Title: 800 MeV Proton Radiography

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pRad Team

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Proton Radiography

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Proton Interactions

Proton Radiography

- Energy Loss
- Nuclear Interaction
- Coulomb Scattering from Nucleus
Marginal Range Proton Radiography

Marginal Range Radiography

- Reduce proton beam energy to near end of range.
- Use steep portion of transmission curve to enhance sensitivity to areal density variations.
- Coulomb scattering at low energy results in poor resolution >1.5 mm.
- Contrast generated through proton absorption.
Scattering Proton Radiography

- Edge detection only
- Limited to thin objects
- Contrast generated through position dependent scattering

Fig. 7. Illustration of how multiple scattering produces its characteristic edge pattern.
1st LANL Proton Radiography (1995)
188 MeV secondary proton beamline at LANSCE

Object  Detector  Magnetic Lens

Image at the detector is substantially blurred.

Magnetic imaging lens preserves image with high resolution.
Magnetic Imaging Lens

10 m

Object

0.1 m

Image

No Object

Quadrupole Identity Lens
Angular distribution of 800 MeV proton nuclear elastic scattering from Iron.

Simple Approximation for Modeling Proton Radiography
- Characteristic Nuclear Collision Length: $\lambda_c$
- Approximate that each interaction removes the proton from the acceptance of the imaging lens.
- Measure the collision Length at 800 MeV

The "true" nuclear interactions are more complicated than this simple assumption and these interactions are reasonably well understood. This can all be simulated, but it is typically not worth the effort for designing small scale experiments.

Transmission

$$T_{\text{nuclear}} = e^{-\frac{x}{\lambda_c}}$$
Multiple Coulomb Scattering

\[ \theta_o = \frac{13.6\text{MeV}}{\beta p} \sqrt{\frac{x}{X_o}} \left[ 1 + 0.038 \ln\left( \frac{x}{X_o} \right) \right] \]

RMS Width
Full Width Half Maximum = 2.35 \( \theta_o \)


**Typical LANL simplification**
Contrast from Multiple Coulomb Scattering

Incident Beam  After Object  After Collimator

Measured transmission provides information of object thickness

$T_{MCS} = 1 - e^{-\theta^2/2\sigma^2}$
Areal Density Reconstruction

\[ T_{\text{nuclear}} = e^{-\frac{x}{\lambda}} \]

Nuclear removal processes

\[ T_{\text{MCS}} = 1 - e^{-\frac{\theta^2}{2\theta_0^2}} \]

Multiple Coulomb Scattering with collimation:

\[ \theta_0 = \frac{14.1 \text{MeV}}{p \beta} \sqrt{\frac{x}{x_0}} \]

\[ \theta_0 \] - scattering angle (radians)
\[ x \] - areal density
\[ x_0 \] - radiation length
\[ p \] - momentum (MeV)
\[ \beta \] - relativistic velocity

\[ T = e^{-\frac{x}{\lambda}} \left( 1 - e^{-\frac{\left(\frac{\theta_0 p \beta}{14.1 \text{MeV}}\right)^2 x_0}{2x}} \right) \]

Total Transmission

- inverted to determine areal density, \( x \)
Radiographic Analysis

“Raw” Radiograph  -  Dark Field  =  Beam Picture

Beam Picture  ÷  =  Transmission
Density Reconstruction

Invert to calculate Areal Density

\[ T = e^{-\sqrt{\lambda}} \left( 1 - e^{-\left( \frac{e_{p\beta}}{14.1\text{MeV}} \right) \frac{x_0}{2x}} \right) \]

Use assumption of cylindrical symmetry to determine volume density (Abel inversion)

Areal Density (g/cm²)

Volume Density (g/cm³)
Radiographic Comparisons

Density Sensitivity

\[ FOM = \frac{\Delta N}{\Delta l} = \frac{l}{\sqrt{N}} dN \]

Statistical sensitivity per fractional change in object thickness

800 MeV Protons*

\[ N = N_0 (1 - e^{-x_c/2l}) \]
\[ FOM = \sqrt{N_0} \frac{x_c}{2l} \frac{e^{-x_c/2l}}{\sqrt{1 - e^{-x_c/2l}}} \]

* Ignore nuclear attenuation
Dynamic Range of 800 MeV Proton Radiography

- 800 MeV proton radiography ranges from 0.05 g/cm² up to 50 g/cm²
Fig. 1  

a. Proton radiograph of a mouse with its feet 2.5 cm from the film and its back in contact with the film. 
b. X-radiograph of the same mouse (22 kV on tungsten). Both a and b have undergone two reversals in processing and so are of the same shading as the original radiograph.
X-Ray Proton Comparison

800 MeV Proton Radiography is roughly equivalent to 5 MeV Brehmsstrahlung x-ray source

X-Rays

Pros:
- Technology is mature and well understood.
- Source is relatively inexpensive.

Cons:
- Multiple-times along the same axis is difficult
- Scatter background results in systematic errors.
- Dynamic range difficult for thick objects

Protons

Pros:
- Multiple-times along the same axis is easy
- Scatter background is significantly reduced
- Dynamic range is easily handled.

Cons:
- Emerging technology
- Proton source is expensive to build.

Protons out perform x-rays for multiple time radiography of thick objects.
A proton source is expensive, but if you already have a source the choice is easy.

Los Alamos
Los Alamos is located in the high desert (>2000 m) on the side of an ancient super volcano in northern New Mexico.
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

Los Alamos
800 MeV pRad Facility at LANSCE
Temporal Resolution

- 19 images at first station
- 22 images at second station
- Typically 100 ns exposure times
- 180 ns inter frame spacing
- Beam available for 1000 μs
Sensitivity with 800 MeV Protons

Areal density contours of constant transmission as a function of atomic number.

10% transmission is near the lower limit of reasonable transmission.

- Perform experiments less than ~50 g/cm² with 800 MeV proton Radiography
Resolution of 12” Lens

- Bare resolution (rms)
  - Station 1: 178 μm
  - Station 2: 280 μm

Gaussian Line Spread Function

- Station 1: Lens + Camera MTF Fit
- Station 2: Lens + Camera MTF Fit
Material Strength Experiments

PTW fit to Hopkinson-Bar data

- **Copper**
  - $T = 300 \text{ K}$
  - $\psi = 0.2$
  - $\psi = 0.15$
  - $\psi = 0.1$
  - $\psi = 0.05$

- **High Explosive**

- **Vacuum Gap**

- **Metal Sample**

- **Calculated Strain Rate**

- **Acceleration Direction**

- **Amplitude (mm)**

- **Time (\mu s)**

Calculated Strain Rate:

- $4.2 \times 10^5 \text{ s}^{-1}$
- $3.1 \times 10^5 \text{ s}^{-1}$
- $2.0 \times 10^5 \text{ s}^{-1}$
- $9.0 \times 10^4 \text{ s}^{-1}$
- $9.0 \times 10^4 \text{ s}^{-1}$

References:

Powder Gun Driven Equation Of State Measurements

Al Flyer
LiF Window
Al target

Catch tank
Proton Beam
12' barrel
Breech
Experimental chamber

Aluminum

Copper

1.4 km/s

Los Alamos
Powder Gun Al/Cu Equation Of State

Table 1: Summary of the experiments with the uncertainties for each quantity shown in parentheses.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Impactor sample</th>
<th>Impactor velocity (mm/s)</th>
<th>Peak stress (GPa)</th>
<th>Initial density (g/cm³)</th>
<th>Calculated density (g/cm³)</th>
<th>Measured density (g/cm³)</th>
<th>Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al 6061-T6</td>
<td>1.455</td>
<td>12.37</td>
<td>2.736</td>
<td>3.067</td>
<td>3.070</td>
<td>0.1%</td>
</tr>
<tr>
<td>2</td>
<td>Al 6061-T6</td>
<td>1.422</td>
<td>13.36</td>
<td>2.776</td>
<td>3.060</td>
<td>3.056</td>
<td>0.1%</td>
</tr>
<tr>
<td>3</td>
<td>OFHC Cu</td>
<td>1.30</td>
<td>29.50</td>
<td>5.928</td>
<td>10.30</td>
<td>10.28</td>
<td>0.2%</td>
</tr>
<tr>
<td>4</td>
<td>OFHC Cu</td>
<td>1.249</td>
<td>27.06</td>
<td>8.929</td>
<td>10.241</td>
<td>10.28</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
Solid-Solid Phase Transitions in Iron

Fe Target

Shock

Phase Transition

Al Flyer

Ambient crystal
1D elastic phase
3D plastic phase
New phase
voids

Shock drive
Release wave

Shock velocity vs. Pressure

Piston velocity vs. Pressure

Taylor Wave EOS Measurements

Shock position measured in each radiograph combined with time between radiographs provides a shock velocity measurement as a function of time.

Infer density jump from measurement of relative transmission.

As the Taylor wave traverses the tin sample the peak shock pressure decreases, providing a measurement along the Hugoniot.

Marsh S P (ed) 1980 LASL Shock Hugoniot Data
- present experiment

Phase Transition

Los Alamos
pRad has been used to study the failure of materials driven by point detonated high explosives.

Experiments were aimed at extending VISAR measurements below the leading spall layer.

Proton radiographs reveal that the deepest damage layers are not well defined.

Multiple pRad experiments show that damage formation deep within the metal is "statistical" in nature and dependent on metal.
Static Objects Surrogate Fuel

Rods

X3 magnifier has T126 ~ 3 meters
E-Loss through object center ~ 13 MeV → resolution ~ 0.5mm at center
Set the Lens to <E_Loss> ~10MeV → 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^8θ*(dE/E)

Thickness of Lucite Degrader

E-Loss across Bare Object

E-Loss across Object + Degrader
The Set up

Zarcaloy tube was aligned on the graded degrader. Radiograph pictures were taken at 181 rotational positions.
Areal Density
CT Reconstruction: Minimize ring artifacts by assuming that the zarcaloy 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
Filtered Back Projection:
Defects in Pellet #4, Slices 78 to 93

Fainter 250 μm long by ~150 to 200 μm diameter inclusions are shown in the circles.

Resolution ~ 80 μm
Diameter_{inclusion} ~ 350 μm
Length_{inclusion} ~ 550 μm
More Defects in Pellet #4: Slices 131 to 142

Diameter_{Inclusion} ~ 225 \mu m
Length_{Inclusion} ~ 450 \mu m
More Defects in Pellet #4: Slices 152 to 160
Resolution Limits of Proton Radiography

1. **Object scattering** - introduced as the protons are scattered while traversing the object.
2. **Chromatic aberrations** - introduced as the protons pass through the magnetic lens imaging system.

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**Object Scattering**

**Chromatic Aberrations**

![Diagram showing proton scattering and chromatic aberrations](image)
Object Scattering Blur

2.5 lp/mm

Sigma = 0.061 mm

Sigma = 0.150 mm

Resolution Pattern at Object Location

\[
\sigma_o = \frac{1}{\sqrt{3}} \frac{\theta}{2} = \frac{14.1}{\sqrt{6}} \frac{1}{PB} \sqrt{\frac{t^2}{x_o}} \propto \frac{l_{safe}}{P}
\]

Los Alamos
Chromatic Aberrations

Set the lens to focus 800 MeV protons

Insert an object which results in 20 MeV of energy loss (~1 cm of Pb).

The focal length of the lens is shortened, resulting in blur at the image location.

Blur is proportional to:

$$\Delta x = T_{126} \phi \delta$$

- $T_{126}$ - chromatic length
- $\phi$ - scattering angle within the object
- $\delta$ - fractional deviation from focus energy
Effect of Chromatic Aberrations on Resolution

Objects of varying thickness result in a position dependent energy loss.
The imaging lens can only be focused for one energy loss. This results in a position dependent blur function.
The blur function is correlated to the object thickness.
Limb: To outline in clear sharp detail

Like phase-contrast radiography:
- Useful to enhance edges
- Problem for density reconstruction

Resolution proportional to energy offset

\[ \sigma = C \frac{E - E_f}{E_f} \theta \]

780 MeV \hspace{1cm} 800 MeV

Protons

Focus on high energy protons

Low + High
Example: Focused on high energy protons

Focus on high energy protons

Low Energy

High Energy (focus)

Low

Low + High

Los Alamos
Thin Lens Approximation

\[
\begin{pmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{pmatrix} = \begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix}\begin{pmatrix}
\frac{1}{(1+\delta)f} & 0 \\
0 & 1
\end{pmatrix}\begin{pmatrix}
1 & 1 \\
0 & 1
\end{pmatrix}\begin{pmatrix}
\frac{1}{(1+\delta)f} & 0 \\
0 & 1
\end{pmatrix}\begin{pmatrix}
1 & 2f \\
0 & 1
\end{pmatrix}\begin{pmatrix}
\frac{1}{(1+\delta)f} & 0 \\
0 & 1
\end{pmatrix}\begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix} = \begin{pmatrix}
-1 & 0 \\
0 & -1
\end{pmatrix}
\]

To make an identity lens

\[ f = \sqrt{ls} \]

Chromatic blur is \sim proportional to lens length

\[ \frac{dM_{12}}{d\delta} = T_{126} = 4(l + s) \]
Thin Lens Approximation

\[
\begin{bmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -2(1+\delta)f & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 2(1+\delta)f & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/(1+\delta) & 1 \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}
\]

\[
f = 2\sqrt{\frac{lm s + (m - 1)s^2}{m + 1}}
\]

\[
z = lm + 2(m - 1)s
\]

\[
b = \frac{2s (lm + (m - 1))}{m(l + 2s)}
\]

\[
\frac{1}{m} \frac{dM_{12}}{d\delta} = \frac{T_{126}}{m} = \frac{m + 1}{m^2( lm + (m - 1)s)} \left[ (2l^2 m^2 + lm(5m - 3)s + 2(m - 1)s^2 \left( (2m - 1) + \sqrt{(m + 1)(lm + (m - 1))} \right) \right]
\]

Chromatic blur is a complicated function of lens spacing

\[
\frac{T_{126}}{m} \approx 2l + \frac{l}{m} \quad \text{In the limit that} \quad \frac{s}{l} \ll 1
\]
Chromatic Aberration and Resolution

- **Identity Lens**
  - 12 inch lens
  - Station 1: 178 \( \mu m \)
  - Station 2: 280 \( \mu m \)
  - Gaussian blur function.
  - 120 mm field of view

- **X3 Magnifier**
  - 4 inch lens
  - Station 1: 65 \( \mu m \)
  - Gaussian blur function.
  - 44 mm field of view

- **X7 Lens**
  - 1 inch lens
  - Station 1: 30 \( \mu m \)
  - Gaussian blur function.
  - 17 mm field of view

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Solid-Solid Phase Transition in Iron

(X3 Magnifier)

Improvement in resolution can be seen from this comparison of radiographs from the identity lens to an equivalent thickness of iron.

Identity Lens \( \frac{\Delta P}{P} = 8.7\% \)

X3 Magnifying Lens \( \frac{\Delta P}{P} = 8.1\% \)

copper

Iron
Results of Scaling 800 MeV Resolution

Resolution: RMS of a ~Gaussian distribution
No Detector Blur

High Explosives

Uranium

Proton Energy (GeV)

Resolution (microns)

4 GeV Protons
25-350 micron resolution in HE
25-1000 micron resolution in Uranium

20 GeV Protons
2-100 micron resolution in HE
2-350 micron resolution in Uranium

Los Alamos
Combine Higher Energy with Magnification

800 MeV Proton Radiography

Thin object resolution: 1mm of iron

Magnification at high energy could result in high resolution (<1 micron?) with a 20 mm field of view
PRIOR Collaboration

4.5 GeV protons
X4 magnification
<10 micron resolution

Proton Microscope for FAIR

GISIT, Los Alamos National Laboratory
Ion Driven WDM Studies at FAIR

A dedicated 90° beam line from SIS-18 for radiography:

- $4.5 \text{ GeV, } 5 \times 10^{12}$ protons or
- $2 \text{ GeV/u, } 10^{11}$ heavy ions

Challenging requirements:
- up to $\sim 20 \text{ g/cm}^2$, high-Z targets
- $< 10 \mu \text{m}$ spatial resolution
- $10 \text{ ns}$ temporal resolution (multi-frame)
- sub-percent density resolution
Intermediate Step

Design, build and commission a magnifier for 4.5 GeV proton radiography to use SIS-18 beam at GSI. Study dynamic systems driven by explosives or pulsed power. This allows opportunity for dynamic materials science experiments that can use the higher resolution of the 4.5 GeV beam as well as commissioning the magnifier system for installation at FAIR.

Proton trajectories through the baseline PRIOR lens design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>4.5 GeV/c^2</td>
</tr>
<tr>
<td>Inner aperture D_i</td>
<td>30 mm</td>
</tr>
<tr>
<td>Outer aperture D_o</td>
<td>100 m</td>
</tr>
<tr>
<td>B_{pole tip} field</td>
<td>1.1 T</td>
</tr>
<tr>
<td>Gradient</td>
<td>115 T/m</td>
</tr>
<tr>
<td>“short” quad length</td>
<td>165 mm</td>
</tr>
<tr>
<td>“Long” quad length</td>
<td>330 mm</td>
</tr>
<tr>
<td>L_1 (object to first quad)</td>
<td>1.3 m</td>
</tr>
<tr>
<td>L_2 (first to second)</td>
<td>0.307 m</td>
</tr>
<tr>
<td>L_3 (second to third)</td>
<td>0.515 m</td>
</tr>
<tr>
<td>L_4 (last quad to image)</td>
<td>7.576 m</td>
</tr>
<tr>
<td>Total length</td>
<td>10.000 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification</td>
<td>4.1</td>
</tr>
<tr>
<td>C_x horizontal Chromatic length</td>
<td>3.99 m</td>
</tr>
<tr>
<td>C_y vertical chromatic length</td>
<td>3.41 m</td>
</tr>
<tr>
<td>Angular Acceptance</td>
<td>5 mrad</td>
</tr>
<tr>
<td>M_x Horizontal Matching Correlation</td>
<td>-0.45 mrad/mm</td>
</tr>
<tr>
<td>M_y Horizontal Matching Correlation</td>
<td>-0.55 mrad/mm</td>
</tr>
</tbody>
</table>
Proposed Magnifier Installation at GSI

Proposal is to install the magnifier in an existing (HHT) beamline at GSI for dynamic experiments
Potential Schedule for Implementation at GSI

**Time schedule and milestones**

<table>
<thead>
<tr>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>optical design of proton microscope</td>
<td>complete engineering design of the system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ordering &amp; production of PMQ and other components</td>
<td></td>
</tr>
<tr>
<td></td>
<td>assembling GSI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>off-line measurements and alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>commissioning with static objects</td>
<td></td>
</tr>
<tr>
<td></td>
<td>commissioning with dynamic objects</td>
<td></td>
</tr>
<tr>
<td></td>
<td>operation</td>
<td></td>
</tr>
</tbody>
</table>

- approval of the project by GSI management: Q2 2009
- international scientific workshop at GSI: Q3 2009
- ordering production of main components: Q4 2009
- submitting first beam time applications: Q2 2010
- assembling and off-line measurements: Q4 2010
- commissioning with static objects: Q1 2011
- commissioning with dynamic objects: Q2 2011
Forward Model Simulations of the PRIOR Magnifier

0.5 mm Cylinder of Copper

100 μm

Derivative of the transmission

Line Spread Function

Gaussian Line Spread Function
3 μm RMS resolution
Prediction with no noise

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Areal Density Sensitivity

\[ FOM = \frac{\Delta N / \sqrt{N}}{\Delta l / l} = \frac{l}{\sqrt{N}} \frac{dN}{dl} \]

Goal:
- 1% density resolution in 10 μm pixel size

Challenges:
- Peak proton current delivered by the SIS-18
- Detector system with high quantum efficiency
Conclusions

- Los Alamos is using proton radiography for dynamic materials science.
- Multi-pulse proton radiography has turned into a useful radiographic probe for dynamic as well as static measurements.
- The next gain in capability will come from combining multi-GeV protons with magnifying lens systems
  - GSI will demonstrate this new capability