Laser-based high-pressure, high-strain-rate materials experiments

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Presented by Thomas Lorenz

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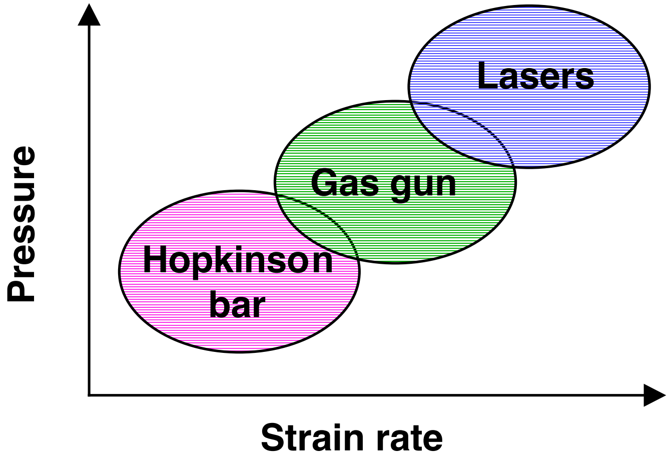
Outline

- Introduction
  - Solid-state experiments at high pressure on a laser
- High pressure strength
  - RT instability in solid Al at high pressure to infer Y(P)
- Dynamic material response
  - Dynamic x-ray diffraction of the lattice level response in Si and Cu
- Wave profile and residual deformation
  - VISAR measurement, sample recovery and characterization

The high pressure response of materials is of interest for many reasons; lasers provide a way to access high pressures and strain rates

- The core of the earth is Fe at 3 Mbar, both solid and liquid
  - Long time scale, diamond anvil experiments
- Survivability of passengers in a car crash depend on the material response of the car
  - ms-μs time scale, Hopkinson bar and gun experiments
- Space station wall integrity from space debris, dust, micro-asteroids
  - μs time scale, gun and high explosives experiments

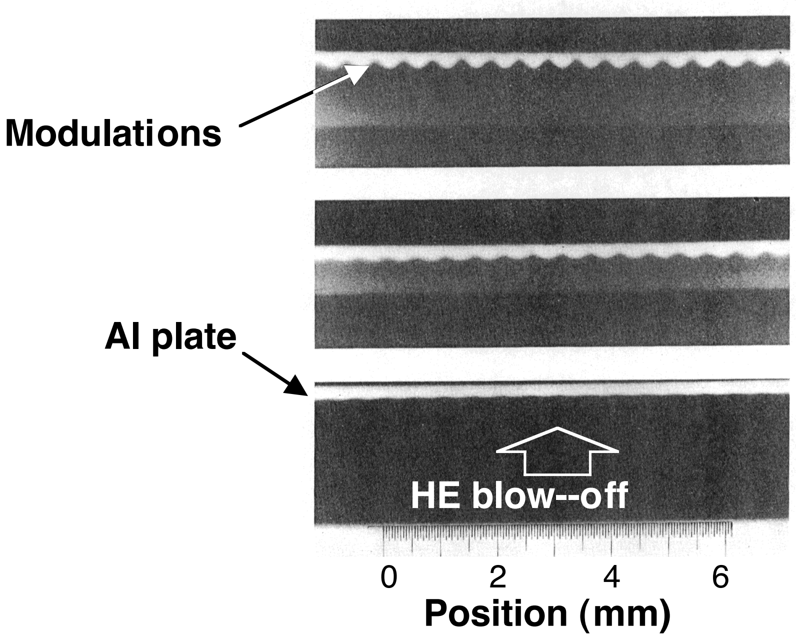


Lasers access unique high pressure, high strain rate regime of material response to test the limits of theories and scaling laws

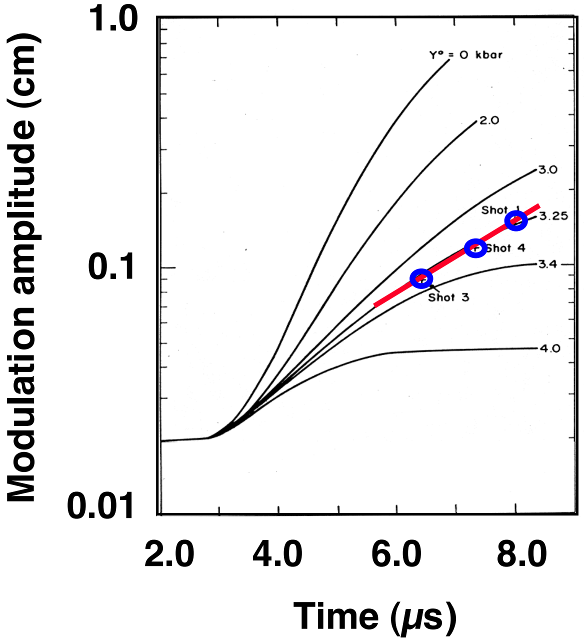
Example - strength measurements at high pressure using a high explosive drive and modulated Al plate

- Shockless HE drive used to compress and accelerate a plate with pre-imposed modulations
- Pre-imposed modulations grow by the Rayleigh-Taylor instability
- The growth is reduced from classical (fluid) due to material strength

Al plate experiment



Growth is reduced from fluid

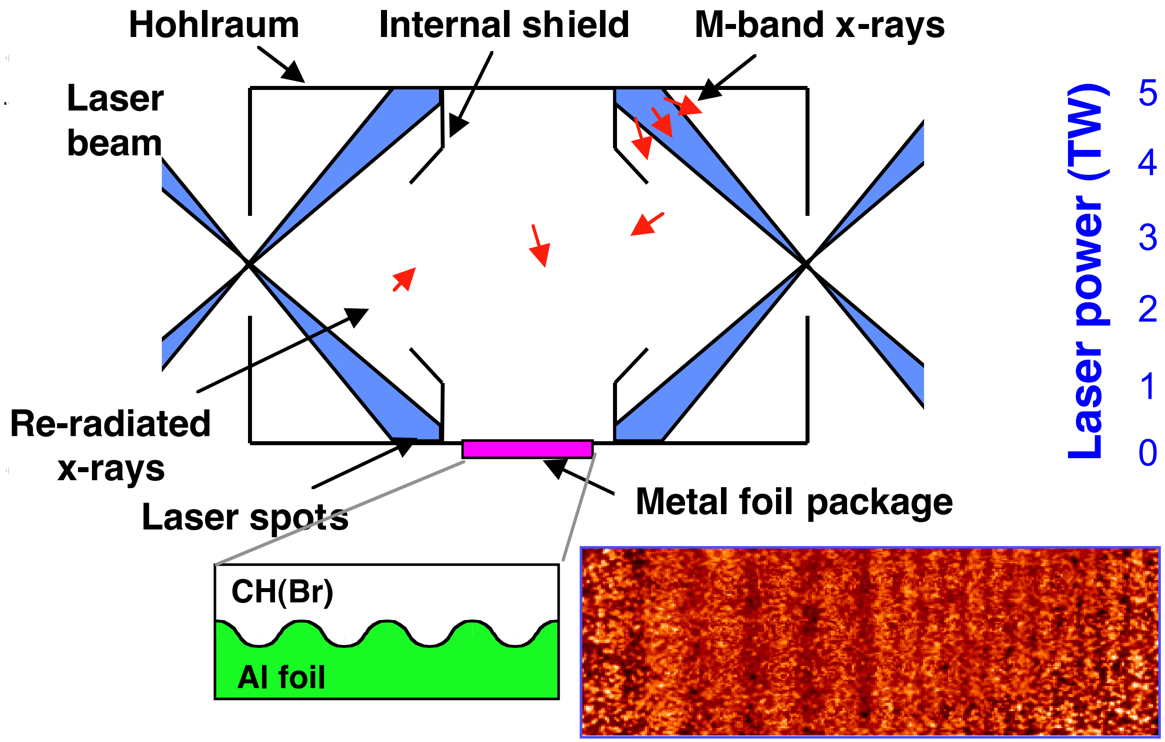


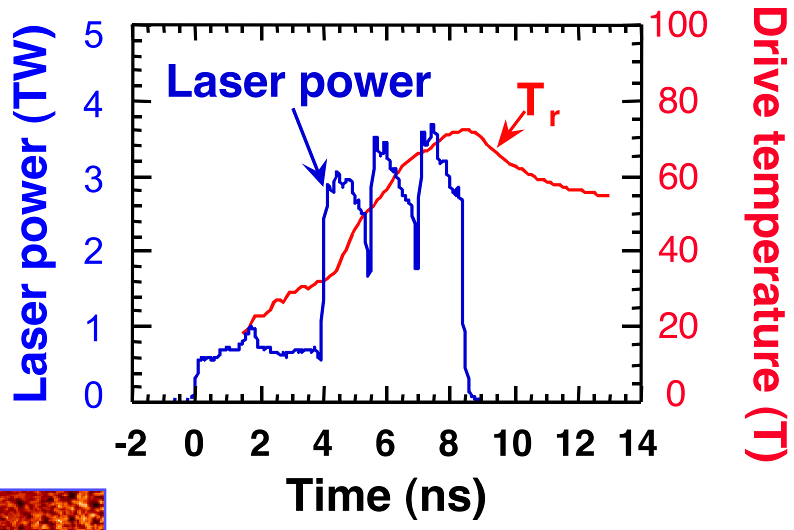
Barnes *et al*, J. Appl. Phys. 45, 727 (1974).

Also Rayevsky and Lebedev

1. Solid state RT instability experiment

- An internally shielded hohlraum is used to shock compress an Al-6061 metal foil at high pressure
- Internal shields block hard x-rays from preheating package
- A shaped laser pulse generates a series of gentle shocks for nearly isentropic compression



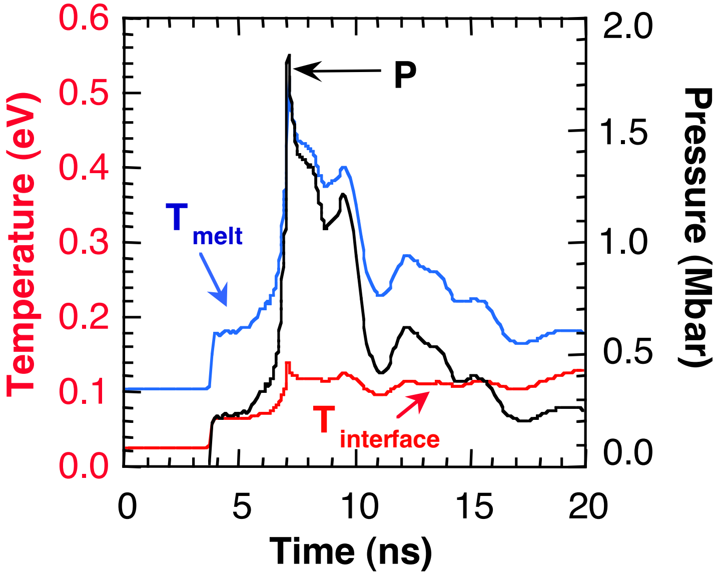


Detailed simulations predict that the Al foil remains solid throughout the experiment

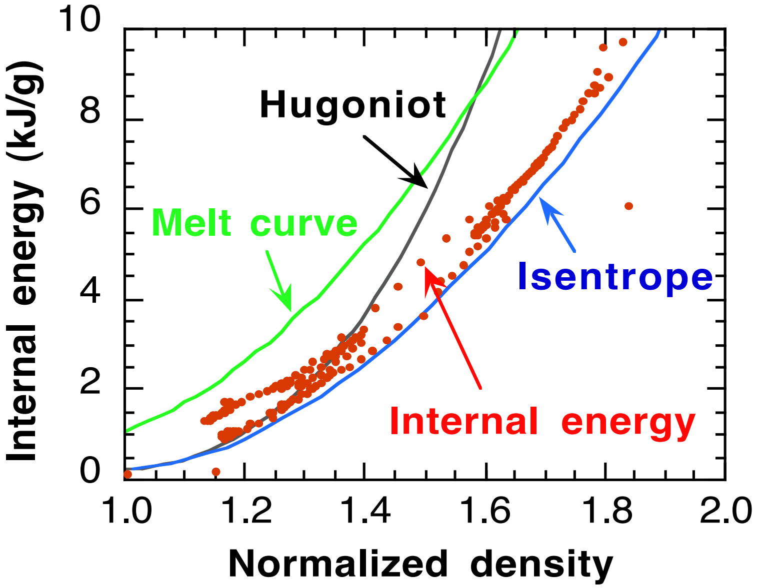
- The Al remains below the melt curve
- The foil trajectory is nearly isentropic to 1.8 Mbar

Lindemann melt model $$T_m = T_{m_o} e^{2a(1-\eta)} \eta^{2(\gamma_o - a - 1/3)}$$

Pressure and temperature at the embedded interface



Calculated internal energy trajectory



Simulations of the instability growth demonstrate sensitivity to the strength of the Al

- **Growth rates with strength are expected to be reduced from classical (fluid)**

Steinberg-Guinan constitutive model

$$Y = Y_o\left(1 + \beta\left(\varepsilon + \varepsilon_i\right)\right)^n \frac{G(P,T)}{G_o}$$

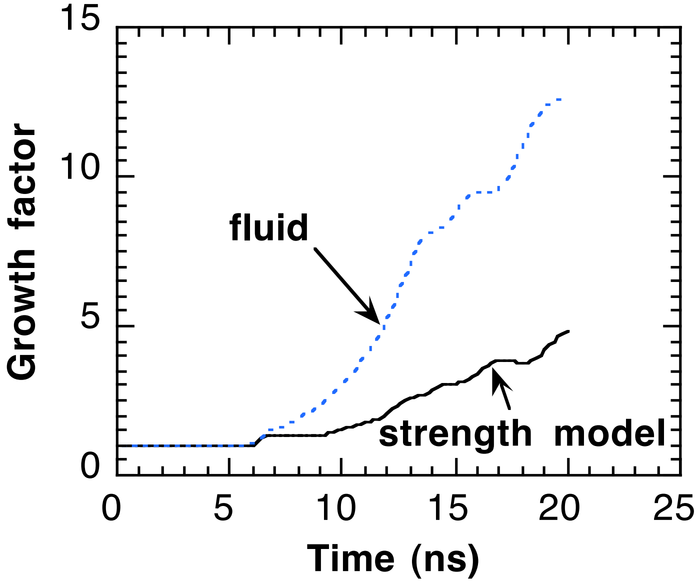
$$G = G_o\left(1 + \left(\frac{G'_P}{G_o}\right)\frac{P}{\eta^{1/3}} - \left(\frac{G'_T}{G_o}\right)(T - 300)\right)$$

Rayevsky Stability boundary formula

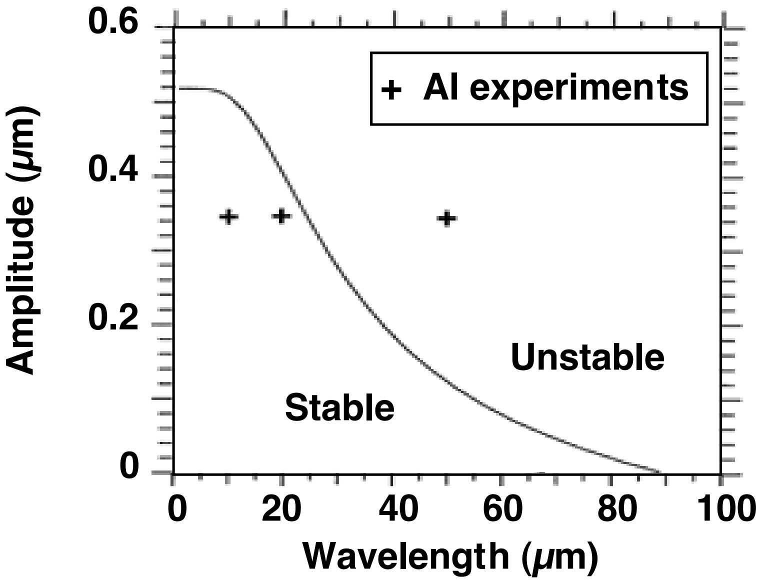
$$\eta_c = \eta_D\left[1 - 0.86e^{-\frac{2\pi H}{\sqrt{3\lambda}}}\right]\left\{\left[1 - e^{-\frac{2\pi H}{\sqrt{3\lambda}}}\right]^2 - \left[\frac{\lambda}{\lambda_M}\right]^2\right\}$$

$$\eta_D = \frac{2Y}{\rho g} \qquad \lambda_M = \frac{4\pi G}{\rho g}$$

Predicted growth factors λ=20 μm

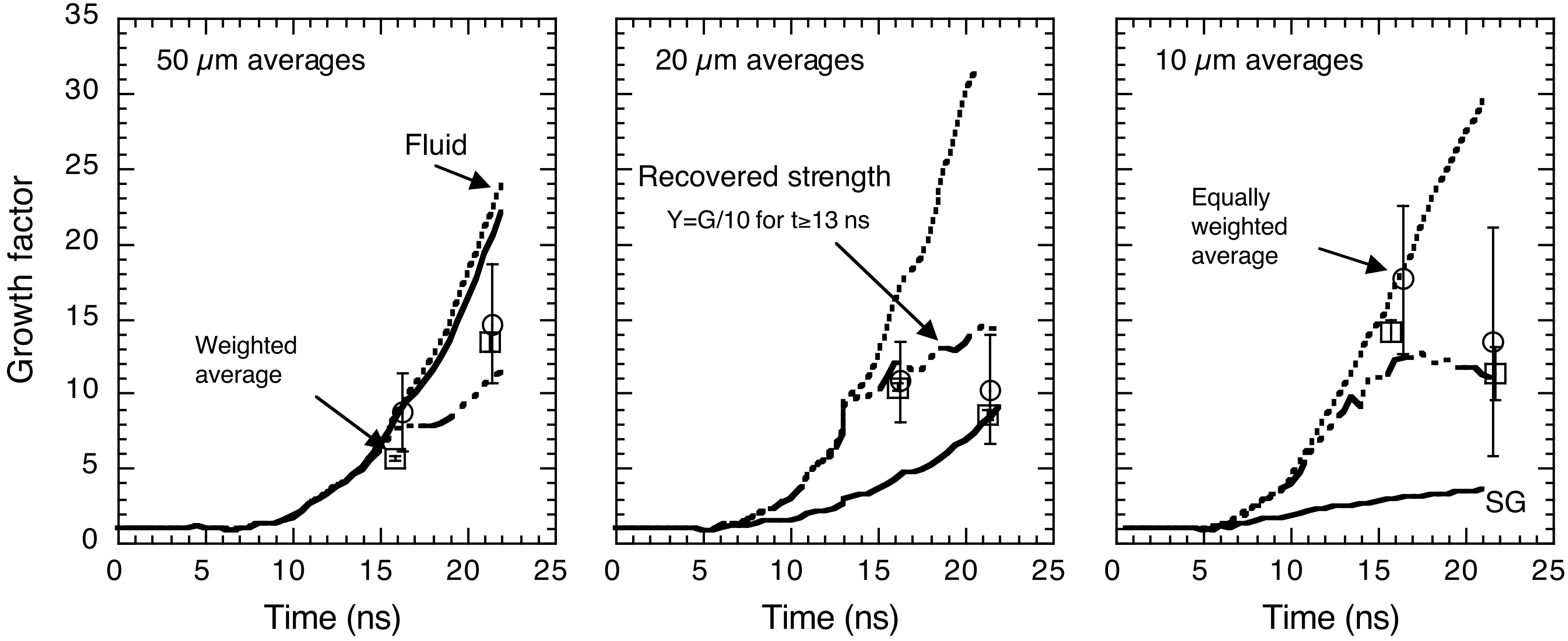


Stability curve (Nizovtsev and Rayevsky, 1991)



The RT growth is nearly fluid at early times, but it is suppressed at later times

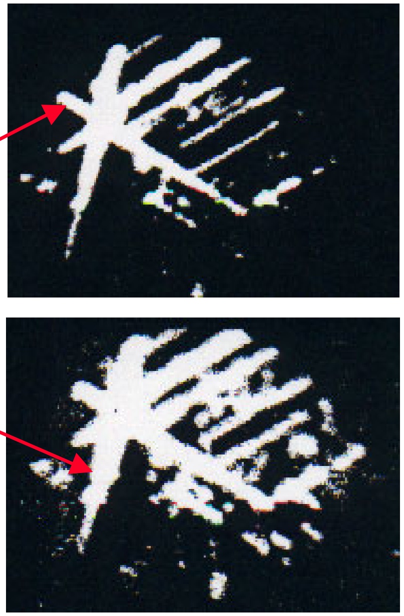
- Experiments were conducted with 10, 20 and 50 *μ*m wavelengths
- Modeling was done assuming the following:
  - Fluid
  - Nominal Steinberg-Guinan
  - Fluid until 13 ns, then S-G with theoretical maximum Y=G/10



The RT growth is nearly fluid at early times, but it is suppressed at later times; suggestive of model from Grady/Asay and data by Rayevsky and Lebedev

- High pressure strain causes localized heating and softening in shear bands; bulk Al flows as fluid due to localized deformation
- As heat conducts into the bulk material, the metal regains bulk solid strength and continued growth is inhibited

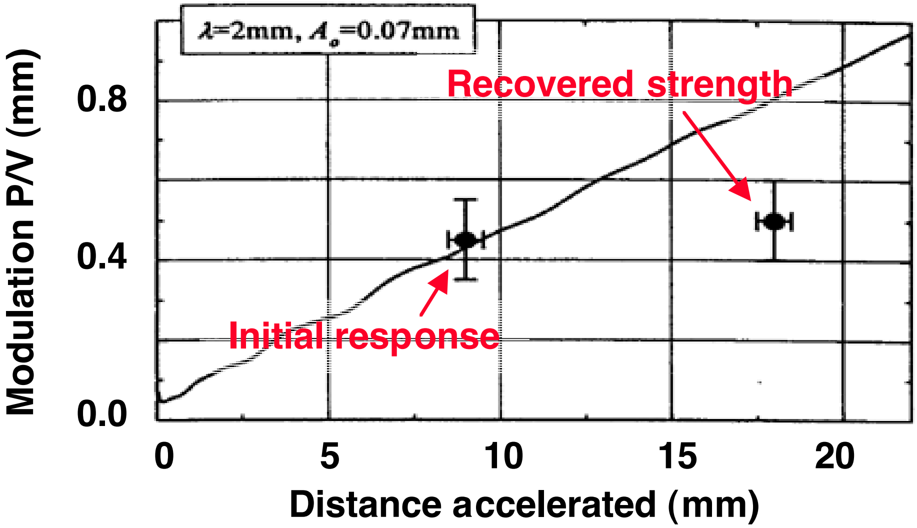
Optical emission from shocked quartz



Heating in localized regions of lattice

Brannon *et al*, SCCM 1983.

Shocked HE experiments show fluid-like response with saturation



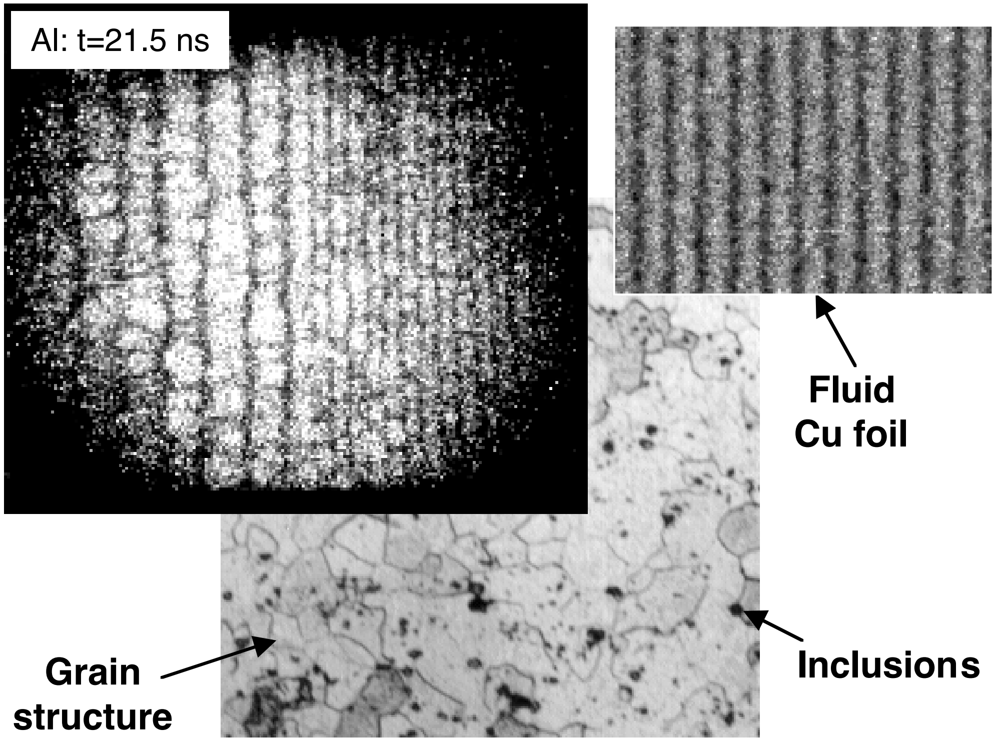
Recovered strength

Initial response

Rayevsky *et al*, IWPCTM, 1999.

The late time images show features that may be due to hydrodynamic imprinting of the grain structure

- The spatial scale of the late-time modulation is similar to initial grain structure
- 2D simulations incorporating the grain boundaries start to show effects at t=18 ns, 3D simulation has been started

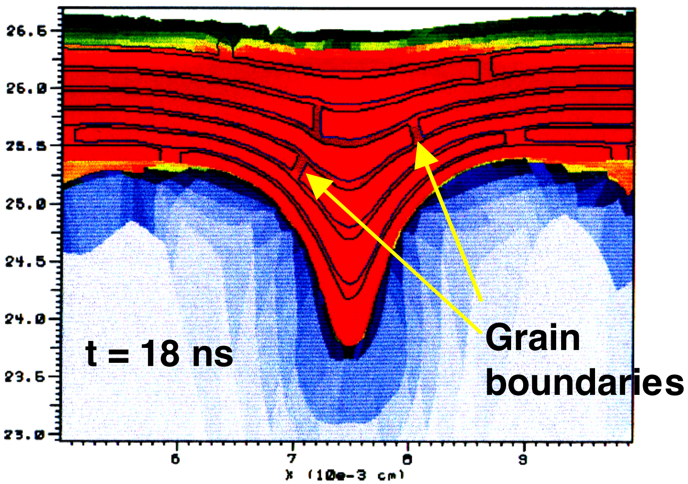


Fluid Cu foil

Grain structure

Inclusions

2D simulation including grain structure

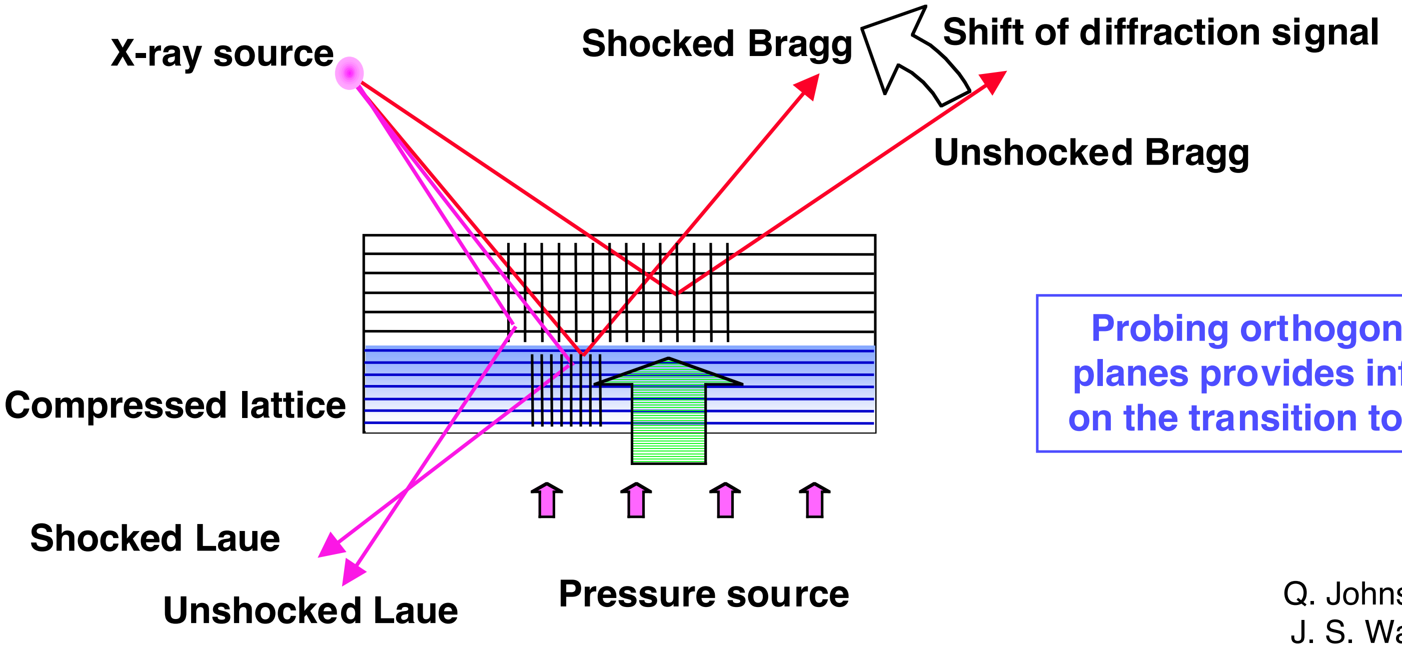


$Y_{grain} = Y_{SG}$ $Y_{boundary} = 0$

Simulations by G. Bazan, 2001

2. Dynamic x-ray diffraction

- *In situ* x-ray diffraction probes the long range lattice order under shock compression
- Shock pressure generated using a hohlraum x-ray drive or by direct laser irradiation
- Time-resolution with x-ray streak cameras provides information on dynamic lattice response

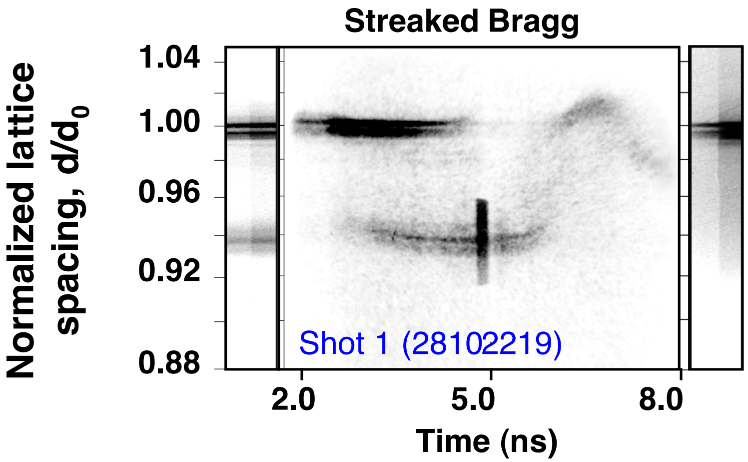


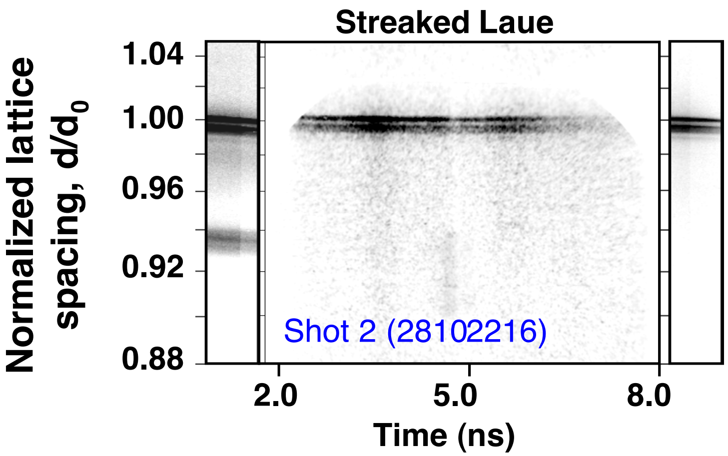
Probing orthogonal lattice planes provides information on the transition to plasticity

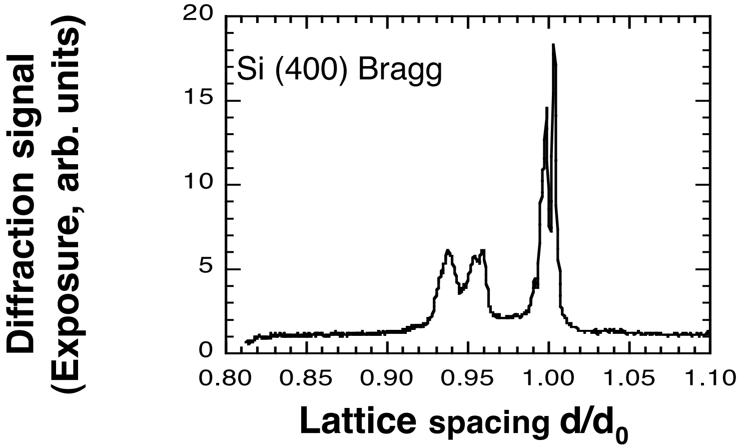
Q. Johnson *et al*, 1970;
J. S. Wark *et al*, 1989.

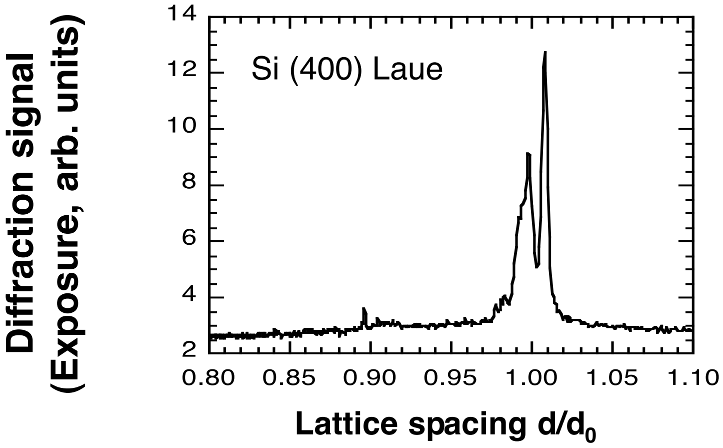
Simultaneous measurements of orthogonal planes indicates Si responds uniaxially on a ns time scale

- 40 μm thick Si shocked along (100) axis
- P=115-135 kbar; HEL=84 kbar



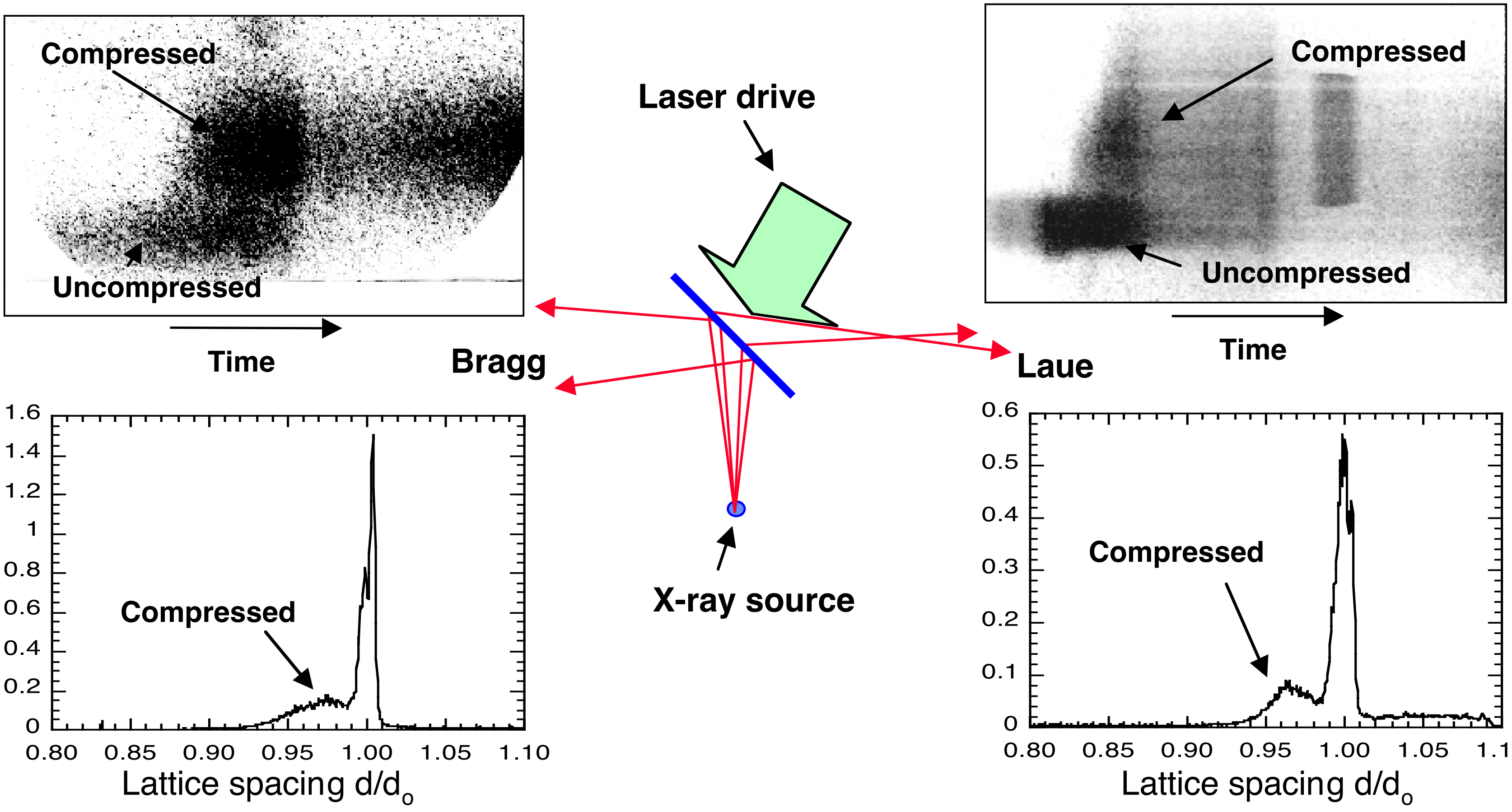






Cu undergoes a transition to 3D lattice compression at high pressure

- 8 μm single crystal Cu shocked along (100) axis
- P = 180 kbar; HEL ~ 2 kbar



The timescale for plastic deformation in Si is much longer than for Cu based on Orowan's equation

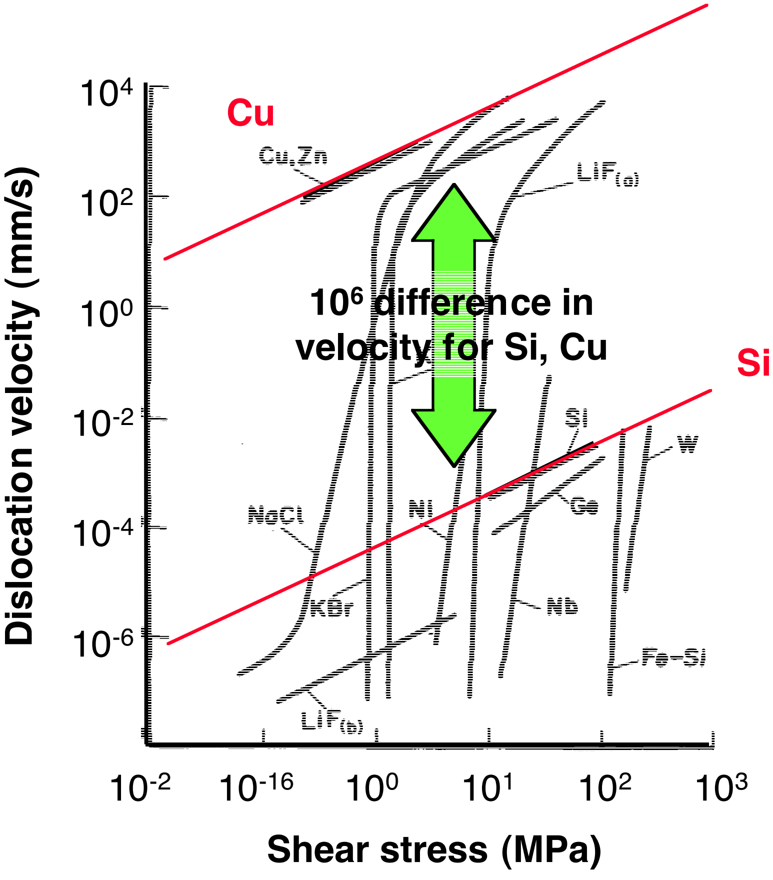
Orowan equation: $\frac{\Delta\varepsilon}{\Delta t} = N\,|\mathbf{b}|\,\mathbf{v}$

Silicon

- **$\Delta t > 1\ \mu s$: dislocations do not move**
  - 5% strain, dislocations separated by at least the Burger's vector (3.8 Å) (diffraction linewidth indicates $N < 10^{14}\ m^{-2}$)
  - Linear extrapolation of dislocation velocity in Si (0.1 mm/s)

Copper

- **$\Delta t < 10$ ps : dislocations do move**
  - 5% strain, dislocations separated by at least the Berger's vector (2.5 Å)
  - Velocity of dislocations calculated to be 400 m/s in MD simulations



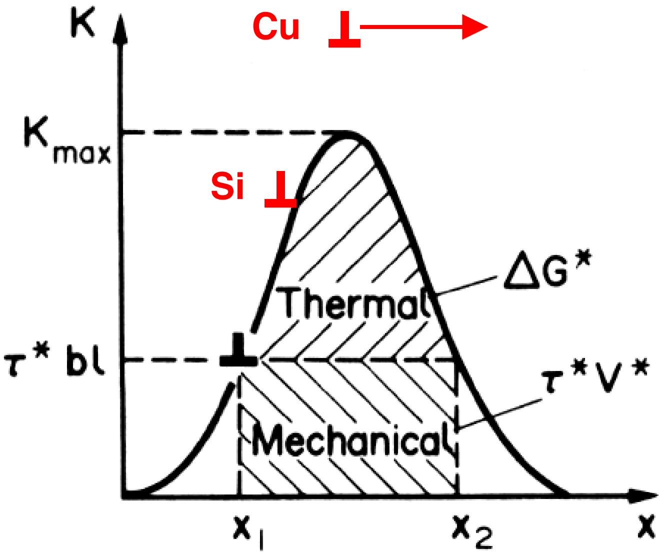
Introduction to Dislocations, Hull and Bacon (Fig. 3.12)

The time scale for plastic deformation in Si is much longer than for Cu, due to its high Peierls barrier and activation energy

- For $\sigma < Y_P$: thermal activation regime, and

$$t = t_{wait} = \frac{1}{\nu_{attempt} \exp\left[\frac{-\Delta F}{kT}\left(1 - \frac{\sigma}{Y_P}\right)^2\right]}$$

- For $\sigma > Y_P$: phonon drag regime, $t = t_{run} = \dfrac{aB}{\sigma b}$



Assume that σ = 3 GPa, and kT = 0.05 eV:

For Si:

$Y_P = 0.07G_0(1+AP/\eta^{1/3}) > 0.07G_0$
giving $Y_P > 0.07$ (63.7 GPa) = 4.5 GPa,
$\Delta F = 0.2Gb^3 = 0.2$ (63.7GPa) (3.83 A)^3 = 4.5 eV

So $\sigma < Y_P$, and kT << ΔF: thermal activ. regime

Assume $\nu_{attempt} = \nu_{Debye}/100 = 10^{11}\ s^{-1}$,
So $1/t_{wait} = (10^{11}\ s^{-1}) \exp[-(4.5/.05)\ (1- 3/4.5)^2]$

Giving t_{wait} > ~150 ns, meaning slow

For Cu:

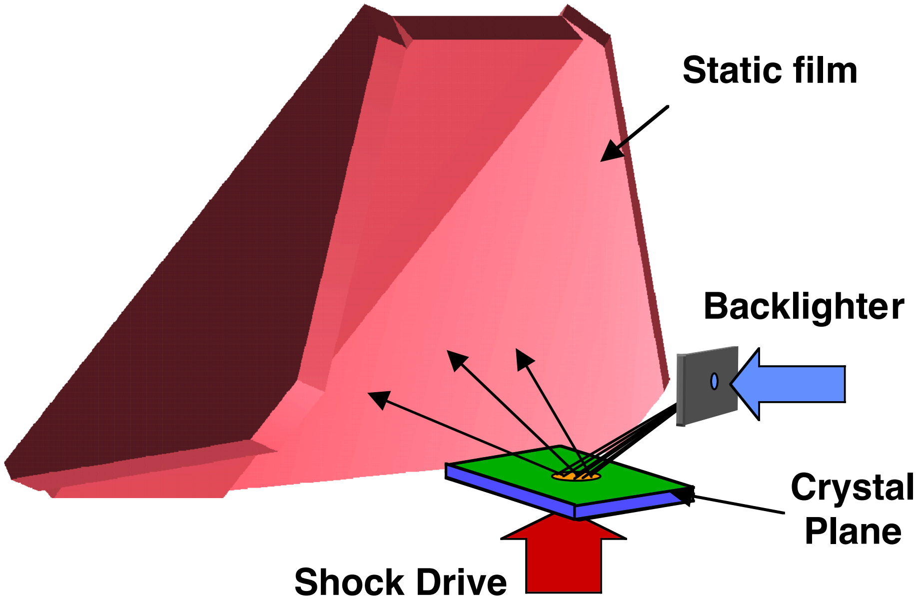
$Y_P = (6.3 \times 10^{-3})G_0(1+AP/\eta^{1/3}) = 0.42$ GPa
So $\sigma > Y_P$, meaning phonon drag regime

Assume B = 10^{-10} MPa·s, and a/b < 10^3,

So $t_{run} < (10^3)\ (10^{-10}$ MPa·s)/(3 GPa) = 30 ps: fast

A new wide-angle film detector is used to record many more lattice planes

- X-rays diffracted from orthogonal lattice planes are recorded with 2 x-ray streak cameras
- A segmented film assembly records x-rays diffracted over a π-solid angle from many more lattice planes



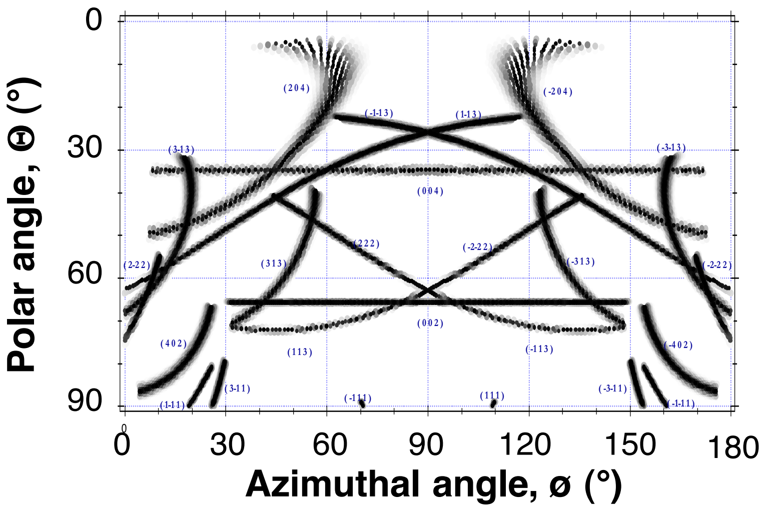
Static film

Backlighter

Crystal Plane

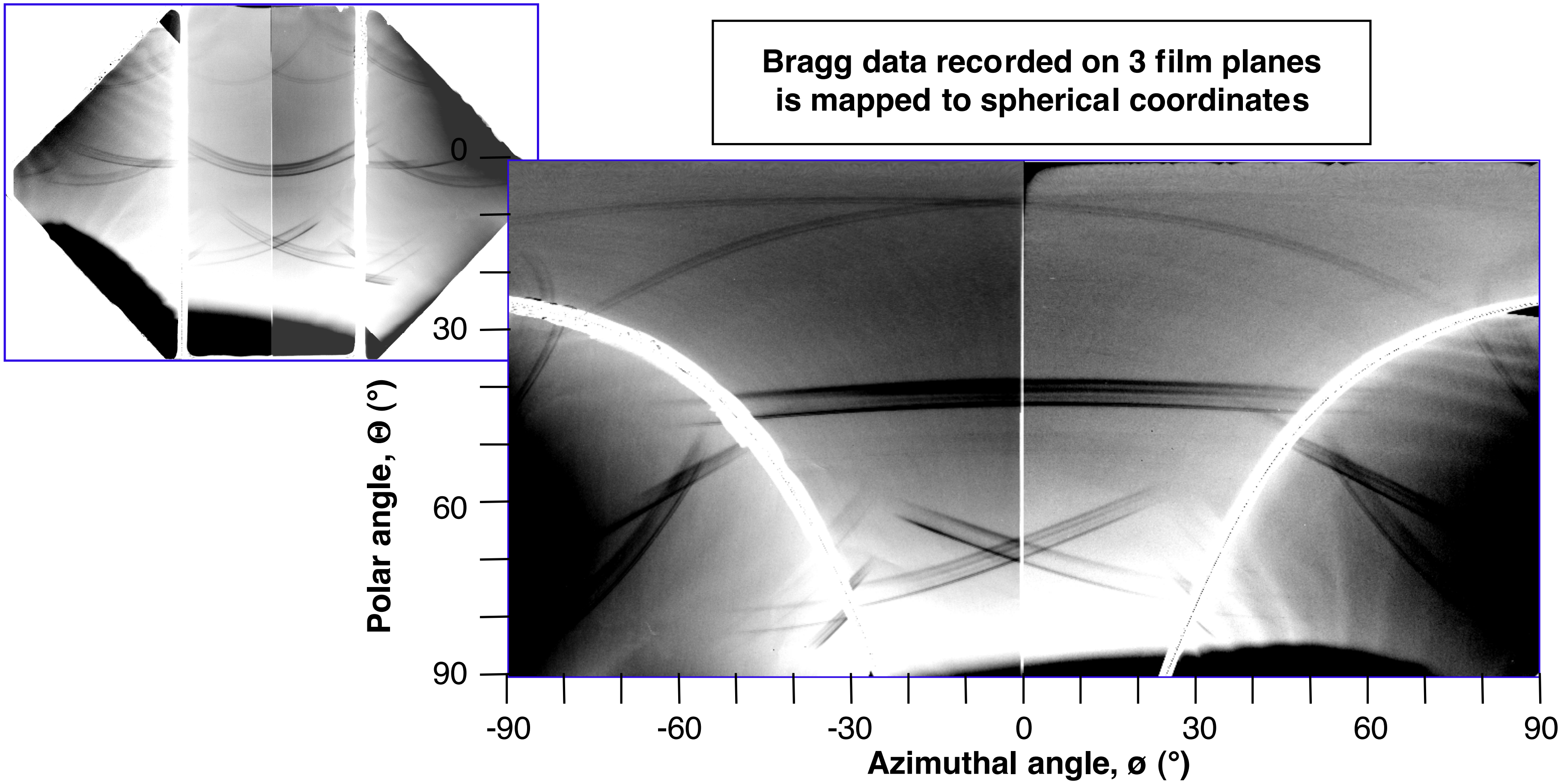
Shock Drive

Calculated diffraction pattern from static Cu



Detailed response of the lattice is better understood by recording diffraction from other lattice planes

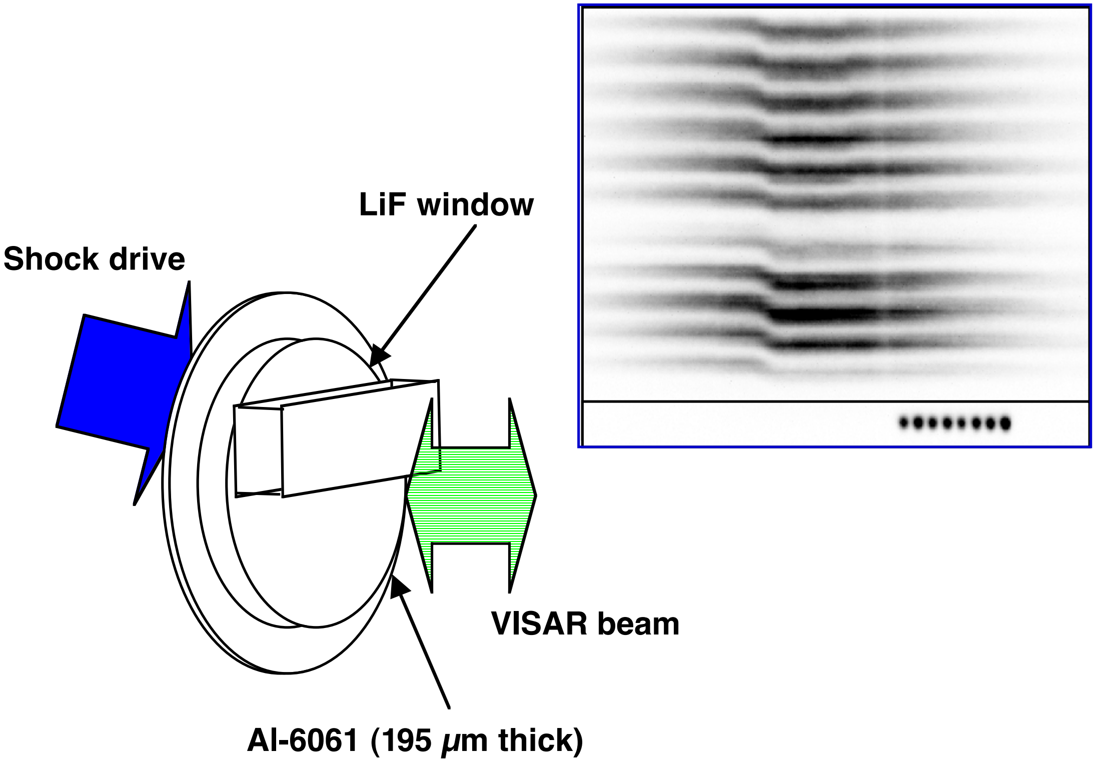
- **Large angle detector has been fielded on Si shock experiments**
- **Shift of many different lines is observed; details are being studied**

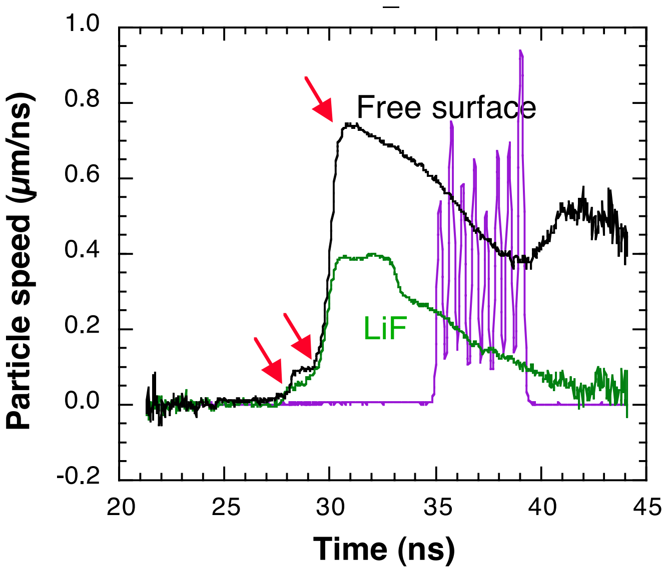


Bragg data recorded on 3 film planes is mapped to spherical coordinates

3. VISAR wave profiles and sample recovery

- Al-6061 wave profile measurements show elastic-plastic response with spall on release
- Fitting the shock breakout wave profile provides best-fit strength parameters

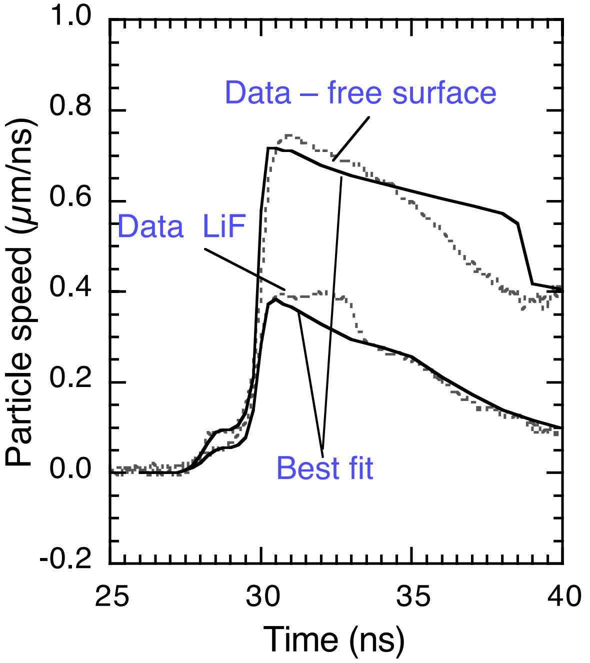




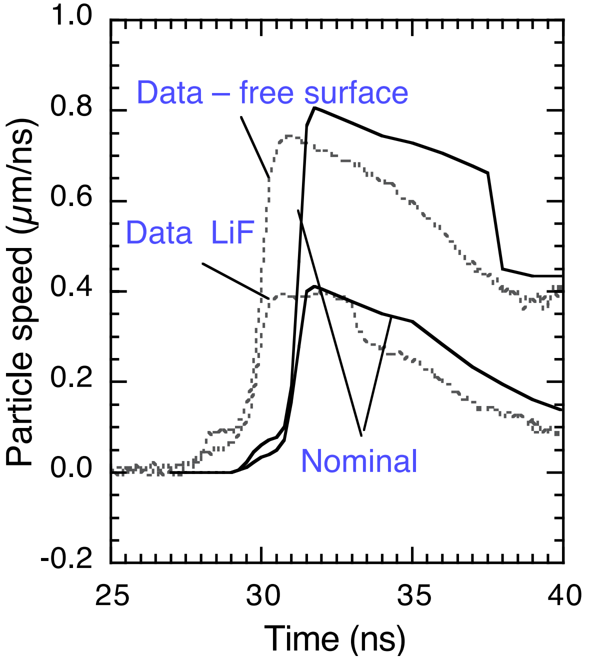
VISAR wave profiles provide information on the strength parameters for the shocked metal

- **The wave profile is sensitive to the constitutive model parameters for the metal foil**
- **Best-fit wave profile provides model parameters:**
  - **Shear modulus G=320 kbar (276)**
  - **Bulk modulus K=794 kbar (742)**
  - **Yield strength Y=4.27 kbar (2.9)**

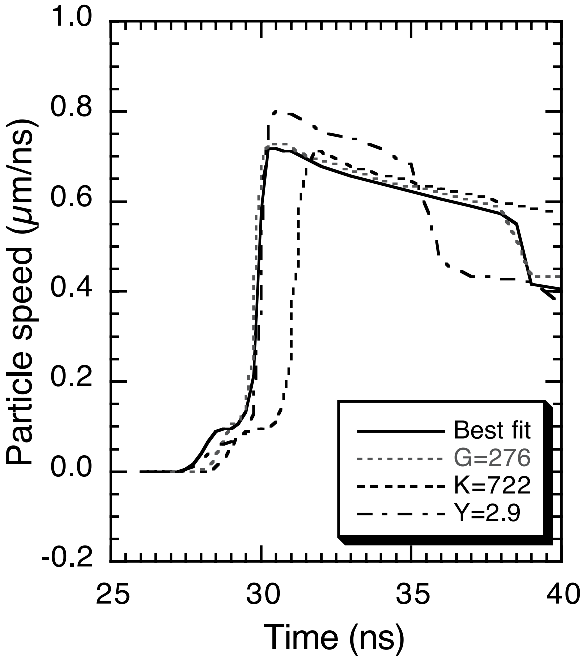
Best fit



Nominal

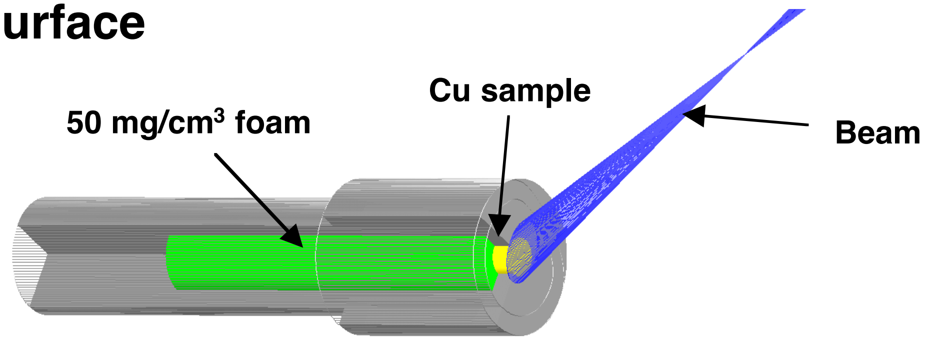


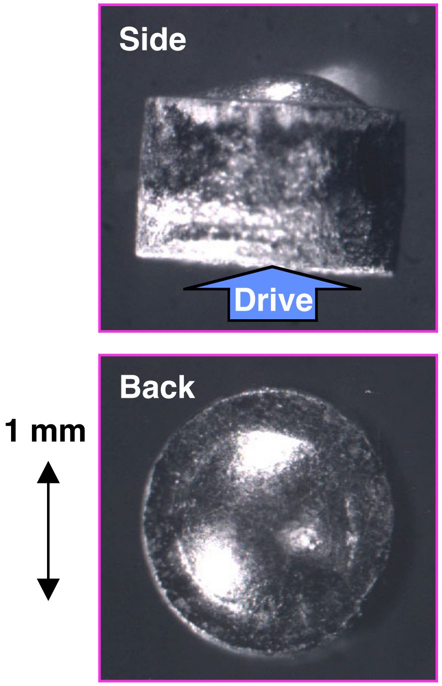
Variations

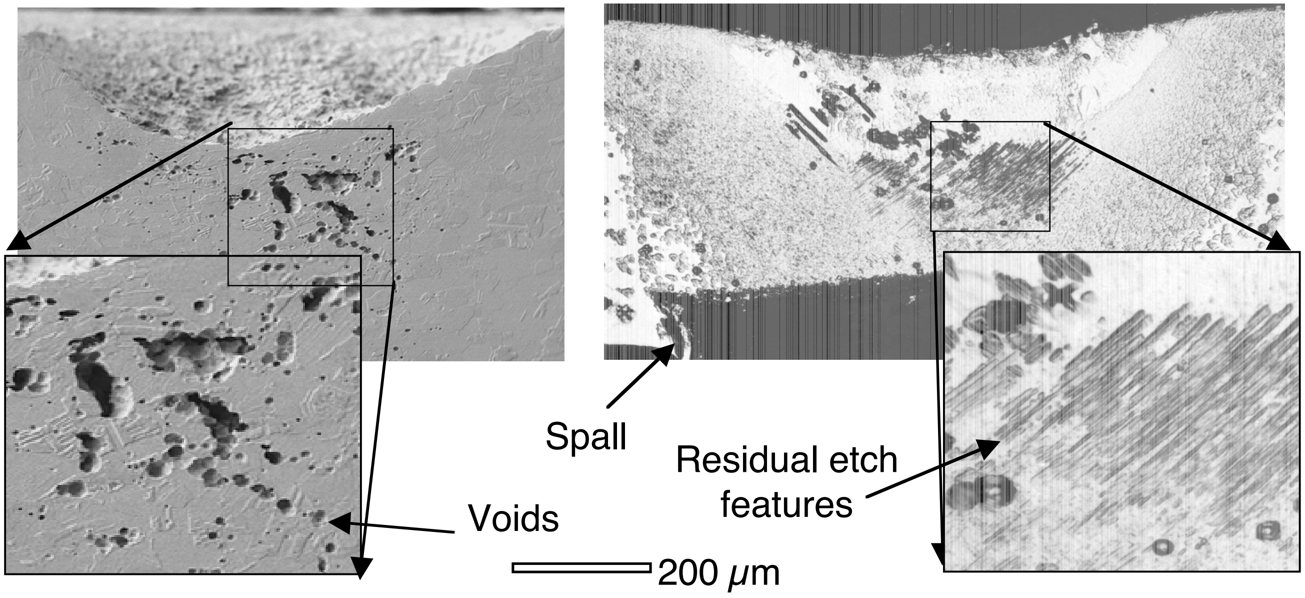


Transmission electron and optical microscope analysis shows residual structure that depends on the drive conditions

- **Shocked samples are recovered in a low density foam-filled tube**
- **Preliminary tests done at OMEGA; shock pressure is ~400 kbar, decays to ~25 kbar at the rear surface**

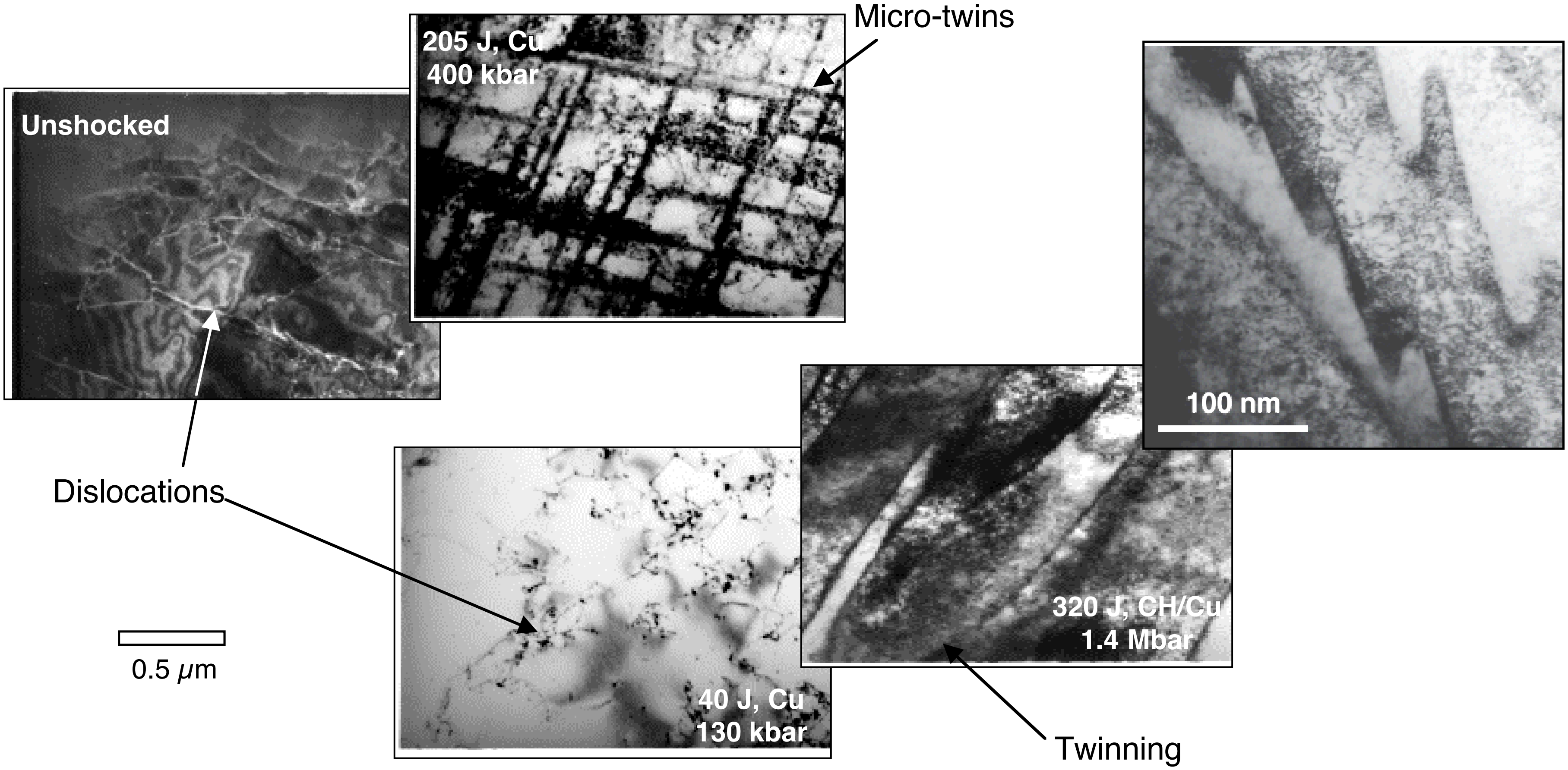






TEM analysis of recovered Cu shows the residual microstructure

- Residual microstructure of recovered single crystal Cu samples
- Higher pressures show twinning



Summary

- Solid state hydrodynamic instability
  - RT instability in Al to infer Y(P)
  - There is possible imprinting due to the initial grain structure

- In situ dynamic x-ray diffraction
  - Time-resolved diffraction relates the lattice behavior to the macroscopic response of Si and Cu under shock loading
  - Si responds uniaxially, Cu deforms plastically

- Shock/recovery experiments
  - Residual deformation structure in Cu depends on the shock pressure