

NEUTRON SOURCES

- Types of Sources
- U.S. Sources Available for Users
- Plans for the Future
- The Neutron Scattering Society of America (NSSA)

Jim Rhyne
Lujan Neutron Scattering Center
Los Alamos National Lab.

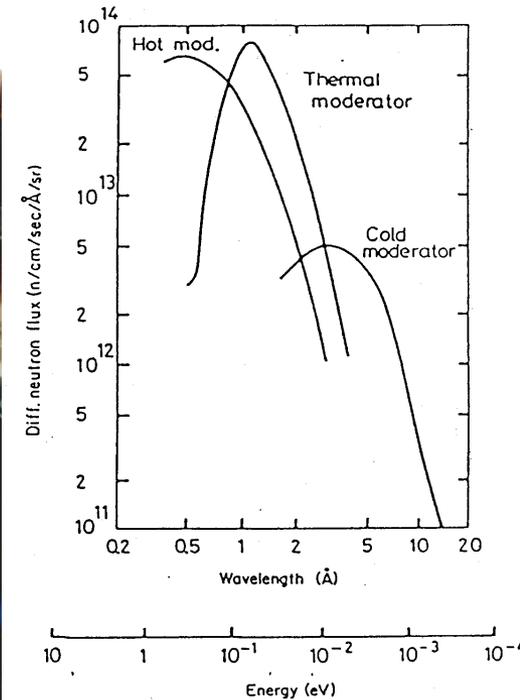
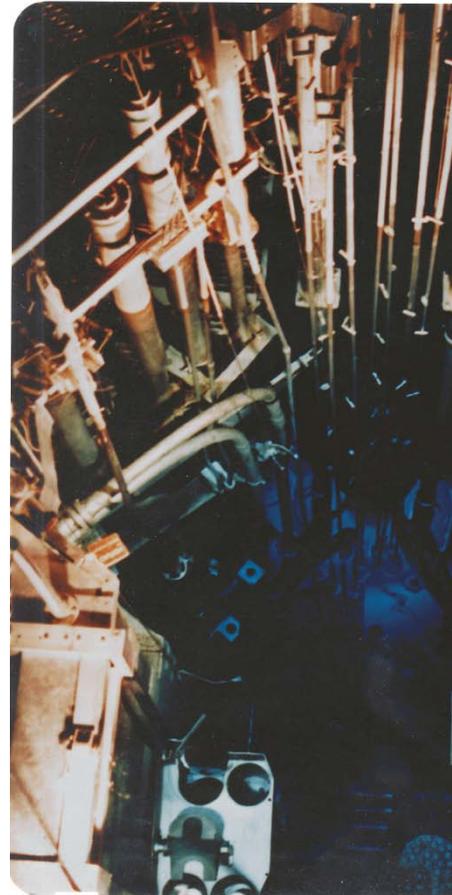
What do we need to do neutron scattering?

- **Neutron Source – produces neutrons**
- **Diffractometer or Spectrometer**
 - Allows neutrons to interact with sample
 - Sorts out discrete wavelengths by monochromator (reactor) or by time of flight (pulse source)
 - Detectors pick up neutrons scattered from sample
- **Analysis methods to determine material properties**
- **Brain power to interpret results**

Sources of neutrons for scattering

- **Nuclear Reactor**

- Neutrons produced from fission of ^{235}U
- Fission spectrum neutrons moderated to thermal energies (e.g. with D_2O)
- Continuous source – no time structure
- Common neutron energies -- $3.5 \text{ meV} < E < 200 \text{ meV}$

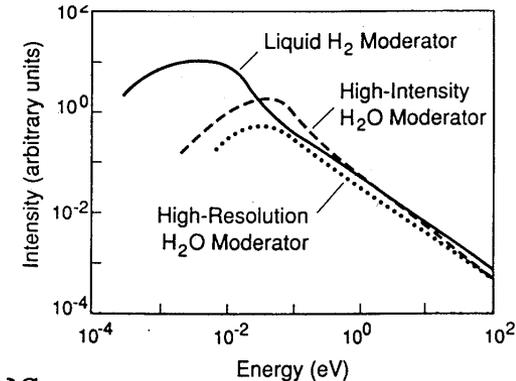
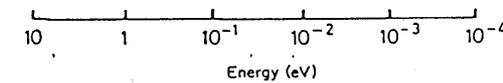
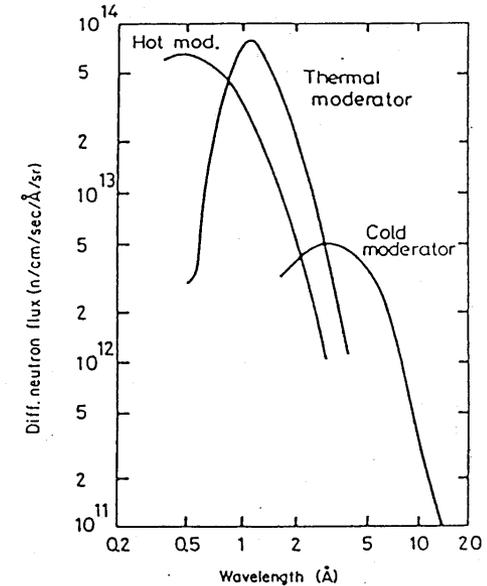


Pulse sources – time structure and wide energy spectrum

Lujan Neutron Scattering Center

WNR Facility

Isotope Production Facility



- **Proton accelerator and heavy metal target (e.g., W or U)**

- Neutrons produced by spallation
- Higher energy neutrons moderated to thermal energies
- Neutrons come in pulses (e.g. 20 Hz at LANSCE)
- Wider range of incident neutron energies

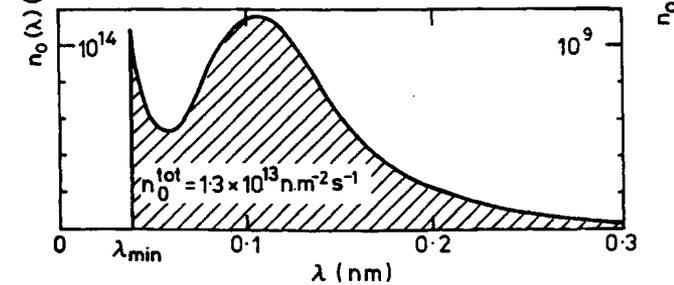
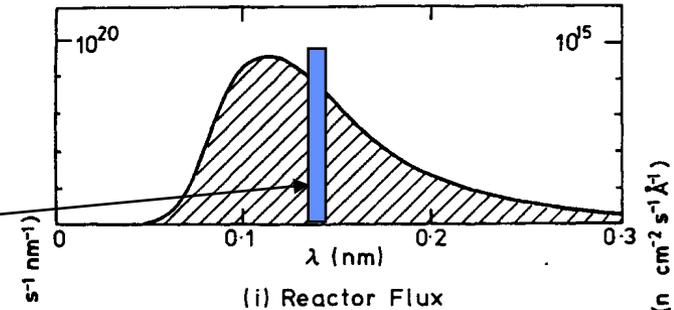
Neutron sources – steady state (Reactors) and pulsed (Spallation)

- **Reactor**

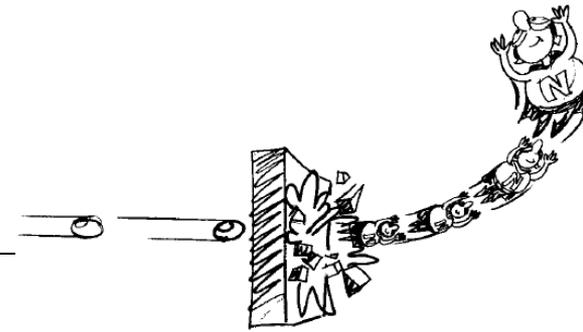
- Fission of U^{235} produces neutrons
- Fission spectrum moderated (slowed down) by either D_2O or H_2O (less good moderator) and neutrons are extracted through beam tubes for spectrometers – fixed wavelength used

- **Spallation source**

- High E protons (e.g., 800 MeV) impinge on target (W, Hg or U)
- Nucleus of target is raised to excited state and subsequent decay produces neutrons (+ γ s, nucleons and neutrinos) – 15 – 25 neutrons produced per proton with average E = 55 MeV
- Neutrons moderated by liquid H, H_2O or methane
- Spallation sources generally operate in pulse mode – 20 Hz at LANSCE, 60 Hz at new SNS



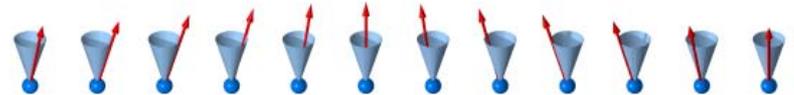
Time of flight is used to sort out wavelengths



What Can Neutrons Do?

Neutrons measure the space and time-dependent correlation function of atoms and spins – *All the Physics!*

- **Diffraction (the momentum [direction] change of the neutron is measured)**
 - Thermal neutron wavelength well-matched to interatomic spacings
 - Atomic Structure via nuclear positions
 - Magnetic Structure (neutron magnetic moment interacts with internal fields)
- **Inelastic Scattering (the momentum and energy change of the neutron is measured)**
 - Energy of thermal (cold) neutron similar to energy of elementary excitations in solids
 - Dispersive and non-dispersive phonon and magnon excitations
- **Neutral charge of neutron provides unique 3-D information (generally low absorption, ex. Gd, B, Cd, etc.)**



Neutron Scattering's Moment in the Limelight

The Nobel Prize in Physics 1994



Clifford G. Shull, MIT, Cambridge, Massachusetts, USA, receives one half of the 1994 Nobel Prize in Physics for development of the neutron diffraction technique.



S Shull made use of **elastic scattering** i.e. of neutrons which change direction without losing energy when they collide with atoms.

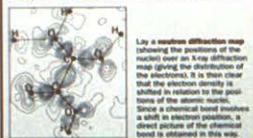
Because of the wave nature of neutrons, a diffraction pattern can be recorded which indicates where in the sample the atoms are situated. Even the placing of light elements such as hydrogen in metallic hydrides, or hydrogen, carbon and oxygen in organic substances can be determined.

The pattern also shows how atomic dipoles are oriented in magnetic materials, since neutrons are affected by magnetic forces. Shull also made use of this phenomenon in his neutron diffraction technique.



In early (1950) neutron diffractometer with flexible wavelength control here used by E.O. Wollan and C.G. Shull (standing) at Oak Ridge National Laboratory.

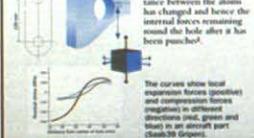
Neutrons see more than X-rays
X-rays are scattered by electrons, neutrons by atomic nuclei. With X-rays it is easiest to see atoms that have many electrons. Hydrogen, for example, which has only one electron, is not so easy to see. With neutrons, all kinds of atoms are visible.



Let a neutron diffraction map (showing the positions of the nuclei) over an X-ray diffraction map (giving the distribution of the electrons). It is then clear that the electron density is shifted in relation to the positions of the atomic nuclei. Since a chemical bond involves a shift in electron position, a direct picture of the chemical bond is obtained in this way.

Neutrons reveal inner stresses

A hole has been punched in an important metal aircraft part. Does the part match up? Neutron diffraction can show how much the distance between the atoms has changed and how the internal forces remaining around the hole after it has been punched.



The curves show local expansion forces (positive) and compression forces (negative) in different directions (red, green and blue) in an aircraft part (AlaSi3Np). (Göppert)

Neutrons show what atoms remember

of their earlier positions when they move randomly in relation to each other in liquids and melts. Even here there is in fact some local order. The atoms cannot move infinitely close to each other. Some distances are more common than others.



The time curve $t = 0$ shows the positions for liquid bromine. The other curves show how the positions of the atoms change with time. (L. de Gennes) (see also a neutron of a neutron) seen with inelastic neutron scattering. Corresponding "memory functions" can also be measured in magnets e.g. near the Curie temperature, the temperature at which magnetic order shifts to disorder.

Neutrons behave as particles and as waves

Neutrons reveal structure and dynamics

Neutrons show where atoms are

When the neutrons collide with atoms in the sample material, they change direction (are scattered) – elastic scattering.



Atoms in a crystalline sample

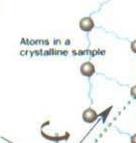
Neutrons bounce against atomic nuclei. They also react to the magnetism of the atoms.

Research reactor



Neutrons show what atoms do

3-axis spectrometer with rotatable crystals and rotatable sample



Atoms in a crystalline sample

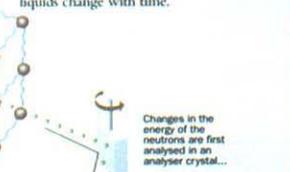
Crystal that sorts and forwards neutrons of a certain wavelength (energy) – monochromatized neutrons

Bertram N. Brockhouse, McMaster University, Hamilton, Ontario, Canada, receives one half of the 1994 Nobel Prize in Physics for the development of neutron spectroscopy.



B Brockhouse made use of **inelastic scattering** i.e. of neutrons, which change both direction and energy when they collide with atoms. They then start or cancel atomic oscillations in crystals and record movements in liquids and melts. Neutrons can also interact with spin waves in magnets.

With his 3-axis spectrometer Brockhouse measured energies of phonons (atomic vibrations) and magnons (magnetic waves). He also studied how atomic structures in liquids change with time.



When the neutrons penetrate the sample they start or cancel oscillations in the atoms. If the neutrons create phonons or magnons they themselves lose the energy these absorb – inelastic scattering

...and the neutrons then counted in a detector.

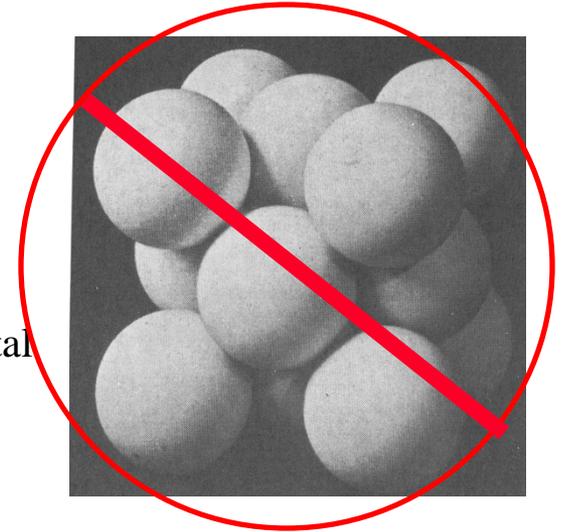
How it started
Brockhouse and Shull made their pioneering contributions at the first nuclear reactors in the USA and Canada back in the 1940s and 1950s. It was then that the resources of the reactors became available for peacetime research.

... how it continues
Thousands of researchers are now working at the many neutron research centers throughout the world. Now and very advanced neutron scattering installations have been built and more are planned in Europe, the USA and Asia. At these super-installations the researchers are studying the structure of new ceramic superconductors, molecular movements on surfaces of interest for catalytic exhaust cleaning, virus structures and the connection between the structure and the elastic properties of polymers.



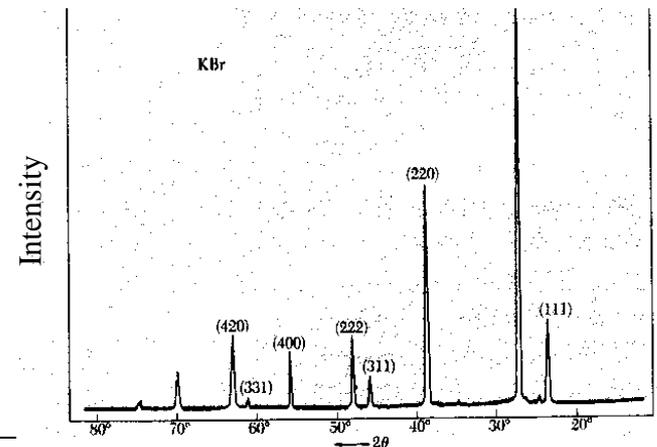
Golden Rule of Neutron Scattering

- We don't take pictures of atoms!



Atoms in fcc crystal

- Job security for neutron scatterers – we live in *reciprocal space*



Neutron scattering machines

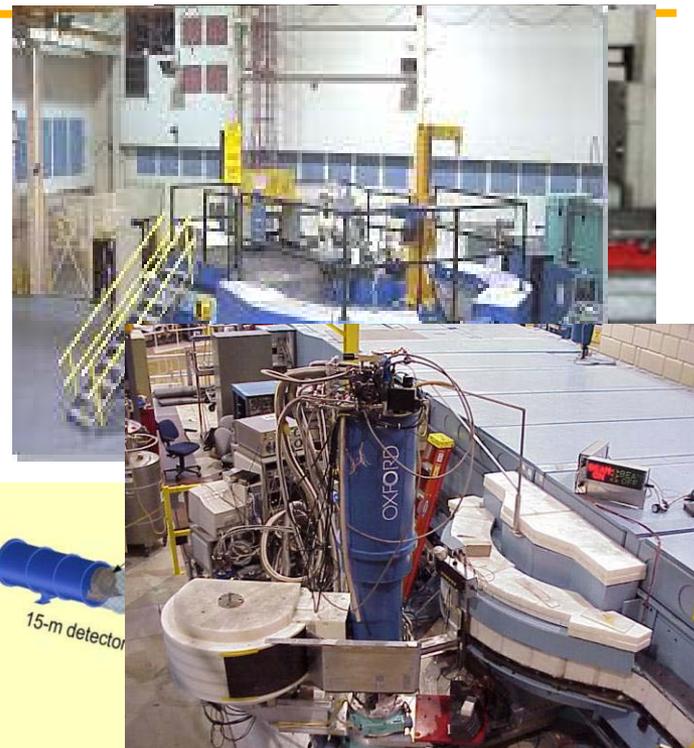
- **Spectrometers or diffractometers**

- typically live in a beam room or guide hall
- are heavily shielded to keep background low and protect us
- Receive the neutrons from the target (or reactor)
- Correlate data with specific neutron wavelengths by time of flight
- Accommodate sample environments (high/low temperature, magnetic fields, pressure apparatus)



User instruments span general purpose and specialized categories

- **Diffraction instruments**
 - Atomic and magnetic structures – polycrystalline and single crystal form
 - Local structure - PDF
- **Inelastic instruments**
 - Dispersive and non-dispersive excitations
 - Magnetic modes (magnons or crystal field excitations)
 - Phonon modes and density of states
- **Special purpose instruments**
 - Neutron reflectivity (depth profile of order parameters)
 - Small angle scattering (bridge between atomic and macro-dimensional structures)
 - Neutron applications to engineering problems
- **Sample environments enable science**



15-m detector

Alternate
Sample Position

Velocity Selector



Sample environments – key to modern experiments

- **Extremes of temperature**

- Low (cryostats)
 - » conventional closed cycle refrigerators [Joule expansion cycles] (4K and up)
 - » He cryostats (1.2 K [pumped] and up)
 - » He³-He⁴ dilution refrigerators (20 mK and up)
- High (furnaces)
 - » Conventional (up to 1200 C)
 - » Special purpose (up to 3000 C)

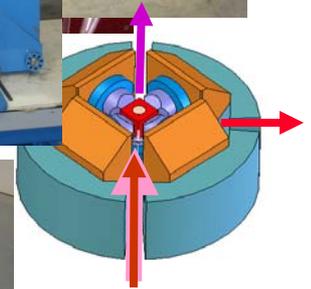
- **Magnetic fields on samples**

- Fe-core magnets (up to about 3T)
- Superconducting magnets (typical – 9T; special [finicky] – 18T)

- **High Pressure**

- Fluid cells (He or liquid) [up to 1.4 GPA (14 kbar)]
- Anvil presses (up to 40 GPa)

- **Other specialized environments – sheer cells, Langmuir troughs, etc.**



National User Facilities

Have sample, will travel
Where do I go to get neutrons?

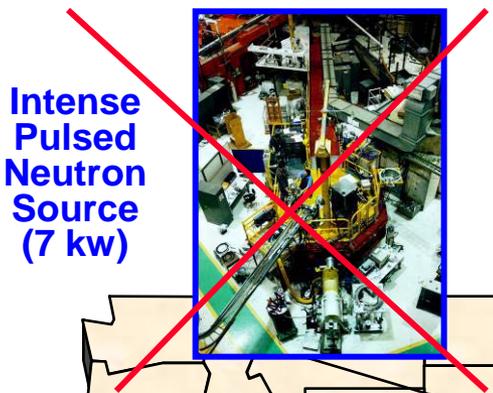
There are ~~five~~ four National User Facilities for neutron scattering in the US

National User Facilities

- HFIR 1966
- NCNR 1969
- IPNS 1981-2008
- Lujan 1985
- SNS 2006

Local/Regional Facilities (University Reactors)

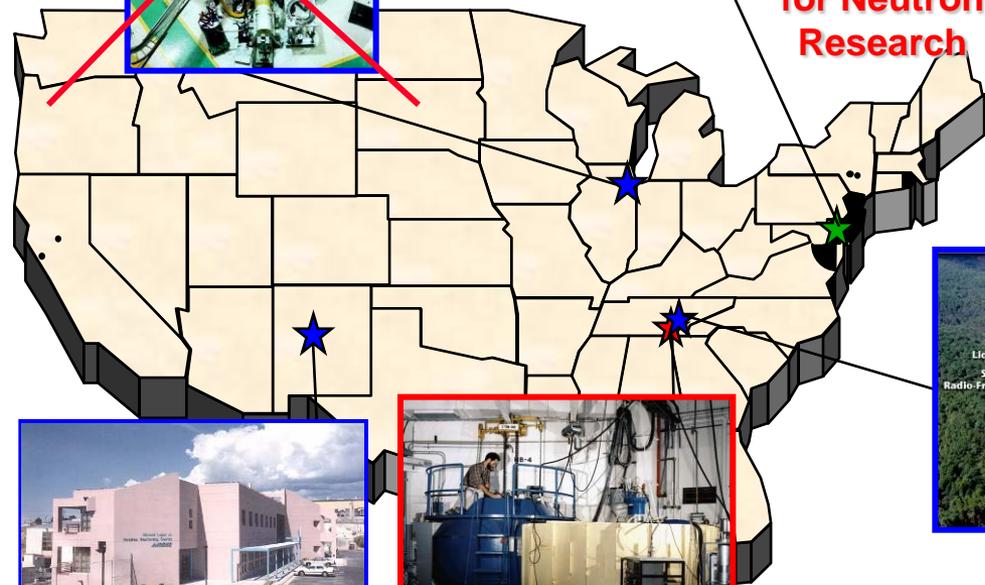
- MIT
- Missouri
- ...



Intense Pulsed Neutron Source (7 kw)



NIST Center for Neutron Research



Manuel Lujan Jr. Neutron Scattering Center (100 kW)



High-Flux Isotope Reactor



Spallation Neutron Source (first neutrons in May 2006 -- operational instruments in 2007) (1400 kW)

US Neutron Source Support

- DOE operates 3 out of 4 of the Major Neutron Sources (and supports fuel for university reactors)
- DOC/NIST operates the only fully internationally competitive neutron facility (NCNR) with the largest user base (cold neutrons)
- NSF, NIH, and DOD support current neutron beam research mostly by supporting university research
 - EXCEPTIONS: NSF funds the Center for High Resolution Neutron Scattering (CHRNS) at NIST, and has supported some construction of instruments at LANSCE, HFIR, IPNS and MURR) NIH has funded a reflectometer at NCNR.

World View of Neutron Scattering Facilities

Facility	Start Operation	Cease Operation	Country	Type	Time structure	Peak Flux x 10 ⁻¹⁴	Power	Instruments			
								Total	Diffraction	Low Q	Inelastic
NRU	1957	2005	Canada	Reactor	Continuous	3	120MW	5	2	1	2
R-2	1960		Sweden	Reactor	Continuous	1	50MW	6	5	0	1
IBR-2	1961		Russia	Reactor	Pulsed		2MW	13	5	4	4
FRJ-2	1962	2006	Germany	Reactor	Continuous	2	23MW	15	5	5	5
DR3	1963	2000	Denmark	Reactor	Continuous	1.5	10MW	7	2	3	2
HFBR	1965	1999	US	Reactor	Continuous	4	30MW	13	7	2	4
HFIR	1966		US	Reactor	Continuous	12	85MW	10	3.7	3	3.3
NCNR	1969		US	Reactor	Continuous	2	20MW	17	2	6	9
ILL	1972		France	Reactor	Continuous	12	58MW	34	15	4	15
BER-2	1973		Germany	Reactor	Continuous	2	10MW	15	10	2	3
Orphee	1980		France	Reactor	Continuous	3	14MW	25	12	6	7
KENS	1980		Japan	Spallation	Pulsed	3	3kW	15	5	4	6
IPNS	1981		US	Spallation	Pulsed	5	7kW	12	5	4	3
ISIS	1985		England	Spallation	Pulsed	20-100	160kW	19	9	3	7
LANSCÉ	1988		US	Spallation	Pulsed	30	56kW	7	3	2	2
JRR-3M	1990		Japan	Reactor	Continuous	2	20MW	23	7	5	11
SINQ	1996		Switzerland	Spallation	Continuous	2	1MW	10	5	2	3
Under development											
FRM-II	2002		Germany	Reactor	Continuous	7	20MW	17			
RR	2005		Australia	Reactor	Continuous	4	20MW	18			
SNS	2006		US	Spallation	Pulsed	200	2MW	24			
JSNS	2006		Japan	Spallation	Pulsed	100	1MW	24			
ESS†	2010		Europe	Spallation	Pulsed	2000	5MW	40			

The number of neutron scattering instruments available in the U.S. now and in the future will be less than half that available in Western Europe and less than available in Japan. On a per capita basis the United States has half the neutron scattering capacity of either Western Europe or Japan – and this shortfall is unlikely to change for the foreseeable future



Center for Neutron
Research



NIST Center for Neutron Research (NCNR)

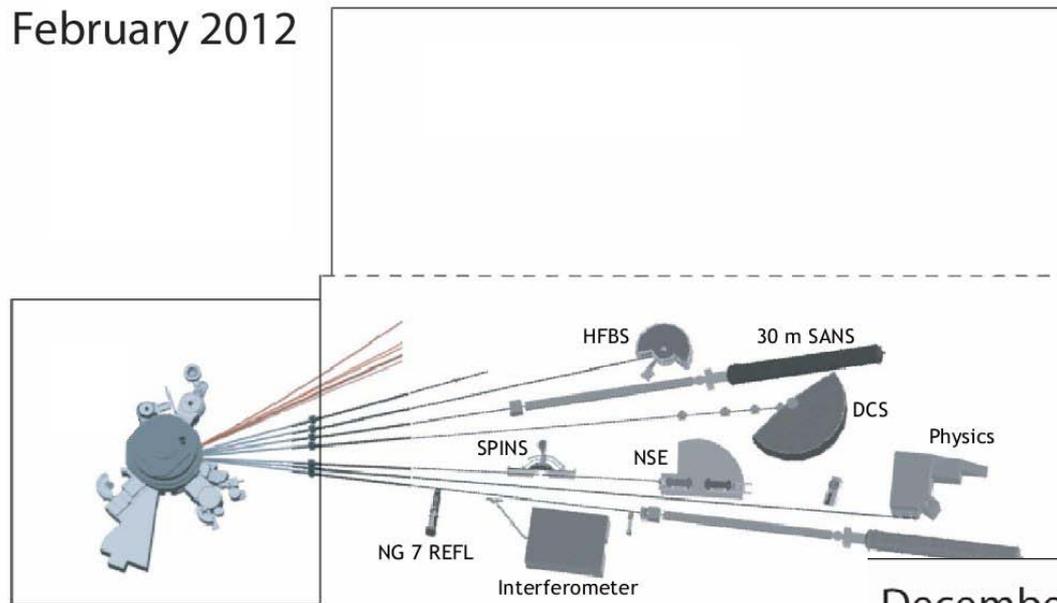
A Comprehensive Neutron User Facility

- 20 MW Heavy-Water-Moderated REACTOR
- A Cold Neutron Source and Guide Hall
- Current Total -- 17 Thermal and Cold Neutron Instruments
- Constructing 2nd guide hall – Amer. Competes Act
- Installation of 2nd guide hall components began March 2011 – reactor down approx. 11 months

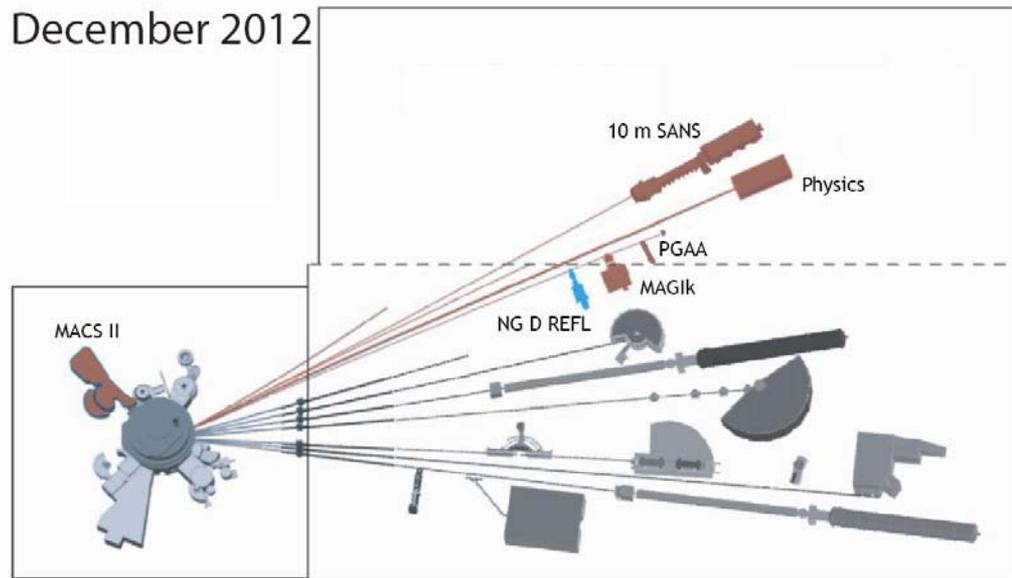


Several existing instruments move in both Reactor Hall and existing Guide Hall

February 2012

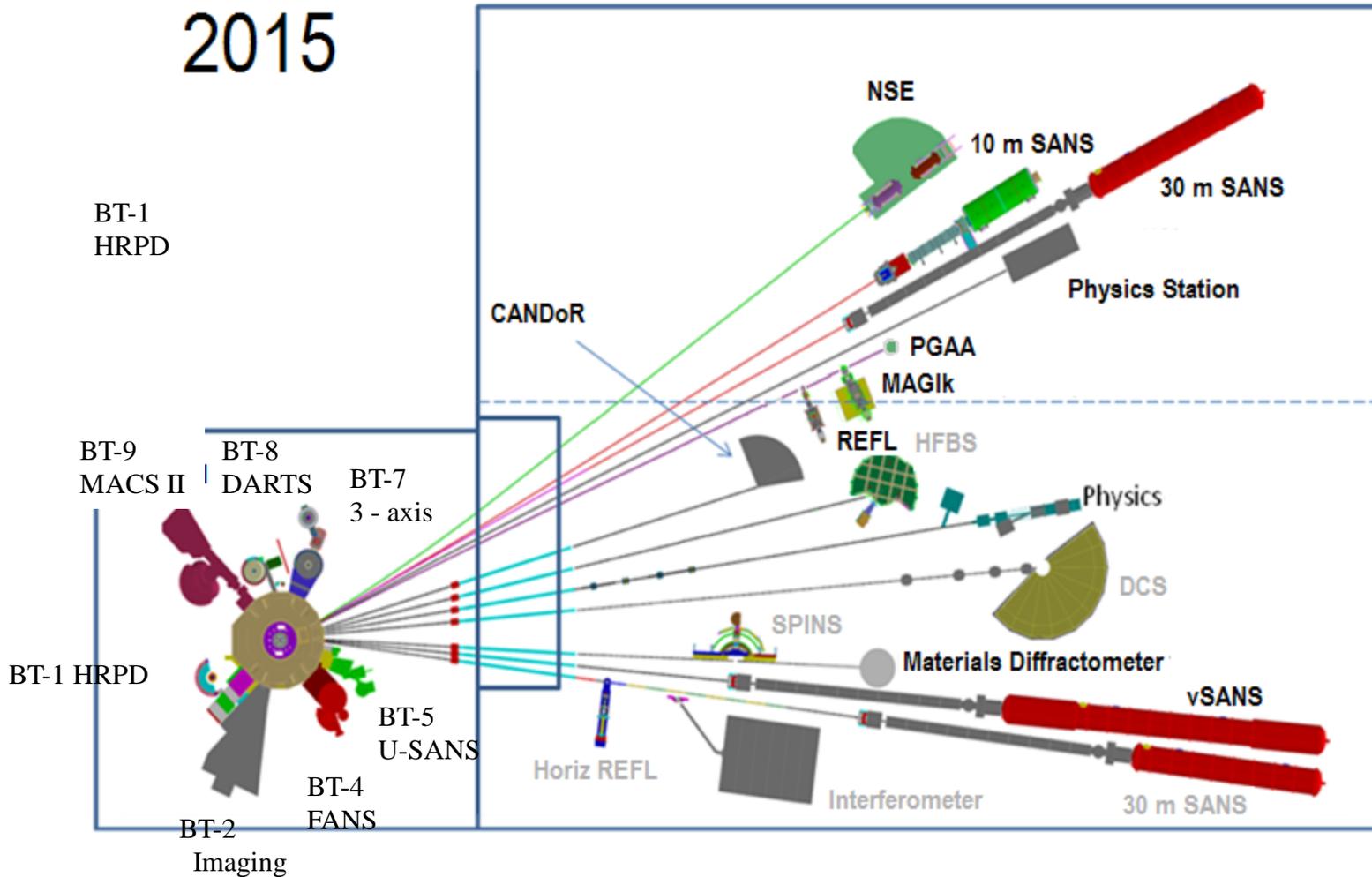


December 2012

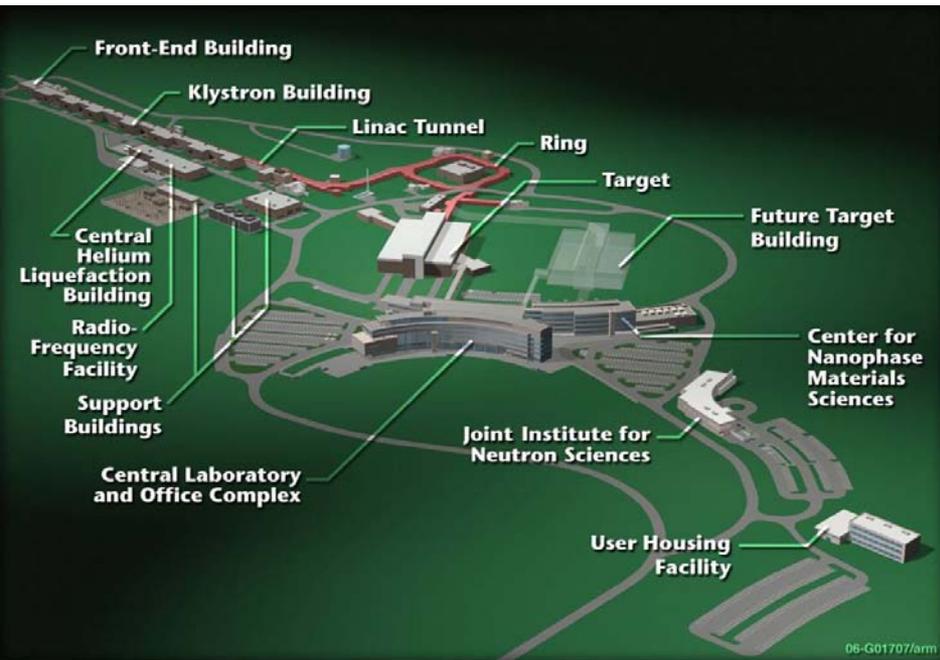


Completion in 2015 -- Guide Hall & Reactor Hall Instruments

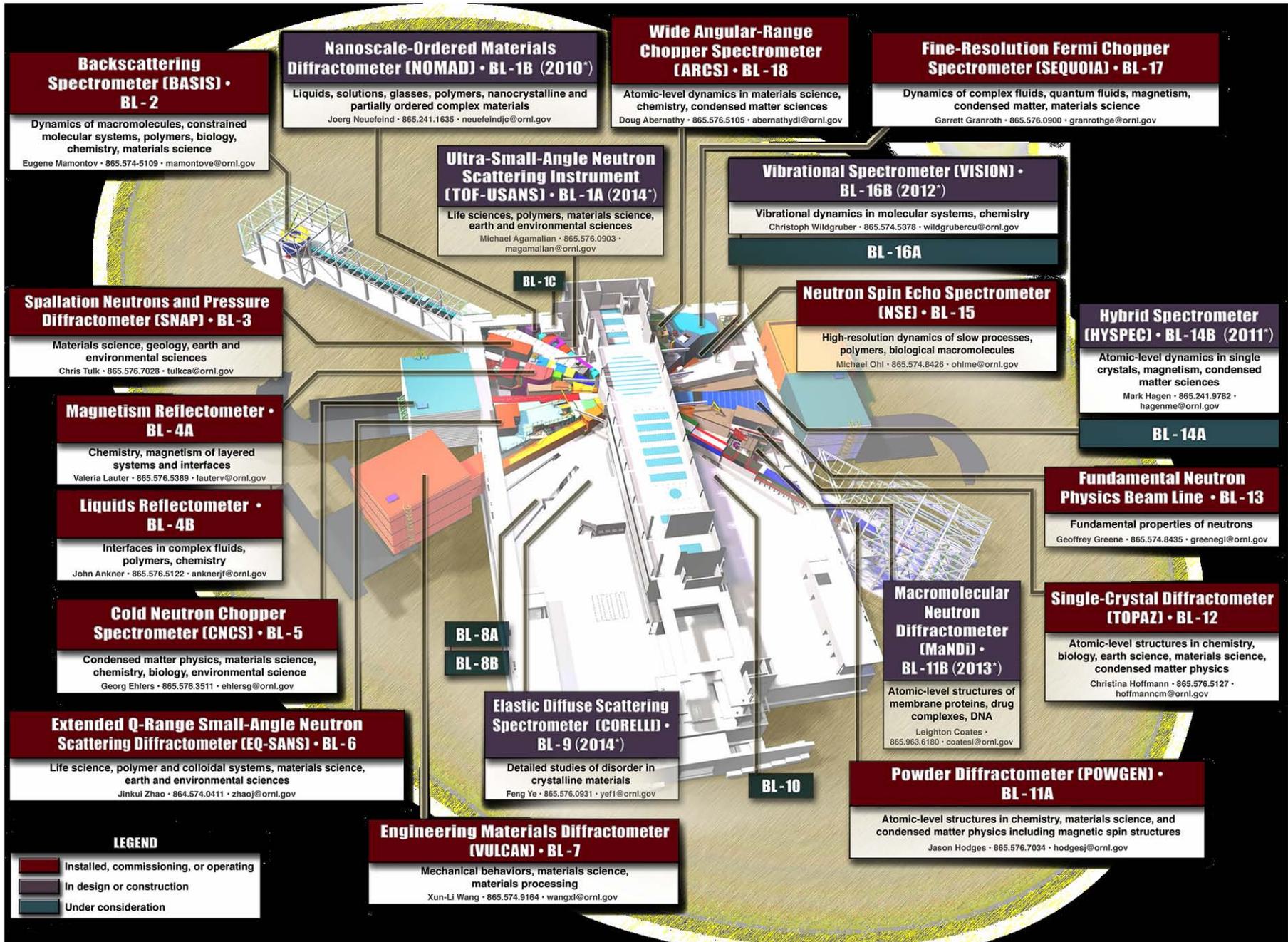
2015



SPALLATION NEUTRON SOURCE



- First neutron production ~~scheduled for June 2006~~
April 28, 2006
2:04 p.m.
- Started with 3 (now 10) instruments operating or in commissioning
- Capacity for a total of 24 instruments – plan for second target
- Accommodate 2000 users/year at full operation



Backscattering Spectrometer (BASIS) • BL - 2

Dynamics of macromolecules, constrained molecular systems, polymers, biology, chemistry, materials science

Eugene Mamontov • 865.574.5109 • mamontove@ornl.gov

Nanoscale-Ordered Materials Diffractometer (NOMAD) • BL - 1B (2010*)

Liquids, solutions, glasses, polymers, nanocrystalline and partially ordered complex materials

Joerg Neufeld • 865.241.1635 • neufeldj@ornl.gov

Wide Angular-Range Chopper Spectrometer (ARCS) • BL - 18

Atomic-level dynamics in materials science, chemistry, condensed matter sciences

Doug Abernathy • 865.576.5105 • abernathyd@ornl.gov

Fine-Resolution Fermi Chopper Spectrometer (SEQUOIA) • BL - 17

Dynamics of complex fluids, quantum fluids, magnetism, condensed matter, materials science

Garrett Granroth • 865.576.0900 • granrothge@ornl.gov

Ultra-Small-Angle Neutron Scattering Instrument (TOF-USANS) • BL - 1A (2014*)

Life sciences, polymers, materials science, earth and environmental sciences

Michael Agamalian • 865.576.0903 • magamalian@ornl.gov

Vibrational Spectrometer (VISION) • BL - 16B (2012*)

Vibrational dynamics in molecular systems, chemistry

Christoph Wildgruber • 865.574.5378 • wildgruber@ornl.gov

BL - 16A

Spallation Neutrons and Pressure Diffractometer (SNAP) • BL - 3

Materials science, geology, earth and environmental sciences

Chris Tulk • 865.576.7028 • tulkca@ornl.gov

Neutron Spin Echo Spectrometer (NSE) • BL - 15

High-resolution dynamics of slow processes, polymers, biological macromolecules

Michael Ohl • 865.574.8426 • ohlme@ornl.gov

Hybrid Spectrometer (HYSPEC) • BL - 14B (2011*)

Atomic-level dynamics in single crystals, magnetism, condensed matter sciences

Mark Hagen • 865.241.9782 • hagenme@ornl.gov

Magnetism Reflectometer • BL - 4A

Chemistry, magnetism of layered systems and interfaces

Valeria Lauter • 865.576.5389 • lauterv@ornl.gov

Liquids Reflectometer • BL - 4B

Interfaces in complex fluids, polymers, chemistry

John Ankner • 865.576.5122 • anknerj@ornl.gov

BL - 14A

Fundamental Neutron Physics Beam Line • BL - 13

Fundamental properties of neutrons

Geoffrey Greene • 865.574.8435 • greene@ornl.gov

Cold Neutron Chopper Spectrometer (CNCS) • BL - 5

Condensed matter physics, materials science, chemistry, biology, environmental science

Georg Ehlers • 865.576.3511 • ehlersg@ornl.gov

BL - 8A

BL - 8B

Macromolecular Neutron Diffractometer (MaNDi) • BL - 11B (2013*)

Atomic-level structures of membrane proteins, drug complexes, DNA

Leighton Coates • 865.963.6180 • coatesl@ornl.gov

Single-Crystal Diffractometer (TOPAZ) • BL - 12

Atomic-level structures in chemistry, biology, earth science, materials science, condensed matter physics

Christina Hoffmann • 865.576.5127 • hoffmanncm@ornl.gov

Extended Q-Range Small-Angle Neutron Scattering Diffractometer (EQ-SANS) • BL - 6

Life science, polymer and colloidal systems, materials science, earth and environmental sciences

Jinkui Zhao • 864.574.0411 • zhaoj@ornl.gov

Elastic Diffuse Scattering Spectrometer (CORELLI) • BL - 9 (2014*)

Detailed studies of disorder in crystalline materials

Feng Ye • 865.576.0931 • yef1@ornl.gov

BL - 10

Powder Diffractometer (POWGEN) • BL - 11A

Atomic-level structures in chemistry, materials science, and condensed matter physics including magnetic spin structures

Jason Hodges • 865.576.7034 • hodgesj@ornl.gov

LEGEND

- Installed, commissioning, or operating
- In design or construction
- Under consideration

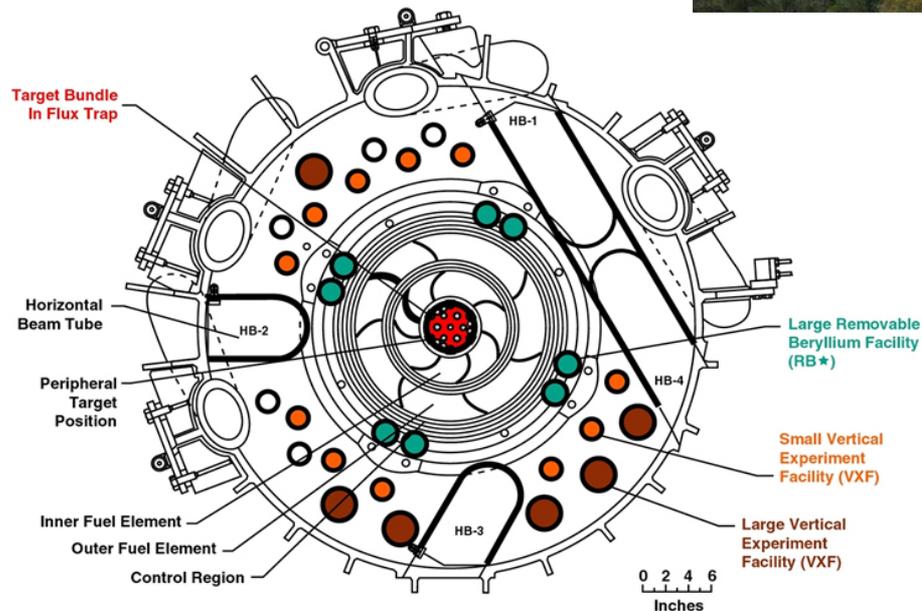
Engineering Materials Diffractometer (VULCAN) • BL - 7

Mechanical behaviors, materials science, materials processing

Xun-Li Wang • 865.574.9164 • wangxl@ornl.gov

High Flux Isotope Reactor

- Oak Ridge, Tennessee
- BES, Department of Energy
- Started Operation: 1966
- 85 MW Light Water Reactor
- Peak Core Neutron Flux
– $12 \times 10^{14} / \text{cm}^2\text{s}$



**Fixed-Incident-Energy
Triple-Axis
Spectrometer •
HB-1A**

Low-energy excitations,
magnetism, structural
transitions

Jerel Zarestky • 865.574.4951
zarestkyj@ornl.gov

**Polarized Triple Axis
Spectrometer •
HB-1**

Polarized neutron studies of
magnetic materials, low-energy
excitations, structural transitions

Masaaki Matsuda • 865.574.6580
matsudam@ornl.gov

**Neutron Powder
Diffractometer •
HB-2A**

Structural studies, magnetic
structures, texture and phase
analysis

Ovidiu Garlea • 865.574.5041
garleao@ornl.gov

**US/Japan WAND •
HB-2C**

Diffuse-scattering studies of
single crystals and time-resolved
phase transitions

Jaime Fernandez-Baca • 865.576.8659
fernandezbja@ornl.gov

**Future Development •
HB-2D**

**Neutron Residual Stress Mapping
Facility • HB-2B**

Strain and phase mapping in
engineering materials

Camden Hubbard • 865.574.4472 • hubbardcr@ornl.gov

**Triple-Axis
Spectrometer •
HB-3**

Medium- and high-resolution
inelastic scattering at
thermal energies

Mark Lumsden • 865.241.0090
lumsdenmd@ornl.gov

**Four-Circle
Diffractometer •
HB-3A**

Small unit-cell crystal
structural studies,
particularly H-bonding

Bryan Chakoumakos • 865.574.5235
chakoumakobc@ornl.gov

**Future
Development •
CG-4A**

**Future
Development •
CG-4B**

**US/Japan Cold
Neutron
Triple-Axis
Spectrometer •
CG-4C (2010*)**

High-resolution inelastic
scattering at cold
neutron energies

Barry Winn • 865.241.0092
winnbl@ornl.gov

**Image-Plate
Single-Crystal
Diffractometer
(IMAGINE) •
CG-4D (2010*)**

Chemical, organic,
metallo-organic, protein
single crystals

Flora Meilleurf • 865.241.2897
meilleurf@ornl.gov

**Cold Neutron
Source**

**Development
Beam Line • CG-1**

Imaging, optics, SERGIS,
sample alignment

Lee Robertson • 865.574.5243
robertsonjl@ornl.gov

**General-Purpose SANS •
CG-2**

Polymer blends, flux lattices in high-Tc
materials, soft materials processing
and structure

Ken Littrell • 865.574.4535 • littrellkc@ornl.gov

Bio-SANS • CG-3

Proteins and complexes,
pharmaceuticals,
biomaterials

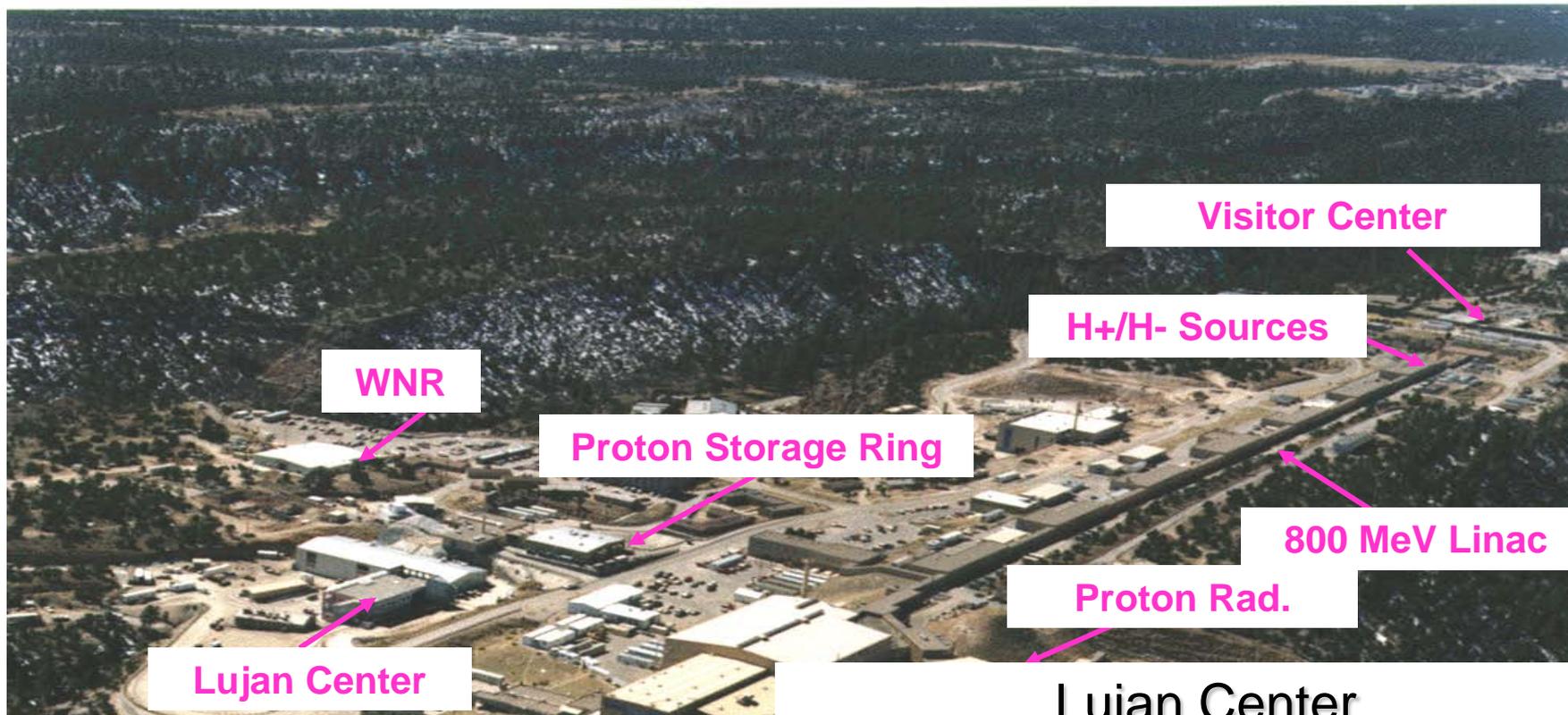
Volker Urban • 865.576.2578
urbanvs@ornl.gov

* Scheduled commissioning date.

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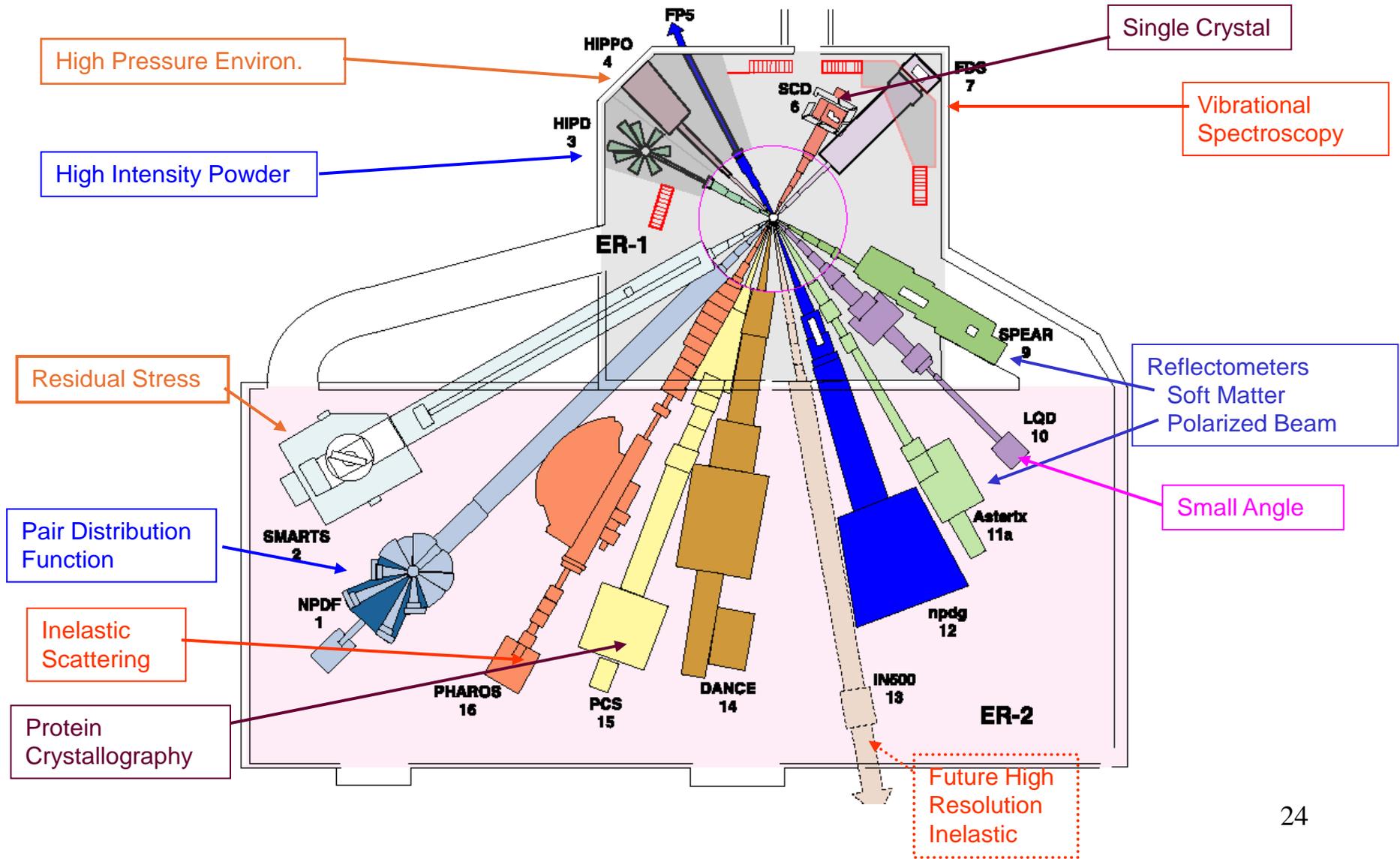
User Facilities at LANSCE: Los Alamos Neutron Science Center



Lujan Center

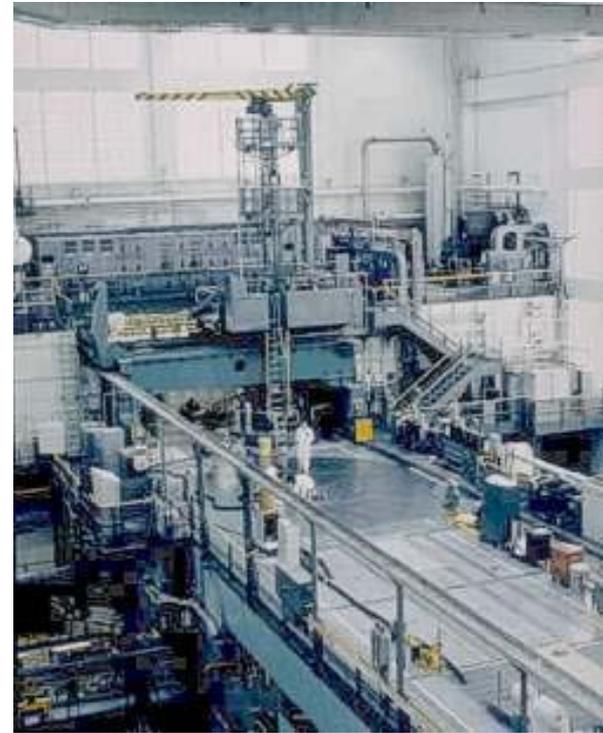
- BES/NNSA, Department of Energy
- Started Operation: 1985
- 85 kW Spallation Source (LANSCE)
- Peak Flux – $30 \times 10^{14} / \text{cm}^2 \text{s}$
- Cold Source
- 11 Instruments

Instruments by functional categories



NRU Reactor – Chalk River, CA

- 125 MW heavy water reactor – Large Core, peak thermal flux of 3×10^{14} , initial operation in 1957
- Seven beam tubes dedicated to neutron instruments
 - DualSpec
 - C2, High Resolution Powder Diffractometer
 - C5, Polarized Beam Triple-Axis Spectrometer / Reflectometer
 - D3 – Reflectometer
 - E3 – Materials Science Diffractometer
 - L3 – Strain-Scanning Spectrometer
 - N5 – Triple-axis Spectrometer
 - T3 – Bioscience Diffractometer
- Neutron Scattering Program Funded/Operated by National Research Council of Canada



Procedure for Obtaining Time on Spectrometers

- Make contact with and discuss proposed experiments with instrument scientist at facility
- Go to facility web site and access proposal form – complete by deadline (caution: usually only 2 per year!)
- Approval (declination) received within about 6 weeks
- Fine tune schedule with instrument scientist (if necessary)
- Complete radiation training module and access approvals in advance of visit (each lab has different procedures).
- If using ancillary equipment, make sure sample dimensions are correct, etc.
- Arrange travel and housing for visit (partial travel assistance may be available for fist-time visitors or students.)
- Arrive at facility in advance of allocated time to set up experiment
- Apply for more time for next series of experiments (max. about 2 – 3 visits/year)

Reports

- ***Neutron Source Upgrades and Specifications for SNS*** (1996)
 - Research Reactor Upgrades, Robert Birgeneau, Chair
 - Spallation Neutron Source Upgrades, Gabriel Aeppli, Chair
 - Technical Specifications for the Next Generation Spallation Source, Thomas Russell, Chair
- ***Review of the High Flux Isotope Reactor Upgrade and User Program*** (October, 1998; Jack Crow, Chair)
- ***Neutron Scattering*** (February, 2000; Martin Blume, Chair)
<http://www.sc.doe.gov/production/bes/BESAC/neutronrpt.pdf>
- ***Review of IPNS/LANSCE*** (March, 2001; Ward Plummer, Chair)
- ***Report on the Status and Needs of Major Neutron Scattering Facilities and Instruments in the United States*** (June 2002; Patrick Gallagher, Chair) <http://www.ostp.gov/html/NeutronIWGReport.pdf>

Information on North American National Neutron Scattering Facilities

- ***Neutron Scattering Society of America (NSSA)*** [on-line or mail-in membership form]
 - <http://www.neutronsattering.org>
 - Announcements of meetings, workshops, etc.
 - Links to major neutron facilities
- ***Oak Ridge Spallation Neutron Source (SNS) and High Flux Isotope Reactor (HFIR)***
 - <http://neutrons.ornl.gov/>
- ***NIST Center for Neutron Research (NCNR)***
 - <http://www.ncnr.nist.gov/>
- ***Los Alamos Lujan Neutron Scattering Center (LANSCE)***
 - <http://lansce.lanl.gov/>
- ***NRU Chalk River***
 - <http://neutron.nrc.ca/intro.html>