HIGH RESOLUTION HIGH ENERGY NEUTRON COMPUTED TOMOGRAPHY AT LANSCE-WNR

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Summary

- Why Fast Neutron Imaging
- What is LANSCE-WNR
- Developments and Testing at LANSCE-WNR (last 4 years)
- Imaging Setup
- Results
- Ongoing Development
- Conclusions/Thoughts
- Questions

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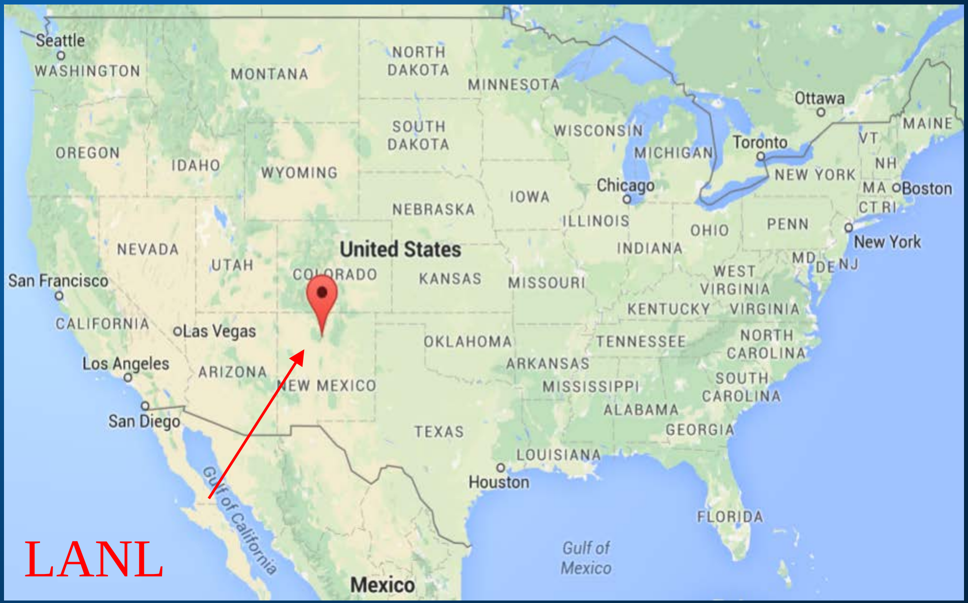
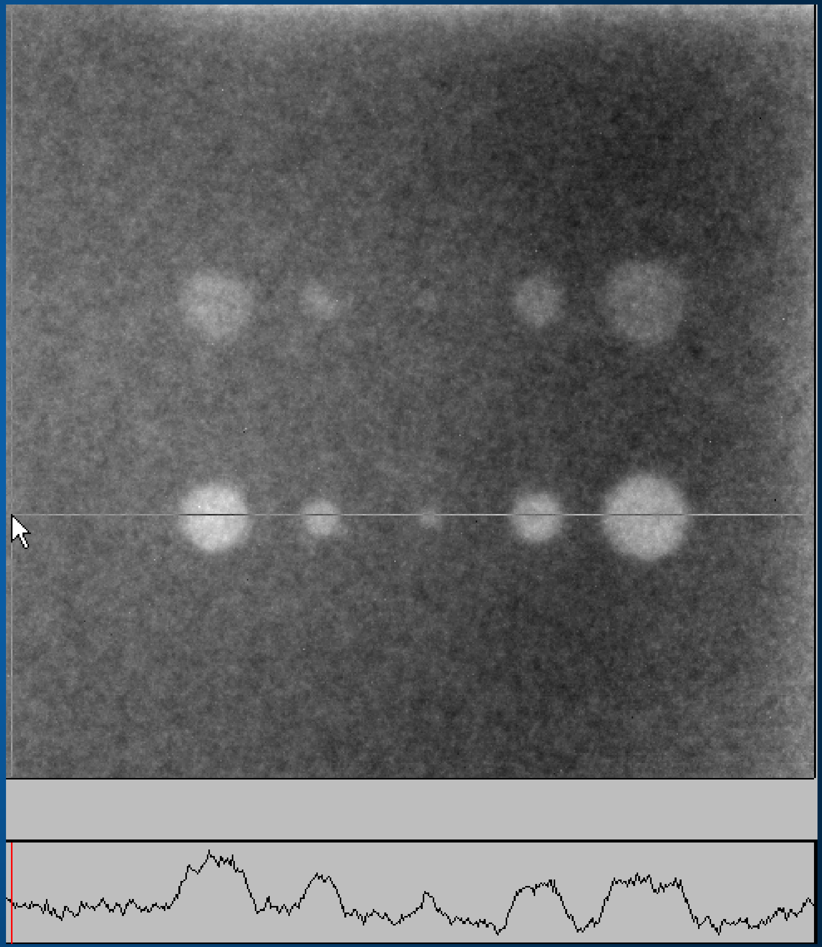


Why Fast Neutron Imaging

- **Image features we cannot image with any other capability**
- **LANL has a range of capabilities we can use**
  - keV-20MeV x-ray sources
  - Cold/thermal neutron beamlines
  - Fast neutrons when other techniques don't work
- **Fast neutrons bring**
  - Better penetration through high Z materials
  - Improved contrast in many low Z materials
- **Cost of fast neutrons**
  - Slower, more expensive and more hazardous than x-ray
  - Lower resolution and very limited source availability
  - Limited field of view (longer scans or smaller parts only)

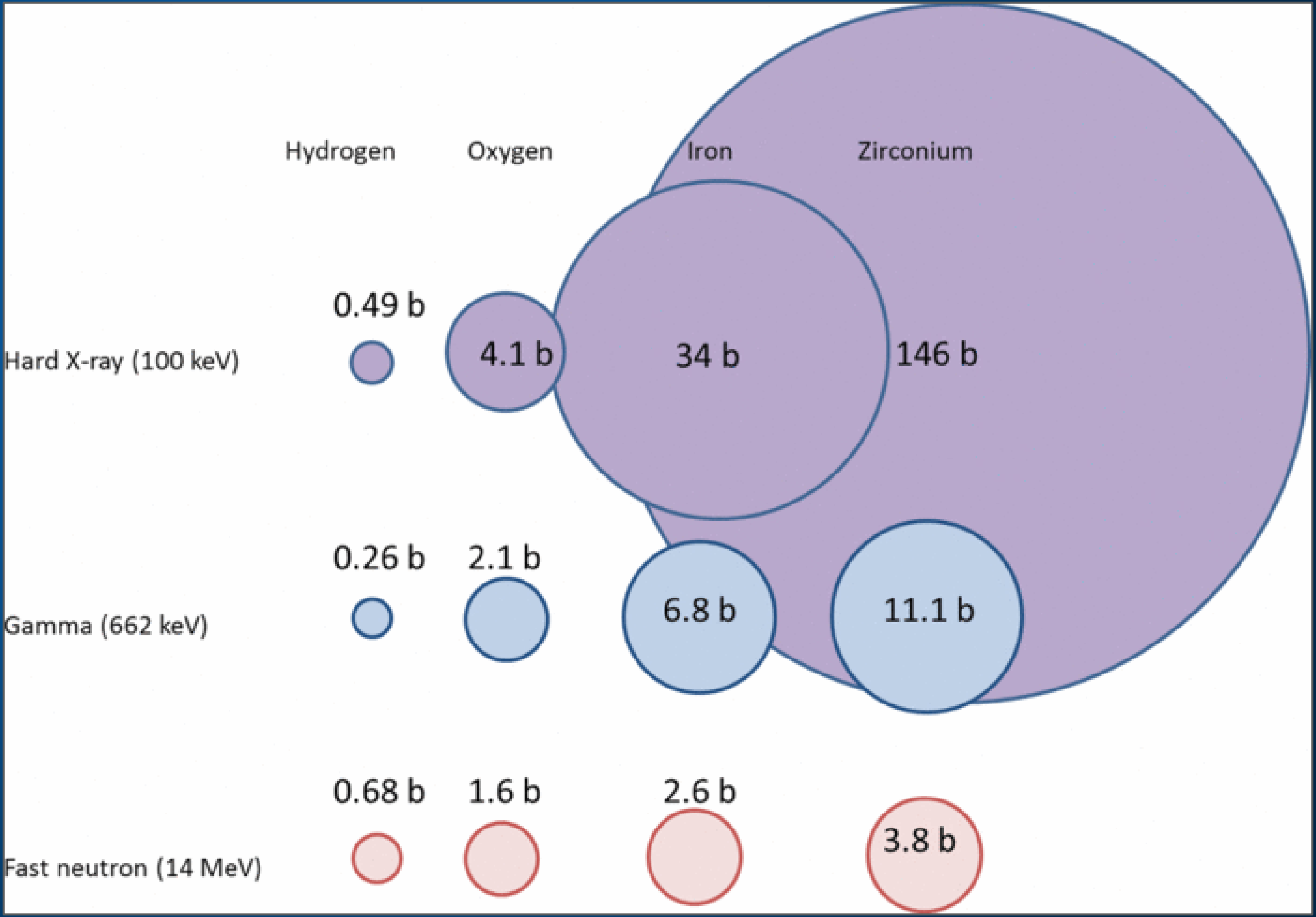


Why fast neutrons example: holes in a 2.54cm poly block behind 7cm of tungsten.

14 MeV Neutron Cross-Section Comparison

14MeV cross-sections illustrate some of the why for fast neutron imaging

- Reduced ratio of cross-sections from high to low Z is key
- LANSCE-WNR produces a broad high energy spectrum (40-50 MeV average)
- Cross-sections continue to flatten at higher energies
- Flat is very different from thermal



From: *Neutron tomography of axially symmetric objects using 14 MeV neutrons from a portable neutron generator*, P. Andersson, E. Andersson-Sunden, H. Sjöstrand, and S. Jacobsson-Svärd, Citation: Review of Scientific Instruments 85, 085109 (2014);

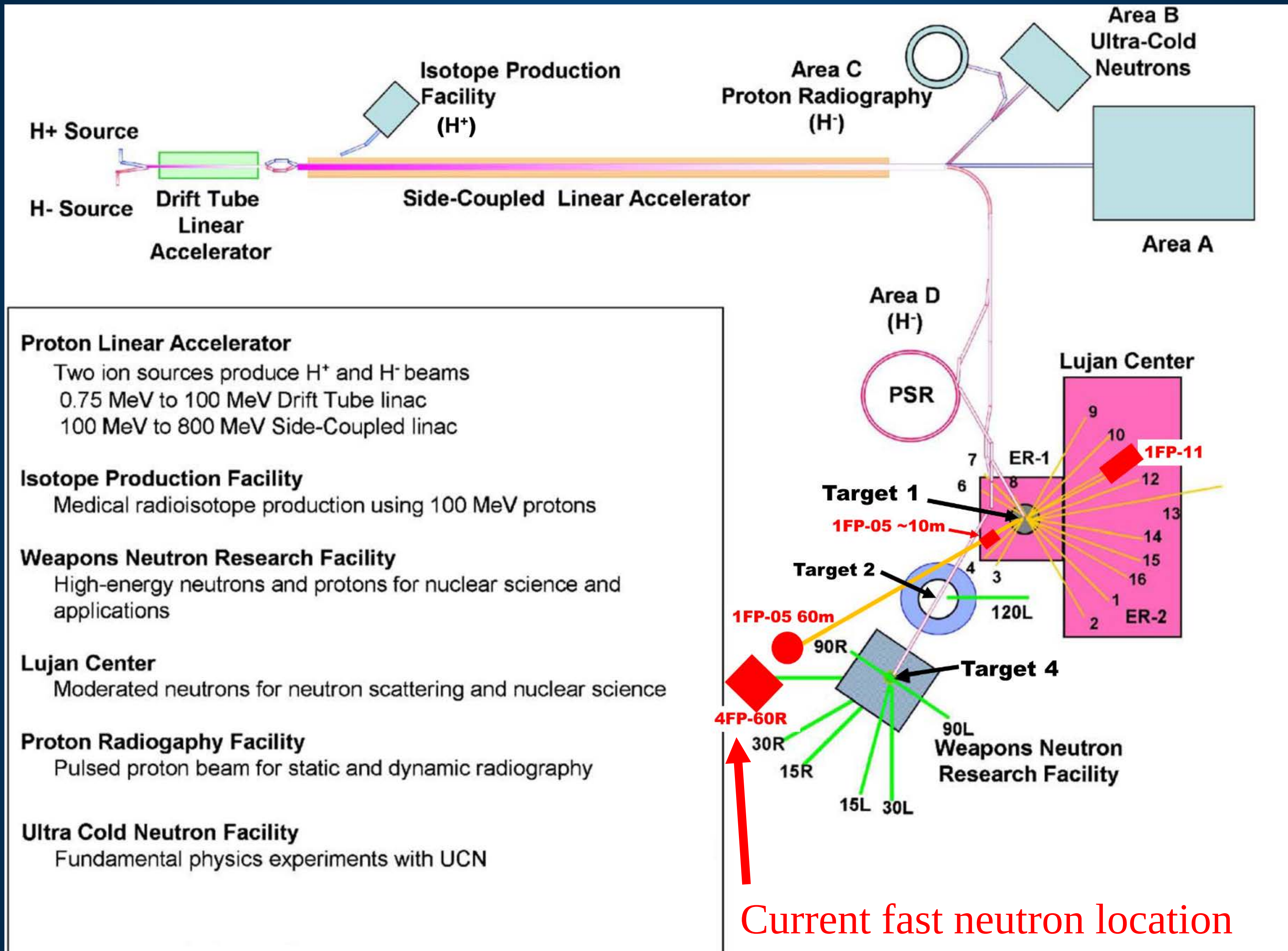
LANSCE-WNR

- LANSCE: 800MeV proton accelerator supporting
  - –Medical isotope production
  - –Thermal/cold neutron target/flight paths (Lujan Center)
  - –Fast neutron target (WNR)
  - –Proton radiography
  - –Ultra cold neutron facility
- WNR is an unmoderated cylindrical tungsten target 3cm diameter x 7.5cm long
- Beam ports view this target with 0.6cm Pb and 1mm borated poly filtration

- Primarily used for nuclear cross-section/reaction measurements and chip irradiation

(Left) View of the LANSCE accelerator site with arrow showing WNR

Overview of the LANSCE Facility

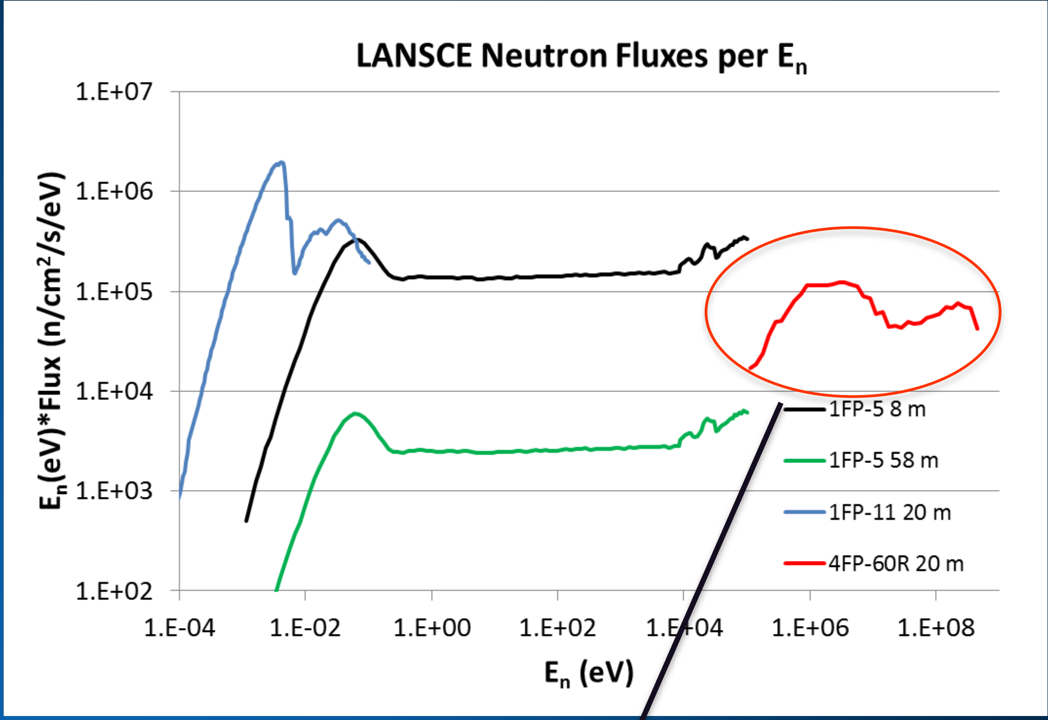


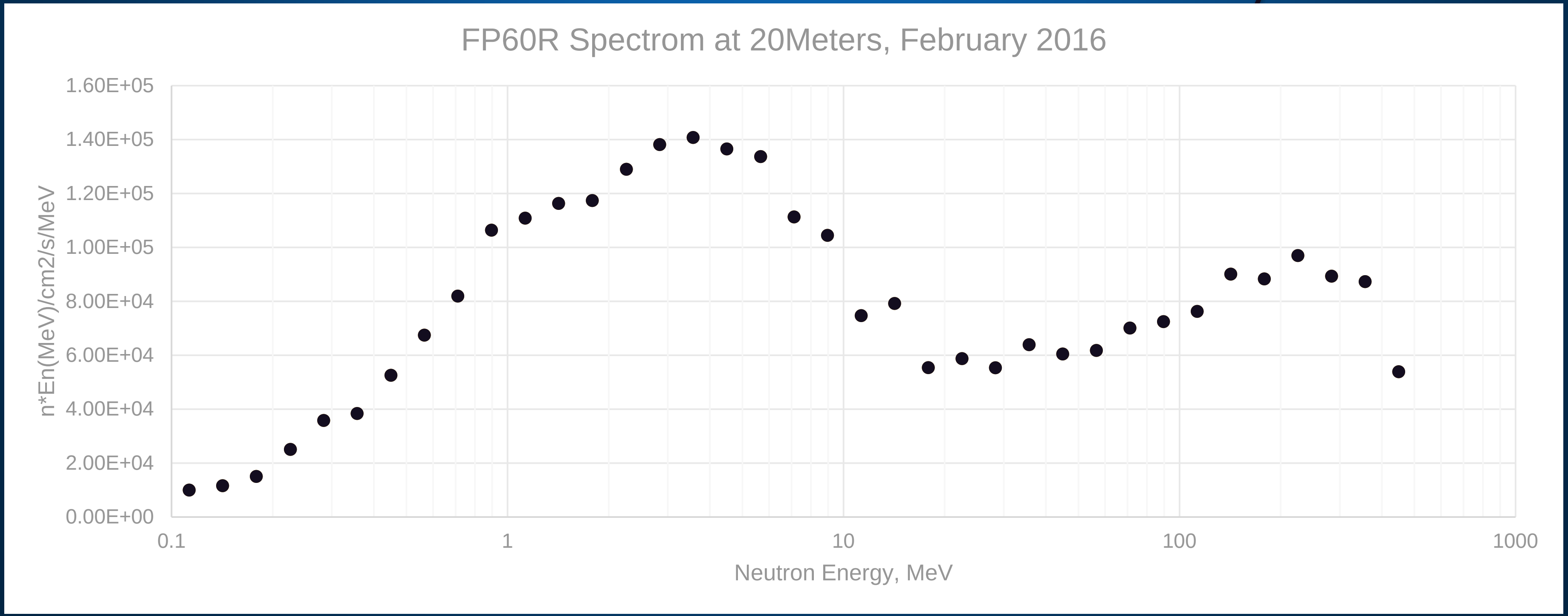
Schematic of the LANSCE facility with radiography flight paths (cold, thermal and fast) in red. This talk discusses work done at 4FP-60R and in the past at 4FP-30L and 4FP-15R. Note that radiography is part of a much larger facility.

Spectra

- Broad spallation spectrum
- Average 40-50MeV
- ~1.6×10^6 n/cm^2/s at detector
- < 1 ns micro pulse

Spectrum for all flight paths used for imaging at LANSCE (right) and a measured spectrum for the fast neutron flight path (below).





Fast Neutron in the Last 4 Years

- **Dedicated flight path constructed**
  - –20M imaging distance (source blur of 200µ)
  - –Rebuilt shielding and beam stop
  - –30x20cm FOV
- **Demonstrated Energy discriminating Time of Flight imaging**
- **Established long scan (48hr) flat panel CT**
- **Established lens coupled camera imager for scintillator testing and general use**
- **Ongoing imaging and scintillator testing**

Building the dedicated flight path: L to R, Beam stop construction, the imaging location with added shielding and the open collimation beam pipe for large FOV.

Setups

Brief overview of imaging setups (see references for detail)

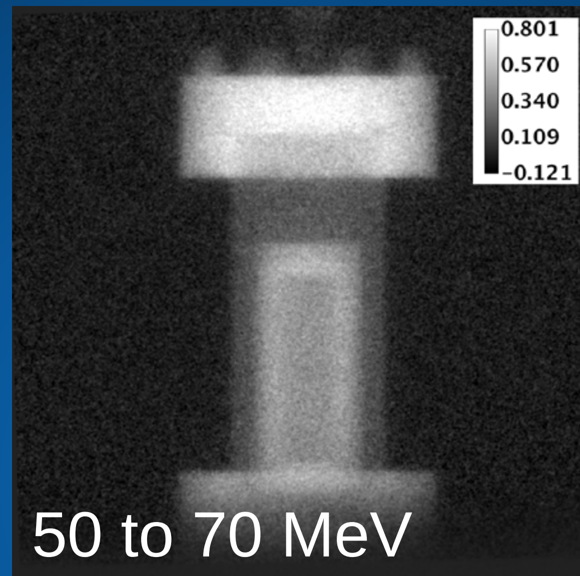
1. Broad spectrum Flat panel radiography and CT
   - Perkin Elmer 1621 detector (200µ pixel pitch)
   - 2.4mm ZnS(Ag) scintillator with and without added poly
   - 20 second single image integration time; 8000-9000 images max per CT (standard 360 degree Feldkamp)
2. Lens Coupled Imager
   - SI 1100S; SI424A CCD 2048x2048x24µ pixels;
   - LINOS F1.3 fixed focus lens with 20x20cm FOV and > 50% MTF at 2.5 line pairs/mm
   - Long integration times as needed (cryo cooled)
3. Time of Flight (ToF) Imager
   - Experimental lens coupled imager using PI-Max 4 Gated ICCD Camera
   - 1024x1024x13µ pixels, Intensifier gated
   - Standard F2 and F4 Edmunds Optics C mount lenses (different FOVs)

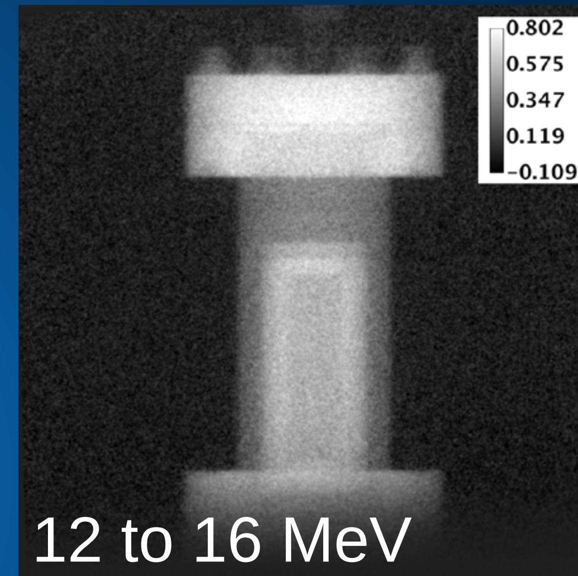
(Top) Interior of the lens coupled time of flight system and (bottom) typical flat panel CT with motion and PE1621 flat panel.

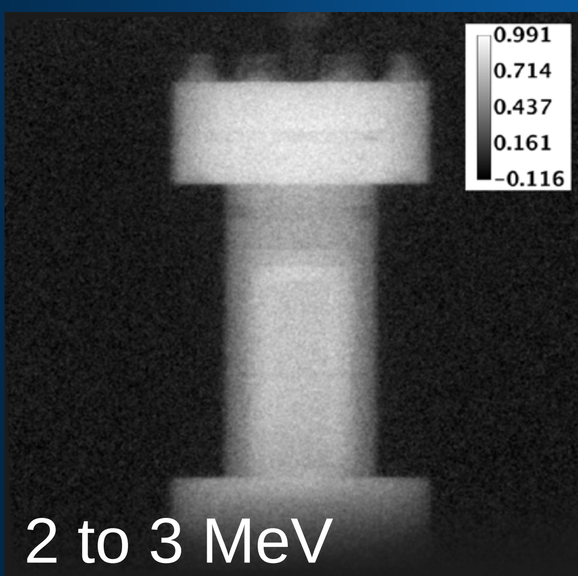
Time of Flight

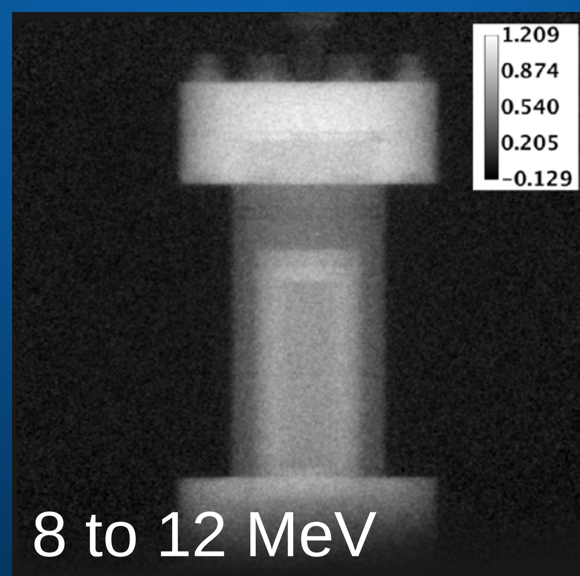
~15cm tall imaging quality test piece made of steel, tungsten, poly and nylon shown at various energy ranges

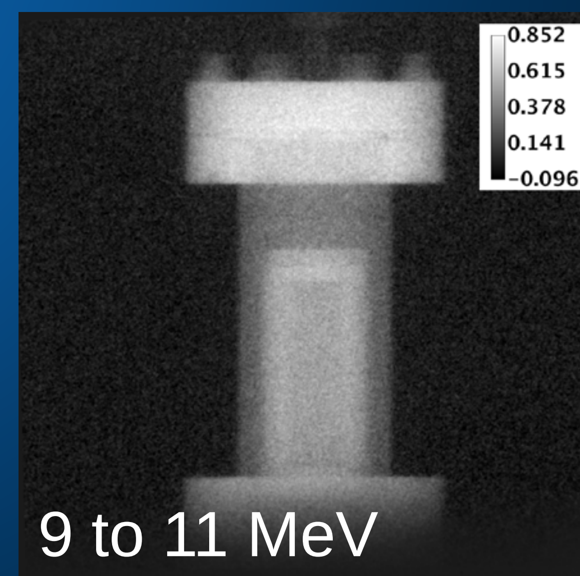
- **Supported by fast pulse structure of LANSCE beam**
- **Energy specific**
- **Some resonance imaging potential**
- **Scatter rejection**
- **Development area**







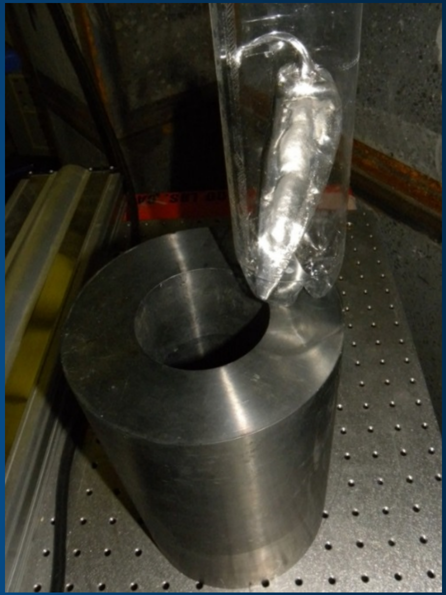


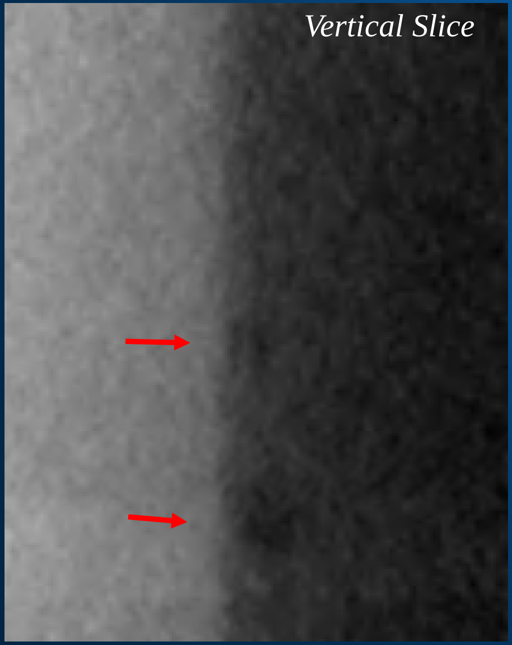


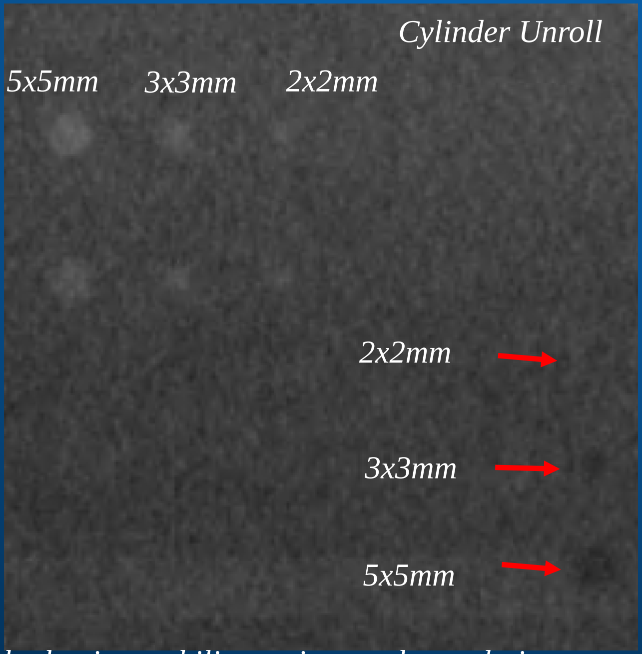
Broad Spectrum Imaging (CT)

<u>Thick Example:</u> Hollow DU Cylinder with various phantoms/IQIs placed inside

- 7472 frames, 2880 degrees (8avg, 934 views over 360 degrees)
- 20sec per image, 41.5hrs total
- 4cm Wall thickness cylinder with a 7.62cm ID. 8cm = 152.8g/cm^2; Longest chord = 13.63cm = 260g/cm^2
- Poly test center with voids and steel pins; 2x2mm void and steel smallest detected: 2mm of void vs. poly is 0.2g/cm^2 variation so contrast of 1:760-1300 over the CT





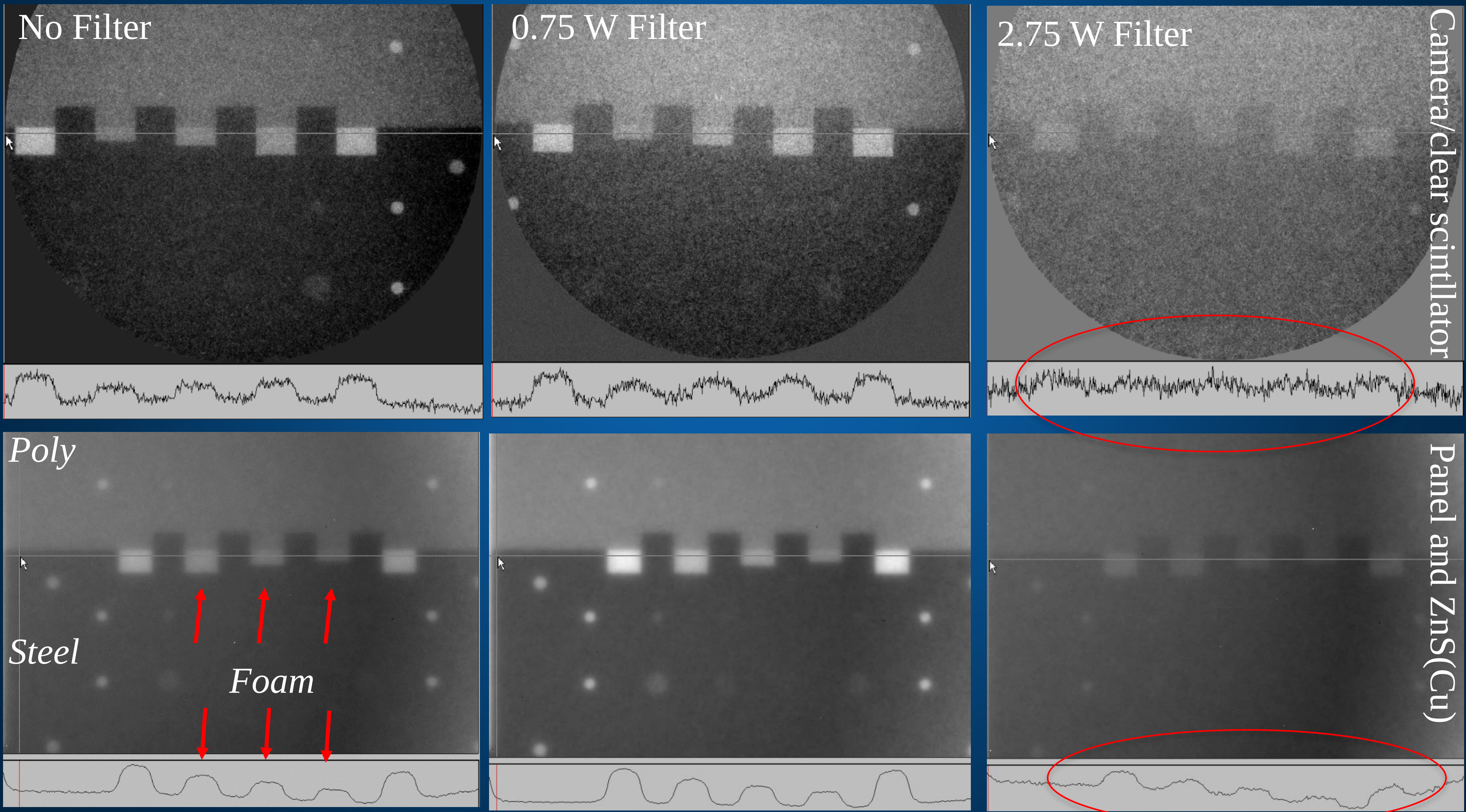


CCW from upper right: DU cylinder with aluminum chili test piece, poly resolution test patterns and results of resolution test pattern CT scan.

Camera vs. Panel Low Contrast Example (Radiograph)

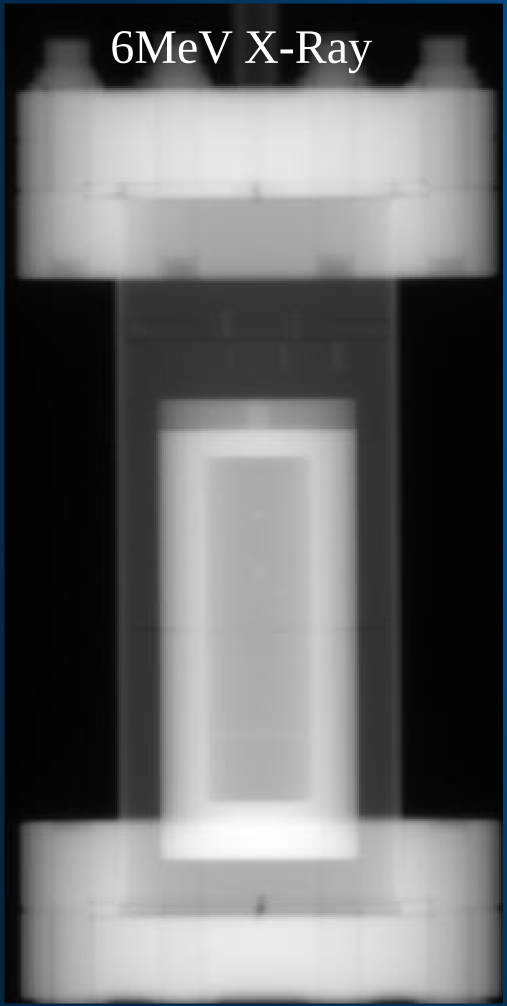
Detector/scintillator radiograph testing example:

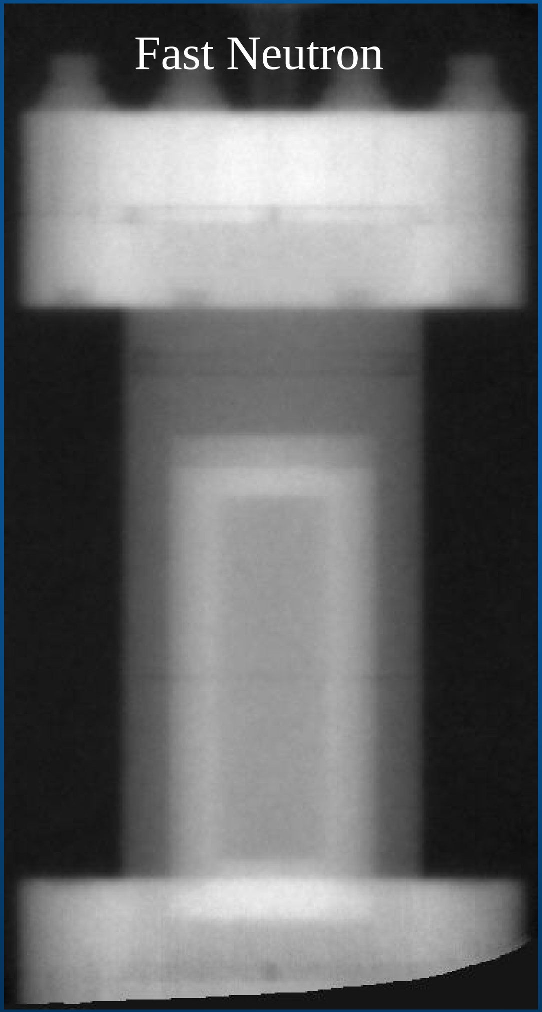
- Camera with thin clear scintillator (top row) vs. panel with thick ZnS(Cu) scintillator.
- 1cm thick steel/poly foam density phantom behind 0, 1.9 and 7cm of tungsten
- Note lineout through compressed foam

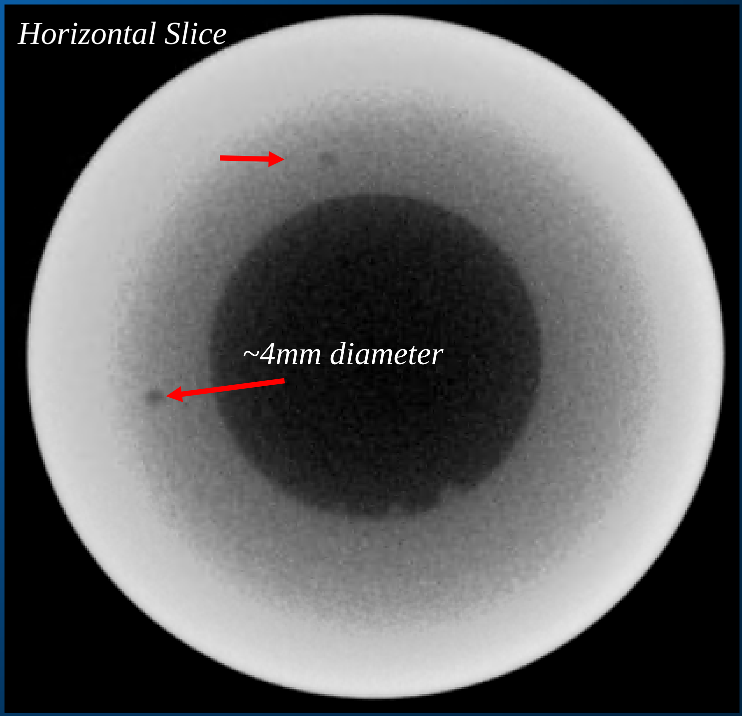


Additional Imaging Examples/Notes

- (Below) Fast Neutron to 6MeV x-ray. If we can see a feature the resolution is higher in x-ray. Neutron provides contrast and penetration.
- (Right) Neutrons show cracks in a ~15cm diameter potted tungsten cathode and below, casting voids in the DU cylinder



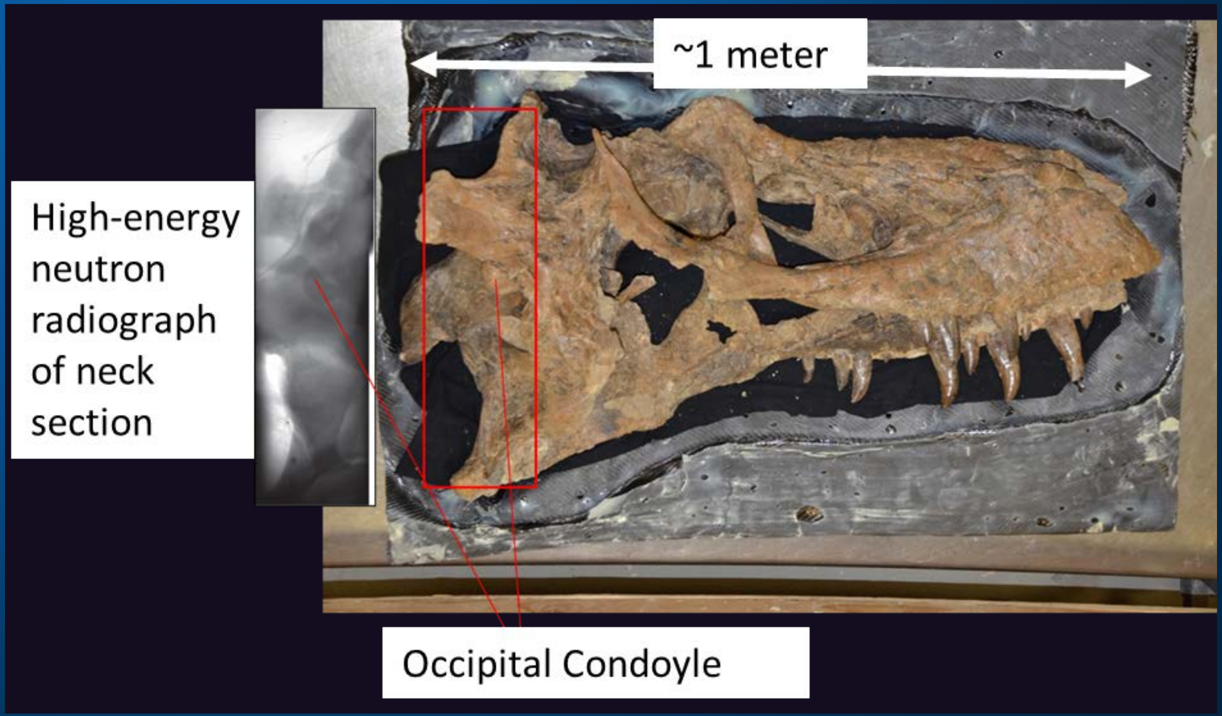




Future Work

- Continued imaging on a range of items (T-Rex predecessor skull example)
- Flight path improvements (FOV, shielding) under consideration
- Scintillator testing and optimization
- Detector/staging optimization
- Multi-energy/spectral investigation (neutron energies and x-ray)

The Bisti Beast skull owned by the New Mexico Natural History Museum was imaged with MeV x-rays and at LANSCE-WNR but the small FOV is necessitating a long data processing time for stitching and reconstruction of the fast neutron data. Raw radiographs show good contrast in the regions of interest.



Thoughts/Conclusions

We have established a fast neutron experimental imaging (radiography and CT) capability at LANSCE-WNR including flat panel, lens coupled and energy resolved time of flight.

<u>Thoughts</u>

- **Stopping power of high resolution scintillators is the largest single issue we see today (bad time vs. resolution trade off)**
- **Very little is done in high flux fast neutron imaging leading to a lack of available literature**
- **FOV, scatter and the resulting shielding are an upfront issue**
  - We are considering moving to a 40x40cm FOV and vault type shielding
- **Fast neutrons remain an appealing option for very thick parts, particularly with mixed high/low Z components**
- **Fast and thermal are very different and misconceptions occur**
  - Unlike thermal, no silver bullet cross-sections (high or low)
  - NOT the same scintillators, detecting thermals is bad in fast neutron imaging
  - Frequently less/different activation than thermal

Questions

Related Publications

- Nelson, R.O.; Vogel, S.C.; Hunter, J.F.; Watkins, E.B.; Losko, A.S.; Tremsin, A.S.; Borges, N.P.; Cutler, T.E.; Dickman, L.T.; Espy, M.A.; Gautier, D.C.; Madden, A.C.; Majewski, J.; Malone, M.W.; Mayo, D.R.; McClellan, K.J.; Montgomery, D.S.; Mosby, S.M.; Nelson, A.T.; Ramos, K.J.; Schirato, R.C.; Schroeder, K.; Sevanto, S.A.; Swift, A.L.; Vo, L.K.; Williamson, T.E.; Winch, N.M. Neutron Imaging at LANSCE—From Cold to Ultrafast. *J. Imaging* 2018, *4*, 45.

- Winch, N.M., Madden, A.C., Hunter, J.F., and Nelson, R.O., Detector Performance for Fast Neutron Radiography and Computed Tomography, IEEE Trans. Nucl. Sci., October 2018

- Madden, A.C., Richard C. Schirato, Alicia L. Swift, Theresa E. Cutler, Douglas R. Mayo, and James F. Hunter, Development and Characterization of a High-Energy Neutron Time-of-Flight Imaging System, IEEE Trans. Nucl. Sci., 2017 64, 1810-16

- R. Simpsona), T. E. Cutler, C. R. Danly, M. A. Espy, J. H. Goglio, J. F. Hunter, A. C. Madden, D. R. Mayo, F. E. Merrill, R. O. Nelson, A. L. Swift, C. H. Wilde, and T. G. Zocco; Comparison of polystyrene scintillator fiber array and monolithic polystyrene for neutron imaging and radiography, Review of Scientific Instruments 87, 11D830 (2016);

- Swift, A., Schirato, R., McKigney, E., Hunter, J., Temple, B., Time gating for energy selection and scatter rejection: High-energy pulsed neutron imaging at LANSCE, Proc. SPIE 9595, Radiation Detectors: Systems and Applications XVI, 95950J (27 August 2015); https://doi.org/10.1117/12.2188440

Abstract

It has long been recognized that neutrons can compliment x-rays for imaging. This is due to their very different attenuation characteristics based on nuclear cross-section, which allows imaging of low Z materials through higher Z materials. Additionally one can use energy dependent Time of Flight (ToF) imaging to exploit phenomenon like nuclear resonances for isotope and element specific imaging. The Los Alamos Neutron Science Center (LANSCE) accelerator is an 800 MeV proton linear accelerator which supplies protons to a range of missions including two spallation neutron targets, one moderated (water and liquid hydrogen) and one unmoderated. This combination of targets provides flight paths which have cold, thermal to epi-thermal and fast neutron energy ranges. In addition the proton pulse structure of the LANSCE accelerator provides neutron pulse lengths of < 270ns for the thermal/cold flight paths and < 1ns for the fast flight paths. These pulse lengths allow for energy discrimination from eV to ~100 MeV.

Over the last 6 years there has been significant renewed interest in utilizing this source for neutron imaging as a complement to existing x-ray and proton imaging capabilities at LANL. To this end thermal to epi-thermal integrated and ToF imaging (2D radiography and Computed Tomography or CT) have been established and cold neutron propogation based phase contrast imaging has been demonstrated. Finally, significant work has been put into developing a fast neutron imaging capability with the goal of reaching sub mm resolution on objects with an integrated density > 200 g/cm^2 and a CT scan time of less than 12 hrs. Fast neutron imaging at high resolution is an area with relatively sparse development due to a lack of available high intensity sources. This talk focuses on advances made in fast neutron imaging at LANSCE-WNR over the last 4 years including flight path modifications, scintillator development and detector testing. Results are shown for a range of scintillators, flat panel detectors and lens coupled camera systems. In addition energy discriminating Time of Flight images from 2 to 60 MeV are shown. Imaging results are shown on imaging quality indicators, a range of industrial parts (cracking, casting voids, etc) and on fossils of various sizes. Where available x-ray CT results are shown on the same parts to demonstrate the pros and cons of fast neutron imaging. Finally, ongoing work and outlook for continued improvement in fast neutron imaging will be discussed.