Neutron Tomography, Imaging, and PEM Fuel Cells

Facility Staff
David L. Jacobson
Daniel S. Hussey
Elias Baltic
Muhammad Arif
Physics Laboratory

Project Design Engineer
James LaRock
Center for Neutron Research

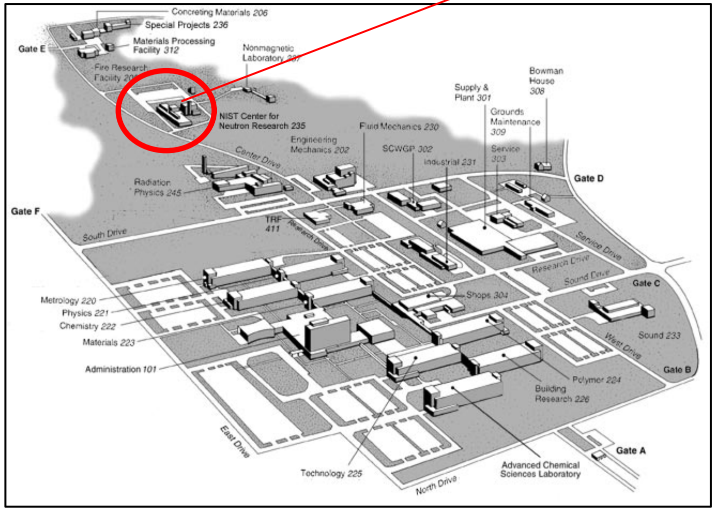
NIST

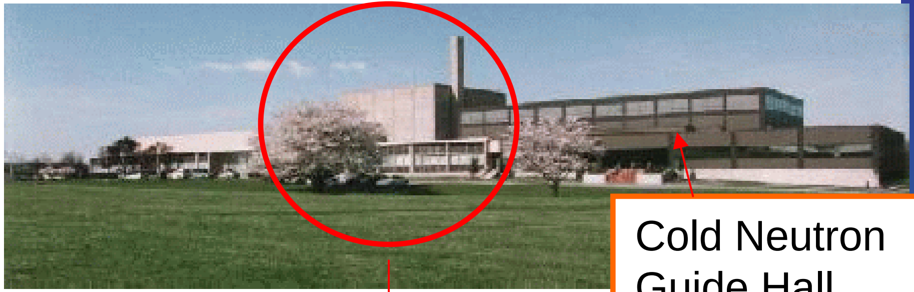
National Institute of
Standards and Technology
Technology Administration
U.S. Department of Commerce

Fuel Cell Partners
Jon Owejan
Jeffrey Gagliardo
Thomas Trabold
General Motor Fuel Cell Activities

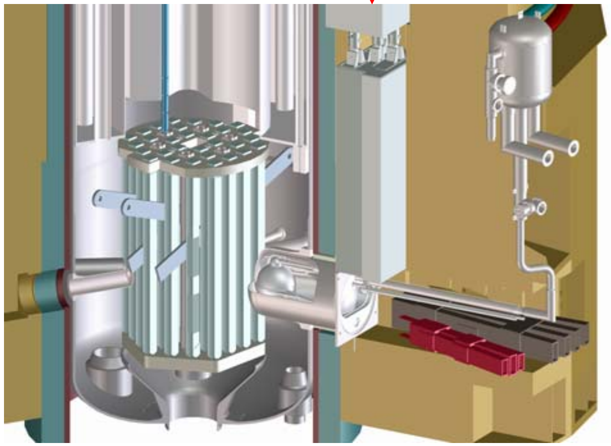
National Institute of Standards and Technology Center for Neutron Research

- Gaithersburg, Maryland Main campus 234 hectare (578 acre)
- Boulder, Colorado 84 hectare (208 acre)
- Annual operating budget of about $771 million
- NIST employs about 3,000 scientists, engineers, technicians, and support and administrative personnel.
- About 1,800 guest researchers complement the staff.
- In addition, NIST partners with 2,000 manufacturing specialists and staff at affiliated centers around the country.





Cold Neutron Guide Hall

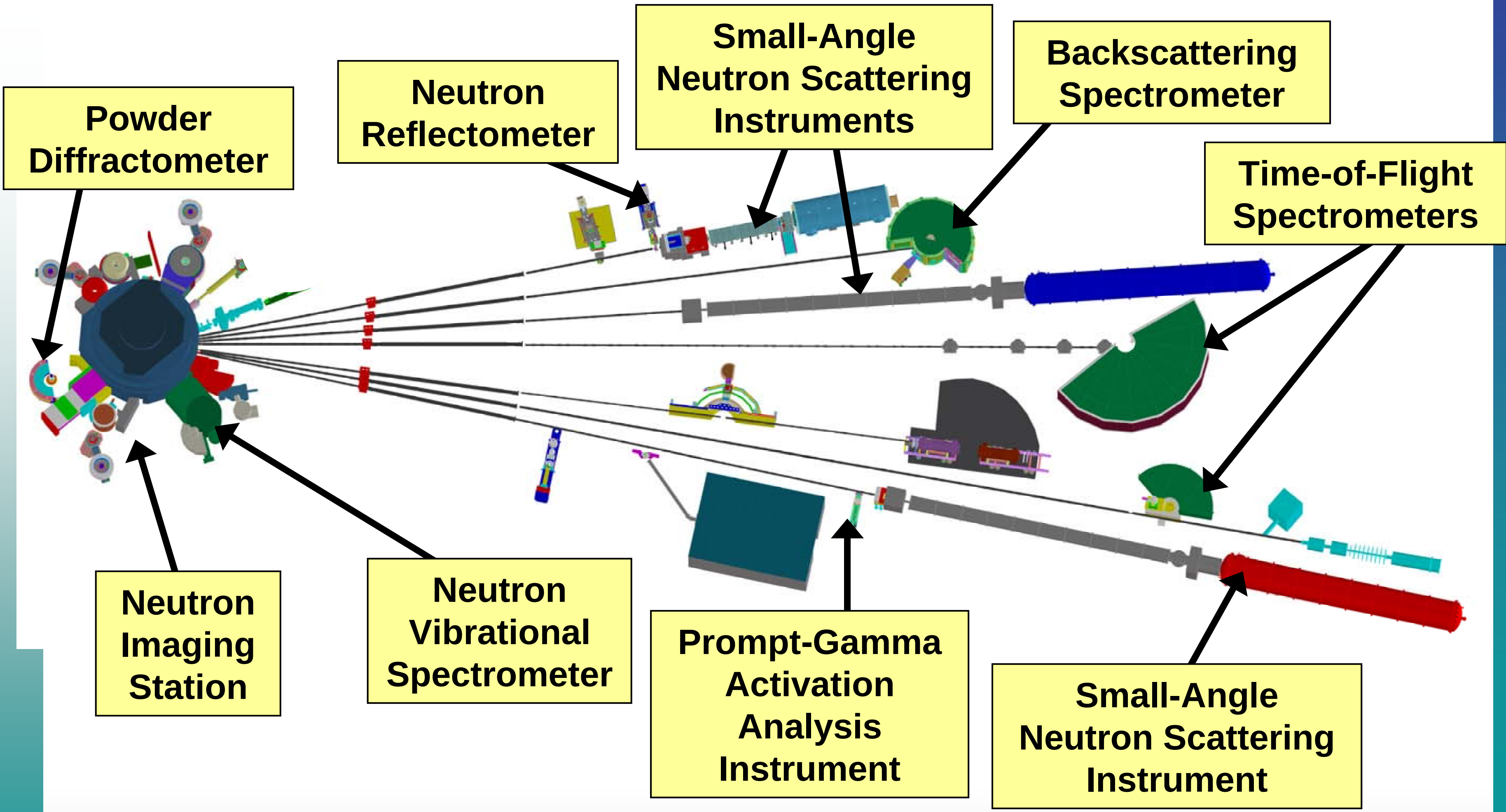


20 MW NBS Reactor

- 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 11 day shutdown for roughly 240 – 280 days/year

NIST **Neutron Imaging Facility**: http://physics.nist.gov/MajResFac/NIF/index.html

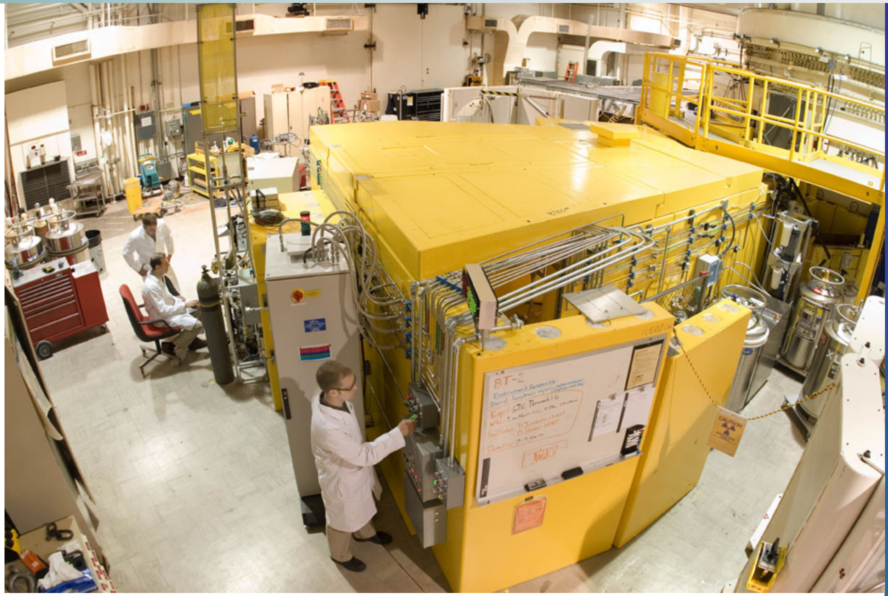
Neutron Instrumentation for Hydrogen-Materials Research at NIST

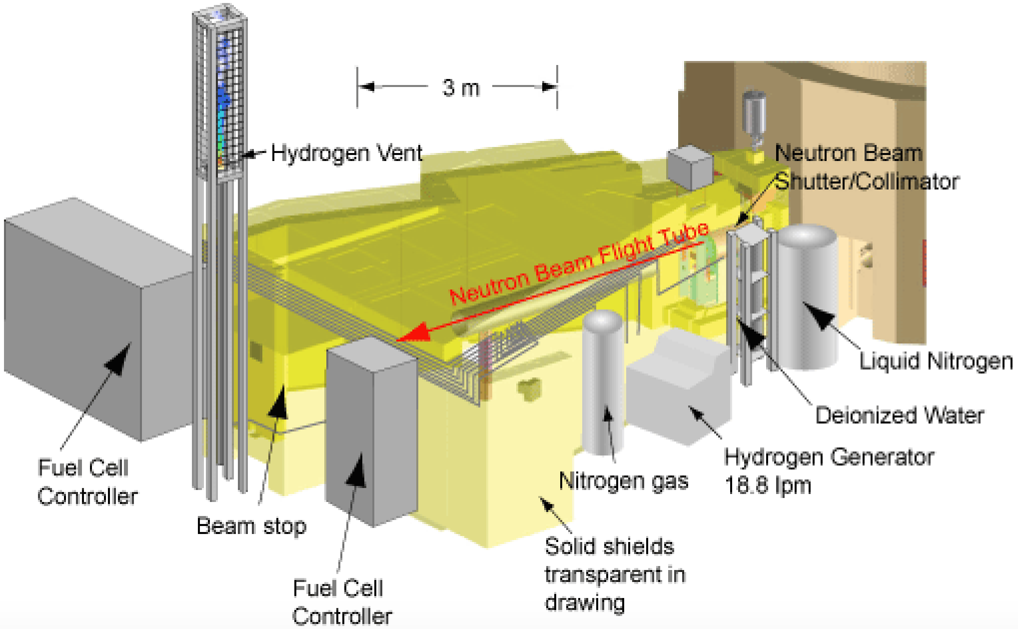


 Neutron Imaging Facility: http://physics.nist.gov/MajResFac/NIF/index.html

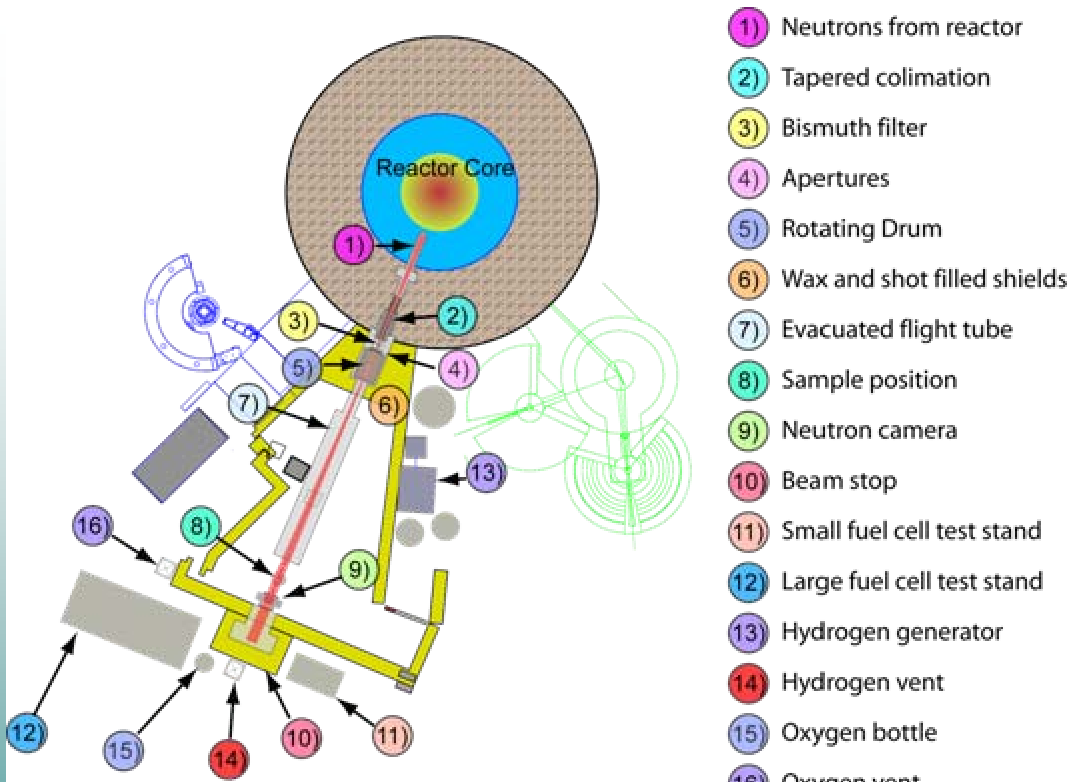
Neutron Imaging Facility

- New facility replaced first facility built in 2003.
- New facility first users February 27, 2006
- Located at BT-2
- Much bigger 30 m^3
- House gases/fluids
  - Hydrogen (18.8 slpm)
  - Oxygen (11.1 slpm)
  - Nitrogen
  - Air
  - Deionized water
  - Chilled water
- Freeze chamber for low temperature testing (-40 ^oC)
- Fuel cell test stands available and supported by NIST staff





Schematic of New Facility

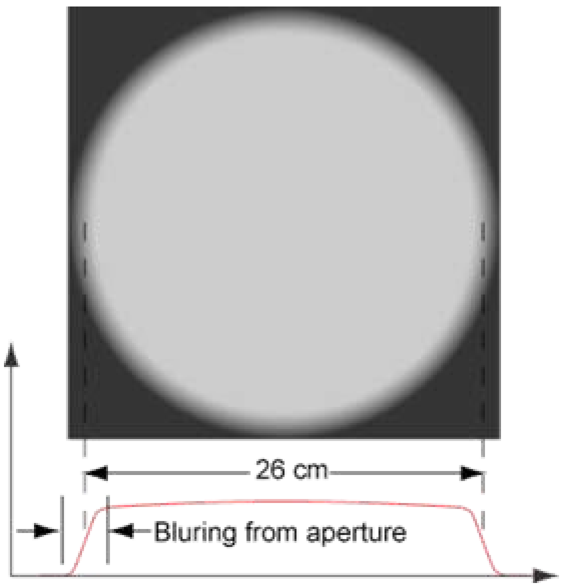


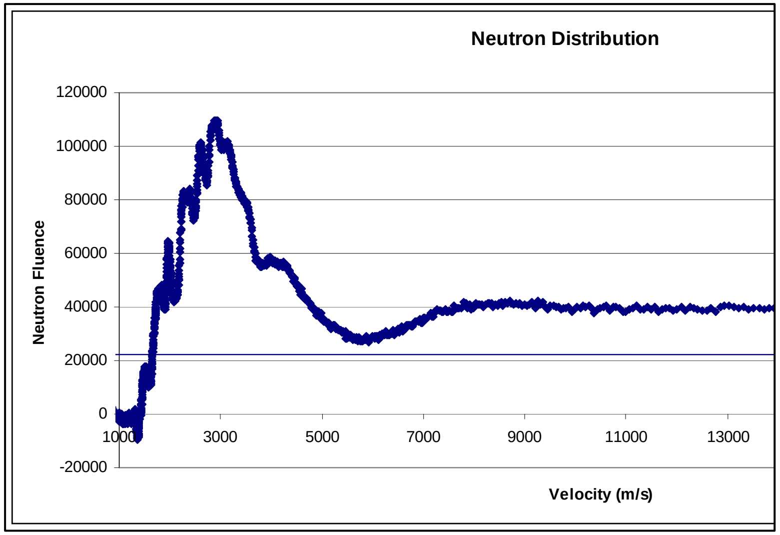
Neutron Imaging Facility: http://physics.nist.gov/MajResFac/NIF/index.html

Beam Properties

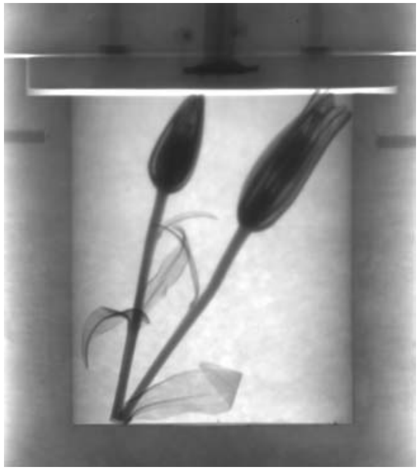
L (m)	D (cm)	L/d	Beam Dia. (cm)	Fluence Rate (s^{-1} cm^{-2})	Fluence Rate No Bismuth (s^{-1} cm^{-2})
2	2	100	8	1.1 $x10^{8}$	3.0 $x10^{8}$
3	2	150	13	6.8 $x10^{7}$	2.0 $x10^{8}$
4	2	200	17	5.0 $x10^{7}$	1.5 $x10^{8}$
6	2	300	26	3.3 $x10^{7}$	1.0 $x10^{8}$
6	1.5	400	26	2.0 $x10^{7}$	5.9 $x10^{7}$
6	1.0	600	26	9.0 $x10^{6}$	2.5 $x10^{7}$
6	0.5	1200	26	2.0 $x10^{6}$	5.9 $x10^{6}$
6	0.1	6000	26	7.8 $x10^{4}$	2.5 $x10^{5}$

At 6 m



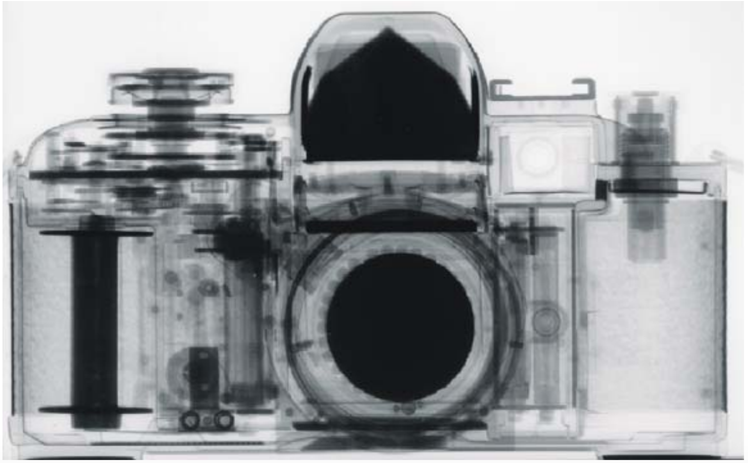


Why Neutron Radiography?

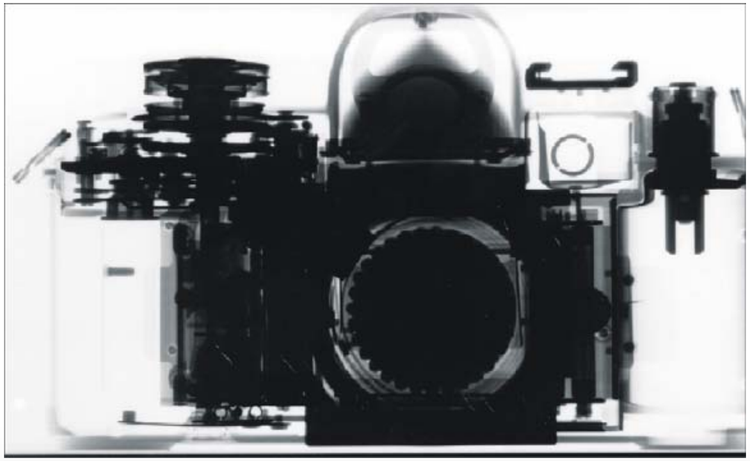


- Neutrons see material differently than x-rays
- The fine details of the water in this Asiatic Lily are clear to neutrons even in a lead cask
- Neutron methods described as complimentary to x-ray methods see the images of the camera below.

Neutron Image of an SLR camera. The metal casing is nearly transparent, while the plastic film reel is easily seen. Also visible are the film advance gears and details of the shutter.

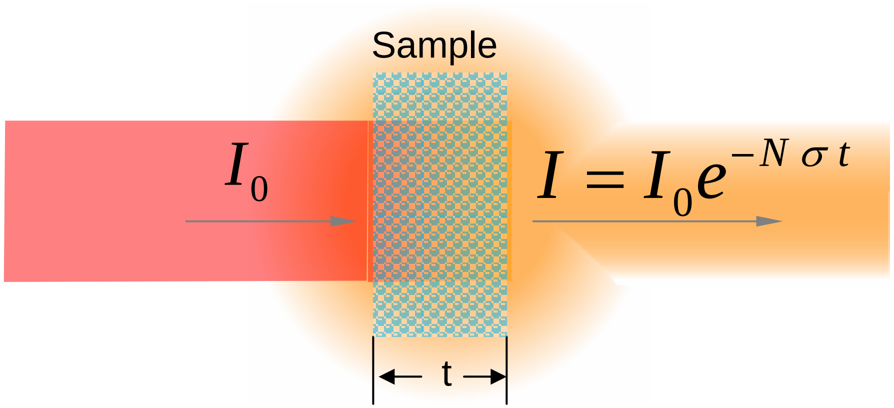


X-Ray Image of an SLR camera. The plastic film reel is invisible to the x-rays. The metal casing obscures the inner workings of the film advance mechanism and the shutter.



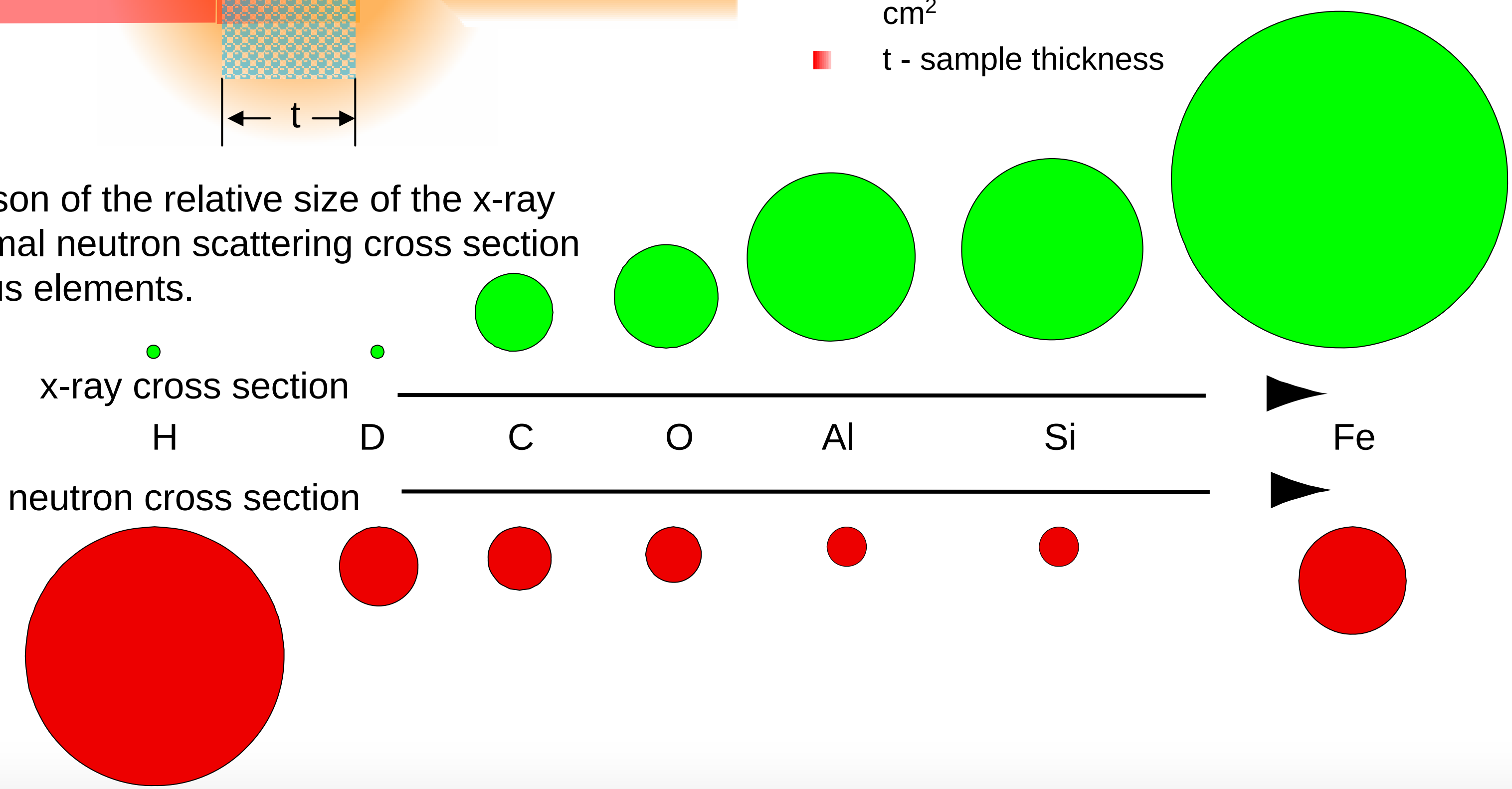
Neutron cross section versus x-ray cross section

Neutrons are an excellent probe for hydrogen in metal since metals can have a much smaller cross section to thermal neutrons than hydrogen does.



- N – numerical density of sample atoms per cm^3
- I_0 - incident neutrons per second per cm^2
- σ - neutron cross section in ~ 10^{-24} cm^2
- t - sample thickness

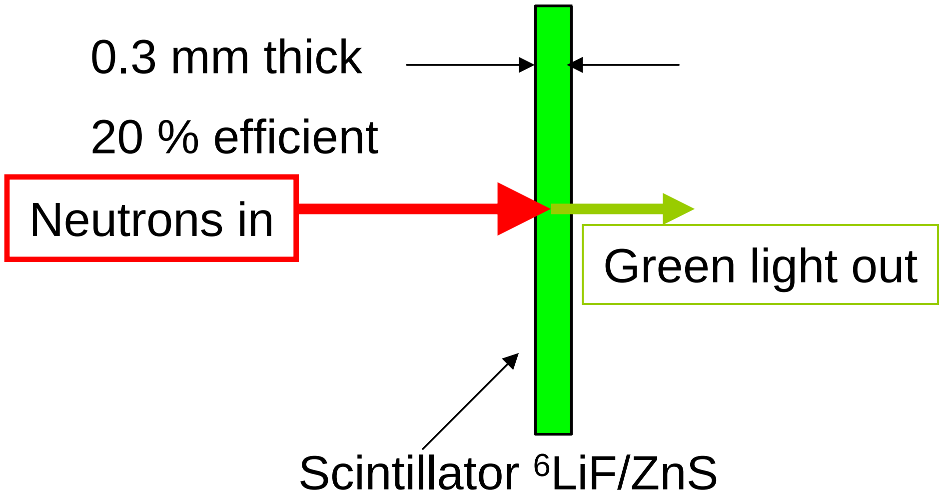
Comparison of the relative size of the x-ray and thermal neutron scattering cross section for various elements.



Neutron Imaging (how we produce an image)

- We don't directly detect the neutron
- Special isotopes that are highly absorbing (^{6}Li, ^{10}B) are used to capture neutrons.
  - $^{6}Li + n^{0} \rightarrow {}^{4}He + {}^{3}H + 4.8$ MeV
- Resulting nuclear reaction produces charged particles with Mega electron volt energies.
- Converter (traditionally ZnS) stops the particles (see top right photo).
- Energy lost by the particles generates a lot of light.
- The spatial resolution of the $^{6}LiF/ZnS$ converter is limited not by the nuclear reaction (this has a 10 micron range), but by the spread of light in the converter. Typically this is about 200 to 300 micrometers or more due to the thick screens needed for high efficiency.

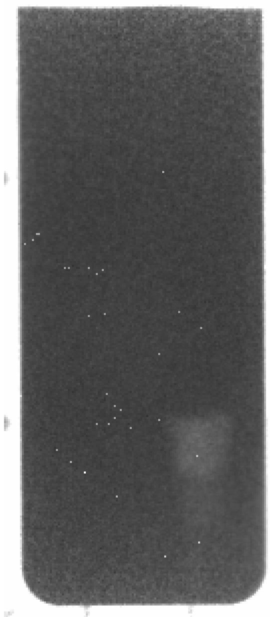
$^{6}Li + n^{0} \rightarrow {}^{4}He + {}^{3}H + 4.8$ MeV



Neutron Imaging Facility: http://physics.nist.gov/MajResFac/NIF/index.html

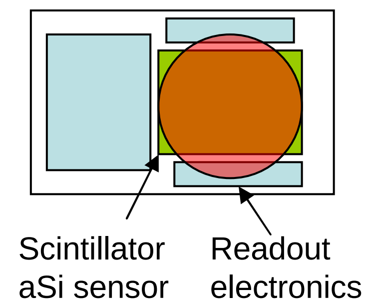
Current Detector Technology

- Amorphous silicon
- Radiation hard
- High frame rate (30 fps)
- 127 micrometer spatial resolution
- Picture is of water with He bubbling through it
- No optics – scintillator directly couples to the sensor to optimize light input efficiency

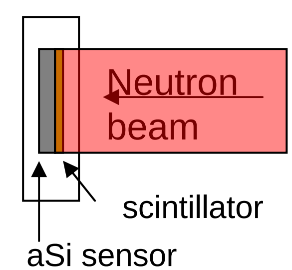


Helium through water at 30 fps

Front view



Side view



NIST **Neutron Imaging Facility**: http://physics.nist.gov/MajResFac/NIF/index.html

High Resolution: What's the limit?

- ^{6}LiF/ZnS:Cu,Al,Au converter is limited in spatial resolution to about 100 microns.
- If the converter could make use of the 10 micrometer range of the charged particles, then 10 micrometer spatial resolution is possible.
- A current collaboration aims to achieve this using a radically new method to detect neutrons.
- Future speculative methods could achieve even sub-micrometer resolution by making use of the energy lost in the converter by the charged particles to further define the position of the neutron absorption event.

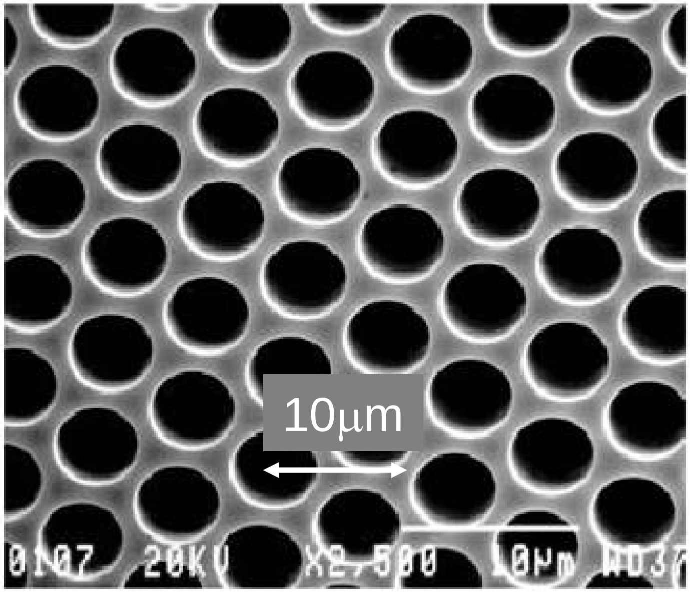
Collaboration

Space Sciences Laboratory, University of California, Berkeley, CA, 94720

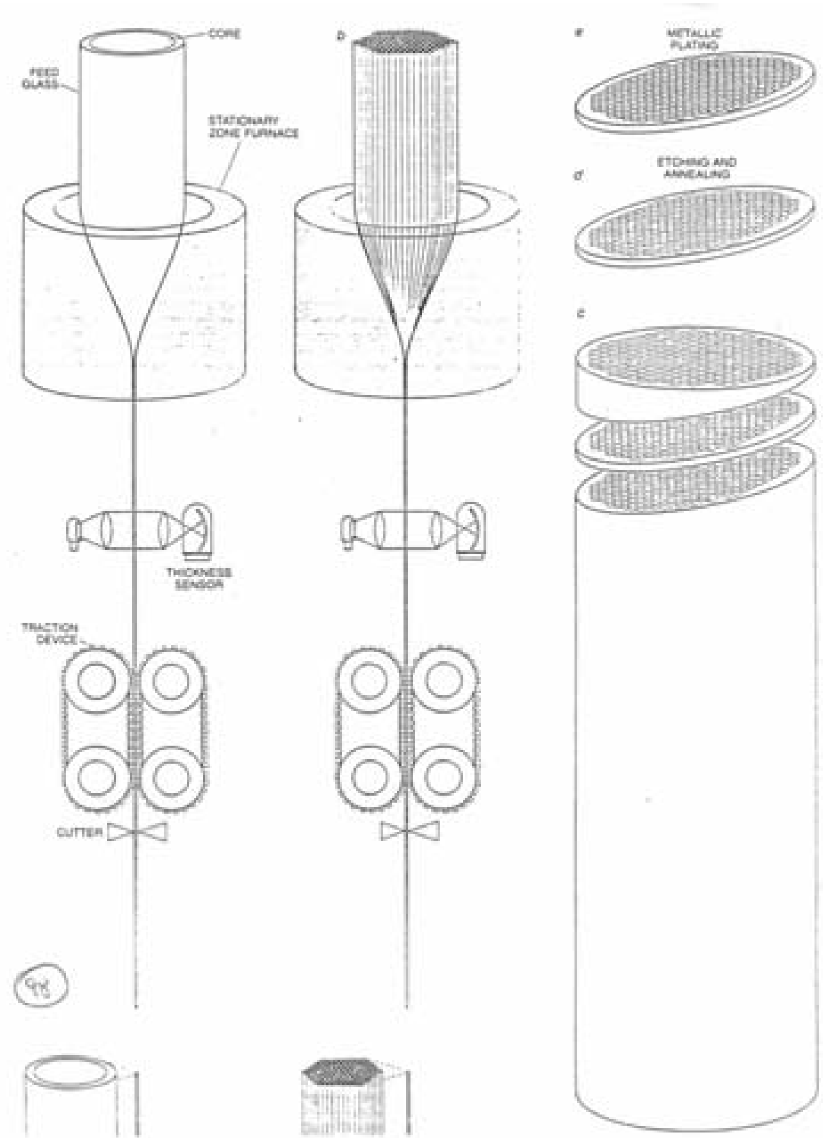
Sensor Sciences LLC, 3333 Vincent Road, Suite 103, Pleasant Hill, CA 94523

Nova Scientific Inc. 10 Picker Road, Sturbridge, MA 01566

Microchannel Plate



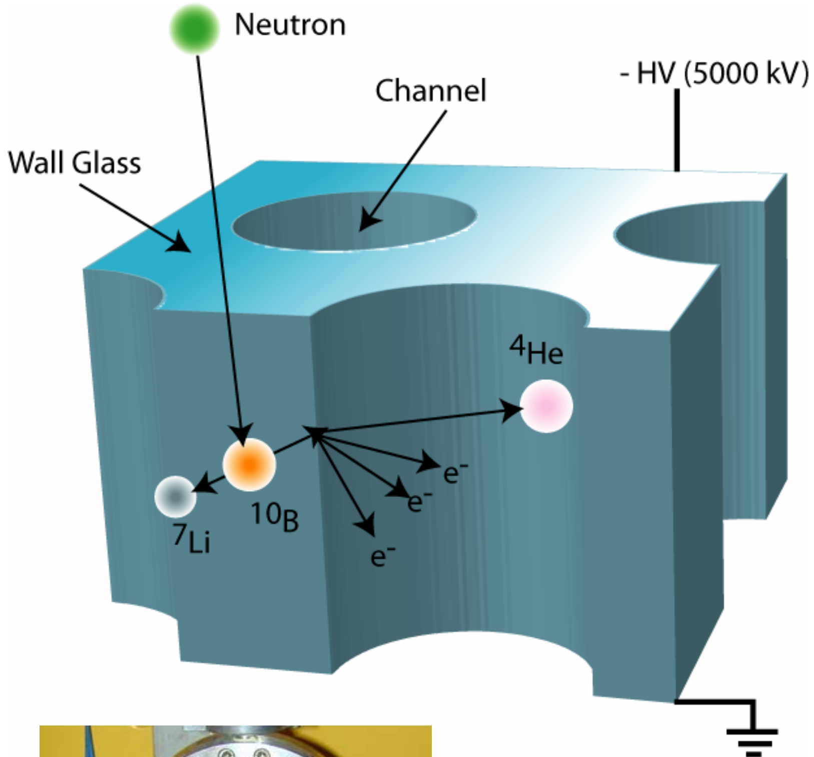
Microscopic view of a Glass Capillary Array with precision 5-micron pores.

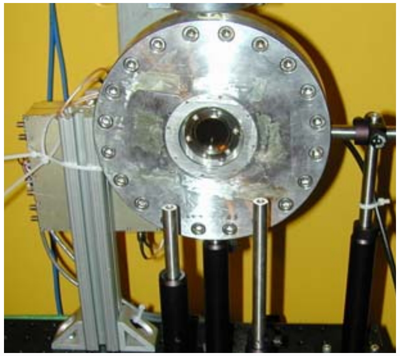


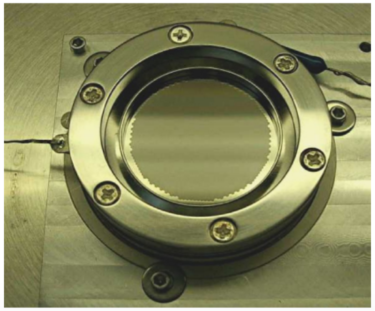
Neutron Imaging with MCPs

$^{10}B \rightarrow {}^{7}Li + {}^{4}He + Q$ (2.79 MeV)

- ^{10}B or ^{nat}Gd in wall absorbs neutron
- Reaction particles initiate electron avalanche down channel
- Charge cloud detected with position sensitive anode
- Spatial resolution limited by channel size and range of charged particle
- Current resolution is 0.025 mm
- Ultimate resolution about 0.01 mm
- Anode read-out is pulse counter
  - 1 % Deadtime at 200 kHz current event rate limit
  - FOV limited to 1 cm^2
- New MCPS and readout expected Spring 08 with 0.01 mm resolution and higher count rate limit

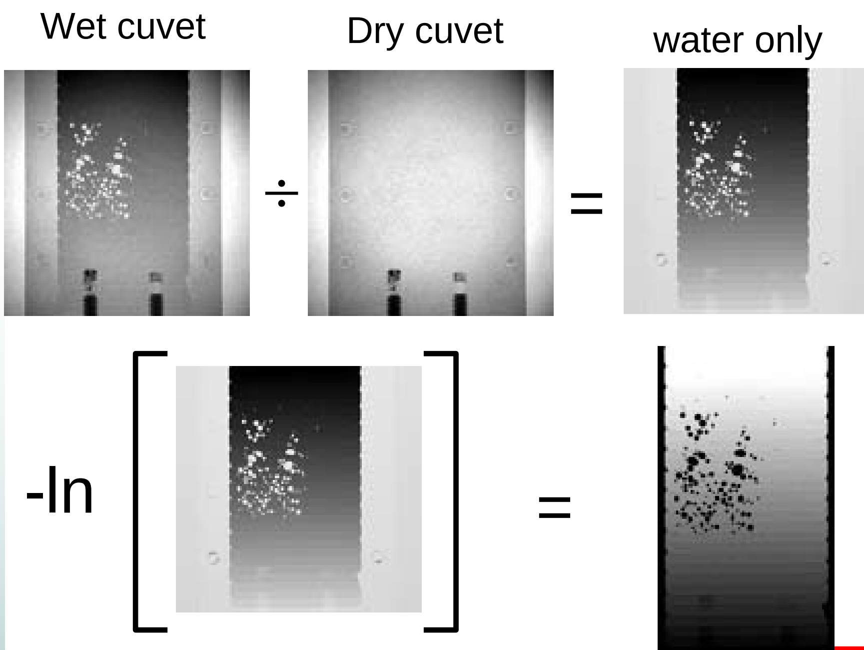


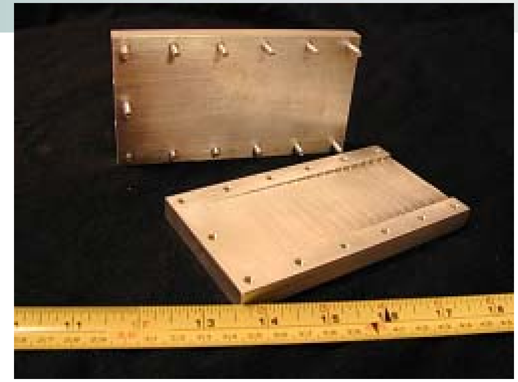




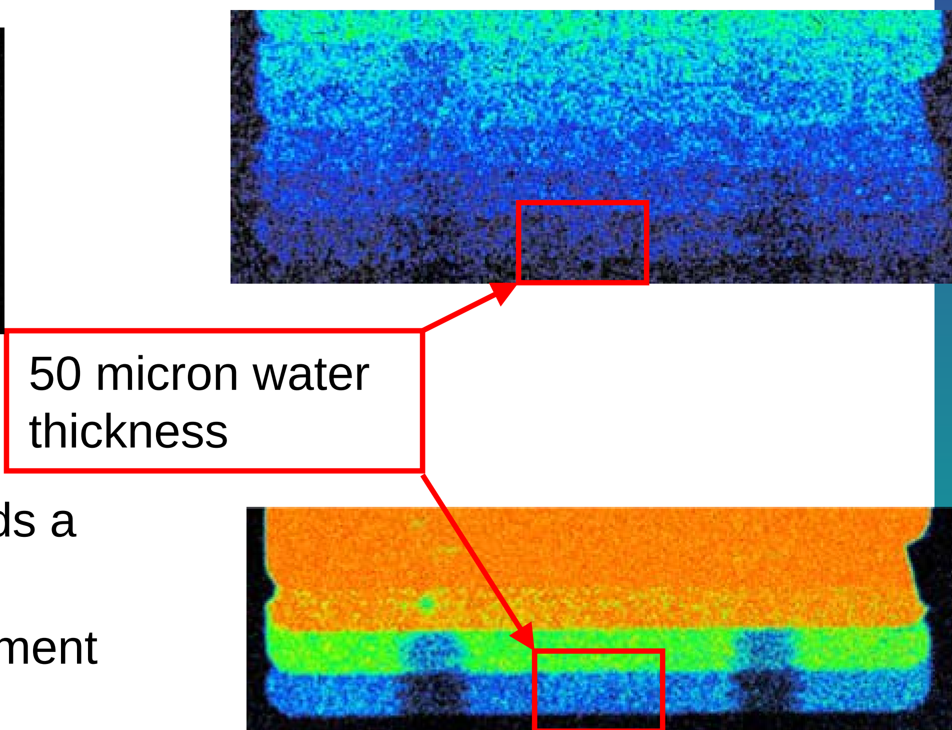
Polymer Electrolyte Membrane Fuel Cells

Water Sensitivity



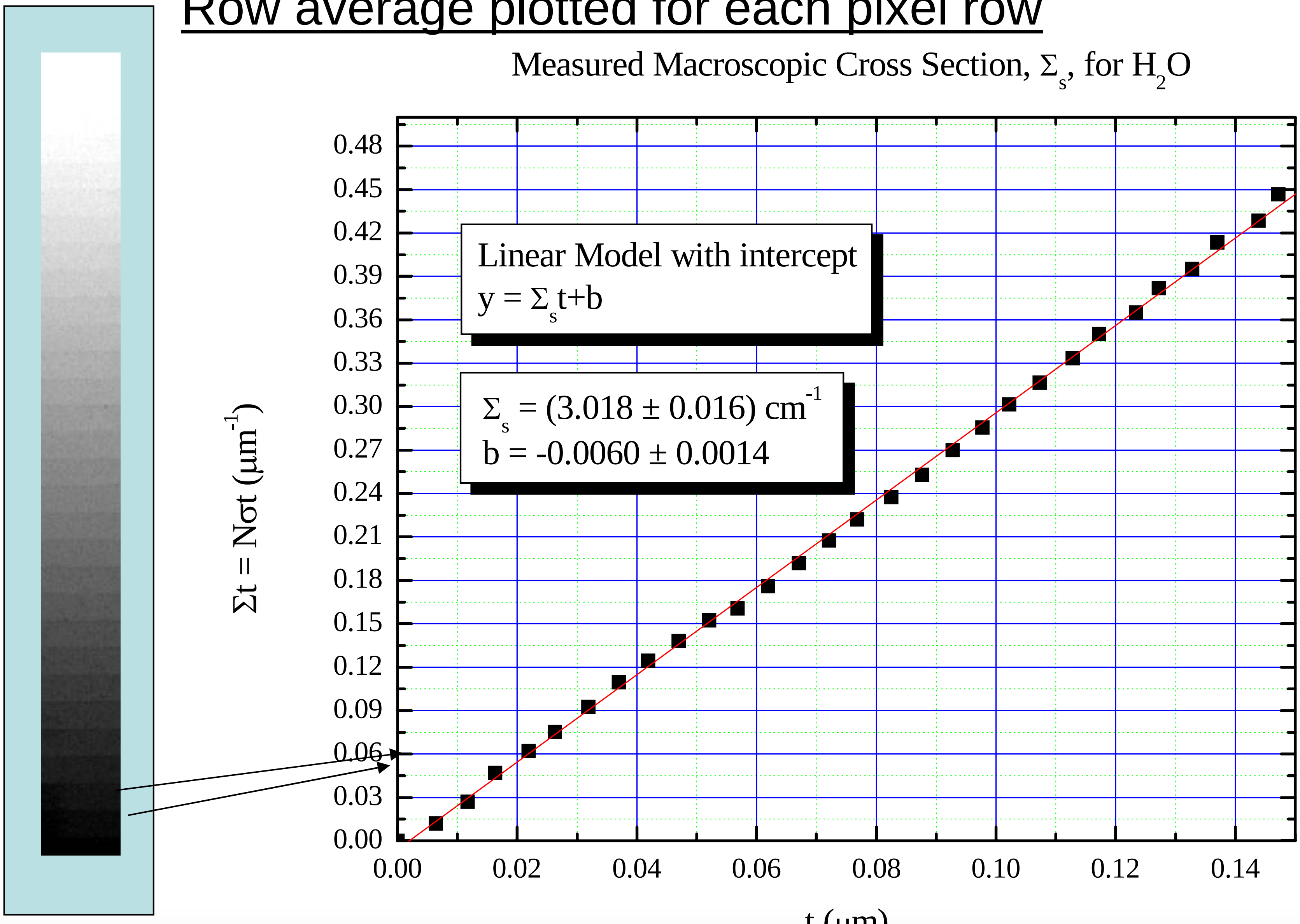


1 s exposure time



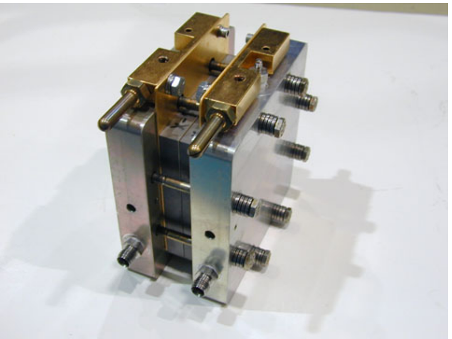
- Steps machined with 50 micron.
- CCD camera exposure of 1 s yields a sensitivity of 0.005 g cm^{-2} s^{-1}
- After 100 s a factor of 10 improvement gives 0.0005 g cm^{-2} s^{-1}

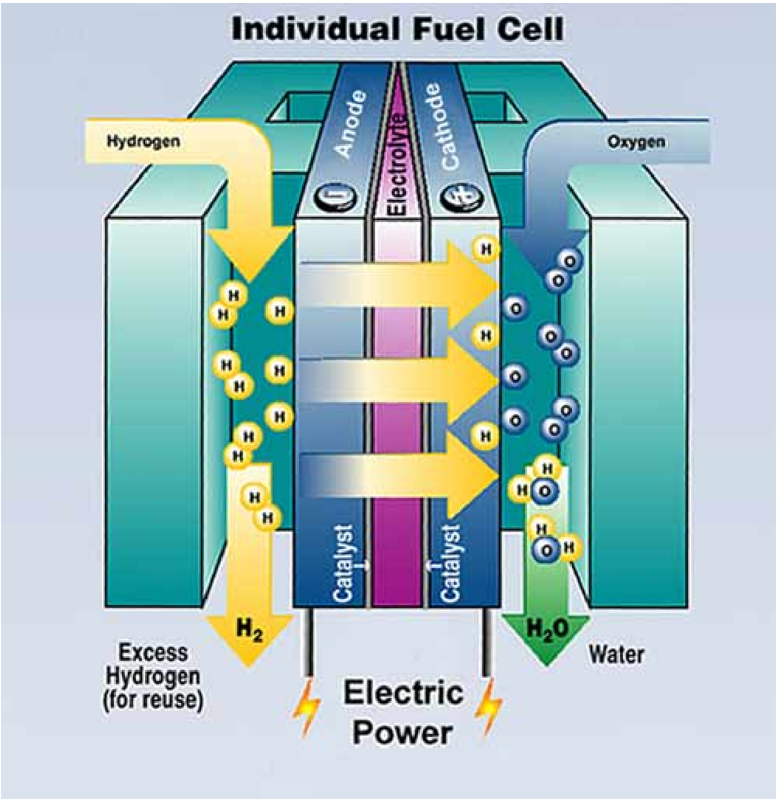
Row average plotted for each pixel row



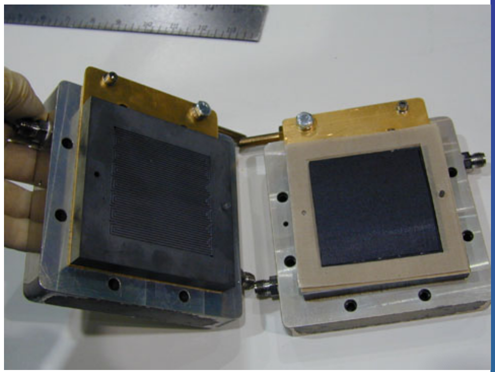
Anatomy of a PEM Fuel Cell

Assembled Cell

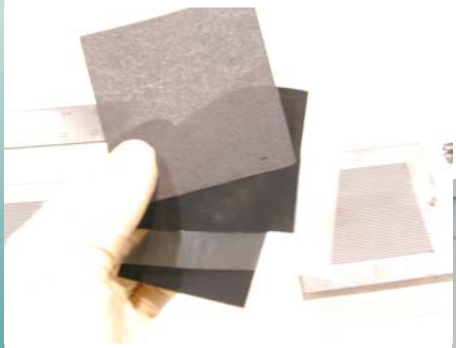


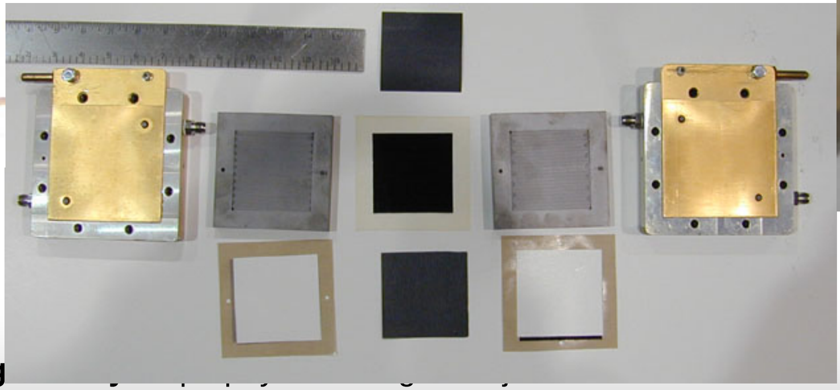


Flow field and soft goods

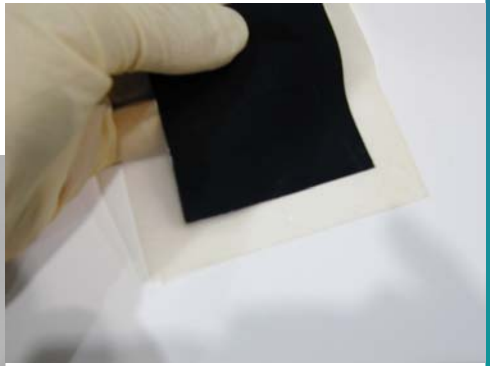


Porous gas diffusion layer GDL

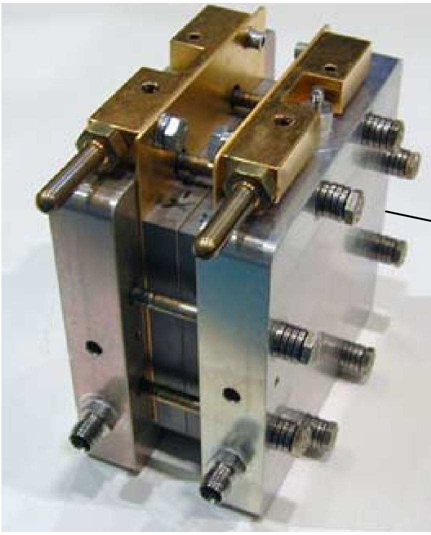


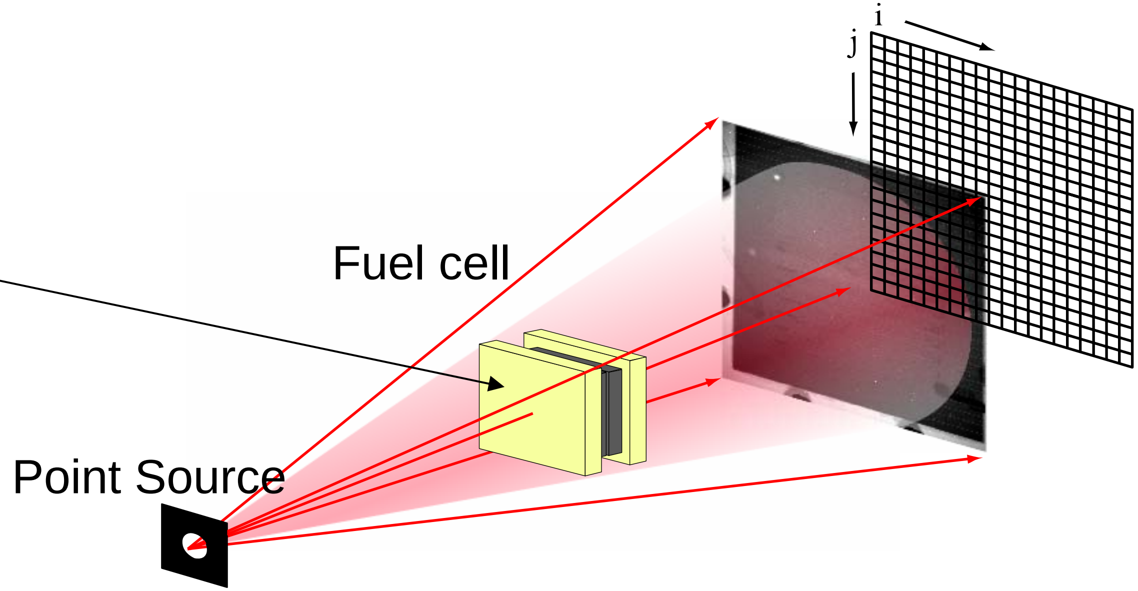


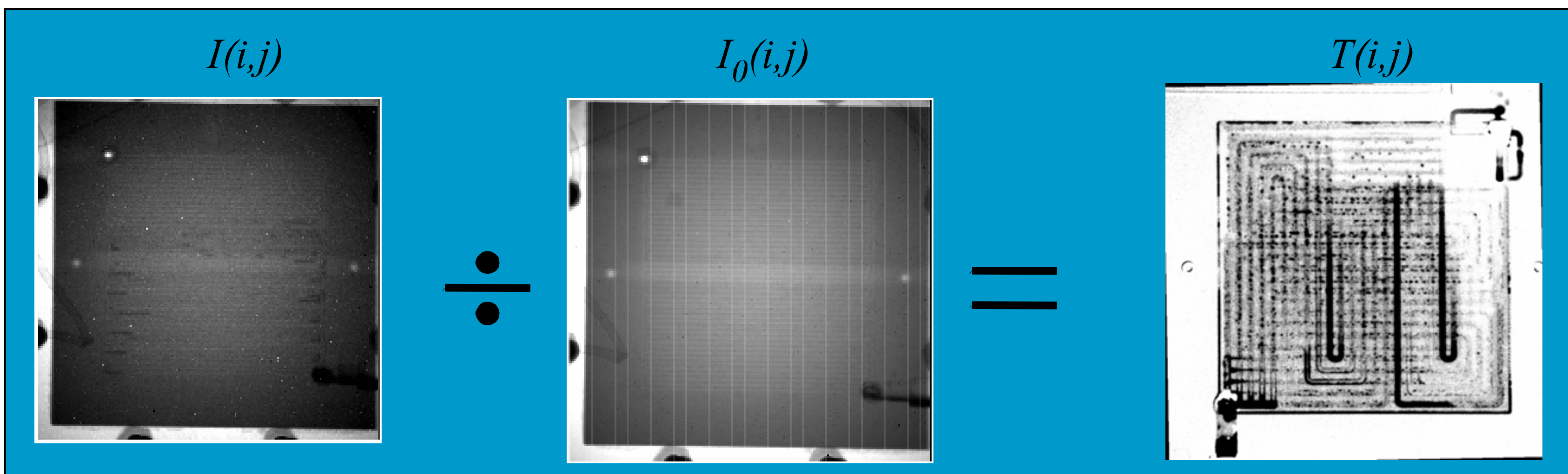
Membrane Electrode Assembly MEA



Imaging Fuel Cells

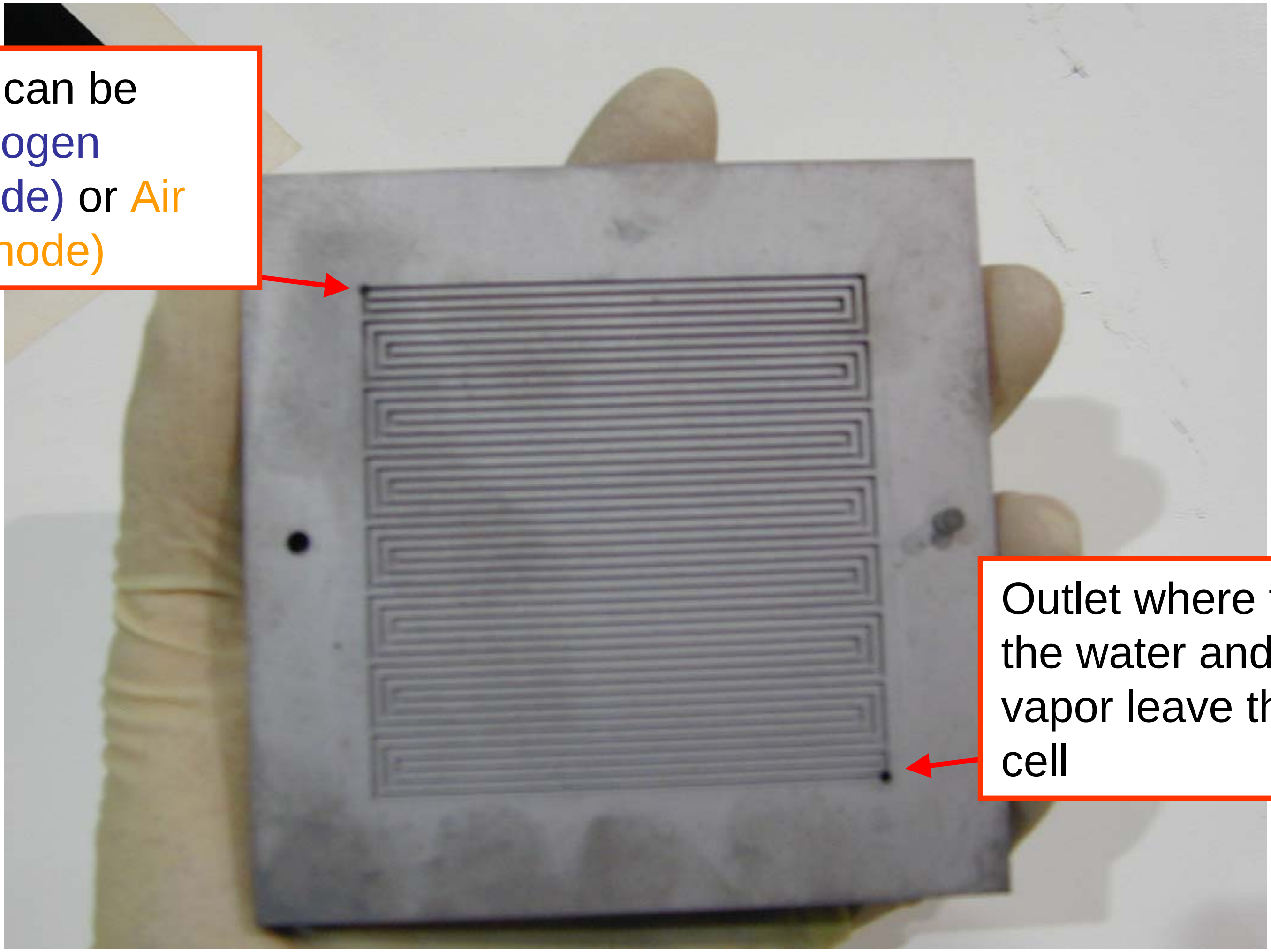






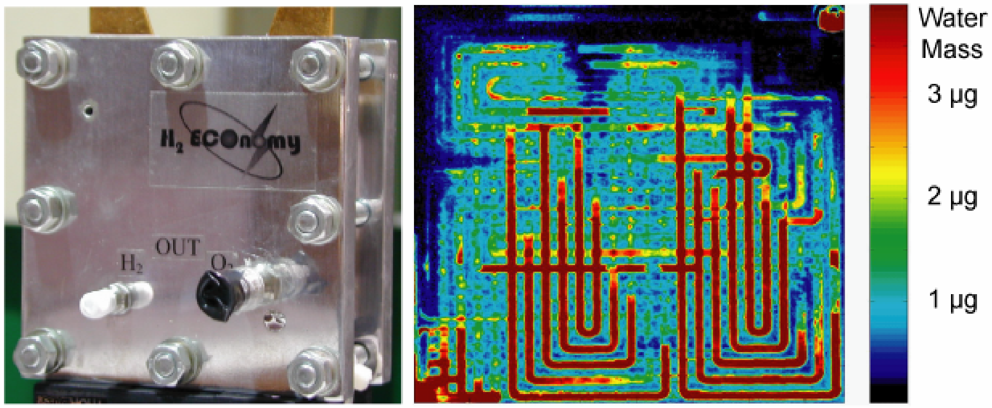
The serpentine flow fields

Inlet can be Hydrogen (Anode) or Air (Cathode)



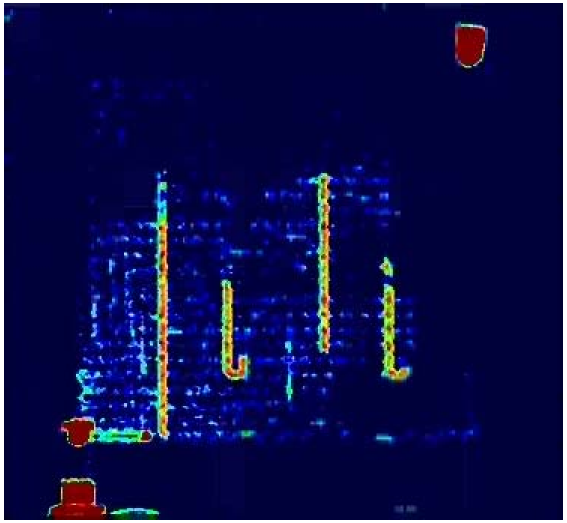
Outlet where the the water and vapor leave the cell

Neutron Imaging for the Hydrogen Economy



Hydrogen Fuel Cells: A little water inside a metal matrix - an ideal problem for neutron imaging.

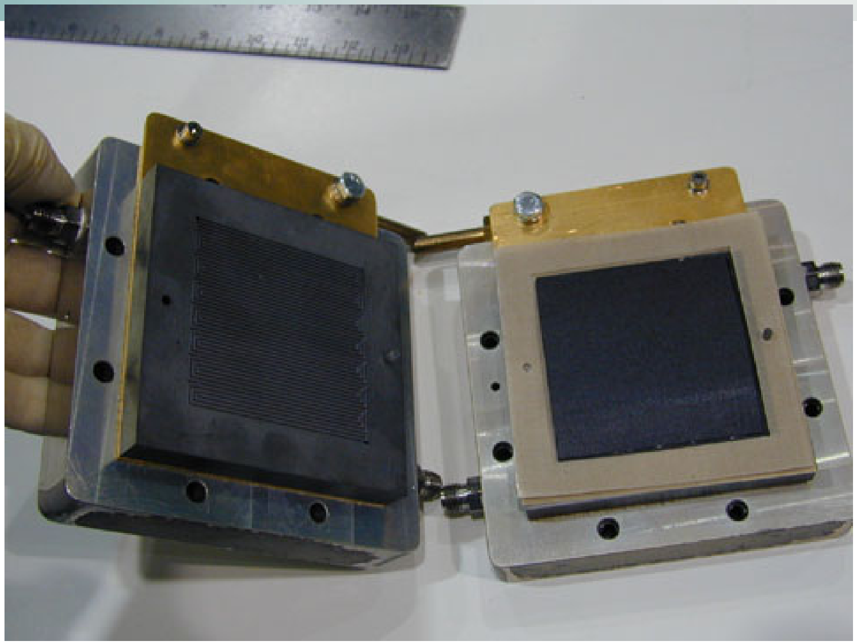
- Neutrons see material differently than x-rays
- Subtle changes in the water distribution inside a running fuel cell impact performance and durability
- Neutron Imaging measures these small changes at video frame rate

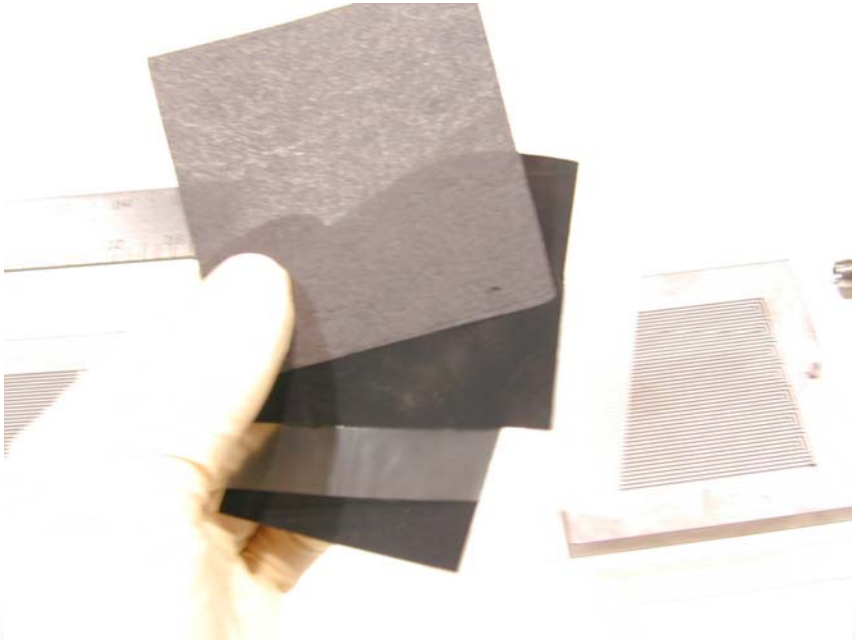


Neutron Imaging Facility: http://physics.nist.gov/MajResFac/NIF/index.html

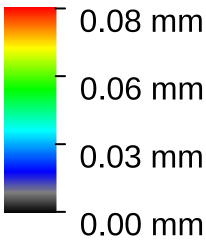
Water Transport

- Cells currently run at or less than 80 ºC.
- Air streams are humidified
  - As fuel stream is used up the carrying capacity is reduced allowing condensation of water
- Evaporation
  - Heat generated locally by the chemical reaction
- Advection/Convection (also ejection)
  - Water is pushed out by the flow stream and/or capillary forces
- Capillary
  - Important but has a much lower impact on total water transport.

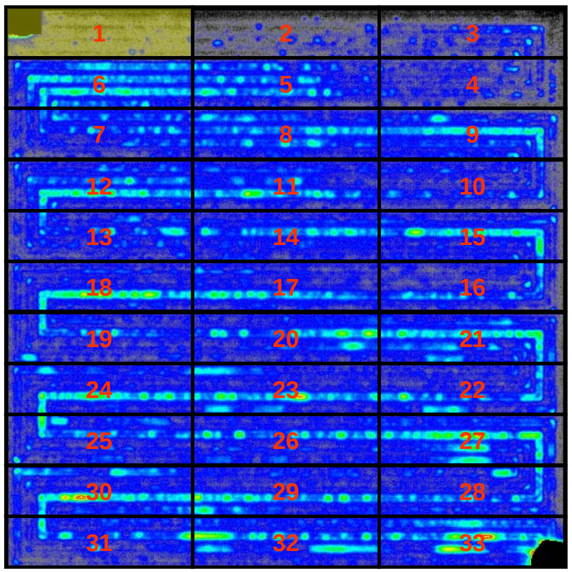




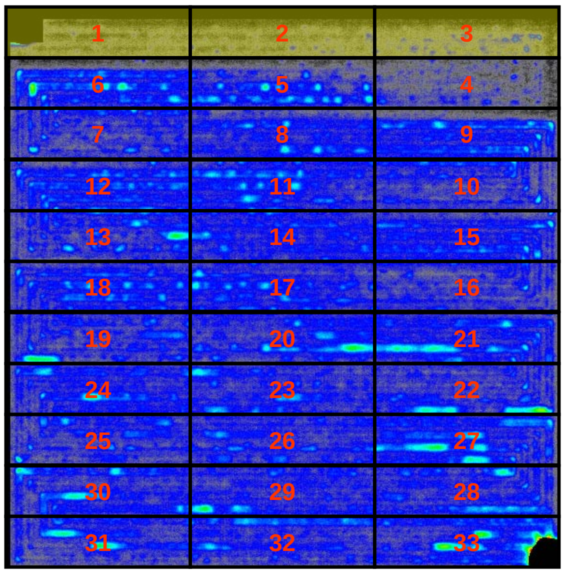
Down-channel condensation – Bulk Cell Temperature of 60°C



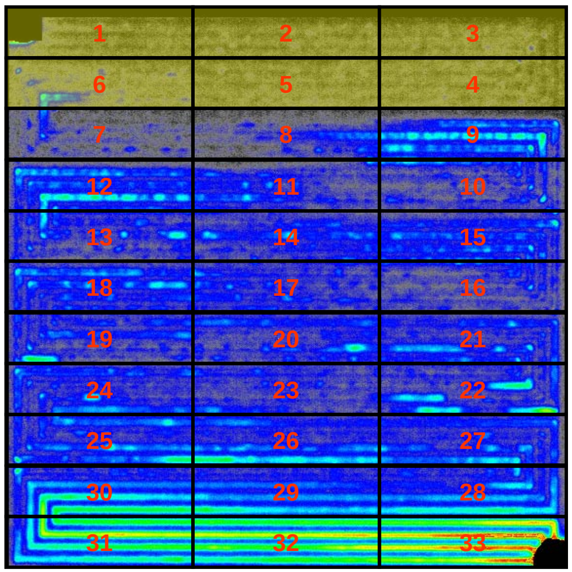
0.5 A/cm²
cell 2 – predicted
cell 2 – actual



1.0 A/cm²
cell 4 – predicted
cell 5 – actual



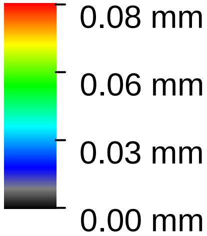
1.5 A/cm²
cell 7 – predicted
cell 8 – actual



Sandia National Laboratories

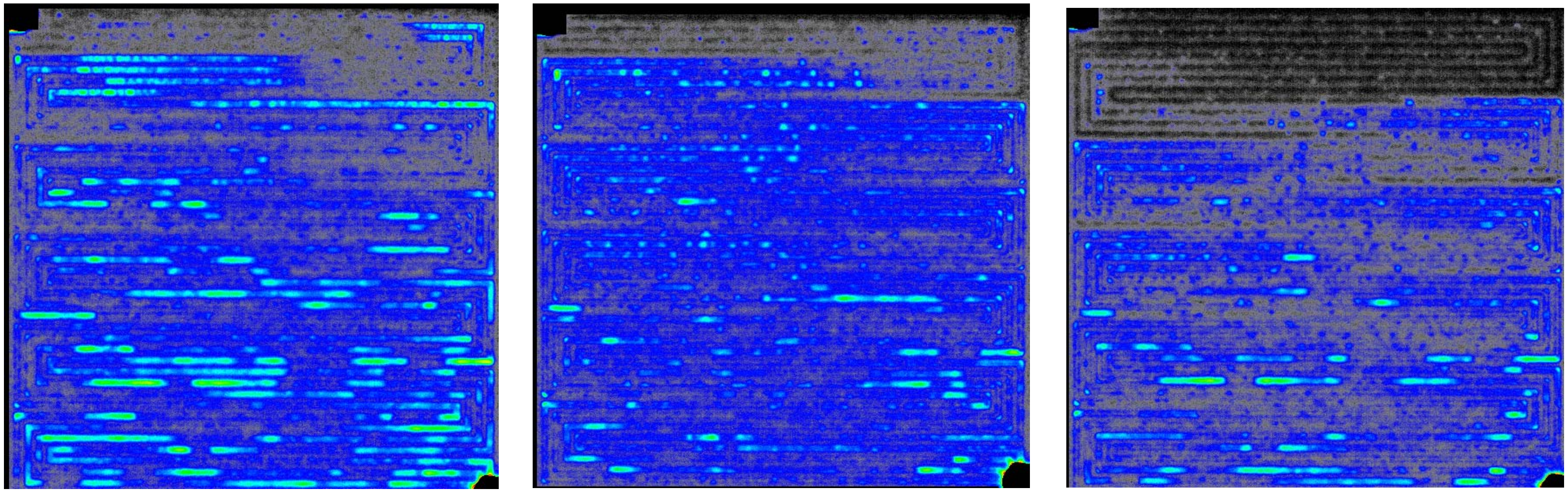
In collaboration with M.A. Hickner, N.P. Siegel, K. S. Chen, D. N. McBrayer

Bulk Temperature Effect on Liquid Water Content



40°C **60°C** **80°C**

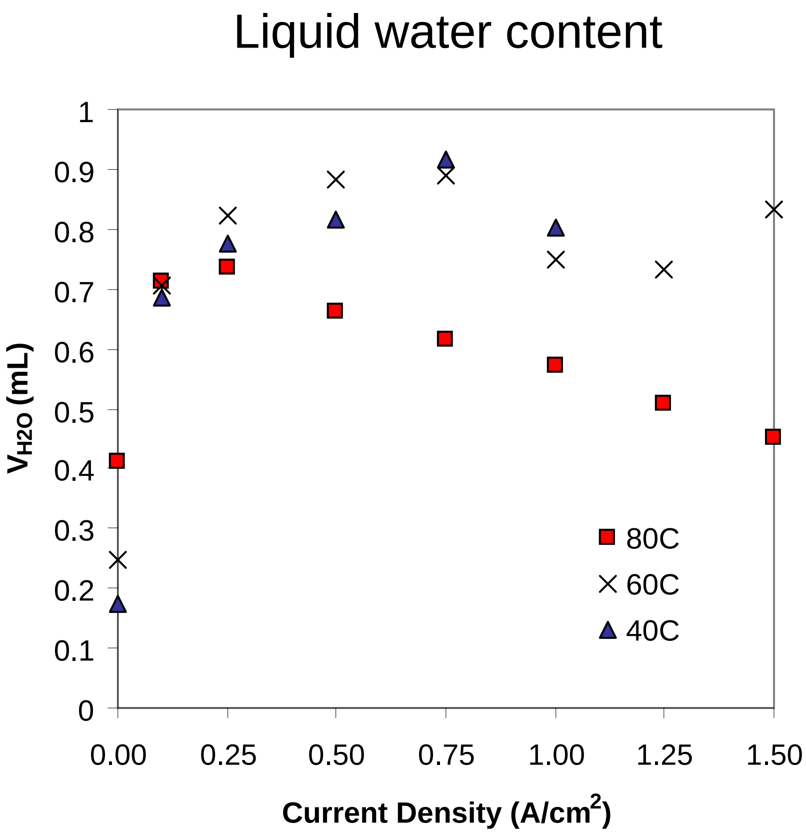
1 A/cm²

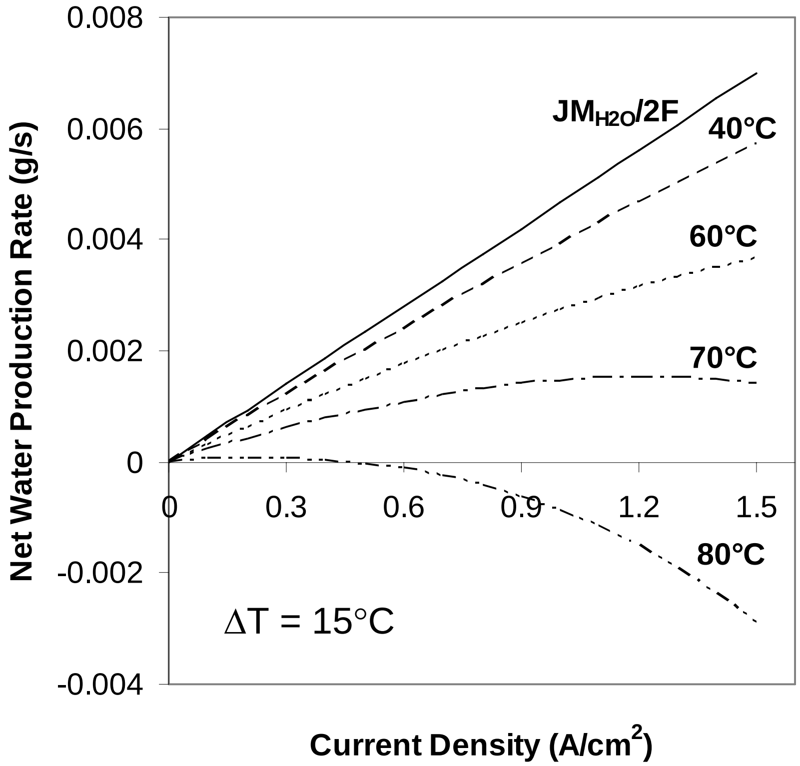


0.80 mL H_2O 0.75 mL H_2O 0.57 mL H_2O

In collaboration with M.A. Hickner, N.P. Siegel, K. S. Chen, D. N. McBrayer

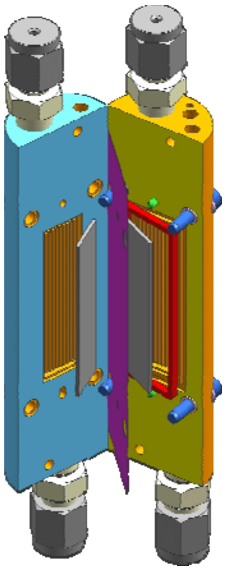
Experimental Data and Current Model Data





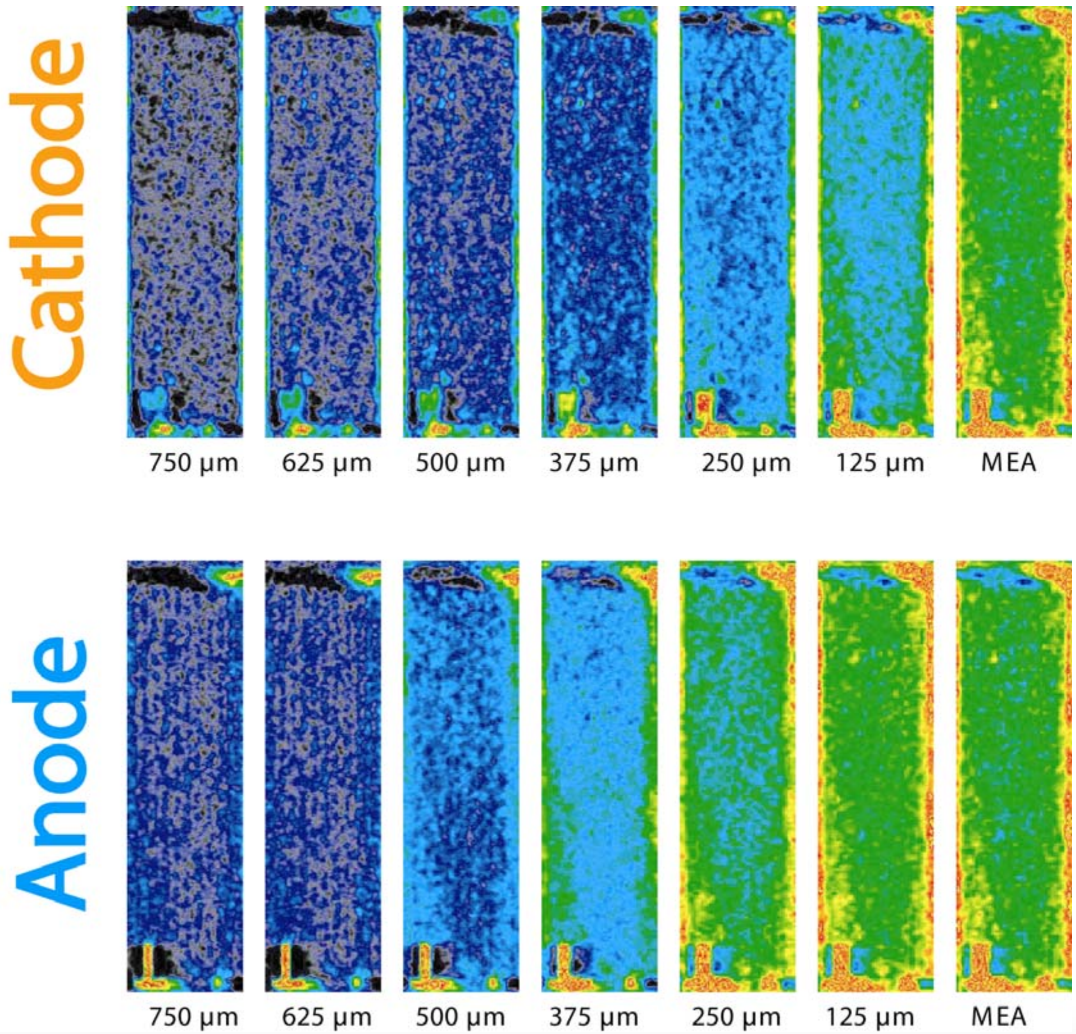
In collaboration with M.A. Hickner, N.P. Siegel, K. S. Chen, D. N. McBrayer

Tomography Fuel Cell Anode v.s. Cathode



- Small Active area cell, 4 cm2
- Thick soft goods, 0.15 mm Membrane, 0.8 mm GDL
- 10 straight channels, 0.8 mm deep
- Blue is Anode, Orange is Cathode, inserts are on the cathode

Water content in the soft goods



Conclusions

- The NIST Neutron Imaging Facility is a productive addition to the the national user facilities at the Center for Neutron Research.
- In collaboration with colleagues we have and are pioneering new methods to reduce the spatial resolution available to neutron imaging by an order of magnitude.
  - For a little perspective - ZnS was invented around 1900 by Rutherford's laboratory to image the backscattering of alpha particles off the nucleus of gold.
  - Potentially we will reduce the resolution by as much as 2 orders of magnitude.
- Neutrons are the perfect probe to study hydrogen fuel cells.
  - Easily penetrates the metal exterior.
  - Sensitive to the water produced inside the fuel cell at the length scales needed to effectively understand the transport mechanisms in the fuel cell.

Users/Collaborators 2007

- General Motors
- DiamlerChrysler
- Plug Power
- Sandia National Laboratory
- Los Alamos National Laboratory
- University of Kansas
- Rensselaer Polytechnic Institute (RPI)
- University of Michigan
- University of Waterloo
- University of Delaware
- Rochester Institute of Technology
- Wayne State University
- University of Connecticut
- Illinois Institute of Technology
- University of Tennesse
- Case Western University
- University of Mississippi
- University of California, Berkeley