Title: Advances in Proton Radiography

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Intended for: Khariton Readings, Sarov Russia 3/14-3/18/2011
Advances in Proton Radiography

Los Alamos National Laboratory has used high energy protons as a probe in flash radiography for a decade. In this time the proton radiography project has used 800 MeV protons, provided by the LANSCE accelerator facility at LANL, to diagnose over three-hundred dynamic experiments in support of national and international weapons science and stockpile stewardship programs. In addition, 24 GeV protons, provided by the Alternating Gradient Synchrotron at Brookhaven National Laboratory, have been used to study the capability of proton radiography at higher beam energies. Through this effort significant experience has been gained in using charged particles as direct radiographic probes to diagnose transient systems. The results of this experience will be discussed through the presentation of data from experiments recently performed at the LANL pRad facility as well as results from previous electron radiography work performed at the Idaho Accelerator Center.
Advances in Proton Radiography

Khariton Readings

March 14, 2011

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Los Alamos National Laboratory
800 MeV Proton Radiography
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Los Alamos
NATIONAL LABORATORY
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Los Alamos Neutron Science Center
Area C Dome
Contained Dynamic Experiments

- Fe Vessel
- 1 m radius
- 5 cm wall
- <4.5 kg/shot
- 2 shots/week
- 3 weeks/month
- 6 months/year
pRad at LANSCE

- Collimator
- Object Location
- Identity Lens
- Matching Quads
- Lens 1
- Lens 2
- Lens 3
- Image Locations

LANSCE Beam

Diffuser

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When is an object too thick?

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

- 10% is near the lower limit of reasonable transmission.
800 MeV Linac Timing Capabilities

42 radiographs per dynamic

Developing flexibility for “asynchronous” dynamic events

Beam Available

Arbitrary wave form

±2 ms

1 ms
High Dynamic Range

Tantalum Foils:

1 μm  1.66 mg/cm²
2 μm  3.32 mg/cm²
4 μm  6.64 mg/cm²
9 μm  14.94 mg/cm²
25 μm 41.50 mg/cm²
50 μm 83.00 mg/cm²
Thick Tantalum Step Wedge (Dynamic Range)

Focus relative to beam energy

-15%  -12%  -9%  -6%  -3%  0

-2% Transmission through thickest step. Could be increased to ~15%.

50% transmission through thinnest step. Would increase to 99% (with 5mRad collimator).

Dynamic range (both Transmission and focus) is a stretching 800 MeV radiography capabilities.

Half the dynamic range fits well.
High Energy Protons are Ideal for Thick Objects

FOM=Figure of Merit

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

\[
N = N_0 e^{-l/\lambda}
\]

\[
FOM = \sqrt{N_0} \frac{l}{\lambda} e^{-l/2\lambda}
\]

FOM is maximized when \( l = 2\lambda \)

X-rays, \( \lambda = 25 \text{ g/cm}^2, l_{\text{opt}} = 50 \text{ g/cm}^2 (4 \text{ MeV}) \)

Protons, \( \lambda = 185 \text{ g/cm}^2, l_{\text{opt}} = 370 \text{ g/cm}^2 (>5 \text{ GeV}) \)
Richtmyer-Meshkov Instability Studies

Photon Doppler Velocimetry

Vacuum 5 bar Xe 5 bar He

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Equation-of-state measurements

- Metal target
- 0.5" diameter steel ring may be affixed around the assembly here (holds HE and target together)

PBX-9501 disk (3 g)

Slow component: TNT (8 g)
Fast component: PBX-9501 (17 g)

P25 lens

Graph: $\frac{p}{p_0}$ vs. $u_s (\text{km/sec})$
Filtered Back Projection:

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

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Combining Higher Energy with Magnifiers

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

GSI
Institute of Problems for Chemical Physics
Institute for Theoretical and Experimental Physics
Los Alamos National Laboratory
Technische Universitat Darmstadt

Proton Microscope for FAIR
Facility for Antiproton and Ion Research

Existing facility
Darmstadt, Germany

HEDgeHOB collaboration
performing ion generated
high energy density

Planned Upgrade
Proton Microscope and Ion Heating at FAIR

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

4.5 GeV Proton Microscopy

Proton trajectories through the baseline PRIOR lens design.

Lens and detector design goals
(in accordance with FAIR pRad specifications):
- less than 10 μm spatial resolution;
- sub-percent density resolution;
- target areal density up to 5 – 50 g/cm², high-Z targets;
- temporal resolution <10 ns (for FAIR), <100 ns (for GSI);
- field of view: 20 mm;

Dynamic experiment design goals:
- HE experiments: GSI is certified for up to 100 g TNT loads;
- HE containment: already available at GSI “red Russian” vessel Beam pipe downstream of the vessel will be a part of the containment system;
- vacuum system capable of achieving < 1 mbar vacuum in containment system.
Intermediate Installation at GSI

Proposal is to install the magnifier in an existing (HHT) beamline at GSI for dynamic HE driven experiments.
Forward Model Simulations of PRIOR Microscope

0.5 mm Cylinder of Copper

100 μm

Line Spread Function

- Gaussian Line Spread Function
- ~8 μm FWHM resolution
- Prediction with no noise
4.5 GeV Protons Available at FAIR

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

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

Challenging requirements:
- up to \(~20\) g/cm\(^2\), high-Z targets
- \(<10\) \(\mu\)m spatial resolution
- 10 ns temporal resolution (multi-frame)
- sub-percent density resolution
Resolution limits

**CCD (1 frame)**
- Total Resolution: 47 µm
- Camera Resolution: 41 µm
- Limit: Fast Gated Diode
- DQE: 15%
- 2000 x 2000 Pixels

**Hybrid Si-CMOS (18 frames)**
- Total Resolution: 70 µm
- Camera Resolution: 65 µm
- Limit: Pixel Count
- DQE: 80%
- 700 x 700 Pixels

**Image Plate**
- Total Resolution: 41 µm
- Detector Resolution: ~41 µm
- Limit: Exposure time
- DQE: ~100%

Hard to increase DQE of fast gated CCD cameras (limited by photo cathode on diodes), increasing pixel count to 1400x1400 and frames/camera>6 appears straight forward (~$2M).
Next Generation Imagers Improving Resolution and Frame Count

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>pRad-1 Imager</th>
<th>New 2nd Generation pRAD Imager</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum integration time (Global shutter)</td>
<td>150 ns</td>
<td>50 ns</td>
</tr>
<tr>
<td>Nominal min. inter-frame time</td>
<td>358 ns</td>
<td>150 ns</td>
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<tr>
<td>Effective Dynamic Range</td>
<td>11.4 bits</td>
<td>12 bits</td>
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<tr>
<td>Read noise</td>
<td>100 e-</td>
<td>~35 e-</td>
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<tr>
<td>Imaging array size</td>
<td>720×720 px</td>
<td>1100×1100 pixels</td>
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<tr>
<td>Number of frames</td>
<td>3</td>
<td>10</td>
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<tr>
<td>Pixel pitch</td>
<td>26 μm</td>
<td>40 μm</td>
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<tr>
<td>Sensor QE @ 415 nm</td>
<td>&gt;80%</td>
<td>&gt;90%</td>
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<tr>
<td>Chip size</td>
<td>21×22 mm²</td>
<td>~44×45 mm²</td>
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<tr>
<td>Optical Fill Factor</td>
<td>~100 %</td>
<td>~100 %</td>
</tr>
<tr>
<td>Saturation level/ Well depth</td>
<td>180 ke-</td>
<td>~150 ke-</td>
</tr>
</tbody>
</table>
The goal: Predict dynamic microstructure and damage evolution

The first experiment: Multiple, simultaneous dynamic in situ diagnostics with resolution at the scale of nucleation sites (< 1 μm; ps – ns)

The model: Accurate sub-grain models of microstructure evolution coupled to molecular dynamics
Transmission High Energy Electron Microscopy

Iron Object of Various Thicknesses

~RMS width of “core” through Iron

Object Thickness (mm of Fe) - Resolution (microns)
Layout of Marie