Title: Looking Inside Explosions: Proton Radiography at Los Alamos

Author(s): Alexander Saunders

Intended for: Presentation at NCSU
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Proton Radiography at Los Alamos: Looking Inside Explosions
Alexander Saunders

Proton Radiography (PRAD) is a diagnostic tool that uses high energy proton beams to generate sequences of flash radiographs of fast moving objects. It has been used at Los Alamos National Lab to study such phenomena as detonation of high explosives and explosively-driven metal deformation, failure, and equation of state. PRAD is the only technique that can generate tens of frames of flash radiography data on time scales ranging from nanoseconds to hours. PRAD principles and techniques will be described, and examples of results from PRAD experiments will be presented.
Looking Inside Explosions: Proton Radiography at Los Alamos

Alexander Saunders
(for the PRAD Team)
NCSU 10/5/2009
Common Radiographic Tools

X-rays and neutrons have no electric charge and their trajectories cannot be manipulated easily. The transmission through matter of areal density $X$ have the forms

\[ T_{X\text{-Rays}}(X) = e^{-\frac{X}{X_0}} \]

$X_0$ is the radiation length
Resolution limitations are due spot size and Compton scattering

\[ T_{\text{Neutrons}}(X) = e^{-\frac{X}{\lambda_{\text{Nuclear}}}} \]

$\lambda_{\text{Nuclear}}$ is the nuclear collision length
Resolution limited by nuclear scattering and to a lesser extent collimation of neutron beam

$\lambda_{\text{Nuclear}}$ is greater than $X_0$ for all elements $Z>6$ → neutrons are good for radiographing dense materials.

In addition to attenuation and energy loss, both X-rays and neutrons scatter. The scattering can result in poor resolution unless the image sensor or converter is close to the object.

It is effectively impossible to make many rapid pulses of intense flash X-rays.
The origins of PRAD

Protons have two key advantages over neutral particles:
1) They can be transported away from the object
2) Many intense pulses can be generated

“Okay. Now that we know bombarding the sample with croutons isn’t the answer, what say we try protons.”
Proton Interactions

Proton Radiography

Energy Loss

Nuclear Interaction

Coulomb Scattering from Nucleus
History (proton range radiography)


Fig. 2 Cerebral infarction. a. Photograph of inferior view of brain with massive infarction of left hemisphere (on right in picture) due to recent thrombotic occlusion of the left middle cerebral artery. b. Proton radiograph (positive) of brain. Note less dense left hemisphere lying inferiorly. c. Photograph of coronal sections through frontal lobes of brain with infarcted hemisphere on right.

Fig. 3. Plus-depth curves for proton and X rays passing through a homogeneous medium. Note the difference in available contrast between the two tests for the detection of mass differences.
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
Magnetic Imaging Lens

A symmetric arrangement of four quadrupole magnets can be used to form a magnetic imaging lens in both x and y planes.

Focal plane depends on the energy of the protons and setting of the quadrupole fields;

But

Protons passing thru thicker parts of the object lose more energy than those passing thru thinner parts of the object.

Therefore, the dominant source of blur is chromatic blur.
Contrast

- Beam scatters as it passes through object.
- Scattering angle at object is mapped to radial position at collimator located at the Fourier point.
- Collimator (18” of steel) stops protons scattered to angles of 10 mrad or larger (this is an adjustable parameter).
- Protons not removed by collimator are re-focused at the image location.
Simple Math and Notation of pRad

- First order TRANSPORT notation
- Object to image identity lens

\[-I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\]

- Fourier point at collimator: prepare with position-angle correlation

\[x_c = M_{11}x_o + M_{12}x'_o\]
\[x'_o = wx_o + \phi\]
\[x_c = (M_{11} + wM_{12})x_o + M_{12}\phi\]
\[w = -\frac{M_{11}}{M_{12}}\]
Chromatic Corrections

- Second order transport notation
- Chromatic corrections to identity lens
  \[ \partial x = T_{116} x \Delta + T_{126} x' \Delta \]

- Minimize chromatic effects
  \[ \partial x = T_{116} x \Delta + T_{126} x' \Delta \]
  \[ x' = wx + \phi \]
  \[ \partial x = (T_{116} + wT_{126}) x \Delta + T_{126} \phi \Delta \]
  \[ w = - \frac{T_{116}}{T_{126}} \]

- Mottershead's Miracle: Correlation required by Fourier point cancels chromatic aberrations
  \[ w = - \frac{T_{116}}{T_{126}} = - \frac{M_{11}}{M_{12}} \]

Second order TRANSPORT

\[ \partial x_i = T_{ijk} x_j x_k \]

\[ T_{ijk} = \frac{\partial^2 x_i}{\partial x_j \partial x_k} \]

\[ x = \begin{pmatrix} x \\ x' \\ \Delta \end{pmatrix}, \Delta = \frac{\partial p}{p} \]
Significant blur Correction (Matching)

\[ x_i = M_{11} x_o + \Delta x \quad \quad \quad y_i = M_{33} y_o + \Delta y \]

\[ \Delta x = (T_{116} x + T_{126} \delta \theta) \frac{\delta p}{p} \quad \Delta y = (T_{336} y_o + T_{346} \delta \theta) \frac{\delta p}{p} \]

\( \Delta x, \Delta y \) are chromatic blur terms

**MATCHING**

Inject beam with position-angle correlation is such a way that the \( T_{116} \) and \( T_{336} \) (position dependent) terms are eliminated. We are then left with the blur terms:

\[ \Delta x = T_{126} \delta \theta \frac{\delta p}{p} \quad \Delta y = T_{346} \delta \theta \frac{\delta p}{p} \]

The above matching scheme also results in the sorting of protons at the Fourier plane by their angle of scattering regardless of the position at the object location suggesting that the remaining chromatic blur can further be reduced by using a collimator at the Fourier plane.

* C.T. Mottershead and J. D. Zumbo, “Magnetic Optics for Proton Radiography”, Proceedings of the 1997 Particle Accelerator Conference
Optimizing pRad
(Assuming no nuclear scattering)

- Minimize blur
  \[ \delta x = T_{126} \cdot \mathcal{G}_{\text{coll}} \frac{\delta E}{E} \]

- Maximize contrast to enhance density reconstruction
  \[ C(X, \mathcal{G}_{\text{coll}}) = \frac{\partial \text{Trans}(X, \mathcal{G}_{\text{coll}})}{\partial X} \tau = g(X, \mathcal{G}_{\text{coll}}) \delta X \]

- Minimize statistical error
  \[ \frac{1}{\sqrt{\text{Trans}(X, \mathcal{G}_{\text{coll}})}} \]

- Statistical Figure of Merit
  \[ Q(X, \mathcal{G}_{\text{coll}}) = g(X, \mathcal{G}_{\text{coll}}) \sqrt{\text{Trans}(X, \mathcal{G}_{\text{coll}})} \]

One can optimize the figure of merit for density reconstructions by choosing the right collimator for the right object thickness.
800 MeV pRad Density Reconstruction

Figure of Merit

Figure of Merit for pRad at 800 MeV as function of Collimator size for various \(X/X_0\):

- \(X/X_0 = 0.1\)
- \(X/X_0 = 1.0\)
- \(X/X_0 = 2.0\)
- \(X/X_0 = 5.0\)
- \(X/X_0 = 10.0\)

Collimator half angle (radians)
Anti-collimator for Contrast Enhancement

For thin objects with small area density variations such as gas targets, the contrast can be enhanced by using anti-collimators instead of collimators.

Figure of merit for Collimator and Anticollimator Config. at X/X0=0.1.

Contrast Function for Collimator and Anticollimator Config. at X/X0=0.1.

Collimator or Anticollimator half size (radians) vs. Contrast function for collimator.

Collimator or Anticollimator half size (radians) vs. Contrast function for anticollimator.

Collimator

Anti-Collimator

\( \theta_{coll} \)

\( \theta_{out} = 0.02 \text{ radian} \)
Typical Uses of pRad

pRad is especially well suited for:

a) where radiographic requirements are such that the object to converter (detector) distance is large such as the radiography of radioactive samples

b) Multi frame imaging of fast (10^{-3} to 10^{-6} s) dynamic processes: that is, explosively-driven systems
LANSCE Experimental Areas

- Lujan Center
  - National security research
  - Materials, bio-science, and nuclear physics
  - National user facility

- WNR
  - National security research
  - Nuclear Physics
  - Neutron Irradiation

- Proton Radiography
  - National security research
  - Dynamic Materials science,
    - Hydrodynamics

- Isotope Production Facility
  - Medical radioisotopes
pRad Facility at LANSCE
-1 Lens
x3 Magnifier (PMQs)

Made up of four 4" bore permanent magnet quads.
x7 Magnifier

Made up of four 1” bore permanent magnet quads; Yet to be commissioned properly
Camera System and Standard Timing

- Precursor (60 ns Pulse)
- 250 us
- Detonation

- 19 images at first station (IL1)
- 22 images at second station (IL2)
- Typically 50 to 200 ns exposure times
The camera Table at IL1

At this station six "Rockwell" cameras with capability of taking three frames at a rate of up to 4 MHz are used.
Failure Cone (Eric Ferm) (-I Lens)

PBX 9502

PRAD157 failure Cone

Failure occurs at d=5.4 to 5.6mm

(3.2°)

Det. Front Pos. [mm]

70
60
50
40
30
20
10
0

7.49mm/μs
0.49mm/μs

0 5 10 15 20

t [μs]

15.0μs
17.2μs
19.3μs
8.6μs
10.7μs
12.9μs
2.1μs
4.3μs
6.4μs
25 mm cone, (7.1°)
Cookoff Experiments

- Beam
- Pulse Ignition (ms)
- Self Heating Takes Over (minutes)

- Laser Pulse Ignition (ms)
- Electric Heat (hours)
- Self Heating Takes Over (minutes)

- Temperature
- Time
Cookoff Experiments

- Beam
- HE
- Al

Graph:
- Temperature
- Time
- Laser Pulse Ignition (ms)
- Electric Heat (hours)
- Self Heating Takes Over (minutes)

HE Density Variations
pRad has been used to make a movie of the development of a Richtmyer-Meshkov (RM) instability in solid tin (W. Buttler)

The target has a sin wave machined in its lower face
Richtmyer-Meshkov with uniform perturbation (RM) instability in molten tin (W. Buttler)
More RMI experiments: A group of three perturbations (W. Buttler)

vacuum  5 atm, of Xe  5 atm, of Ne
Material Strength Experiments (Olson Series)

The technique utilizes a flat metal plate with perturbations of known wavelength and amplitude machined into one side of the plate. High explosive is used to generate shock-free, planar loading on the perturbed side of the plate and the amplitude of the Rayleigh-Taylor (R-T) unstable perturbations are measured from radiographs acquired as a function of time (see Fig. 1). The perturbation growth rate is directly related to the dynamic shear strength of the metal and thus can be compared directly to that predicted by various strength models via hydrodynamic calculations.

- Utilized improved resolution capability of new magnifier system.
- Six (or more) dynamic experiments performed to study instability growth versus drive pressure by varying HE standoff.
- Demonstrated shockless acceleration and reproducibility.
Demonstration of new EOS measurement capability with proton Radiography

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
Expanding Uranium

What fraction of the area is DU vs empty?
How empty are the empty areas?

Protons
DU
HE
d=40 mm
Detonator

What fraction of the area is DU vs empty?
How empty are the empty areas?
Quasi Static Systems (msec to seconds):
Dynamic studies of He Bubble formation in Hg in Support of the SNS High Current Target Development

He bubble formation in stagnant (left) and flowing (right) mercury.

In the case of the stagnant Hg, the bubbles form, grow in size and break off in about \( \frac{1}{4} \) sec. When the Hg is flowing, the bubbles break off at much faster time scales.

Thousands of such pictures were taken with the Rockwell cameras in movie mode at 20Hz under various He and Hg flow rates.
Static Objects Surrogate Fuel Rods

X3 magnifier has T126 ~ 3 meters

E-Loss through object center ~ 13 MeV \(\Rightarrow\) resolution ~ 0.5mm at center

Set the Lens to \(<E_{\text{Loss}}> \sim 10\text{MeV} \Rightarrow \) resolution ~ 0.113 mm at center

For Static Objects One can reduce chromatic blur by use of “Graded Degraders”
Mitigating Chromatic Blure: E-Loss Flattening Scheme

Chromatic term (T126) = 3m*δ*(dE/E)
Mitigating Chromatic Blur: E-Loss Flattening Scheme

Chromatic term (T126) = 3m*δθ*(dE/E)
The Set up

Zarcaloy tube was aligned on the graded degrader.
Radiograph pictures were taken at 181 rotational positions.
Transmission Image to Areal Density Transformation

Transmission $T$, 

$$T(X) = e^{-\frac{X}{\lambda}} \left(1 - e^{-\frac{\theta_{coll}^2 X_0}{2\alpha^2 X}}\right)$$

$\alpha$ is a kinematic factor given by 

$$\alpha = \frac{14.1}{p\beta}$$

$p =$ beam momentum [MeV/c] 

$X =$ Areal density 

$\lambda =$ Nuc. Interaction Length 

$X_0 =$ Radiation Length 

$\theta_{coll} =$ Collimator size

Pixel by pixel inversion of the transmission equation
Areal Density
Density reconstruction uncertainties from reconstructed Slices;

A slice thru the zircaloy section

Line outs

Single Pixel rms Jitter ~ 4%
Five Pixel rms Jitter ~2%

Bad pixels due to tile boundary contribute to reconstruction artifacts above
This can be avoided in future measurements
Better CT algorithms can be used
CT Reconstruction: Minimize ring artifacts by assuming that the zircaloy portion of the images is homogeneous and therefore has no ring structure in the density.

Default ring removal parameter

Increased ring removal parameter
CT Reconstructed Slices:
Interesting Regions: Part of Zarcaloy portion, all of Pellet#4, Part of Pellet#3
## Summary:

Imaging Lenses at pRad/ Available Frames

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<th>LENSES SYSTEM (Bore)</th>
<th>Magnification</th>
<th>FOV (mm)</th>
<th>T126 (Normalized) (m)</th>
<th>T346 (Normalized) (m)</th>
<th>Bare Resolution (μm)</th>
<th>Available Image Frames</th>
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For dynamic experiments there are two drivers:
1) Up to 10lb of TNT equivalent explosives
2) A Powder gun to launch flyers mainly used for EOS studies
PRAD Core Team


(Students)
Concluding Remarks:

Uses:

a) Study of HE detonation characteristics
b) Material strength and EOS studies with HE or powder gun drivers
c) Tomographic characterization of static objects (voids, density variations, etc.) and study of quasi static phenomena (eg. bubble formation and transport in mercury)

Main Feature:

• Versatile timing possible due to flexibility in time patterns of the LANSCE proton beams
• Multiframe capability: up to 41 frames per dynamic event
• x1, x3 or x7 magnifications available covering 120mm, 40mm or 17mm FOV

Other Diagnostic Tools:

VISAR and PDV (laser velocimetry technologies) can also be deployed to measure velocities of HE driven surfaces