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Title: Direct Shock-Density Measurements using Plate Impact and Proton Radiography

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Form 836 (7/06)

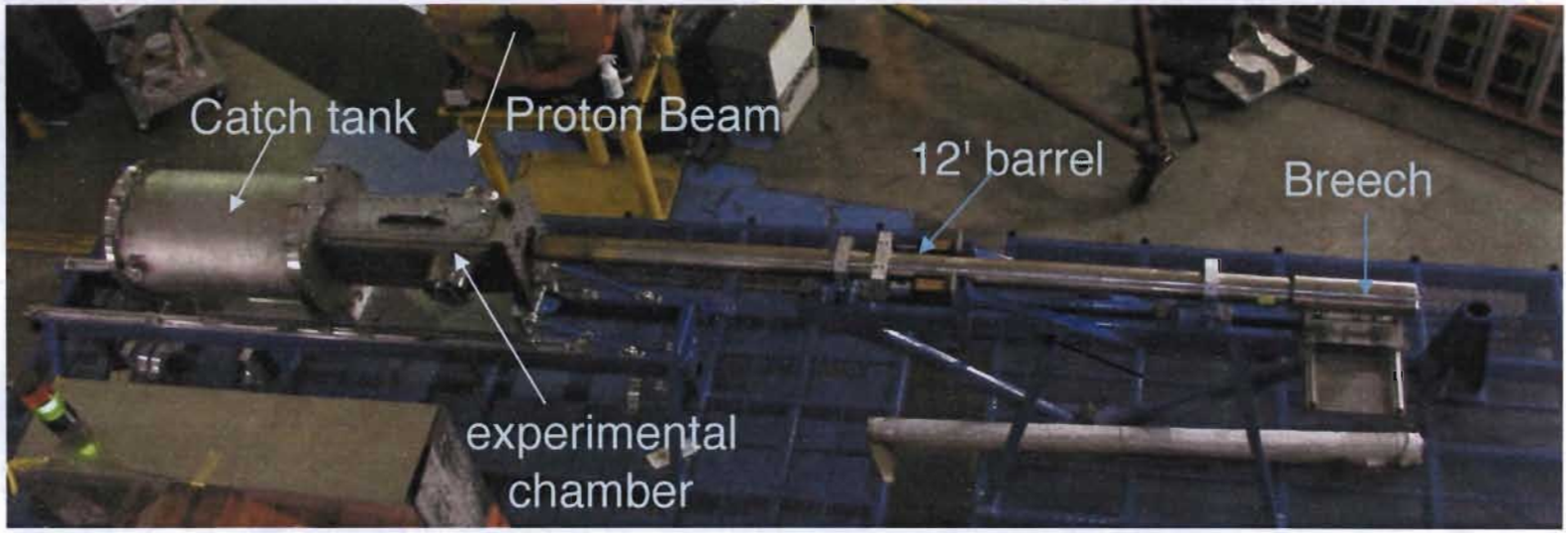
Direct Shock-Density Measurements using Plate Impact and Proton Radiography

P. A. Rigg, WX-9, Los Alamos National Laboratory

Abstract

Proton radiography (pRad) is a powerful new diagnostic with the potential of producing accurate (1%) direct density measurements from dynamically loaded materials. Experiments have been performed to investigate the feasibility of using proton radiography (pRad) to obtain dynamic radiographs of shock-compressed materials during plate impact experiments. This work has involved the design, manufacturing, and testing of a new 40mm single-stage, powder driven gun, the development of methods to synchronize the shock event generated with the gun to proton output, and initial proof-of-principle experiments in Area C at LANSCE. The method used to attain synchronization of the shock event to proton beam output will be discussed and the results of our initial experiments will be presented.

Direct Shock Density Measurements Using Plate Impact and Proton Radiography



P. A. Rigg, C. L. Schwartz, R. S. Hixson,
F. E. Merrill, C. L. Morris, A. Saunders, pRad Team
Los Alamos National Laboratory

Imperial College Diagnostics Short Course

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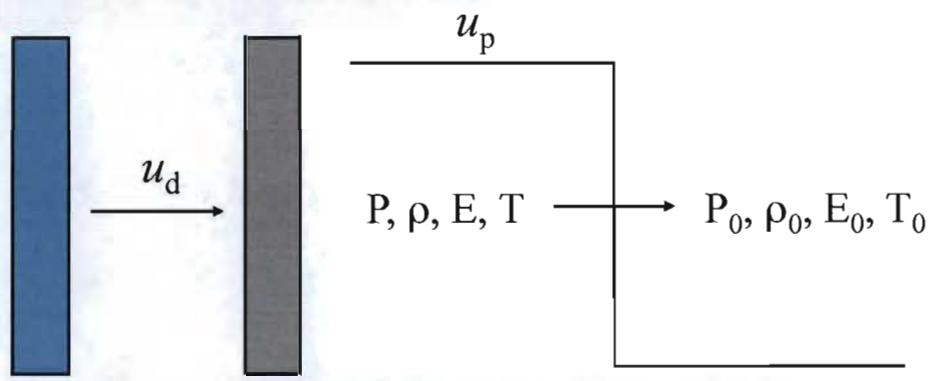
Introduction – Length Scales

- Shock wave measurements primarily at continuum level
  - Diagnostics suited for macroscopic measurements
  - Conservation equations relate fundamental observables

(1) $$\frac{\rho_0}{\rho} = 1 - \frac{(u_p - u_{p0})}{(u_s - u_{p0})}$$ mass

(2) $$P - P_0 = \rho_0 (u_s - u_{p0})(u_p - u_{p0})$$ momentum

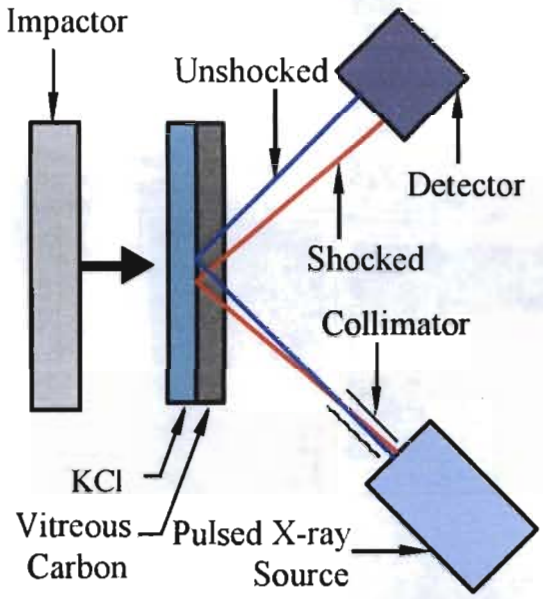
(3) $$E - E_0 = \tfrac{1}{2}(P + P_0)(V_0 - V)$$ energy



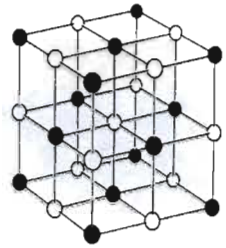
- Strong need for methods to probe micro- and meso-scale
- Difficult to couple micro- and meso-scale diagnostics to plate impact experiments.

Examples of Micro-Scale Measurements

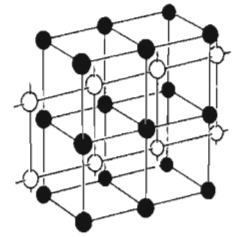
- Dynamic X-Ray Diffraction
  - Elastic-Plastic Deformation
  - Phase Transitions



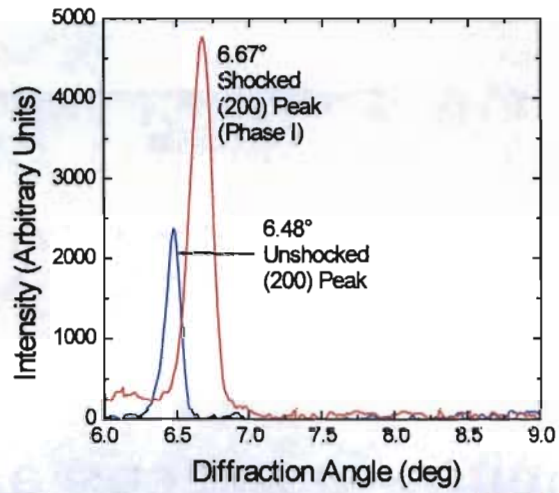
Phase I (NaCl)



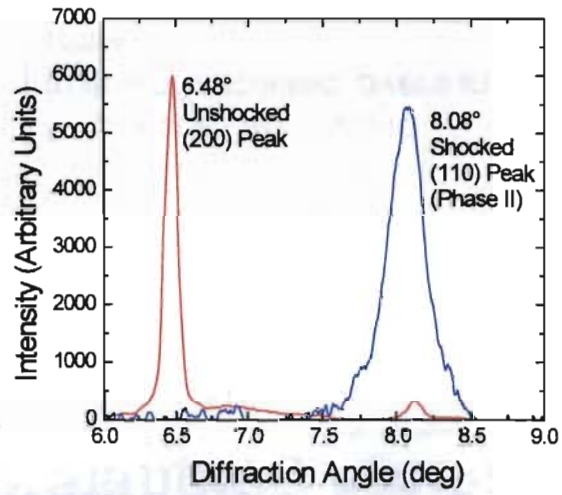
Phase II (CsCl)



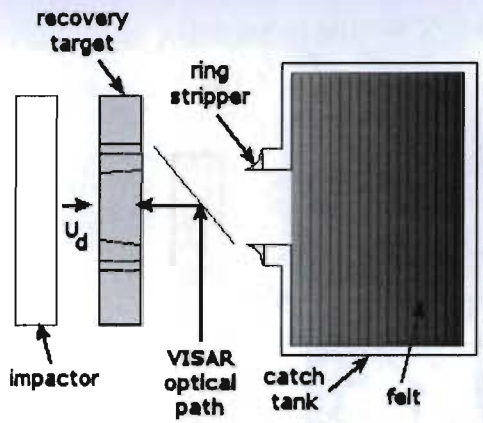
KCl[100] shocked to 2.0 GPa

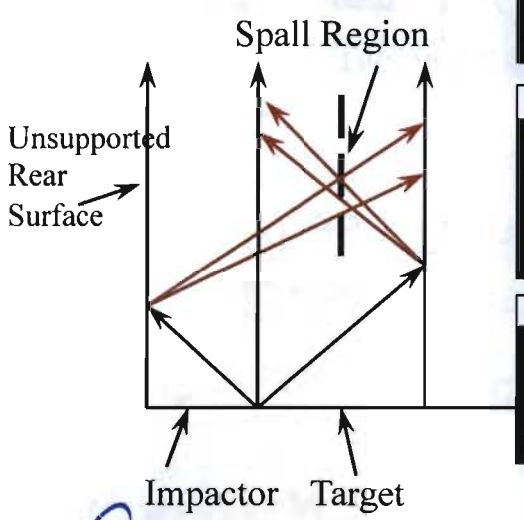


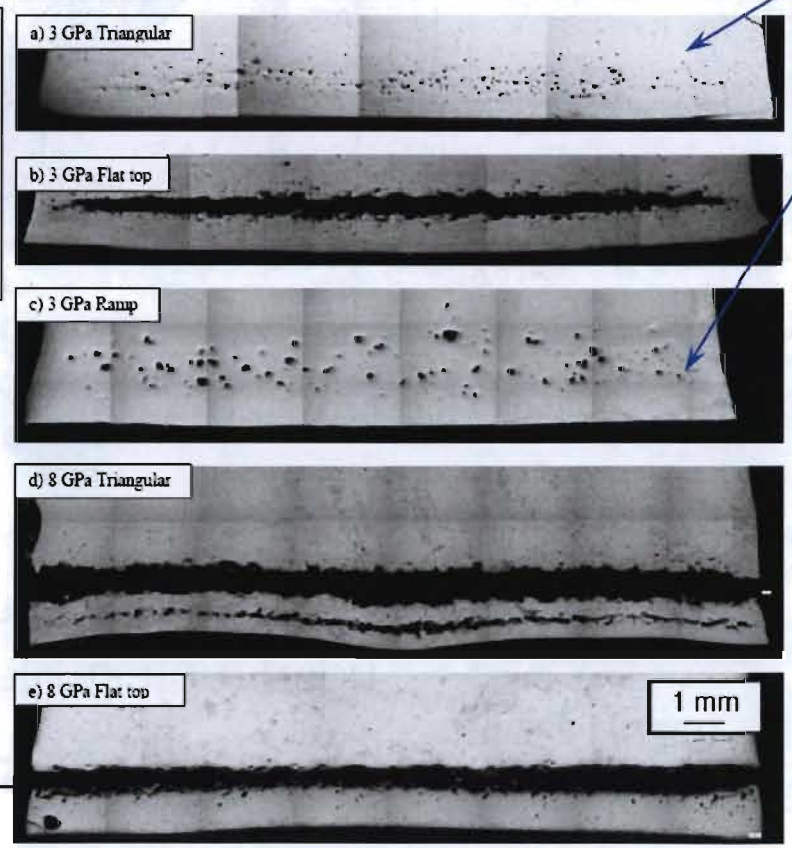
KCl[100] shocked to 6.8 GPa



Mesoscopic Shock Wave Research – Understanding Failure



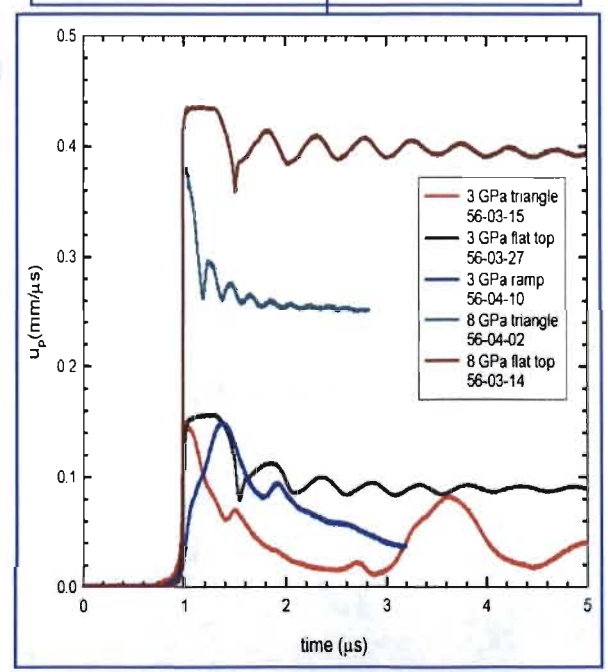




0.70% void fraction

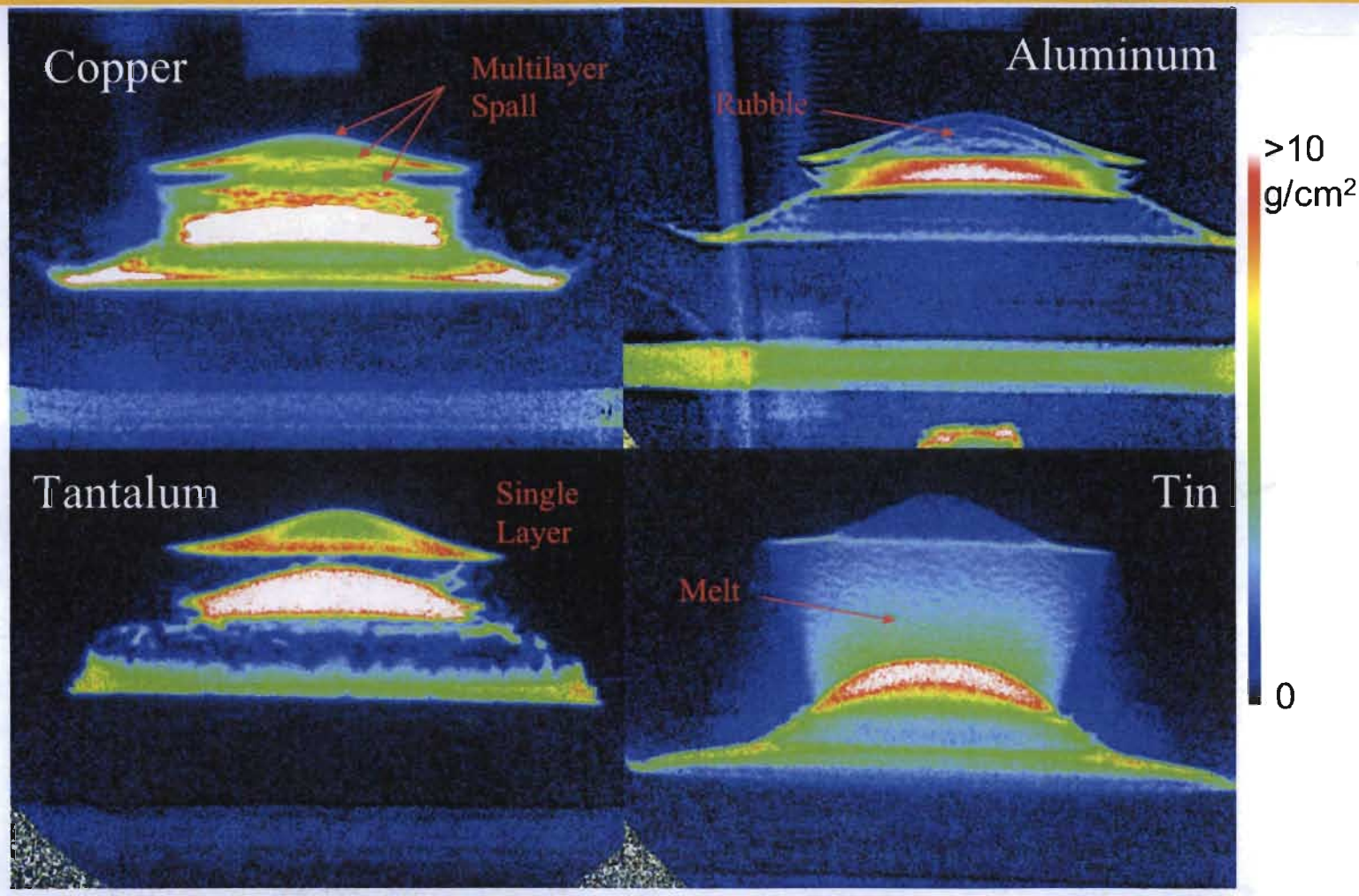
4.1% void fraction

VISAR analysis shows reflections from both full failure spall layers and insipiently spalled layers in the material.



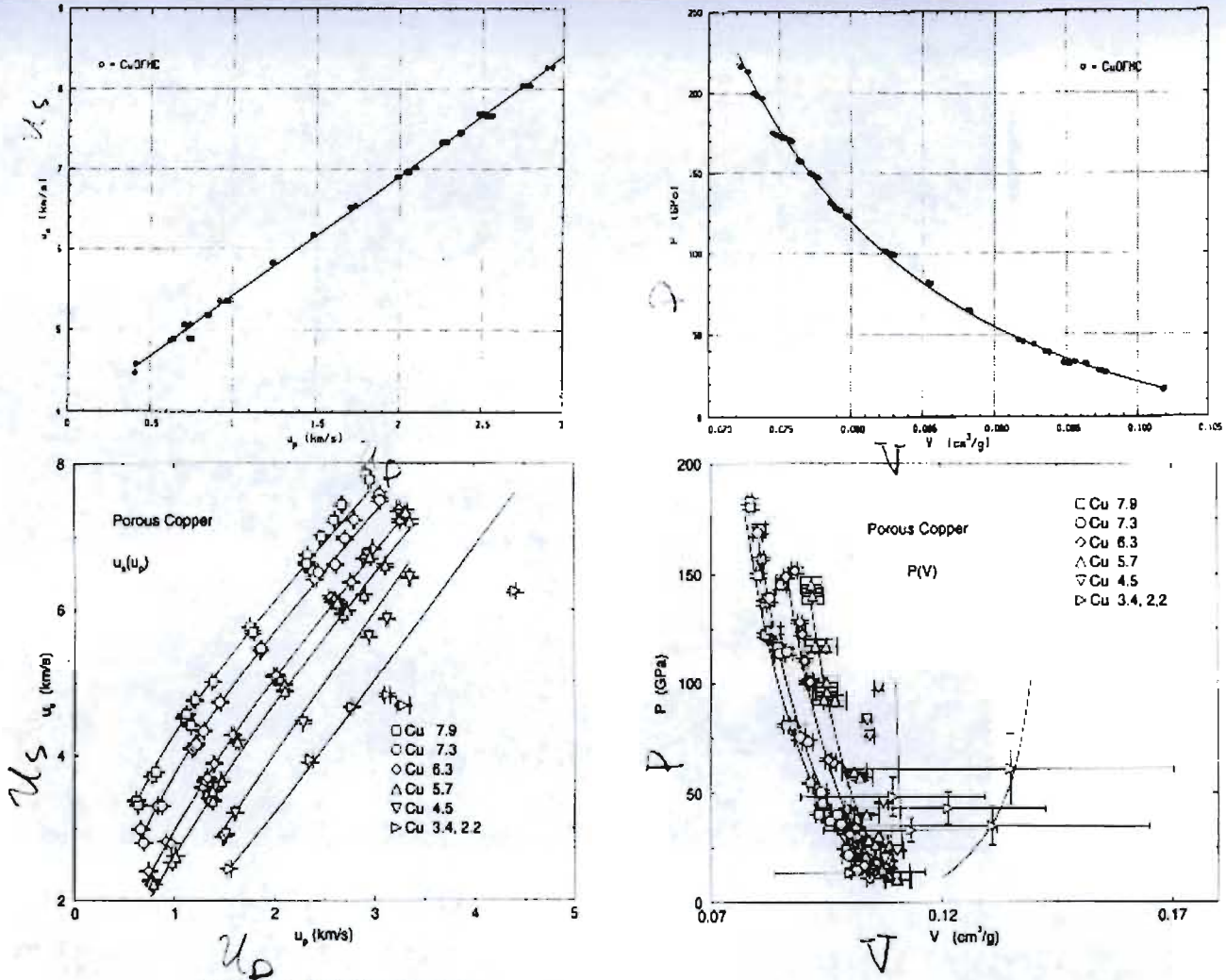
Koller et al. (2006)

Proof of Concept Experiment – Taylor Wave Spall in Metals
D. Holtkamp



The Need for Direct Density Measurements

- Conventional shock physics method for measuring densities in shocked states:
  - Measure Us and Up (or Ud).
  - Apply conservation of mass, calculate density
  - This can lead to very large error bars, particularly for porous materials:



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Error Analysis for Density

Using standard propagation of errors of measured quantities

$$\frac{\Delta\rho}{\rho} = \frac{1}{\rho_0}\left\{\Delta U_S\left[\frac{U_P}{\left(U_S - U_P\right)^2}\right] + \Delta U_P\left[\frac{U_S}{\left(U_S - U_P\right)^2}\right]\right\}$$

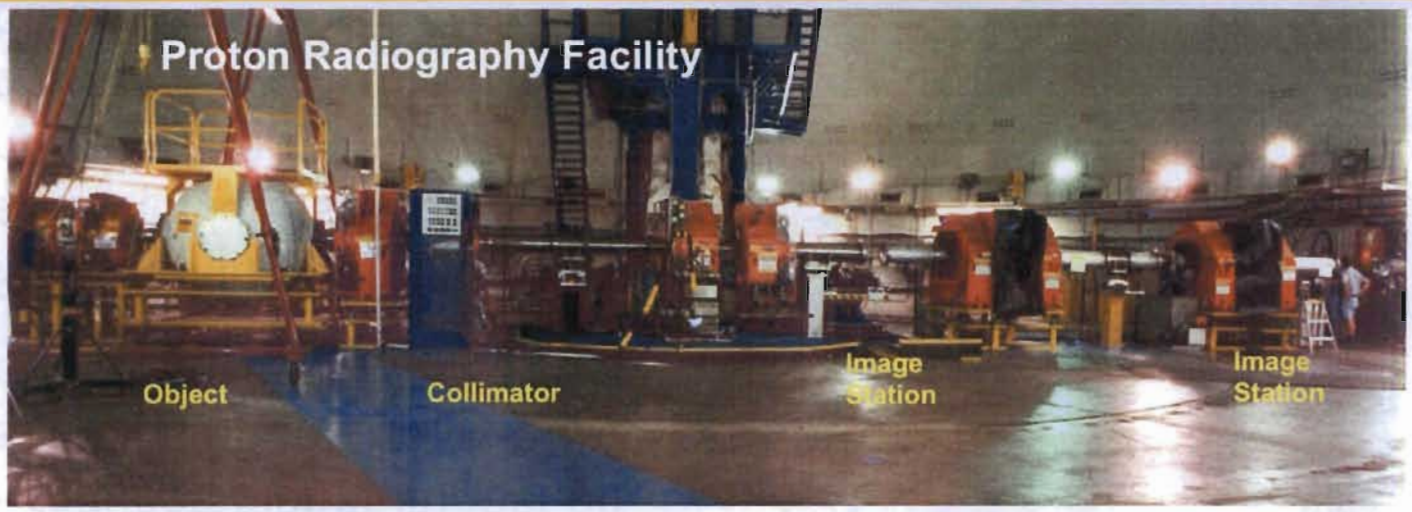
Easy to see that as $U_P \rightarrow U_S$ the error in density diverges

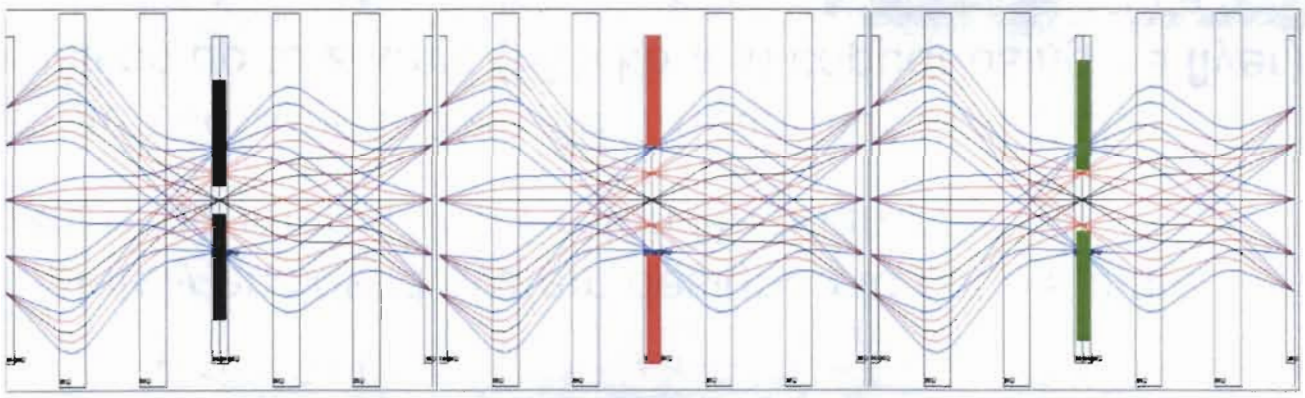
- A direct density measurement with accuracy of 0.5 – 2% would complement current measurement techniques for a single shock in non-porous materials
- Direct density measurements in off-Hugoniot states (shock/reshock, shock/release, ramp loading, etc.) and in shocked porous materials would help advance Equation of State development for material subjected to dynamic loading

Combining Plate Impact with Proton Radiography

- Reasons/Incentives
  - Plate impact technique provides well-characterized 1-D shock loading to samples
  - Powder gun provides relatively large experimental regime (projectile velocities of 0.3 to over 2.0 km/s)
  - pRad can potentially provide both direct density measurements and resolution of mesoscale feature with many frames of data per experiment
- Difficulties
  - Synchronization of proton beam to shock-wave event potentially difficult (1 ms time window)
  - Alignment of target to gun and gun to beam must be carefully considered

Advantage of Proton Imaging over X-Radiography





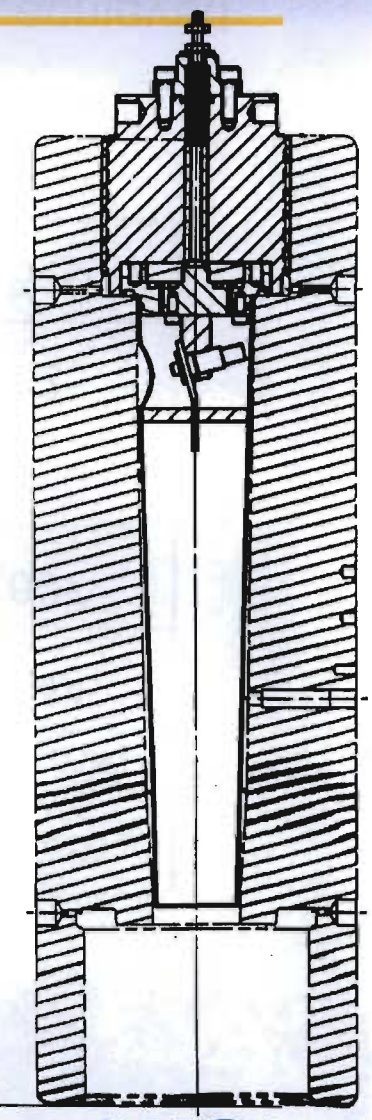
Beam prep Collimator Object Collimator Image Collimator Image

40mm Launcher Design Details

- Completely enclosed system designed to couple plate impact experiments with Proton Radiography
- Uses gun powder and an SE-1 detonator to launch projectiles up to 2 km/s (600 kbar in copper using Ta flyer)
- Produces planar impact on samples up to 40mm in diameter
- Free floating barrel design and shock absorber system minimize recoil load transferred to Proton beam tubes

Overcoming Experimental Difficulties – Synchronization

- Gun system time: 5-10ms
- Proton packet width: 1 ms square pulse @ 20 Hz
- Desirable for experiment to occur in the middle of this pulse
- Gun must be fired by the accelerator, otherwise target impact and proton arrival would be out-of-sync
- Gun system time jitter should be no more than 400 μs to ensure successful synchronization during every shot
- Used detonator and Mild Detonating Fuse (MDF) to initiate gun powder to launch projectile
  - Detonator and MDF alone have low jitter (<1 μs)
  - Similar firing system used on LANL two-stage gun
  - Easily ties into pRad firing system
  - Total system jitter was unknown



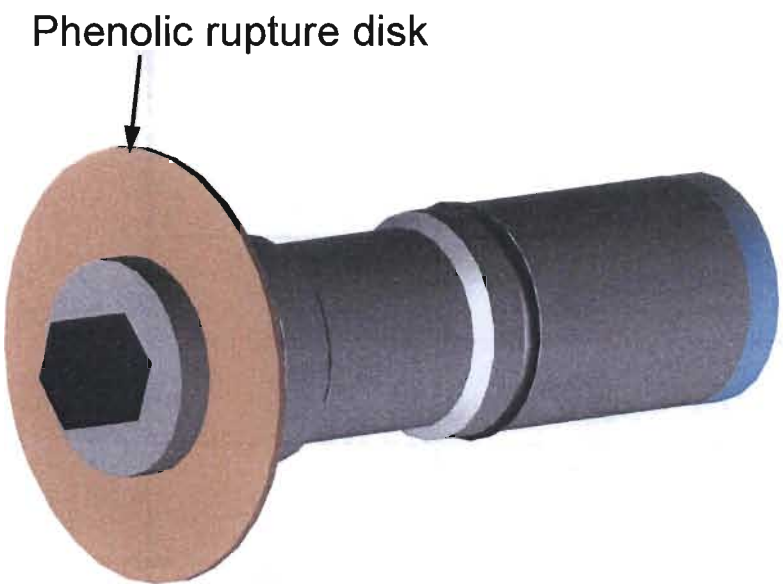
System Time Test Results: First Attempt

Shot	Charge (g)	Projectile (g)	Velocity (mm/μs)	System Time(ms)
1	200	152.45	–	6.144
2	200	156.84	1.18	5.607
3	200	191.36	1.17	5.250
4	200	192.11	1.16	5.225
5	200	187.77	1.07	6.610

- Unacceptably high system time jitter
- Due to detonator pushing projectile before full initiation achieved

Projectile Modified to Reduce Jitter

- Phenolic rupture disk prevents pre-launch of projectile before full initiation of the powder is achieved

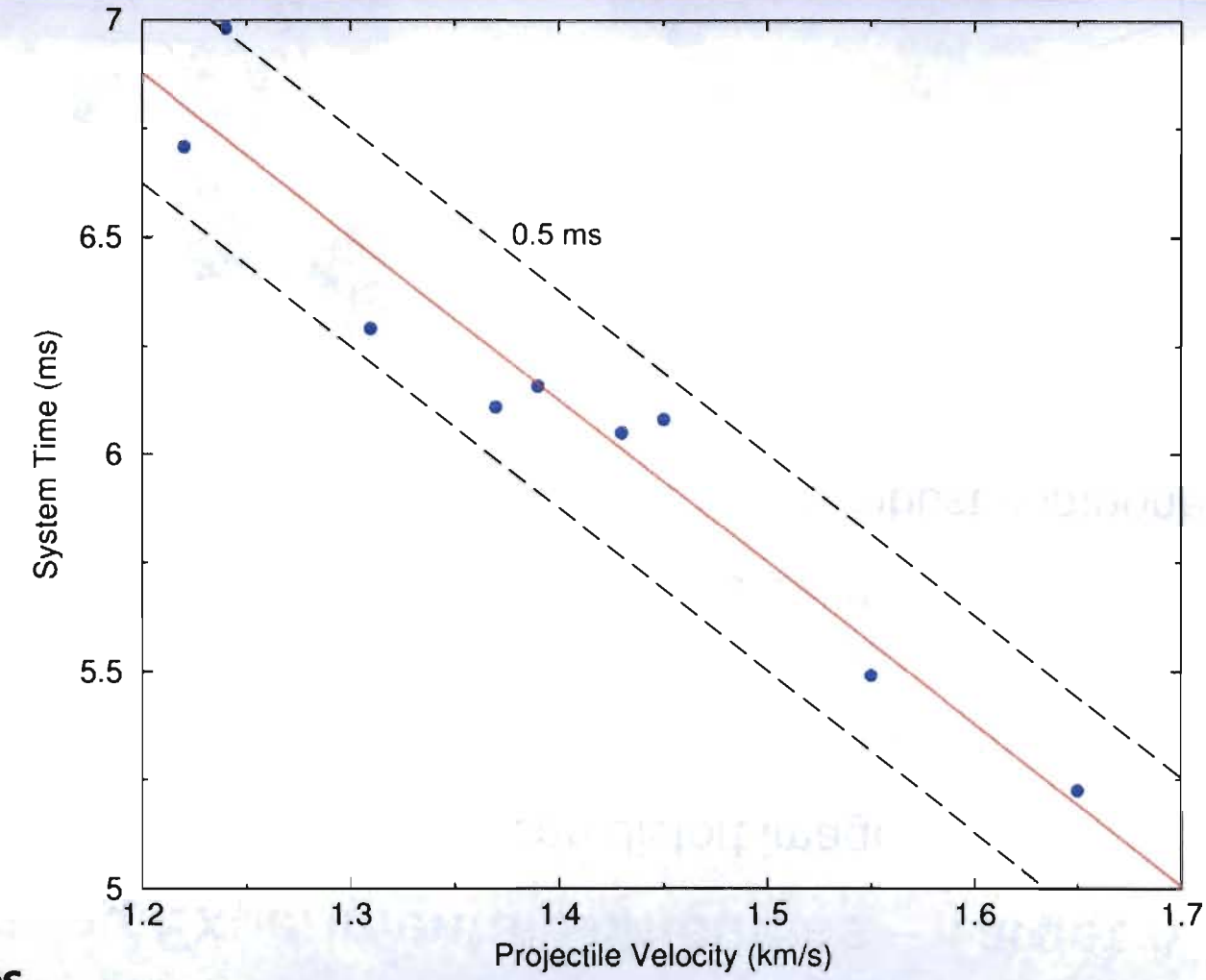


System Time Test Results: Second Attempt

Shot	Charge (g)	Projectile (g)	Velocity (mm/μs)	System Time(ms)
6	200	194.3	–	6.001
7	200	243.6	–	5.989
8	200	243.5	1.37	6.110
9	200	283.9	1.31	6.292
10	200	245.4	1.39	6.158

- Addition of rupture disk to projectile reduced jitter to ~ 300 ms

System Time Scatter for 40mm Launcher



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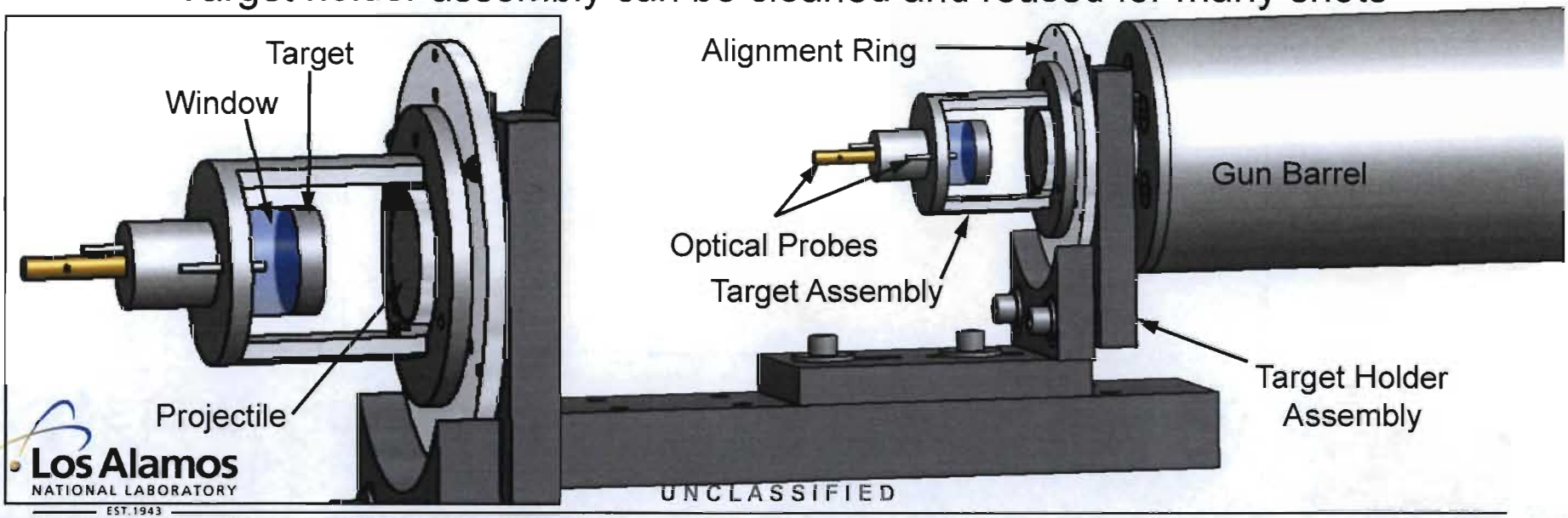
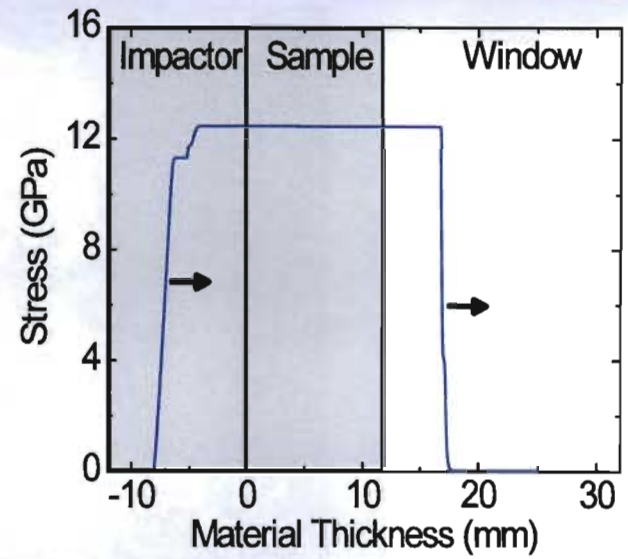
Overcoming Experimental Difficulties – Target Alignment

- Objects in beam near target can distort image
- Necessary to "suspend" target in beam while maintaining alignment
- Target assembly must be aligned from top or rear
  - No side access to target chamber because of beam pipes
- Final design provides quick alignment with robust components
  - Target holder assembly can be cleaned and reused for many shots



Density Measurements in Aluminum and Copper

- Four symmetric impact experiments were completed
  - Two experiments on 6061-T6 Aluminum
  - Two experiment on OFHC Copper
  - All samples backed by LiF window to maintain stress at back

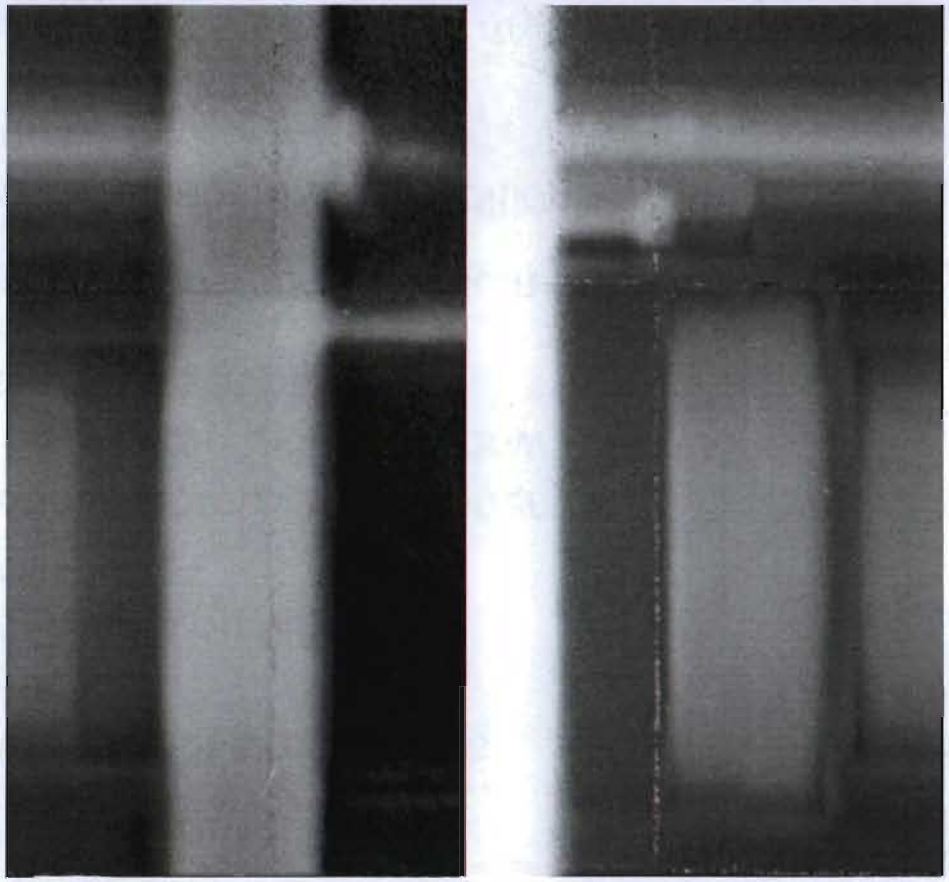


- High confidence in EOS for Aluminum and Copper
- Calculate density using Jump Conditions given $P(u_P)$ and measured projectile velocity, u_0

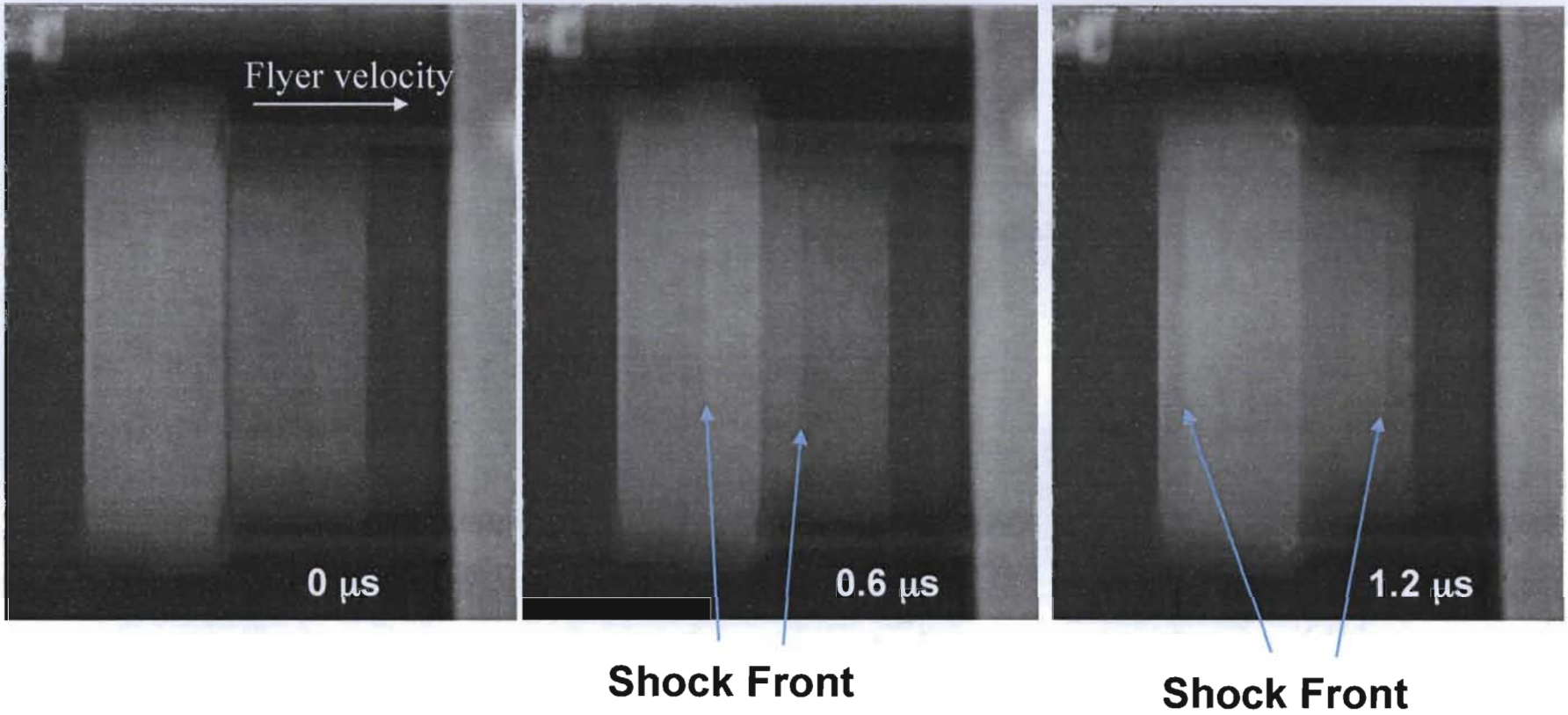
$$u_P = \frac{1}{2}u_0 \qquad P = \rho_0 U_S u_P \qquad \rho = \frac{\rho_0 U_S}{U_S - u_P}$$

- Measure u_P at Sample/Window interface as check

Radiography Results – Aluminum Symmetric Impact



Radiography Results – Aluminum Symmetric Impact



Density Calculation – Jump Conditions

Impact Velocity

$u_0 = 1.452 \pm 0.012$ mm/μs

Particle Velocity: ½ u_0

$u_P = 0.726 \pm 0.006$ mm/μs

$P(u_P)$ for 6061-T6 Al

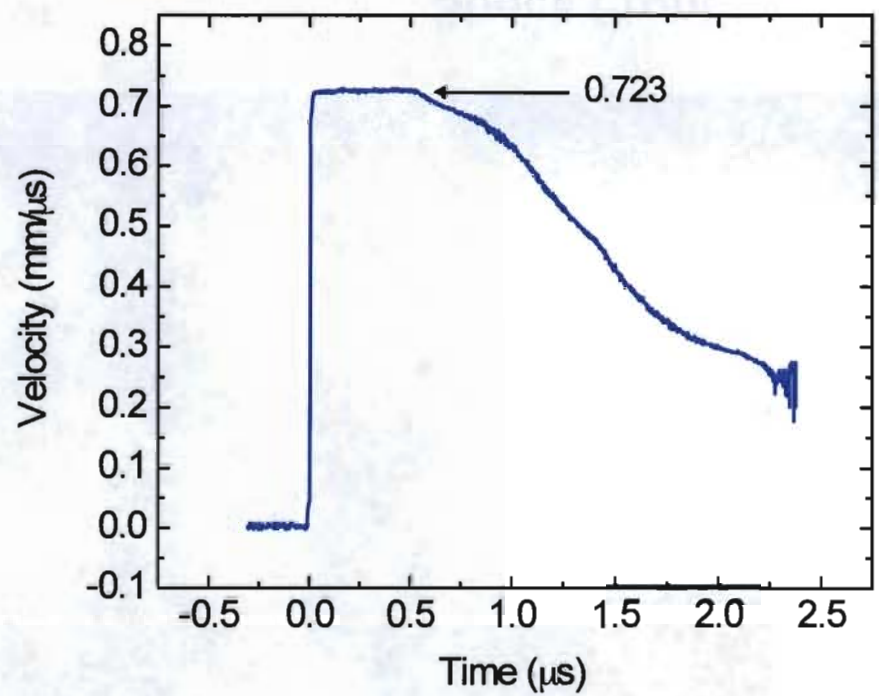
$P = 1.184 + 140.2u_P + 37.38u_P^2$

$P = 12.27 \pm 0.09$ GPa

Initial density from immersion

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

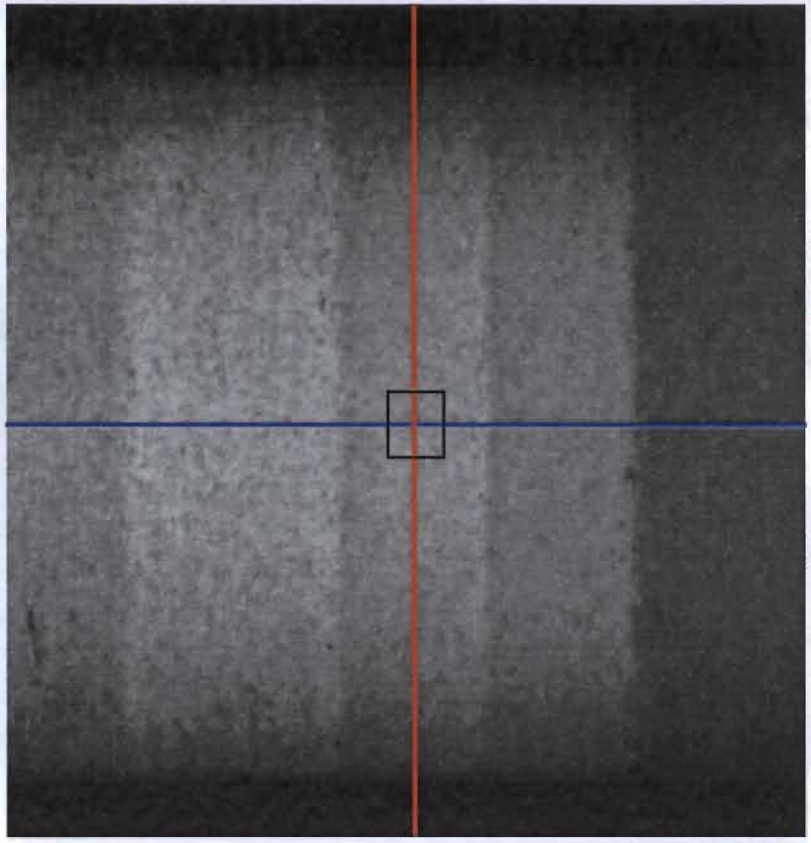
VISAR Record for Shot prad 0198

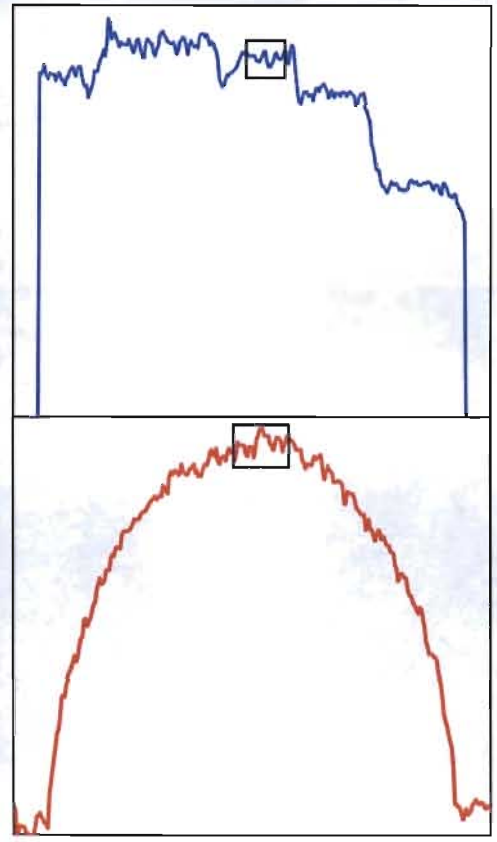


Calculate density from Jump Conditions

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

Density Calculation – Abel Corrected Radiograph

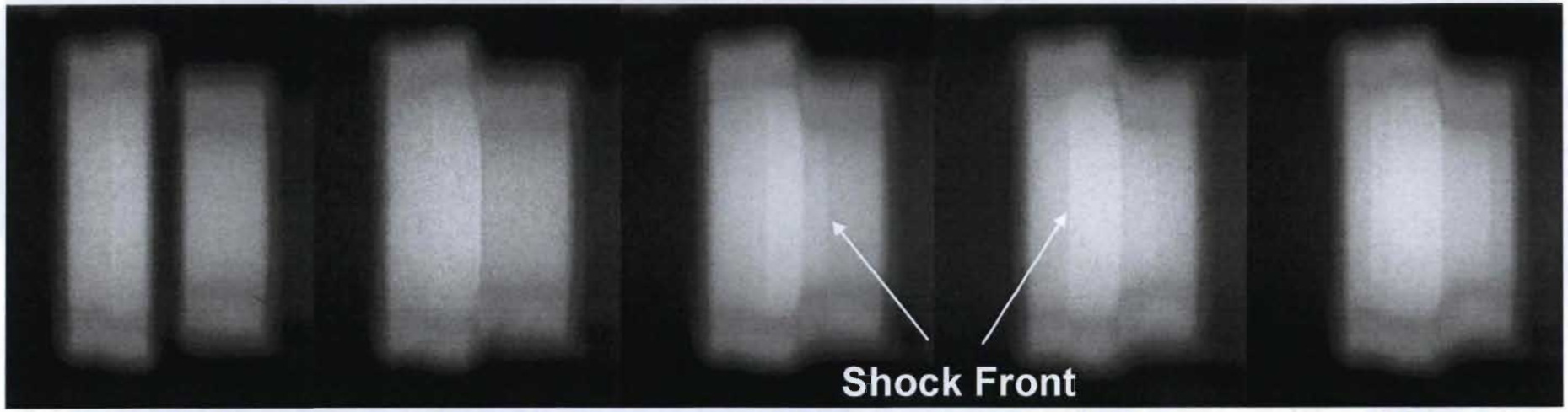




Density: $\rho = 3.07 \pm 0.03$ g/cm^3 (1.1%)

Results from Copper Symmetric Impact Experiment

Flyer velocity →



-1.54μs 0 .57μs 0.86μs 1.26μs 1.66μs

- Significant distortion present due to higher density of copper
- Distortions do not affect measurement

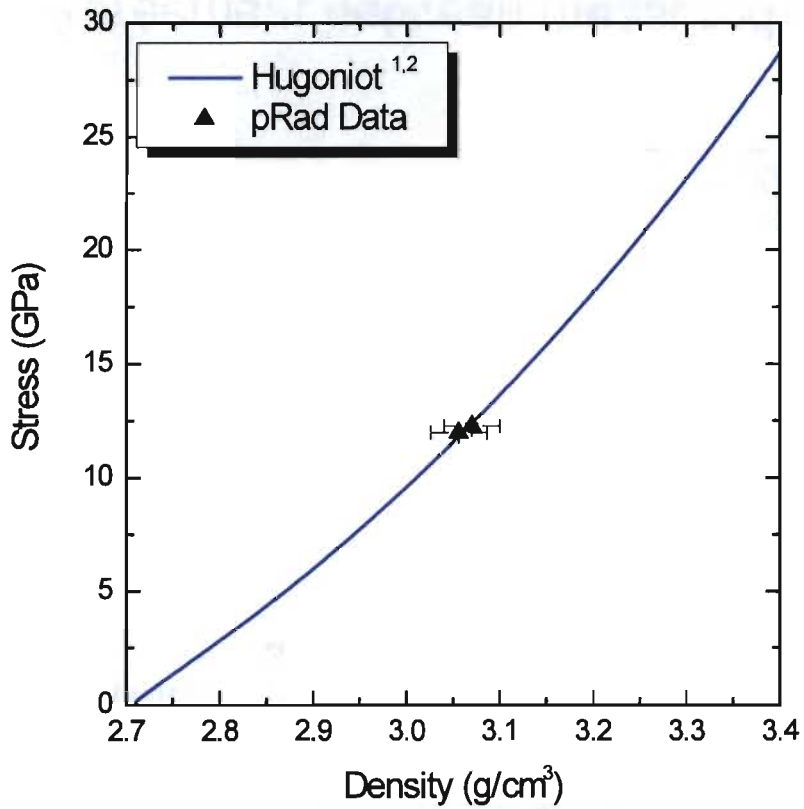
Experiment Summary

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%

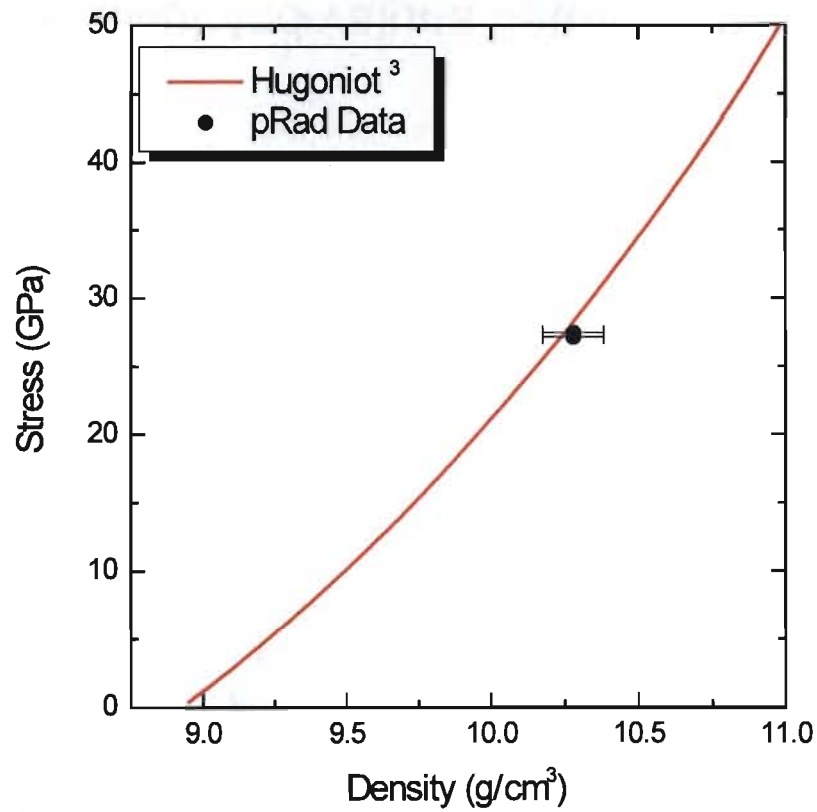
- Agreement between measured and calculated values better than 0.5% for all experiments

Measured Density Values Lie on Hugoniots

6061-T6 Aluminum

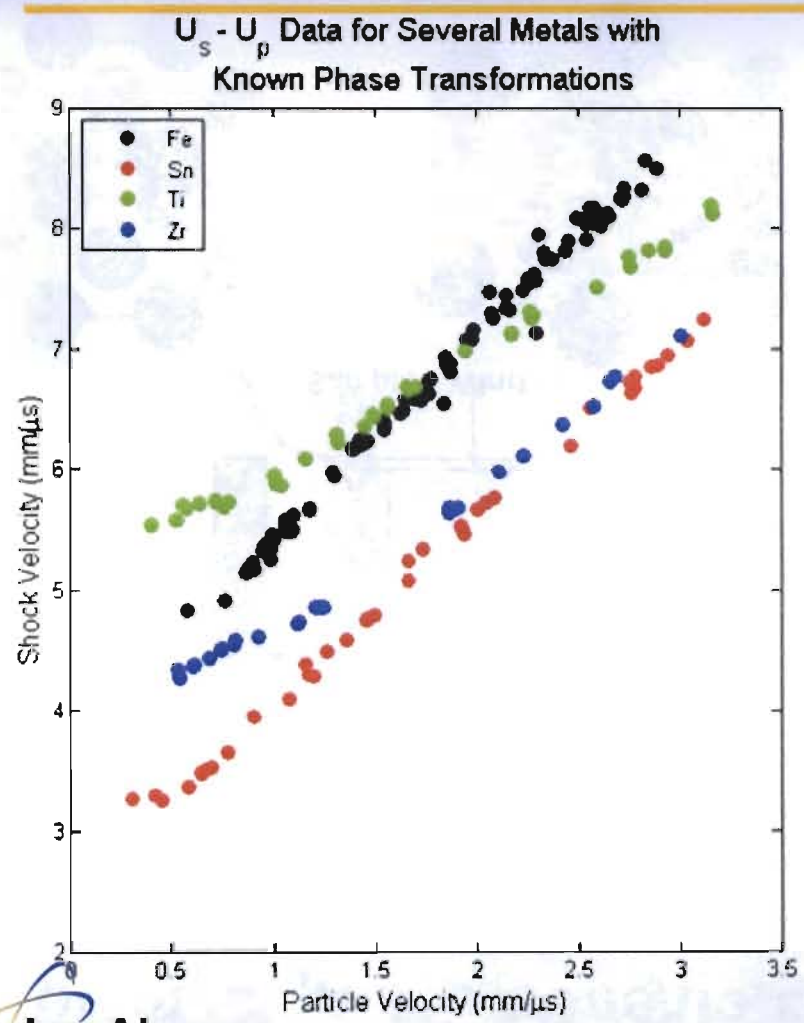


OFHC Copper



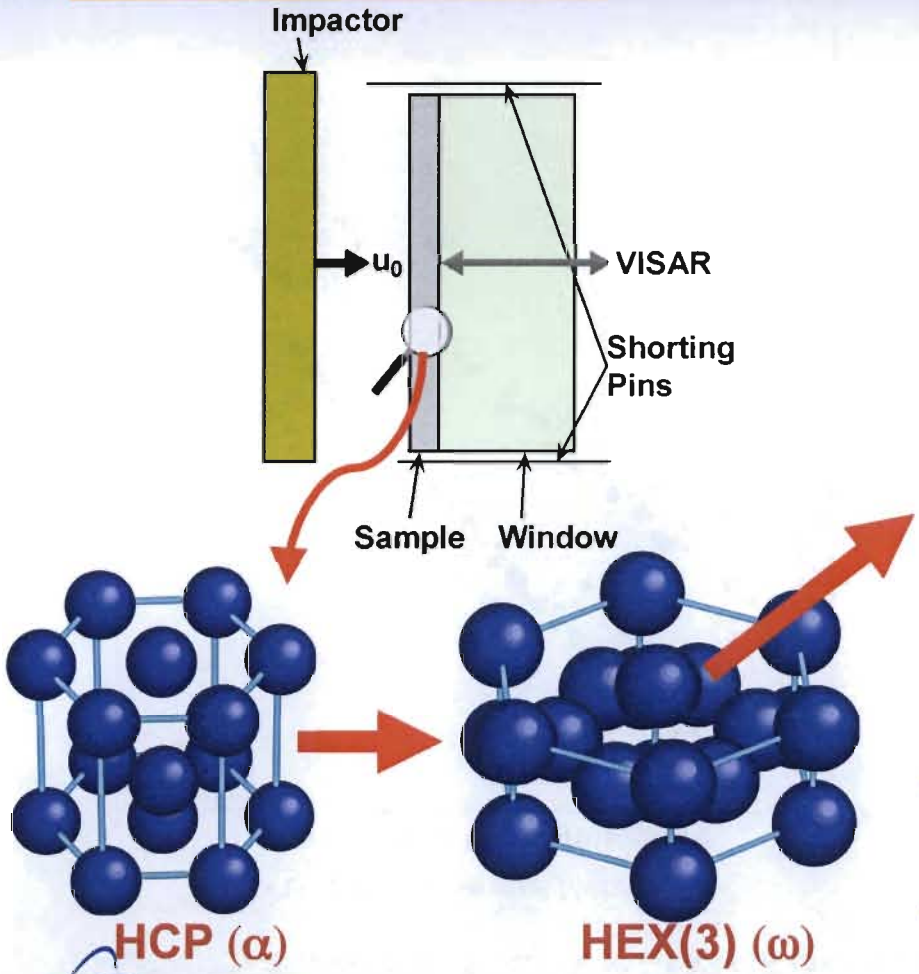
(1) C. D. Lundergan and W. Herrmann, J. Appl. Phys. **34**, 2046 (1963).
(2) W. M. Isbell and D. R. Christman, Tech. Rep. MSL-69-60, General Motors (1970).
(3) R. G. McQueen, S. P. Marsh, J. W. Tayor, et. al., *High Velocity Impact Phenomena* (Academic Press, New York, 1970).

Solid-Solid Phase Transitions Present in Many Materials

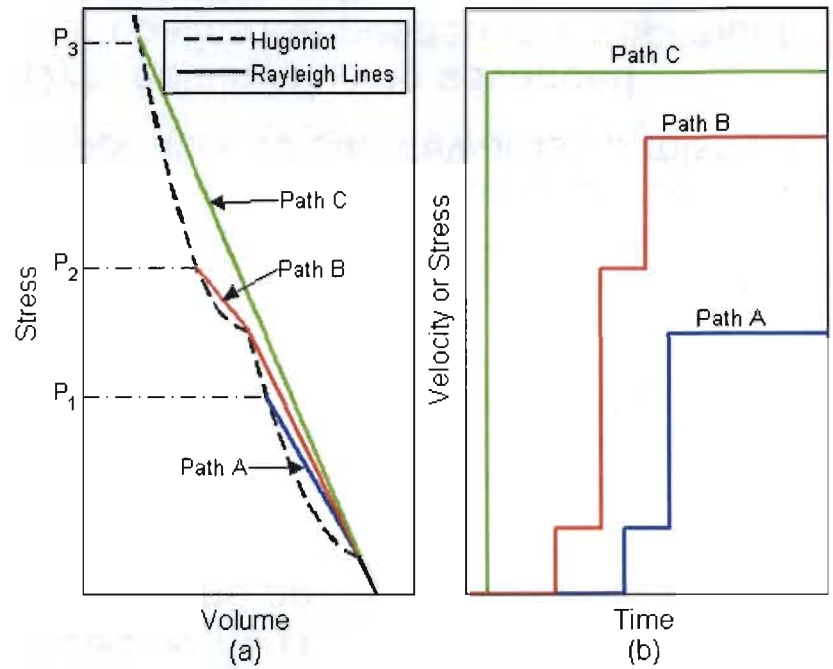


- Decades of shock compression experiments have provided Hugoniot data on a large number of materials.
- A kink in the $U_S - U_P$ curve can indicate the presence of a solid-solid phase transition.
- These data tell us nothing about the kinetics and underlying atomic level mechanisms responsible for the phase change
- Developing accurate, physics-based multi-phase equations of state to describe these materials is of vital importance to our stewardship mission
- Data obtained using advanced diagnostics are needed to compliment existing data sets
- Zirconium is well suited for such studies

Velocimetry is used in shock compression experiments to detect phase transitions in real time



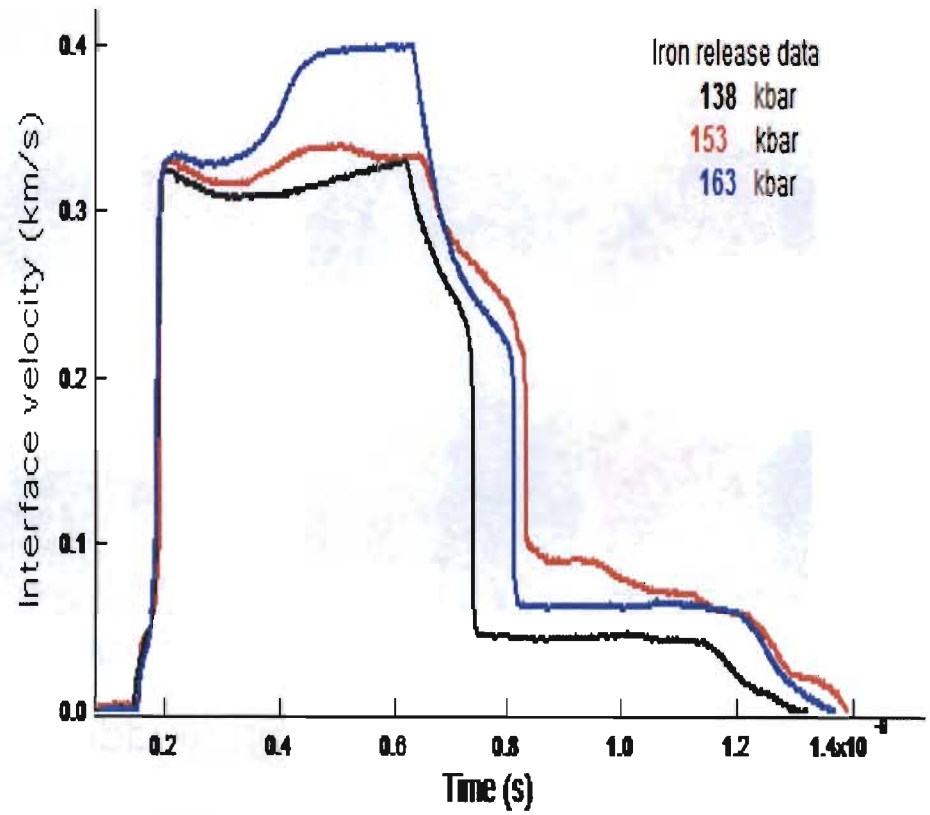
Loading Paths and Ideal Wave Profiles



- Wave profiles measured at an interface – Wave interactions!
- Can pRad be used to measure phase transition in-situ?

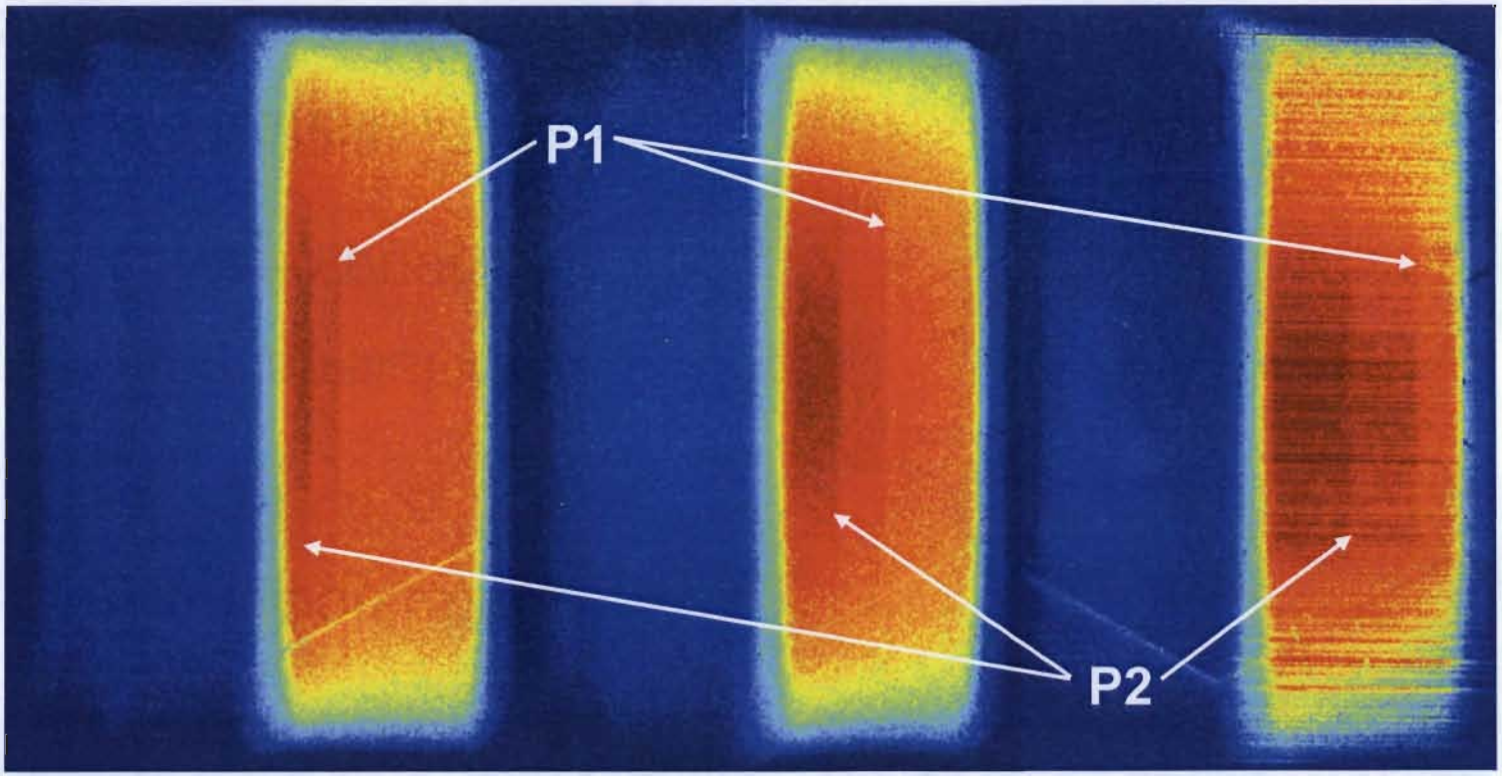
Phase Transition Studies: Iron

- α to ε transition observed in Fe at ~13 GPa
- Transition is relatively insensitive to purity
- Reverse transition clearly observed as evidence by rarefaction shock

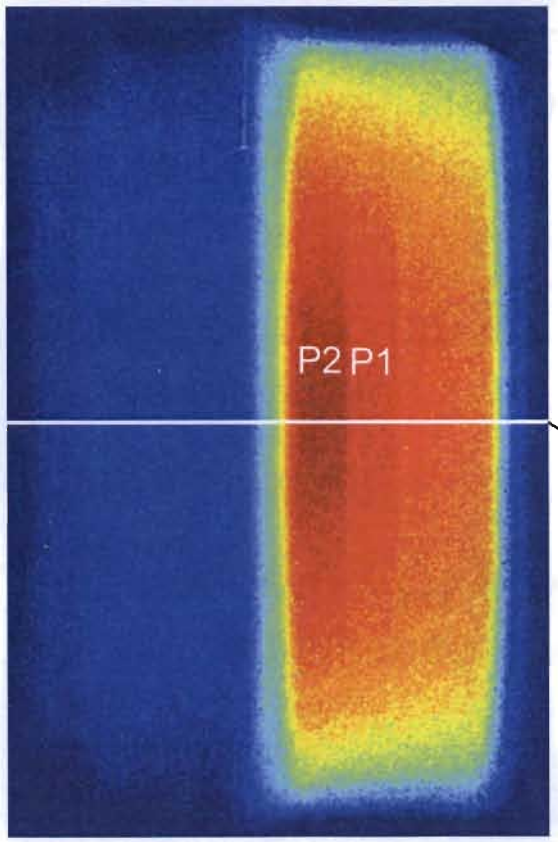


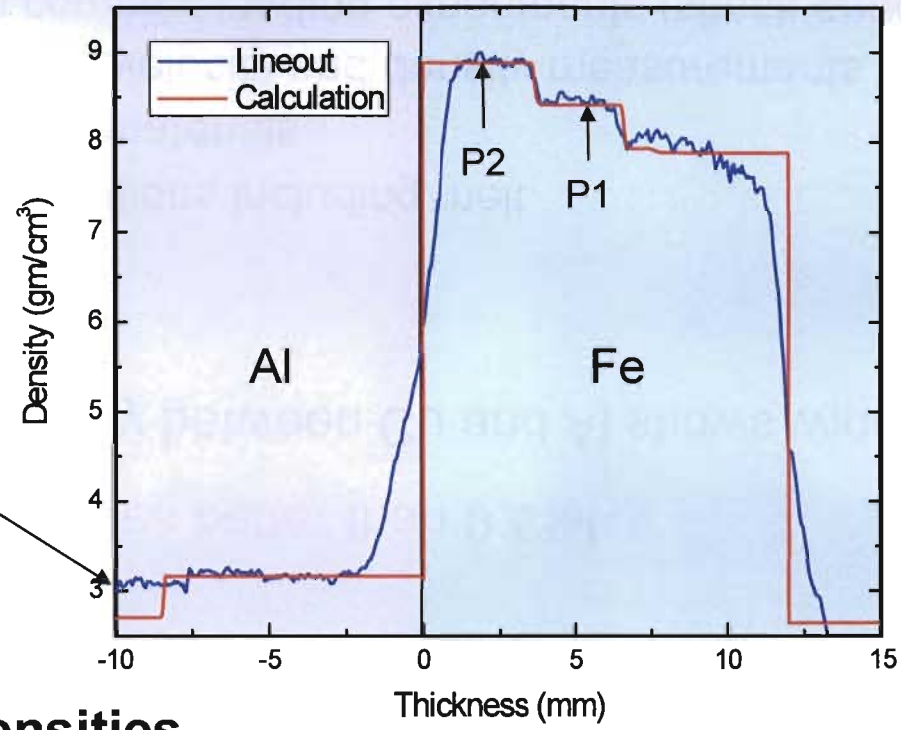
Two-wave structure observed in Iron

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



Measured and Calculated Densities - Iron





Densities

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

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Conclusions

- Successfully coupled proton radiography with plate impact experiments
- Direct density measurements obtained in shocked aluminum, copper and iron with ~1% precision
- Agreement with calculated values better than 0.5%!
- Large difference in initial density between Cu and Al shows wide applicability to other materials
- Future work:
  - Continue work on phase transitions including melt
  - Investigation shocked porous materials
  - Focus on simultaneous shock velocity and density measurements
  - Density measurements in complex loading experiments (shock-shock, shock-release, ramp loading)