Title: A Proton Radiography Concept at NNSS (U)

Author(s): Robert D. Fulton, Chris Morris, Kris Kwiatkowski, Nick King

Intended for: DOE radiography workshop

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.
Abstract for “A Proton Radiography Concept at NNSS”(U)

Experience in 800MeV dynamic proton radiography at the Los Alamos LANSCE facility coupled with a series of static measurements completed at the Brookhaven AGS at 24GeV/c have resulted in obtaining a good understanding of the anticipated performance of a facility tailored to meet future radiography requirements at the NNSS. This is to a large degree an update to a previous study completed in 2004 addressing the same topic.

A more complete analysis of the AGS data, a comparison of test object results between current x-ray and proton radiography capabilities, and more dynamic results relevant to scaling and surrogacy issues are included. Strong evidence is provided to indicate proton radiography can meet or exceed current radiographic requirements for a future facility in a timely and cost effective manner.
A Proton Radiography Concept at NNSS
Unclassified slides

Doug Fulton
Chris Morris, Kris Kwiatkowski, and Nick King
5/4/2011
Proton Interactions

Proton Radiography

Energy Loss
Changes focus; causes blur

Nuclear Interaction
Attenuation; used for material i.d.

Coulomb Scattering from Nucleus
Scattering used to measure density
Contrast from Multiple Coulomb Scattering

Incident Beam → After Object → After Collimator → Measured transmission provides information of object thickness

Transmission

\[ T = e^{-\frac{\theta p E}{14.1 \text{MeV}}} \left( 1 - e^{-\frac{x_o}{2x}} \right) \]
LANSCE 800 MeV proton radiography facility (U).

Beam prep  Collimator  Object  Collimator  Image 1  Collimator  Image 2

Confinement vessel

Proton Radiography
Science Based Stockpile Stewardship
An example of the concept at BNL/AGS

AGS accelerator at Brookhaven

Proton Radiography Line U

RHIC

255m

24 GeV/c protons
30 ns long pulses
$5 \times 10^{10}$ protons per pulse

pRad magnetic imaging lens system in Line U Tunnel
Schematic Layout of Accelerators
(dimensions in meters)

11 MeV linac
15 mA H- ions

500 MeV Booster
56 m circumference
8 dipoles, 16 Quads
2 GeV transition energy

20 GeV Main Ring
608 m circumference
56 dipoles @ L=5 m.
76 quadrupoles @ L=0.8 m
Up to 10 bunches in the ring
10 ns long pulses
5-10 \times 10^{10} protons per pulse

Proton energy determines ring size;
Ring size determines orbit time;
Orbit time / kicker time determines # of pulses

Notional proton pulse exiting ring
Detector Technology: Two-Component CMOS-Hybrid

- Independent optimization of detector and readout IC
- QE -84-95% (400-900 nm), ~100% optical fill factor
- Fast 150ns CMOS shutter, 250 ns inter-frame time
- Excellent extinction ratio; 3-frame in pixel storage

(1) Photo-Sensor Pixel Array (photon-charge conversion)

- 7 cameras (720x720 px) built & in use since 2005 (prototype $1.16M)
- 2nd gen (1100x1100 px) in design stage

(2) CMOS Readout IC (ROIC): charge-to-voltage conversion, signal storage & processing, logic and A/D conversion

System on Chip: photons-to-bits
## Existing vs. 2nd Gen CMOS Hybrid Imager

We are evaluating the use of the 2nd generation imager on DARHT.

<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>
</tr>
<tr>
<td>Effective Dynamic Range</td>
<td>11.4 bits</td>
<td>12 bits</td>
</tr>
<tr>
<td>Read noise</td>
<td>100 e-</td>
<td>~ 35 e-</td>
</tr>
<tr>
<td>Imaging array size</td>
<td>720×720 px</td>
<td>1100×1100 pixels</td>
</tr>
<tr>
<td>Number of frames</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>26 μm</td>
<td>40 μm</td>
</tr>
<tr>
<td>Sensor QE @ 415 nm</td>
<td>&gt;80%</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Chip size</td>
<td>21×22 mm²</td>
<td>~44×45 mm²</td>
</tr>
<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>
Reducing the Risks

Low risk – demonstrated technology
Medium risk – modification of existing technology
High risk – new technology

Window 80 cm from Object (window resolution is inversely proportion to window radius)

<table>
<thead>
<tr>
<th>Model</th>
<th>1.0 mm</th>
<th>2.0 mm</th>
<th>3.0 mm</th>
<th>1.5 mm</th>
<th>0.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>No window</td>
<td>σ=0.01</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>2.5 cm Aluminum</td>
<td>σ=0.027 cm</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>2.5 cm Steel</td>
<td>σ=0.061 cm</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td></td>
</tr>
</tbody>
</table>

We believe the schedule risk continues to be high.
Backup
pRAD-2 10-frame imager for 800MeV pRAD at LANSCE – Project Status

2nd gen CMOS-hybrid: 10-frame capability, improved resolution (1.2Mpx), excellent QE, 50ns shutter, good radiation resistance

- Total estimated cost of prototype development $3.5M (two camera systems will be delivered)

- As of April-2011, CMOS readout chip (ROIC) design is 90% completed; $160k to finished (funded, PO to Teledyne underway)

- Next step: ROIC chip fabrication - min. needs 10-wafer CMOS run at TowerJazz Semiconductor; then testing (TIS). Partially funded (PR in purchasing) - $417k and $271k; needs additional $270k for second CMOS run and automated wafer probing

- Funding for FY12 to complete the project: $2M (will cover: pixelated photo-sensor fabrication, bump-bonding to ROIC, digital logic controller, dewar, TEC cooling, lenses, acquisition software,...). Does not include any contingency.