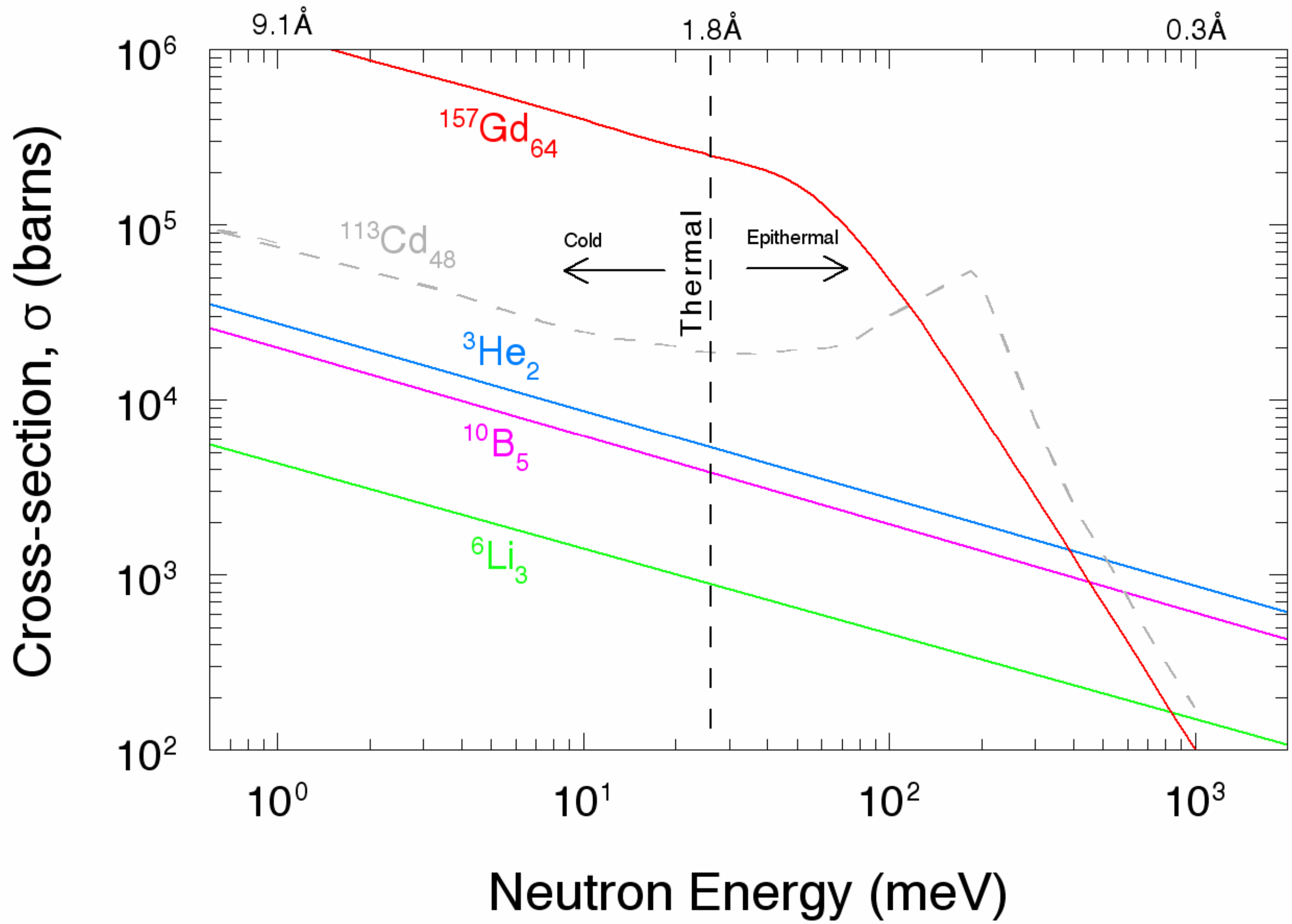
Thermal Neutron Detectors at BNL

Graham Smith
Instrumentation Division
March 12, 2008

Overview

- Some fundamentals of thermal neutron detection.
- Detectors developed for the High Flux Beam Reactor (HFBR), and where they went.
- Development of very large area detectors and their installation at major user facilities.
- Ongoing advanced detector development.

Thermal Neutron Capture Cross-Sections



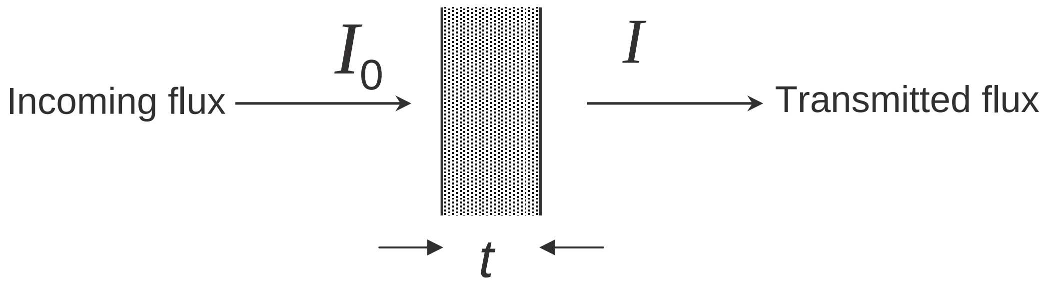
1 barn = 10^{-24} cm^2

Most Probable Nuclear Interactions

	Q-value (MeV)	Abs^n Depth (25 meV)
1. $^3He_2 + n \rightarrow {}^3H_1 + p$	0.764	7 cm.atm
2. $^6Li_3 + n \rightarrow {}^3H_1 + \alpha$	4.8	230 μm
3. $^{10}B_5 + n \rightarrow {}^7Li_3 + \alpha + 0.48$ MeV γ	2.3	20 μm
4. $^{157}Gd_{64} + n \rightarrow {}^{158}Gd_{64} + (\gamma\text{'s} + e\text{'s})$		1.3 μm

Main E_e= 29, **71**, 78 and 131 keV

Absorption (Conversion) in a Detection Medium



$$I / I_0 = e^{-N\sigma t}$$

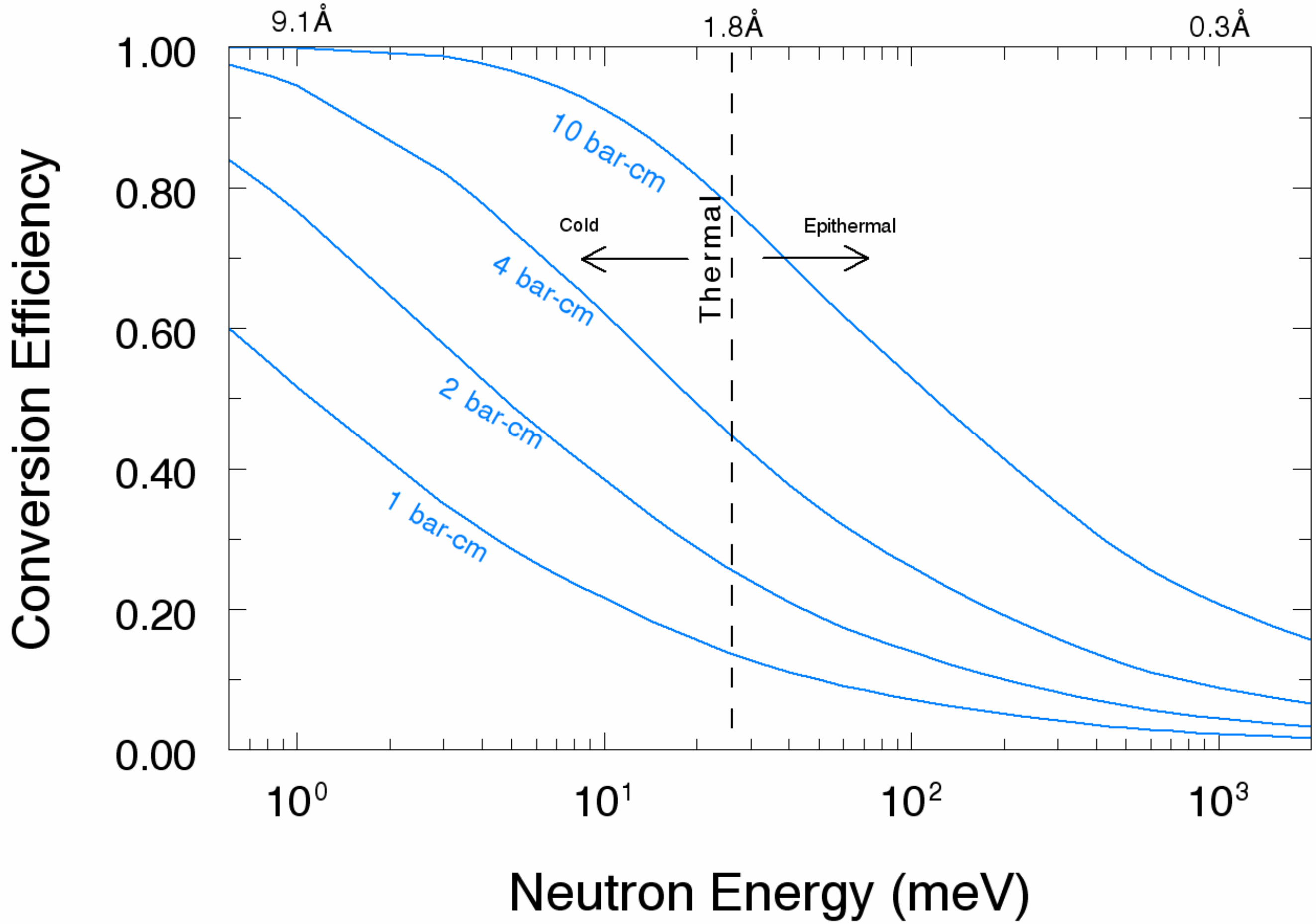
where N = number of atoms/molecules per unit volume (cm^{-3})

σ = cross-section (barns: 10^{-24} cm^2)

t = thickness (cm)

Fraction converted = $1 - I / I_0$

Thermal Neutron Conversion Efficiency in ^3He

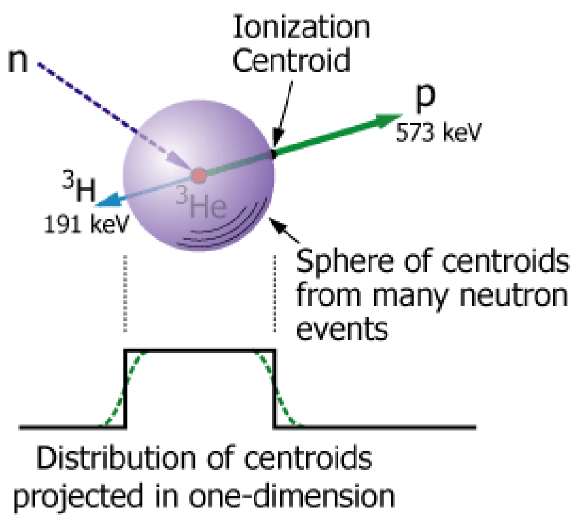


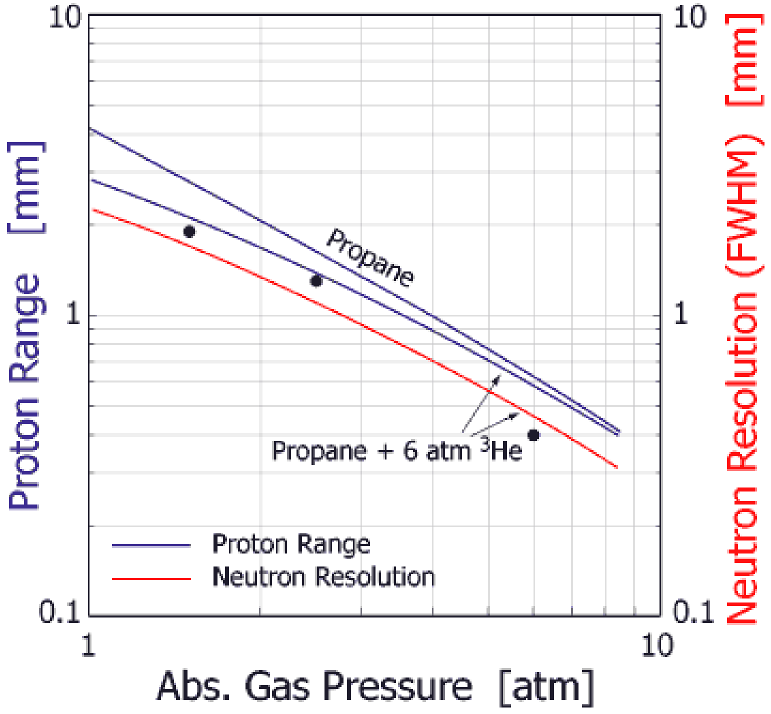
Thermal Neutron Detection in ^3He and Position Resolution Limit

$n + {}^3He \rightarrow p + {}^3H + 764\ keV$

↓

~25000 electron-ion pairs





FWHM ~ 0.8 × proton range
(~4.2mm in 1 atm. propane)

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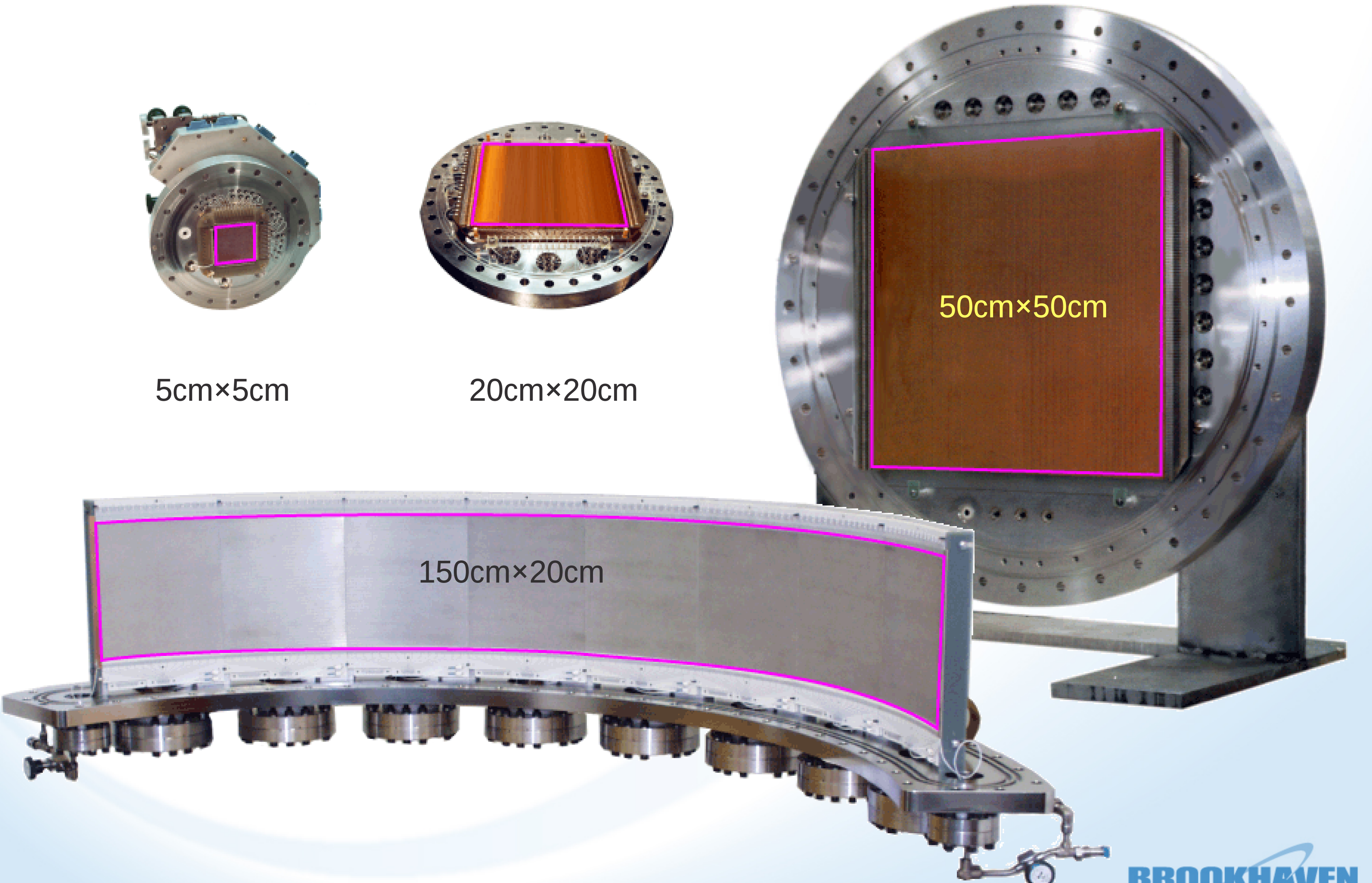
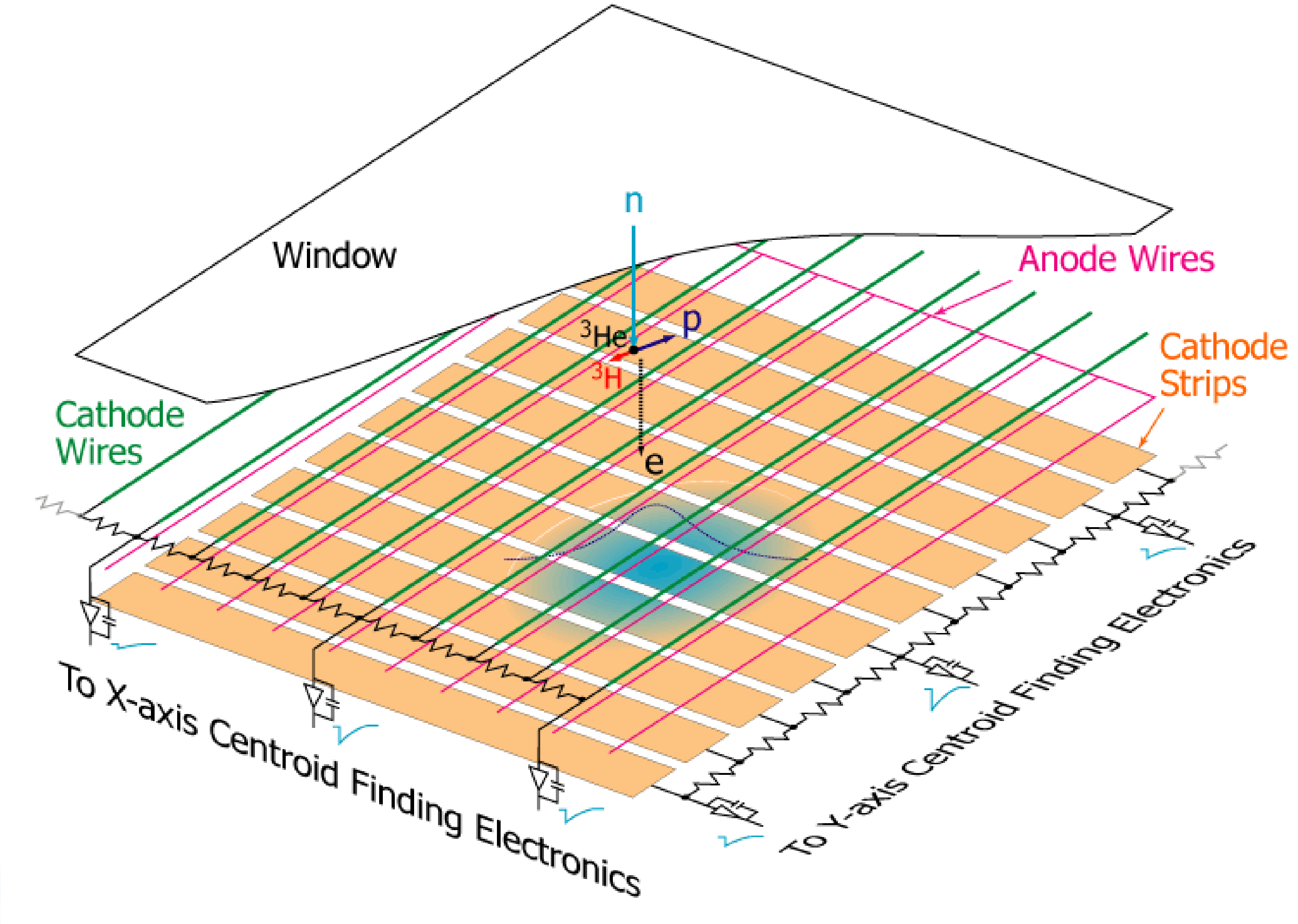
Suite of Wire-based Detectors



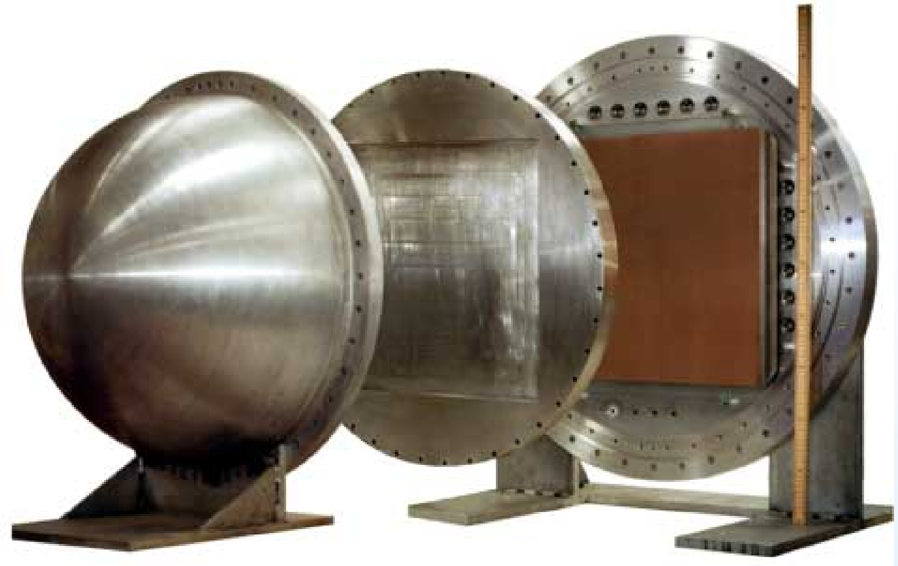
Position Encoding with Interpolating Cathode Strips



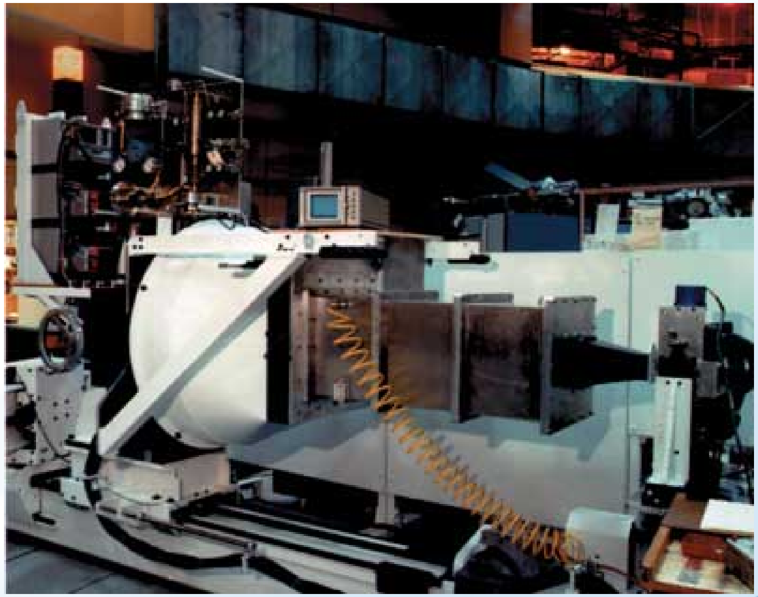
J.L. Alberi and V. Radeka, IEEE Trans. Nucl. Sci 23 (1976) 251-258

G.W. Fraser, E. Mathieson & K.D. Evans, Nucl. Instrum. & Meth. 180 (1981) 269-279

50cm×50cm Detector



- Developed for Small Angle Neutron Scattering (SANS)
- 4 atm. ^{3}He + 1.8 atm. Propane
- 2mm FWHM position resolution
- Absolute position stability 50µm

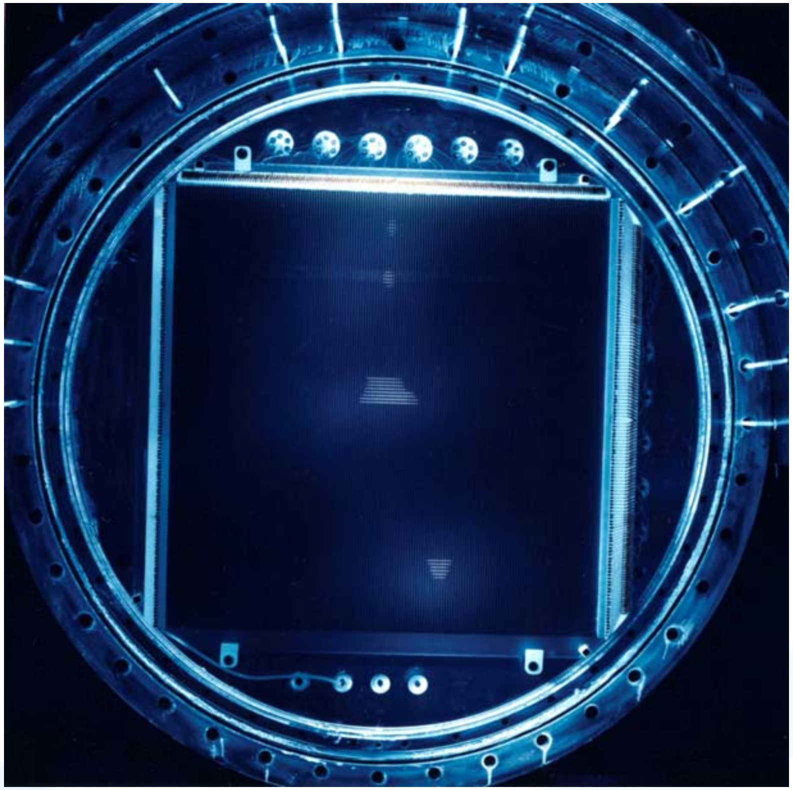


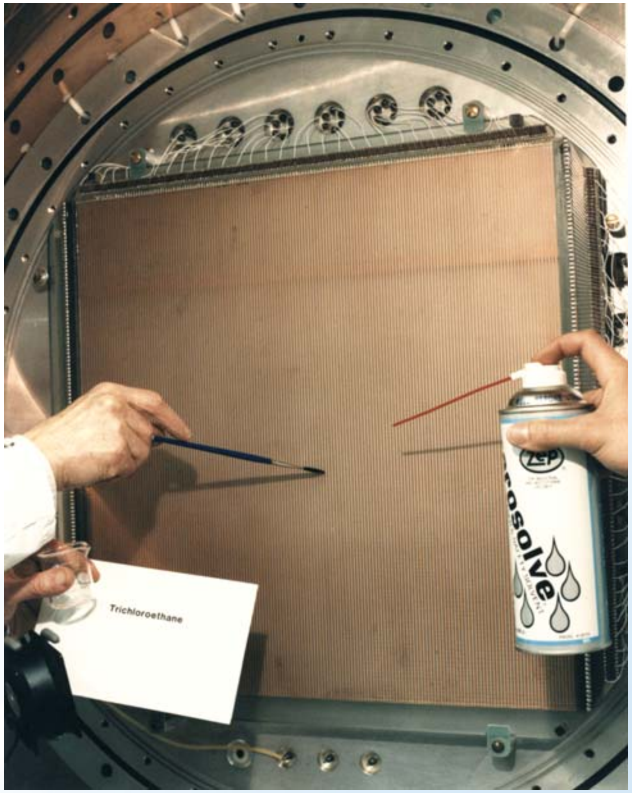
Beam Line H9B

HFBR

50cm × 50cm Detector

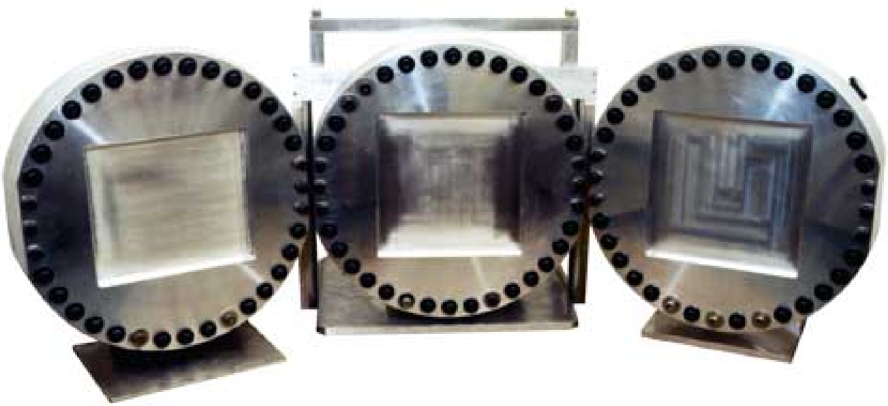
This detector ran continuously from 1985 until the HFBR ceased operations, with just one major service to remove polymerization deposits:

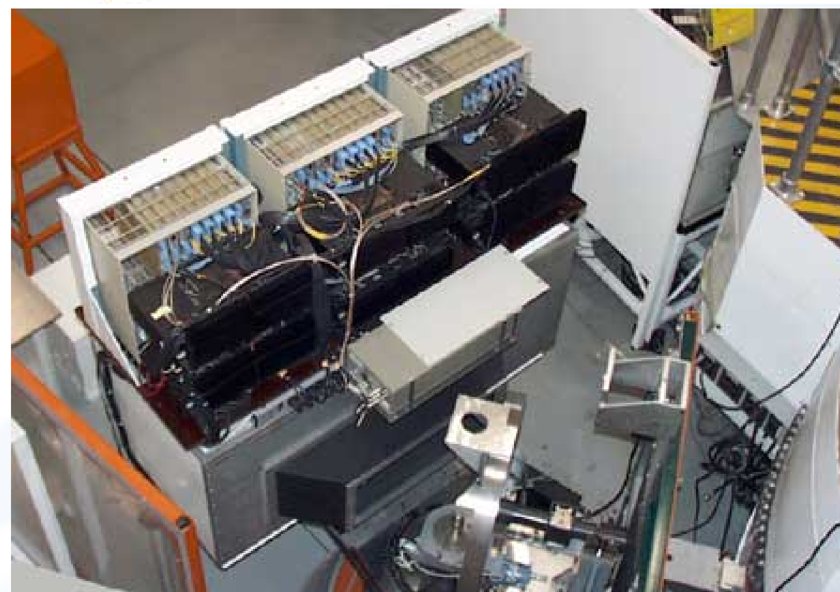




High Precision 20cm×20cm Detectors

- Developed for SANS and LANS, particularly protein crystallography
- 6 atm. ^3He + 2.5 atm. Propane
- Position resolution ~ 1.3mm FWHM
- 3 detectors along an arc for greater angular coverage (with gaps)





Beam line H6B1

HFBR

Re-deployment of detectors from HFBR

User/Activity	HFBR Beam Line	Ser. #	Nominal Size	Nodes		Deployed to:
				X	Y	
Dieter Schneider: Macromolecular Crystallography (Array of three)	H3A	100	20×20 cm^2			?
		104	20×20 cm^2	17	15	LANL (LANSCE): Protein Crystallography Eval^n
		110	20×20 cm^2	20	17	BNL (NNS Dept): Imaging: Coded Aperture Masks
Anand Saxena: Membrane Diff 'n	H3B	103	20×20 cm^2	13	9	?
John Larese: Mat'ls Chemistry	H5	N/A	5×5 cm^2	15	15	SNS?
John Larese, Tom Koetzle: Single X^l Diff 'n (Array of three)	H6B1	105	20×20 cm^2	20	17	ORNL (SNS): Liquids Reflectometer
		108	20×20 cm^2	20	17	ORNL (SNS): Magnetism Reflectometer
		109	20×20 cm^2	20	17	ORNL (HFIR): Test Beam
Dieter Schneider: SANS	H9B	N/A	50×50 cm^2	33	33	ANL (IPNS): SANS
IO: Experimental	IO	105e	20×20 cm^2	20	17	NIST (NCNR): Advanced Neutron Reflectometer

Legend:

LANSCE: Los Alamos Neutron Science Center

SNS: Spallation Neutron Source

HFIR: High Flux Isotope Reactor

IPNS: Intense Pulsed Neutron Source

NCNR: NIST Center for Neutron Research

20cm × 20cm Detectors at the SNS

OAK RIDGE NATIONAL LABORATORY — NEUTRON SCIENCES

The NEUTRON PULSE

Volume 8
Number 1
Spring 2007

SNS Instrument Status

Ken Herwig, herwigkw@ornl.gov

During the summer and fall of 2006, several significant events occurred on the Spallation Neutron Source (SNS) instrument floor. The Backscattering Spectrometer was joined by the Magnetism and Liquids reflectometers as operating instruments. The two reflectometers opened their shutters for the first time in July 2006. All three instrument teams have been busy with commissioning activities (e.g., calibrating detectors and motors, improving shielding and reducing backgrounds, and testing polarization optics on the Magnetism Reflectometer)

Continued on page 5

HFIR Update: Cool Times Ahead

Stephen Nagler, naglerse@ornl.gov

The High Flux Isotope Reactor (HFIR) cold source project passed a major milestone in September with the successful completion of the "helium" heater test. The cold source maintained vacuum and temperature in situ, while cooling to temperatures below 20 K (see below). This was accomplished with an applied heat load equivalent to that expected in actual operations and fully validated the existing cold source performance models. Helium was used as a cryogen for the test. As of this writing, a second test has been successfully completed using supercritical hydrogen as a cryogen. The next required step is an operational readiness review. Users are looking forward to resumption of HFIR operations, with the anticipated production of cold and thermal neutrons during May 2007.

Continued on page 4

In this Issue

Bottom left: sample stage of the SNS Magnetism Reflectometer. The front left side shows the detector table and spin analysis optics; the middle shows the hexapod sample support and omega rotation table; and the right back shows the incident optics table. Center: the HFIR cold source maintains vacuum and temperature while cooling to below 20 K. Right: interior of the SNS Backscattering Silicon Spectrometer large evacuated flight path.

The Neutron Pulse,

Vol. 8, No. 1, Spring 2007

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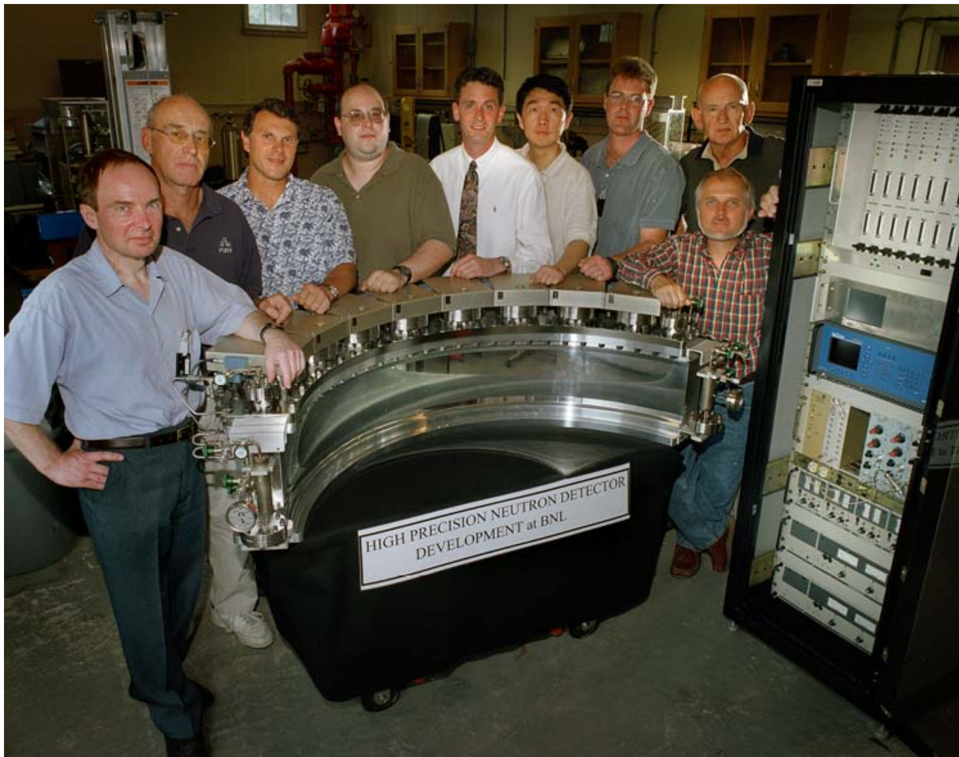
120º Neutron Detector: Protein Crystallography Station (PCS) at LANSCE, Los Alamos



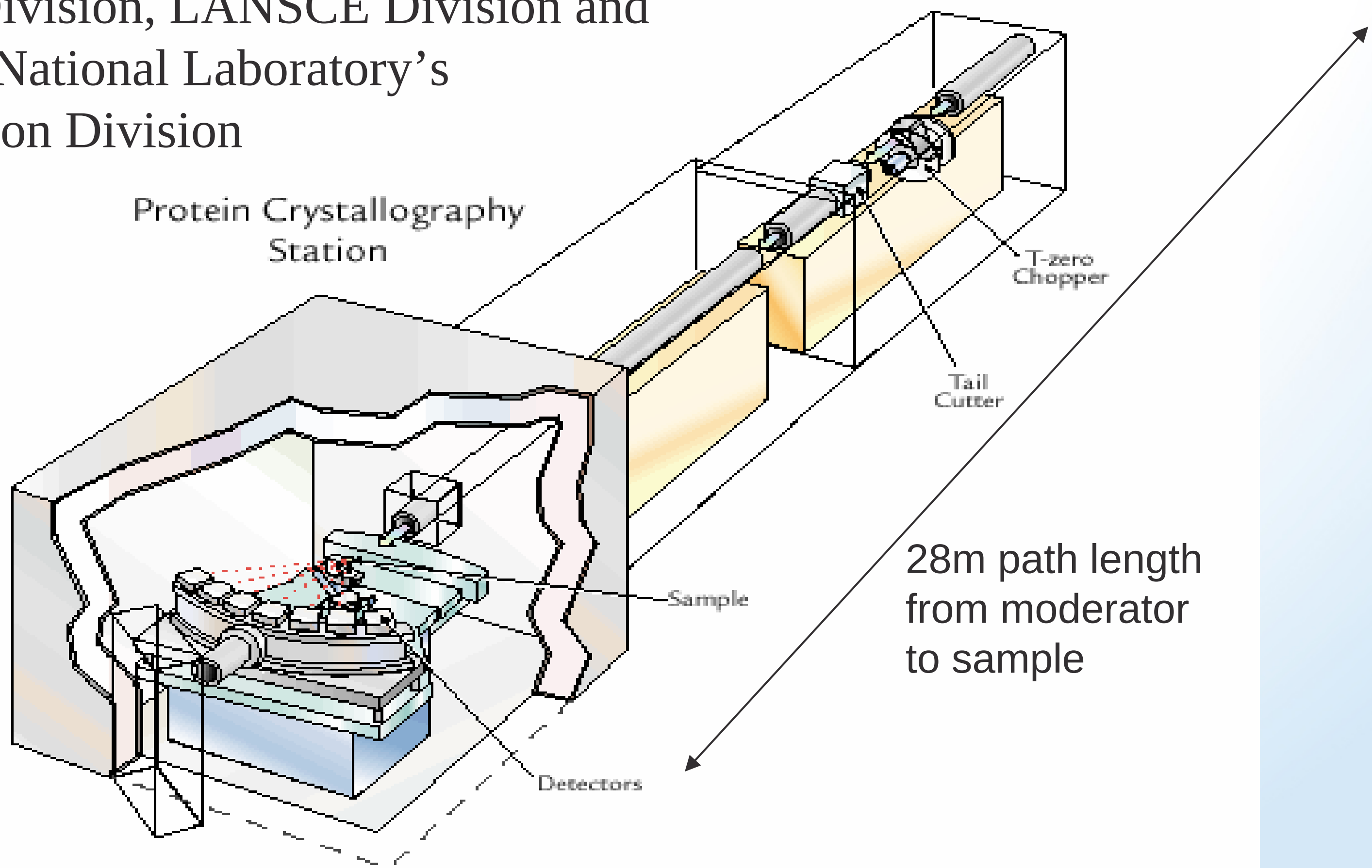
Detector and Data Acquisition System

Shipping Day, July 27, 2001

BNL → LANL

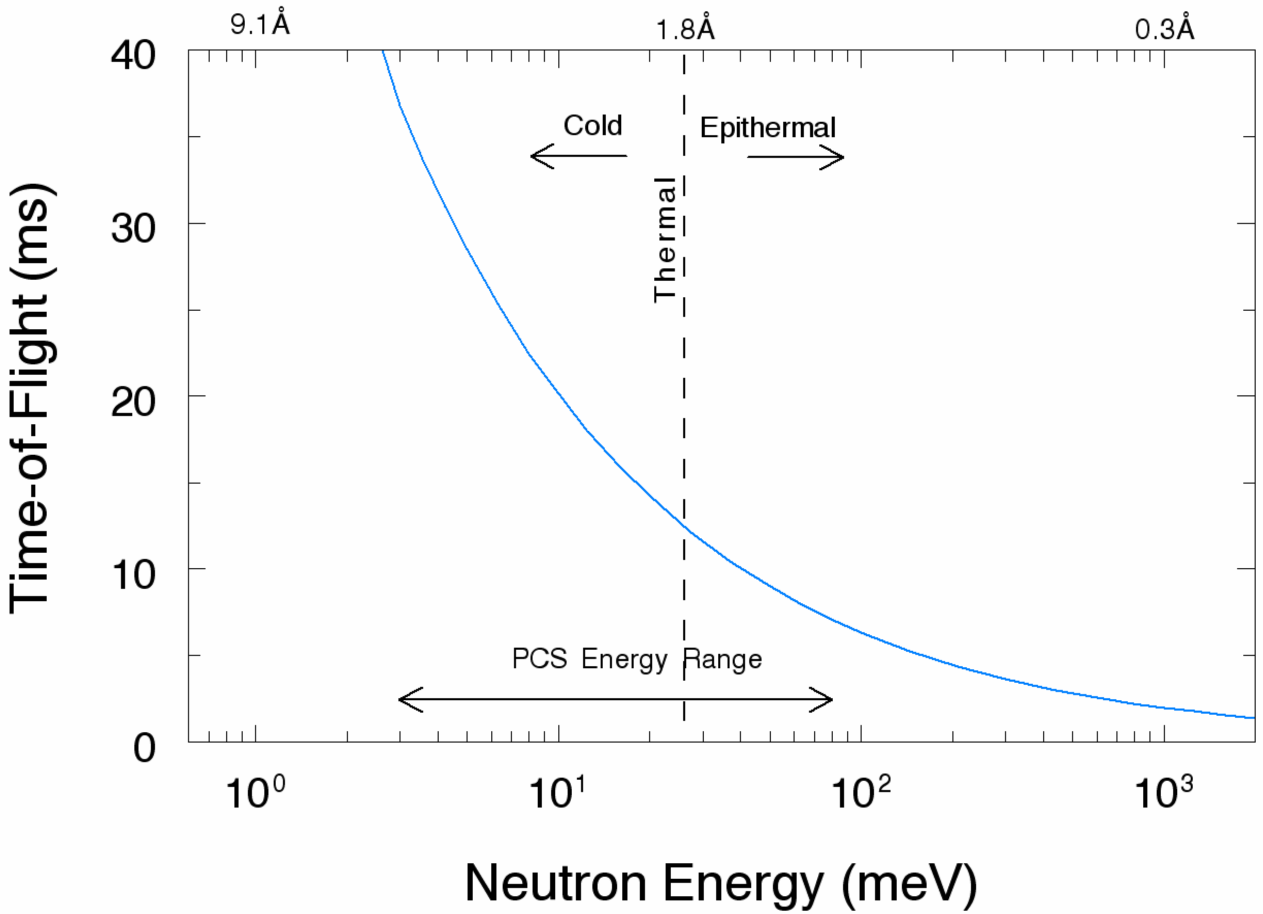
Spallation Neutrons:
A new arena for protein crystallography

A DOE-OBER partnership between Bioscience Division, LANSCE Division and Brookhaven National Laboratory's Instrumentation Division



Langan et al, *J. App. Cryst.* (2004) 37, 24-31
Schoenborn et al, *J. Synch. Rad.* (2004) 11, 80-82

Neutron Time-of-Flight Over 28m Path



Physics Today, November 2003

Neutron Diffraction Overcomes Flux Limits to Resolve a Large Protein Structure

To demonstrate the effectiveness of neutron diffraction in biology, crystallographers bring neutrons to bear on an important industrial enzyme.

On paper, thermal neutrons seem ideal for probing the structure of crystallized biomolecules. At a few tenths of a nanometer, the de Broglie wavelength of thermal neutrons matches molecular bond lengths. And thermal neutrons interact strongly enough with matter to pick up structural information but weakly enough to pass through crystalline samples.

Another desirable property of thermal neutrons has to do with hydrogen. same strength as potassium.

Scattering strength also varies from isotope to isotope. Conveniently for crystallographers, one of the strongest differences is between hydrogen and deuterium. Substituting deuterium for hydrogen at a specific chemical site reveals the site's spatial location through a simple comparison of diffraction patterns.

Knowing where hydrogen atoms are is invaluable for understanding

third-generation synchrotrons flood samples with 10^{19} x-ray photons per second per square centimeter, a reactor source, such as the one at the Institut Laue–Langevin in Grenoble, France, emits about 10^{15} neutrons per second per square centimeter.

Because of the relatively low intensity of neutron beams, it takes crystallographers far longer to collect a neutron diffraction pattern than an

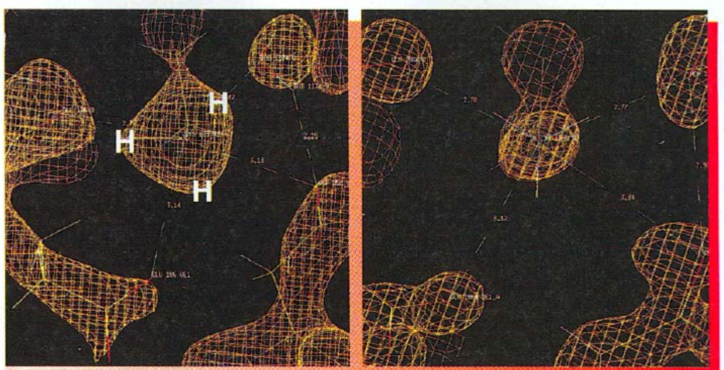


Figure 2. The terminal nitrogen of lysine-183, a key amino acid in xylose isomerase, is the central feature of both the neutron density map on the left and the electron density map derived from x rays on the right. Unlike the electron map, the neutron map reveals the three hydrogen atoms around the terminal nitrogen of lysine-183. (Courtesy of Gerry Bunick.)

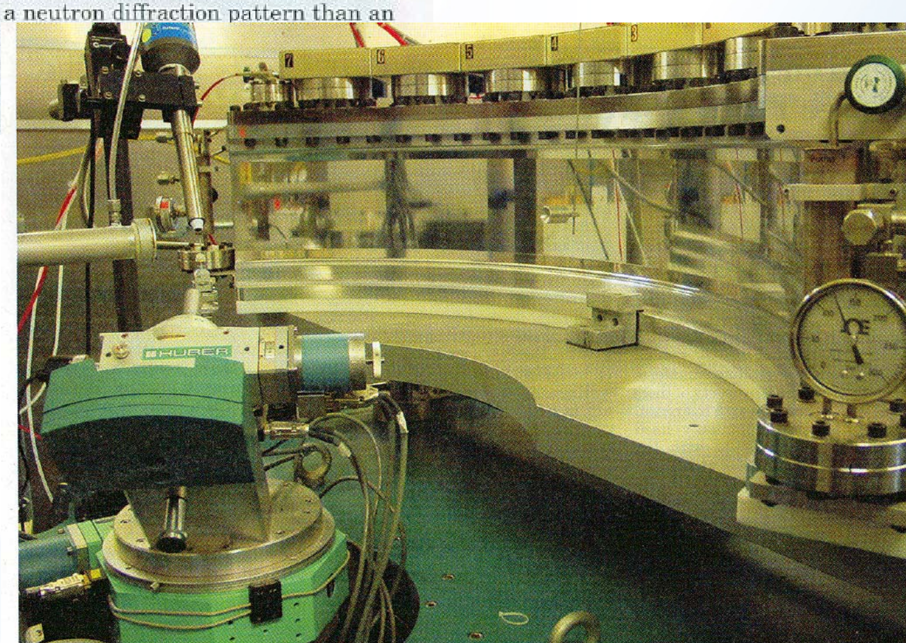
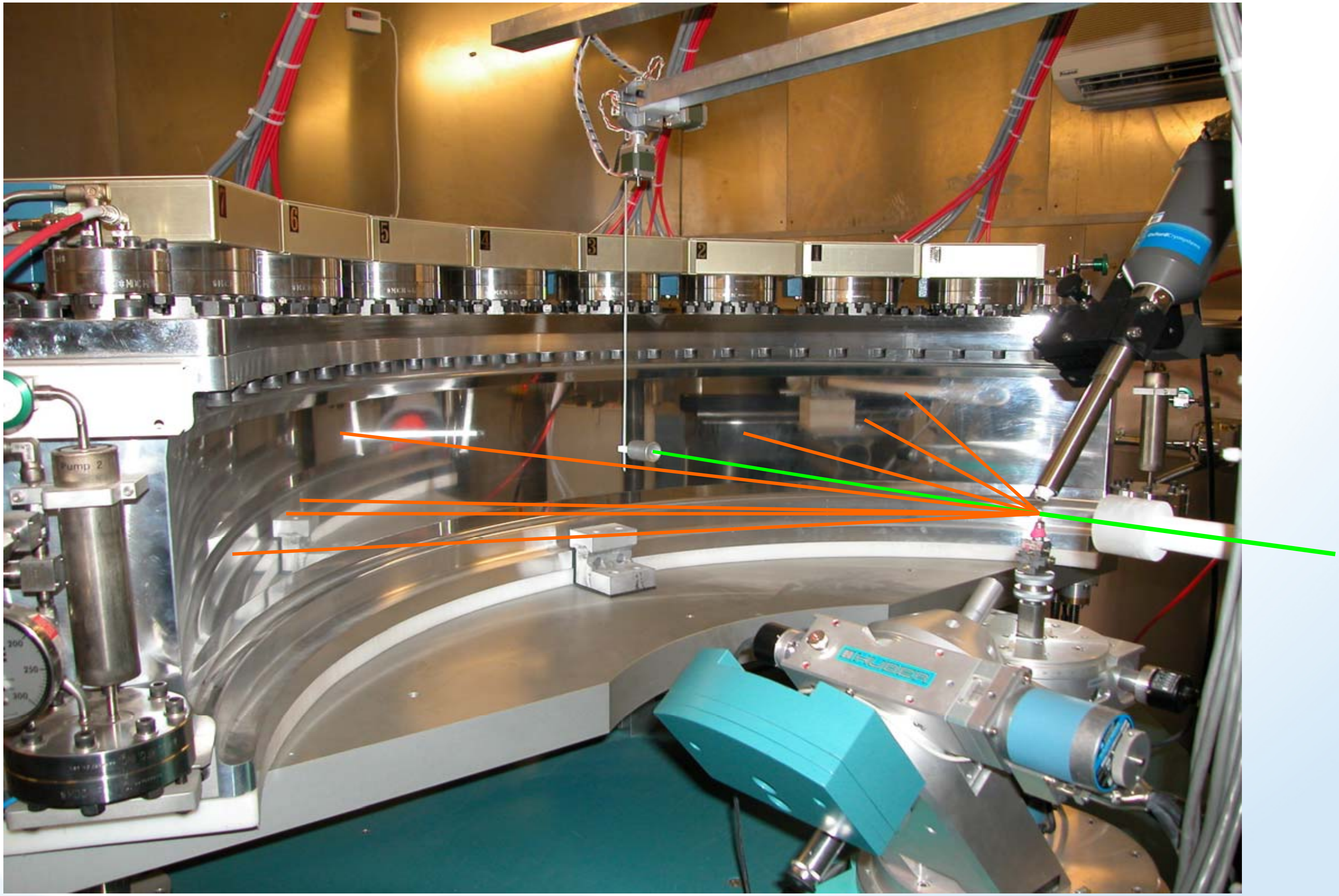
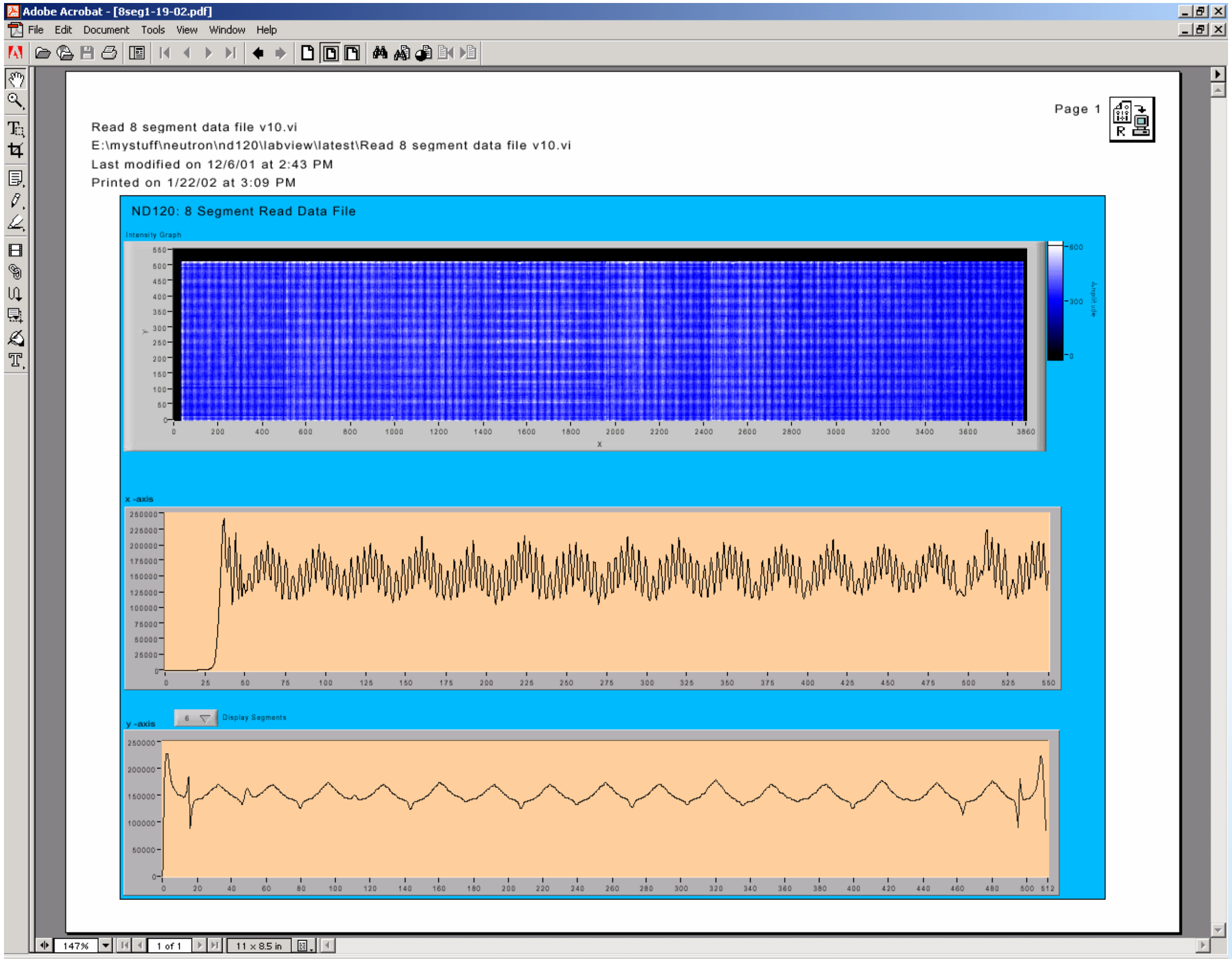


Figure 1. The Protein Crystallography Station at the Los Alamos Neutron Science Center. The sample is held by the rotating stage at the bottom left. Eight detectors are arrayed about 1 meter away from the sample to collect the scattered neutrons. (Courtesy of Gerry Bunick.)

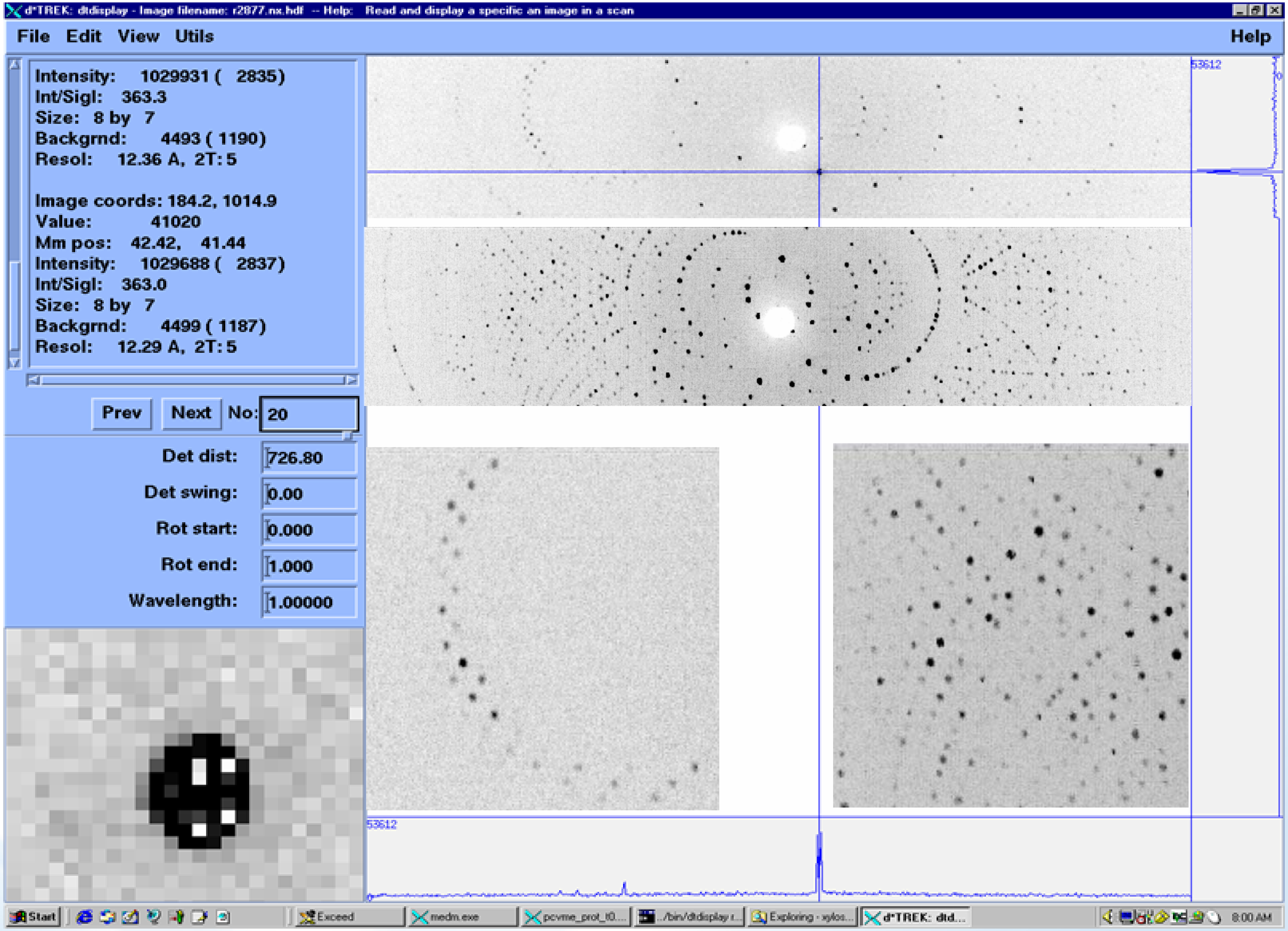
120º Detector Installed at the PCS, LANSCE



UIR (Uniform Irradiation Response) of 120º Detector (8-segments)



Diffraction Spectra from the 120º Detector at the PCS



BROOKHAVEN NATIONAL LABORATORY

120º Detector Installation at the PCS of LANSCE, LANL

Front Covers of ACA Newsletter

Winter 2002

Winter 2005

120º Detector Installation at the PCS LANSCE, LANL

- PCS: Protein Crystallography Station
- LANSCE: Los Alamos Neutron Science Center
- System optimized for a spallation source
- Station oversubscribed with users by a factor 3
- Has run since January 2002 without interruption
- March 2007: DAQ upgrade and ^{3}He topped up
- Upgrade proposed to OBER – reviewed very favorably
- Results from PCS have been the catalyst for MaNDi at SNS
- Results from PCS fuelled interest from ANSTO in similar system

Reduction in stored energy

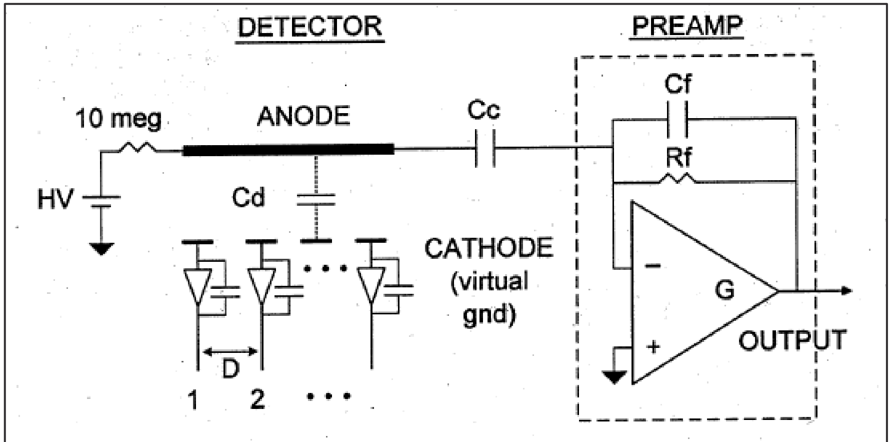


Fig. 1. Simplified sketch of a position-sensitive gas proportional detector. Preamplifiers are connected to cathode strips and serve as charge collection nodes for position computation. The high-voltage anode is connected to a low impedance preamplifier with a large valued, high-voltage capacitor (C_c). The stored energy is $\sim\frac{1}{2}(C_d + C_c)V^2$ and can be very large.

Conventional preamp connection

Revised preamp connection

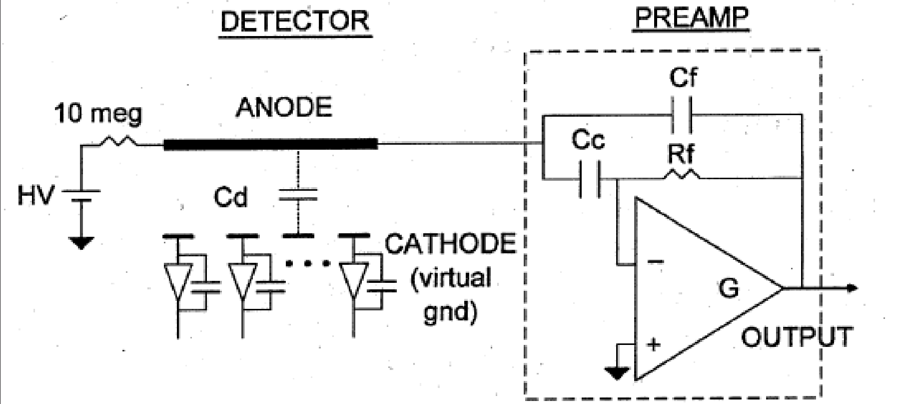
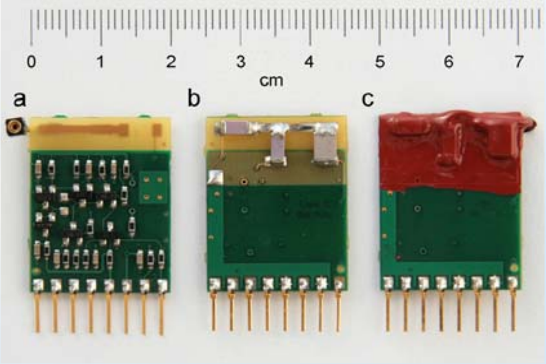


Fig. 2. By incorporating C_c into the anode preamplifier feedback loop, low-input impedance is achieved with a small value for C_c and much less stored energy than the circuit of **Fig. 1**.



J.A. Harder et al.,

NIM A576 (2007) 397-402

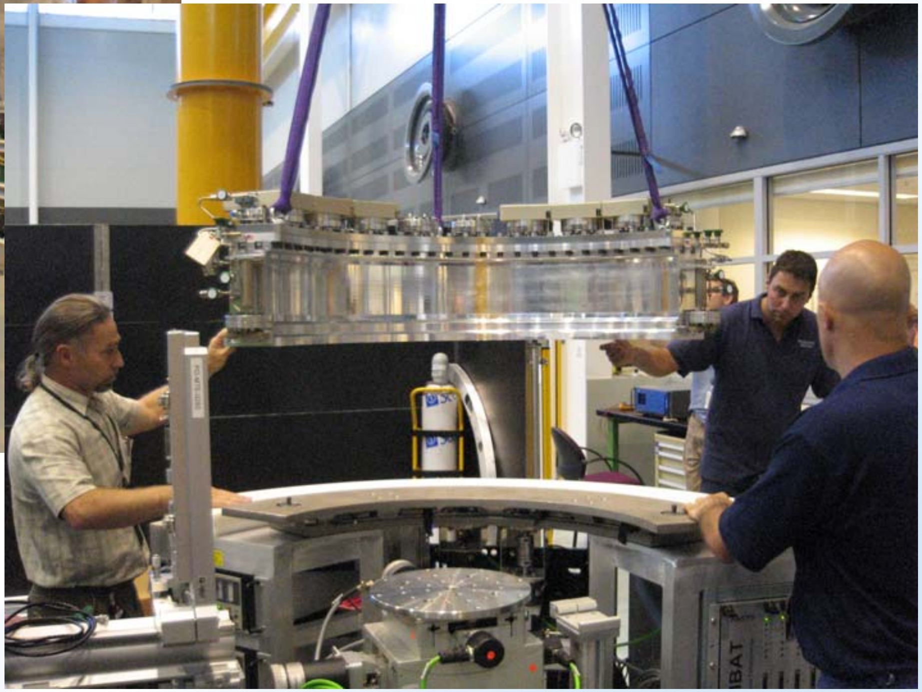
120º Neutron Detector for OPAL Reactor ANSTO, Australia

OPAL Reactor: Open Pool Australian Light-water Reactor
ANSTO: Australian Nuclear Science and Technology Organization

Shipping Day,
Dec 18, 2006
BNL → ANSTO

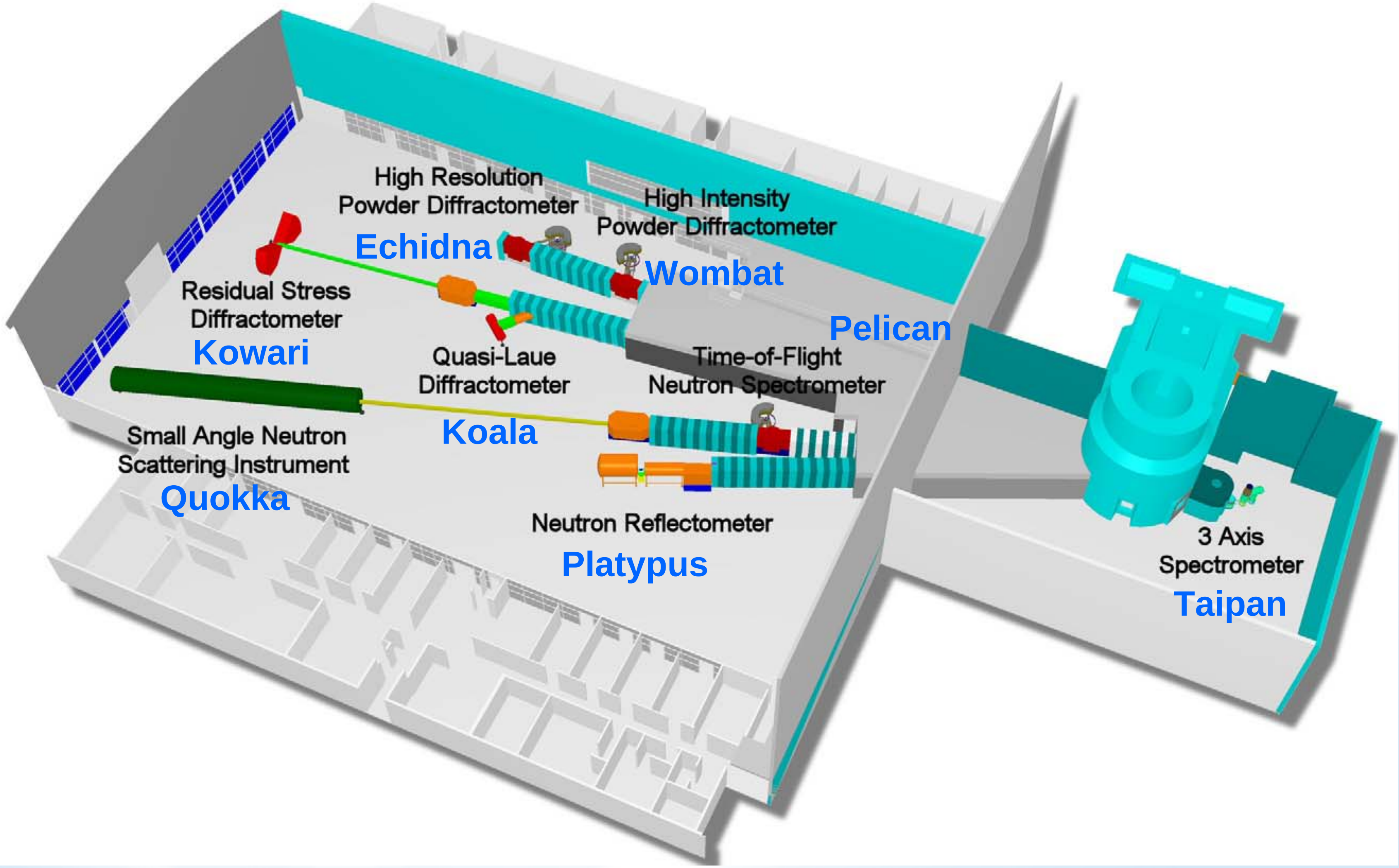
120º Neutron Detector: ANSTO, Australia

Checking out the detector on arrival



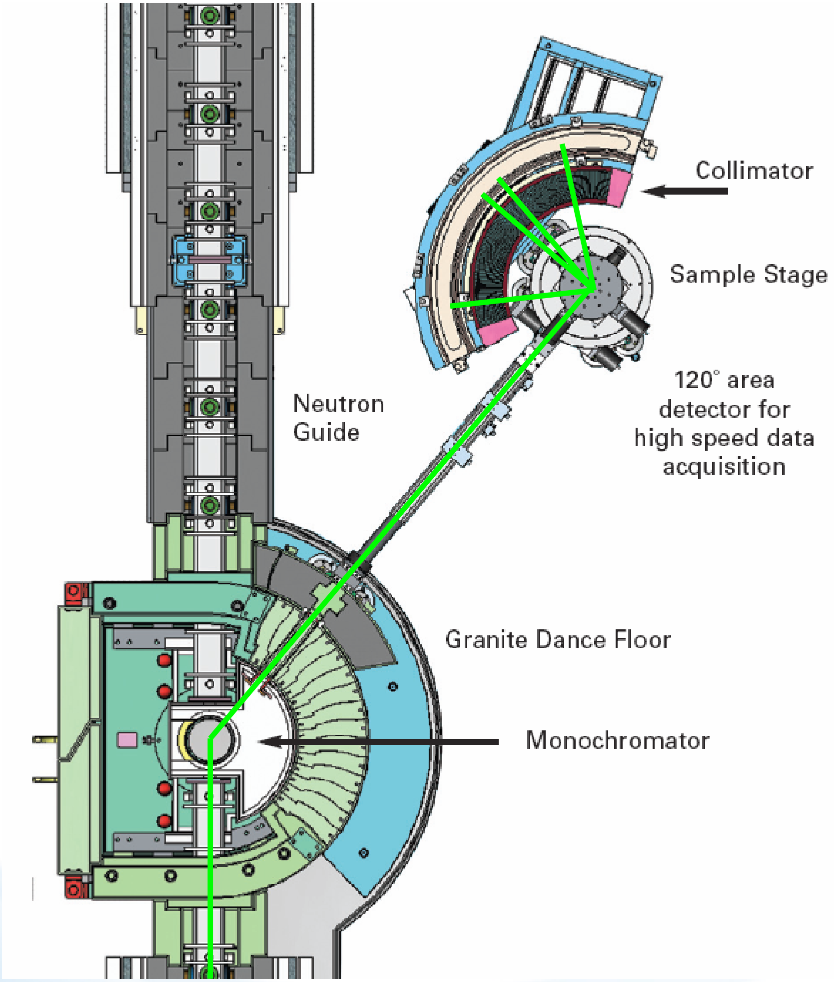
Lowering detector onto goniometer

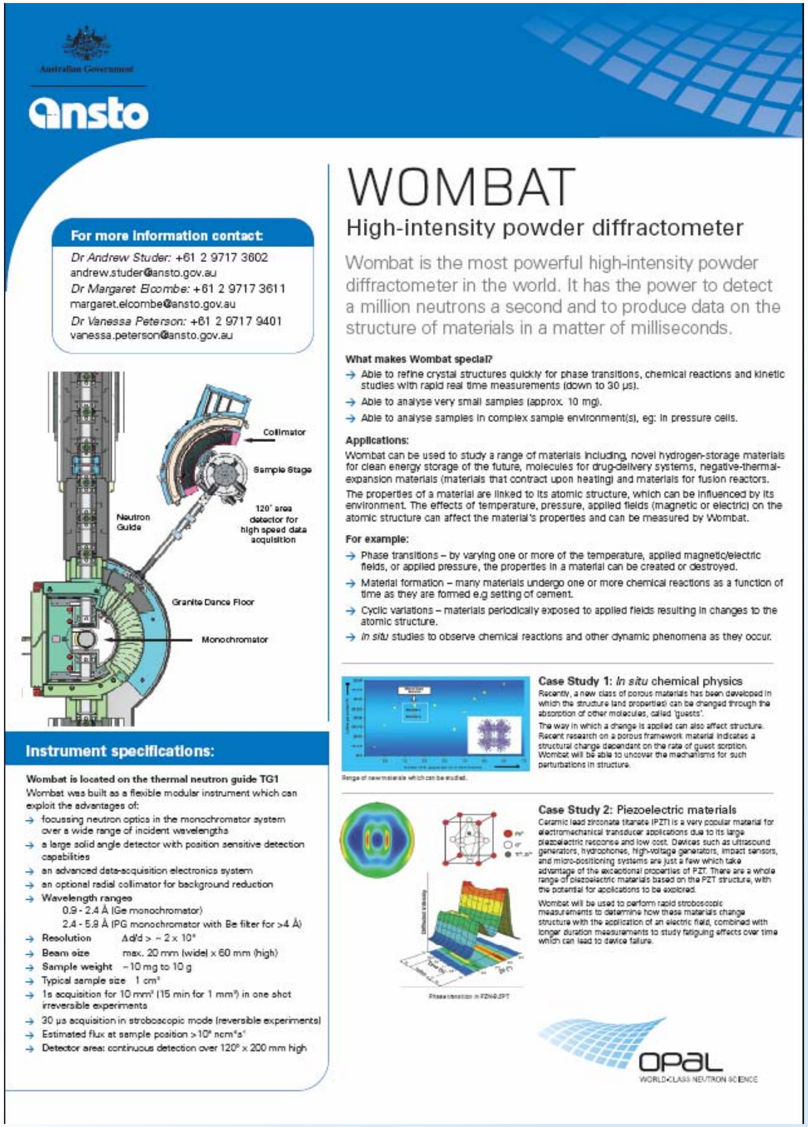
OPAL Reactor: Beam-lines in Guide Hall



HIPD (WOMBAT)
High Intensity Powder Diffractometer

http://www.ansto.gov.au/__data/assets/pdf_file/0016/24226/Wombat_Fact_Sheet.pdf





Australian Government
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WOMBAT
High-intensity powder diffractometer

Wombat is the most powerful high-intensity powder diffractometer in the world. It has the power to detect a million neutrons a second and to produce data on the structure of materials in a matter of milliseconds.

What makes Wombat special?

- Able to refine crystal structures quickly for phase transitions, chemical reactions and kinetic studies with rapid real time measurements (down to 30 μs).
- Able to analyse very small samples (approx. 10 mg).
- Able to analyse samples in complex sample environment(s), eg: in pressure cells.

Applications:

Wombat can be used to study a range of materials including, novel hydrogen-storage materials for clean energy storage of the future, molecules for drug-delivery systems, negative-thermal-expansion materials (materials that contract upon heating) and materials for fusion reactors.

The properties of a material are linked to its atomic structure, which can be influenced by its environment. The effects of temperature, pressure, applied fields (magnetic or electric) on the atomic structure can affect the material's properties and can be measured by Wombat.

For example:

- Phase transitions – by varying one or more of the temperature, applied magnetic/electric fields, or applied pressure, the properties in a material can be created or destroyed.
- Material formation – many materials undergo one or more chemical reactions as a function of time as they are formed e.g setting of cement.
- Cyclic variations – materials periodically exposed to applied fields resulting in changes to the atomic structure.
- *In situ* studies to observe chemical reactions and other dynamic phenomena as they occur.

Instrument specifications:

Wombat is located on the thermal neutron guide TG1

Wombat was built as a flexible modular instrument which can exploit the advantages of:

- focussing neutron optics in the monochromator system over a wide range of incident wavelengths
- a large solid angle detector with position sensitive detection capabilities
- an advanced data-acquisition electronics system
- an optional radial collimator for background reduction
- Wavelength ranges
  - 0.9 - 2.4 Å (Ge monochromator)
  - 2.4 - 5.9 Å (PG monochromator with Be filter for >4 Å)
- Resolution $\Delta d/d > \sim 2 \times 10^{-3}$
- Beam size max. 20 mm (wide) x 60 mm (high)
- Sample weight ~10 mg to 10 g
- Typical sample size 1 cm^3
- 1s acquisition for 10 mm^3 (15 min for 1 mm^3) in one shot irreversible experiments
- 30 μs acquisition in stroboscopic mode (reversible experiments)
- Estimated flux at sample position >10^8 $ncm^{-2}s^{-1}$
- Detector area: continuous detection over 120° x 200 mm high

Case Study 1: *In situ* chemical physics

Recently, a new class of porous materials has been developed in which the structure (and properties) can be changed through the absorption of other molecules, called 'guests'.

The way in which a change is applied can also affect structure. Recent research on a porous framework material indicates a structural change dependant on the rate of guest sorption. Wombat will be able to uncover the mechanisms for such perturbations in structure.

Range of new materials which can be studied.

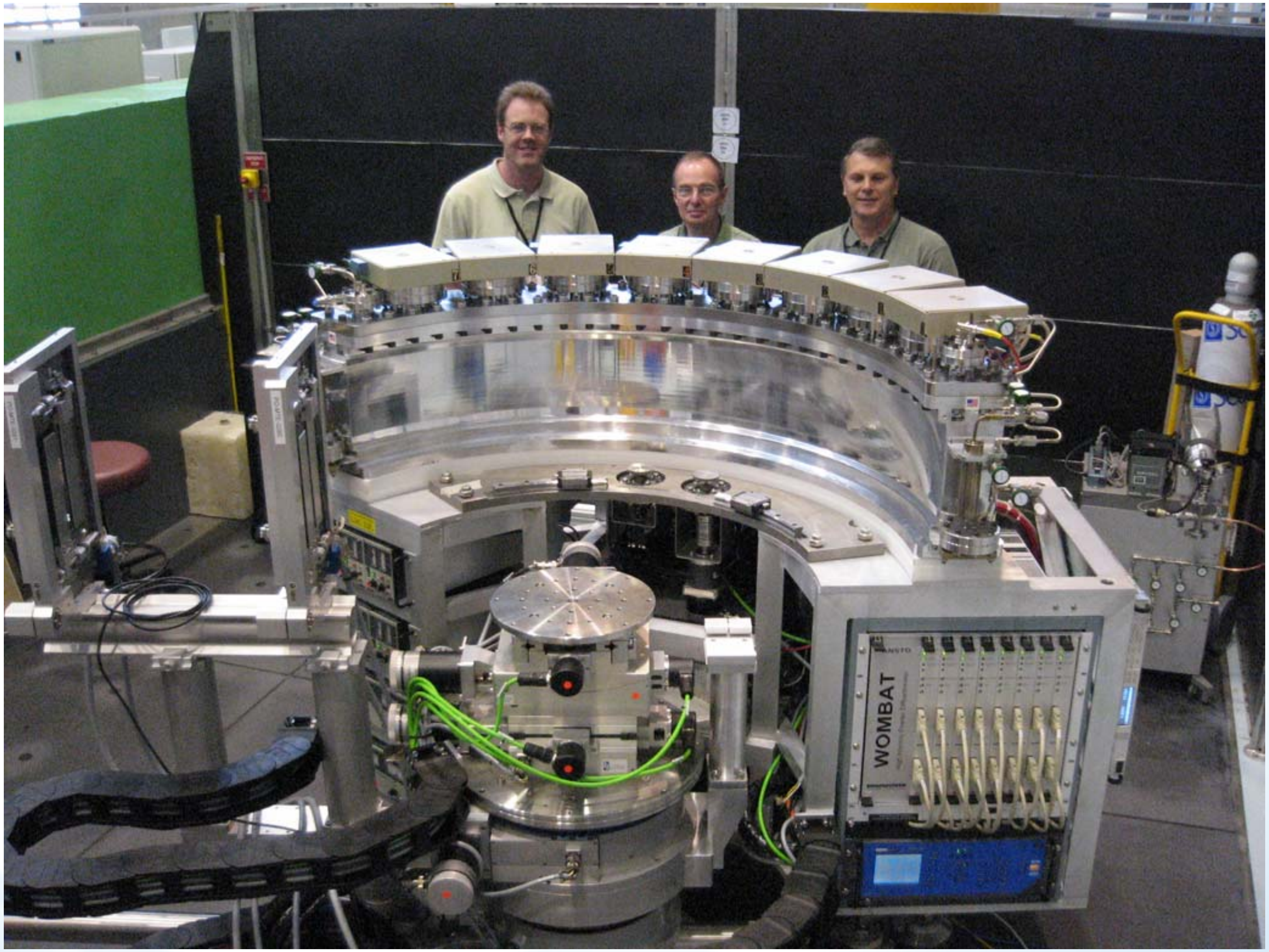
Case Study 2: Piezoelectric materials

Ceramic lead zirconate titanate (PZT) is a very popular material for electromechanical transducer applications due to its large piezoelectric response and low cost. Devices such as ultrasound generators, hydrophones, high-voltage generators, impact sensors, and micro-positioning systems are just a few which take advantage of the exceptional properties of PZT. There are a whole range of piezoelectric materials based on the PZT structure, with the potential for applications to be explored.

Wombat will be used to perform rapid stroboscopic measurements to determine how these materials change structure with the application of an electric field, combined with longer duration measurements to study fatiguing effects over time which can lead to device failure.

OPAL
WORLD-CLASS NEUTRON SCIENCE

120º Neutron Detector: HIPD, ANSTO, Australia



Detector fully installed and operating on the goniometer of the HIPD

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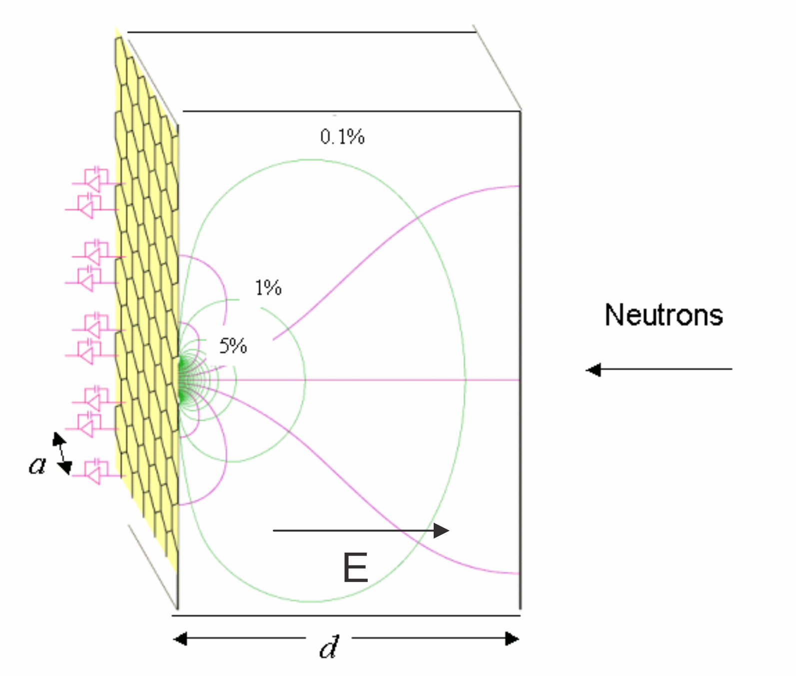
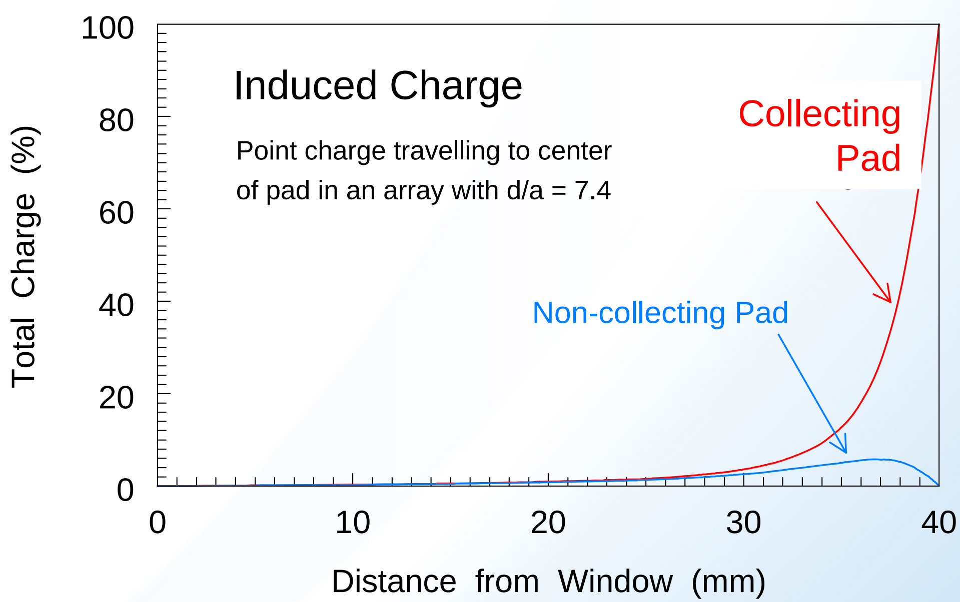
Detectors Operating in Ionization Mode

n + ^{3}He → p + ^{3}H + 764 keV

→ 30,000 electrons





Area of each pad ~ 25 mm^{2}

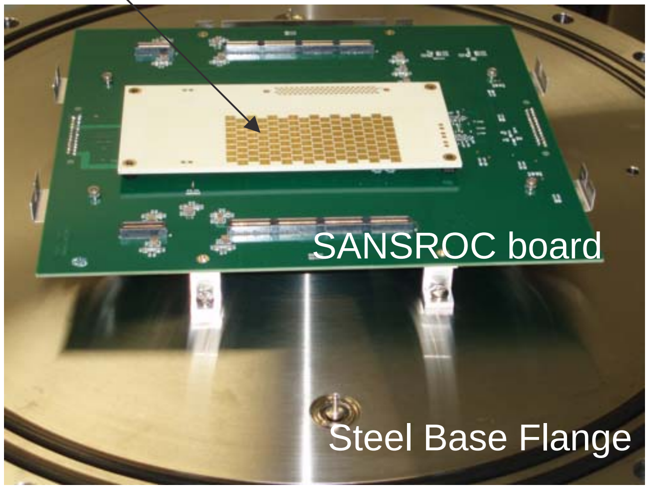
a ~ 5.4 mm

d = 40 mm

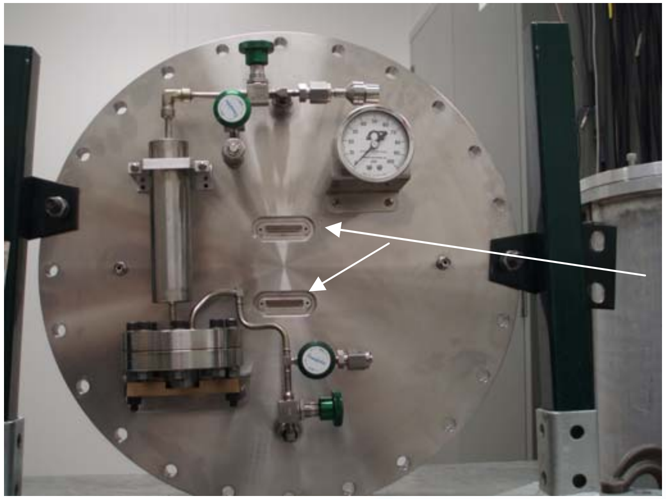
d/a ~7.4

Detector Components

1. 8 × 8 pad board

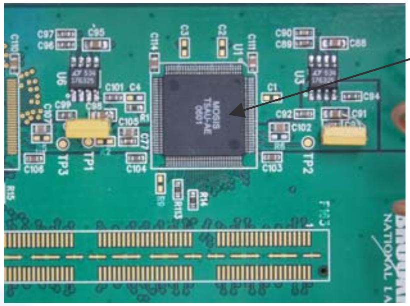


2. Rear of steel flange



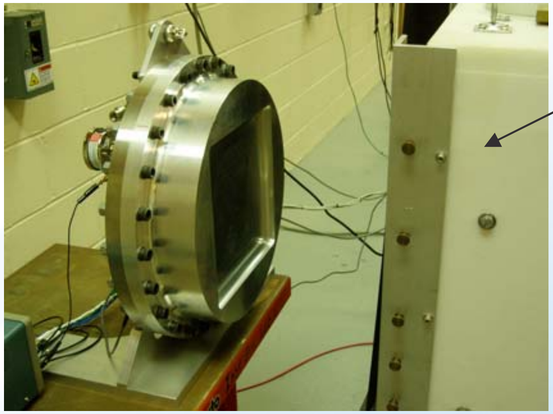
Connectors to analysis computer

Underside of 8 × 8 pad board



64 ch ASIC
CMOS 0.25μm
LPQP

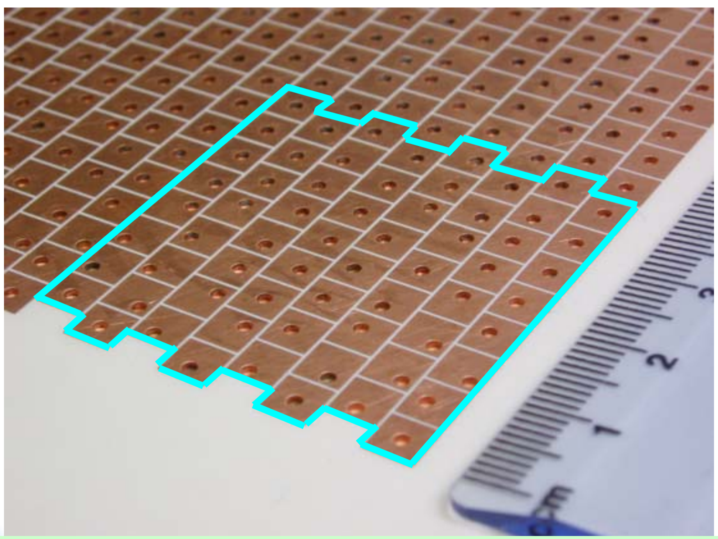
3. Full assembly



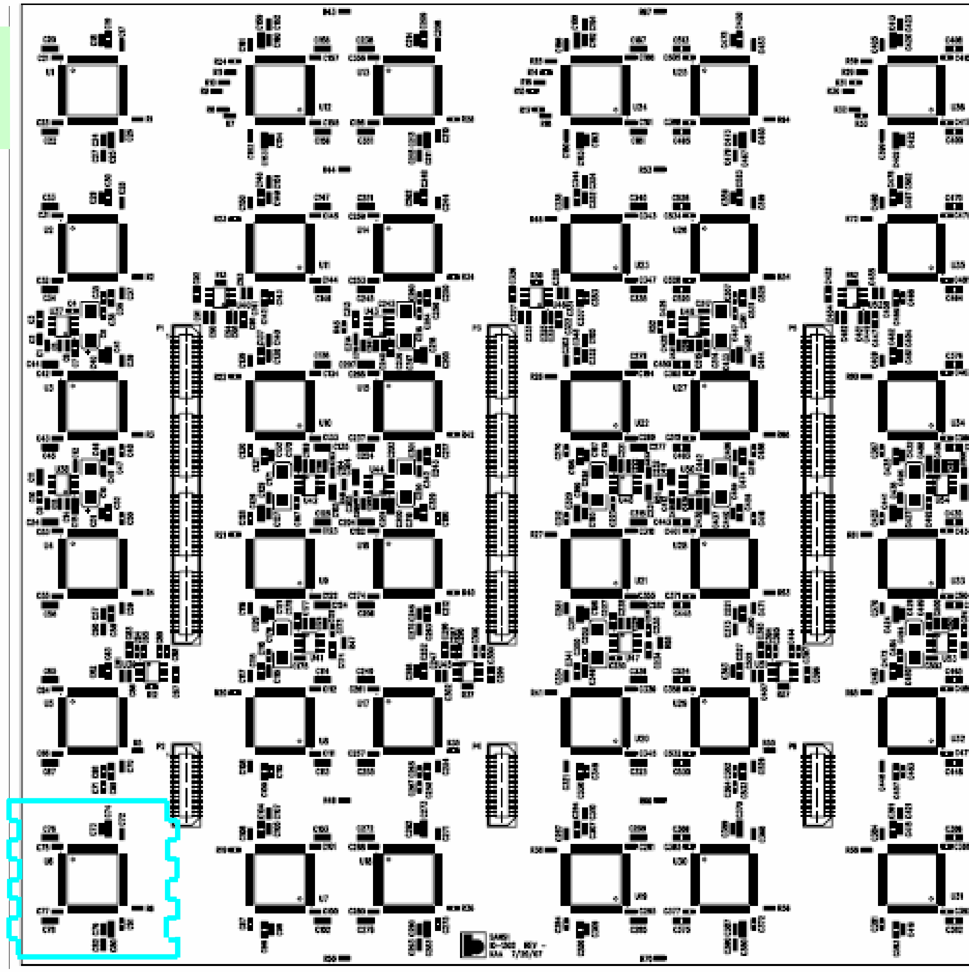
Am/Be neutron source

48 × 48 Anode Pad Board

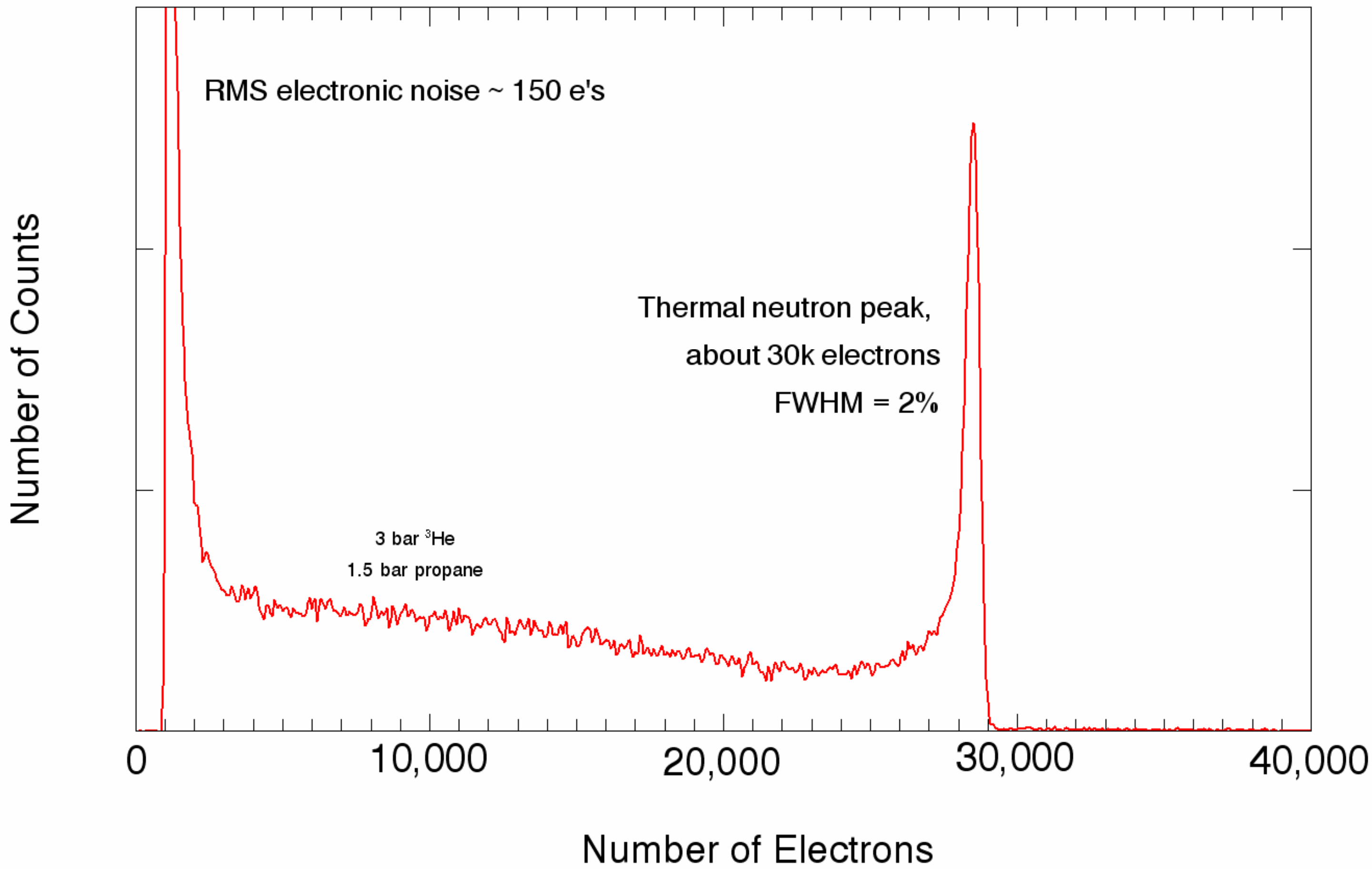
Full board populated by 36 ASICs, or 2304 channels. Size is 24cm ×24cm,



One corner of 48 × 48 pad board. Each 8 × 8 section feeds one ASIC



Pulse height distribution from a single pad
under uniform irradiation of neutrons



Some Attributes of Ionization Mode

- Ultra high count rate capability:
  ~10^5 /s per pixel, >10^8 /s per detector
- Superb Pulse Height Resolution
- No gas amplification:
  - No ageing effect
  - Stability and reliability
- Flexible geometry:
  - Pixel dimension: ~ 1 – 5mm
  - Parallax reduction
  - Large area, complex geometry possible
- Reliant on development of low noise ASICs
- Future Detectors for the SNS and other new facilities

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