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Development of an intensified neutron camera system for high sensitivity white-beam imaging

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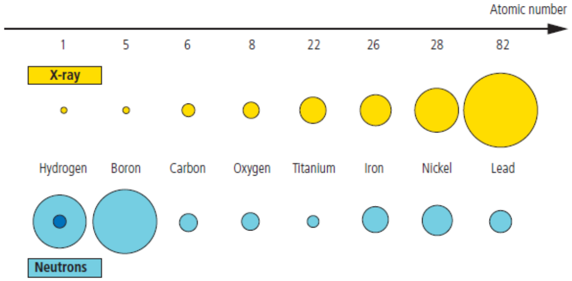
Science & Technology Facilities Council
ISIS

Motivation

Neutron Imaging

- Thermal Neutron radiography is an important tool for materials science, archaeology, nuclear fuel imaging and many other fields
- Thermal neutrons are complementary to x-rays and provide higher sensitivity to low atomic number materials, especially Hydrogen and Carbon, while having excellent penetration of most metals.
- There are a limited number of facilities worldwide with neutron imaging capabilities
- Smaller flux neutron sources including research reactors and neutron generators are under-utilized, partially due to the relatively low sensitivity of existing detector techniques
- To fully exploit this non-destructive evaluation technique requires improved neutron imaging techniques

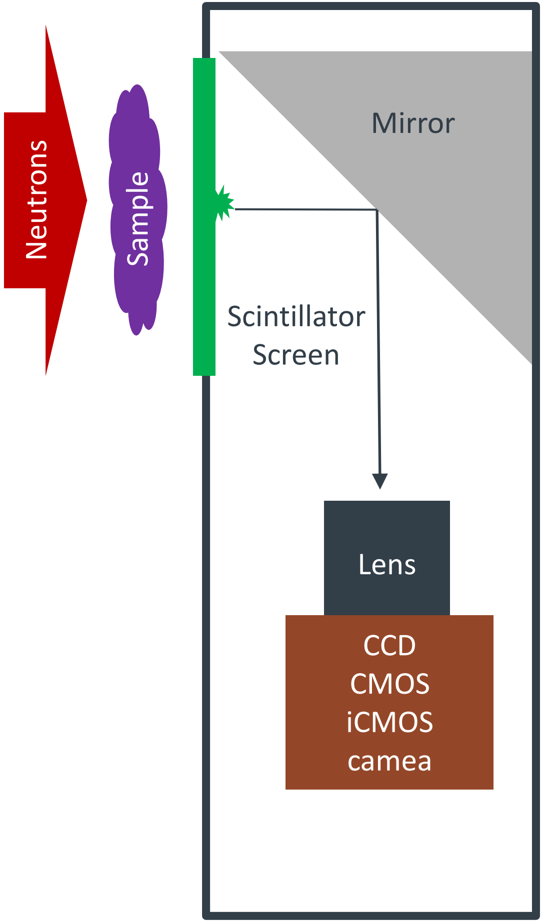


PSI Neutron imaging Brochure 2016

Motivation

Current Limitations

- The most common real-time neutron imaging systems use a scintillator screen lens coupled to a CCD, CMOS or Intensified Camera
- Light collection of the lens is often < 0.1%
- The basic trade-off to be made is resolution vs sensitivity:
  - Gd_2O_2S:Tb (GADOX) is about 100X more efficient at thermal neutron capture than ^{6}LiF:ZnS
    - Resolution can be tens of microns at 50% capture efficiency
    - Lens coupling can reduce light at sensor to < 1 photon/neutron reducing effective sensitivity
  - ^{6}LiF:ZnS is generates about 100X greater light than GADOX per neutron
    - Resolution of hundreds of microns at ~20% capture efficiency
    - Lens coupling provides tens of photons/neutron with smaller impact on sensitivity
- Limited ability for time resolved imaging – energy selective or stroboscopic

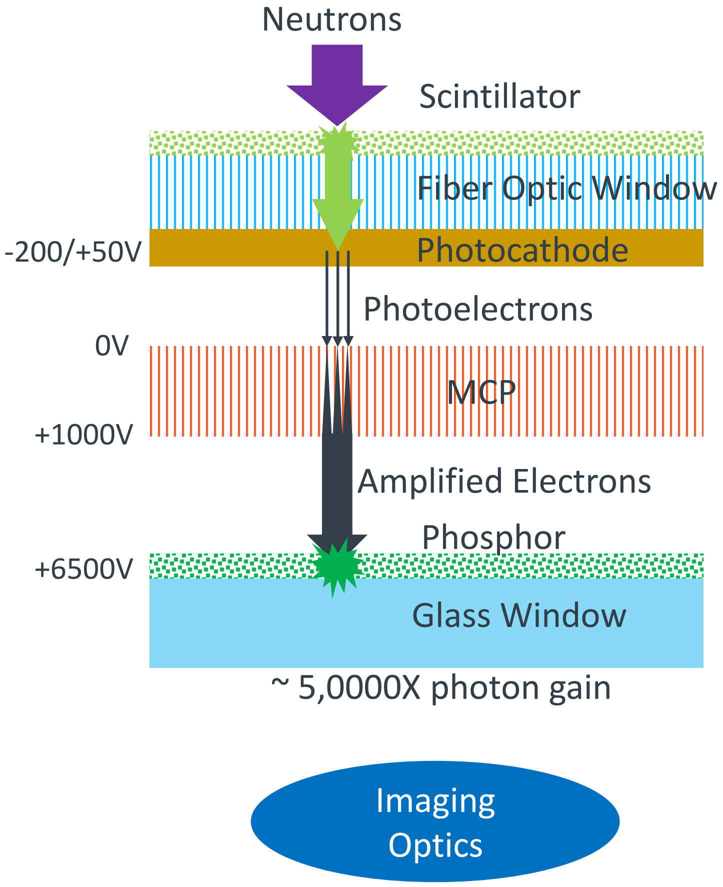


June 28, 2021 iWoRID 2021

Motivation

Intensified Neutron Phosphor Solution

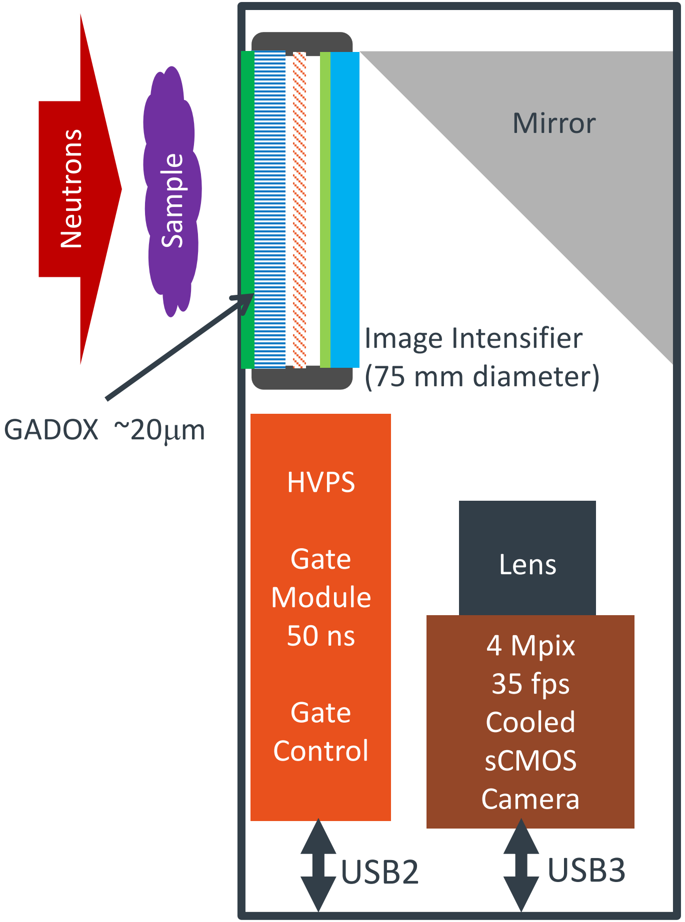
- Image Intensifiers can be made neutron sensitive by adding a scintillator to the input window
- This enables a significant increase in sensitivity by amplifying the light generated in the scintillator prior to imaging by a CCD or CMOS imager
- Imaging optics between a 75 mm detection area and a typical CMOS imager can be < 0.1% efficient and the intensifier compensates for this inefficiency
- GADOX screens can be used for cold and thermal neutrons to simultaneously maximize detection efficiency and resolution
- Can be gated ON/OFF in tens of ns



Camera System

System Description

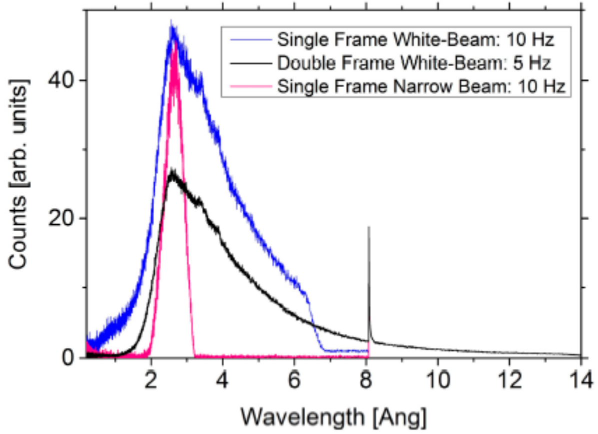
- 7.3 mg/cm^2 Gd_2O_2S:Tb screen, 20 µm thick, no aluminizing
- 75 mm diameter Image Intensifier with Fiber optic input, S20 photocathode, single MCP, P46 phosphor, glass output window
- 45° front-surface mirror bends the optical axis 90° to a Schneider-Kreuznach Componon 2.8/40 macro lens
- Tuscen Dhyana 400D sCMOS camera with 2048 x 2408 6.5 µm pixels, 35 fps, 30,000 e$^-$ full well, 2 e$^-$ noise and -15°C cooling controlled via USB3 (38µm pixel at GADOX for 75 mm FOV)
- Intensifier bias voltages provided by modular High Voltage Power Supply with integral 50 ns cathode gating and controlled by asingle board Gate Control Unit (GCU) controlled via USB2
- A beam synchronization pulse input to the GCU



ISIS Beam Test

Beam Test Parameters

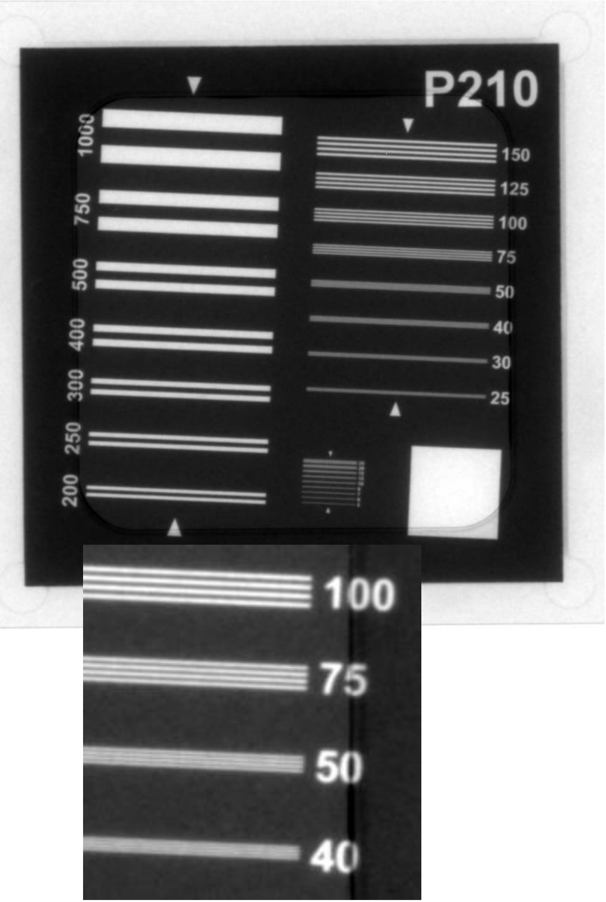
- A beam test was performed in December 2019 at the IMAT cold-neutron imaging facility of Rutherford Appleton Labs ISIS pulsed neutron source
- The single frame white-beam setting was used, the blue spectrum shown from Kockelmann et. al., *J. Imaging* **2018**, 4, 47
- The GADOX screen has a calculated 85% neutron capture integrated over this spectrum with about 55% of these captures resulting in a detectable Internal Conversion Electron for an external Detection Quantum Efficiency of 47%
- Goals of the 24 hour test included:
  - Measure resolution
  - Measure effective QE
  - Measure Contrast-to-Noise
  - Feasibility of Tomography, Energy Selection, Neutron Counting



ISIS Beam Test

Spatial Resolution

- Spatial resolution was determined using a Paul Scherrer Institut *Line Gauge Prototype for Neutron Radiography* with a Gadolinium line-pair test pattern and slant edge box
- The IMAT beam had a flux of 5 x 10^6 n/$cm^2 \cdot$s and an L:D of 250:1
- The test pattern was placed 3.7 mm in front of the GADOX screen yielding an image blur of about 15 µm, roughly 30 lp/mm
- The Image intensifier has limiting resolution of 16 lp/mm
- Nyquist limit is ~ 13 lp/mm for the 38 µm pixel at 75 mm FOV and ~ 30 lp/mm for the 16 µm pixel at 30 mm FOV
- A 300 s acquisition is shown here in the 75 mm FOV mode, and the 10 lp/mm pattern is just resolved



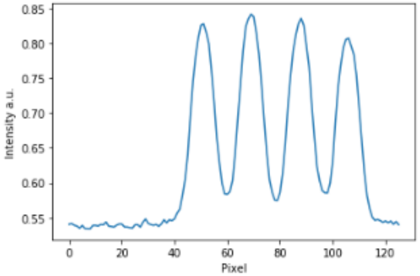
ISIS Beam Test

Spatial Resolution

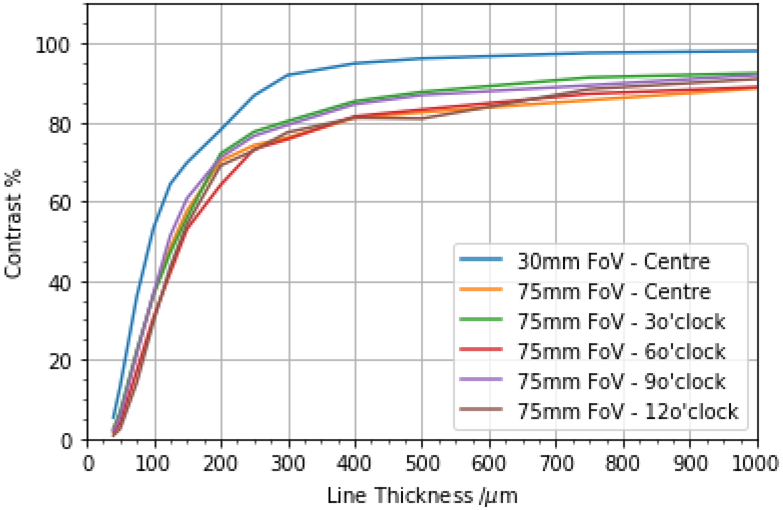
- The PSI test pattern was moved around the perimeter of the Image Intensifier’s 75 mm FOV as well as the center for both 75 mm and 30 mm FOV
- The limiting resolution was measured using the line contrast between adjacent line pairs as shown in the adjacent image:

$$Contrast = \frac{I_{peak} - I_{min}}{I_{peak} + I_{min}}$$

- In all cases the limiting resolution is 10 lp/mm for the 75 mm FOV and 12.5 lp/mm for the 30 mm FOV
- There is a slight right-left, up-down discrepancy possibly related to the Image Intensifier



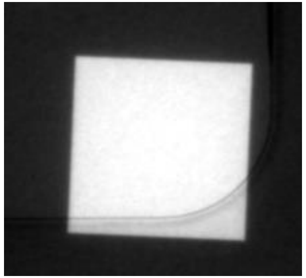
Example 3.33 lp/mm line contrast



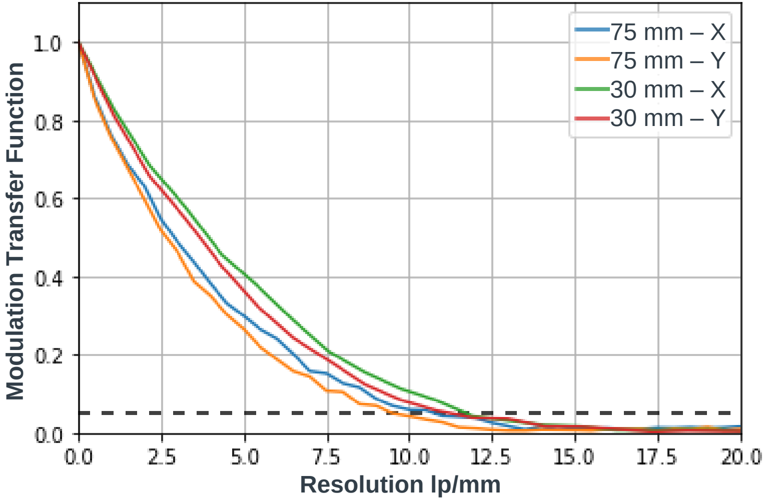
ISIS Beam Test

Spatial Resolution

- The Modulation Transfer Function (MTF) was also calculated using the slant edges incorporated into the PSI test pattern
- Shown here are MTFs at the center of the FOV for both 75 mm and 30 mm FOV and in X and Y directions
- The resolution values are in good agreement with those obtained visually and using the line contrast technique
- The X-Y directional variation, while small, is observable at both magnifications.
- Spatial resolution showed no change down to 5 s integrations



Slant Edges used for MTF calculation



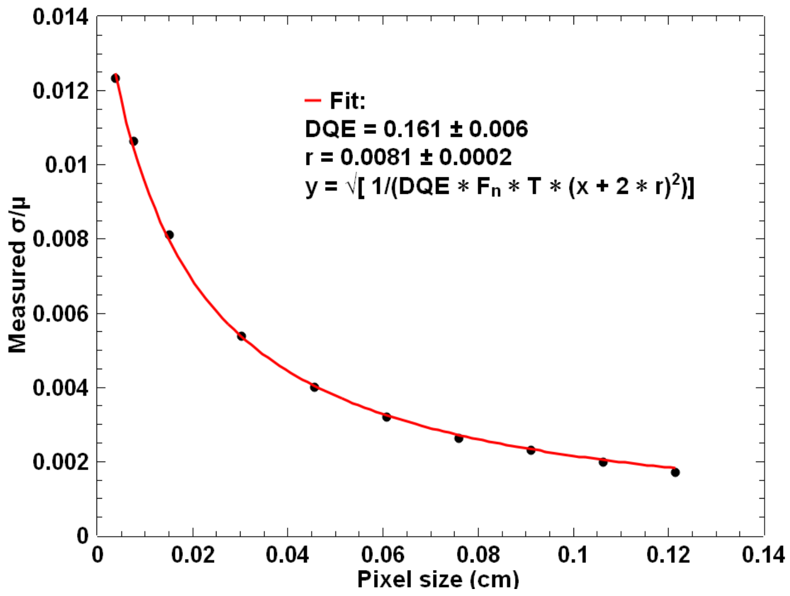
ISIS Beam Test

Detective Quantum Efficiency

- A simplified model is used to estimate the detective Quantum Efficiency of the system assuming Poisson Statistics dominate:

$$\frac{\sigma_{FF}}{\mu_{FF}} = \frac{1}{\sqrt{N(x)}} \cong \frac{1}{\sqrt{DQE \times F_N \times T \times (x+2r)^2}}$$

- *N(x)* is the number of neutrons contributing to signals in a pixel of size *x*, F_N is the neutron flux in units of n/cm^{2}s, *T* is the integration time, and *r* is the neutron correlation scale length in cm
- The SNR of was measured over a 24 mm x 24 mm region with different binned pixel sizes, a flux of 2 x 10^8 n/cm^2·s, a 5 s signal image and a 150 s flat field image
- Fitting the data with the above equation finds
  - DQE = 16.1%
  - Correlation length = 80µm

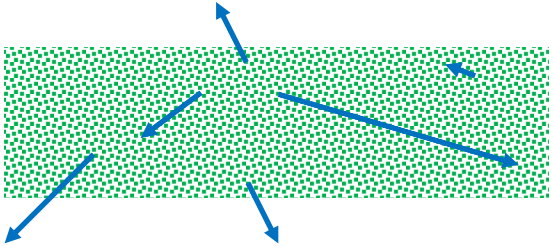


ISIS Beam Test

Detective Quantum Efficiency

- The difference between the estimated DQE of 16% and the theoretical 47% implies a Noise Factor of about 1.7
- The Noise Factor captures degradation in the signal due to the wide pulse height distribution of the neutron signal in GADOX
- ICE emitted near the surface of the screen can deposit little energy while higher energy ICE emitted along the screen can deposit large energy
- Other sources of noise include non-uniformities throughout the detection chain and the multiplication process in the MCP

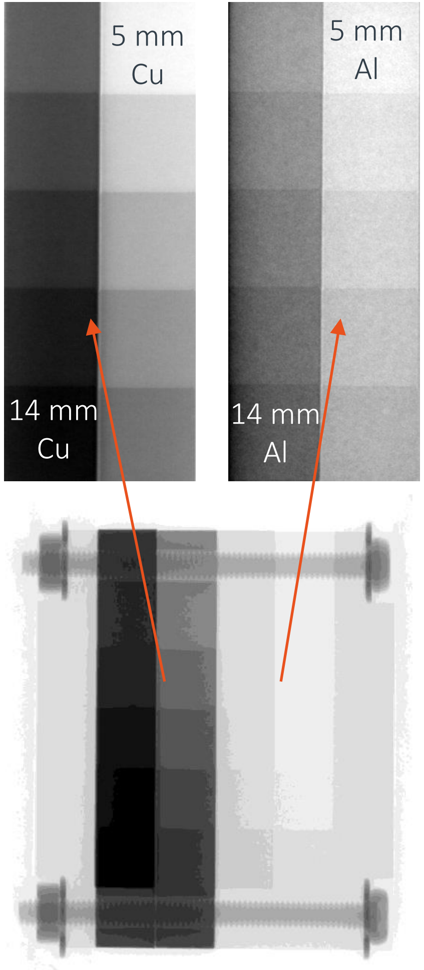
Representation of various paths for ICE within the GADOX layer



ISIS Beam Test

Contrast to Noise

- A contrast target was fabricated using 10 thicknesses each of C101 Copper and 6082-T651 grade Aluminum, from 5 mm through 14 mm in 1 mm increments
- Each section of the target was 5 mm x 5 mm in cross-section.
- The target was imaged using a nominal neutron flux of 2 x 10^7 n/cm^2·s and L:D of 125:1, with 600 s integration time
- The mean and standard deviation of an interior region of each step was calculated
- Notice that there is non-uniform signal over each step believed to be due to neutron scattering from thicker portions of the wedge to thinner portions. This is not accounted for in the following calculations



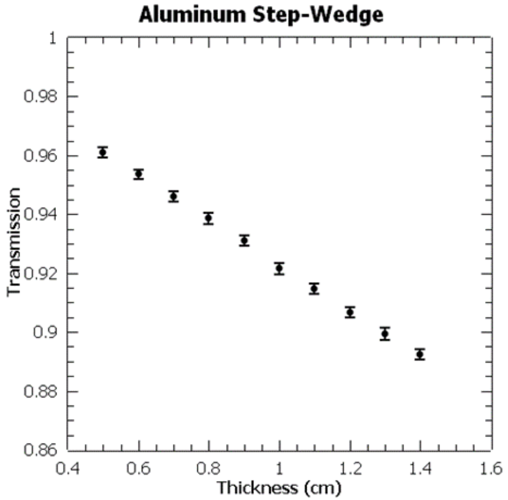
ISIS Beam Test

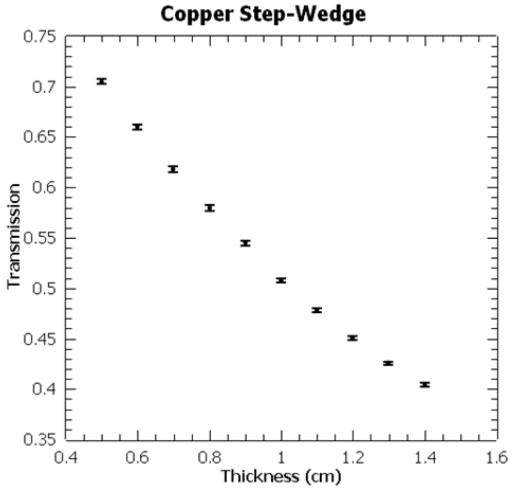
Contrast to Noise

- Contrast-to-Noise is calculated for using the mean intensity and standard deviation of two adjacent regions, A and B, as

$$CNR = \frac{|\ I_A - I_B\ |}{\sqrt{\sigma_A^2 + \sigma_B^2}}$$

- From this data the CNR between the 1.0 and 1.1 cm thick Aluminum sections is found to be 2.6 and for the same copper sections the CNR is 11.4
- Assuming that a CNR of 1.0 is the minimum detectable contrast we find for the aluminum data that the minimum contrast detectable is about 0.26% and the minimum detectable contrast for the copper data is about 0.30%, indicating that there are roughly **350 gray scales in the image**
- This is a lower limit due to effects of neutron scattering

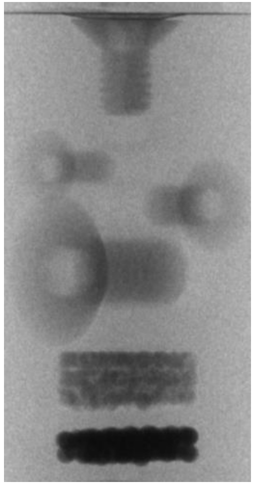

Aluminum Step-Wedge


Copper Step-Wedge

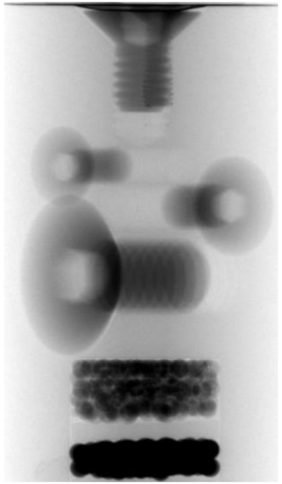
ISIS Beam Test

Tomography

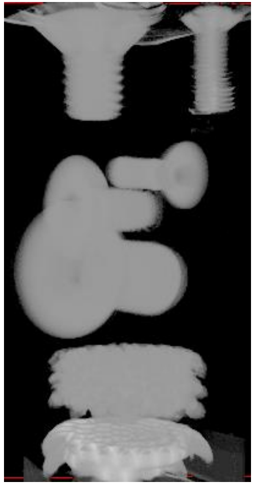
- Data for a tomograph was taken using a flux of 1.1 x 10^7 n/cm2·s and L:D of 125:1
- 180 projections were obtained with a total with 105 s integrations per projection
- Just beginning reconstruction work. Minimum exposure times are 2.5 s
- Plan to determine tomographs performance as a function of integration time and pixel size.



2.5 s integration



105 s integration



Preliminary reconstruction

ISIS Beam Test

Single Neutron Imaging

- To demonstrate single neutron counting we placed neutron shielding in from of the camera to reduce the incident flux to about 1 x 10^4 n/cm^2·s
- Acquired 35 fps, as shown in this vide
- The variation in intensity reflects the variation in light output per neutron.
- For neutron generators this mode will be very effective as it is close to noiseless and spatial resolution is significantly improved due to centroiding of each neutron spot.

Future Directions

Future Modifications & Tests

- Make a replaceable scintillator screen deposited on a thin fiber optic to enable optimization of screens for different applications and for long-term field replacement – design has recently been completed
- Test $Gd_2O_2S:Pr$ with ~ 7 µs decay time for use in energy resolved imaging as compared to 1.5 ms decay of $Gd_2O_2S:Tb$
- Testing with a neutron generator to occur this fall
- Implementation of neutron counting algorithm to perform real-time event centroiding based on algorithm developed for photon counting camera

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