Designing a Fast-Gated Scintillator-Based Neutron and Gamma Imaging System

Advanced Imaging Team
P-23 Neutron Science & Technology

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Verena Geppert-Kleinrath, Matthew Freeman, Frank Merrill, Petr Volegov, Carl Wilde

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Summary

1. The Advanced Imaging team has been providing neutron images of inertial confinement fusion processes at the National Ignition Facility since 2011

2. Two additional neutron & gamma lines-of-sight plus advanced reconstruction techniques will deliver 3D shape information

3. Building two new imaging systems drives necessity for careful design study at LANSCE & OMEGA

4. Focus on monolithic scintillator design over a fiber array for better resolution, light output & noise properties
• The neutron imaging system at NIF

• Designing new systems for 3D reconstruction

• Scintillator characterization campaigns at LANSCE & Omega

• Light output, resolution, and noise results

• An ultra-fast imaging cell for a short line-of-sight
Neutron production is a direct indicator for fusion – making neutron imaging a powerful diagnostic

\[ ^2_1 \text{D} + ^3_1 \text{T} \rightarrow ^4_2 \text{He} + ^1_0 \text{n} \]

Deuterium-tritium capsules are compressed and heated using laser drive resulting in fusion inertial confinement fusion ICF.

- 6-12 MeV Neutrons
- 14.1 MeV Neutrons
- 4.4 MeV $\gamma$
The current Neutron Imaging System at NIF – NIS1 has been providing images since 2011

- Fast-gated imaging recording both sides of a scintillator
- Use time-of-flight to gate on fusion or down-scattered neutrons
- We image a 100 micron source from 28 m distance!
Planning two additional lines-of-sight: 3D neutron imaging provides hot spot and fuel density

3D Hot Spot

Cold Fuel Density Distribution

& Down-Scattered Image

Structure of the compressed shell becoming clearer => Transformative result for NIF!

3D reconstruction algorithms in place

The baseline design for a dual line-of-sight: Two lens-coupled scintillators and three cameras

Scintillator is key design part for active system!

- high spatial resolution
- enough neutron interactions & light
- fast decay – little afterglow

Fiber scintillator drawbacks:

• Costly, difficult to procure
• Fixed pattern noise
• Dead space (packing fraction 60-70%)
• Light loss in extramural absorber
• Co-registration issue
LANSCE beam time allowed extensive design study in house to test various scintillator materials

OMEGA 60 at LLE
14 MeV fusion neutrons
High yield glass capsules

WNR/LANSCE at LANL
800 MeV proton accelerator
tungsten spallation target
Pulse structure (1.8 micros) -> TOF

1.5*10^{14} yield shot at OMEGA = ~20 min at LANSCE WNR
Prototype tests with commercial lens to fully characterize over 20 different scintillators

22 scintillators studied - fiber vs monolithic (Plastic, liquid, deuterated, 0.2 to 5 cm thickness)

Lens (Canon f#1.8) coupled with 25mm Photek MCPII and SI800 CCD

Liquid VI imaging cell developed with Eljen Technology

CEA deuterated liquid glass capillary array
A monolithic scintillator outperforms pixelated arrays when light is collected with a lens.
Fiber array introduces fixed pattern noise and requires a flatfield correction.

Fiber array needs to be flatfielded (1/yr at NIF)
Uncertainty still larger than monolithic
Considerations for shorter polar line-of-sight:
Liquid VI is fast enough to move to 12 m

Magnification is similar = resolution ok
Liquid VI 30% of light output
~ half distance = 4x neutrons/ pixel -> light ok

Ratio of light in down-scattered (6-12 Mev) vs primary window (13-17 MeV)

<table>
<thead>
<tr>
<th>Distance</th>
<th>Liq-VI</th>
<th>EJ232</th>
<th>BCF99-55</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 m</td>
<td>0.6%</td>
<td>2.1%</td>
<td>1.8%</td>
</tr>
<tr>
<td>12 m</td>
<td>1.8%</td>
<td>2.9%</td>
<td>8.0%</td>
</tr>
</tbody>
</table>

Summary

1. Advantages of monolithic scintillators for flash neutron imaging
   - 2x light of 5 cm fiber, equal resolution, equal DQE at 2 cm thickness
   - Better SNR, no co-registration issue
   - cost (<1k vs 500k), simple design -> allowing multiple LOS

2. Flexible options thanks to monolithic design (Liquid VI cell)

3. Using LANSCE allowed extensive design study for novel NIS

4. Upcoming work:
   - NIF prototype, lens design, gamma scintillator study
Thank you for your attention!

Advanced Imaging Team
P-23 Neutron Science & Technology
The National Ignition Facility (NIF)

NIF is the largest laser source in the world (& a Star Trek movie set)

192 lasers deliver ~1.5MJ to the x-ray producing hohlraum
~150kJ absorbed by 1 mm target capsule

Lawrence Livermore National Laboratory

Paramount Pictures
Planning two additional lines-of-sight: Asymmetric drive simulation shows benefits of 3D neutron imaging

2 additional lines-of-sight (LOS) with active scintillator detectors planned at NIF
Gamma ray imaging (GRI) will be added to new LOS
Fiber is less bright than originally assumed

2 cm monolithic plastic is 2 times brighter than 5 cm thick fiber
DQE is ~equal if considering packing fraction
Light per MeV deposited is 70% for fiber versus monolithic
Fraction of light collected by lens is equal
Fiber is only 65% as bright as expected

if lens acceptance is smaller than fiber emission angle, collection is the same (~1% for our main testing lens) for fiber and monolithic
Extra mural absorber dims fiber light emission

moving \(^{90}\)Sr source

PMT uncoated coated fiber

single fiber experiment moving radioactive source (up to 2.25 MeV beta)

shows effect of extra mural absorber

30% intensity reduction additional surface roughness effects possible (up to 20%)

Edge spread function determines spatial resolution

- 5 cm fiber
- 2 cm monolithic
- 2 cm Liquid VI

- $\sigma = 0.43 \pm 0.005$ mm
- $\sigma = 0.47 \pm 0.015$ mm
- $\sigma = 0.33 \pm 0.011$ mm
Higher absolute noise in fiber

Noise power spectrum shows artifacts related to fixed pattern noise even after flatfield correction.
Noise study: Power spectrum density vs thickness

EJ204 plastic
1, 2, 3 and 4 cm NPS evolution
Lens design for monolithic scintillator requires large depth-of-field across field of view & telecentricity.

Numerical aperture f# < 2.5 to collect > 100 photons/neutron optical blur < 200 micron.

Matlab Optometrika for preliminary ray tracing.
Lens design for thick scintillator: telecentric

Telecentric lenses remedy off-axis effects for thick scintillator

Magnification independent of object distance

Circle of confusion optical blur depends on scintillator thickness and refractive index, and lens NA

\[ n_i \sin \theta_i = n_j \sin \theta_j \]

\[ \theta_{accept In} = \sin^{-1} \left( \frac{NA_{lens}}{n_i} \right) \]
Optical depth of field (circle of confusion) varies with f#}

- **f#1.8 lens** has highest optical resolution, steep DOF
- **f#6.7 lens** has same highest resolution, very wide DOF
- **f#1.4 lens** has lower optical resolution, ok DOF

**NIS1 lens:** ~ 200 micron resolution at +- 100 micron DOF
**NA 0.15 f# ~ 3.3**