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Title: Proton Radiography of Thermal Explosions and Structural Phase Transitions

Author(s): Schwartz, C.L.

Intended for: Invited talk at Cavendish Laboratory, Cambridge Univeristy
Proton Radiography Workshop at GSI, Darmstadt, Germany

Los Alamos
NATIONAL LABORATORY
EST. 1943

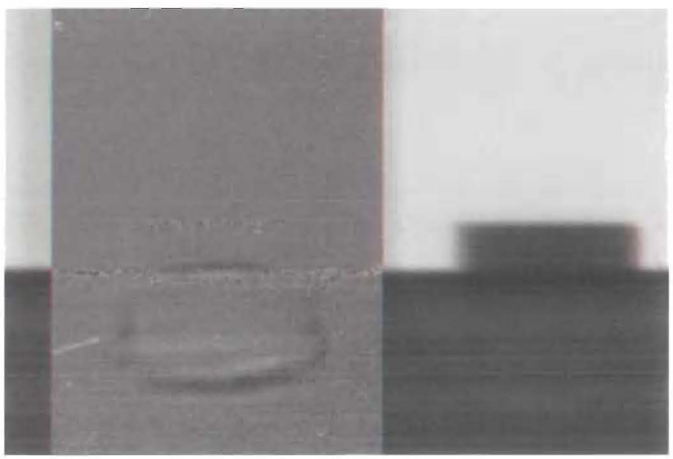
Looking inside thermal explosions

Cynthia Schwartz
Physics Division
Los Alamos National Laboratory

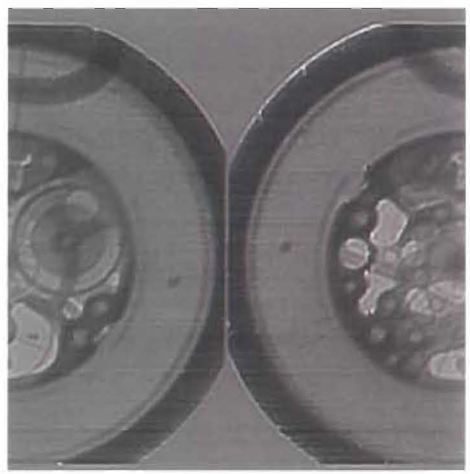
X-rays!!
Weapons to homeland security

G. I. Jane
Why do I do this?
"because I get to blow stuff up!"

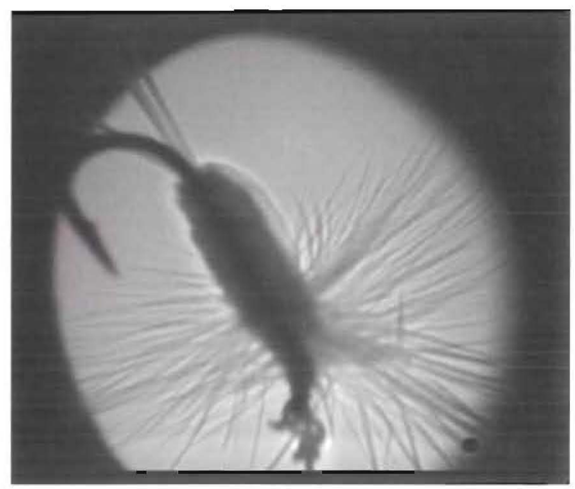
5×10^{6} Hz
800 MeV p



2 Hz
800 MeV p



30 MeV e

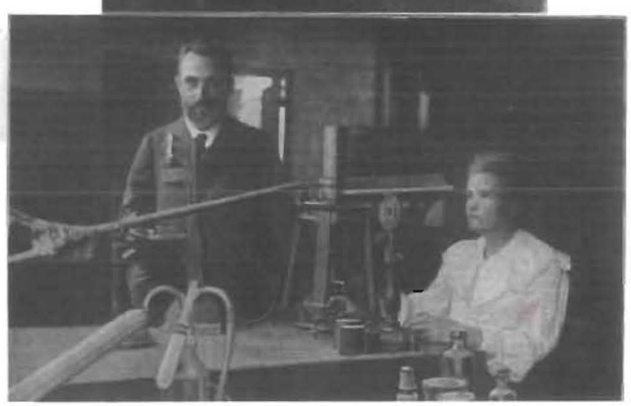


Radioactivity, three discoveries-three Nobel prized

Wilhelm Conrad Roentgen
Discovered x-rays in 1895
First Nobel prize in physics 1901

Burndy Library

Antoine Henri Becquerel
Discoveried Radioactivity in 1896 shared the Nobel prize in physics with **Pierre and Marie Curie**, 1903



Victor Franz Hess
1910-1913 showed cosmic rays come from outside the solar system. Shared the Nobel prize in 1936 with C.D. Anderson

1895-the beginnings of radiography

Burndy Library

Prof. Wilhelm Conrad Röntgen

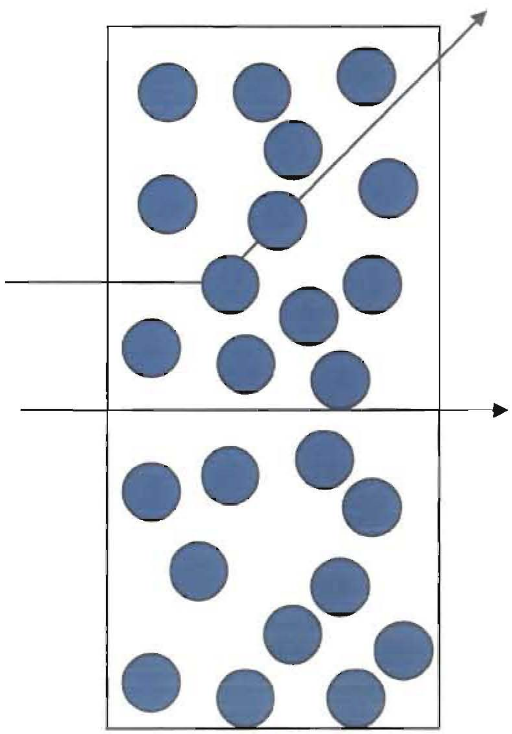
Burndy Library

Gunshot in the hand

Prof. Michael I. Pupin of Columbia University first heard of Röntgen's discovery directly from a German physicist friend. He immediately set up the equipment to perform X-ray experiments and, in the first days of February, 1896 was asked to radiograph the hand of a New York attorney accidentally shot. The above, signed by Pupin, is one of the earliest records of the aid to surgery made possible by the invisible rays.

[1] W. C. Röntgen, Nature **53** (1896) 274.

Cross section/mean free path-vocabulary, what Röntgen figured out



In 3 - d

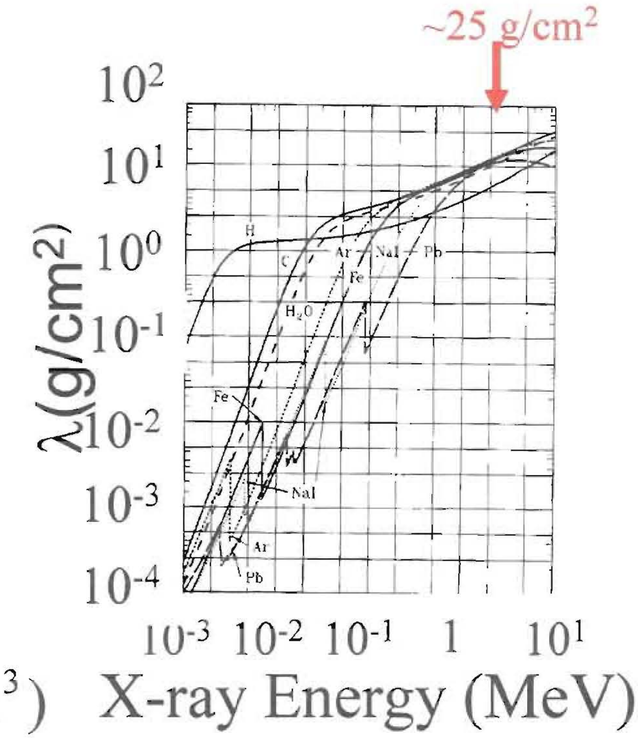
$$\sigma = \pi r^2$$

$$\lambda = \frac{1}{\sigma \rho}$$

λ is the mean free path

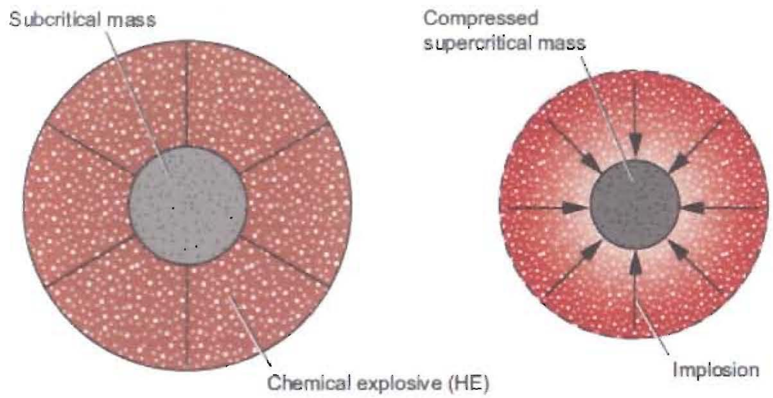
σ is the cross section

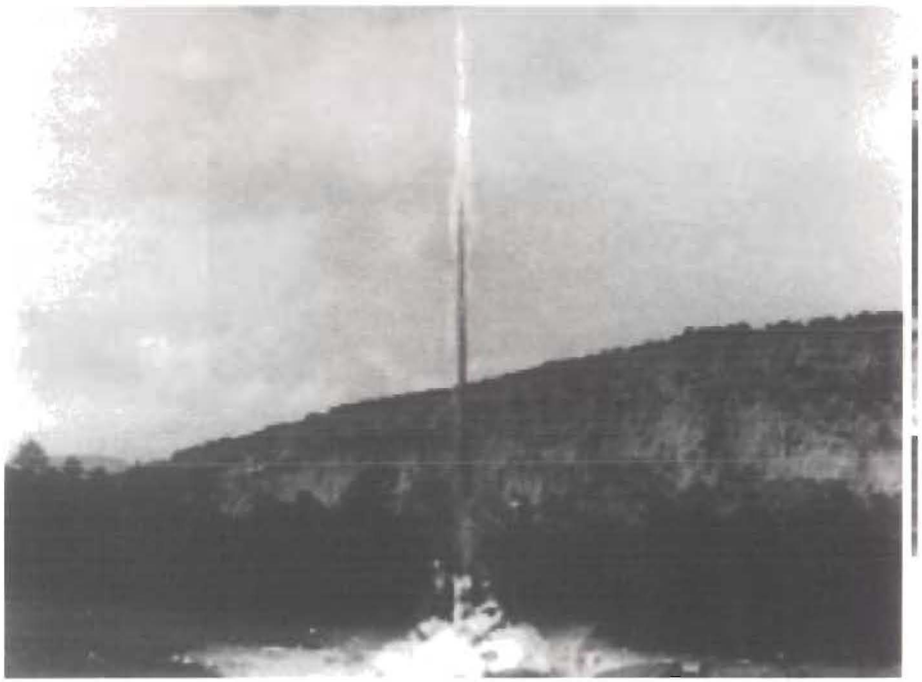
ρ is the density (atoms/cm^3)

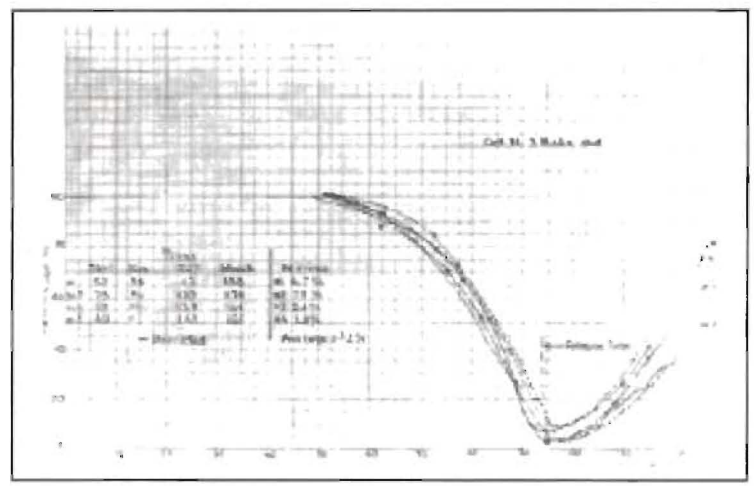


RaLa experiments

Extreme! Chain reaction!





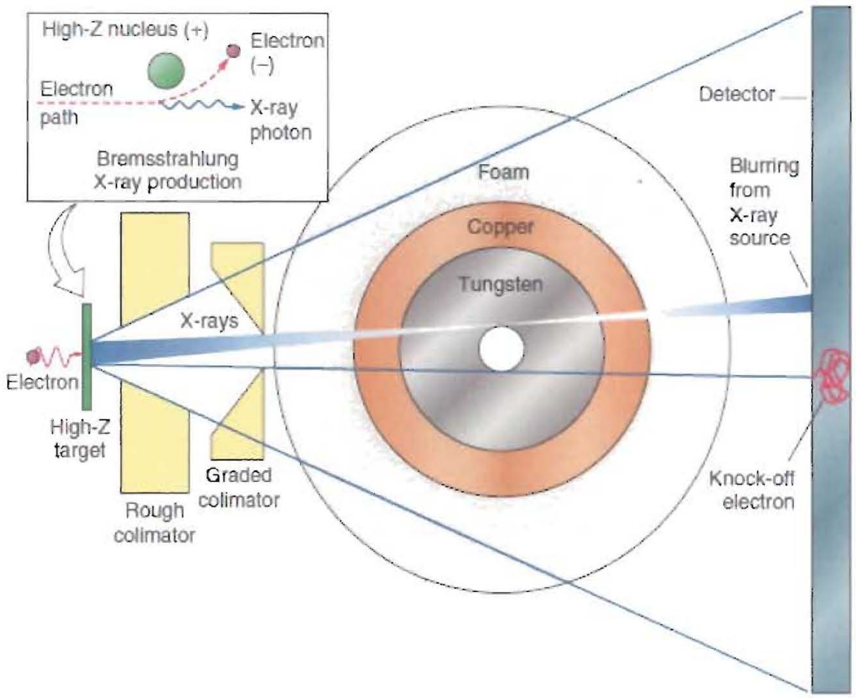


Robert Serber

Flash radiography of a surrogate material implosion (Manhattan project)

- 15 MeV betatron X-ray source
- 1 μsec long pulses
- Wilson cloud chamber detector

Flash Radiograpgy

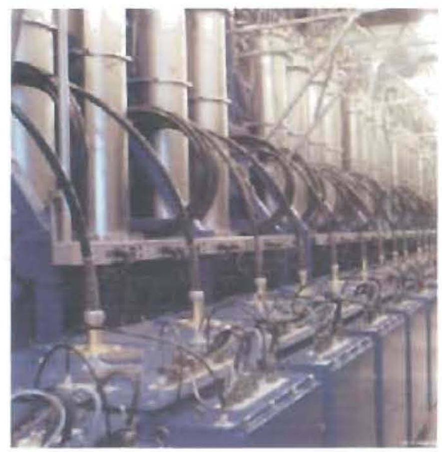


[1]Glen Seay (1952); Douglas Venable, "Phermex", Physics Today **17**, 19 (1964)

How do we take care of the nuclear stockpile without nuclear testing?

- Cold war stockpile
  - Remanufacture?
  - Science (back to WWII)?
  - Redesign?
  - Negotiated reductions?

- Implosions with surrogate materials coupled with modeling and simulation.
- Scientific understanding of shock waves and explosions



John Hopson and Tim Neal

Beer's law*

Ideal radiography
- No background
- Mono-energetic

$$\frac{dN}{dz} = -\lambda N$$

$$N = N_0 e^{-\frac{z}{\lambda}} \, ^*$$

$$l = -\lambda \ln\left(\frac{N}{N_0}\right)$$

Error analysis
- Poisson statistics

$$\Delta l = \frac{\lambda}{\sqrt{N}}$$

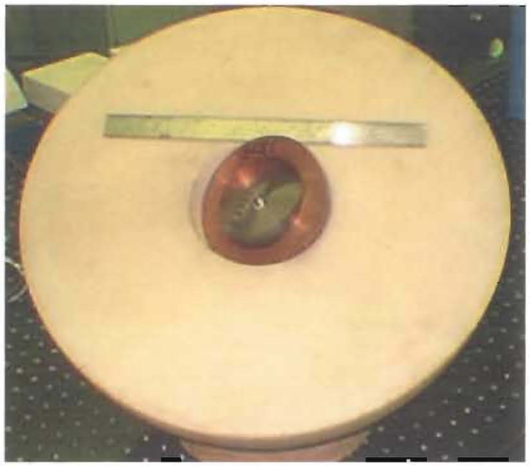
$$\frac{d(\Delta l)}{d\lambda} = 0$$

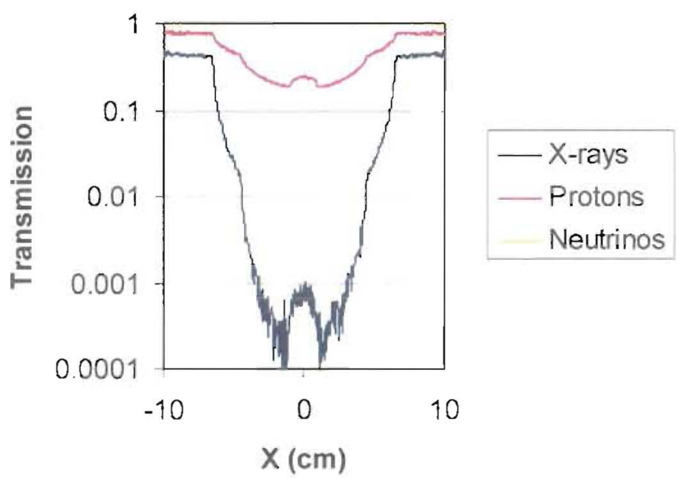
$$\Rightarrow \lambda = \frac{l}{2}$$

*A. Beer, *Ann. Physik. Chem.* **86** (1852) 78.

Different probes-10^9 incident particles.

French test object (FTO)



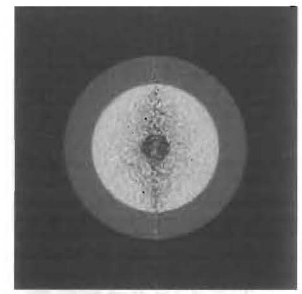


Simulated radiograph

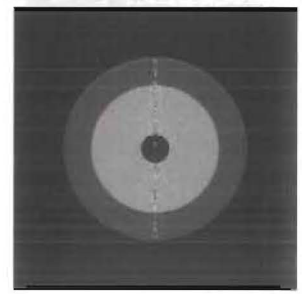
Density reconstruction

bb's
λ=0. g/cm^2

X-rays
λ=25. g/cm^2



Protons
$\lambda\approx$185. g/cm^2

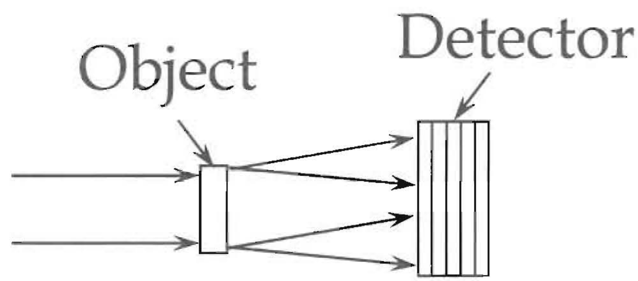


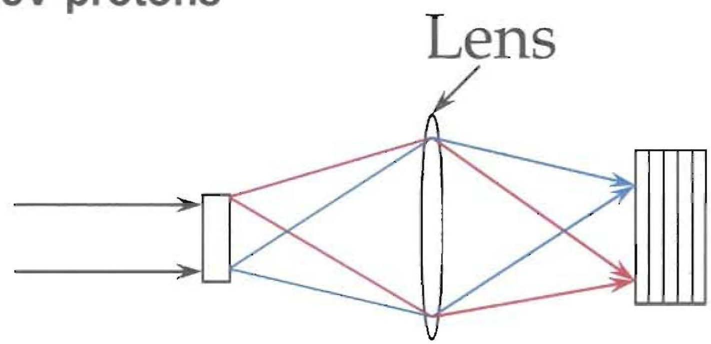
Neutrinos
$\lambda=\infty$ g/cm^2

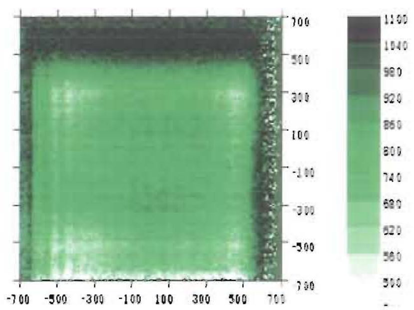
The idea-focus the transmitted protons with magnetic lenses

Transmission radiography FY95

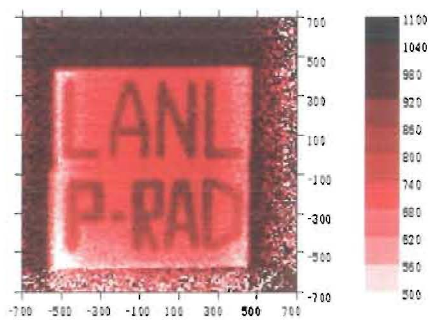
with 188 MeV protons



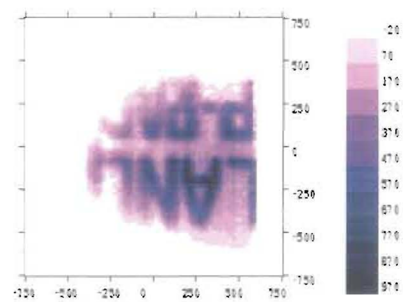




At the detector



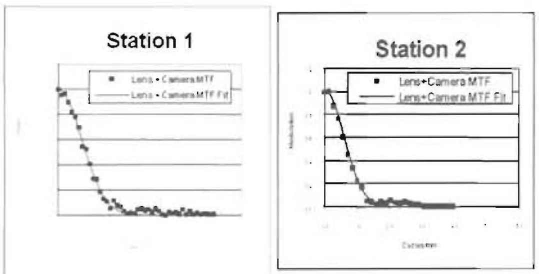
Projected to the object

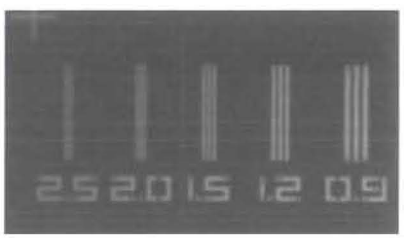


After a lens

800 MeV LANL Spatial Resolution

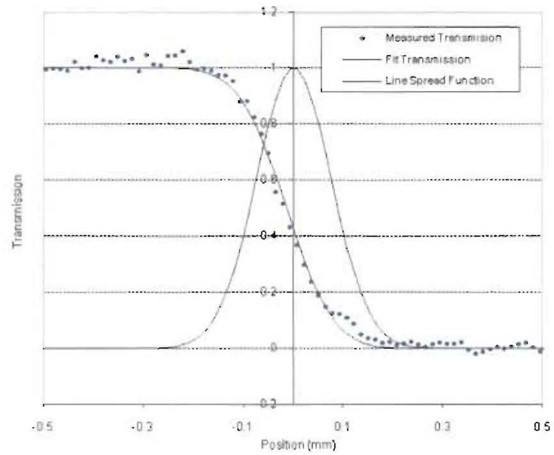
Identity Lens



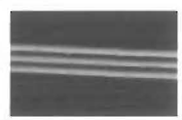


- Station 1: 178 μm
- 120 mm field of view

X3 Magnifier

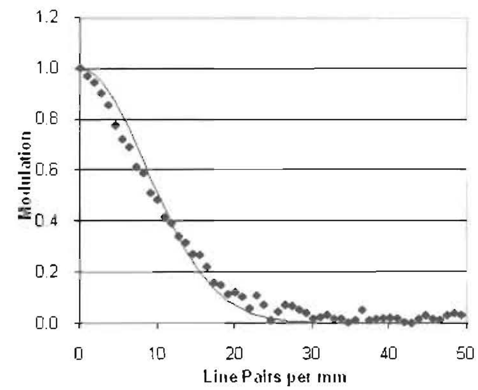


2.5 lp/mm



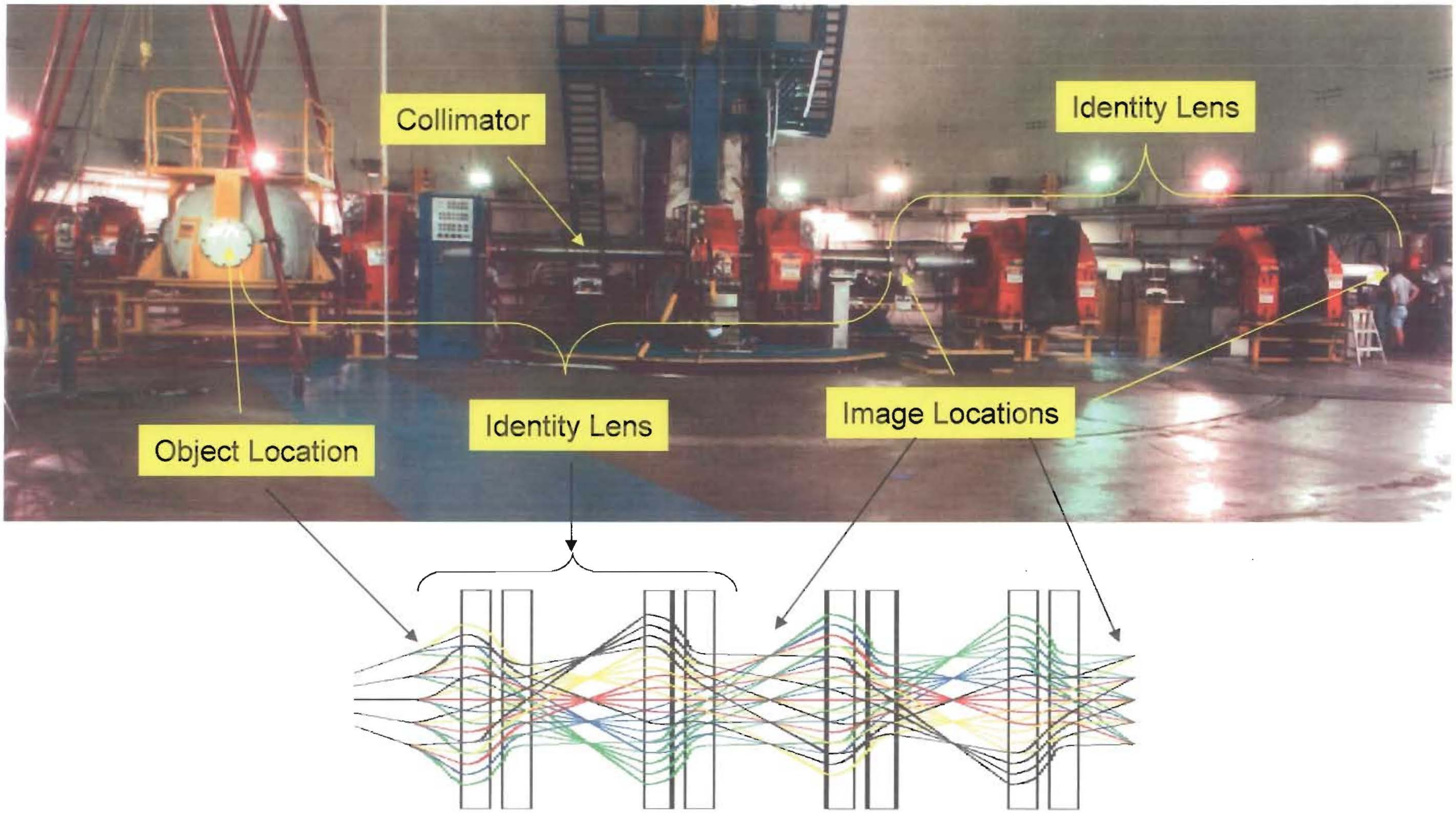
- Station 1: 65 μm
- 44 mm field of view

X7 Lens



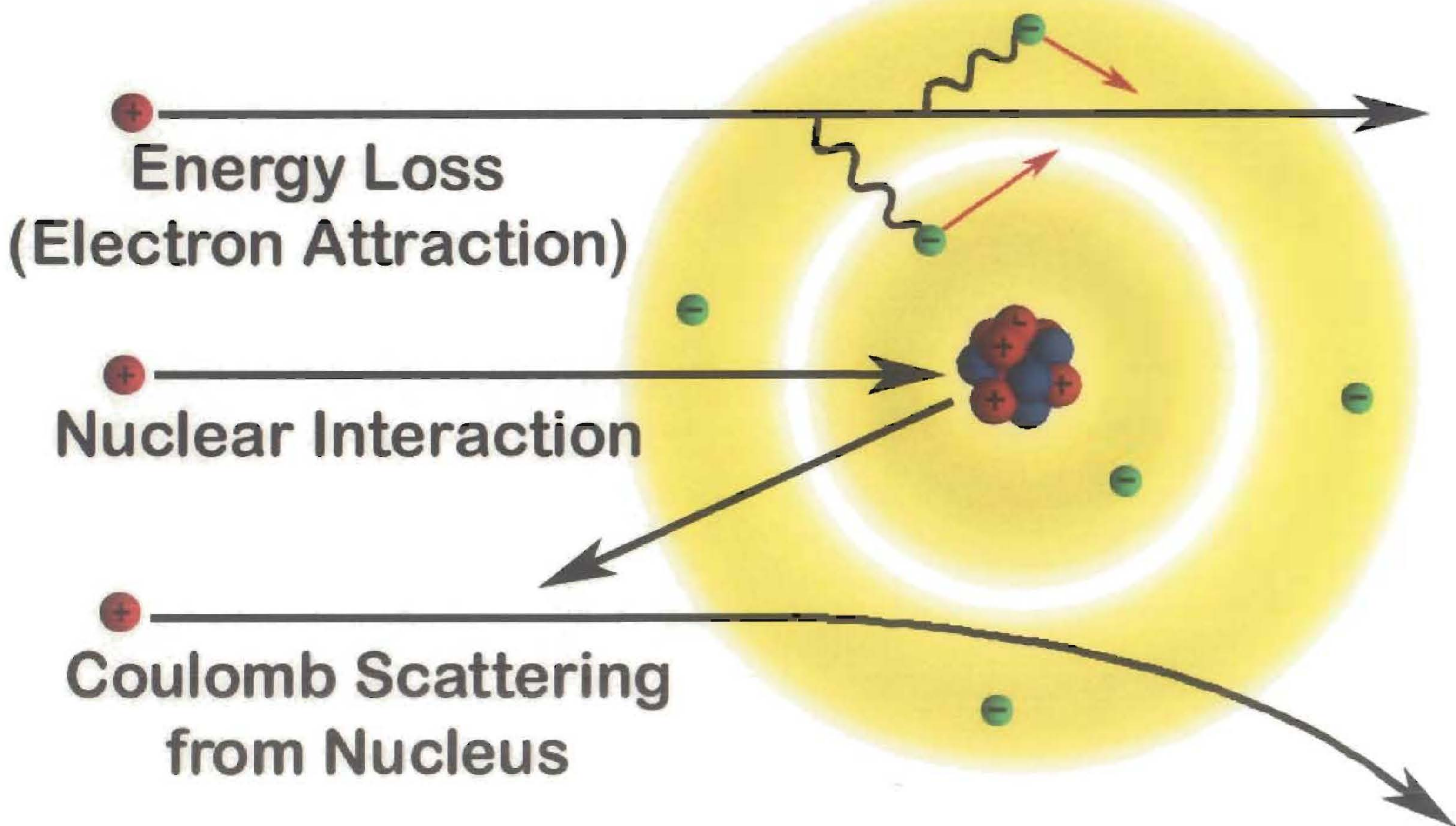
- Station 1: 30 μm
- 17 mm field of view

pRad Facility at LANSCE



Proton Interactions

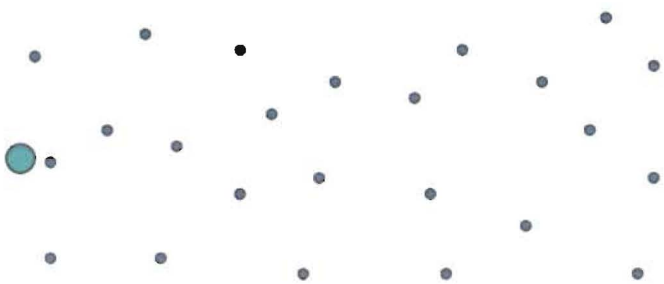
Proton Radiography



Two Interactions

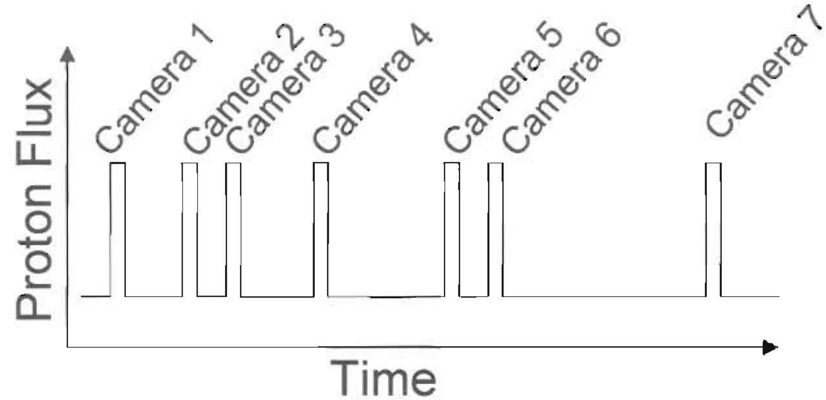
The Coulomb interaction

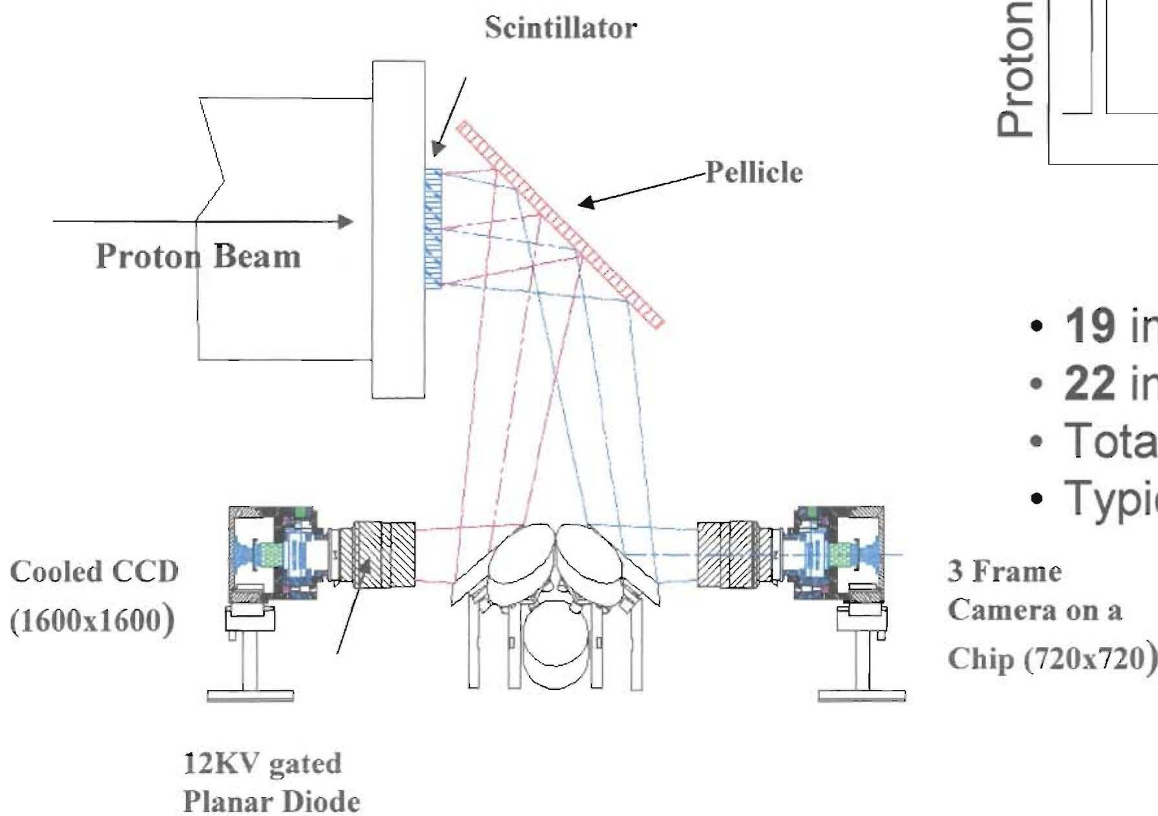
The nuclear interaction



$$t = e^{-\frac{l}{\lambda_0}\left(1 - e^{-\frac{\theta_c^2}{X + X_F}}\right)}$$

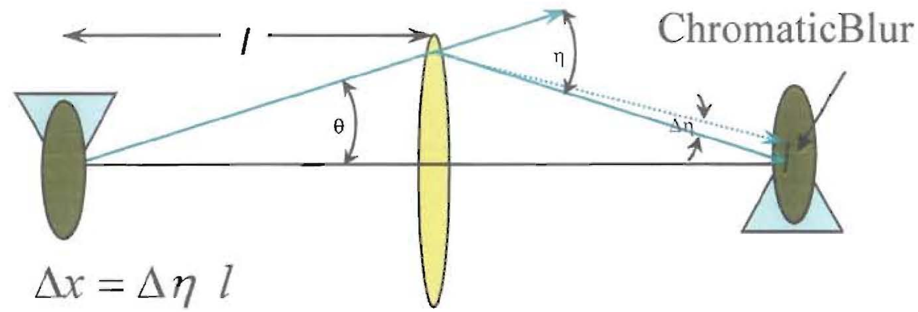
Temporal Resolution





- **19** images at first station
- **22** images at second station
- Total **41** possible image times
- Typically **50 ns** exposure times

Proton radiography- angle matching



The leading aberations are chromatic :

$$x_{image} = x_{object} + (x \mid \theta\delta)\theta\delta + (x \mid x\delta)x\delta + \cdots$$

Setting :

$(x \mid \theta\delta)\theta\delta = -(x \mid x\delta)x\delta$ gives :

$$\theta = \frac{-(x \mid x\delta)}{(x \mid \theta\delta)} x$$

- Uniform acceptance
  - analysis simple
- Reduced aberrations
  - pin hole camera

$\langle (x|\theta\delta) \rangle = 7.8m$

$\langle \theta \rangle = 0.01 \text{ radians}$

$\langle \delta \rangle = 0.001$

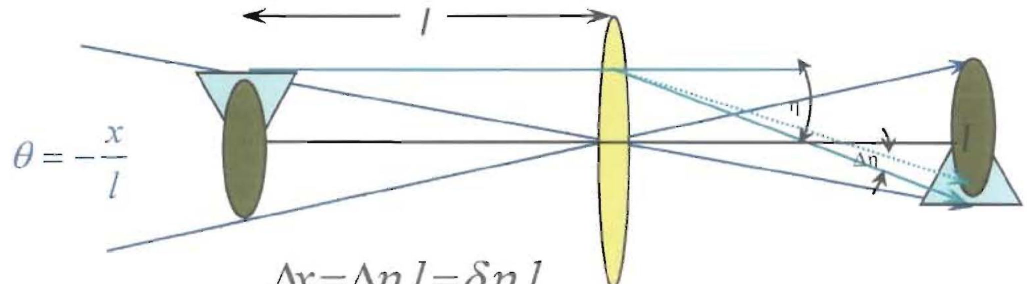
$\langle x \rangle = 80\ \mu m$

$\Delta x = \Delta \eta\ l$

$$\delta = \frac{p - p_0}{p_0}, \eta = 2\theta, \Delta\eta = -\delta\, 2\theta, \text{so}$$

$\Delta x = \delta 2\theta\, l$

$(x \mid \theta\delta) = 2l$



$\Delta x = \Delta\eta\, l = \delta\eta\, l$

$$\eta = \frac{2x}{l}, \text{so}$$

$(x|x\delta) = 2$

Tom Mottershead and John Zumbro

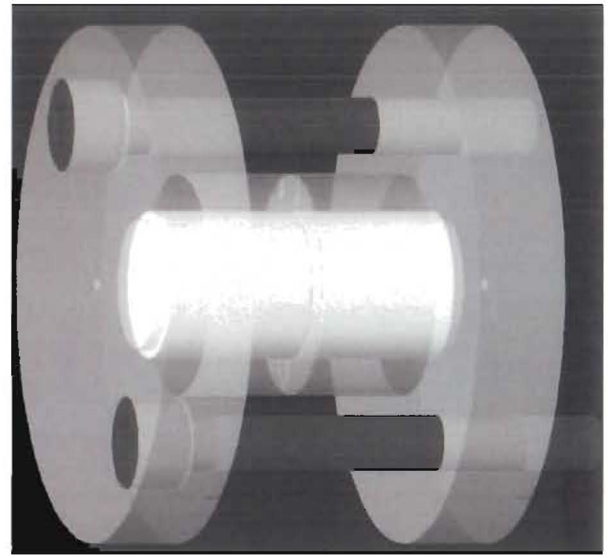
LANSCE

pRad has allowed the mechanism for high explosive cookoff to be better understood

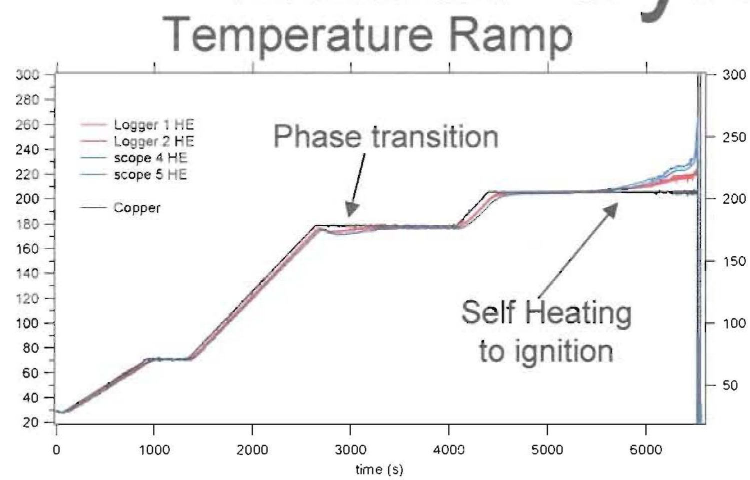
Smilowitz, Henson and pRad Collaboration

Cookoff Experiments

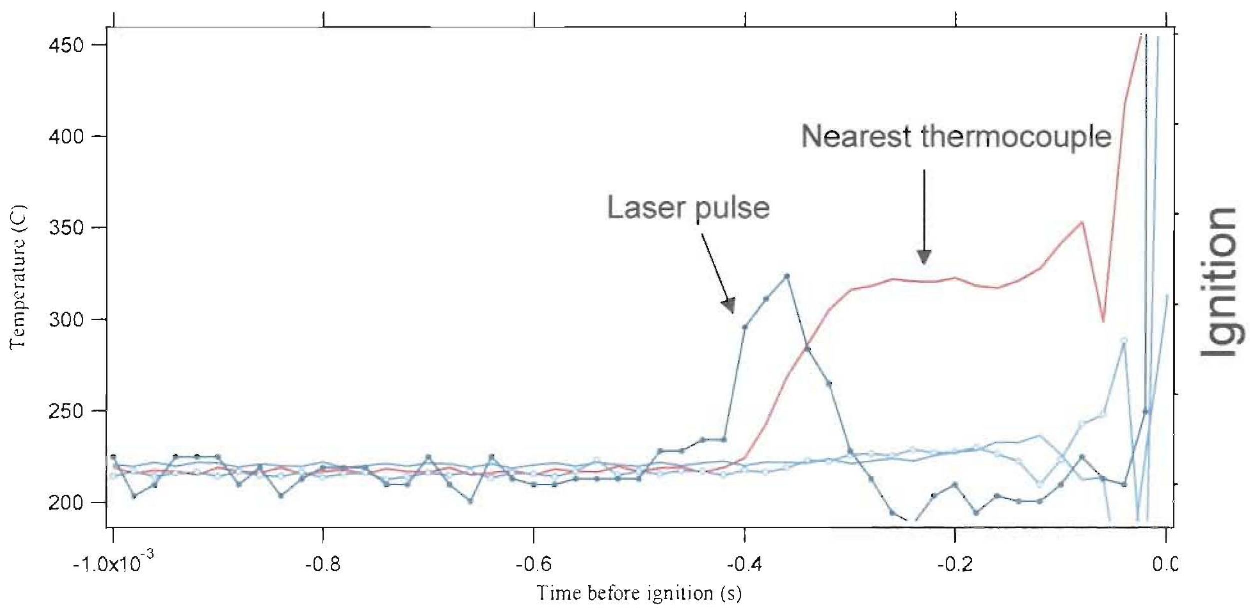
- Thermal ignition experiment studying properties of PBX-9501 for the surety program
- Study preignition material density changes
- Study postignition reaction propagation
- Material drive mechanisms
- Previous measurements have been performed with optical diagnostics
- Proton radiography provides information on:
    - Pre-ignition density variations of HE
    - Ignition propagation
    - Encasing material drive



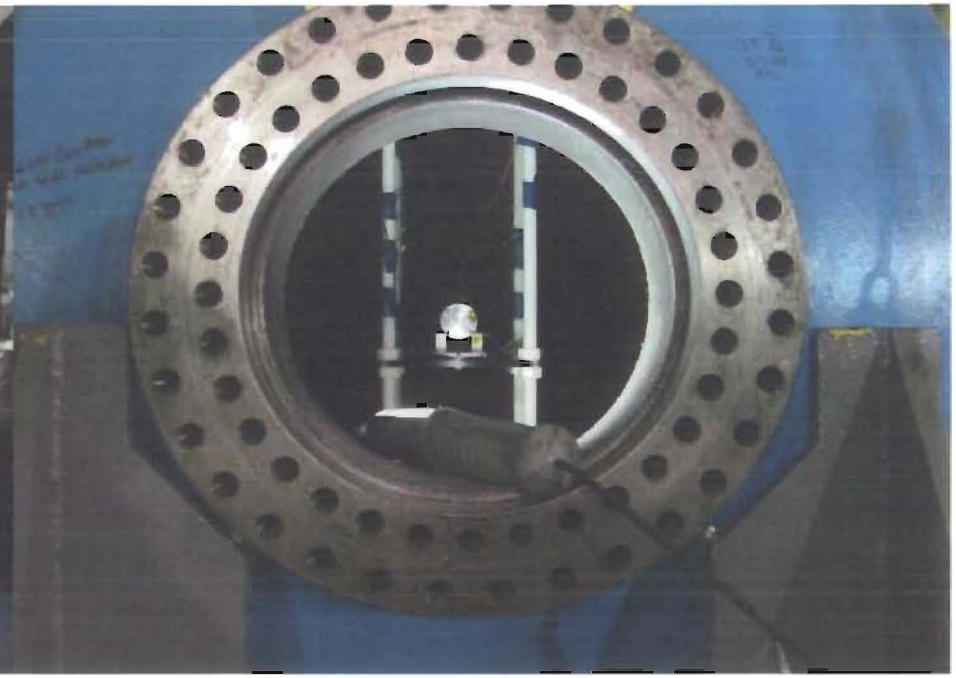
Laser Synchronization



- Human synchronization to within a minute.
- Laser induced ignition synchronization of event and beam to ~100 µS.



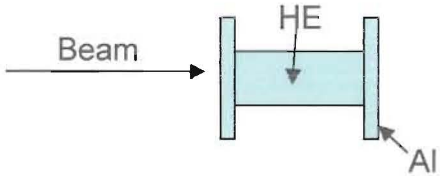
Cookoff Shot Setup

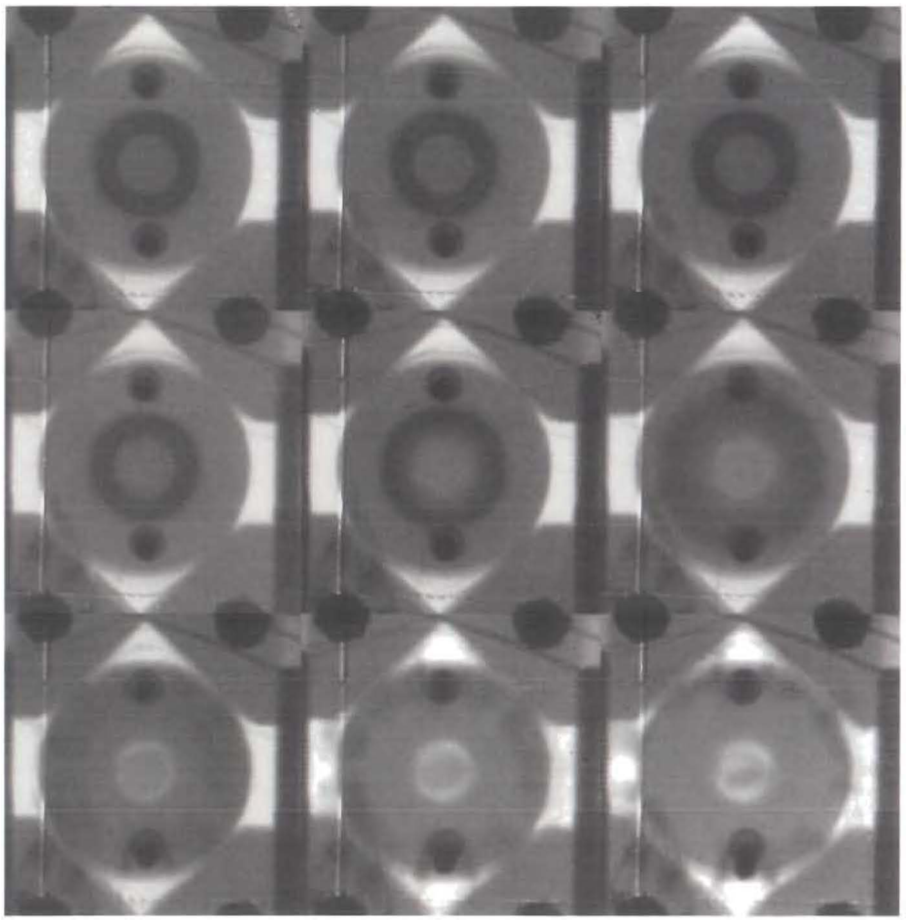



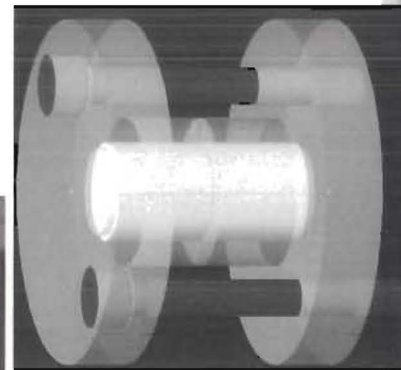
Fiber optic cable attached for laser ignition

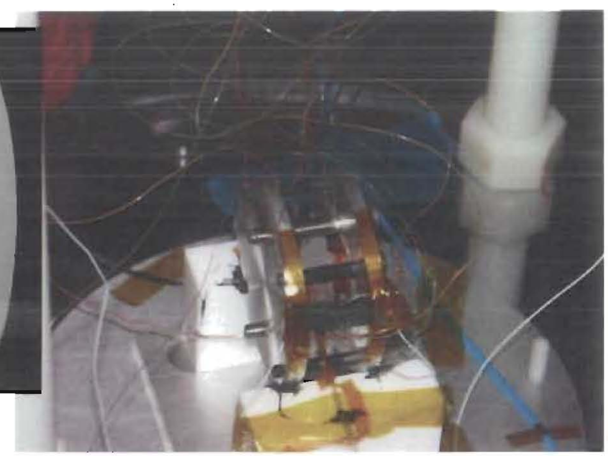
Thermocouples embedded for temperature reading

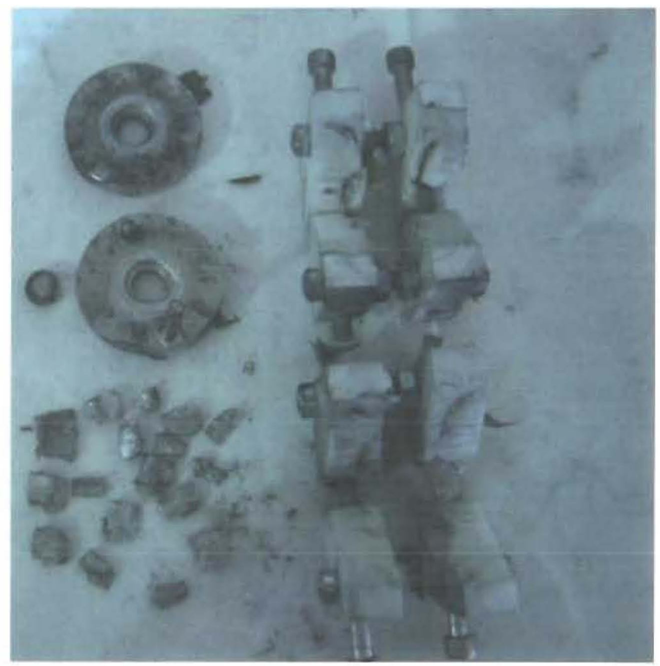
Successful Synchronization



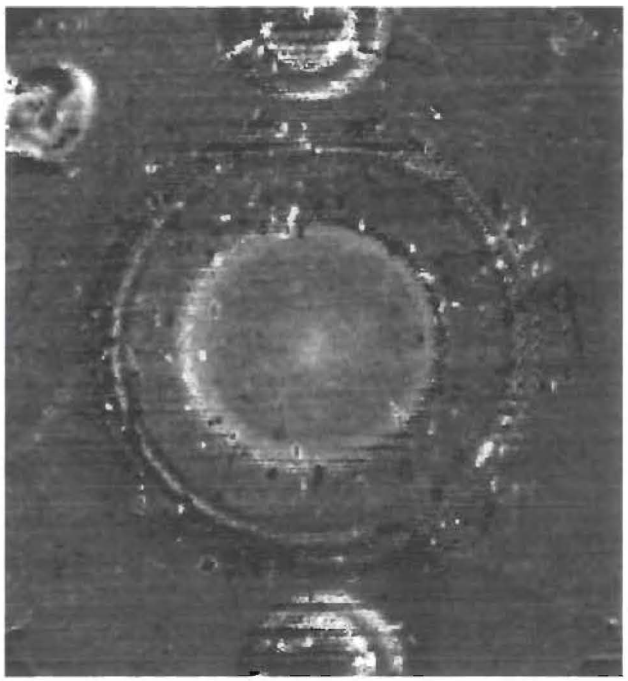


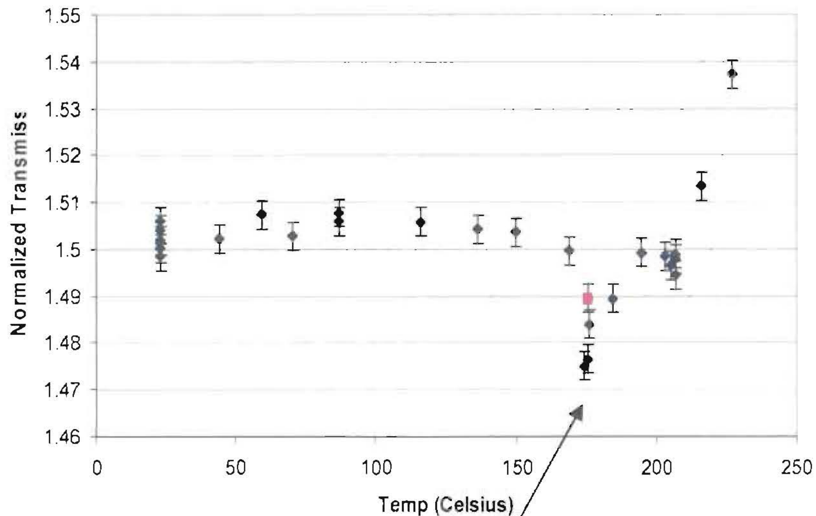




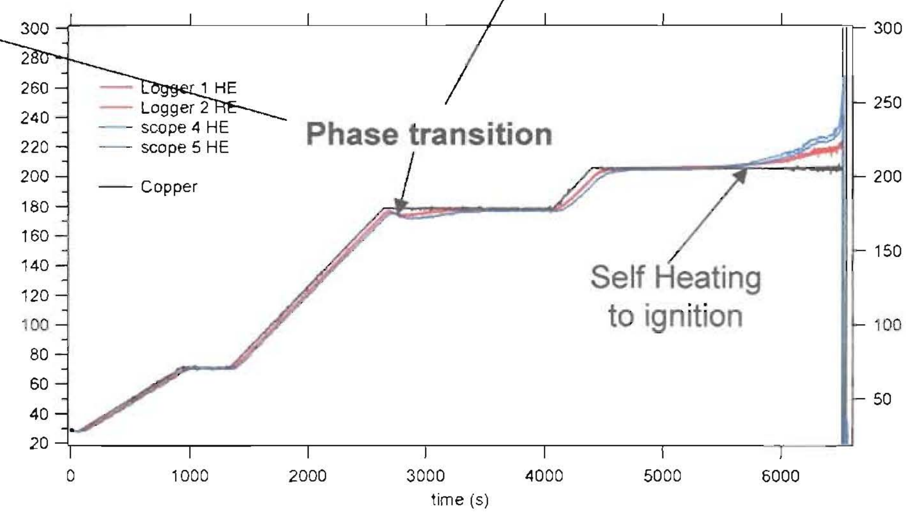


Preignition Density Variation

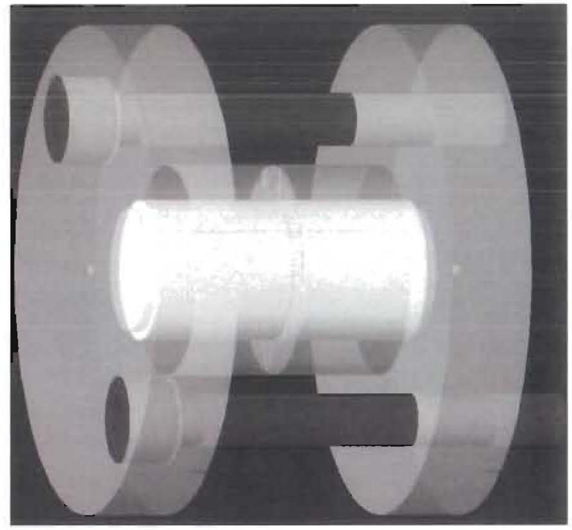




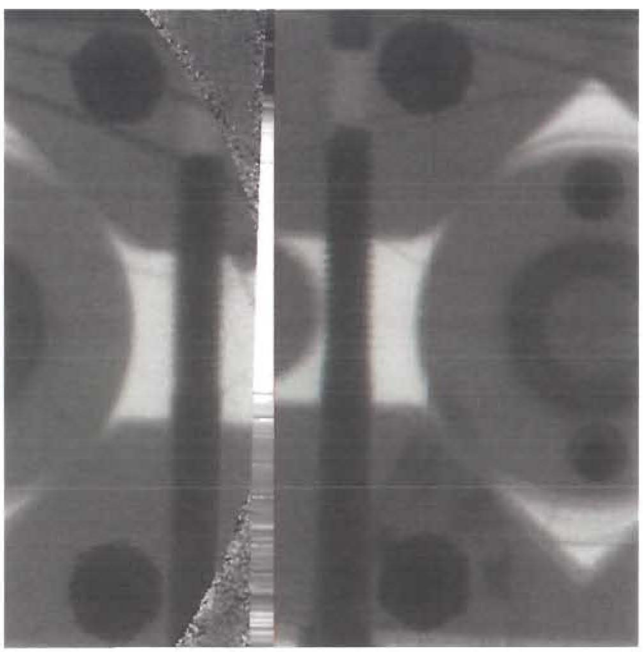
Temperature Ramp

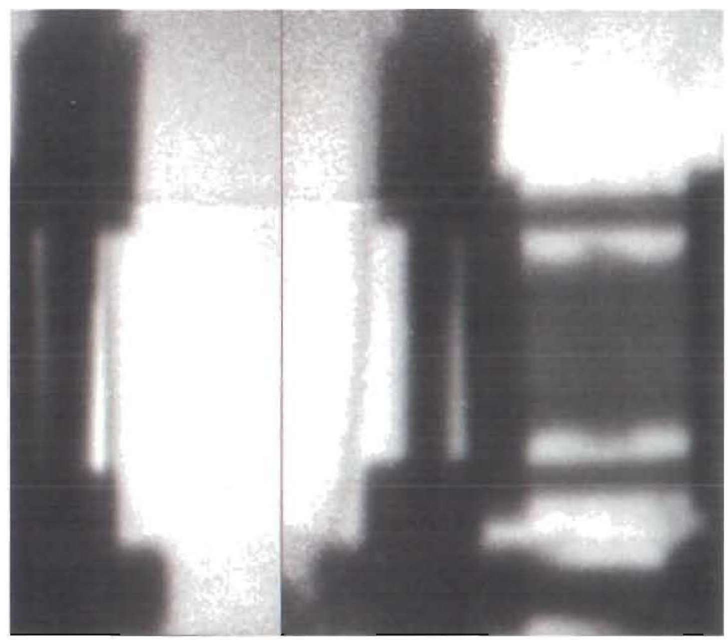


pRad has allowed the mechanism for high explosive cookoff to be elucidated (L. Smilowitz and C. Schwartz)



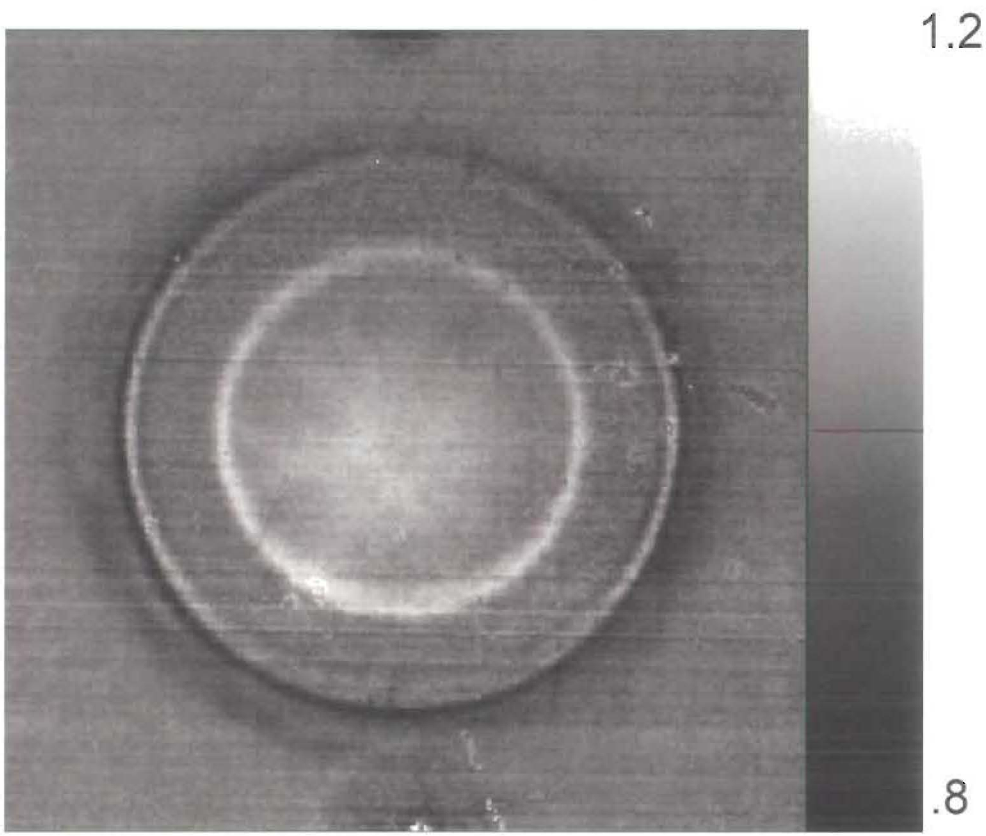
- Thermal ignition experiment studying properties of PBX-9501 for the surety program
- Proton radiography provides information on:
    - Pre-ignition density variations of HE
    - Ignition propagation
    - Encasing material drive





Ignition Propagation

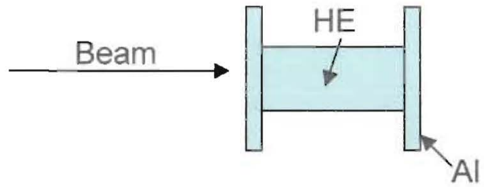
Transmission Images

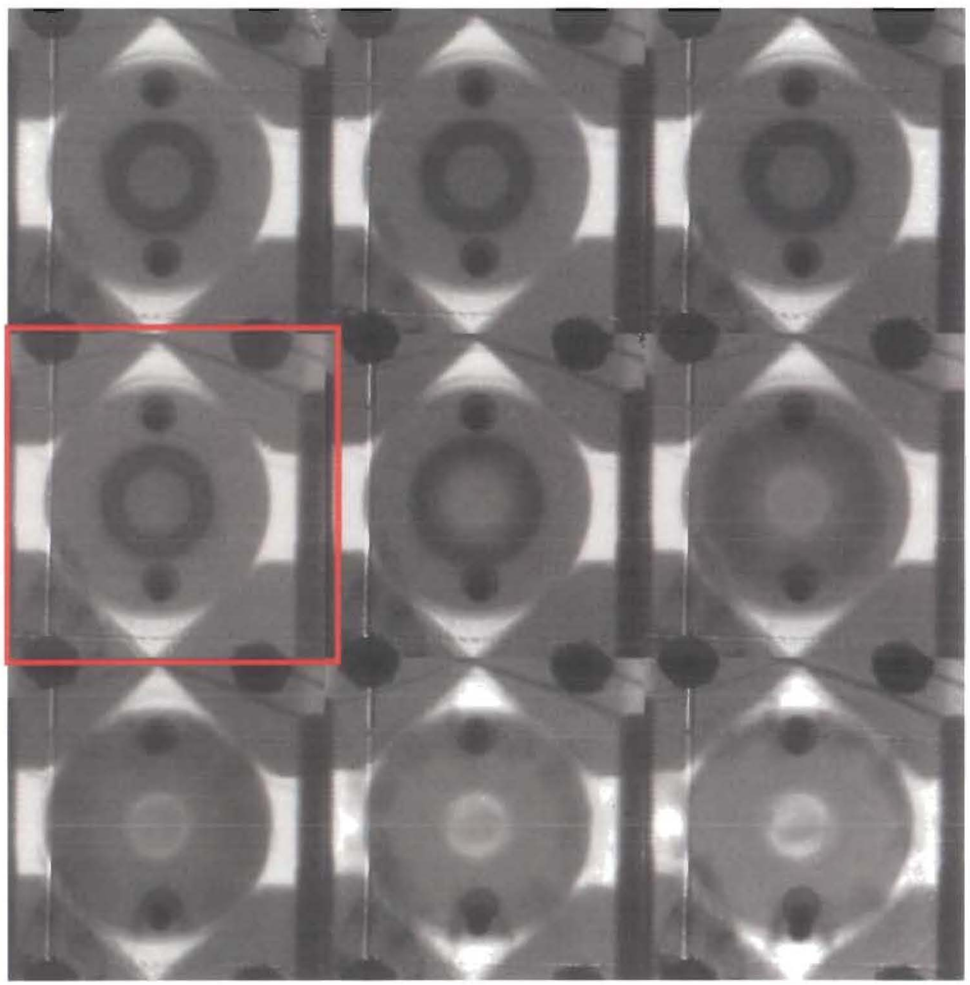


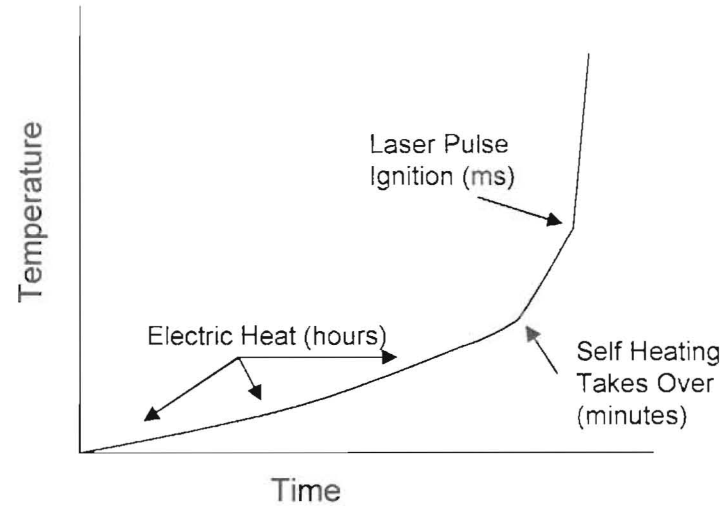
<u>Results</u>
Central ignition
Radial propagation
"star" ignition pattern

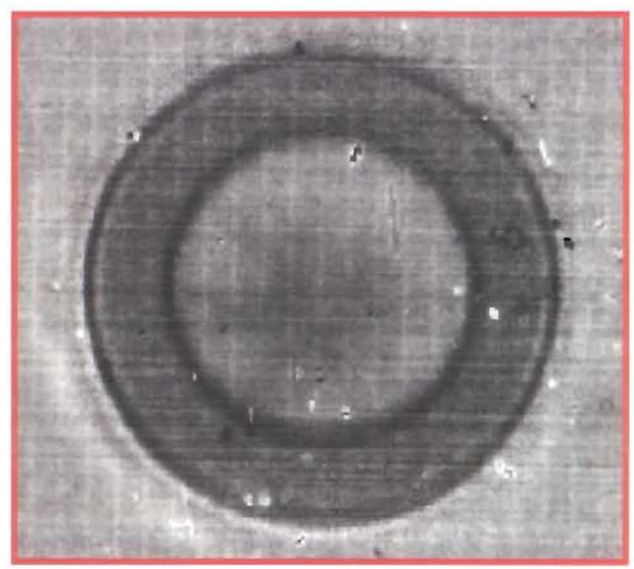
Detailed comparisons with models ongoing within C division and P division

Cookoff Experiments



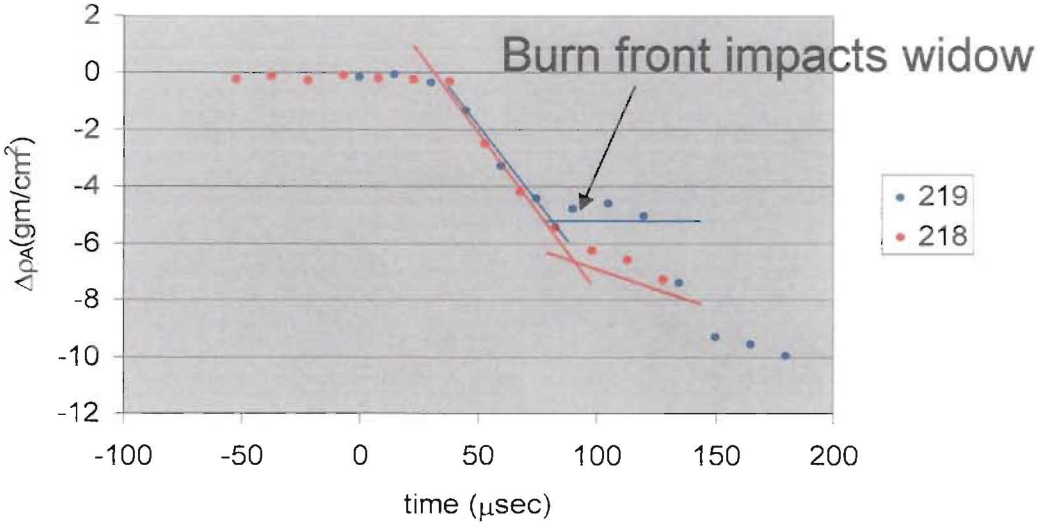




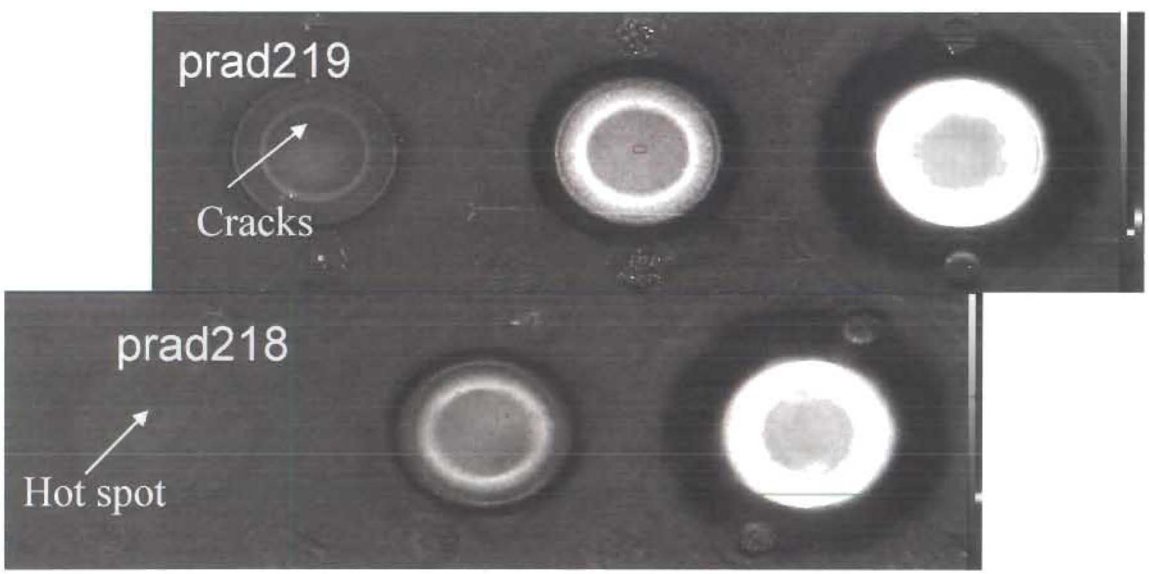


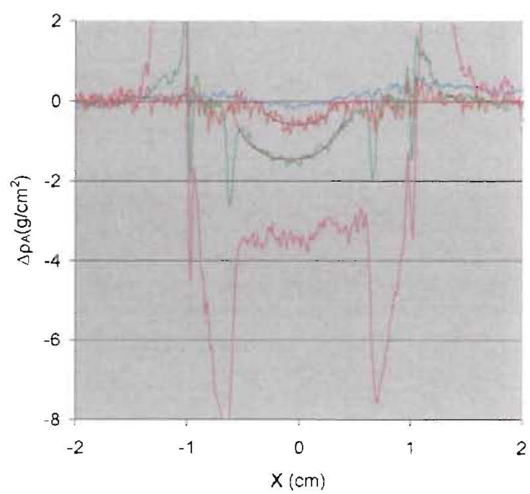
HE Density Variations

Combining data from two experiment shows features of the ignition mechanism

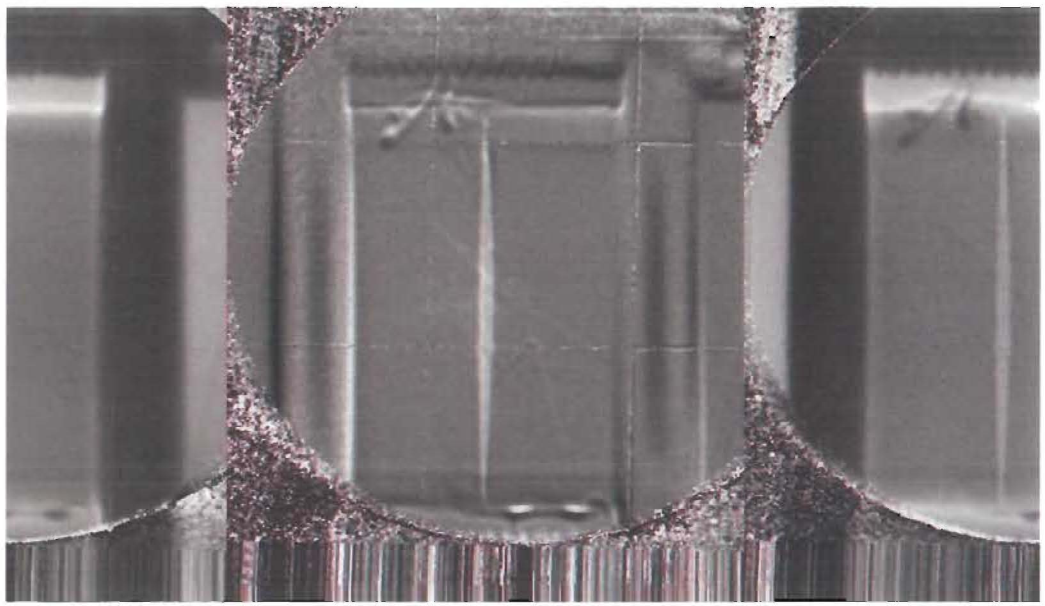


- Hot spot develops
- Ignition propagates along cracks
- Reaction burns remaining material



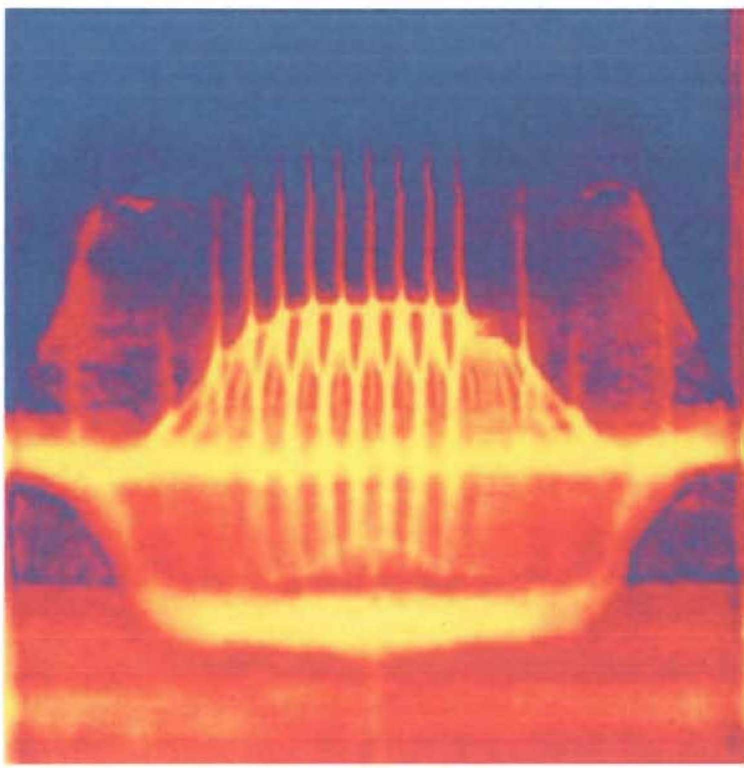


A recent proton radiography movie shows features of the ignition mechanism



Structural Phase Transitions

Cynthia L. Schwartz and the pRad collaboration,
Los Alamos National Laboratory



pRad Core Team

P-25

Eduardo Campos, Camilo Espinoza, Gary Hogan, Brian Hollander, Julian Lopez, Fesseha Mariam, Frank Merrill, Christopher Morris, Matthew Murray, Alexander Saunders, Cynthia Schwartz, T. Neil Thompson, Dale Tupa

DE-3

Joe Bainbridge, Robert Lopez, Mark Marr-Lyon, Paul Rightley

HX-4

Wendy McNeil

P-23

Gary Grim, Nicholas King, Kris Kwiatkowski, Paul Nedrow

LANSCE-NS

Leo Bitteker

NSTech

Douglas Lewis, Josh Tybo

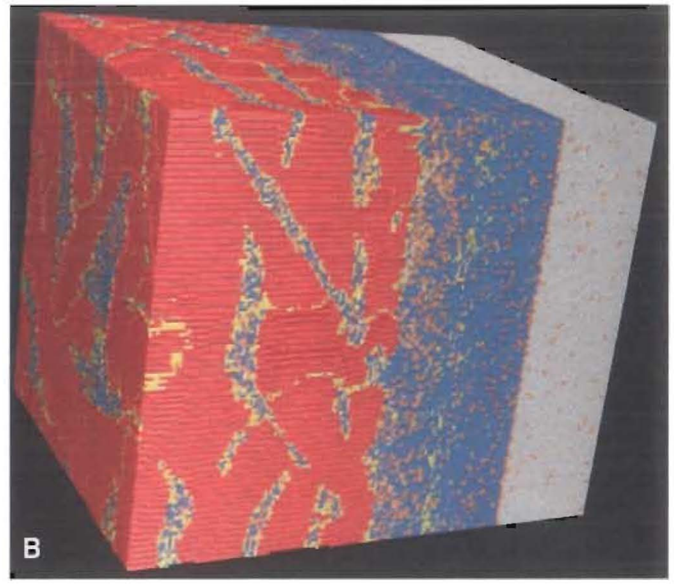
Transition Stress, Mechanisms, Kinetics and Hugoniot response depend on crystal orientation

Polycrystalline Material

- Distribution of grain orientations
- Grain boundaries serve as heterogeneous nucleation sites
- Decreased transformation threshold
- Fast mechanism

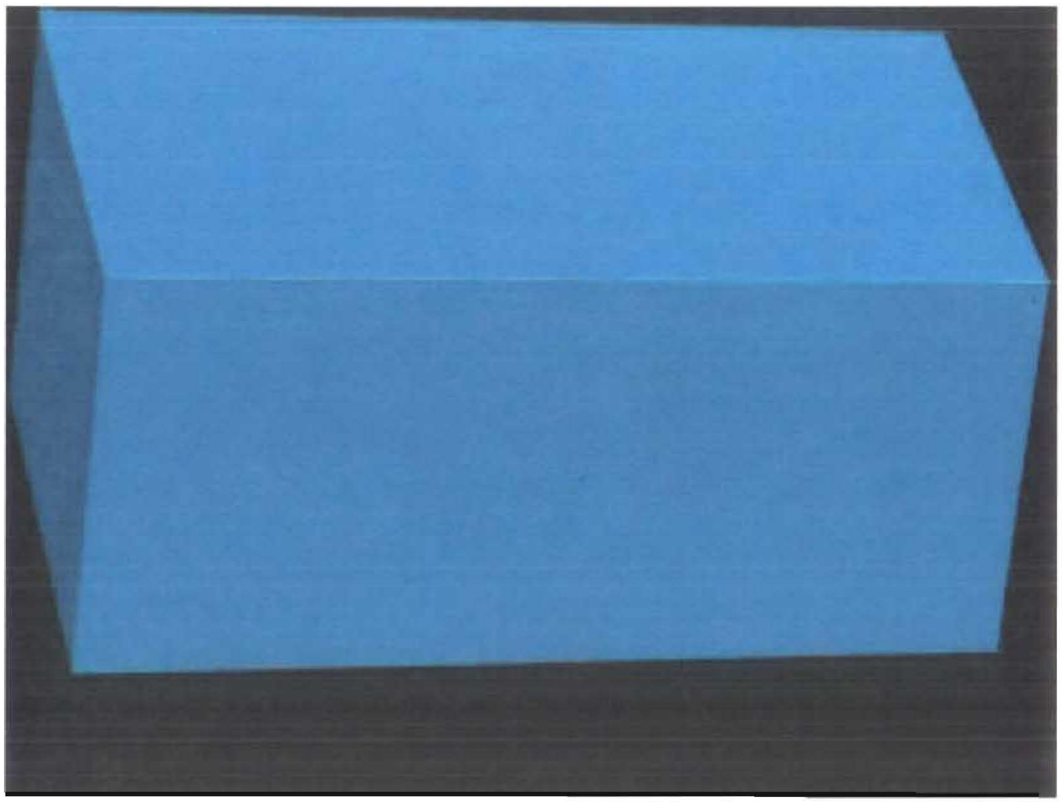
Single Crystal Material

- Mulitmillion atom MD simulations for single crystal iron
- Homgeneous nucleation
- Slower mechanism
- Increased transformation threshold

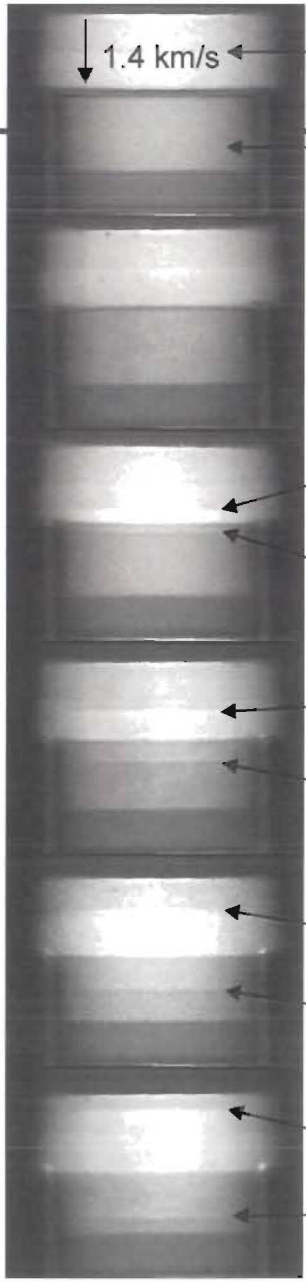


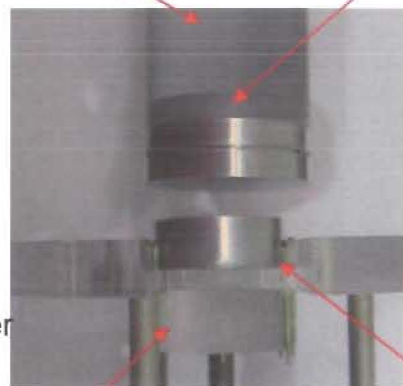
K. Kadau, T. C. Germann, P. S. Lomdahl, and B. L. Holian, *Science* **296**, 1681 2002.

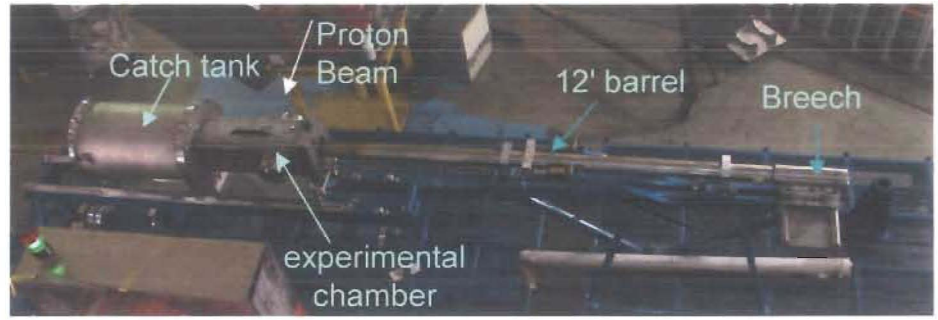
MD Simulation of Gallium

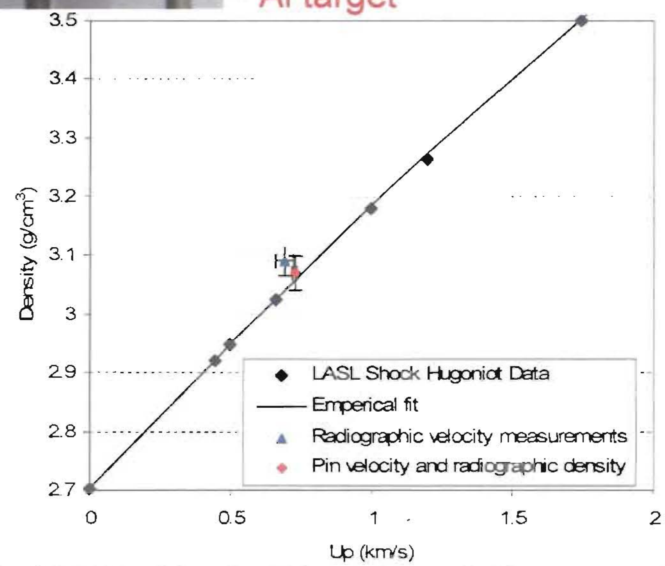


Demonstration Powder Gun Experiment









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

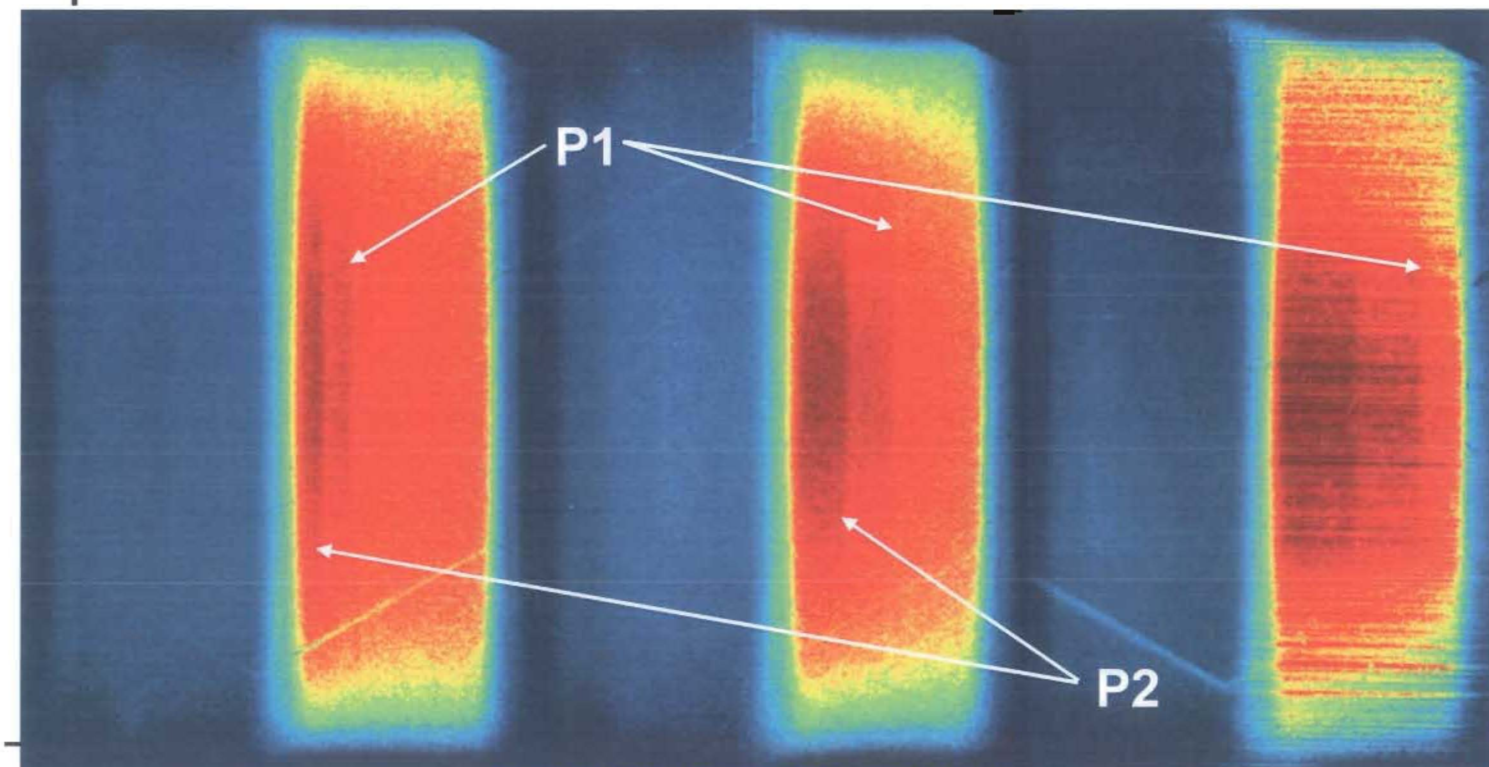
- Radiographic measurement of density behind shock front.
- Simultaneous measurement of particle and shock velocity

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

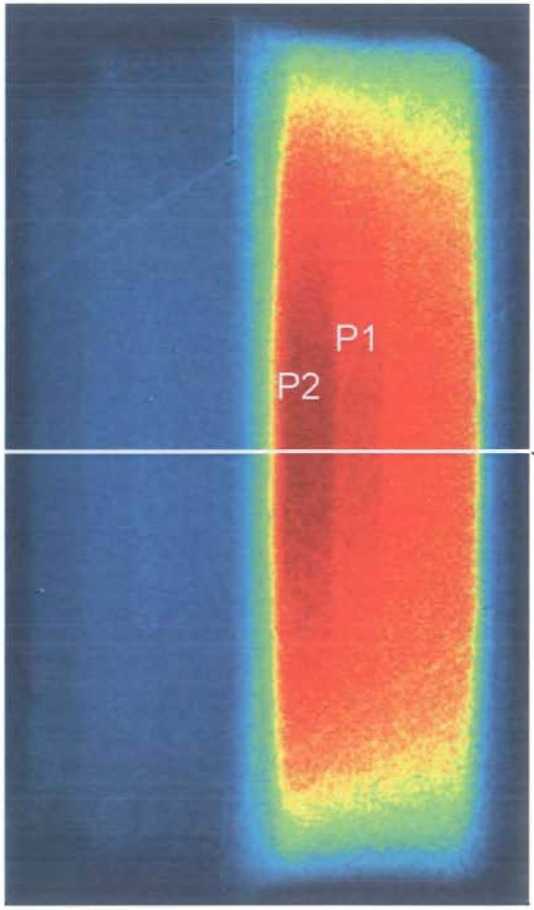
Rigg, Schwartz, et al., *Phys. Rev. B*, Jun 08, vol. 77, iss. 22 220101

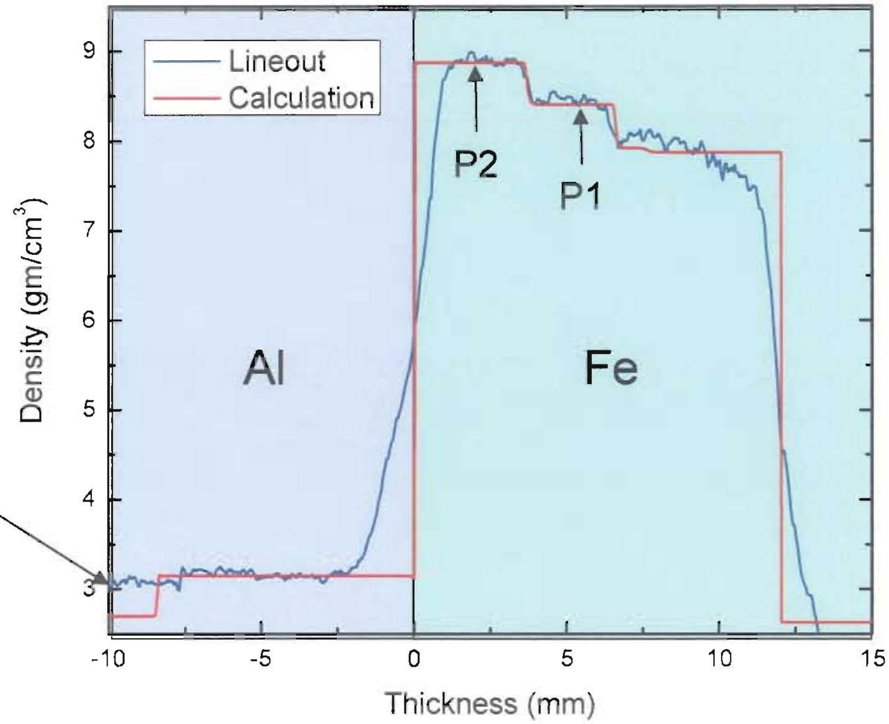
Two-wave structure observed in Iron

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



Powder Gun-Driven
Measured and Calculated Densities - Iron





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

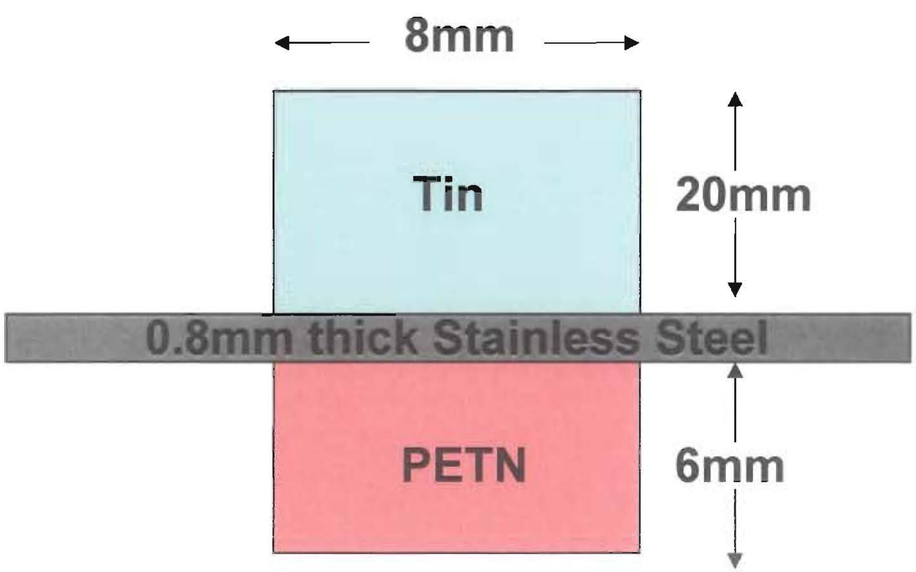
Fe Densities

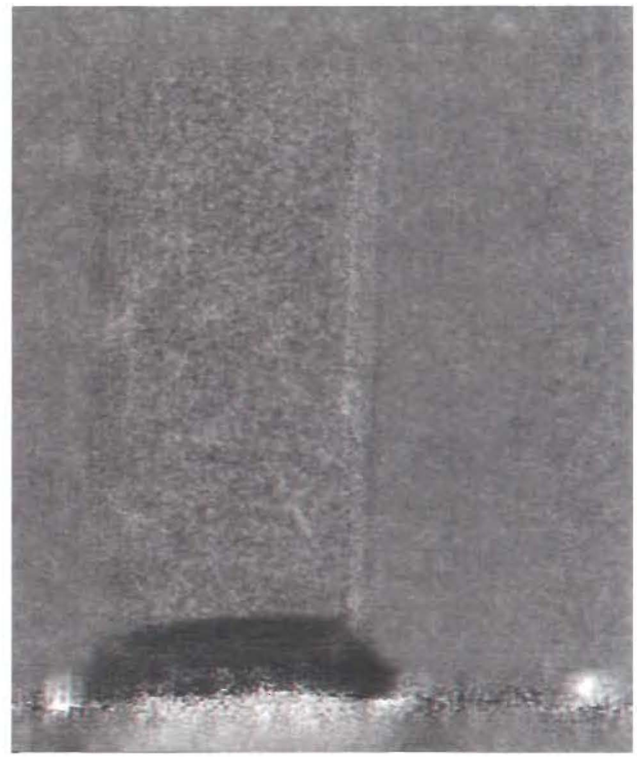
State	Measured	Calculated*	Agreement
P1	8.346	8.342	<0.1%
P2	8.854	8.846	0.1%

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

Taylor Wave-Driven Tin

- Explosive-driven "Taylor Wave" shock
- Multiple pressures, decaying over time
- Stainless steel membrane

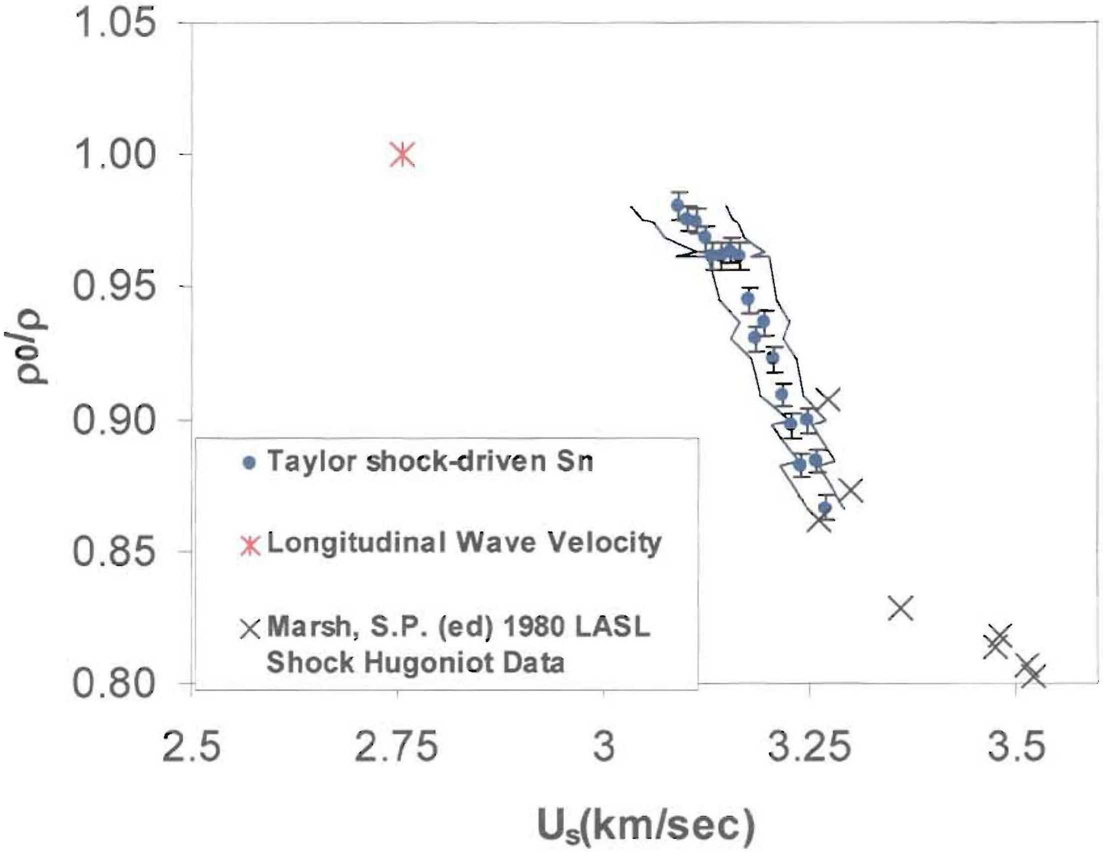




Dynamic / Static transmission radiographs

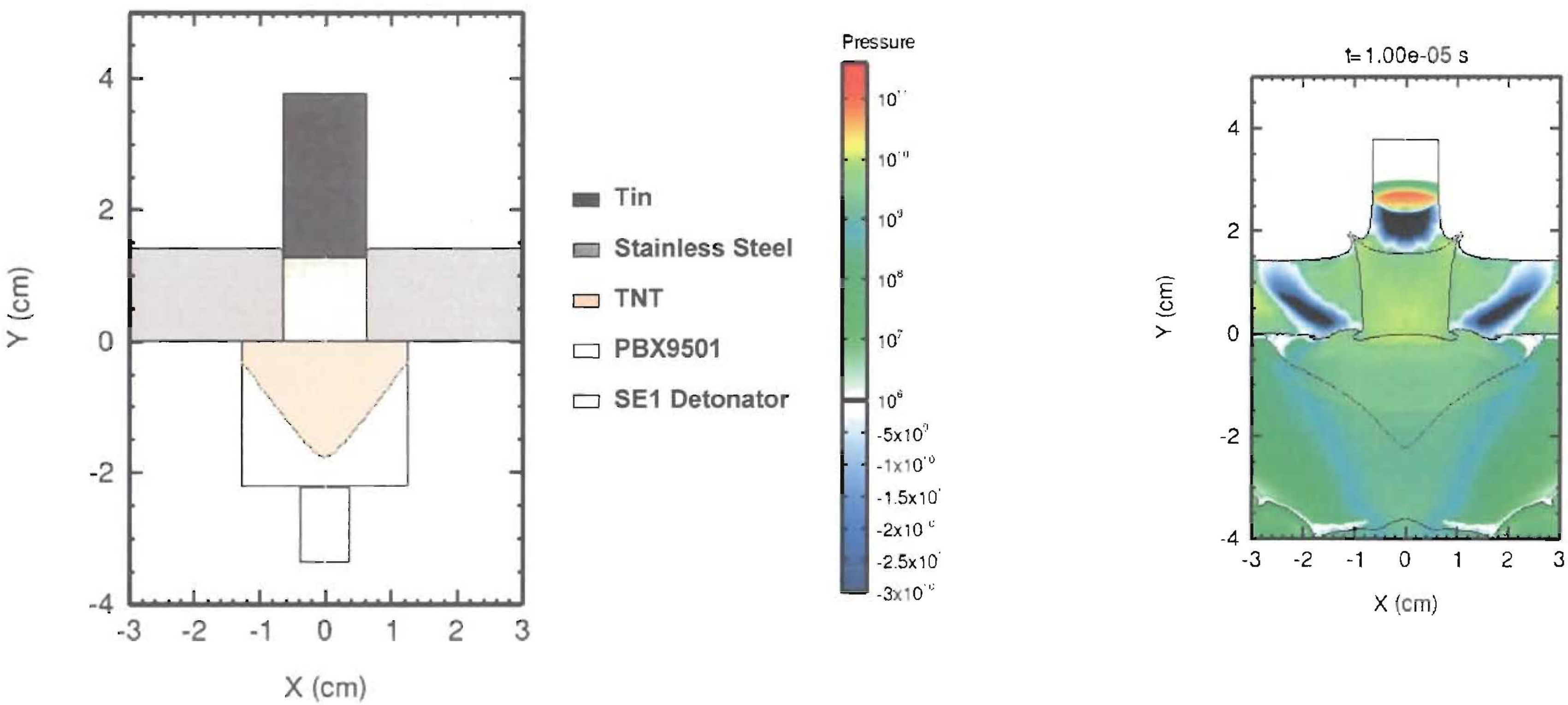
Single experiment, Multiple Measurements

- •Single experiment measures many Hugoniot points
- •Agreement with LASL Hugoniot data
- •Hugoniot points measured from peak shock velocity down to nearly sound velocity



Taylor Wave-Driven Summary

- Measured points on the Hugoniot from peak shock velocity down to nearly sound wave velocities
- 19 images in single experiment equates to 19 points on the Hugoniot (we measured 18 points)
- Agreement between present measurement and known Hugoniot with less than 1% density and 0.3mm/μsec (1%) shock velocity statistical uncertainty

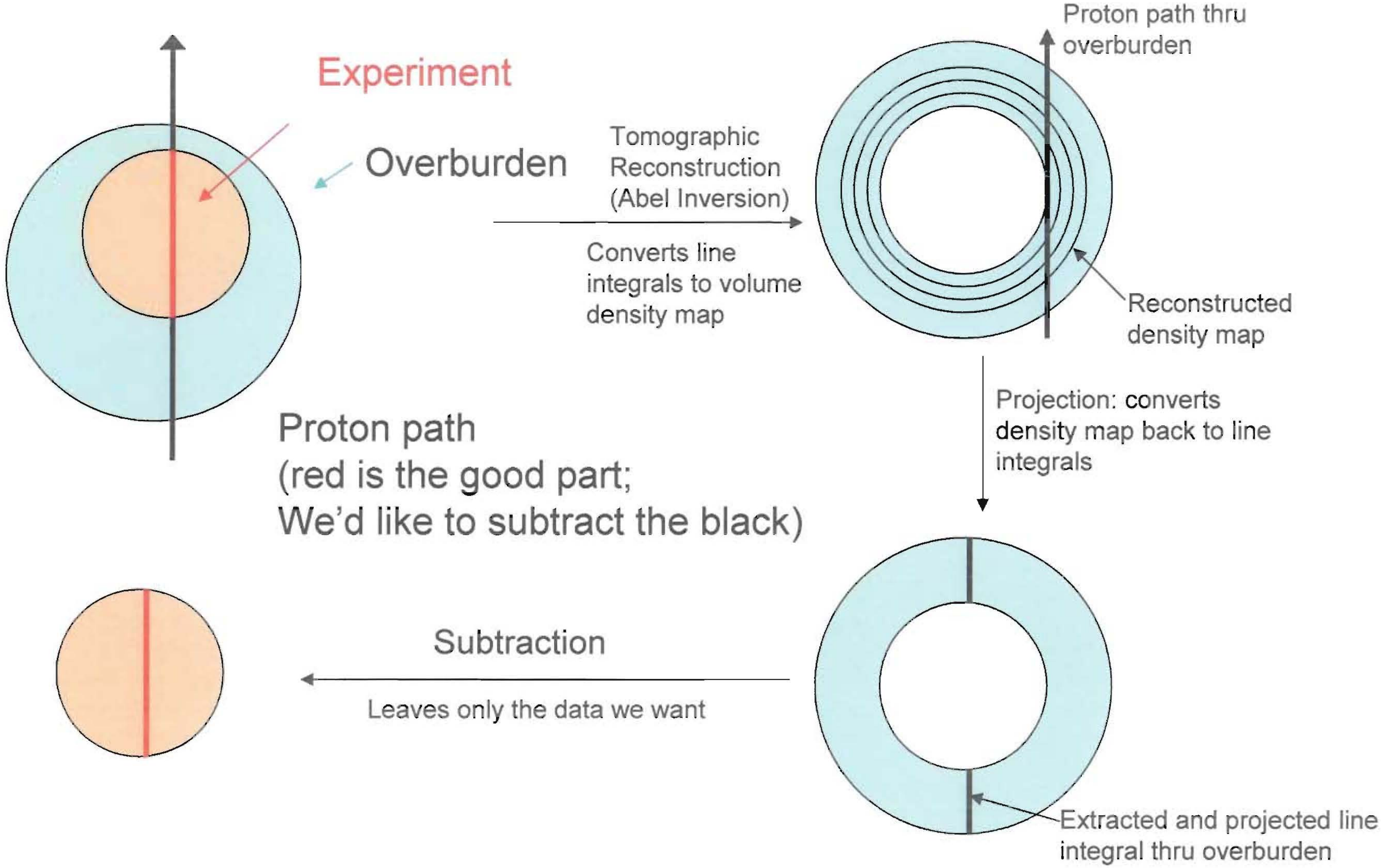


CTH Simulation of new drive on Tin target sample

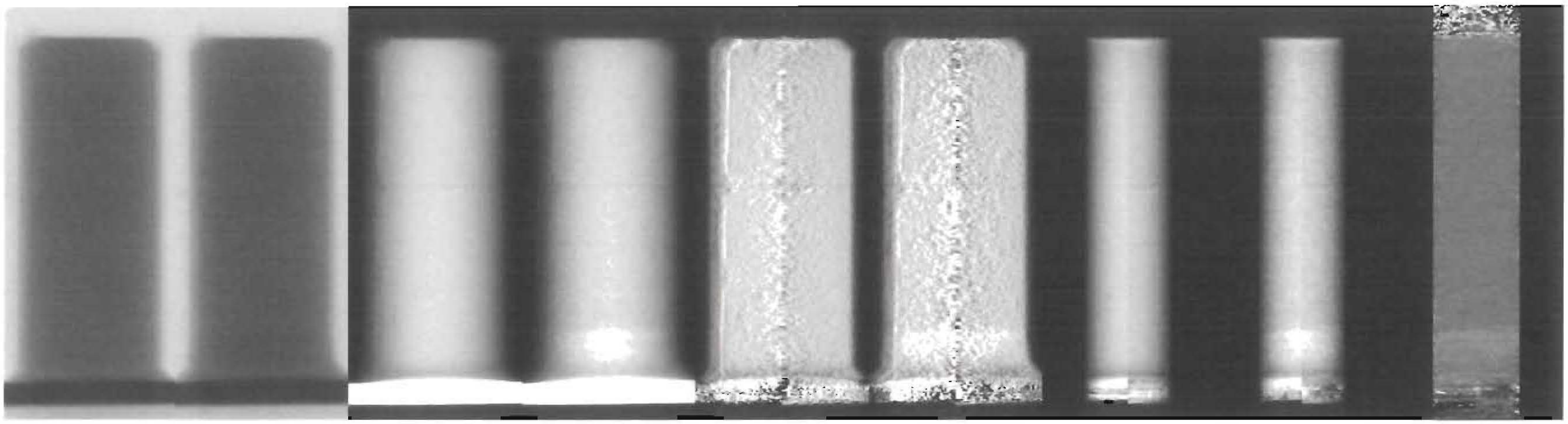
Recent Experiments

- We have recently performed proof of principle experiments with Al, Cu
- To optimize radiography, samples are 12.7mm in diameter
- To optimize number of measured position, samples are 40mm in thickness (length)
- Redo Sn with different drive and no membrane to complete the β->γ phase transition

Tomographic reconstruction and subtraction of overburden

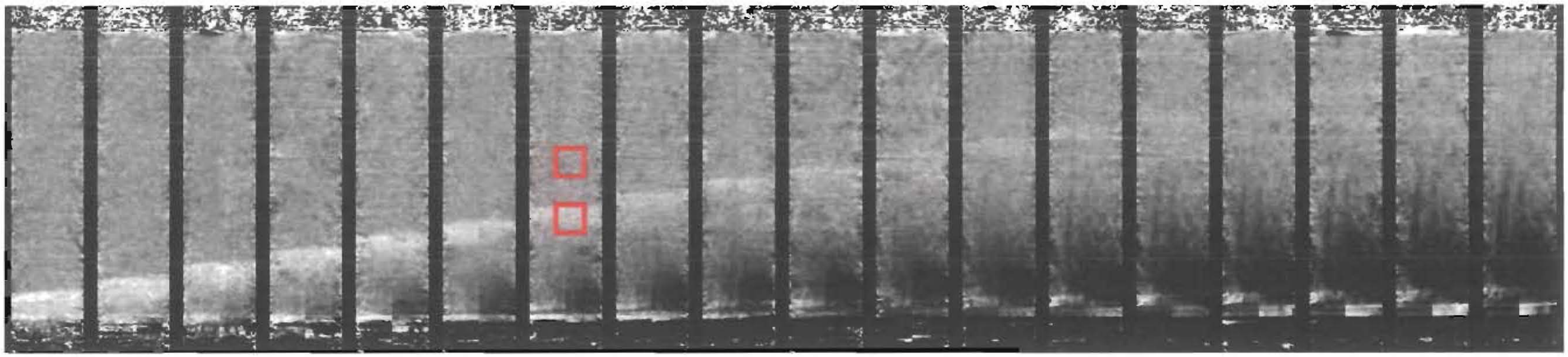


Trimmed density reconstruction

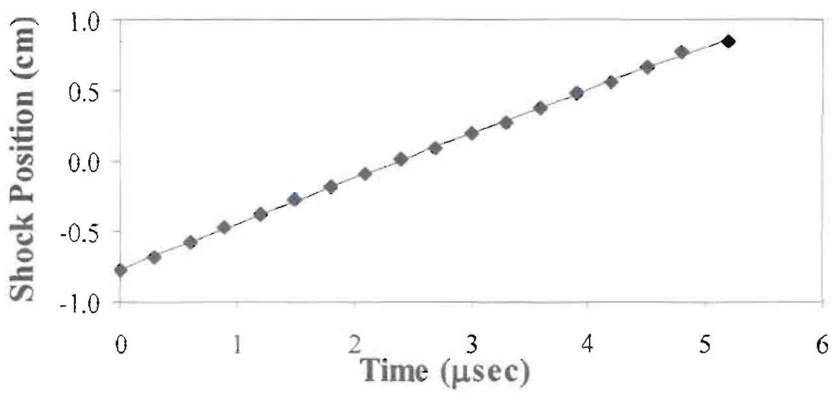


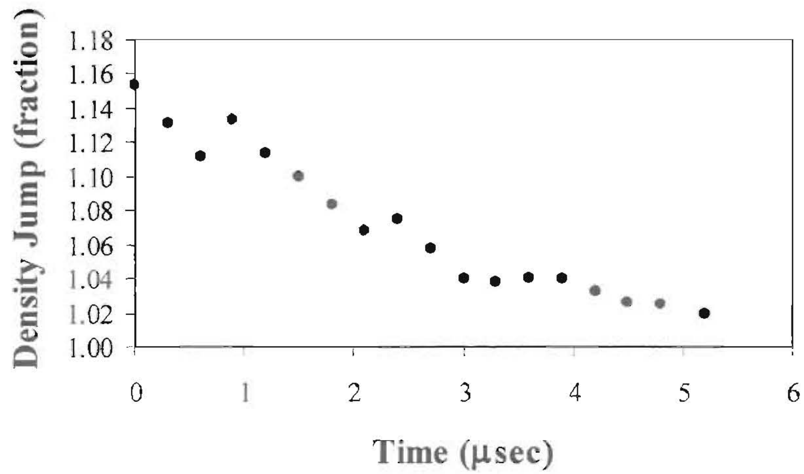
Technique that subtracts overburden and release effects from areal density radiographs

Position and Density



1.8μsec Time → 6.9μsec





Single experiment, Multiple Measurements

- Single experiment measures many Hugoniot points
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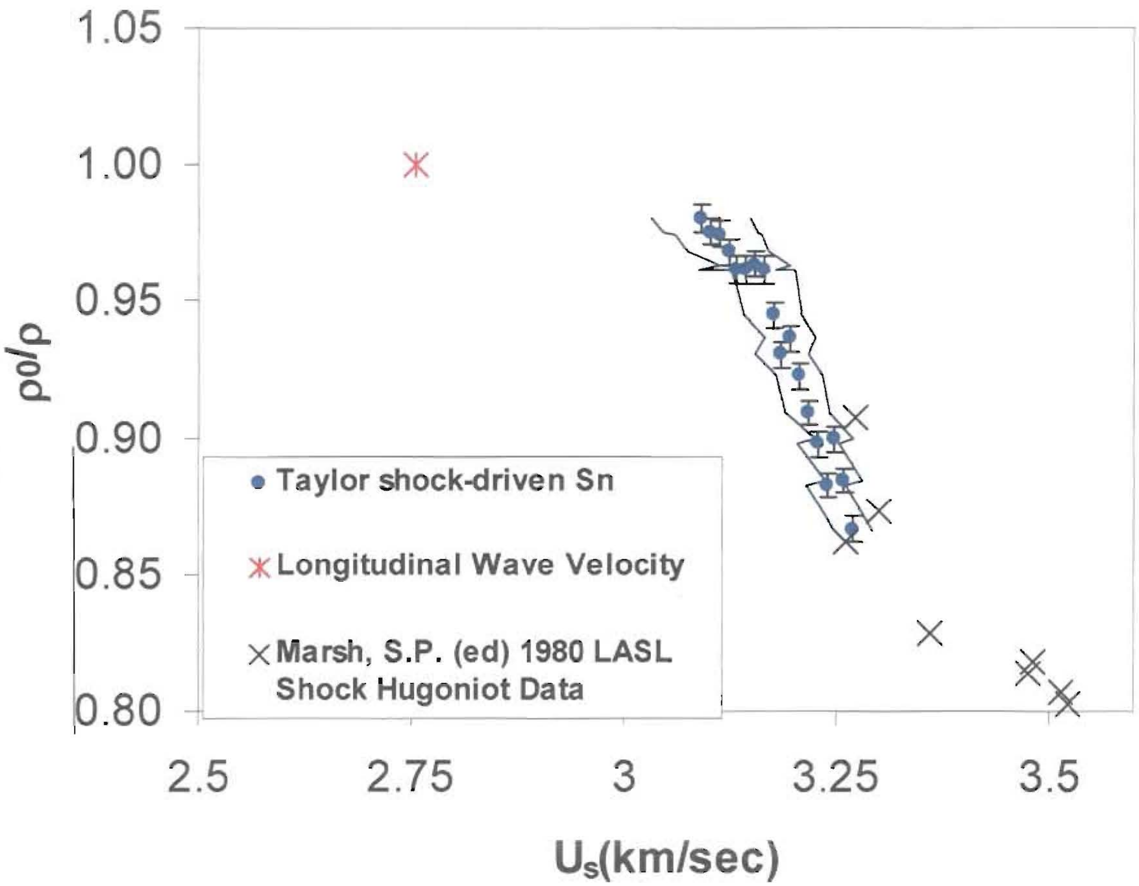

Water-bearing Minerals

- High Pressure properties important in study of earth's and planetary interiors
- Adundant in primitive meteorites (assumed similar to planetesimals)
- Relate impact velocity of planetesimals accreting to shock induced entropy increase

CalTech Shock Wave Laboratory

(Left) The rear of the 40 mm propellant gun
(Right) 90 mm/25 mm light gas gun

•Samples may be preheated to
•temperatures of 2000 K,
as well as pre-cooled to 20 K,
allowing compression studies
of both silicate magmas and planetary ices.
•High-speed radiometers are in active use in the laboratory to measure shock temperatures
•Dynamic pressures of shock wave range
•from 10kbar to 4000kbar,
the behavior of minerals in the pressure range extending from the base of the Earth's crust to very nearly the center of the Earth are being actively studied.

Conclusions & Future Work

- Measured points on the Hugoniot from peak shock velocity down to nearly sound wave velocities
- 19 images in single experiment equates to 19 points on the Hugoniot
- Agreement between present measurement and known Hugoniot with 1% density and 0.2mm/μsec shock velocity uncertainty
- Strategic materials possible