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Title: Solid-Solid Phase Transformation Science on Proton Radiography Facilities

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Los Alamos NATIONAL LABORATORY EST. 1943

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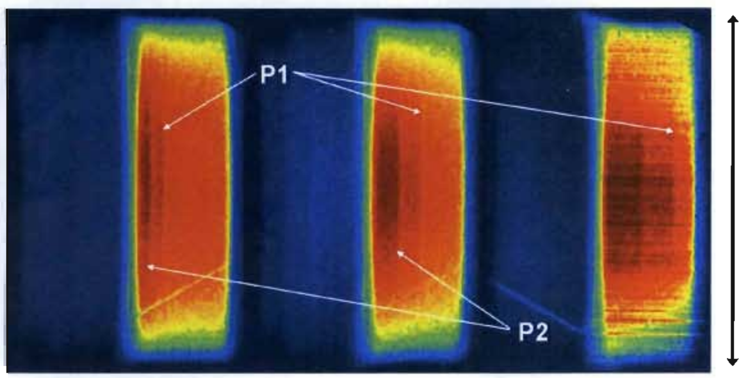
Solid-Solid Phase Transition Measurements in Iron

C. Schwartz, Los Alamos National Laboratory

Previously, dynamic experiments on iron have observed a non-zero transition time and width in the solid-solid α-ε phase transition.[1,2] Using Proton Radiography at the Los Alamos Neutron Science Center, we have performed plate impact experiments on iron to further study the α-ε phase transition which occurs at 13GPa. A 40mm bore powder gun was coupled to a proton radiography beam line and imaging system and synchronized to the impact of the projectile on the target sample with the proton beam pattern. A typical experimental configuration for the iron study, as shown below in 3 color-enhanced radiographs, is a 40mm diameter aluminum sabot impacting a 40mm diameter of polycrystalline ARMCO iron. The iron is backed by a sapphire optical window for velocimetry measurements. The aluminum flyer on the left of the iron is barely visible for visual display purposes.



Direct density jumps were measured[3] which corresponded to calculations to within 1% using a Wondy multi-phase equation of state model. In addition, shock velocities were measured using an edge fitting technique and followed that edge movement from radiograph to radiograph, where radiographs are separated in time by 500 ns. Preliminary measurements give a shock velocity (P1 wave) of 5.251 km/s. The projectile velocity was 0.725 km/s which translate to a peak stress of 17.5 GPa.

Assuming the P1 wave is instantaneous, we are able to calibrate the chromatic, motion, object and camera blur by measuring the width of the P1 wave. This approximation works in this case since each of the two density jumps are small compared to the density of the object. Subtracting the measured width of the P1 wave in quadrature from the width of the P2 wave gives a preliminary measurement of the transition length of 265 μm. Therefore, a preliminary measured phase transition relaxation time τ = transition length/u_s = 265 μm/5.251 km/s = 50 ns.

Both Boettger[1] & Jensen[2] conclude that the transition rate and likely the transition mechanisms depend on the impact stress and the sample thickness. Since Proton Radiography can measure directly the transition length as well as the shock velocity, a transition time can be directly calculated. We propose to perform a series of experiments to measure the phase transition relaxation time, τ, as a function of drive, sample size and crystal orientation.

1. J.C. Boettger and D. Wallace, "Metastability and dynamics of the shock-induced phase transition in iron", Phys. Rev. B **55**, 2840 (1997).

2. B.J. Jensen, G.T. Gray III and R.S. Hixson, "Direct measurements for the α-ε transition stress and kinetics for shocked iron", Journ. Appl. Physics **105**, 103502 (2009).

3. P.A. Rigg, C. L. Schwartz, et al., "Proton radiography and accurate density measurements: A window into shock wave processes", Phys. Rev. B **77**, 220101 (2001).

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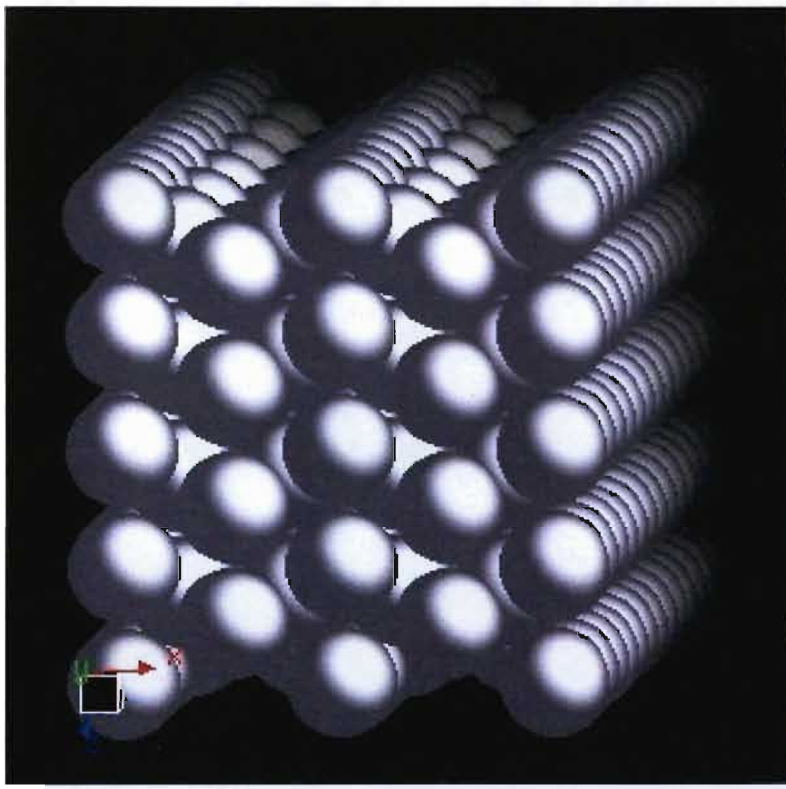
Solid-Solid Phase Transformation Science on Proton Radiography Facilities

Cynthia L. Schwartz and Proton Radiography Team
Los Alamos National Laboratory

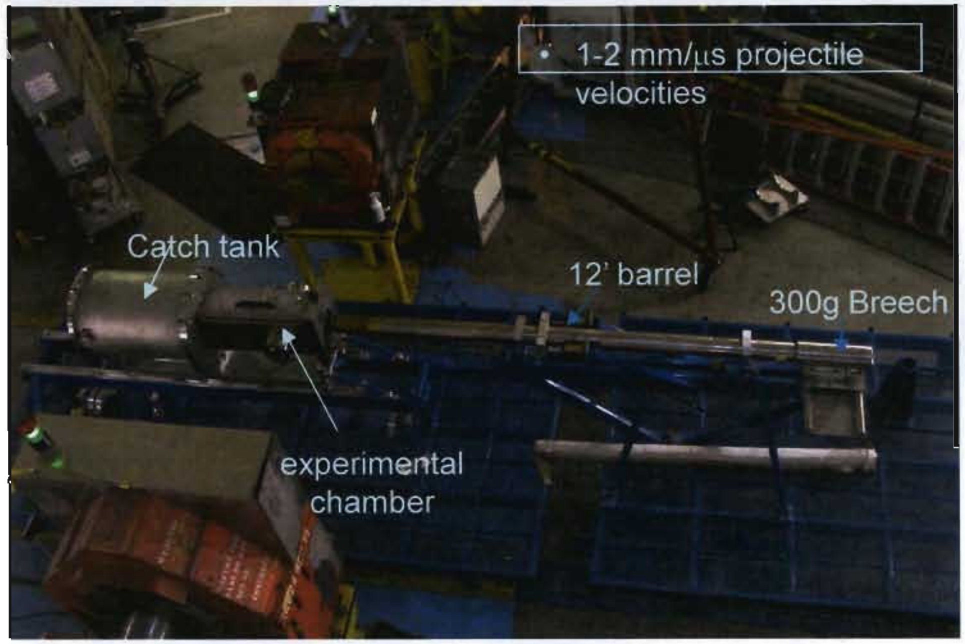


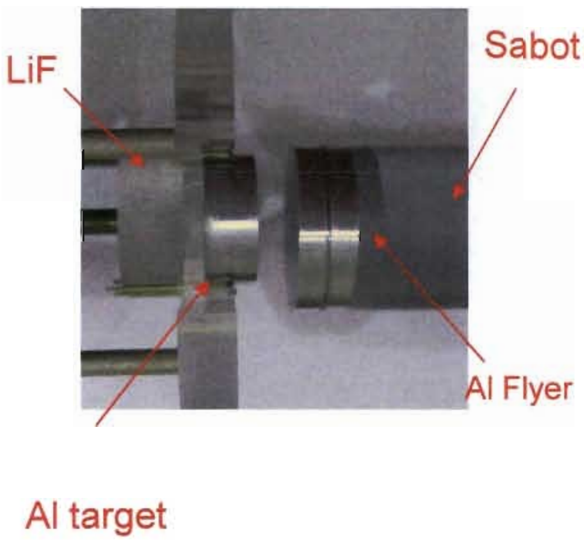
Motivation

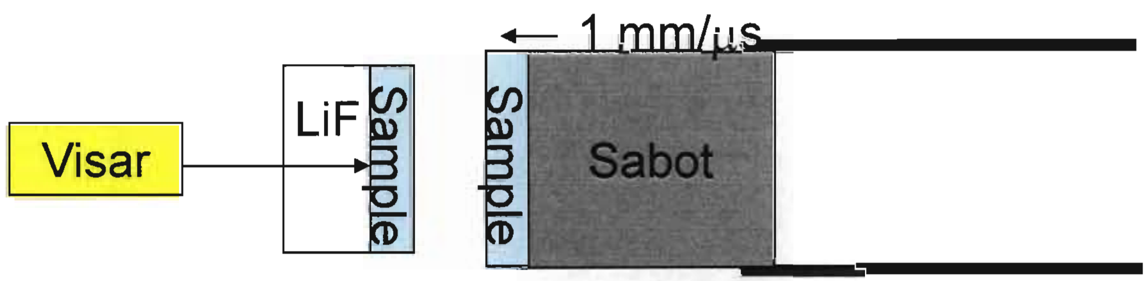
- Highly accurate equations of state are needed to incorporate into models
- Density measurements with 0.5% to 2% accuracy needed to develop accurate equations of state
- Off-Hugoniot measurements are needed to further develop predictive models that accurately describe the behavior of a material undergoing phase transition.
- High fidelity Off-Hugoniot measurements will help develop analytical equations of state
- Release isentropes have information that currently is not in models, ie. Material strength, sound speed, etc.
- Proton Radiography is unique to measure density and wave evolution

Powder Gun Experiments on Al and Cu

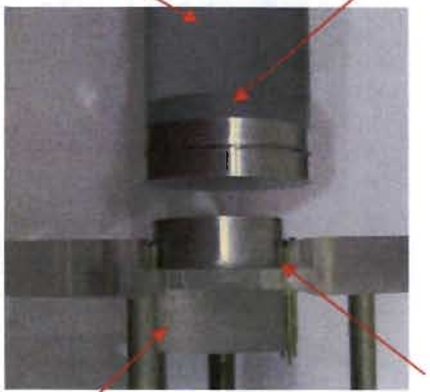
- 1-2 mm/μs projectile
- Planar drive
- Synchronized to proton pulses
- Supported shock wave

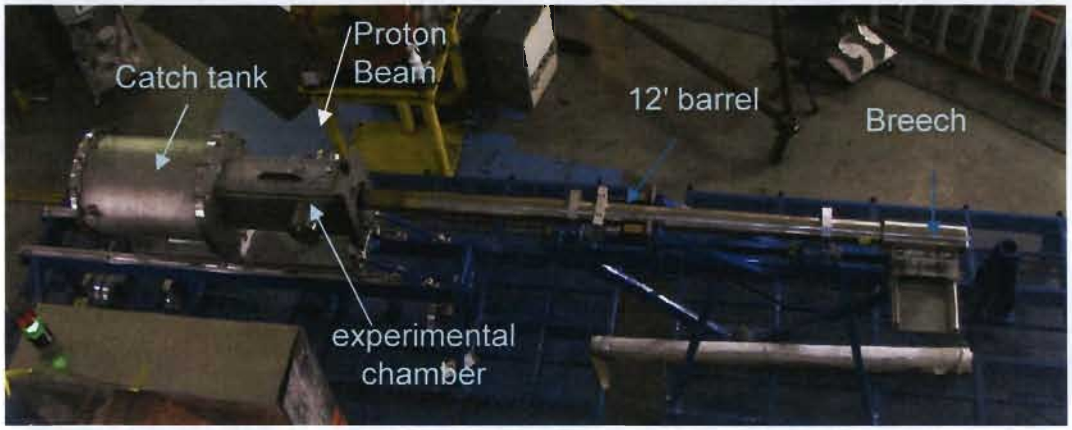


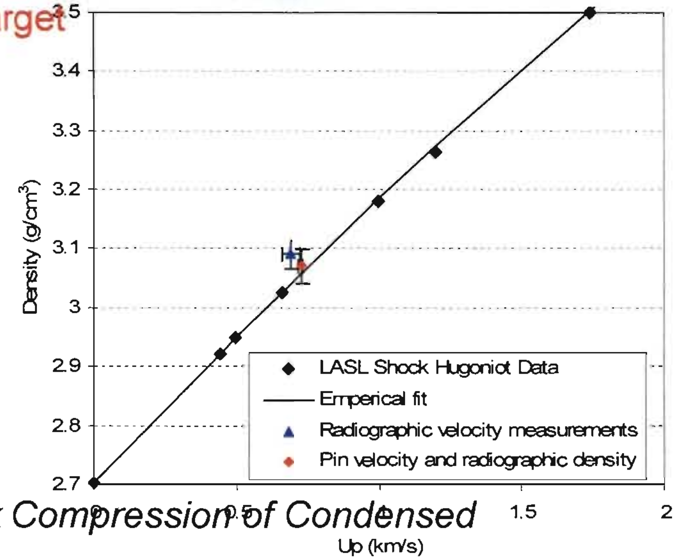




Powder Gun Experiments on Al and Cu







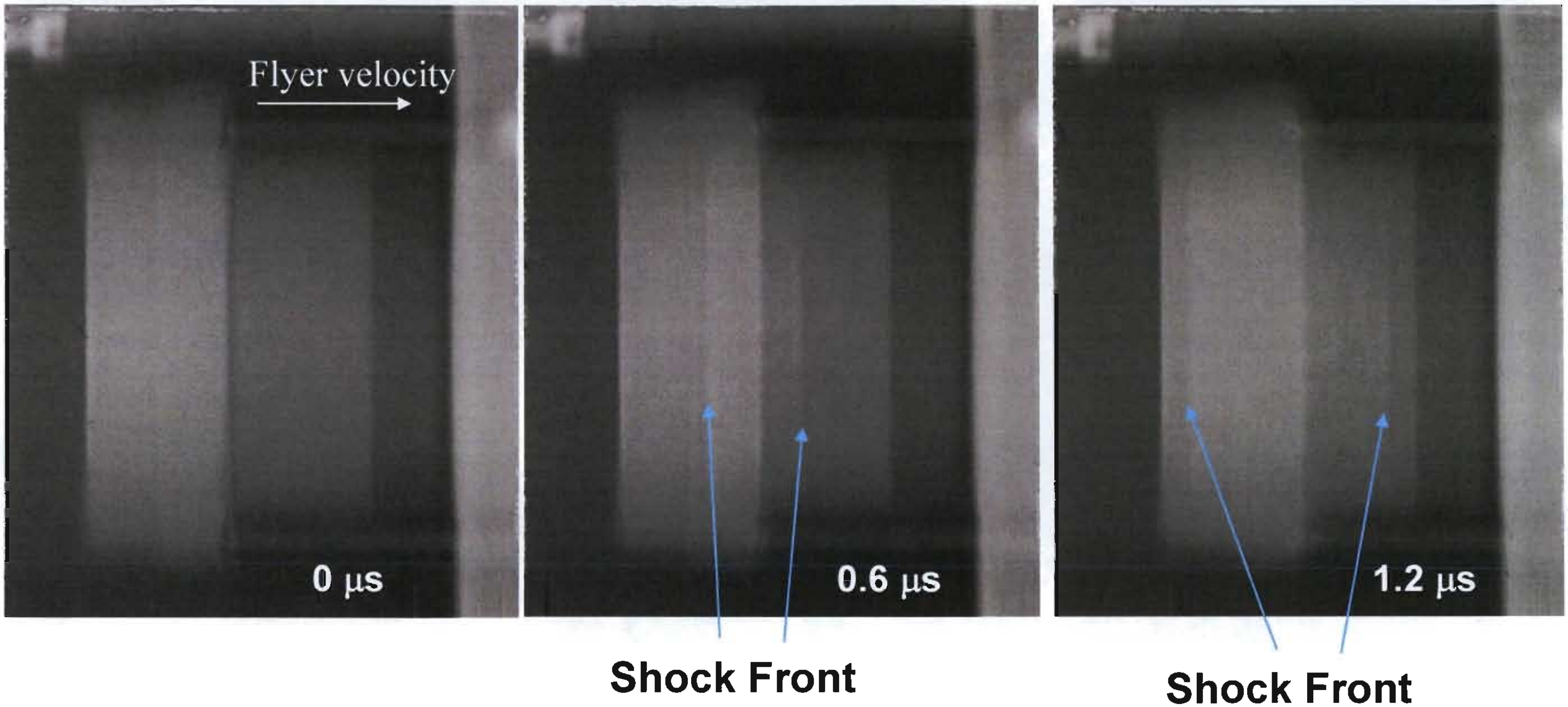
Two methods of measuring a point on shock Hugoniot per dynamic event:

- Radiographic measurement of density behind shock front.
- Simultaneous measurement of particle and shock velocity

Invited Talk : Paulo Rigg, *Shock Compression of Condensed Matter*, 2007

Rigg, Schwartz, et al., *Phys. Rev. B*, Jun 08, vol. 77, iss. 22 220101

Radiography Results – Aluminum Symmetric Impact



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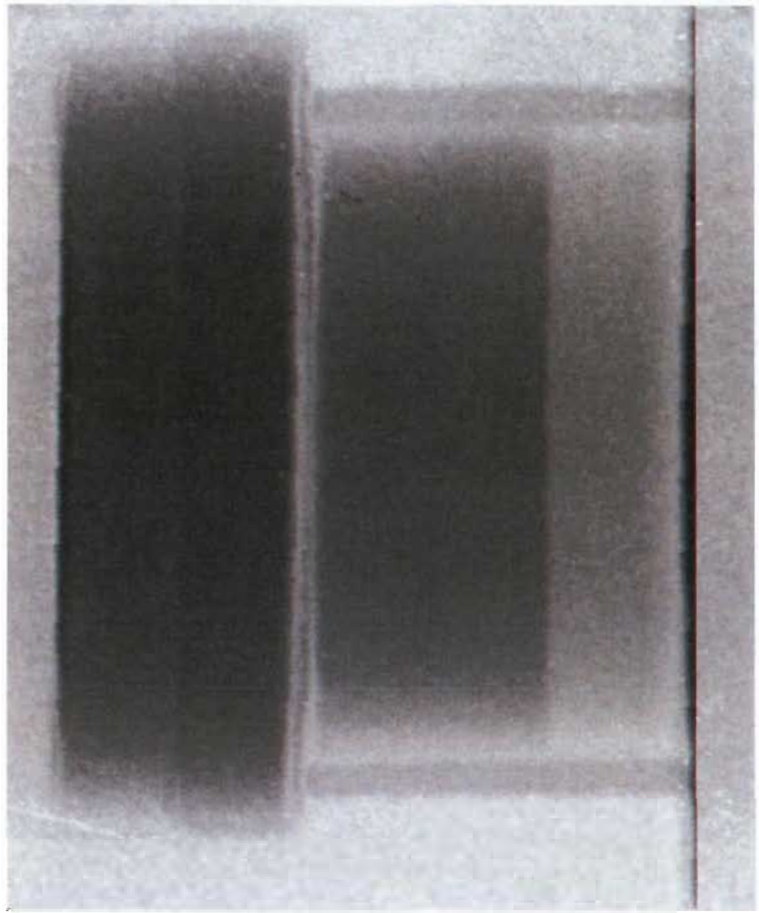


Two methods of measuring a point on shock Hugoniot per dynamic event

- Simultaneous measurement of particle and shock velocity

Impact Velocity

$u_0 = 1.452 \pm 0.012\ mm/\mu s$

Particle Velocity: $\frac{1}{2}\, u_0$

$u_P = 0.726 \pm 0.006\ mm/\mu s$

$P(u_P)$ *for 6061-T6 Al*

$P = 1.184 + 140.2u_P + 37.38u_P^2$

$P = 12.27 \pm 0.09\ GPa$

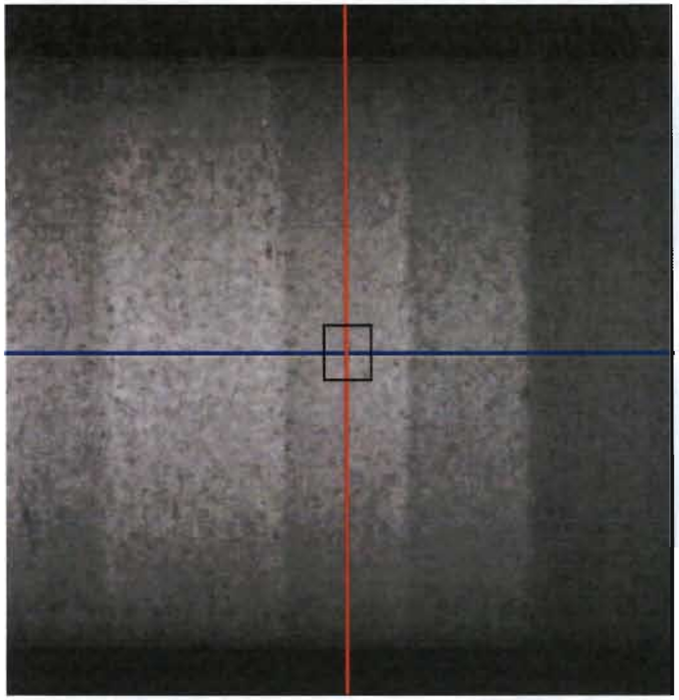
Initial density from immersion

$\rho_0 = 2.710 \pm 0.003 g/cm^2$

Calculate density from Jump Conditions

$$\rho = \frac{\rho_0 P}{P - \rho_0 u_P^2} \Rightarrow \rho = 3.067 \pm 0.009\ g/cm^3\ \ (0.3\%)$$

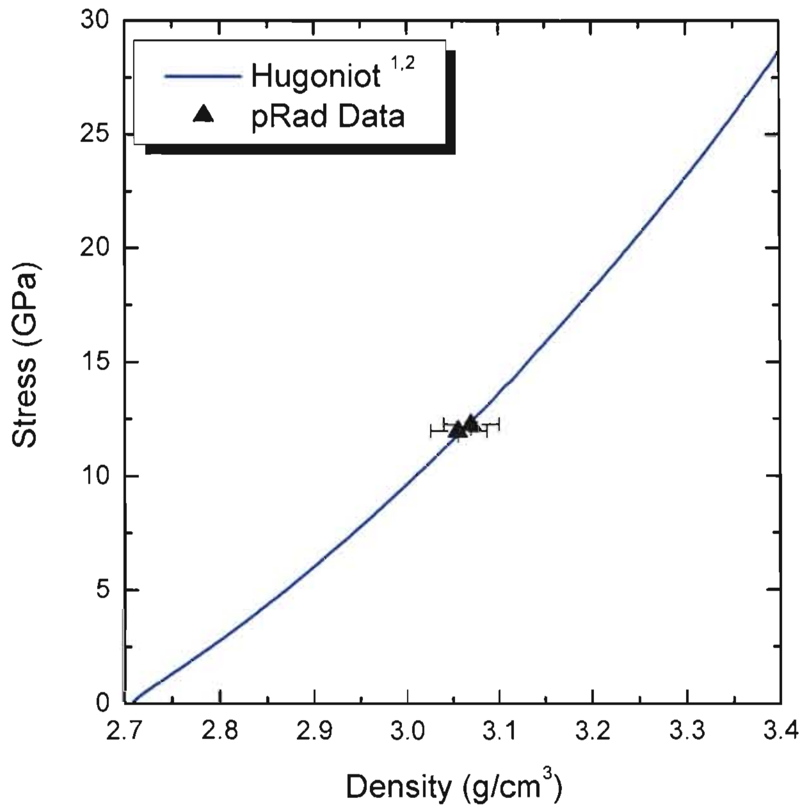
- Radiographic measurement of density behind shock front and particle velocity



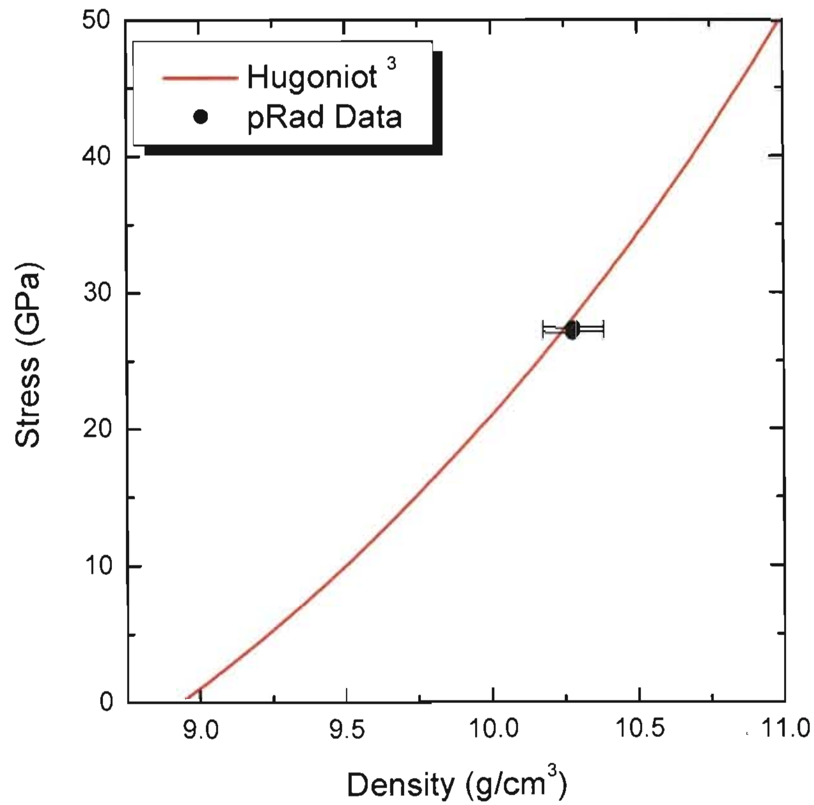
$\rho = 3.07 \pm 0.03\ g/cm^3\ (1.1\%)$

Measured Density Values Lie on Hugoniots

6061-T6 Aluminum



OFHC Copper



(1) C. D. Lundergan and W. Herrmann, J. Appl. Phys. **34**, 2046 (1963).
(2) W. M. Isbell and D. R. Christman, Tech. Rep. MSL-69-60, General Motors (1970).
(3) R. G. McQueen, S. P. Marsh, J. W. Tayor, et. al., *High Velocity Impact Phenomena* (Academic Press, New York, 1970).

Experiment Summary

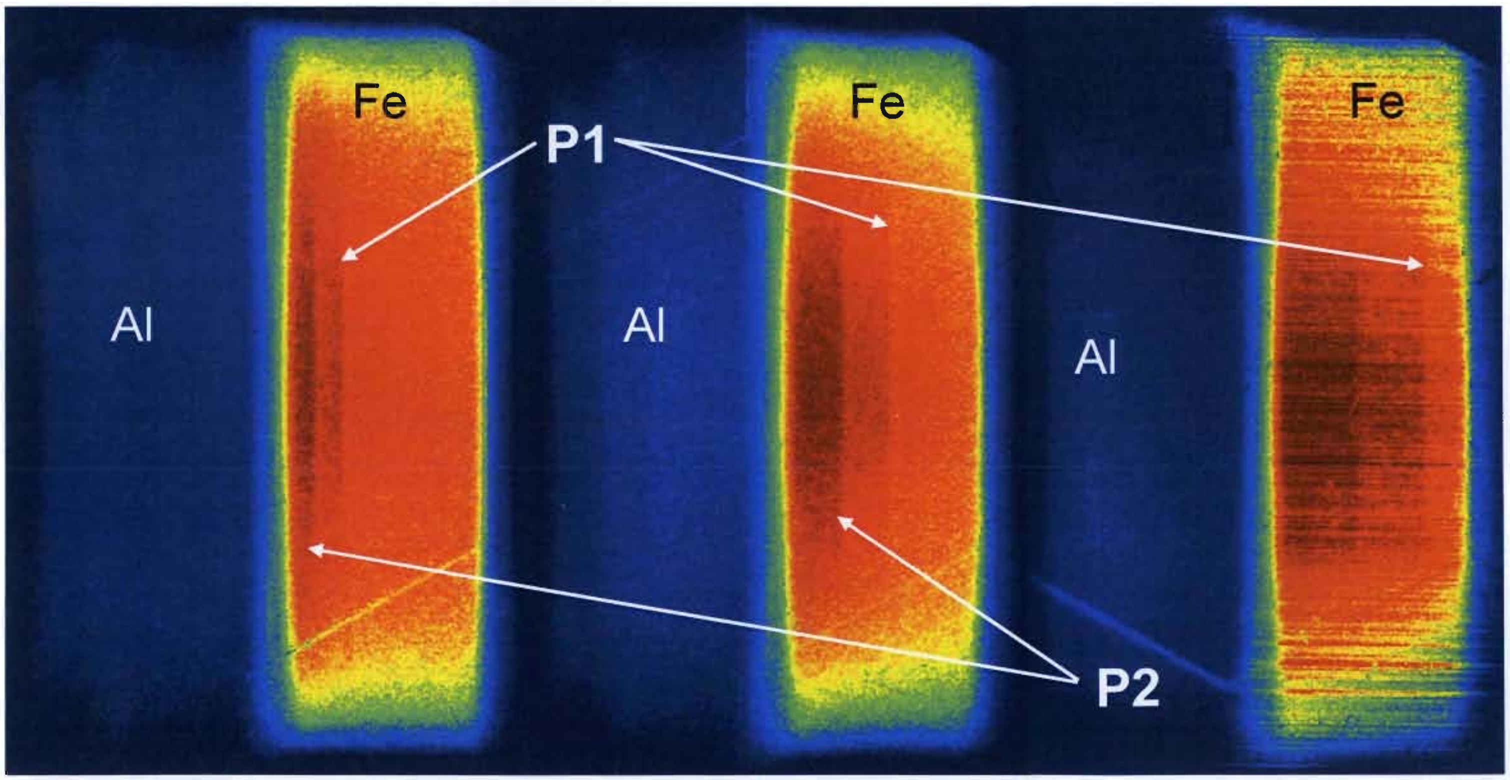
Experiment	Impactor/ Sample	Impactor Velocity (km/s)	Peak Stress (GPa)	Initial Density (g/cm^3)	Calculated Density (g/cm^3)	Measured Density (g/cm^3)	Agreement
1	Al 6061-T6	1.452 (0.012)	12.27 (0.11)	2.710 (0.003)	3.067 (0.005)	3.07 (0.03)	0.1%
2	Al 6061-T6	1.422 (0.002)	11.98 (0.03)	2.710 (0.003)	3.060 (0.004)	3.056 (0.03)	0.1%
3	OFHC Cu	1.30 (0.04)	28.59 (0.91)	8.928 (0.003)	10.30 (0.05)	10.28 (0.10)	0.2%
4	OFHC Cu	1.249 (0.002)	27.16 (0.06)	8.928 (0.003)	10.241 (0.006)	10.28 (0.10)	0.4%

- Agreement between measured and calculated values better than 0.5% for all experiments

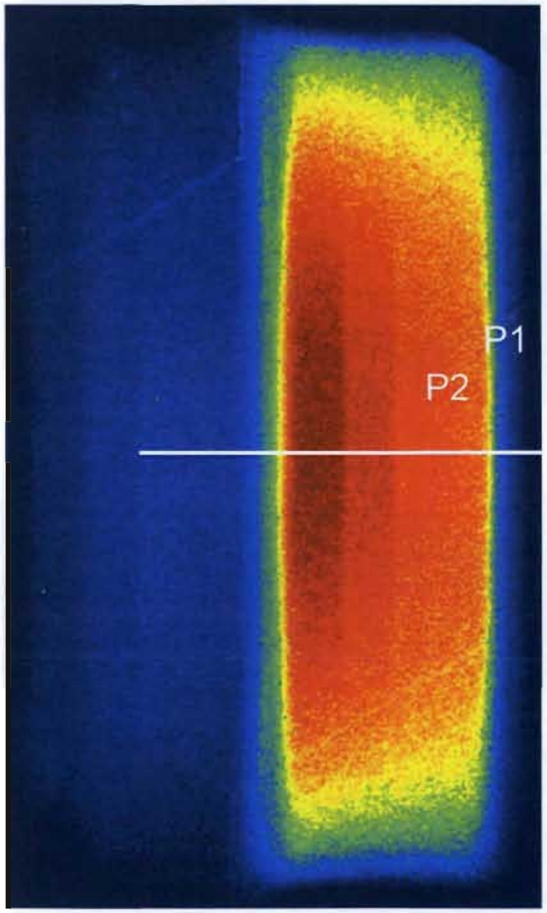
P.A. Rigg, et al., "Proton radiography and accurate density measurements: A window into shock wave processes", Phys. Rev. B **77**, 220101 (2001).

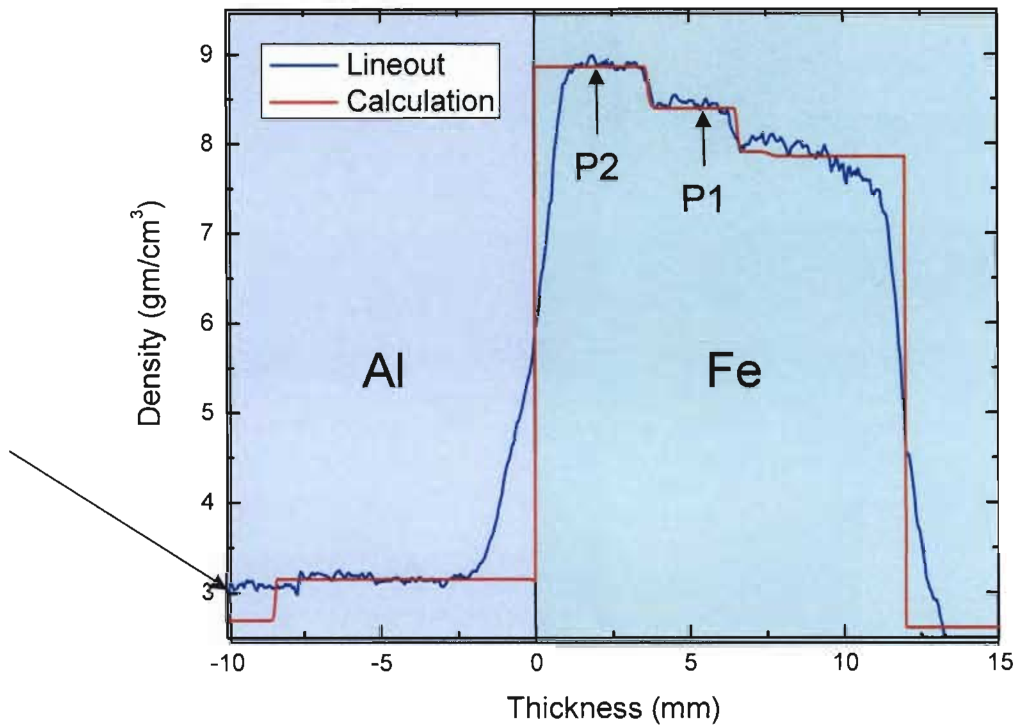
Two-wave structure observed in Iron

- Aluminum impacting Iron backed by Sapphire @ 1.45 km/s -> 175 kbar in Fe
- 3X pRad Magnifier used to enhance contrast and sharpness
- 3 camera times captured separated by 500ns



Powder Gun-Driven
Measured and Calculated Densities - Iron





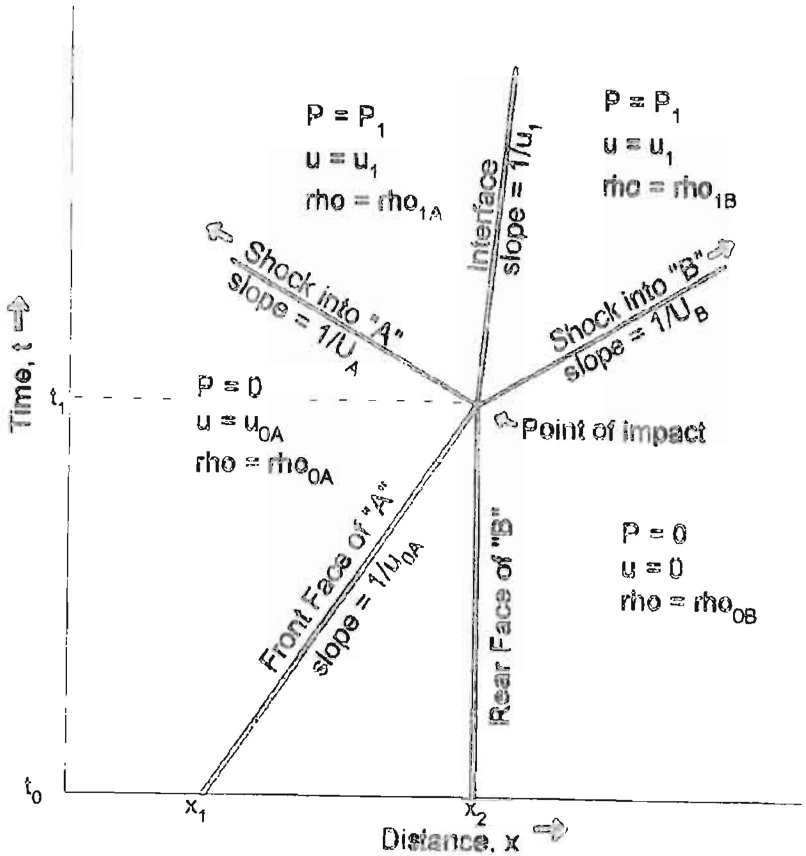
Schwartz, et. al, IP Conference Proceedings (12 Dec. 2007) vol.955, no.1, p.1135-8

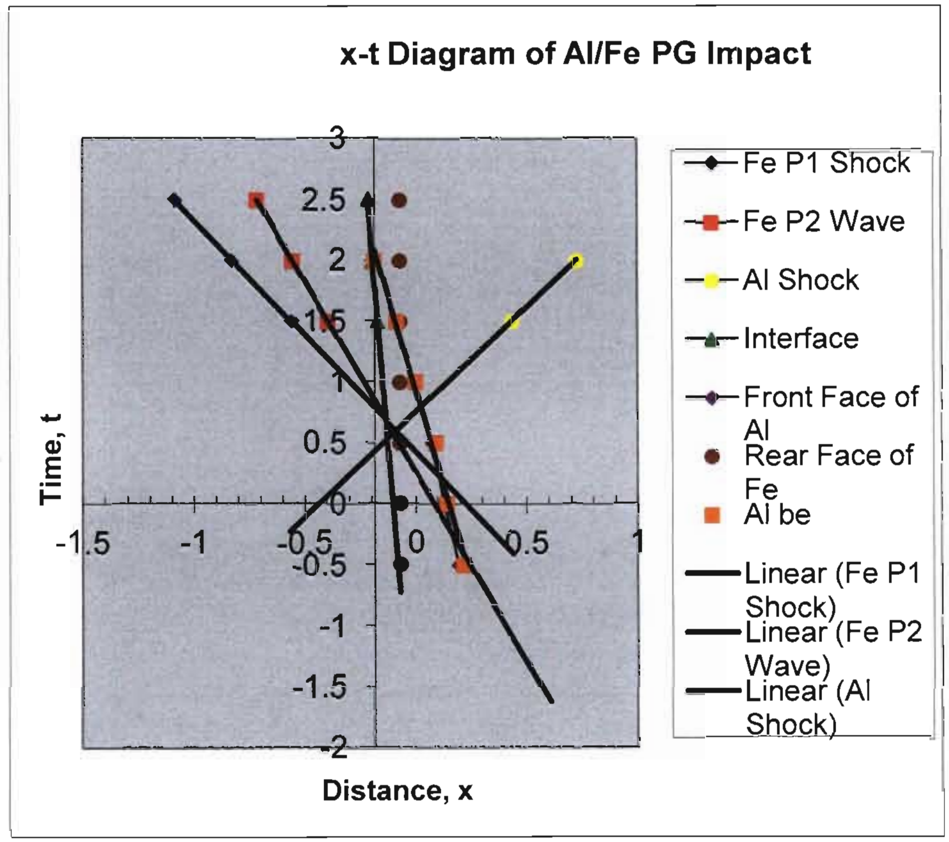
Fe Densities

State	Measured	Calculated*	Agreement
P1	8.346	8.342	<0.1%
P2	8.854	8.846	0.1%

*calculated values from 1-D Multi-Phase EOS for Fe model

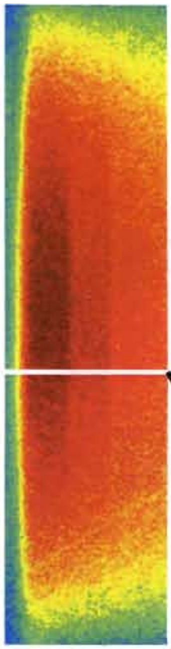
x-t diagram of impact of two slabs

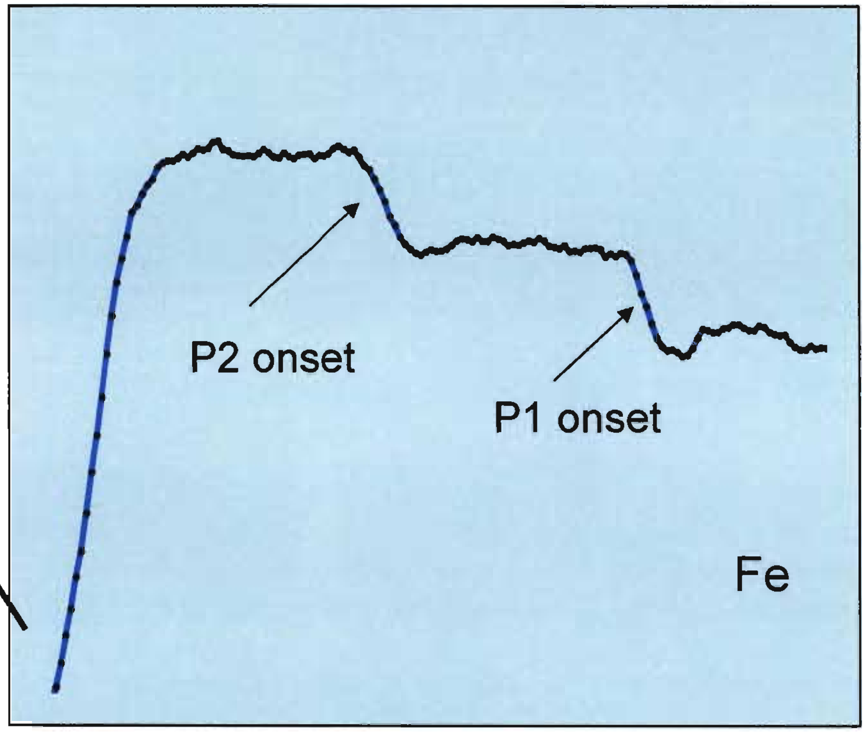




Resolution Calibration

The nearly instantaneous P1 wave can be used to calibrate the resolution of the radiographic system





in-situ measurement of the relaxation time

Agreement with surface velocimetry experiments on Fe

J.C. Boettger and D. Wallace, "Metastability and dynamics of the shock-induced phase transition in iron", Phys. Rev. B **55**, 2840 (1997).

B.J. Jensen, G.T. Gray III and R.S. Hixson, "Direct measurements for the a-e transition stress and kinetics for shocked iron", Journ. Appl. Physics **105**, 103502 (2009).

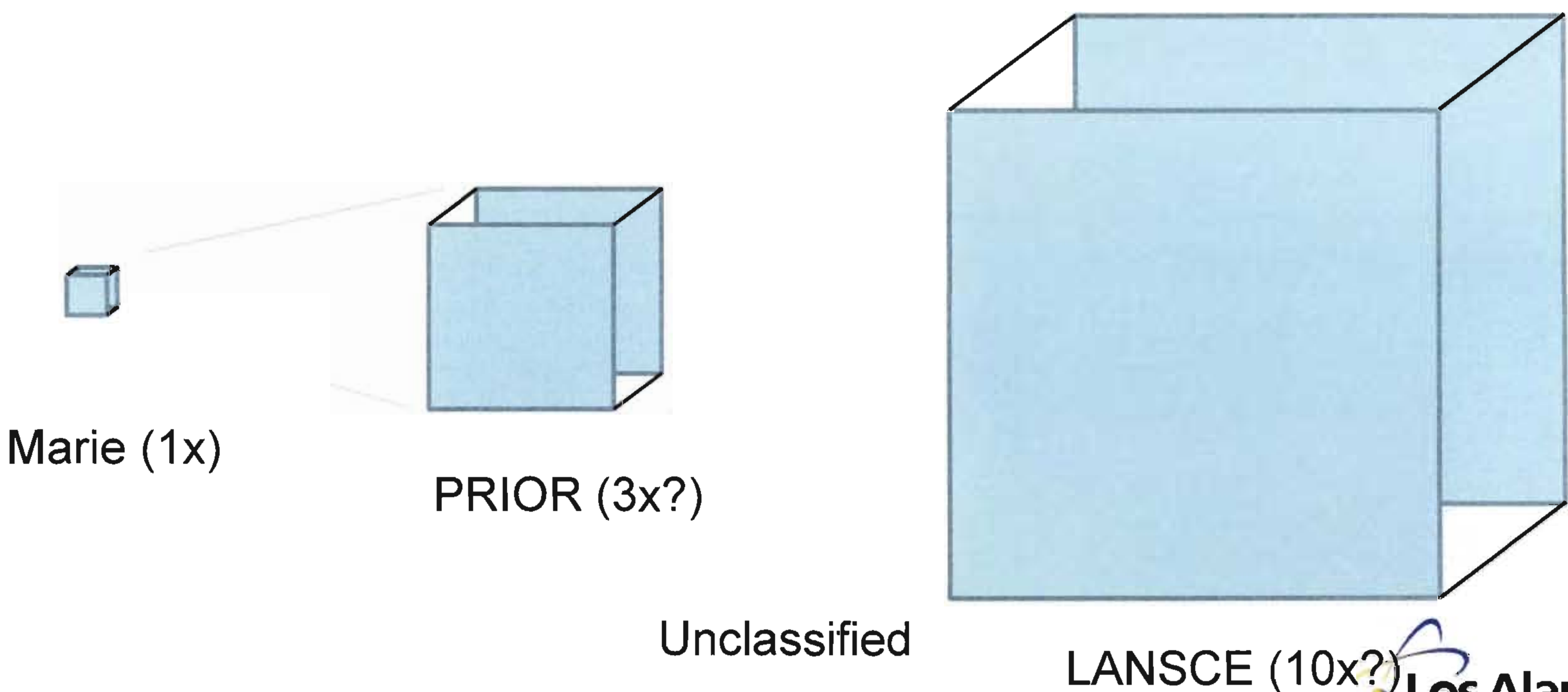
ζ= P2 rise time- P1 rise time= 265 μm

u_s = 5.251 μm/ns

τ = relaxation time = ζ/u_s = 50 ns

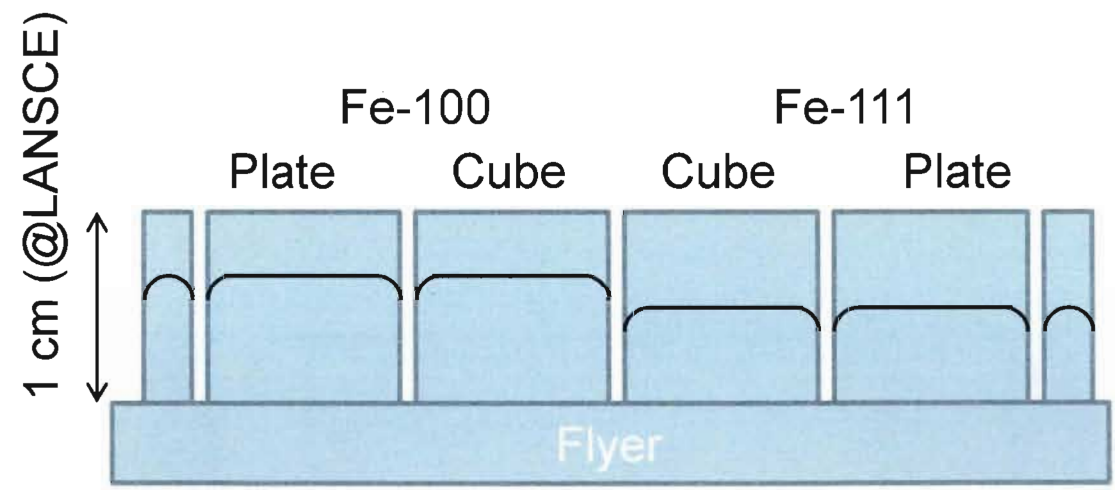
Scaled MaRIE-type experiments

- How important are edge effects on the Marie physics?
- pRad @ Line C or PRIOR cannot reach Marie scales
- But they can access large scale replicas of Marie experiments
- Edge effects are expected to scale with experiment size



Proposal: single shot, multiple experiments To be done at LANSCE and PRIOR

- Mount multiple objects to be hit by single flier
- Scale experiment to LANSCE and PRIOR FOV and resolution
- Radiograph experiment both directions simultaneously
- Actual experiments TBD; Fe crystals as example



Hugoniot vs. Isentrope

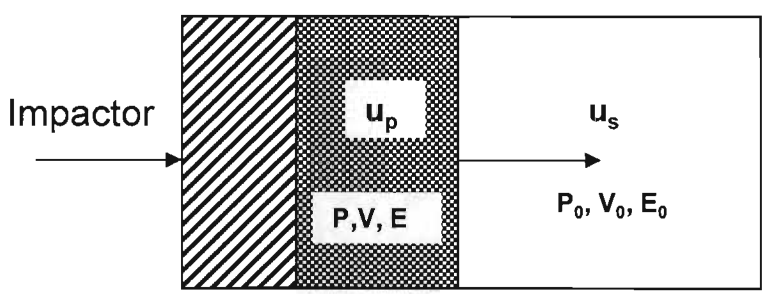
Rankine-Hugoniot Equations

•Hugoniot is locus of p-v states attainable behind a shock

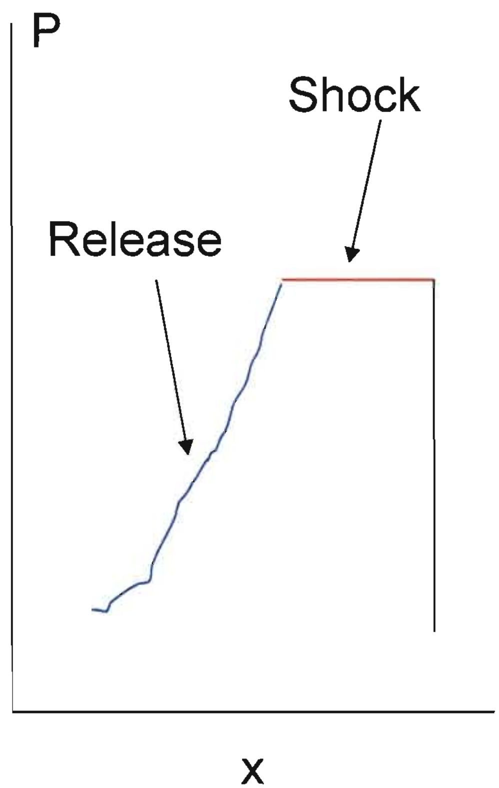
$$\frac{V}{V_0} = 1 - \frac{u_p}{u_s}$$

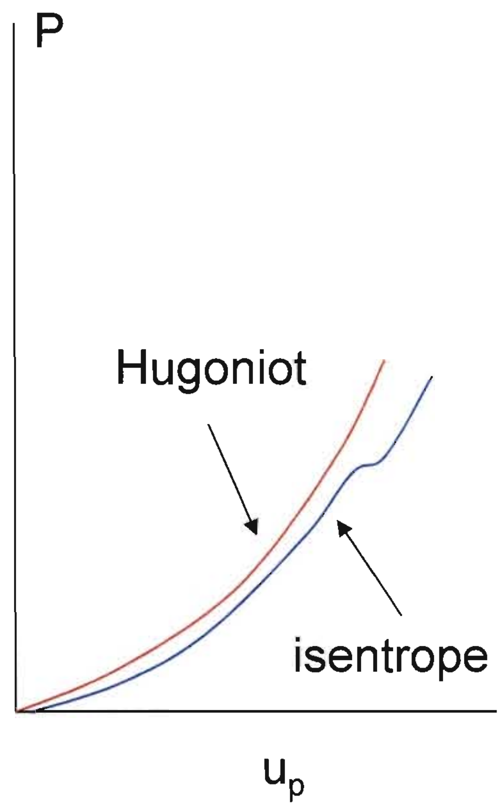
$$P - P_0 = \frac{u_s u_p}{V_0}$$

$$E - E_0 = \frac{1}{2}(P + P_0)(V_0 - V)$$

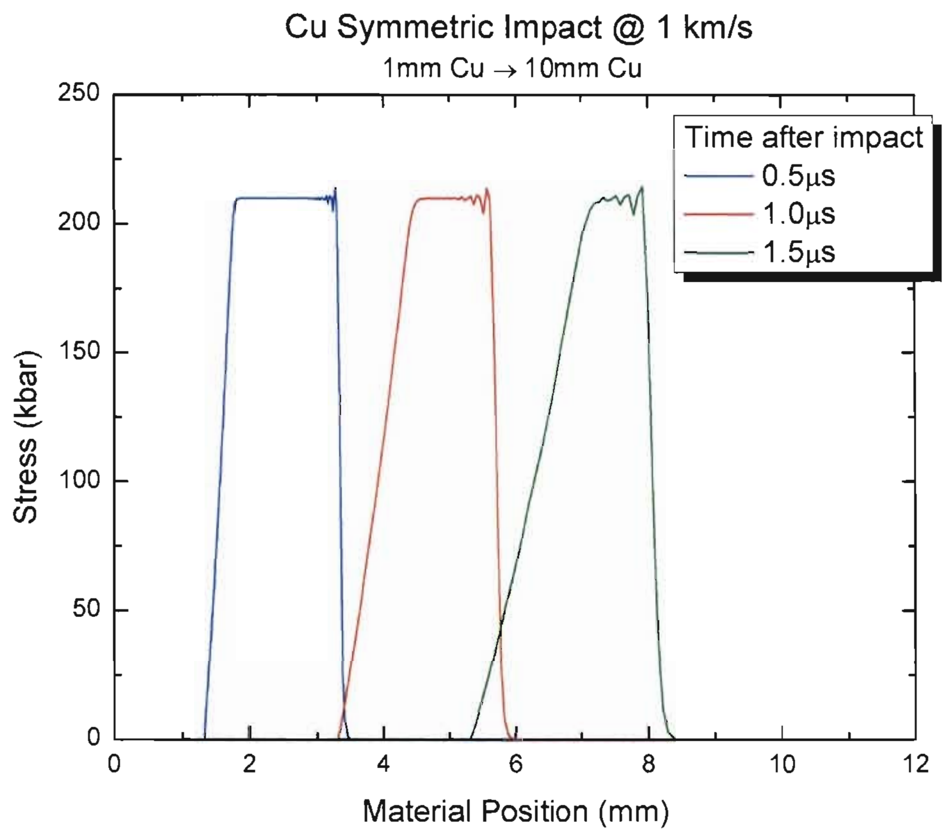


No mechanical strength





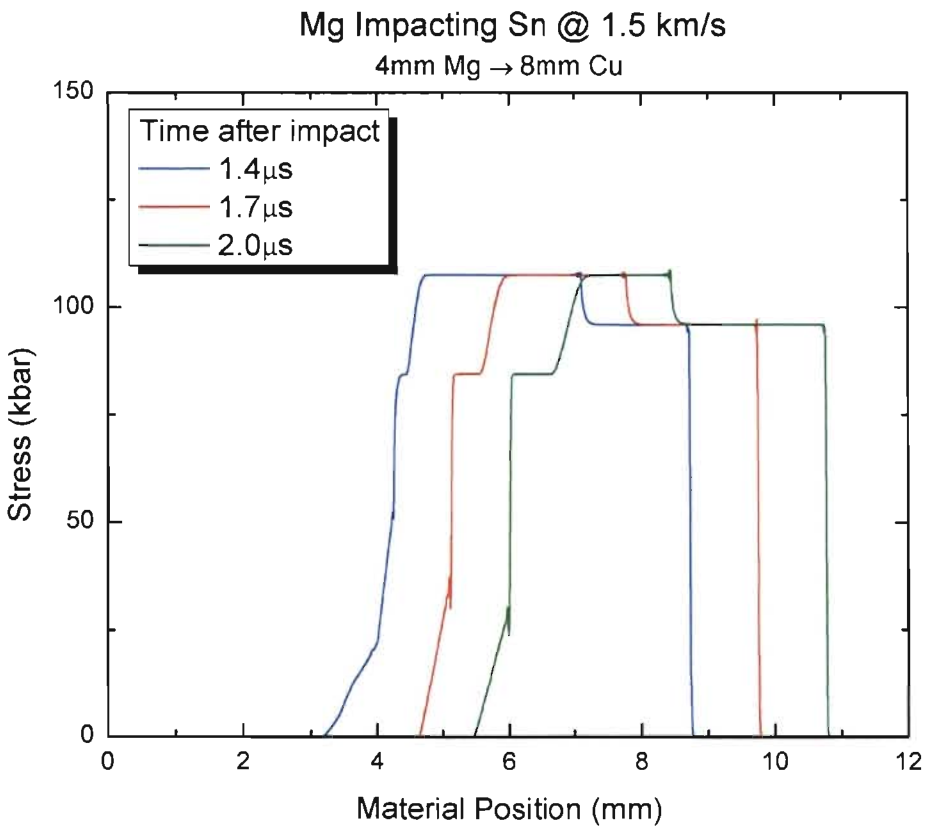
Wondy Calculation: Isentrope shape changes with time



- Shape of the isentrope changes over time and within a given radiographic time
- Want to measure the density as a function of position within a given time as well as density sets over time
- Copper and Aluminum fairly well understood
- Significant strength affects isentrope

Pressure proportional to measured density

Wondy Calculation: Isentrope shape changes within a given time



- Phase transitions have more complex release wave structure
- Some transitions, such as Tin, have phase reversal
- Significant strength affects isentrope
- Incorporate into predictive models such as CTH, Wondy, ALE3, FLAG, etc.

Summary

- Perform experiments on Iron
  - well studied
  - atomistic MD simulations for comparison
  - Experimental data for comparison

- Perform experiments with multiple single crystal orientations as well as polycrystalline in iron to understand the affect of crystal orientation on Hugoniot response
  - Measure shape and evolution of P2 wave using P1 wave as a resolution calibration

- Begin off-Hugoniot studies
  - Design deep release experiments
  - Measure shape and evolution of release isentrope for iron to calibrate and validate EOS models
  -