SAND2007-3696C

Analyzing Ramp Compression Wave Experiments

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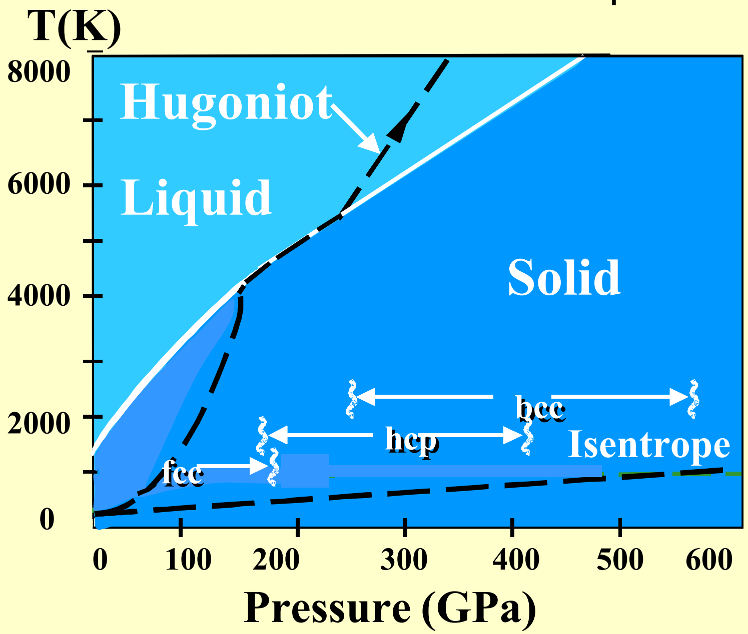
Isentropic **C**ompression**E**xperiments (**ICE**) access states of matter at large compression and low temperature



". . . to present a talk on the analysis of isentropic compression data and perhaps a brief overview of isentropic compression"
Ricky Chau, Co-chair SCCM 2007

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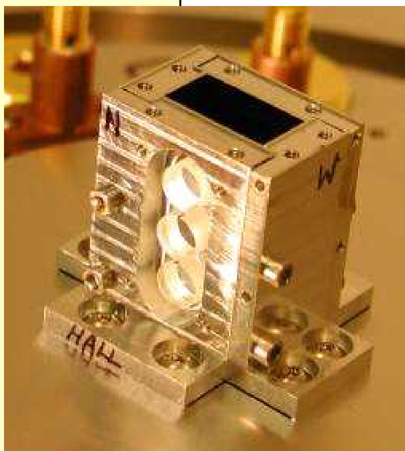
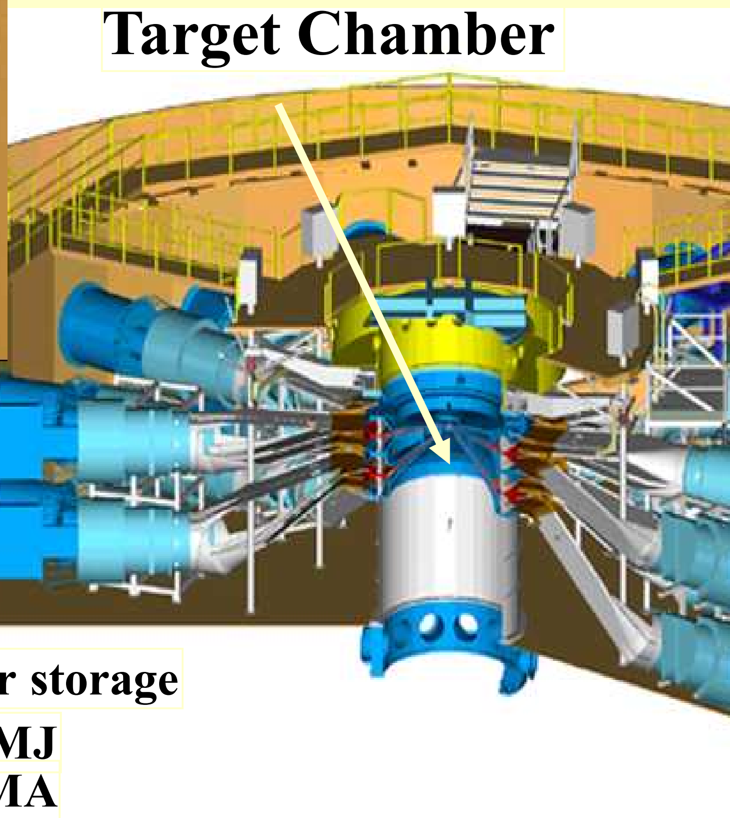
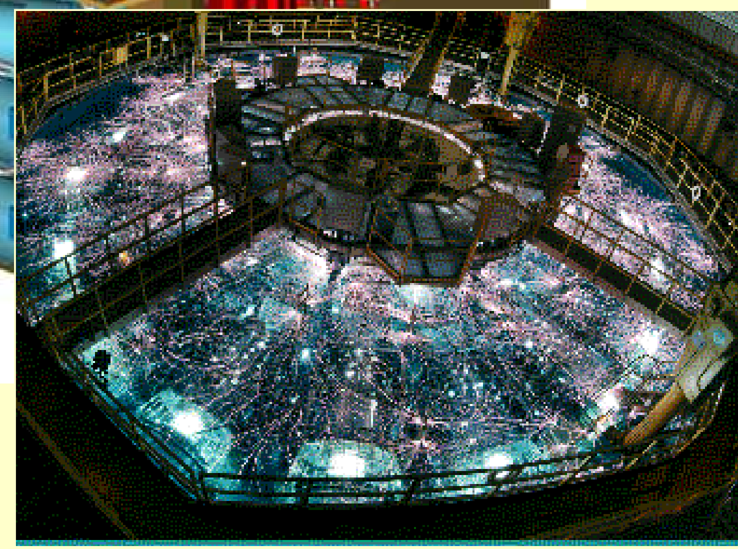
Z is a large pulsed power machine that can produce high pressures for material studies







350 GPa very planar pressure load ramped over 100's of nanoseconds

The ICE Technique On Z Has Enabled Diverse Investigations

Co-workers

Doug Adolf – SNL
Jim Asay –SNL
Mel Baer – SNL
Jean-Paul Davis – SNL
Clint Hall – SNL
Marcus Knudson – SNL
Ray Lemke – SNL

Bill Anderson – LANL
Frank Cherne – LANL
Rusty Gray – LANL
Carl Greeff - LANL
Rob Hixson – LANL
Dan Hooks – LANL
Paulo Rigg – LANL
Doug Tasker – LANL
John Vorthman - LANL
Anna Zurek – LANL

Jerry Forbes – LLNL
David Reisman – LLNL

Steve Rothman - AWE

Material Investigations

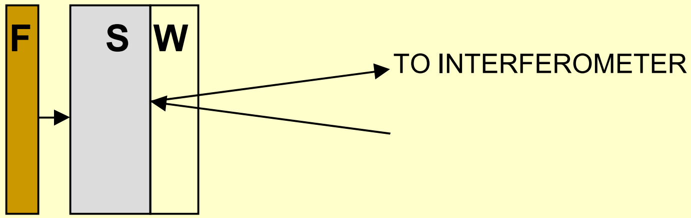
Compression isentropes of metals
Compression isentropes of dielectrics
Optical properties of sapphire
Twinning dynamics of uranium alloys
Structural phase changes in crystalline solids
Melting and freezing under compression
Highly compressed states of unreacted explosives
Composite materials

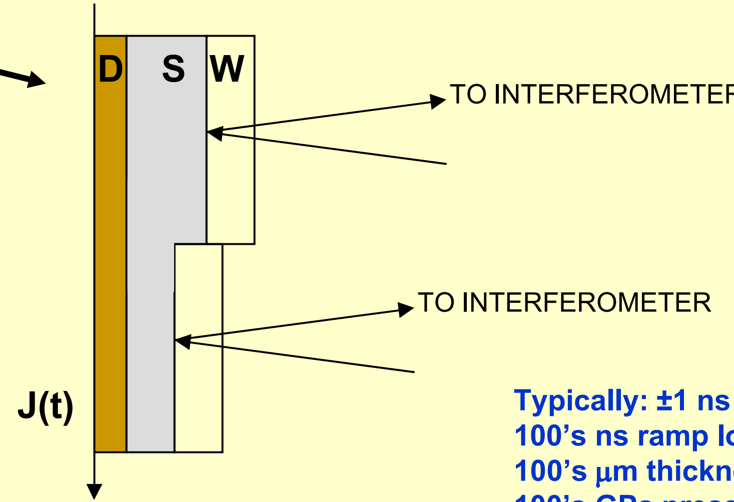
Analysis Problem Areas

Absolute calibration of standards
Interface perturbations
Shock formation
Interferometry
- ramp compression
- shock forming in windows

Uniqueness of results

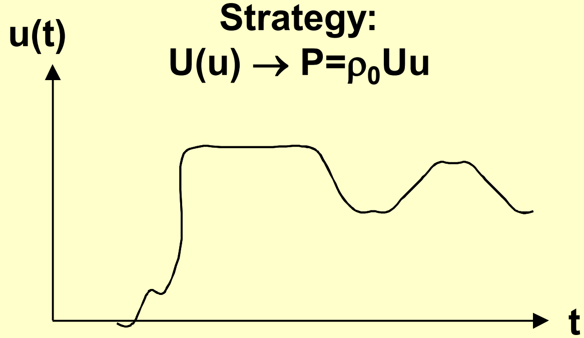
1-D SHOCK AND RAMP COMPRESSION EXPERIMENTS ARE QUITE DIFFERENT





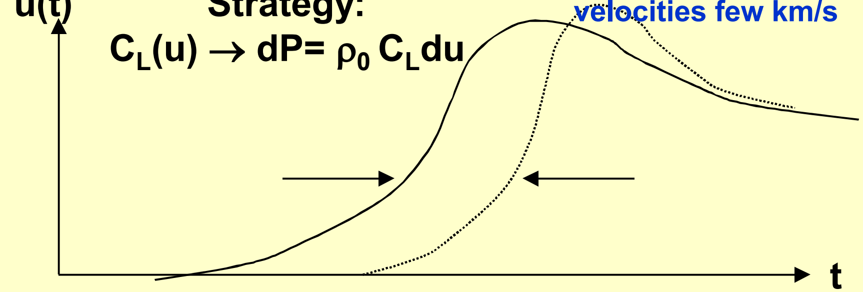
Typically: ±1 ns timing, 100's ns ramp loading, 100's μm thicknesses, 100's GPa pressures, velocities few km/s

Strategy:
$U(u) \rightarrow P=\rho_0 Uu$



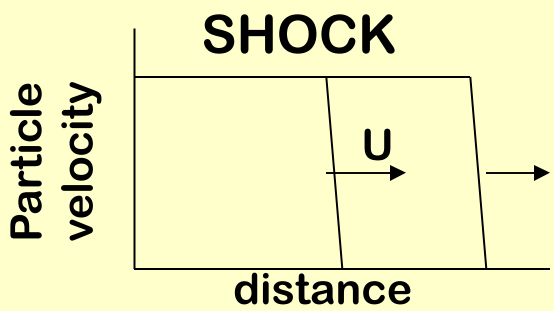
- defined arrival times
- steady waves
- absolute standards
- interfaces manageable
- flyer reverberations o.k.

Strategy:
$C_L(u) \rightarrow dP= \rho_0 C_L du$



- undefined arrival times
- unsteady waves in sample (and shocks)
- shock formation in window
- no standards yet
- interfaces require large corrections
- drive reverberations not o.k.

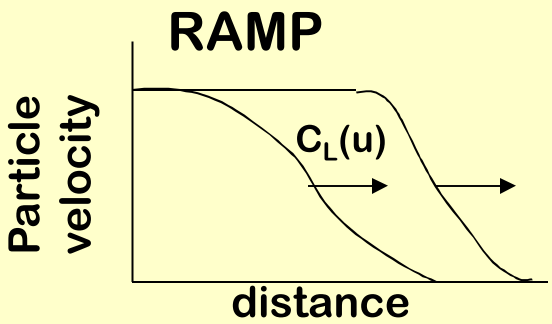
Ramp wave results are path dependent



$$\sigma = \rho_0 U u$$

$$V = V_0\left(1 - \frac{u}{U}\right)$$

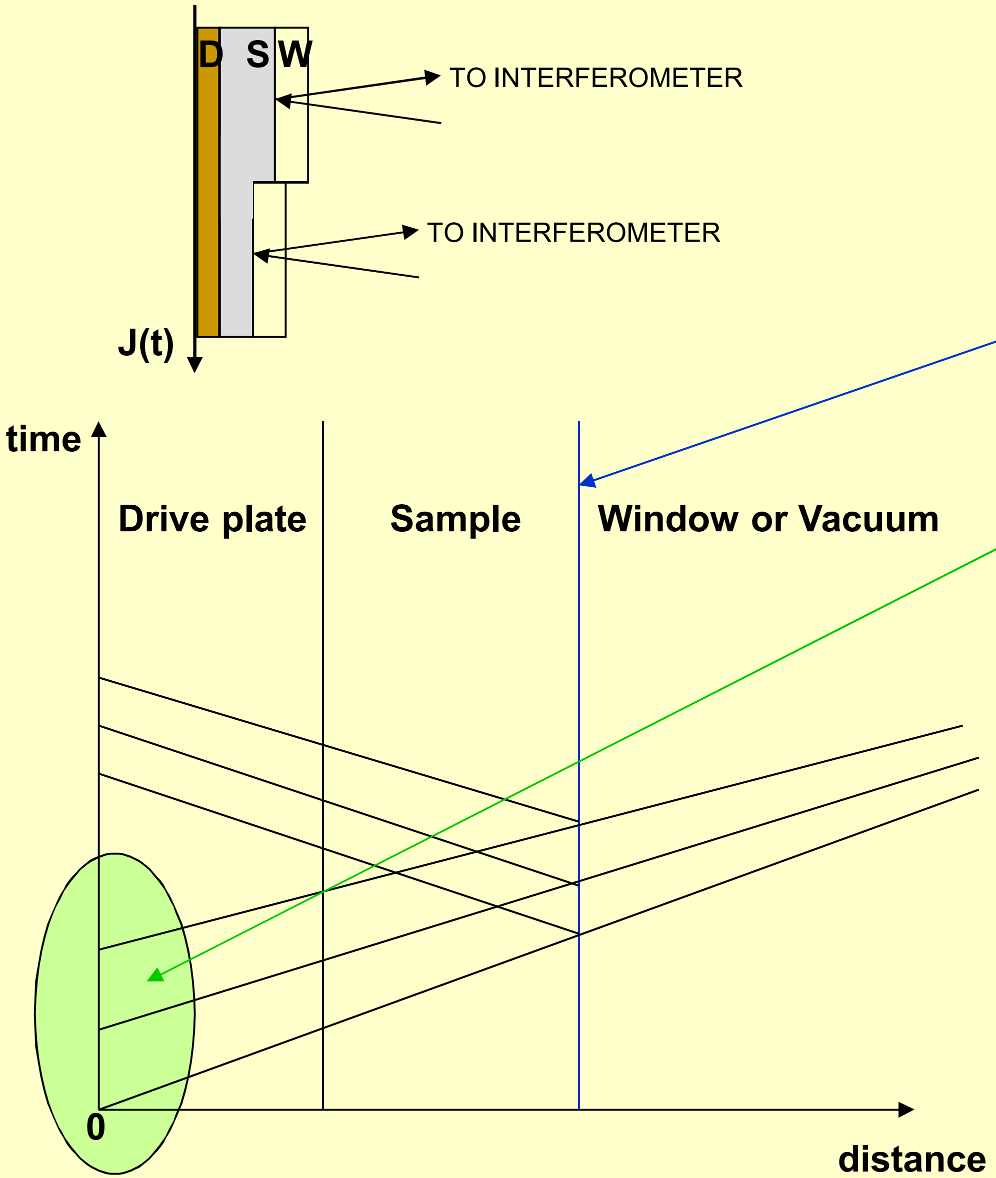
- Measure u, U
- σ, V <u>independent</u> of processes in shock front



$$\sigma = \rho_0 \int C_L(u)\,du$$

$$V = V_0\left(1 - \int \frac{du}{C_L(u)}\right)$$

- Measure u, $C_L(u)$
- σ, V <u>depend</u> on details of preceding compression path



"Backward" procedure takes VISAR information from the measurement plane and, using the equations of motion and a test P(V) isentrope, integrates backward in space, to a region where reflections were not present --- giving P(0,t).

Motion of all samples derive from the same p(0,t). This constrains p(V) --- sometimes uniquely and sometimes approximately.

OUTLINE

Does a windowed VISAR work the same way for ramp waves as for shock waves?

Yes, for all practical purposes

How does one correct for free (or windowed) surface perturbations?

Integrate the equations backward in space to an unaffected region

Can we measure index of refraction of a window with ramp waves?

Yes, by measuring Doppler shift and velocity simultaneously

How do we treat hysteretic sample materials? e.g., elastic-plastic?

Get pressure load from a “standard” and match forward calculations to experiments

How about when a shock forms in the window?

Do Doppler shift calculations on the fly in a forward hydro calculation

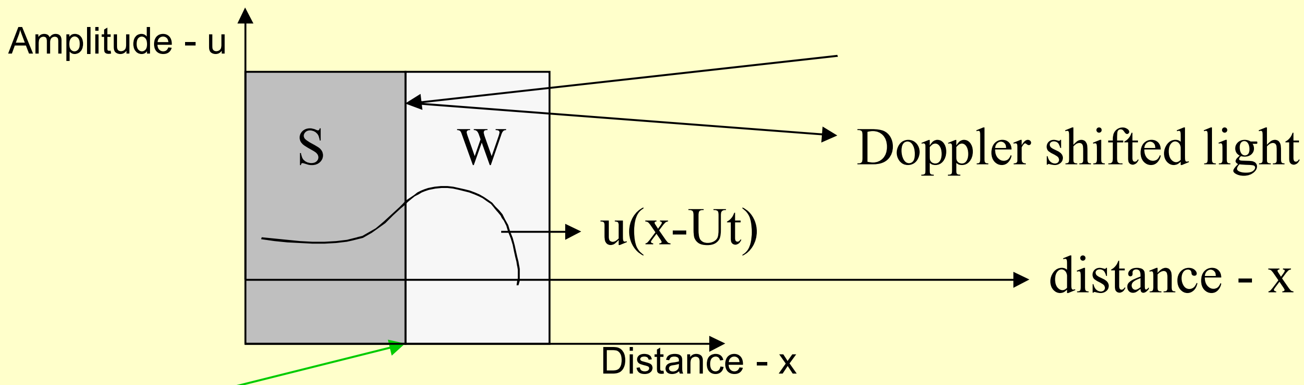
What can we learn on the back of an envelope?

- experiments at very high strains (compressible; high P, phase change,. . .)
  * difficult to design
- pillows and other layered impactors
  * small tilt is the driver
- A-B comparison screening experiments
  windowless seems the best

Conclusion

- ICE is a powerful experimental technique
- some of our favorite shock wave assumptions are invalid for ramps

VISAR: steady wave in the window



$u(t)$ = (VISAR Eq.) / $(1+\delta\nu/\nu_0)$

u_V = the VISAR apparent velocity ↑ (VISAR Eq.)

optical correction for window ↑ $(1+\delta\nu/\nu_0)$

Compression wave in the Window affects the Doppler shift and must be corrected for. (after Barker, 1970)

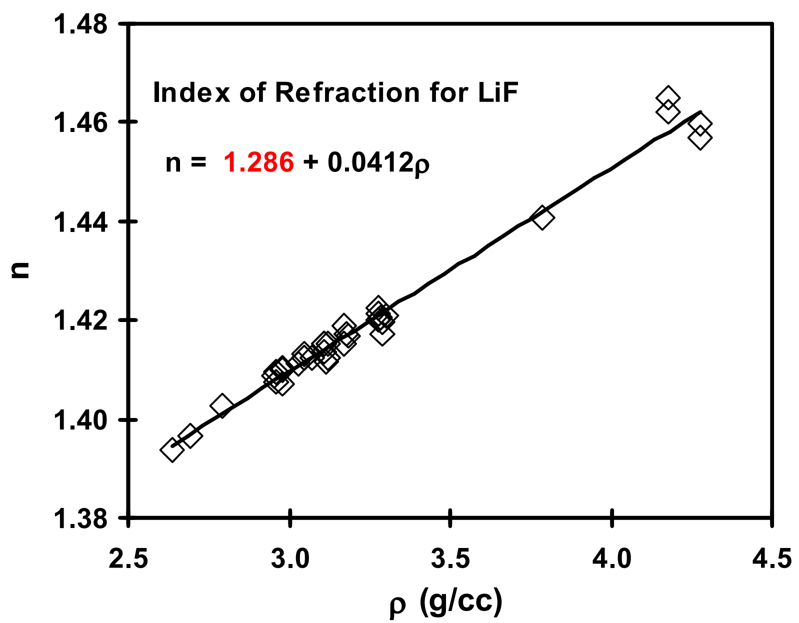
$u_V = -dZ/dt$

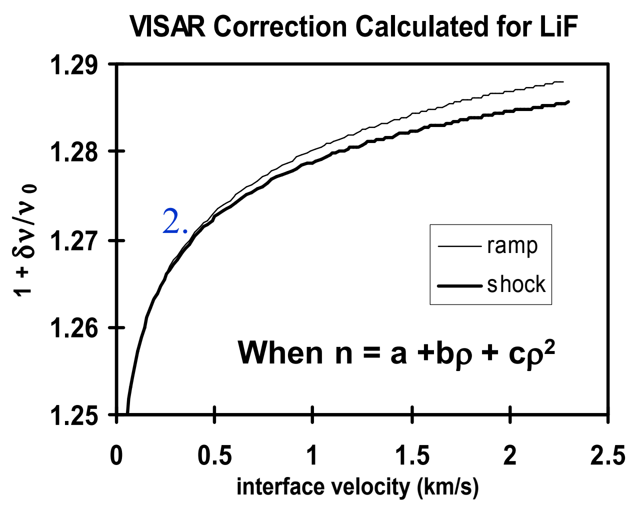
The apparent VISAR velocity is simply related to the optical path of the compressed window

SPECIAL CASE

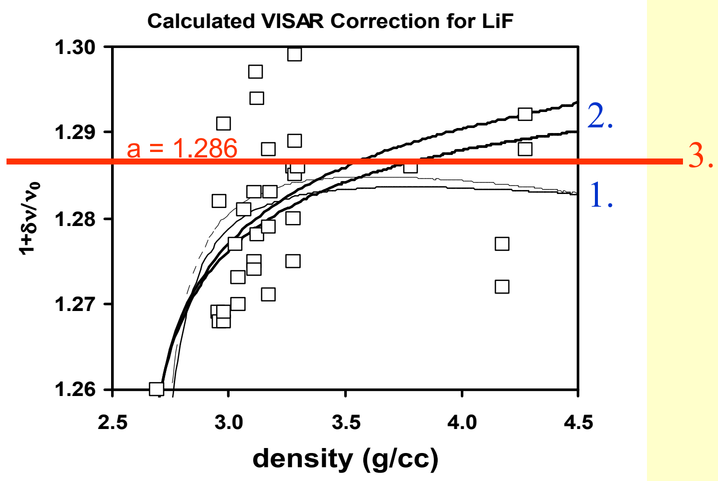
if $n = a + b\rho$

then $(1+\delta\nu/\nu_0) \equiv a$





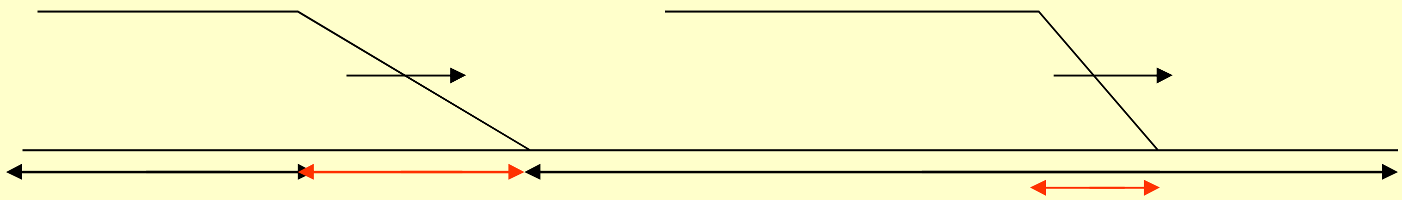
Index data is well represented by linear fit of n – ρ



LiF Windows

Measurements: Chhabildas & Wise

Unsteady wave in the window



$$Z(t) = \int_{x_0(t)}^{C_0 t} n(x,t)dx + n_0(L - C_0 t)$$

$$dh = \frac{\rho}{\rho_0} dx$$

Need to solve the wave equation

$$h(u,t) = \left[t - t_0(u)\right] C_h(u)$$

$$dh = \left[(t - t_0)C_h' - C_h t_0'\right] du$$

$$u_V \equiv -\frac{dZ}{dt} = n_0 C_0 - nC + \int_0^u \frac{\rho_0}{\rho} n C_h' du$$

$$\frac{du_V}{du} = n - \rho \frac{dn}{d\rho}$$

SPECIAL CASE FOR UNSTEADY WAVES

if $\quad n = a + b\rho$

then $\quad (1+\delta\nu/\nu_{\mathbf{0}}) \equiv a$

Same as steady waves!

For n $\neq a + b\rho$, a is different for steady and for unsteady waves

D. B. Hayes, *Unsteady Compression Waves in Interferometer Windows*, J. Appl. Phys. **89** (2001) p6484

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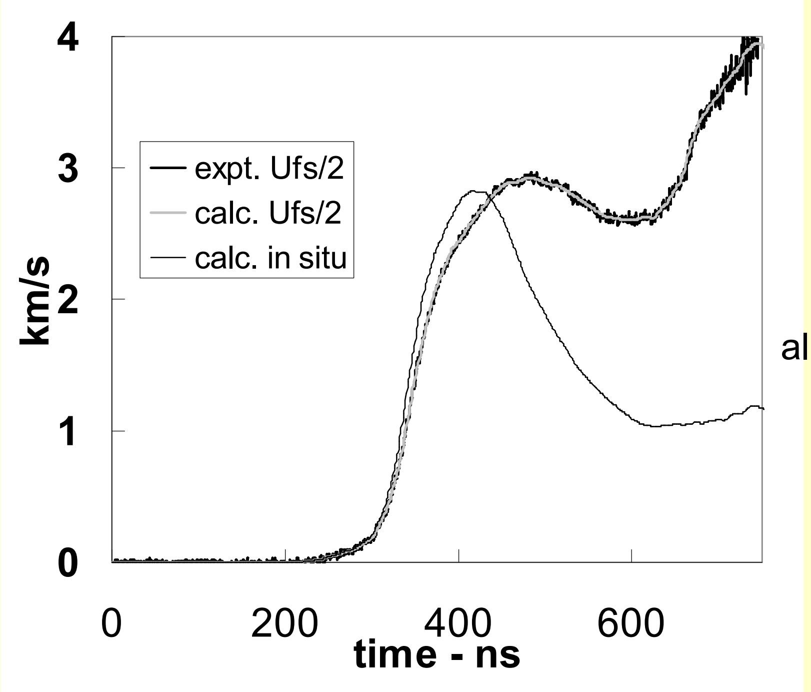
For shocks, $\mathbf{u}_{in\ situ} = \mathbf{u}_{fs}/2$ to third order in strain

(For a 720 kbar shock, $\mathbf{u}_{in\ situ} = \mathbf{u}_{fs}/2$ to ~ 0.3%)

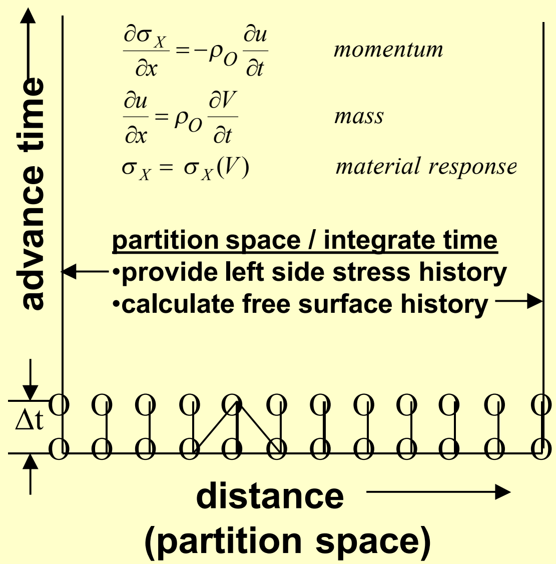
For ramps, $\mathbf{u}_{in\ situ}$ and $\mathbf{u}_{fs}$ can be quite disparate



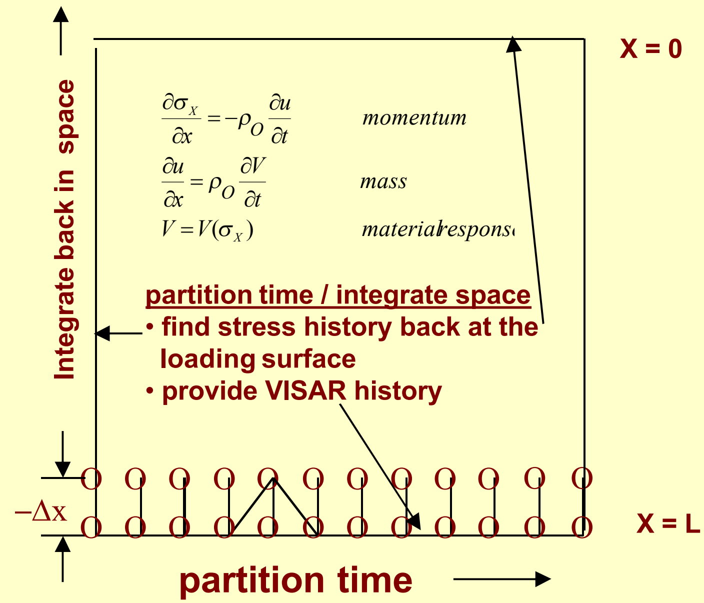
aluminum @ 720 kbar

backward method allows free surface corrections for unsteady waves

Common hydrocode for the "forward" solution i.e., WONDY



Method for the "backward" solution



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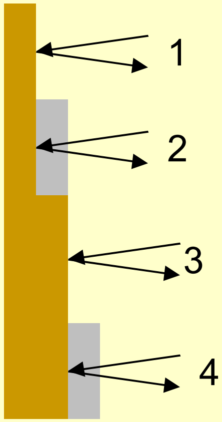
Continuous index of refraction in sapphire using the unsteady VISAR equation:

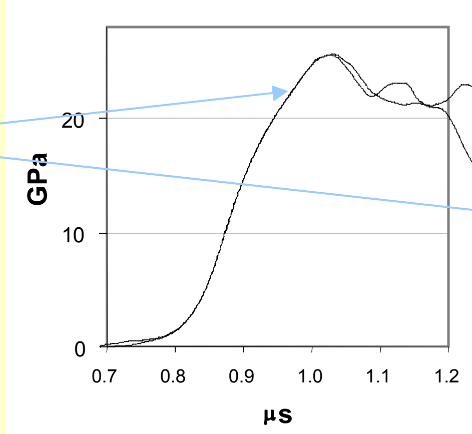


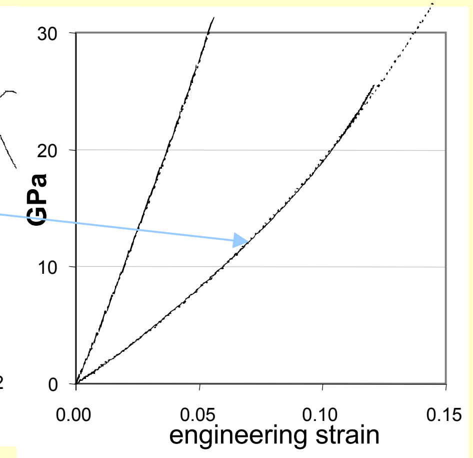
Use 1 & 3 (backward): P(0,t), $P_{Cu}(V)$

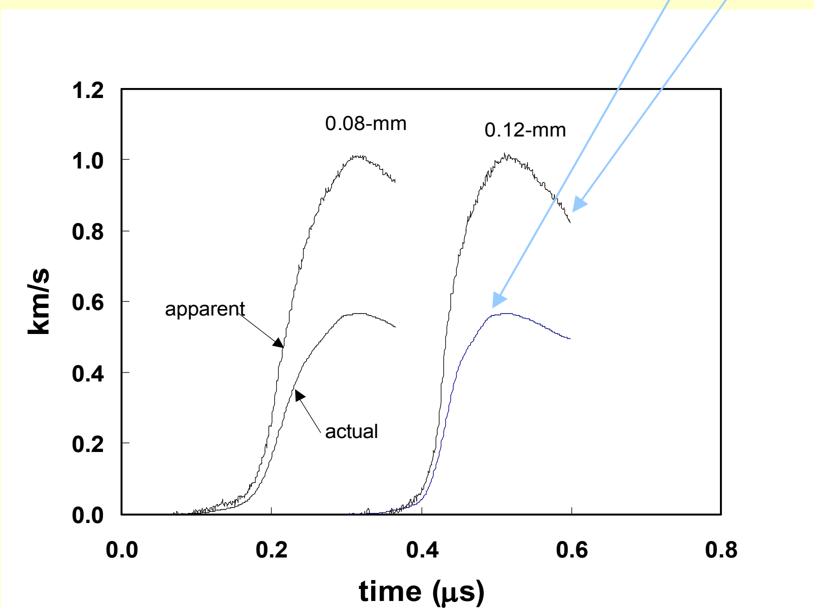
Use 2 or 4 (forward) with p(0,t):u(t)

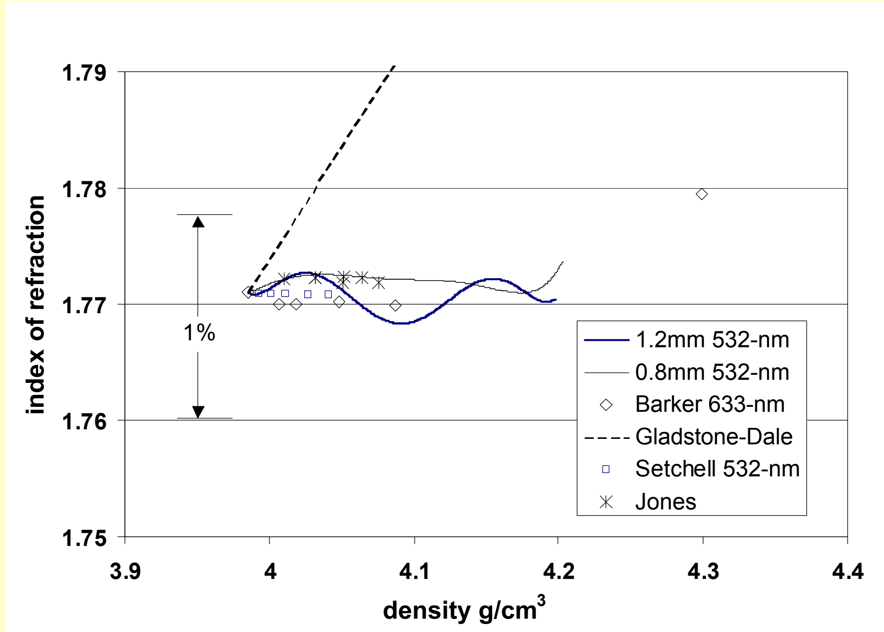
Use 2 or 4 (uncorrected VISAR): $u_V(t)$

$$\frac{du_V}{du} = n - \rho \frac{dn}{d\rho} \quad : n(\rho)$$









D. B. Hayes, C. A. Hall, J. R. Asay and M. D. Knudson, *Continuous Index of Refraction Measurements to 20 GPa in Z-Cut Sapphire*, J. Appl. Phys. 944 (15Aug 2003) ,p. 2331

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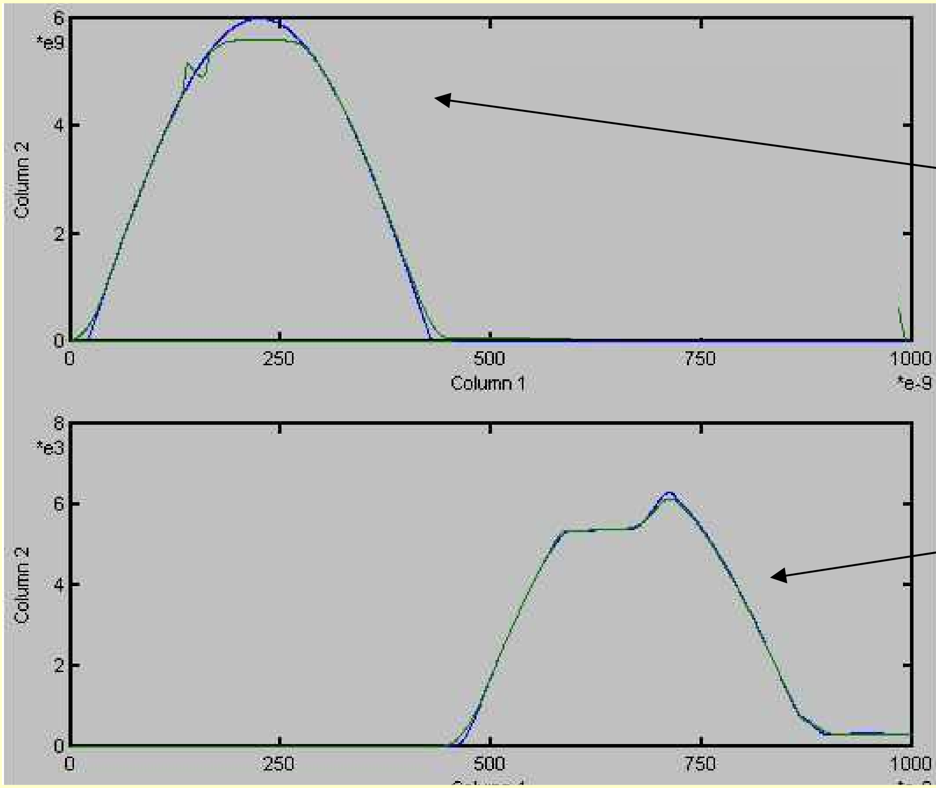
elastic-plastic, rate-dependent and other hysteretic materials do not have unique backward solutions



two different pressure loads ($dyne/cm^2$,s)

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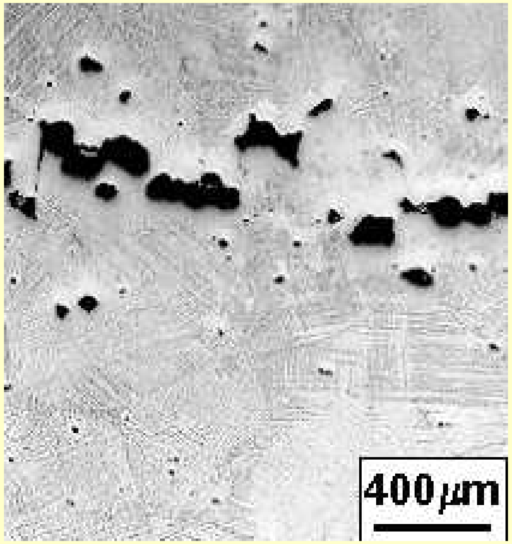
produce the same VISAR record (cm/s)

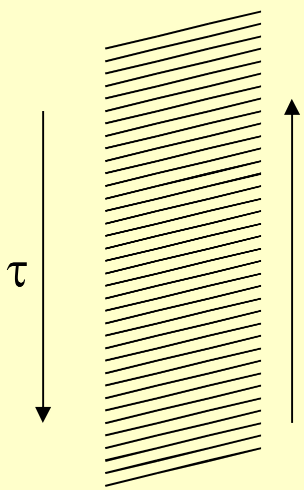
only hyperbolic problems are well posed: p'(V)<0; p''(V)>0

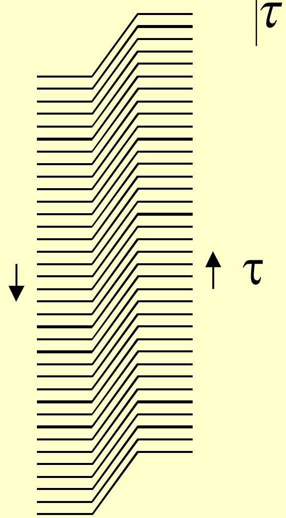


- compression waves in solids produce shear stresses (τ)
- twinning in U6Nb dramatically reduces that shear stress

$$\dot{\tau} = \mu\dot{\varepsilon} - \mu\Theta\dot{m}\,; \quad \tau = \frac{\sigma_n - \sigma_t}{2}\,; \; elastic - plastic$$

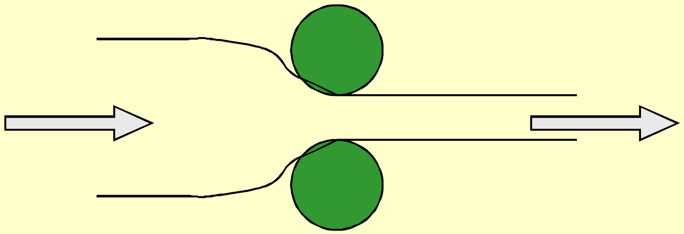
$$|\tau| \le \frac{Y}{2} \qquad von - Mises\ yielding$$

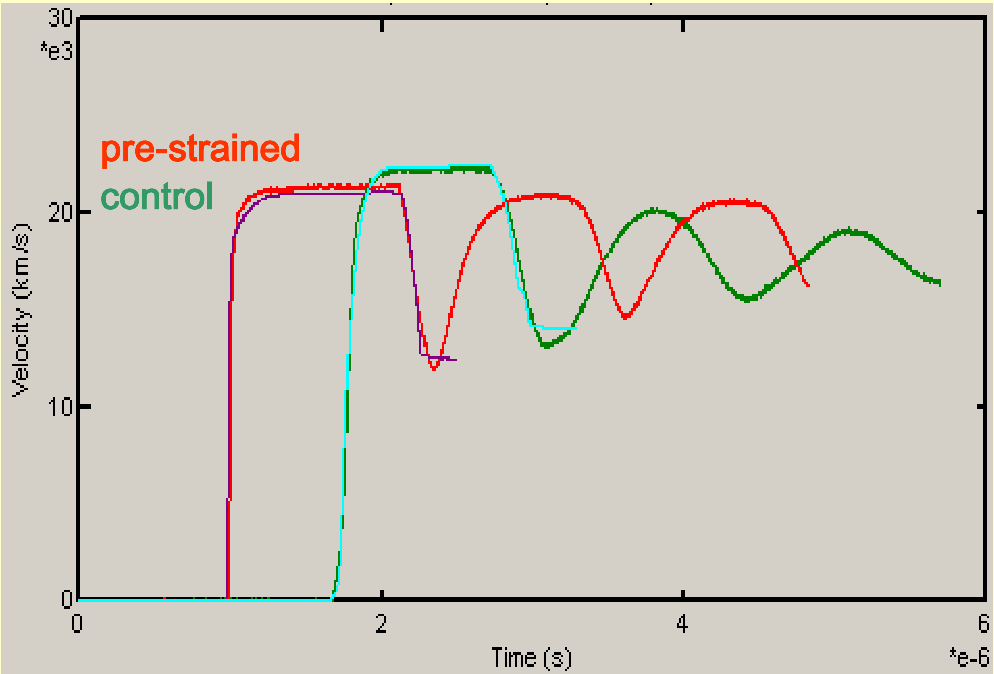




twinning is time dependent so compression waves are unsteady

U-Nb(6-wt)% was heavily pre-rolled to pre-twin the sample and thus suppress that mode of stress-relaxation





pre-strained/static

- no twinning stress relaxation
- elastic/plastic; Y ~ 10kbar
- τ_{crit} small

pre-strained; 55 kbar experiment

- no precursor
- sharp arrival
- stress relaxation
- sharper release

pre-strained analysis

- τ_{crit} increased to ~5kbar
- Y increased to 10 kbar
- plastic strain <1%

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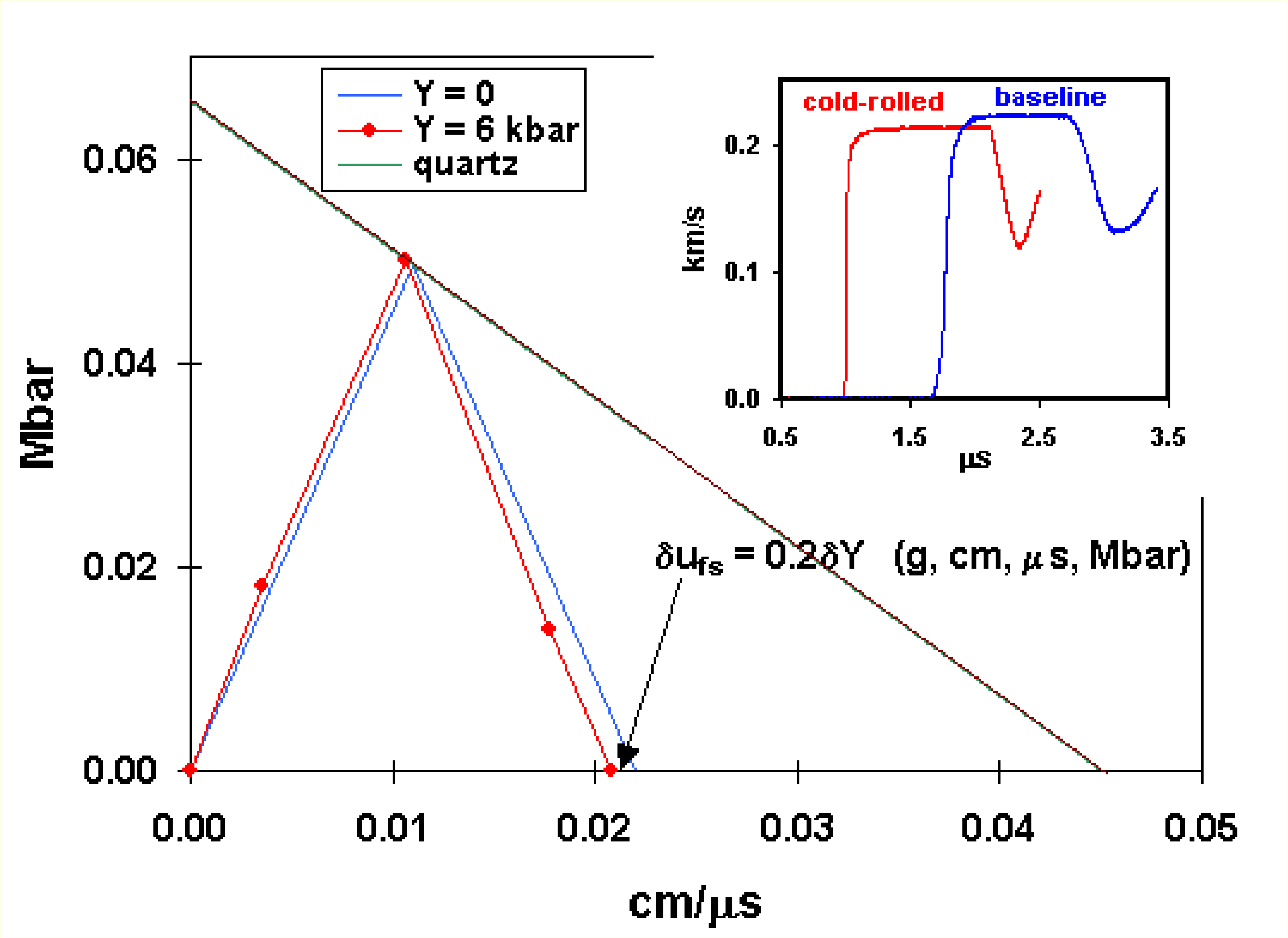
COLD-ROLLING DIMINISHES THE FREE SURFACE VELOCITY IN SHOCK EXPERIMENTS (but still no precursor)



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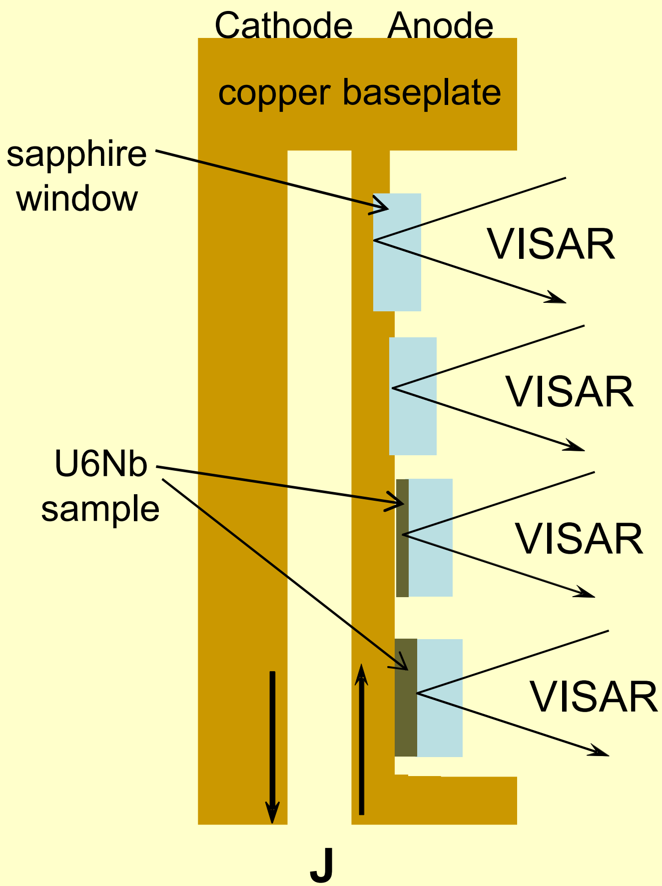
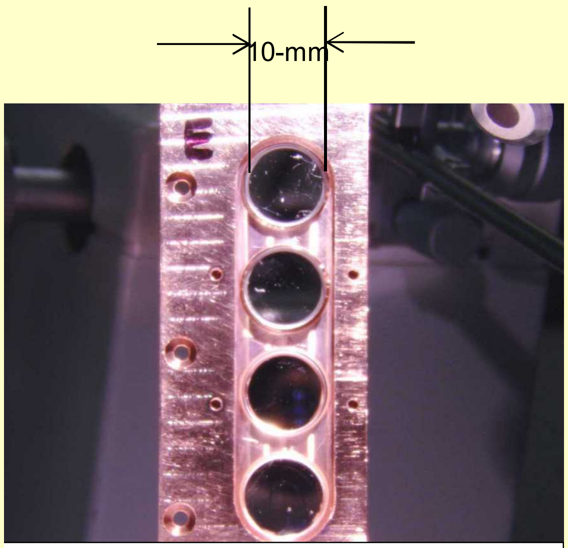
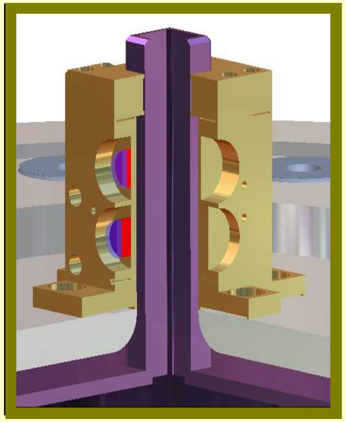
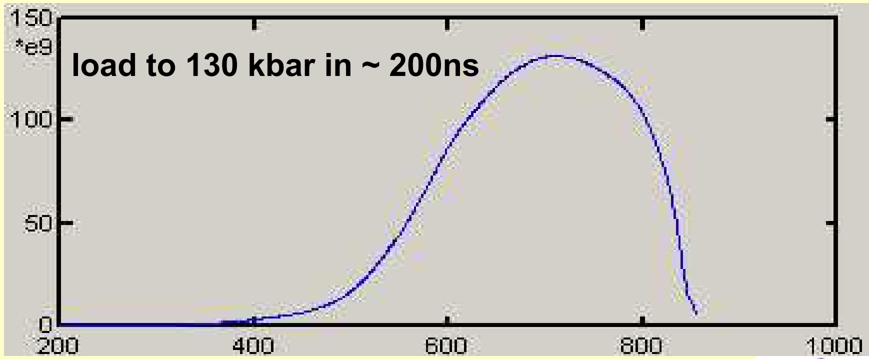
ramp wave compression from Sandia's Z machine load U6Nb fast enough to produce measurable shear stresses



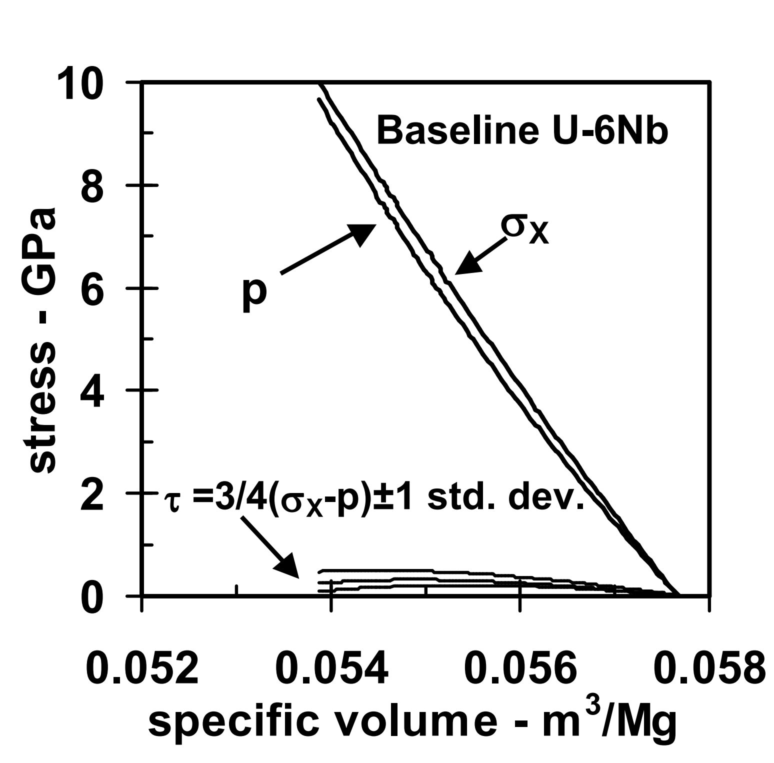


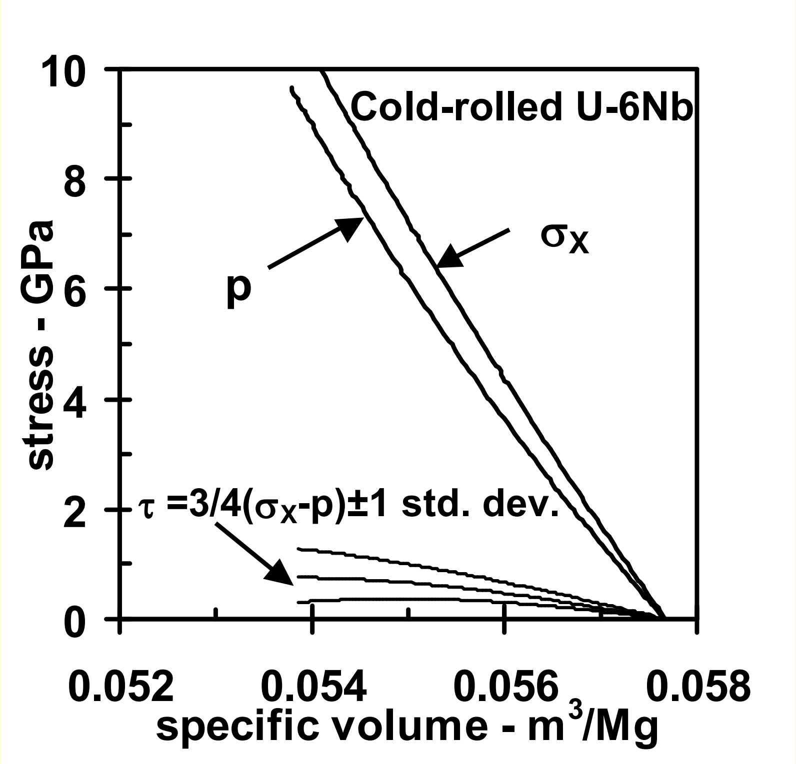
East Panel Final Assembly





Despite the rather large error bars, Z-derived stress-volume measurements show very plausible strength effects





D. B. Hayes, G. T. Gray III, R. S. Hixson,A. K. Zurek, J. E. Vorthman, W. W. Anderson, SHEAR STRESS RELAXATION IN SHOCK-LOADED U-Nb(6-wt%) Shock Compression of Condensed Matter-2005, American Institute of Physics 2004.

D. B. Hayes, G. T. Gray III, R. S. Hixson, C. A. Hall[1], M. E. Byers and J. E. Vorthman , submitted to Int. J. Plasticity, March 2007

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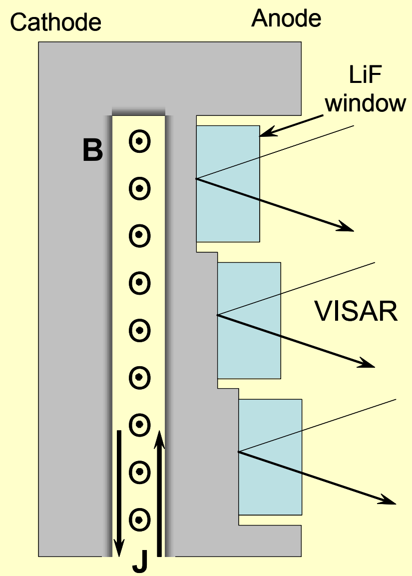
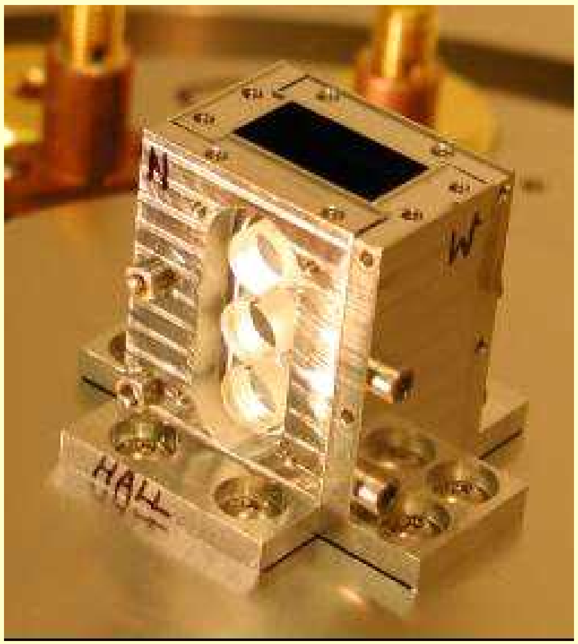
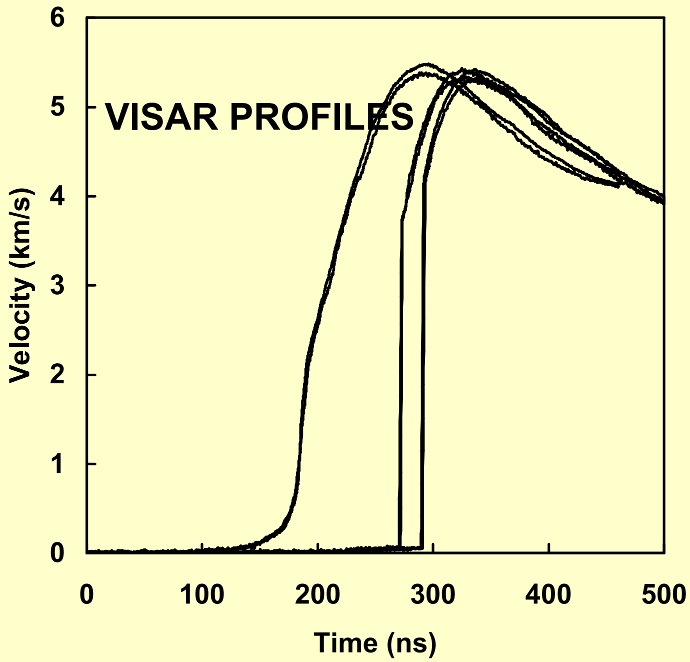




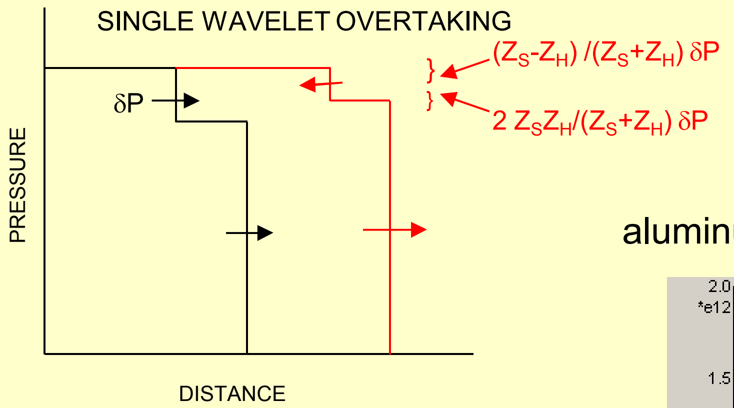
ALUMINUM AT 185 GPa

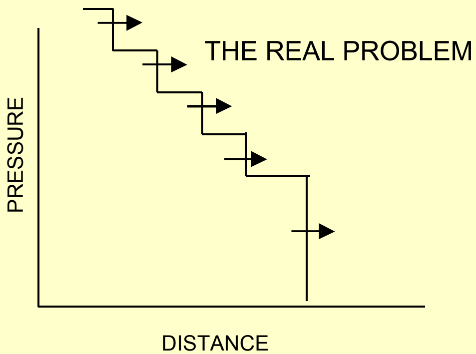
At higher pressures, it becomes difficult to get shockless profiles at multiple thicknesses

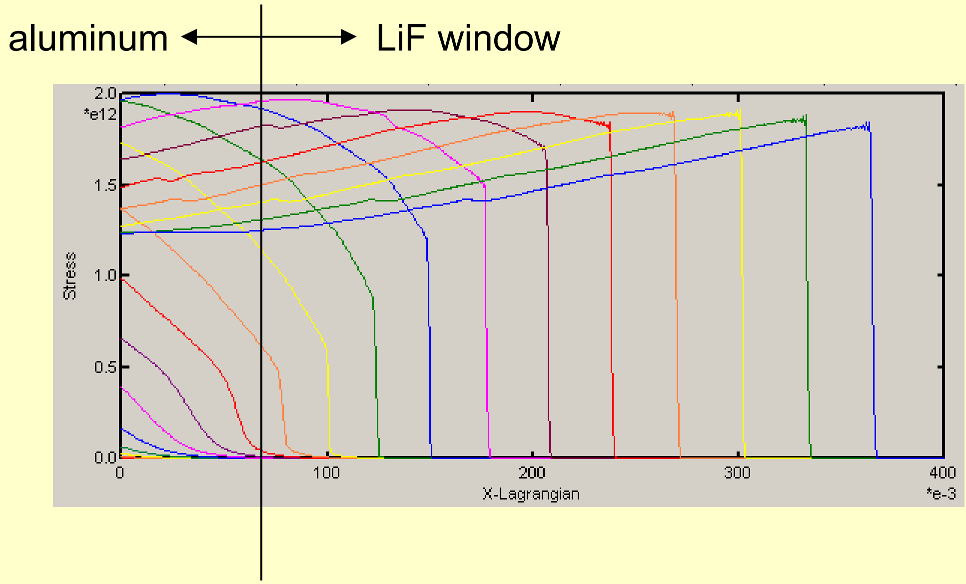


- mixed ramp and shock requires backward/forward analysis technique
- shock growth in the window violates VISAR assumptions

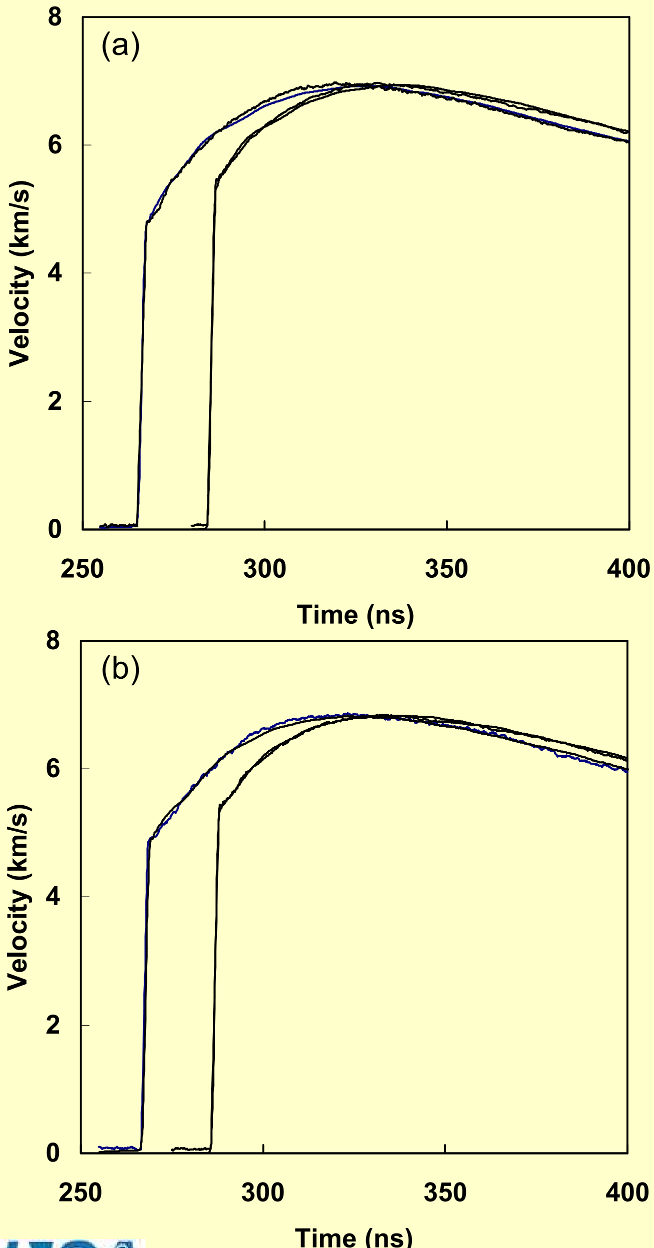
When shocks form in a window, backward-going waves form violating two of the three fundamental VISAR assumptions







Analyze The Apparent Velocities (no window correction)



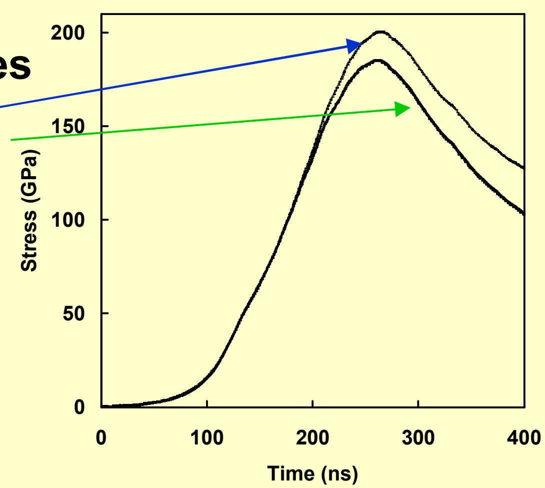
- Pressure :first guess p from simple backward
  $p'(0,t)=p(0,t)[1 + \alpha(t - t_0) + \beta(t - t_0)^2]$, $t > t_0$

- Calculate "shocked" experiment using forward code with p'(0,t) as left hand boundary condition.

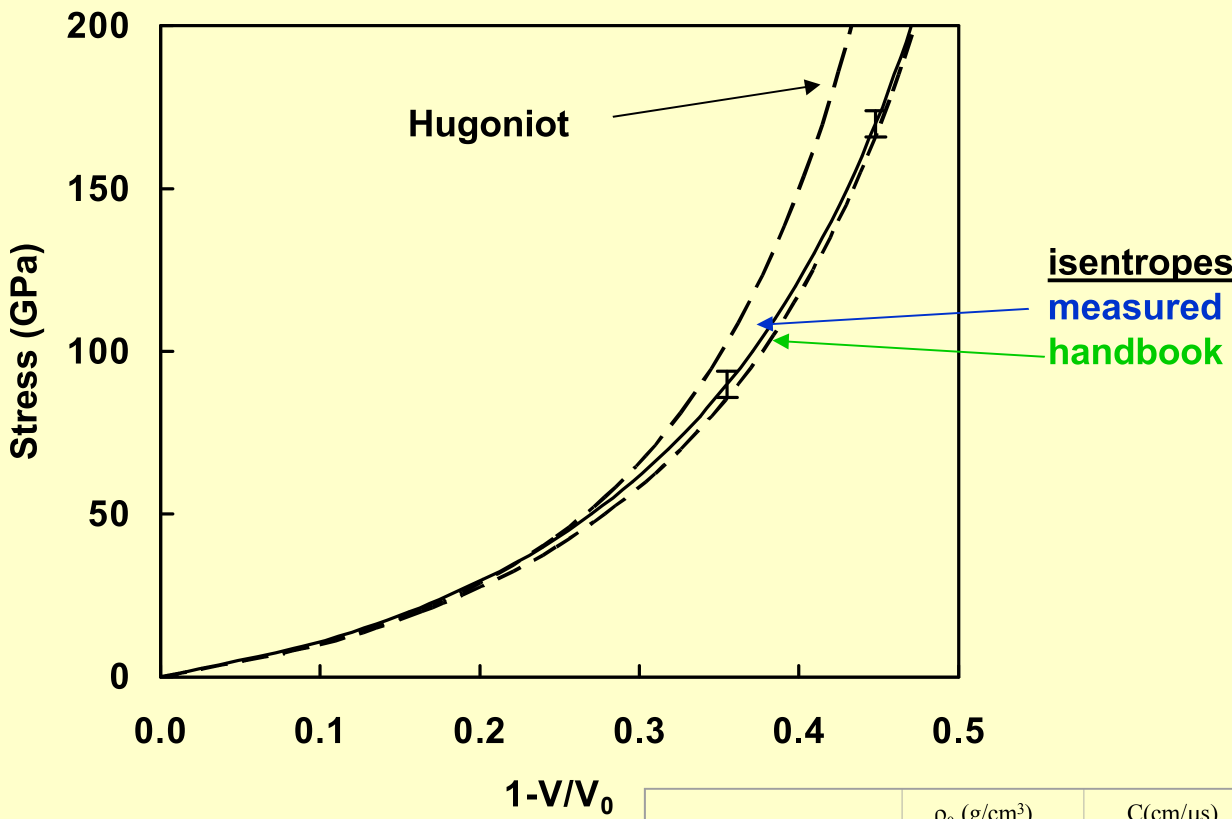
- Calculated the apparent VISAR velocity (Doppler shift) in WONDY using:
  $u_a = -dZ/dt$ and $n = 1.286 + 0.0412\rho$

- Minimize RMS between experimental and calculation apparent velocities adjusting C, S, t_0, α, β

pressure histories
first guess p(0,t)
two final p'(0,t)'s



“handbook” and experimental isentropes



	ρ_0 (g/cm^3)	C(cm/μs)	S	γ
Reference	2.703	0.5288	1.3756	2.14
North0603/1403	2.703	0.5558	1.3394	2.14
North0603/1603	2.703	0.5561	1.3289	2.14
South0601/1401	2.703	0.5497	1.3602	2.14
South0603/1601	2.703	0.5471	1.3501	2.14
Expt.RMS: 4 GPa	2.703	0.5522	1.3446	2.14

Measurement of the Compression Isentrope for 6061-T6 Aluminum to 185 GPa and 46% Volumetric Strain Using Pulsed Magnetic Loading
D. B. Hayes, C. A. Hall, J. R. Asay and M. D. Knudson
J. Appl. Phys. 96 (November 2004)

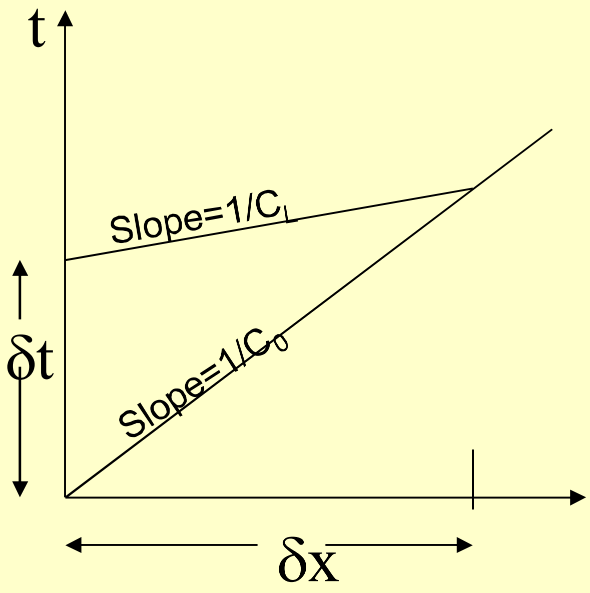
OUTLINE

Does a windowed VISAR work the same way for ramp waves as for shock waves?
Yes, for all practical purposes
How does one correct for free (or windowed) surface perturbations?
Integrate the equations backward in space to an unaffected region
Can we measure index of refraction of a window with ramp waves?
Yes, by measuring Doppler shift and velocity simultaneously
How do we treat hysteretic sample materials? e.g., elastic-plastic?
Get pressure load from a "standard" and match forward calculations to experiments
How about when a shock forms in the window?
Do Doppler shift calculations on the fly in a forward hydro calculation
What can we learn on the back of an envelope?
- experiments at very high strains (compressible; high P, phase change,. . .)
  * difficult to design
- pillows and other layered impactors
  * small tilt is the driver
- A-B comparison screening experiments
  windowless seems the best

Conclusion
- ICE is a powerful experimental technique
- some of our favorite shock wave assumptions are invalid for ramps

Samples must be VERY thin to do experiments at large compression (pressure)

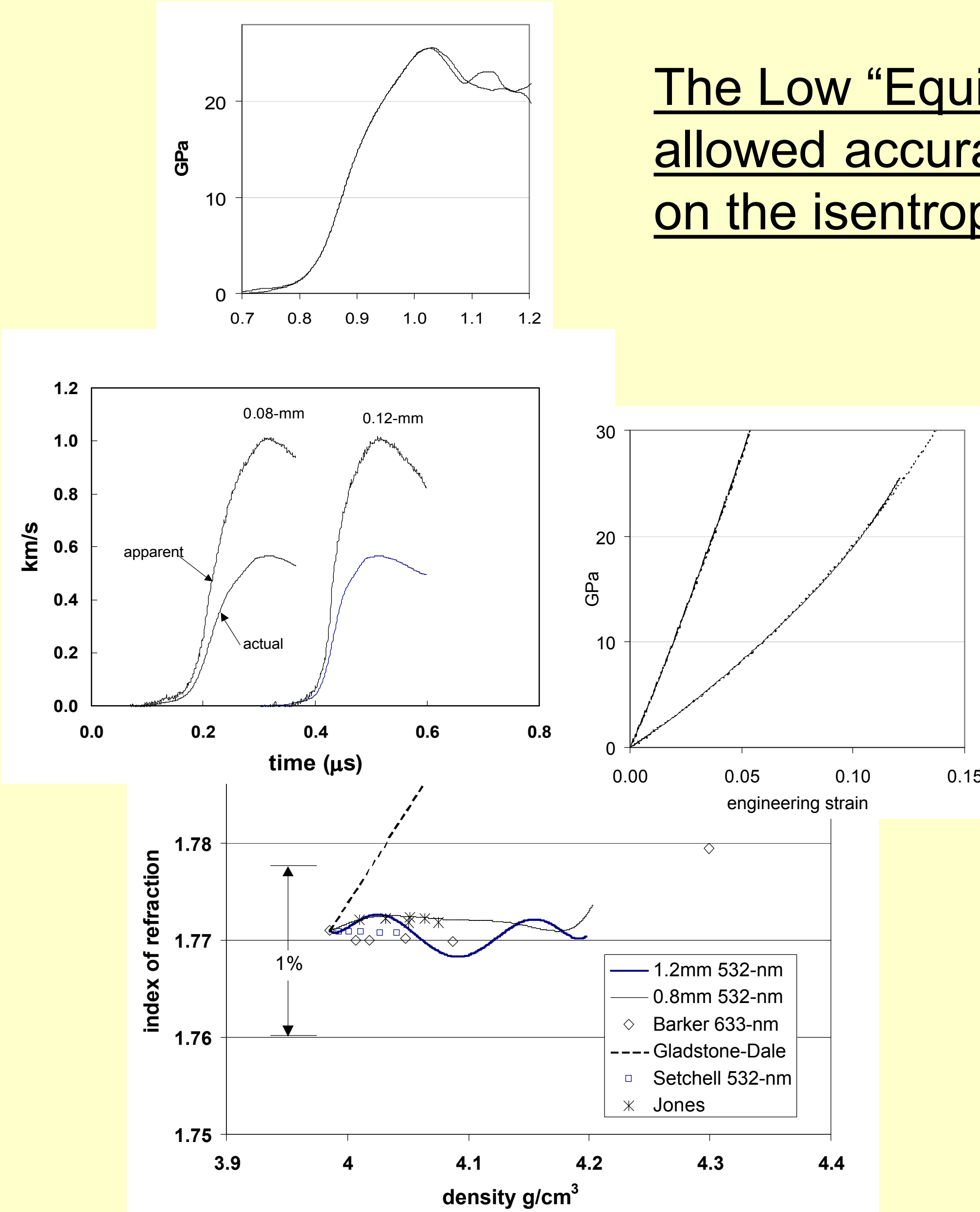
ξ - ns ramps greater than ~1Mbar overtake in ~ 1.4 ξ –μm



$$\delta x = \frac{C_0 \delta t}{1 - \frac{C_0}{C_L}} \cong C_0 \delta t$$

since

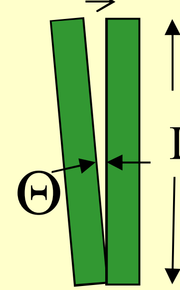
$$1 - \frac{C_0}{C_L} \sim 1$$



The Low "Equivalent Tilt" of Z Experiments allowed accurate P-V measurements (~ ±1%) on the isentrope of sapphire and copper

Gas guns with pillow impactors must match that equivalent tilt

$U\delta t = L\Theta$



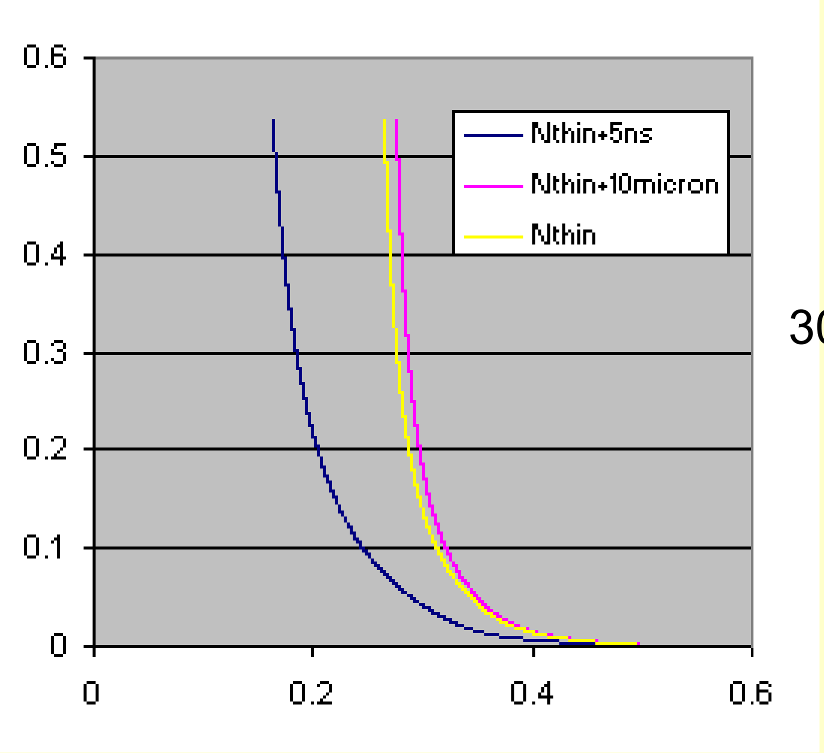
U ~ 1 mm/μs – "impact" velocity

δt ~ 1 ns – timing

L ~ 10 mm – sample separation

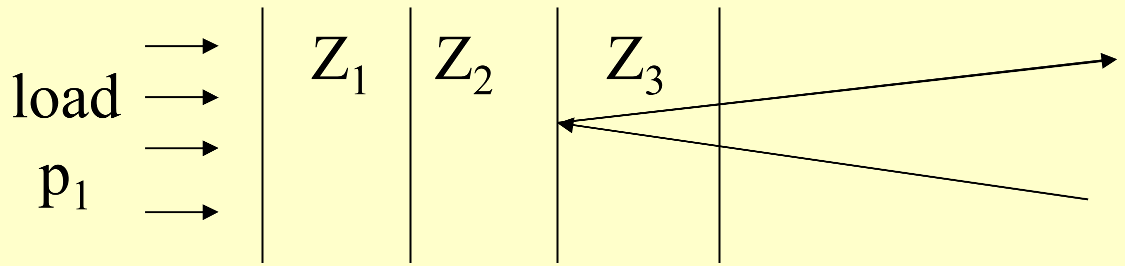
Θ ~ 0.1 mrad. equivalent tilt

Thin samples that ring up give results that are very sensitive to timing accuracy



300 μm HMX (010) single crystal

For shocks, impedance matching is often good because the principal measurement is time. But . . .



$$p_2 = p_1 \frac{2Z_2}{Z_1 + Z_2} \qquad (1)$$

$$p_3 = p_2 \frac{2Z_1}{Z_1 + Z_2} = 4p_1 \frac{Z_1 Z_2}{(Z_1 + Z_2)^2} = \frac{4p_1\phi}{(1+\phi)^2}; \qquad \phi \equiv \frac{Z_2}{Z_1} \qquad (2)$$

$$\left(\frac{\delta p_3}{p_3}\right) = \left(\frac{\delta\phi}{\phi}\right)\left(\frac{1-\phi}{1+\phi}\right) \qquad (3)$$

When the sample is impedance matched to the window, the amplitude measurement is **completely insensitive** to material property variations!

Conclusions

Several assumptions commonly used in analyzing shock compression experiments are invalid for ramp compression:

- analyses are stress-strain path dependent
- interface correction are mandatory
- VISAR analyses can differ
- results can be non-unique

Nonetheless, ramp compression experiments:

- give data not otherwise available
- yield continuous vs. point data
- are very sensitive to phase changes and other phenomena not available in shock experiments