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.

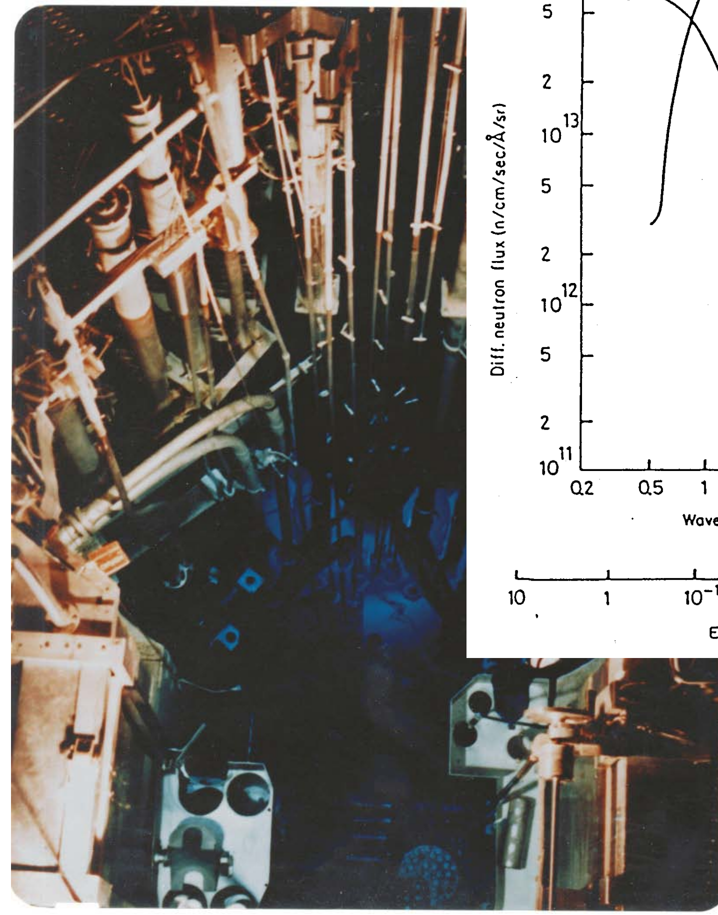
SNS/ANL School on Neutron and x-Ray Scattering, June 2011

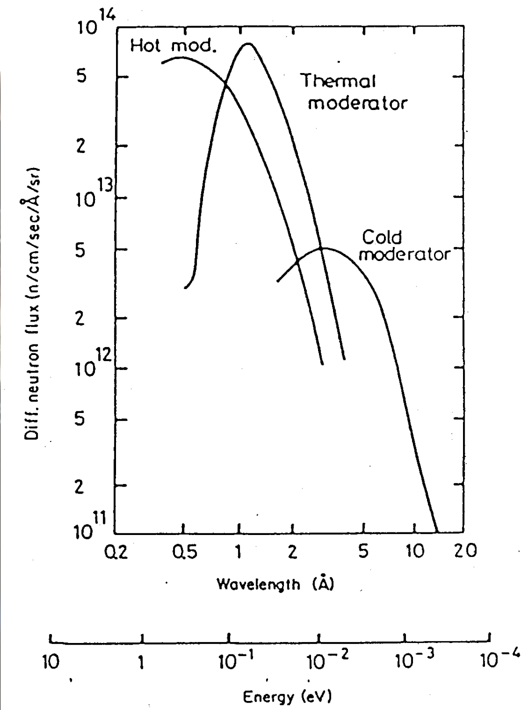
What do we need to do neutron scattering?

- **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

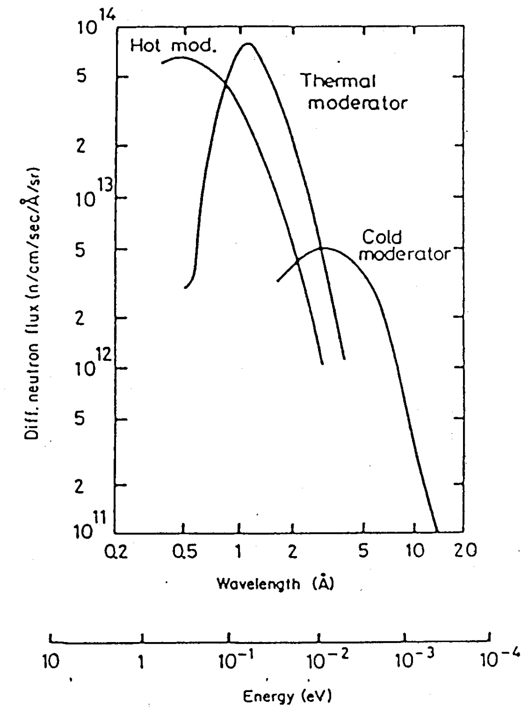
- **Nuclear Reactor**
  - Neutrons produced from fission of ^{235}U
  - Fission spectrum neutrons moderated to thermal energies (e.g. with $D_2 0$)
  - Continuous source – no time structure
  - Common neutron energies -- 3.5 meV < E < 200 meV

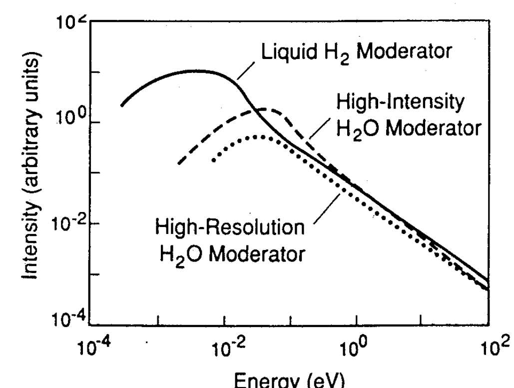




Pulse sources – time structure and wide energy spectrum

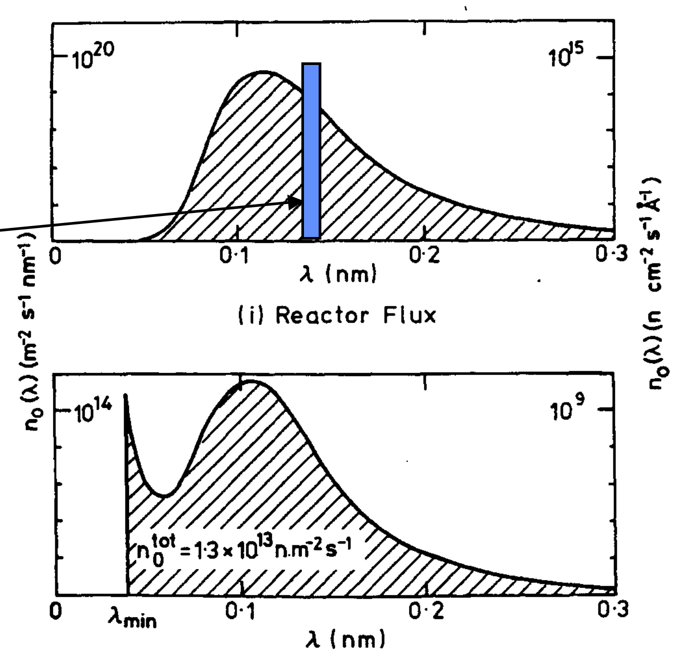
- **Proton accelerator and heavy metal target (e.g., W or U)**
  - Neutrons produced by spallation
  - Higher energy neutrons moderated to thermal energies
  - Neutrons come in pulses (e.g. 20 Hz at LANSCE)
  - Wider range of incident neutron energies



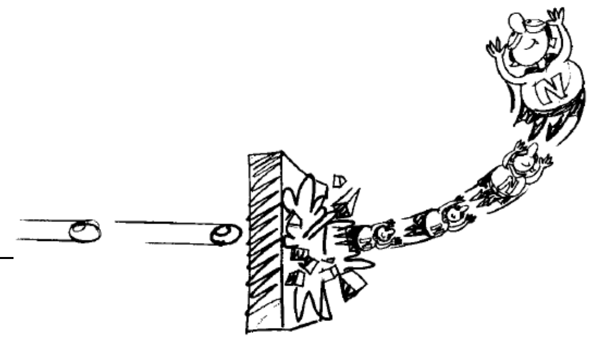


Neutron sources – steady state (Reactors) and pulsed (Spallation)

- **Reactor**
  - Fission of U^{235} produces neutrons
  - Fission spectrum moderated (slowed down) by either D_2O or H_20 (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 (+ γs, neucleons and neutrinos) – 15 – 25 neutrons produced per proton with average E = 55 MeV
  - Neutrons moderated by liquid H, H_20 or methane
  - Spallation sources generally operate in pulse mode – 20 Hz at LANSCE, 60 Hz at new SNS



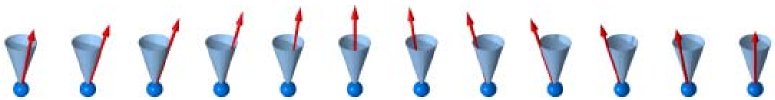
Time of flight is used to sort out wavelengths



What Can Neutrons Do?

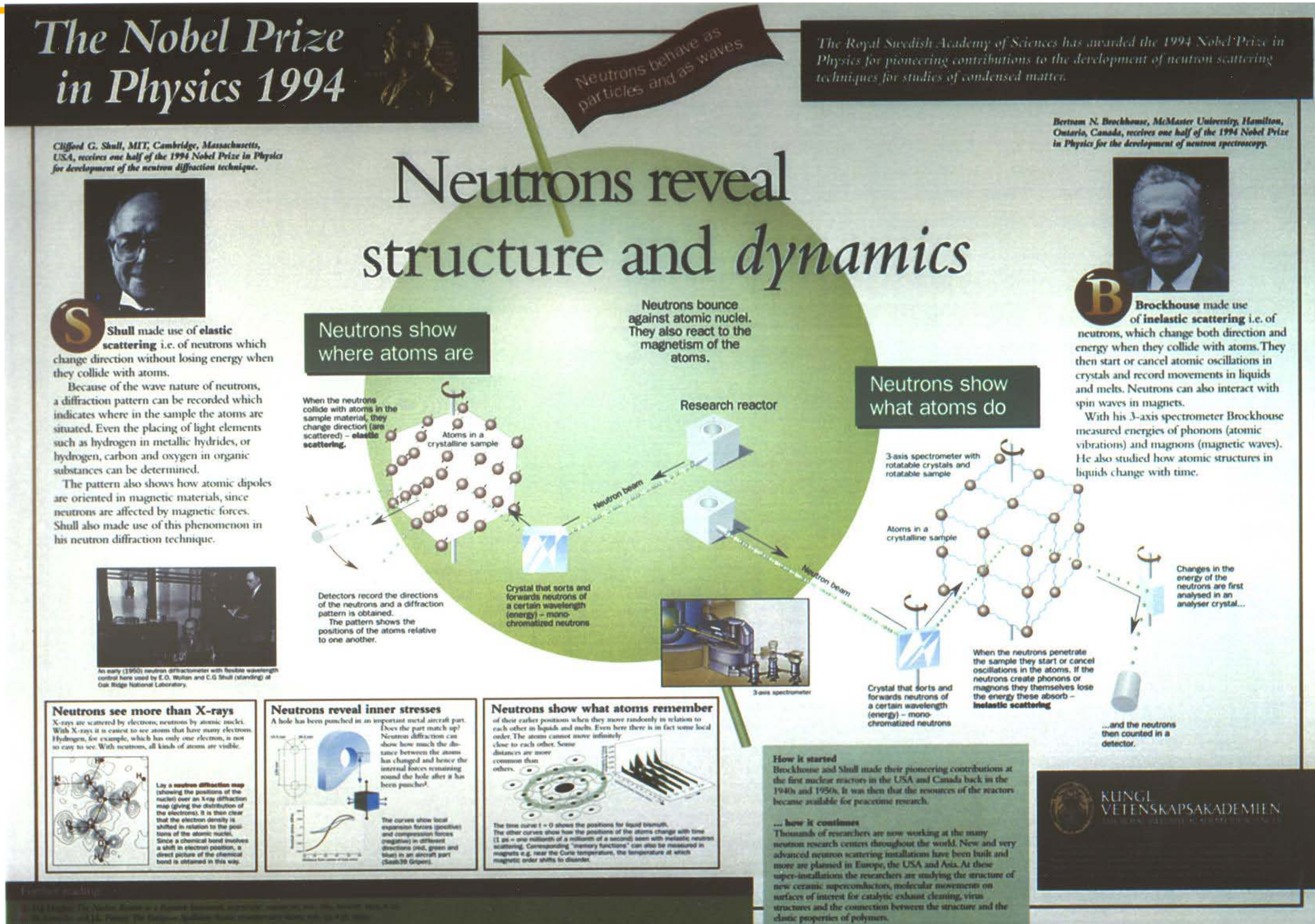
Neutrons measure the space and time-dependent correlation function of atoms and spins – *All the Physics!*

- **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

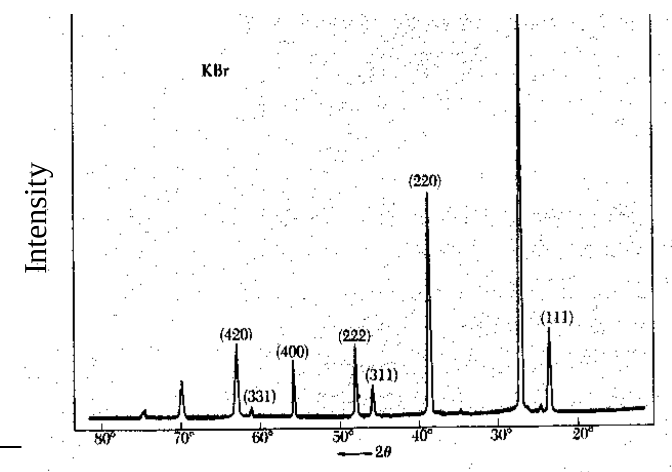


Golden Rule of Neutron Scattering

- **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)

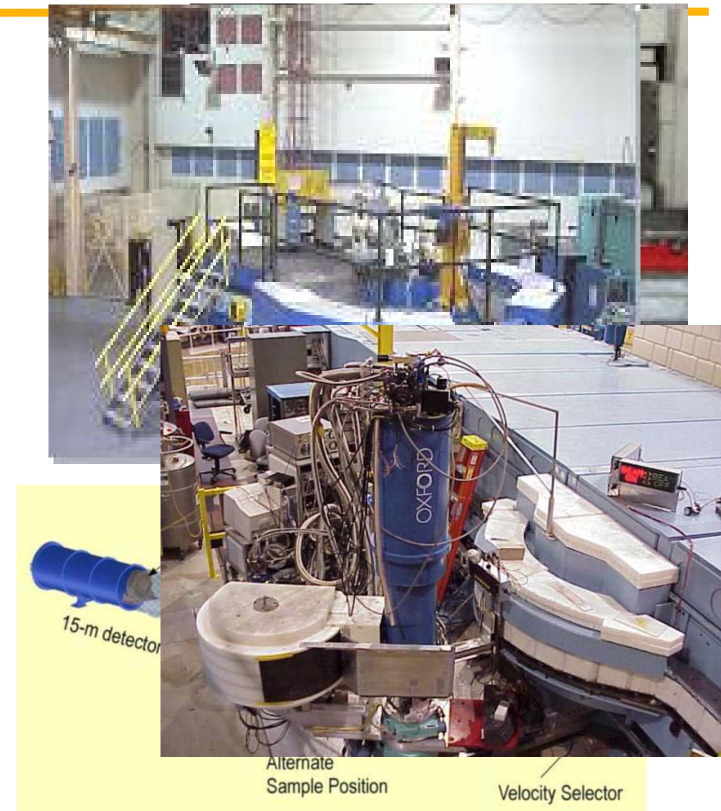
User instruments span general purpose and specialized categories

- **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

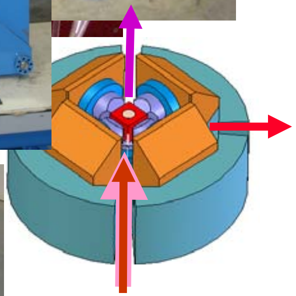
- **Special purpose instruments**
  - Neutron reflectivity (depth profile of order parameters)
  - Small angle scattering (bridge between atomic and macro-dimensional structures)
  - Neutron applications to engineering problems

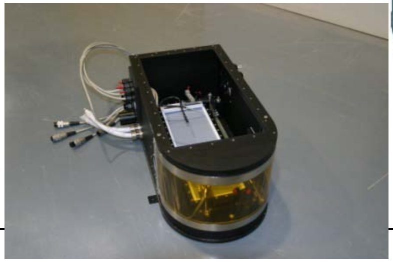
- **Sample environments enable science**



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)
    - » He^3-He^4 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

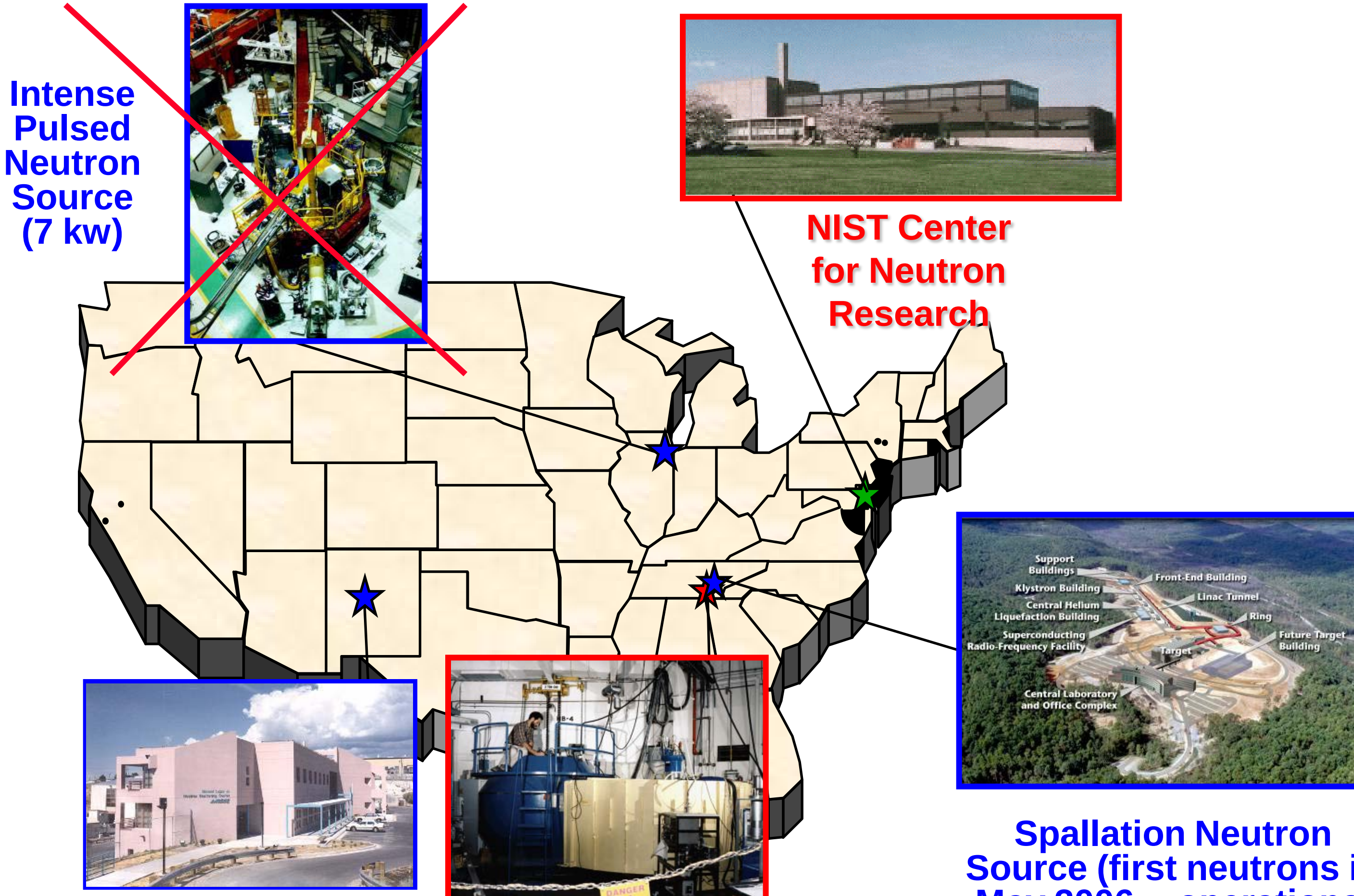
Have sample, will travel

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
…



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
LANSCE	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 forseeable future

---- Ref. ***Report on the Status and Needs of Major Neutron Scattering Facilities and Instruments in the United States,*** June 2002

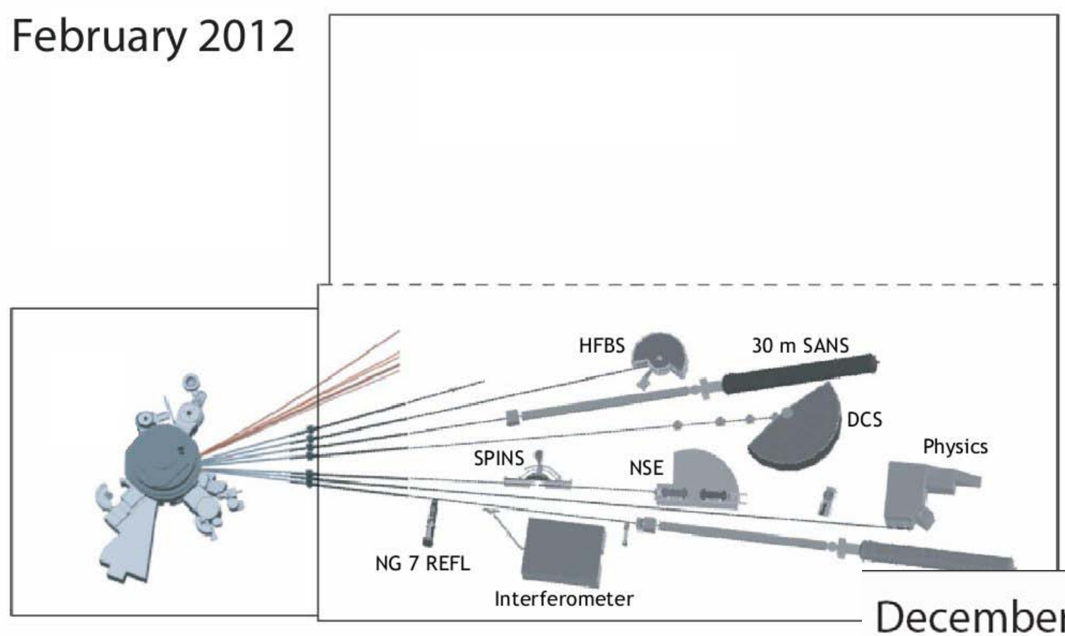
Center for Neutron Research

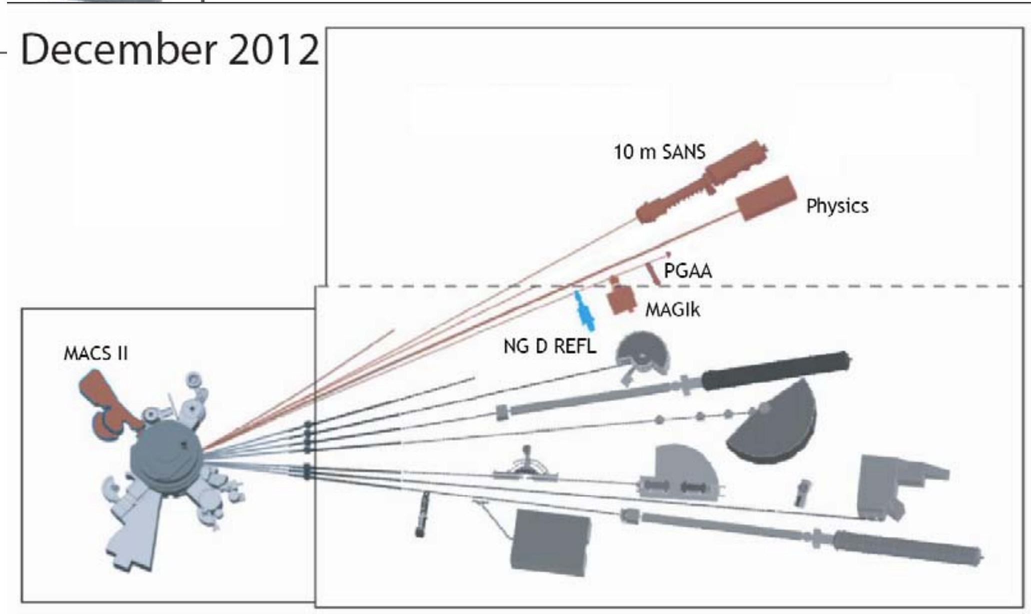
NIST Center for Neutron Research (NCNR)

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

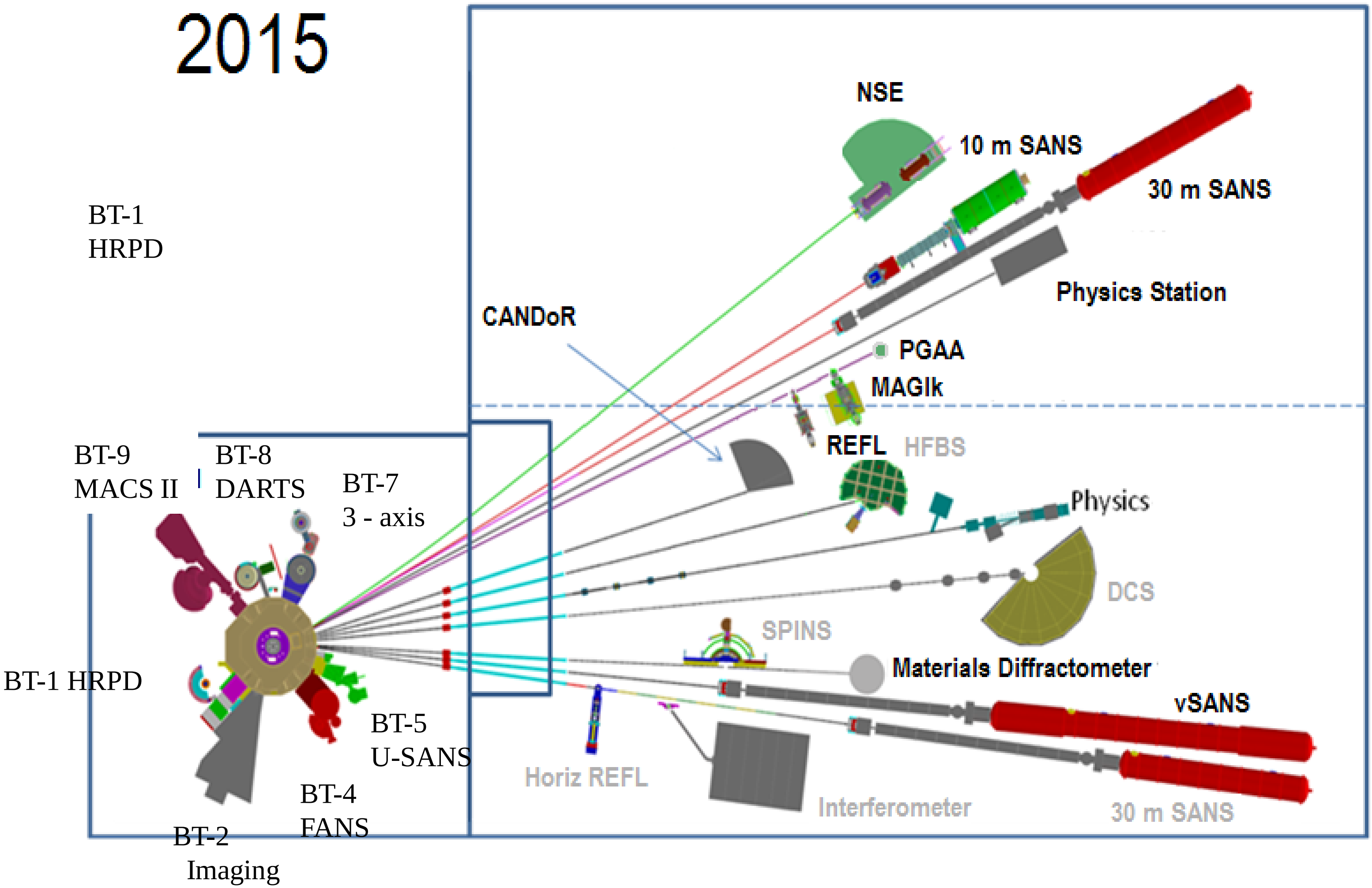
Several existing instruments move in both Reactor Hall and existing Guide Hall



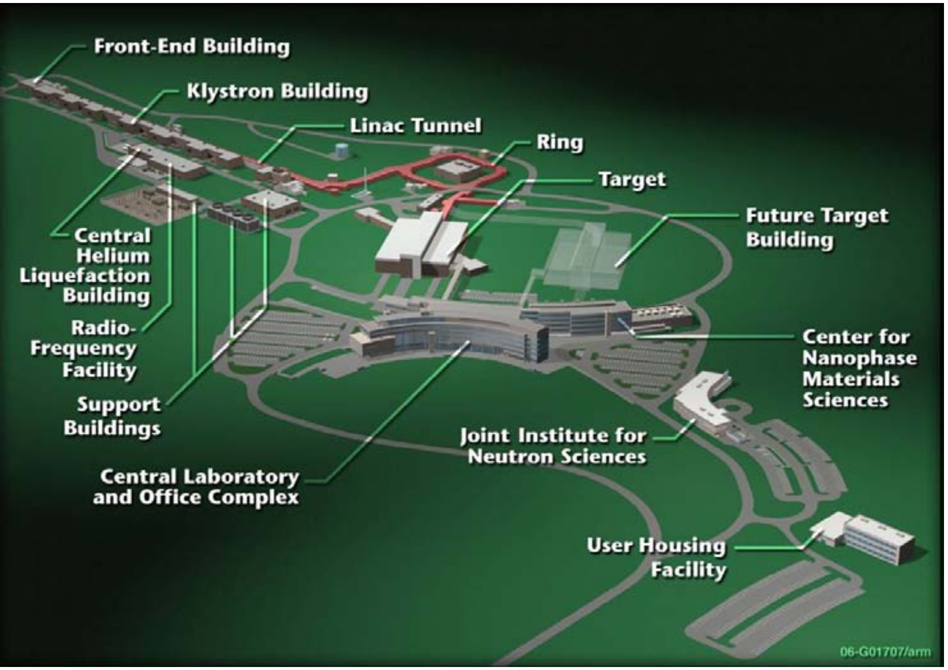


Center for Neutron Research

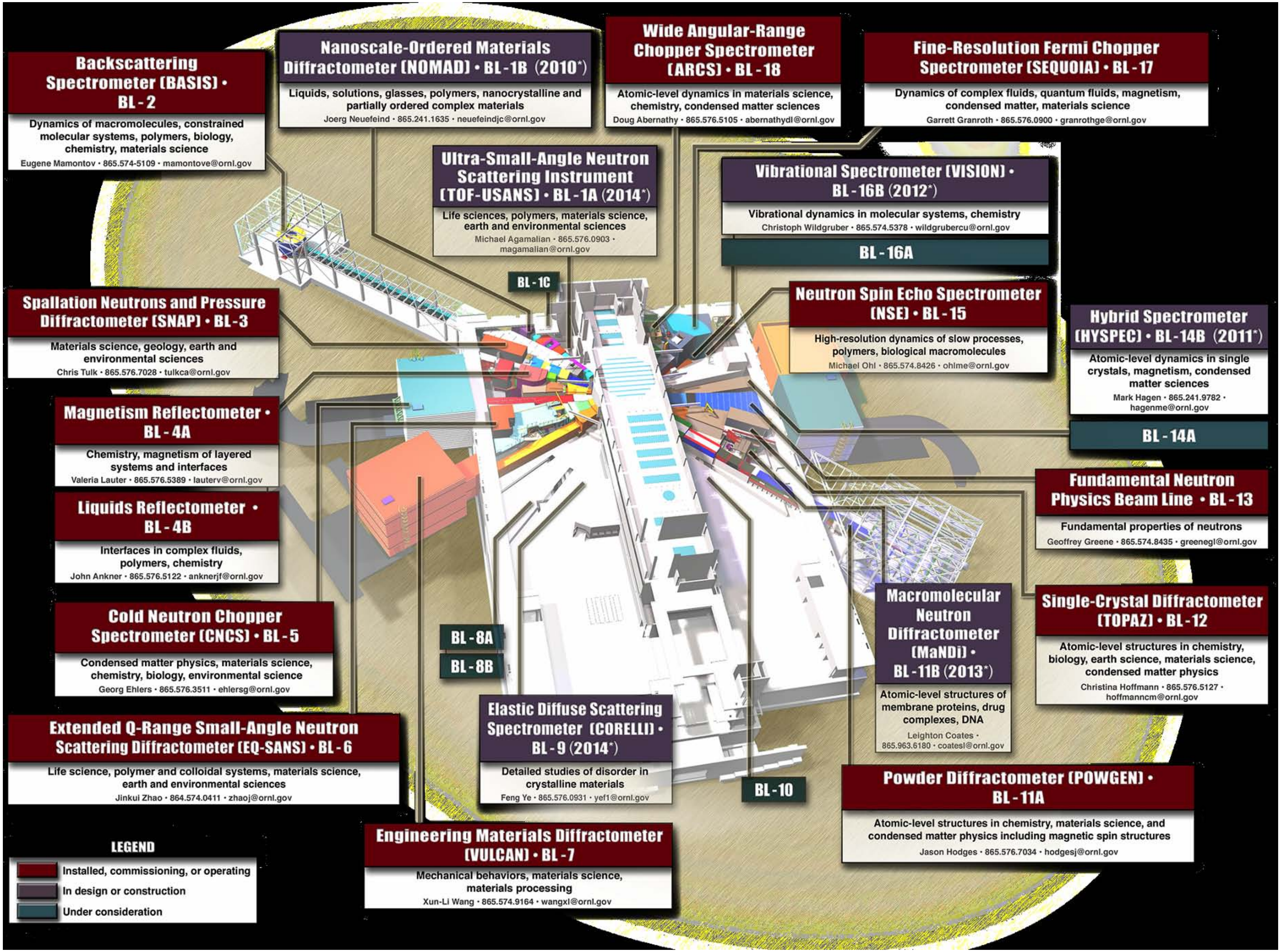
Completion in 2015 -- Guide Hall & Reactor Hall Instruments



SPALLATION NEUTRON SOURCE



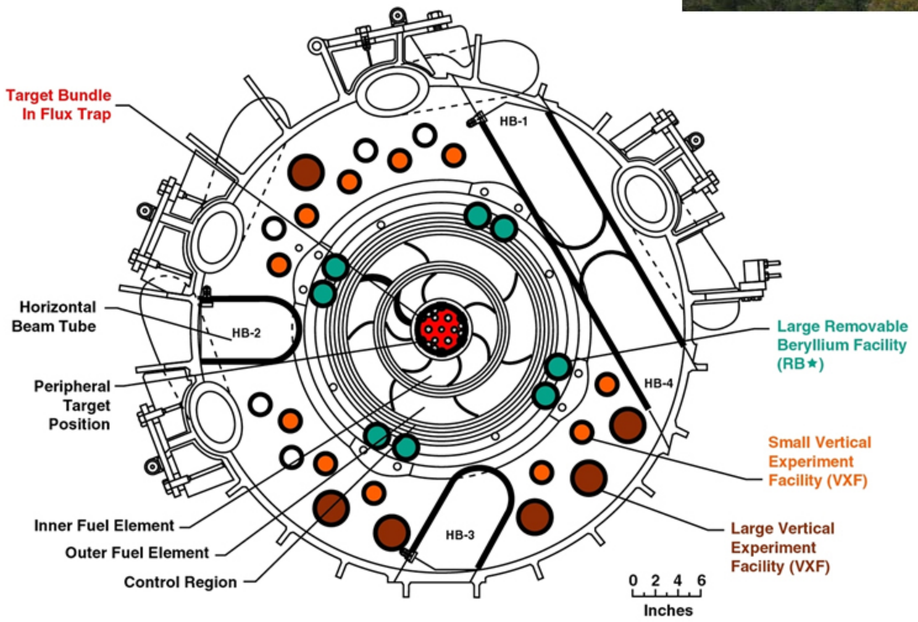
- First neutron production ~~scheduled for~~ June 2006
  April 28, 2006
  2:04 p.m.
- Started with 3 (now 10) instruments operating or in commissioning
- Capacity for a total of 24 instruments – plan for second target
- Accommodate 2000 users/year at full operation

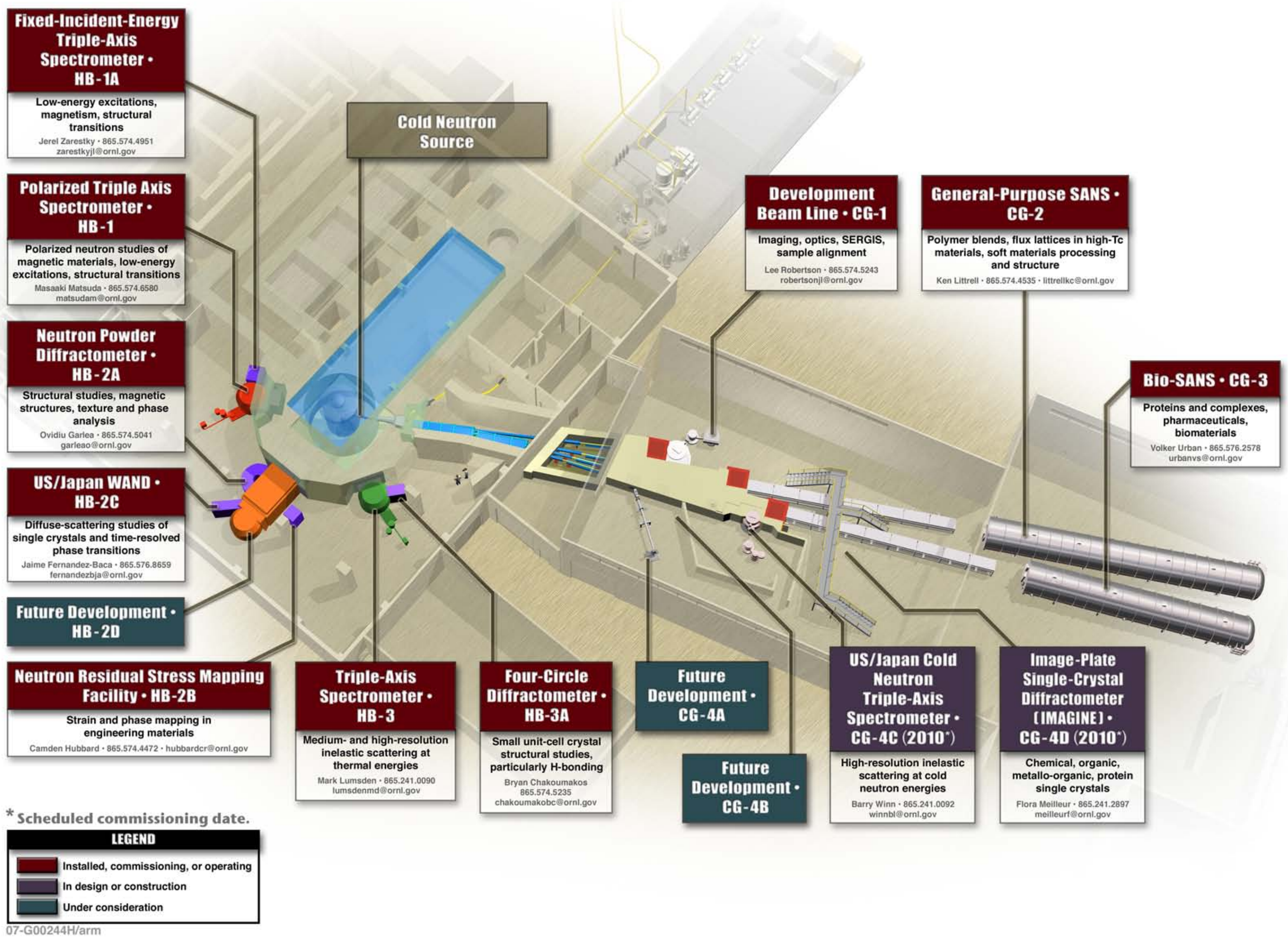


Backscattering Spectrometer (BASIS) • BL-2
Dynamics of macromolecules, constrained molecular systems, polymers, biology, chemistry, materials science
Eugene Mamontov • 865.574-5109 • mamontove@ornl.gov
Nanoscale-Ordered Materials Diffractometer (NOMAD) • BL-1B (2010*)
Liquids, solutions, glasses, polymers, nanocrystalline and partially ordered complex materials
Joerg Neuefeind • 865.241.1635 • neuefeindjc@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 • abernathydl@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 • wildgrubercu@ornl.gov
BL-16A
BL-1C
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
BL-14A
Liquids Reflectometer • BL-4B
Interfaces in complex fluids, polymers, chemistry
John Ankner • 865.576.5122 • anknerjf@ornl.gov
Fundamental Neutron Physics Beam Line • BL-13
Fundamental properties of neutrons
Geoffrey Greene • 865.574.8435 • greenegl@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

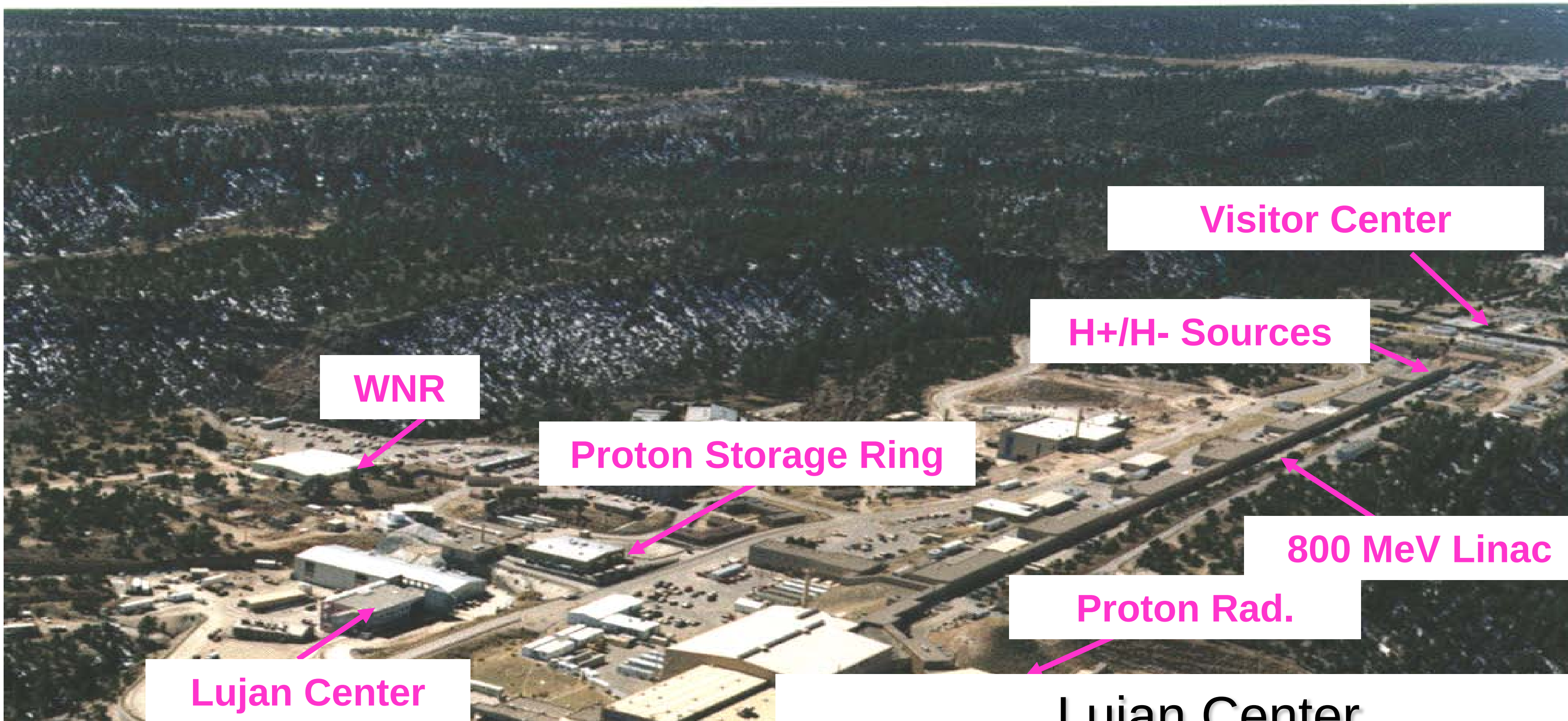
- Oak Ridge, Tennessee
- BES, Department of Energy
- Started Operation:1966
- 85 MW Light Water Reactor
- Peak Core Neutron Flux
  - 12 x 10^{14} /cm^{2}s





Fixed-Incident-Energy Triple-Axis Spectrometer • HB-1A
Low-energy excitations, magnetism, structural transitions
Jerel Zarestky • 865.574.4951
zarestkyjl@ornl.gov
Cold Neutron Source
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
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
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 Meilleur • 865.241.2897
meilleurf@ornl.gov
* Scheduled commissioning date.
LEGEND
Installed, commissioning, or operating
In design or construction
Under consideration
07-G00244H/arm

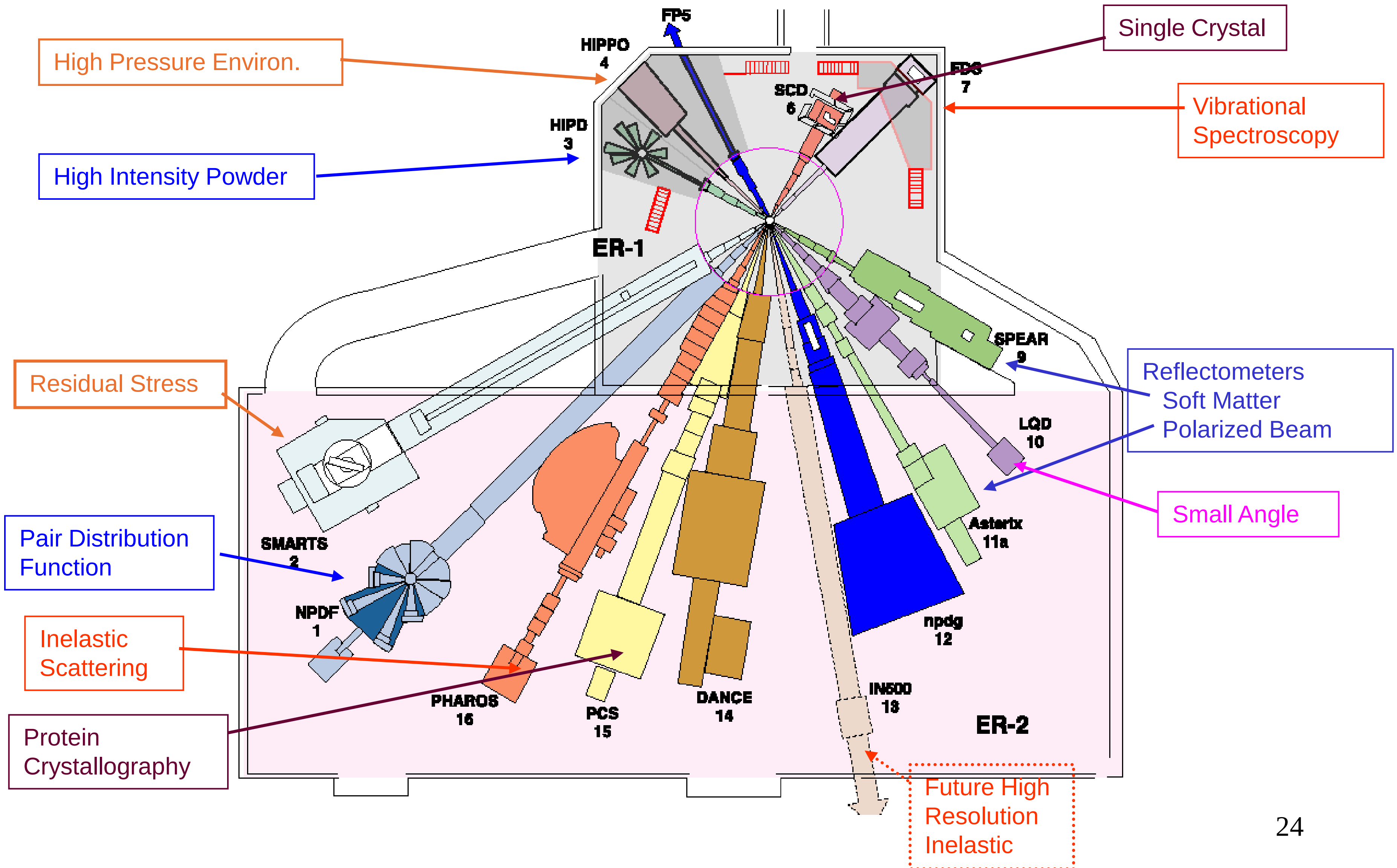
User Facilities at LANSCE: Los Alamos Neutron Science Center



Lujan Center

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

Instruments by functional categories



NRU Reactor – Chalk River, CA

- 125 MW heavy water reactor – Large Core, peak thermal flux of $3x10^{14}$, 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.neutronscattering.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***