UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899-8461

Neutron Imaging Facility

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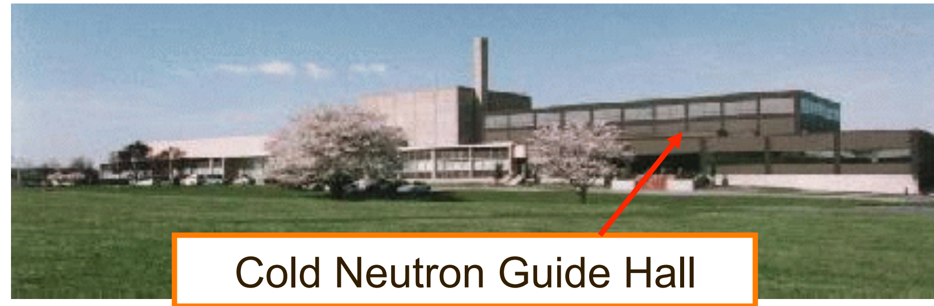
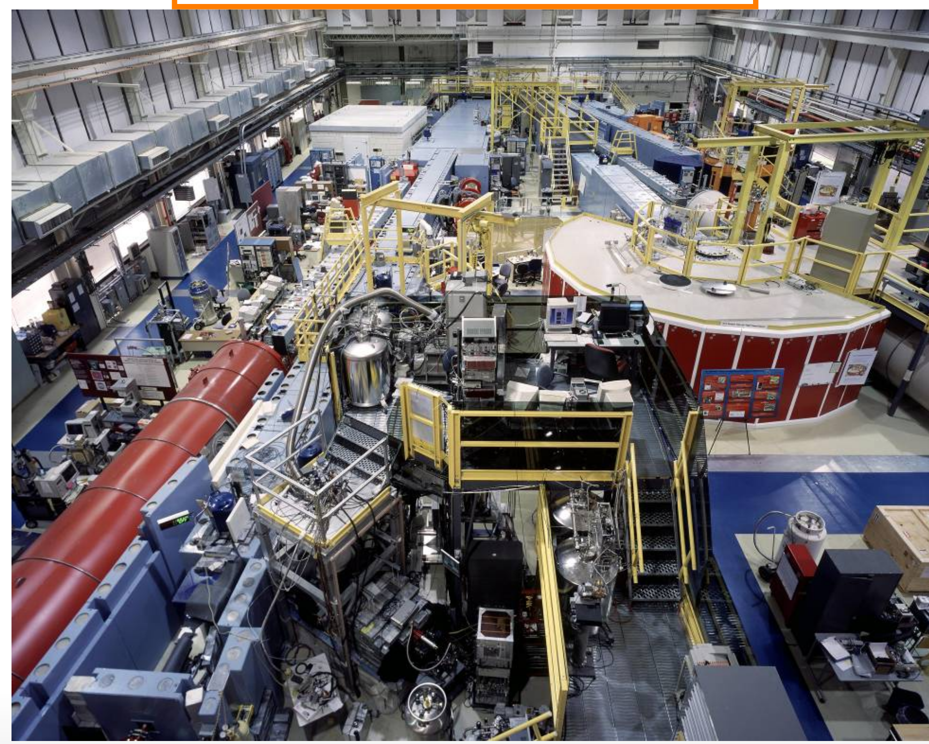
Who am I?

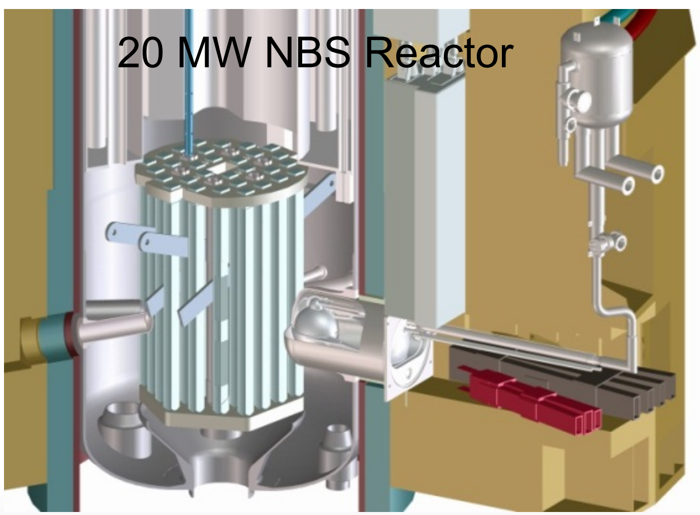
- 1988-1990 Westminster College, Fulton, Missouri, BA Physics and Mathematics
- 1989 Summer Research Internship Missouri University Research Reactor (10 MW), Columbia, Missouri, Advisors Sam Werner and Helmut Kaiser
- 1990-1996, University of Missouri, Columbia, Missouri, Thesis Title: "Spectral Modulation, Gravity and Time Dependent Correlations in Neutron Interferometry."
- 1996-Present, National Institute of Standards and Technology, Physicist in the Physical Measurement Laboratory but working at the NIST Center for Neutron Research
- 2002, Built the first Neutron Imaging Facility at NIST
- 2006, Scientific project leader of second Neutron Imaging Facility at NIST and subsequent team leader of Neutron Imaging Team at NIST
- 2015, Advisor to Dan Hussey who is the scientific project leader of the 3rd generation facility the NIST Cold Neutron Imaging Facility

National Institute of Standards and Technology
Center for Neutron Research

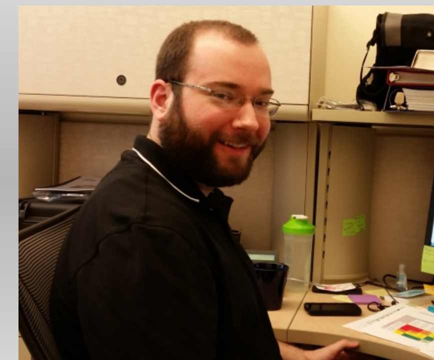
- NCNR provides a large cold neutron research facility
- U.S. national user facility
- Instruments are staffed and run by many different divisions at NIST
- Reactor facility runs 38 days with an 10 day shutdown for roughly 290 days/year
- > 2,000 users per year





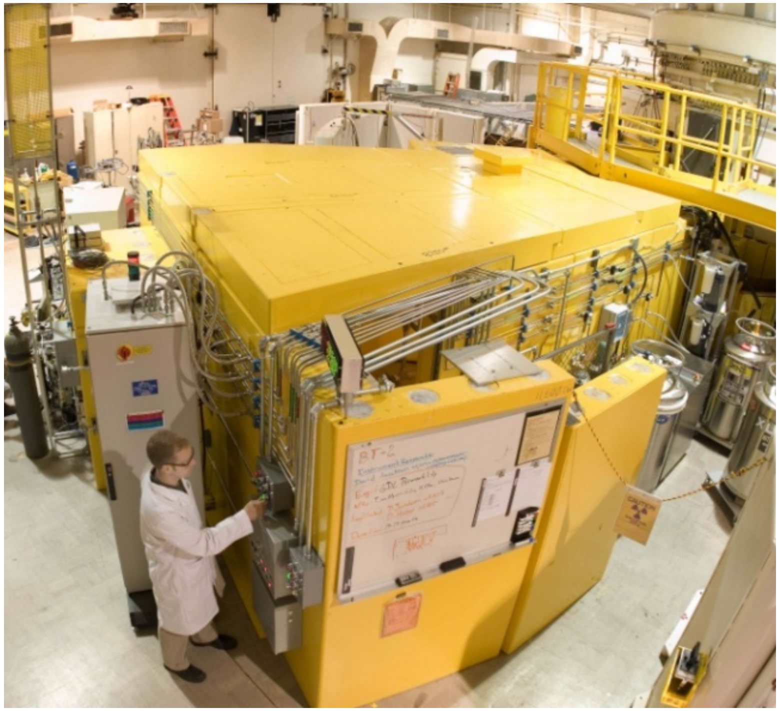


NIST Neutron Imaging Research Team



This facility was supported by the U.S. Department of Commerce, the NIST Radiation Physics Division, the Director's office of NIST, the NIST Center for Neutron Research, and the Department of Energy interagency agreement No. DEAI01-01EE50660.

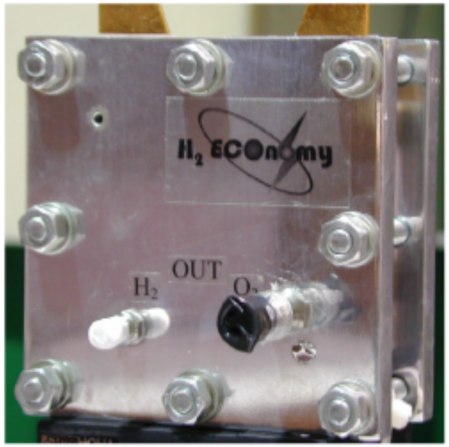
The NIST Thermal Neutron Imaging Facility at BT2

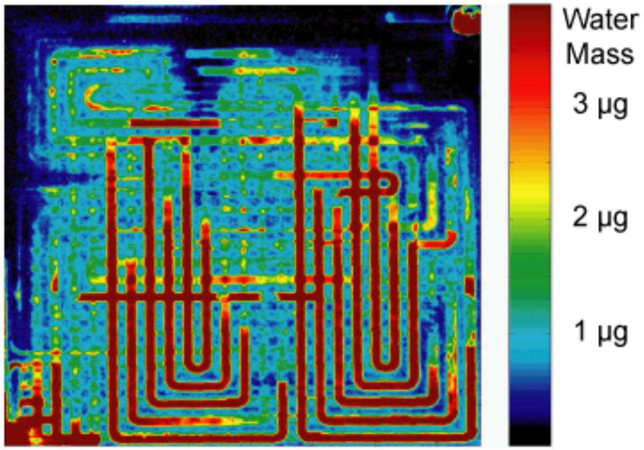


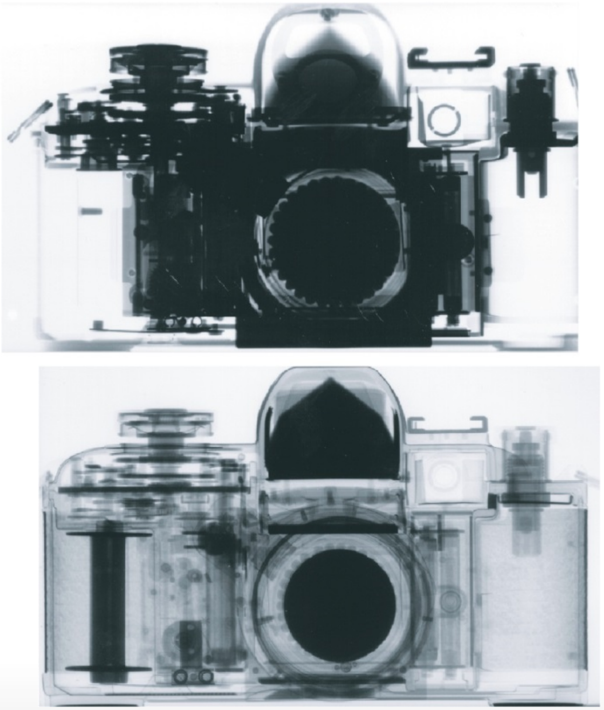
- Purpose built to study water transport in fuel cells as partnership with GM & DOE
- Facility characteristics:
  - Thermal neutron spectrum
  - L/D from: 300 to 6000
  - Flux from: 3×10^{7} to 8×10^{5} cm^{-2} s^{-1}
  - Beam diameter 26 cm
  - Large area for ancillary equipment
  - All digital radiography
  - Large suite of PEFMC test & control tools
- Facility access:
  - Free Access: open literature research, RFP twice/year; rapid access available too.
  - Proprietary Access: user pays full cost recovery to own the data
  - If travel cost is a burden, can arrange for "mail-in service"; only available for open literature research

Advantages of Neutrons

- Neutrons penetrate many materials well yet remain extremely sensitive to liquid water, hydrocarbons and lithium
- This allows one to “non-destructively” study a wide range of transport related issues like:
  - Liquid water in fuel cells
  - Lithium in batteries
  - Multiphase flow in geological rock cores

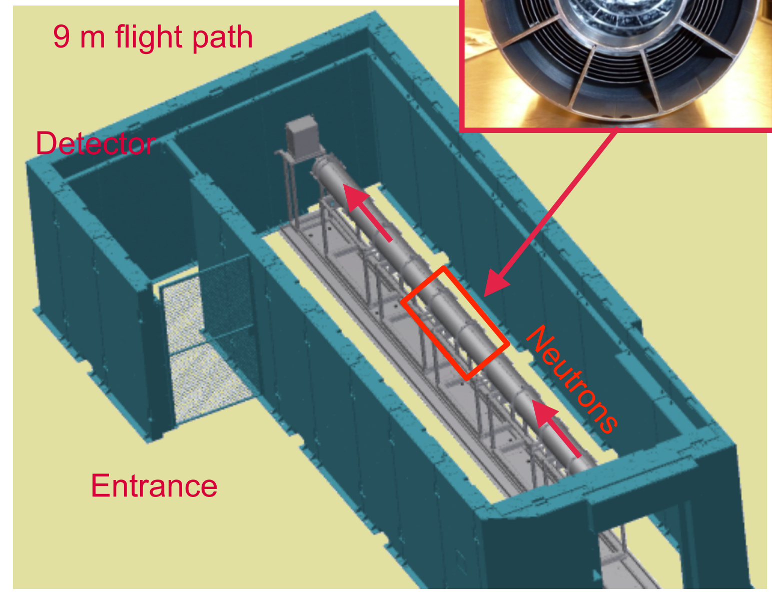






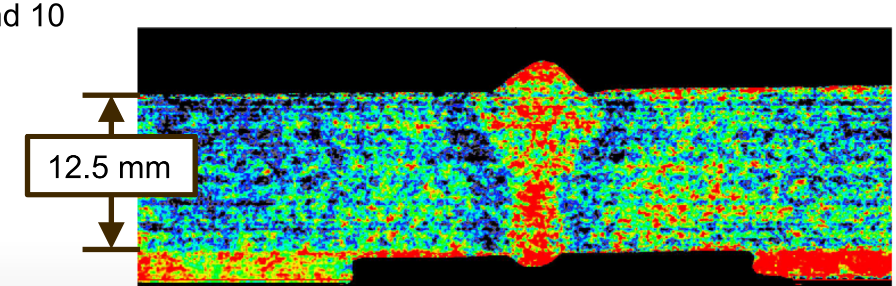
NIST Cold Neutron Imaging

- Cold neutron imaging facility
  - New as of September 2015
  - Attenuation coefficient 2x larger than thermal neutrons
  - Longer wavelengths more suited to energy selective methods using monochromators or velocity selectors.
- Neutron microscope
  - NIST, NASA, MIT collaboration
  - Innovative NASA Wolter optic for x-ray astronomy
  - Neutron optics are identical to x-ray so design transfers.
  - 10x magnification could allow for 1 μm micron neutron spatial resolution by 2018 – 2020 timeframe.
- Phase imaging
  - Spatial resolved small angle neutron scattering
  - Bulk magnetic domain imaging
- Bragg edge imaging
  - Visualize strain with potentially 100 μstrain resolution and 10 μm spatial resolution
  - Advanced manufacturing



Attenuation

Phase Contrast

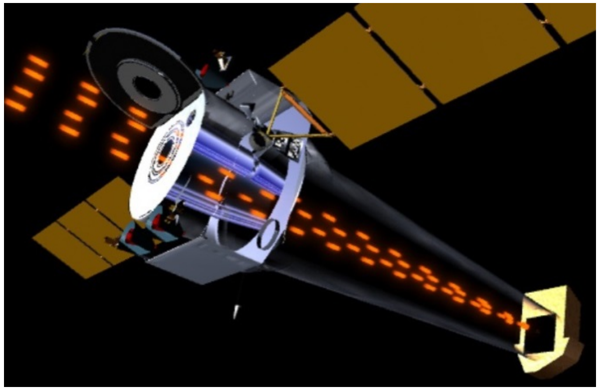


Neutron Imaging Facility

In recent years the technique of Neutron Imaging has experienced a renaissance at neutron sources worldwide enabled by the great technical strides that are continuing to be made in imaging and computing technologies. Originally only radiography was possible, but computing power has enabled the 3 dimensional computed tomography (CT) as well. Using energy selection new methods like phase contrast imaging, Bragg edge imaging and diffraction contrast are also now possible. Spatial resolution has been improved by an order of magnitude to near the current limit of 10 micrometers and may see yet another order of magnitude improvement with other enabling technologies such as the new Wolter optic lens that is currently being developed for x-ray astronomy and for neutron imaging/scattering. The method has also been used to study fuel cells, both alkaline and lithium batteries, geology in situ, advanced manufacturing and various multi-phase phase systems that are difficult to study with x-rays.

High resolution MEA water content:
NASA's CHANDRA Inspired a Neutron Microscope

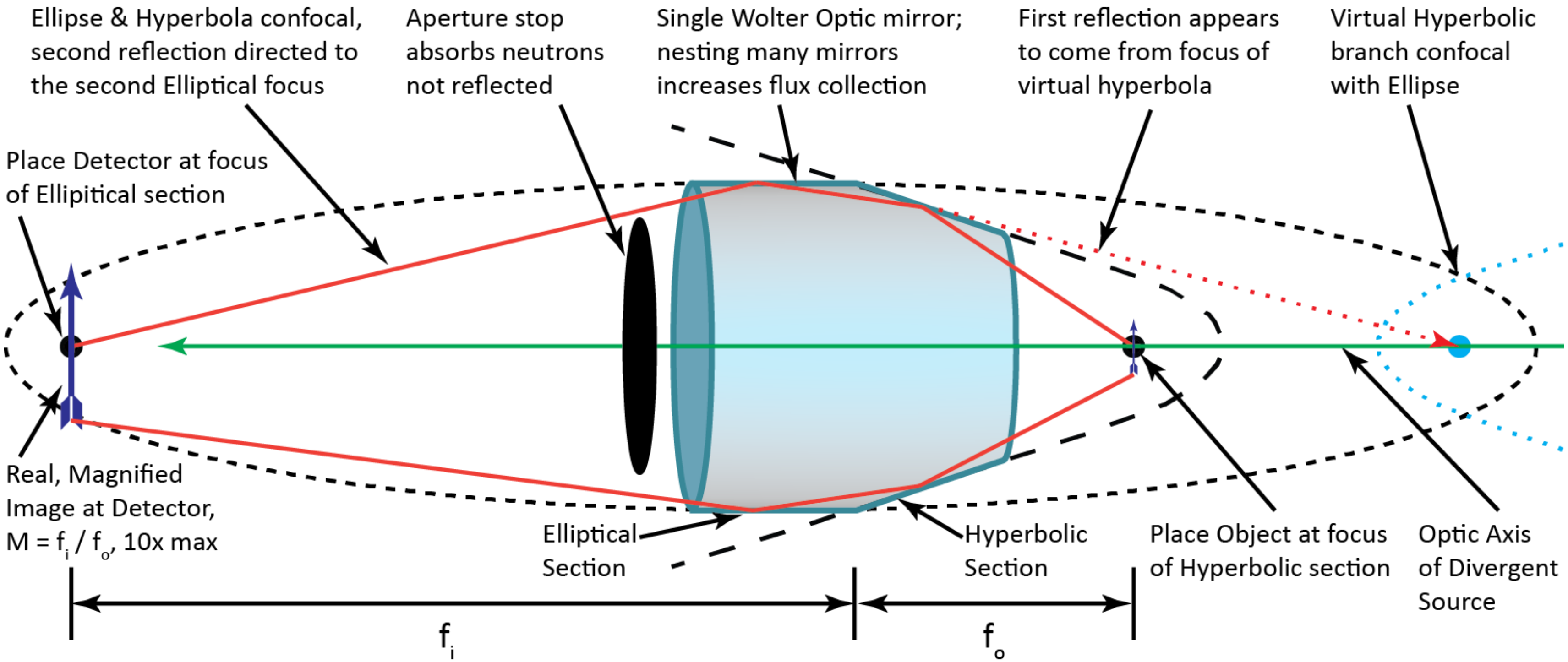
- Faint x-ray sources (nebula, etc.) need to be focused for good imaging
- In CHANDRA, the mirrors are coated on 2 cm thick glass substrates, which are heavy for space flight, and impractical for neutrons
- NASA is developing a new fabrication technique to create Wolter Optics from nested Ni-foil mirrors – light for space telescopes and *perfect for neutrons*
- NASA is excited by non-space applications
- Resolution from the lens not collimation
- No collimation for resolution can yield *100-1000 flux increase* for imaging
- Magnification of 10x can improve *spatial resolution to 1 μm*
- ***Ongoing collaboration with Boris Khaykovich (MIT), Dahzi Liu (MIT), and Misha Gubarev (NASA) to further develop the technology for fuel cell imaging***



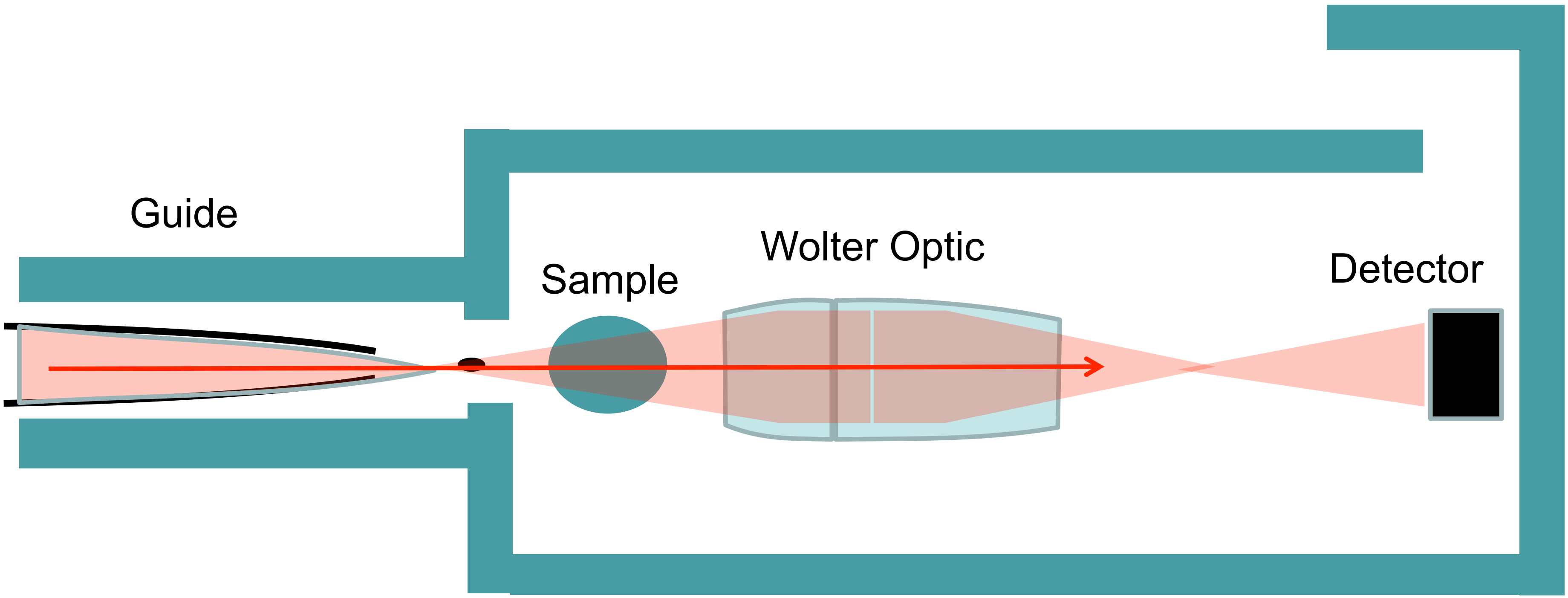
Wolter Optics power CHANDRA

Ni-foil Focused X-ray Solar Imager

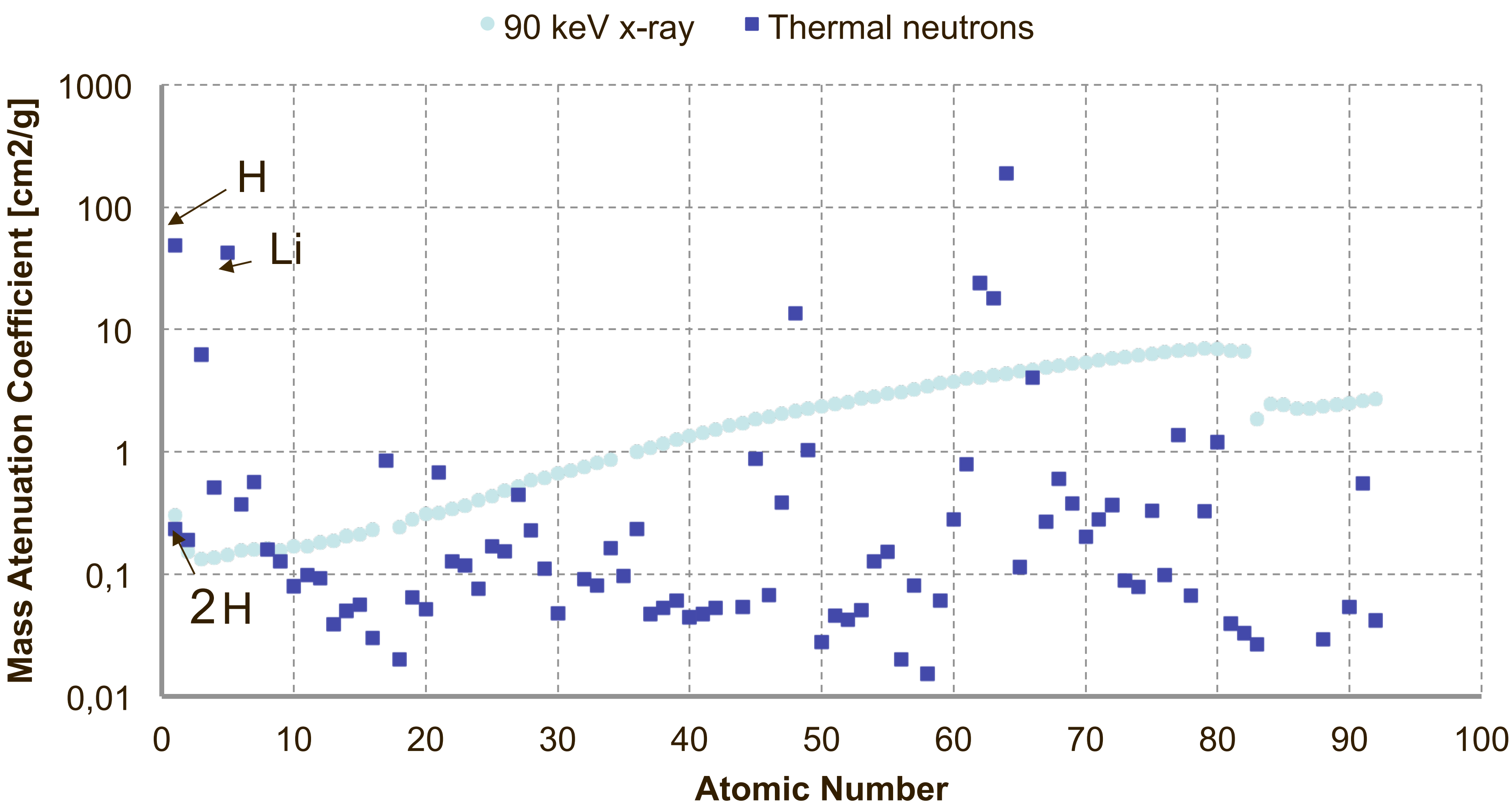
Geometry of a Neutron Microscope using Wolter Optics



Strawman Neutron Imaging Instrument

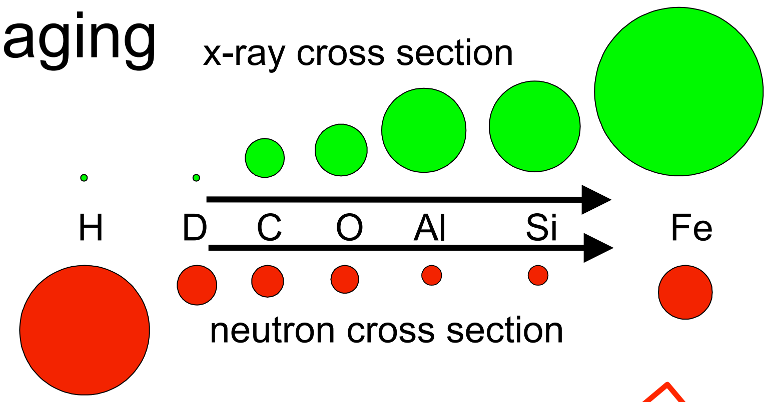


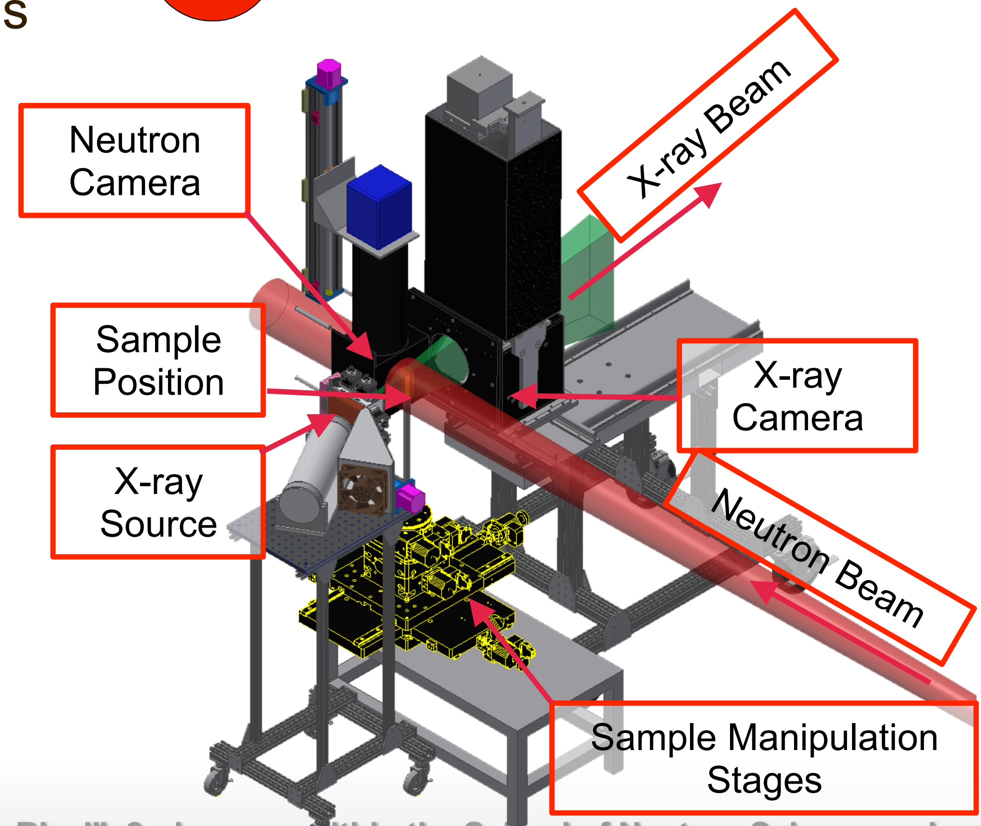
Neutron and X-Ray Complementarity



Simultaneous Neutron and X-ray Imaging

- Installed June 2015
- Image the same sample region with x- & n-ray to improve composition determination
- Can match image spatial resolutions or have superior x-ray resolution
- X-ray microfocus
  - 20 keV – 90 keV
  - 80 W max power
  - 20 μm spot size





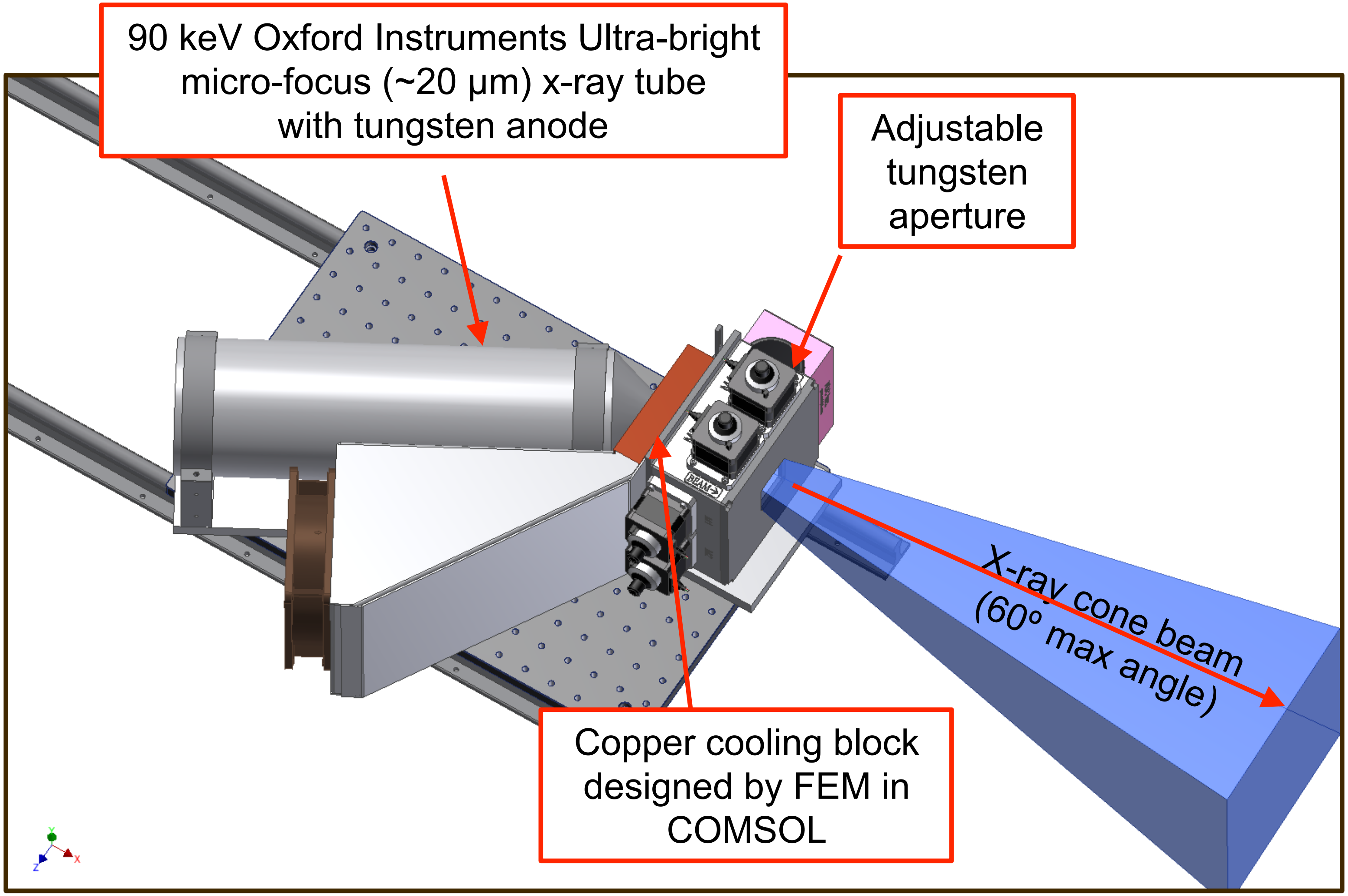
Rich, complementary data set from combined x-ray and neutron tomography

A Hot Wheels car (right) was imaged with neutrons (bottom left) and x-rays (bottom right)

Neutron image

X-ray image

X-ray Source


90 keV Oxford Instruments Ultra-bright micro-focus (~20 μm) x-ray tube with tungsten anode
Adjustable tungsten aperture
X-ray cone beam (60º max angle)
Copper cooling block designed by FEM in COMSOL

R.A. Livingston, A.M. Amde, and S. Feuze, Univ. of MD

Tomography of Concrete: Ettringite Phase

Electron microscopy used at select locations shows presence of Ettringite growth

Bright rims around aggregates