Gated Neutron Image at the NIF

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Lawrence Livermore National Laboratory

Image system statistics are determined by three principle components

$$N_{\det} \sim S_N * \varepsilon_{acc} * \mathrm{DQE}$$

- S_n = the strength of the source producing the image, i.e. Yield
- ε_{acc} = the imaging system resolution element acceptance.
- DQE = the detective quantum efficiency of the resolution element.
  - DQE is the efficiency of the detector, corrected by its statistical performance, i.e.: $DQE = \left(\frac{SNR_{out}}{SNR_{in}}\right)^2$

Resolution element acceptance/signal is comprised of 3 components as well..

1. Aperture acceptance: $\varepsilon_{ap} \sim \mu \left(\frac{\delta_{ap}}{d_{obj}} \right)^2$

   δ_{ap} the “effective” aperture “diameter”
   d_{obj} is the object distance
   μ is the aperture multiplexing ~4.

2. Subdivison into resolution elements: $\varepsilon_{res} \sim \left(\frac{\delta_{res}}{R_{src}} \right)^2$

   δ_{res} is the system resolution
   R_{src} is the source radius
   μ is the aperture multiplexing

3. Intensity of the resolution element:
   1. For a uniform emitter: $I(x) \sim \sqrt{1 - \left(\frac{r}{R_{src}} \right)^2} = \sqrt{1 - x^2}$

      The 17% contour occurs at x = 0.98.

4. For primary NI, resolution element signal may be approximated by:

$$\varepsilon_{acc}(x) \sim \mu \left(\frac{\delta_{ap} \delta_{res}^{sp}}{4 d_{obj} R_{src}} \right)^2 \sqrt{1 - x^2}$$

For nuclear imaging, Yield is the principle lever for improving SNR.

$$SNR_{NI} \sim \frac{\delta_{ap}\delta_{res}^{sp}}{d_{obj}R_{src}}\sqrt{Y_n \cdot DQE}$$

- Resolution competes with SNR
- Object distance is generally at a minimum.
- Source size is fixed and competes with resolution.
- Some improvements may come through DQE, but these are likely limited.
  - Typical nuclear imaging system DQE's are a few percent.

CNXI demonstrated that cost savings can result by playing parameters against each other

Image resolution depends on detector location

$$\delta_{res}^{sp} \approx \alpha_{rec} \sqrt{\delta_{ap}^2 + \left(\frac{\delta_{img}}{M}\right)^2} \Rightarrow \sqrt{2}\,\frac{\delta_{img}}{M}$$

$$\Rightarrow SNR_{NI} \sim \frac{\delta_{ap}}{d_{obj} R_{src}} \frac{\delta_{img}}{M} \sqrt{Y_n \cdot DQE}$$

α_{rec} is the recon improvement
δ_{img} is the camera resolution
M is the system magnificaiton

If δ_{img} is decreased, (i.e. CH/IP stacks), then M may be decreased to maintain SNR.

This allowed a substantial savings to NP-NI, by locating the primary detector inside the Target Bay.

This savings could only be realized if the new DQE was comparable to the old, (slightly degraded, but not significant)

What might a gated imager for scattered neutrons on NP-NI look like?

- Deuterated scintillator
- Bare MCP
- CH enhanced MCP
- Pixelated Solid-State

Deuterated Scintillator

- Benefit: Resolution improvement ~2× over CH.
- Image Cost: Scintillation output ~2/3 that of CH, assuming other DQE impacts negligible.
- Magnification required to keep SNR constant:

$$DQE_i \cdot \left(\frac{\delta_{img}}{M_i}\right)^2 = \frac{2}{3} DQE_i \cdot \left(\frac{\delta_{img}}{2M_f}\right)^2 \Rightarrow M_f = \sqrt{\frac{1}{6}} M_i$$

- Comparable performance to (90,315) with detector @ ~1160 cm.
- Other Issues:
  - — Gating of scintillation light – requires MCP or GOI
  - — Scintillation decay – At 1160 cm time
  - — Digitizer shielding

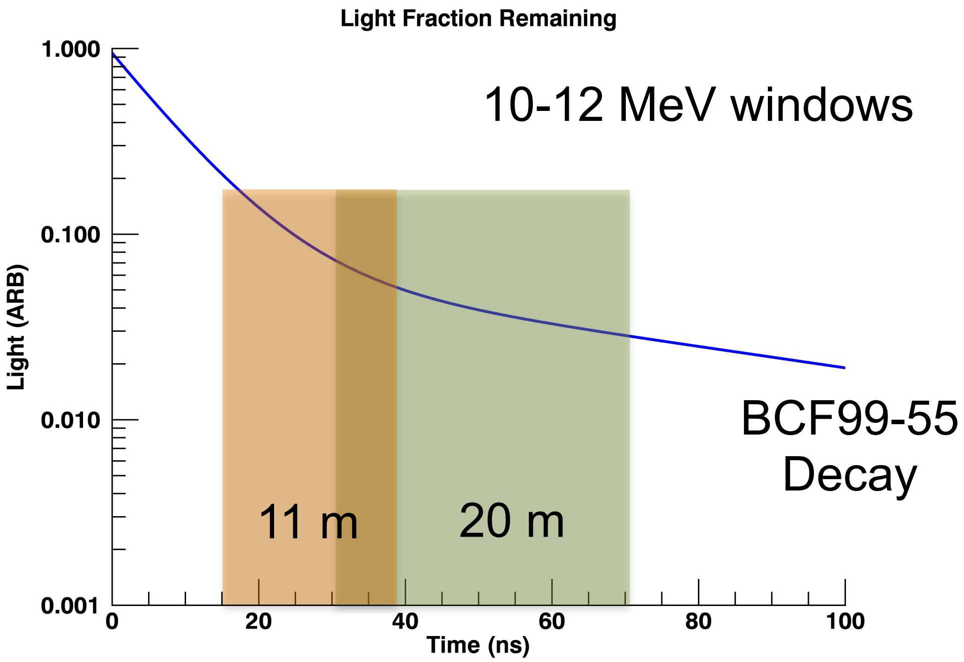
Deuterated Scintillator Issues

Residual light from primary neutrons becomes a more significant correction for shorter flight paths.

(90,315) correction to 10-12 MeV image is ~2% of primary signal.

Moving detector to:

@ 20 m ➔
  4% of primary (100% correction)
@ 11 m ➔
  12% of primary (300% correction)



Scintillation decay speed and characterization needs study

Scintillator trade-offs

- In a scintillator/MCP system, the scintillator provides high interaction probability (~40%), while the subsequent light production, optical relay and photocathode are relatively inefficient ≤ 0.1%, resulting in a DQE which is relatively low, O(≤5%).

- Further, resolution is determined by the recoil range of reactions in the scintillator and its sampling frequency.
  - For (90,315) this is ~700 µm for protons, sampled by 250 µm fibers.
  - The (90,315) measured resolution is ~1.1 mm.

- Why not trade high interaction probability and low efficiency for low interaction probability, but high efficiency?

Low interaction detector options for scattered neutrons

- Direct neutron detection using an MCP
- Enhanced neutron detection using a CH/MCP stack.
- Direct neutrons detection in a pixelated solid-state device.

General properties of these types of detectors

- By construction these detectors will necessarily be relatively thin.
    - — ≤ 10 mm.

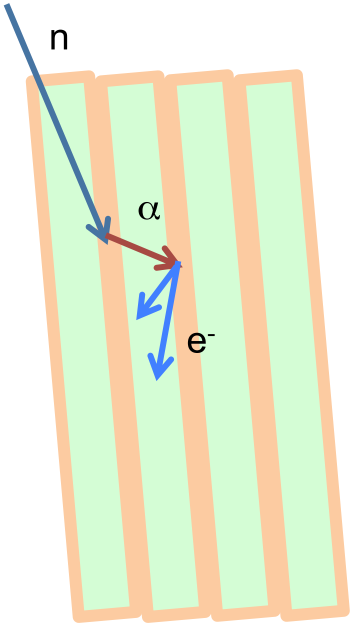
- With densities in the range of 1-3 g/cm^3

- The dominant neutron interaction within these types of detector will be (n,α), with some (n,p) and (n,d) contributing as well.
    - — NB these will be threshold interactions and with energy dependent cross sections that may require care in subsequent analysis.
    - — The thresholds and heavier recoils do provide enhance efficiency and resolution.

- Typical cross sections in the 10-12 MeV range (^{28}Si, ^{16}O, and ^{12}C) are ~0.2 b.

- ***Thus, the range of interaction probabilities will be O(1%)***.

MCP direct detection



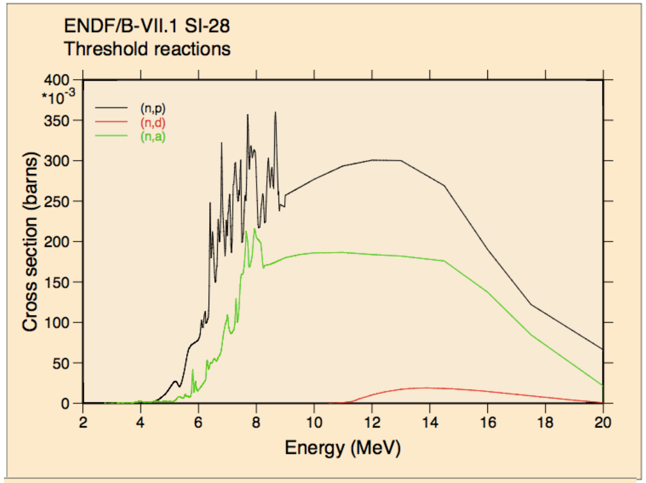
This is an idea that has been running around for some time particularly for thermal neutrons, but the premise is the same.

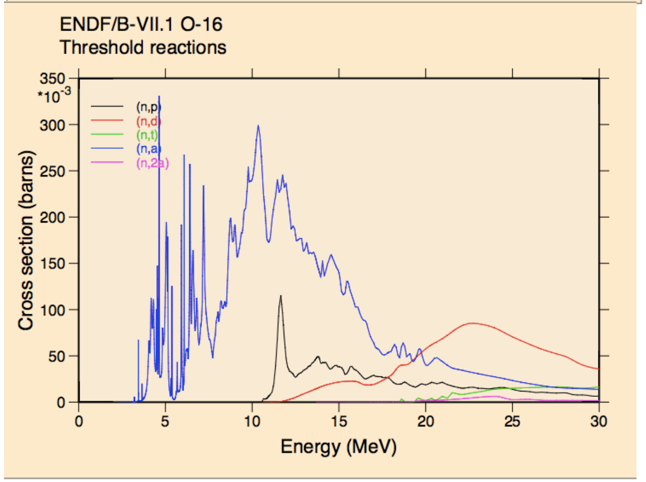
1) Neutrons interact with a nucleus within the channel plate.
2) A recoil proton, deuteron, or alpha particle is ejected into the pore.
3) Secondary electron emission occurs as the charged particle interacts with the surface of the pore.

The advantages of this detector are its speed and resolution.
The disadvantages of this are the small initial interaction probability and DQE for a single detector.

A 1 cm thick MCP detector has ~0.7% interaction probability.

A 1 cm thick MCP plate at 2 g/cm^3 and 50% fill fraction gives a $\rho\Delta L$ of 1 g/cm^2.





Assuming an SiO2 plate with and the following cross sections at 10 MeV:

$$Si(n,p) = 0.25\ b$$
$$Si(n,a) = 0.16\ b$$
$$O(n,p) = 0.25\ b$$

The interaction probability given by:

$$\rho\Delta L*N_a/M_{SiO2}*<\sigma> \approx 0.7\%$$

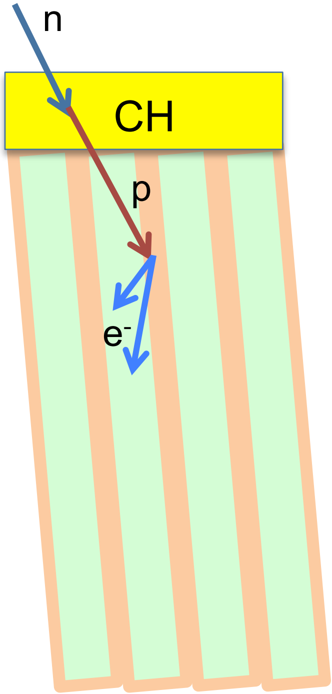
This is ≤ 1/5 the DQE of the (90,315) system.

Issues with the MCP detector

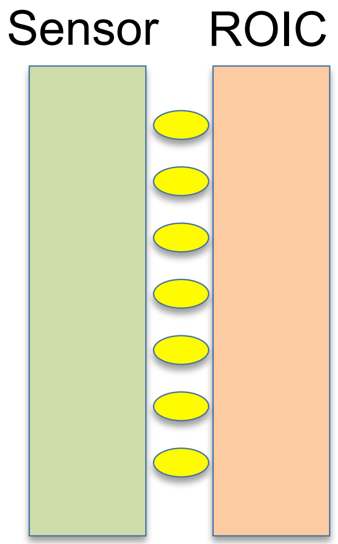
- The low interaction probability means that the resolution element, relative to (90,315), would have to be increased to ensure similar statistical power.
- What was excluded from this calculation was the “depth dependent” detection efficiency which would likely need to be empirically determined, and lower the DQE.
- Similar to the AXIS detector, a 2nd plate could be added to improve efficiency.

The MCP interaction probability could be enhanced with a CH layer.

- To enhance the MCP initial detection, a CH foil could be added to the top of the plate.
- The foil needs to be thin to ensure resolution and recoil protons can escape, so use 2 mm, and assume 1 g/cm^3 density.
- Assume the (n,p) elastic cross section is ~0.7 b
- The interaction probability is ~0.6%
- Thus, total interaction probability would be ~1.3%.
- More detailed study is required to understand resolution and DQE performance.



A pixelated diamond detector would have to be 6.6 mm thick for 1% interaction probability

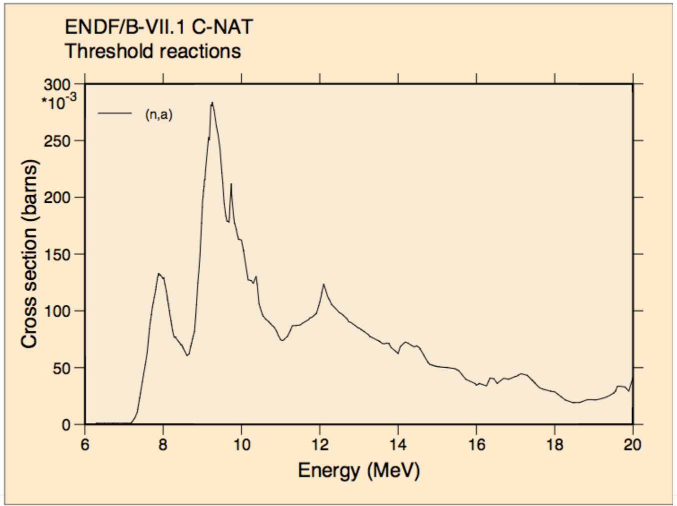


Using a “diamond” sensor as the detector material, with density of 3 g/cm^3.

Assume a principle cross section for producing charged recoils (n,a) of 0.1 b.

Then a 1% interaction probability requires a sensor thickness of 6.6 mm.

This thickness assumes the resulting charge could be fully collected, which has been difficult to prove in the past.



Summary

- Fusion product imaging at the NIF with high resolution is fundamentally limited by yield.
- It is possible to increase the number of diagnostics without incurring great cost, by exploiting trade offs between different aspects of the system.
- Four different types of gated systems were scoped for the NP-NI, each having a different set of issues that require further study.
- Fundamentally, interaction probabilities of non-scintillator systems will be O(1%), limiting the DQE and requiring resolution requirements to be relaxed.