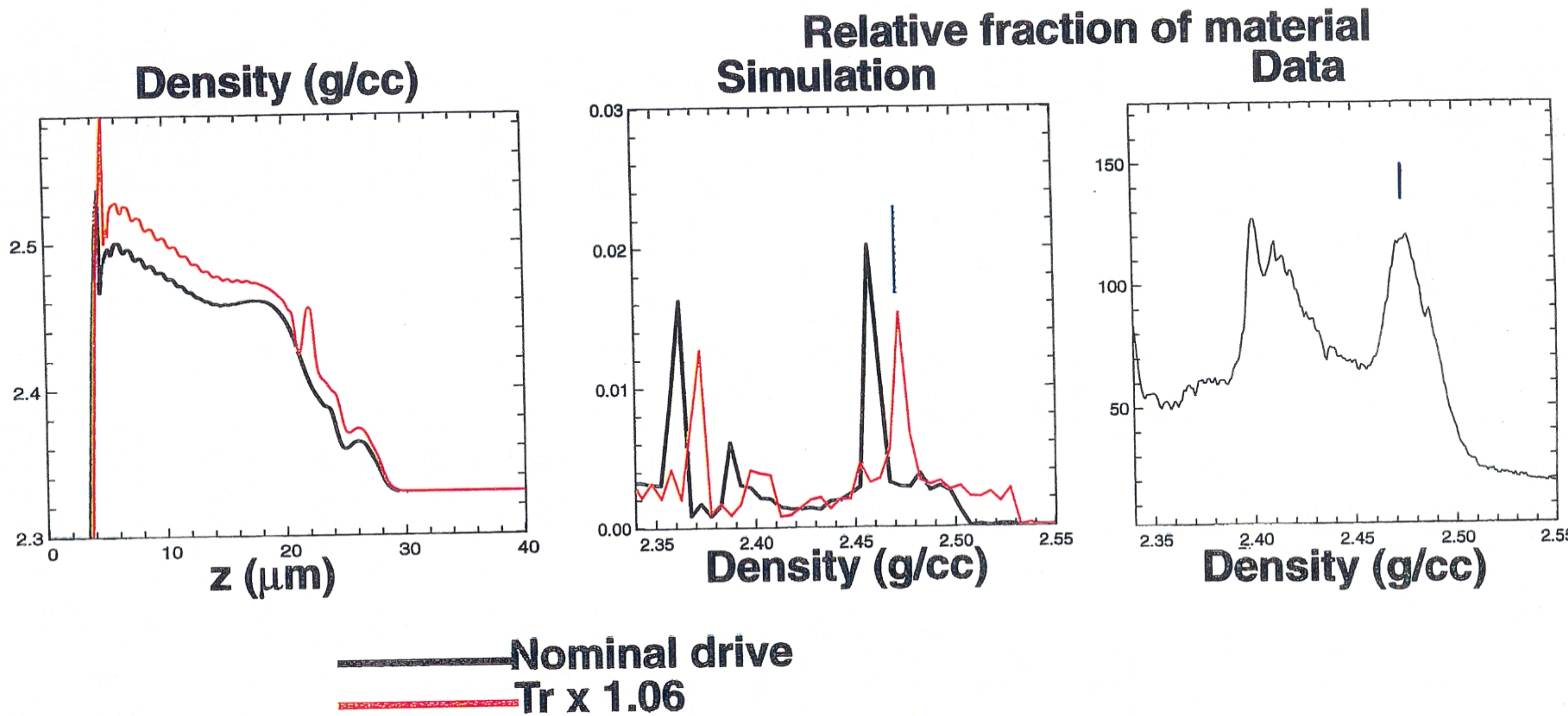
Simulation done by D. J. Roundy

The density structure depends in a complicated way on the drive temperature



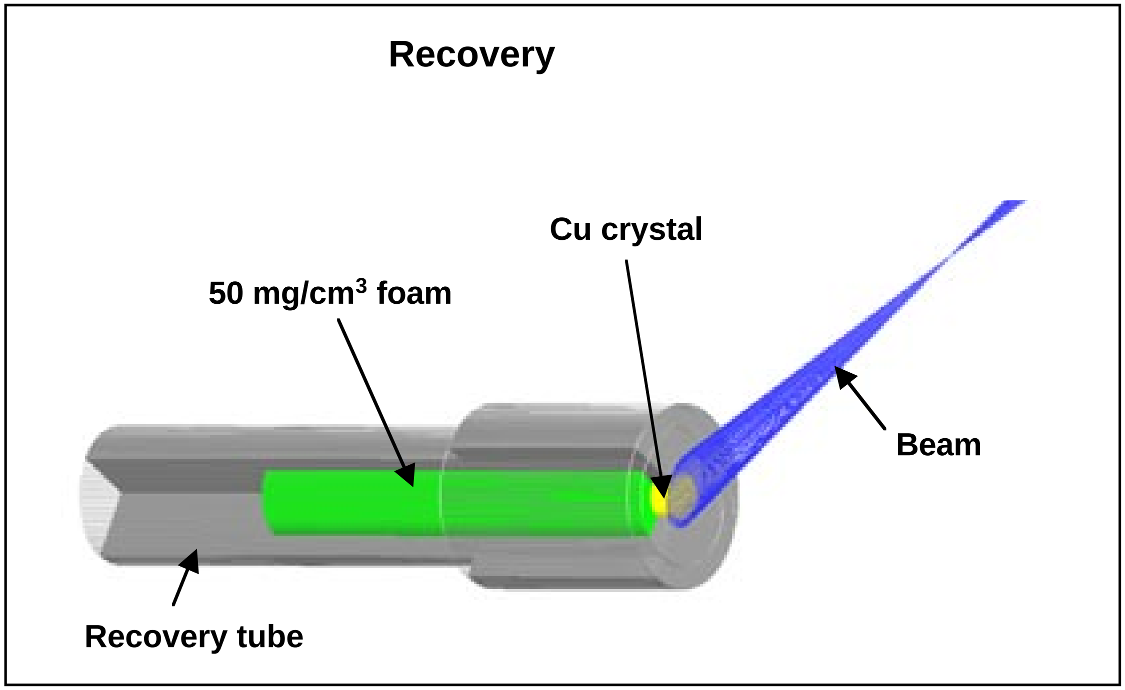


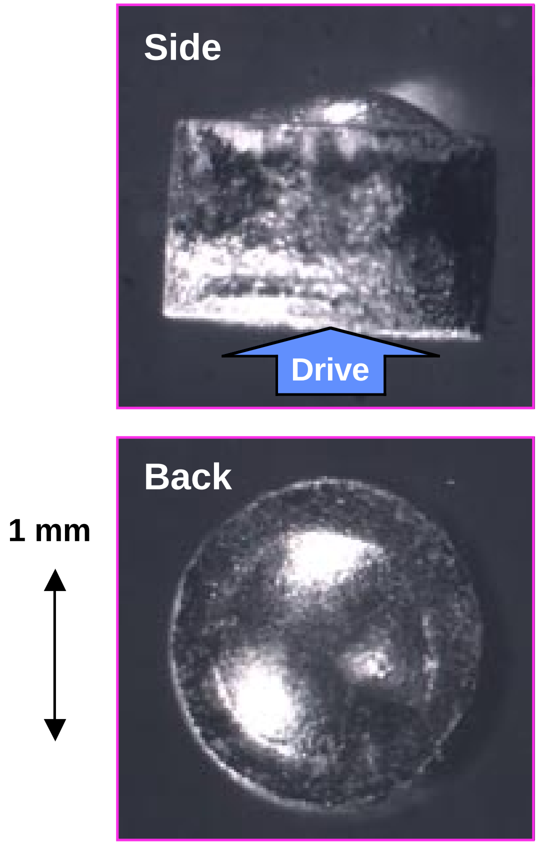
By increasing the drive, we can match part of the data



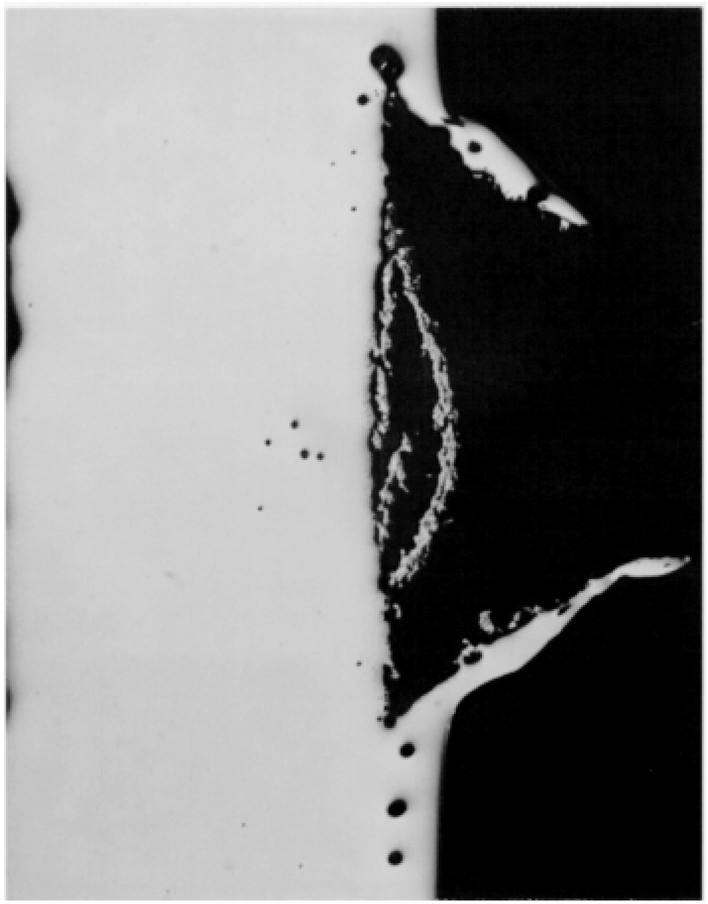
We have recovered samples to study the residual effects due to these high strain rate laser experiments

- Single crystal Cu samples were shocked by direct laser irradiation and captured in a foam-filled cavity
- Preliminary tests done at OMEGA; shock pressure is >1 Mbar, decays to ~50 kbar at the rear surface

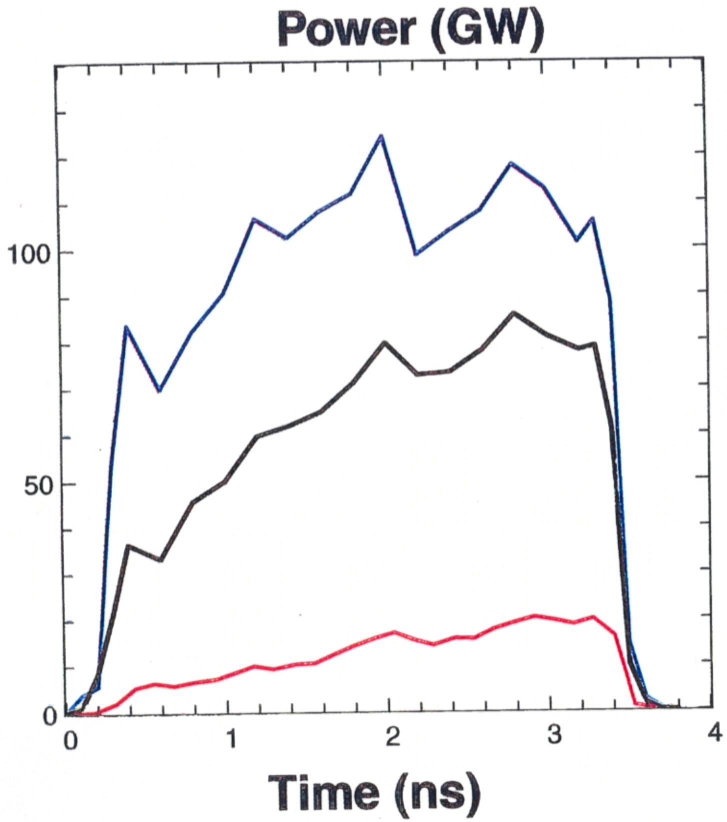


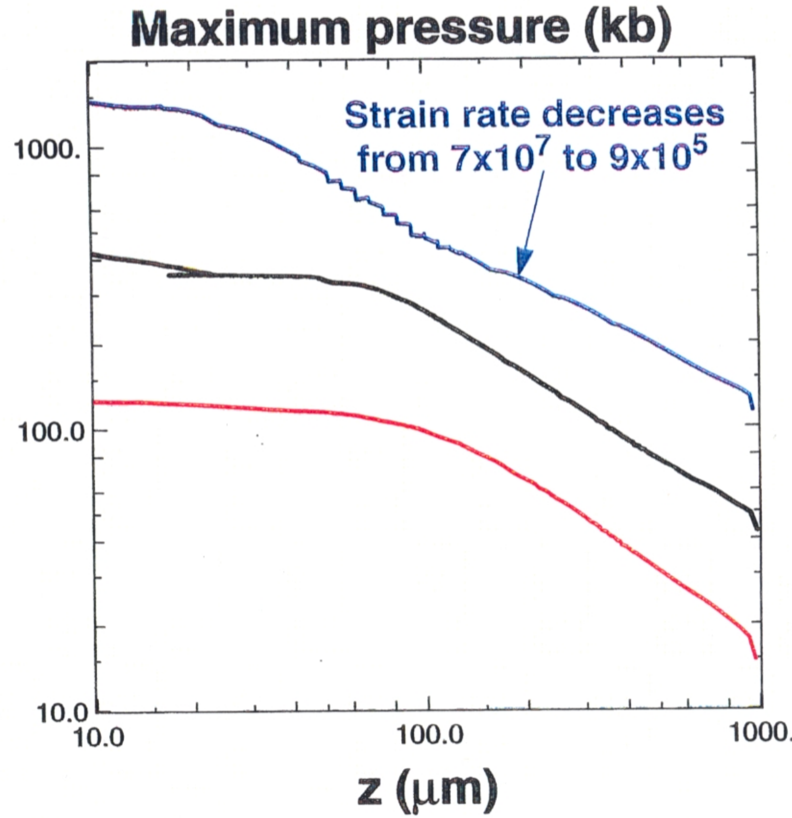


We see spall on a Cu sample driven by Janus



Shock strength falls roughly as distance$^{-3/4}$ in Cu





Summary and future work

- VISAR provides free surface velocity history
    - Gives shear modulus, bulk modulus and yield strength
    - Gives information on fracture model and spall
- X-ray diffraction provides information about lattice deformation

- Future work
    - Correlate VISAR with x-ray diffraction
    - Relate VISAR with post-shock recovery and residual deformation of structure