Neutron Instrumentation

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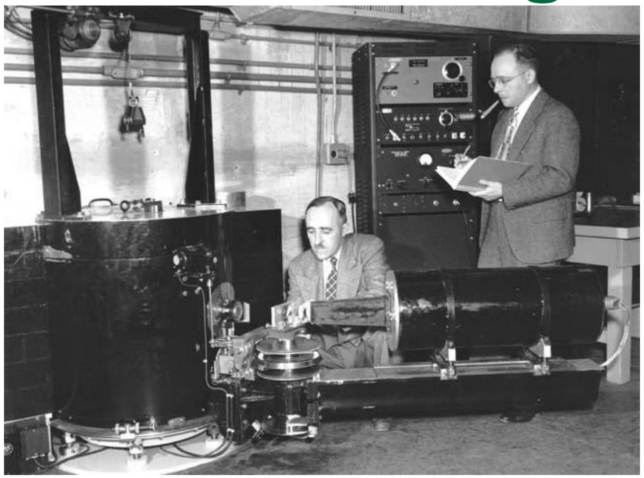
OUTLINE

- **Neutrons**
- **Neutron Sources SNS & HFIR**
  - **Instrument Suite and Science Examples**
- **Beam lines – components and optics**
- **Instrumentation**
- **other exotic things with neutrons….**

Oak Ridge – has been developing neutron scattering from the beginning ….



In the 1940's Wollan and Shull applied the ideas of x-ray diffraction to neutrons (Oak Ridge Graphite Reactor)

The Diffraction of Neutrons by Crystalline Powders
E. O. Wollan and C. G. Shull

The Physical Review, Vol. 75 No 8, 830-841, April 15, 1948

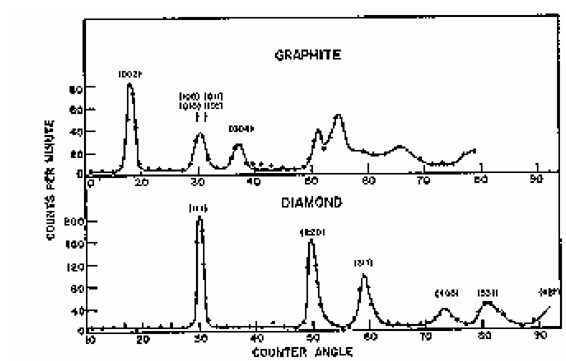
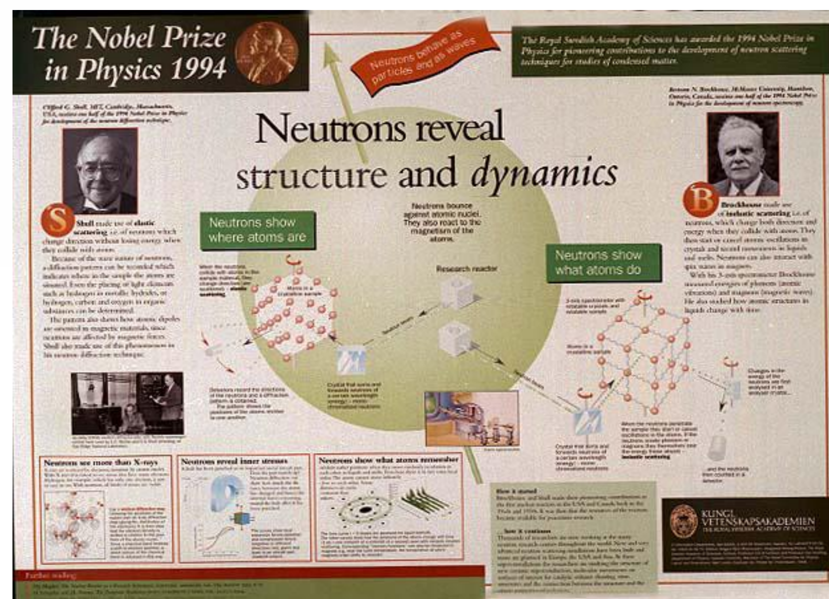


FIG. 3. Powder diffraction patterns for diamond and graphite. The major part of the diffuse scattering in these patterns arises from multiple scattering in the samples.

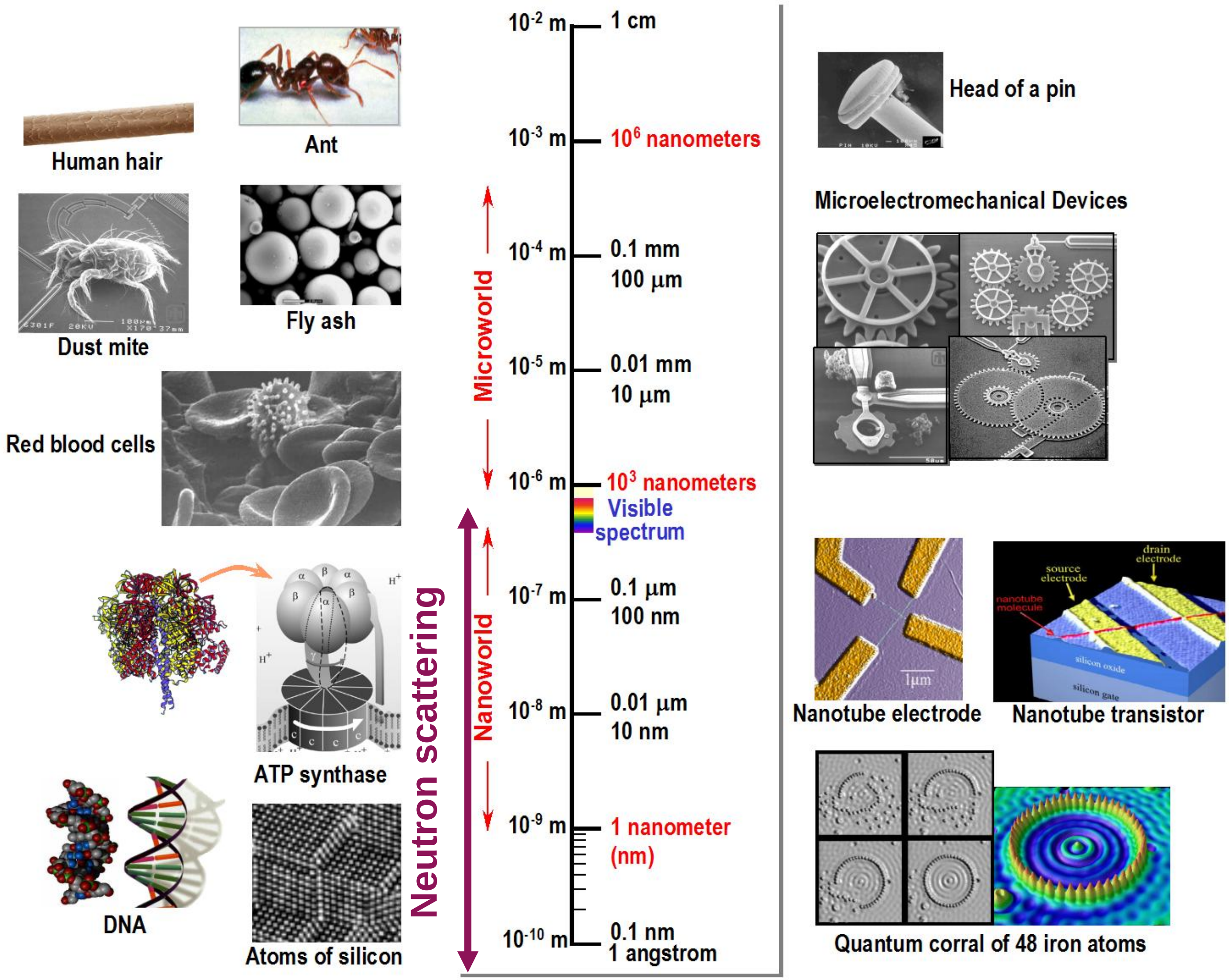


1994 Nobel Prize in Physics for the development of the neutron scattering technique

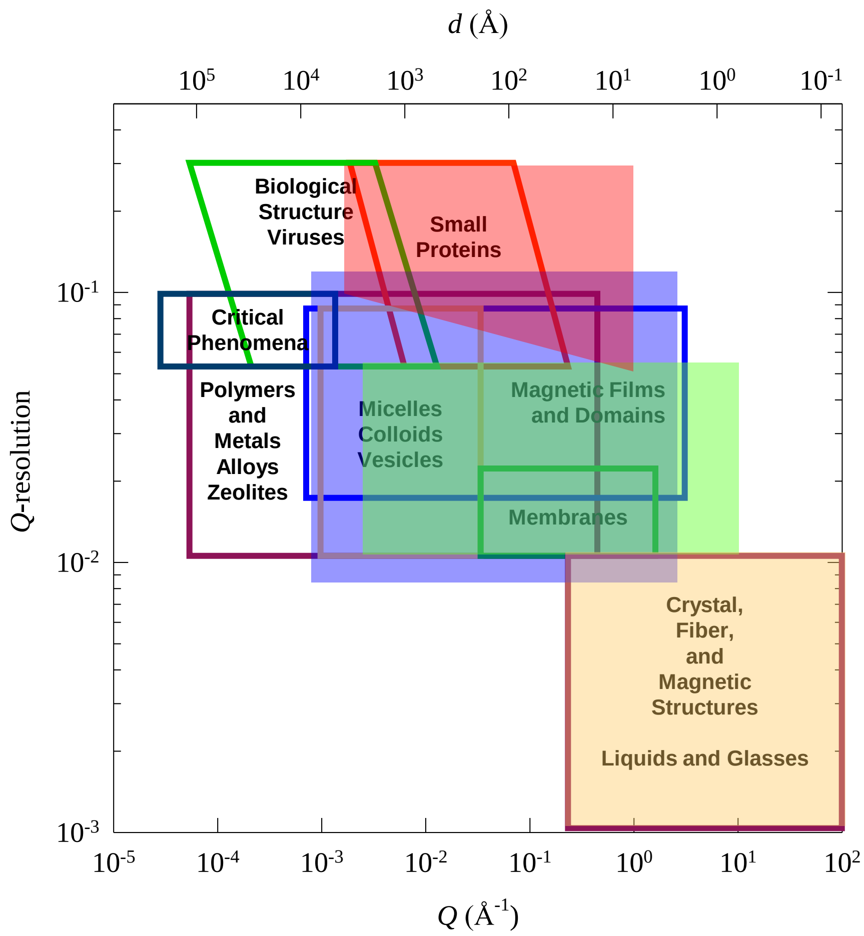
…and continues today as the world's foremost center for the study of materials using neutrons

- **SNS and HFIR provide unprecedented capabilities for understanding the structure and properties of materials across the spectrum of biology, chemistry, physics, and engineering**
- **Stay at the leading edge of neutron science by developing new capabilities, instruments, and tools.**

Neutrons: microns to angstroms!



Structure: From Atoms to Materials
The ORNL Elastic Instrument Suite



STRUCTURE:

– scattering is independent of Z

(good for light atoms)

(isotopic contrast variation)

– scattering lengths are constant with Q ***(better structural precision)***

– neutrons scattered by electron Spin

(magnetic structure)

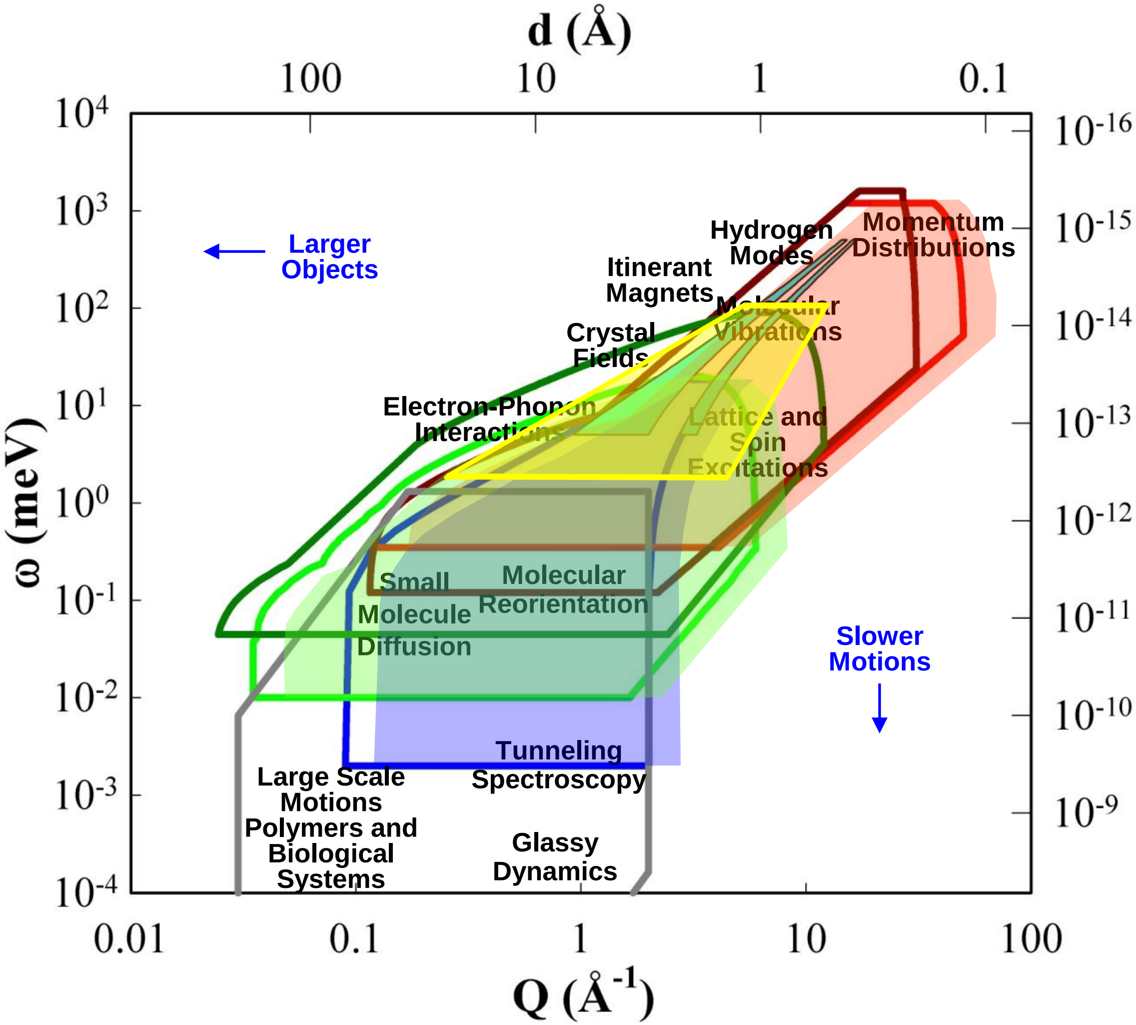
– many metals are "transparent"

(in situ, high & low T, H field)

– reflectometry: contrast vs depth

(direct phasing)

Dynamics: Time and Distance too !
The ORNL Inelastic Instrument Suite



DYNAMICS: Spectroscopy:

– scattering intensity cross-section ***(easy to model)***

– no selection rules

– simultaneously measure ΔQ (momentum) & Δω (energy)

==> time & distance

– greatest sensitivity for H

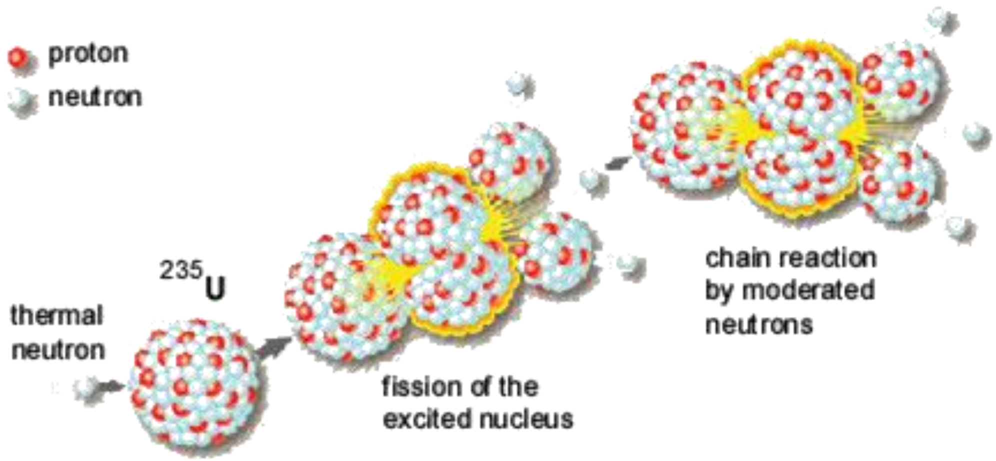
– time scale spans 10^7

–distance scale spans 10^3

(Unique capability)

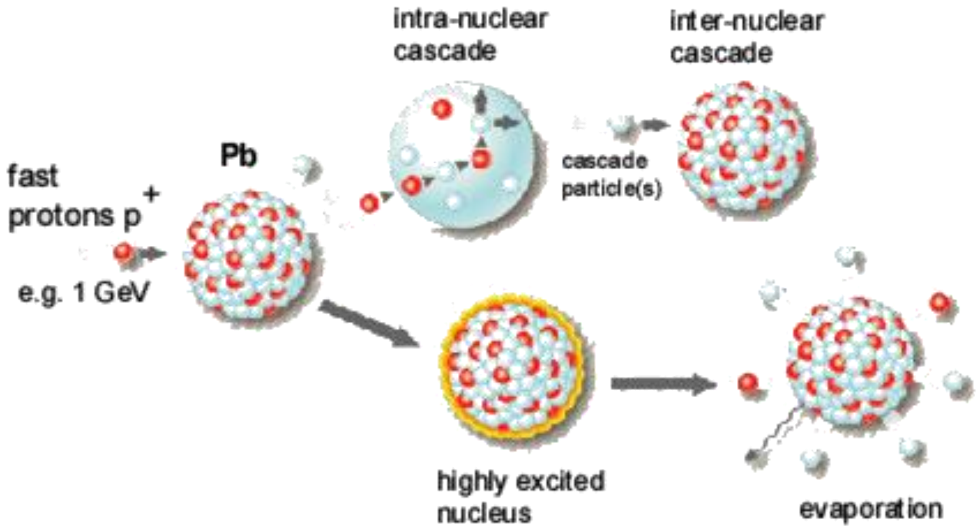
(Fast measurements or dilute systems)

How do we produce neutrons?



Fission

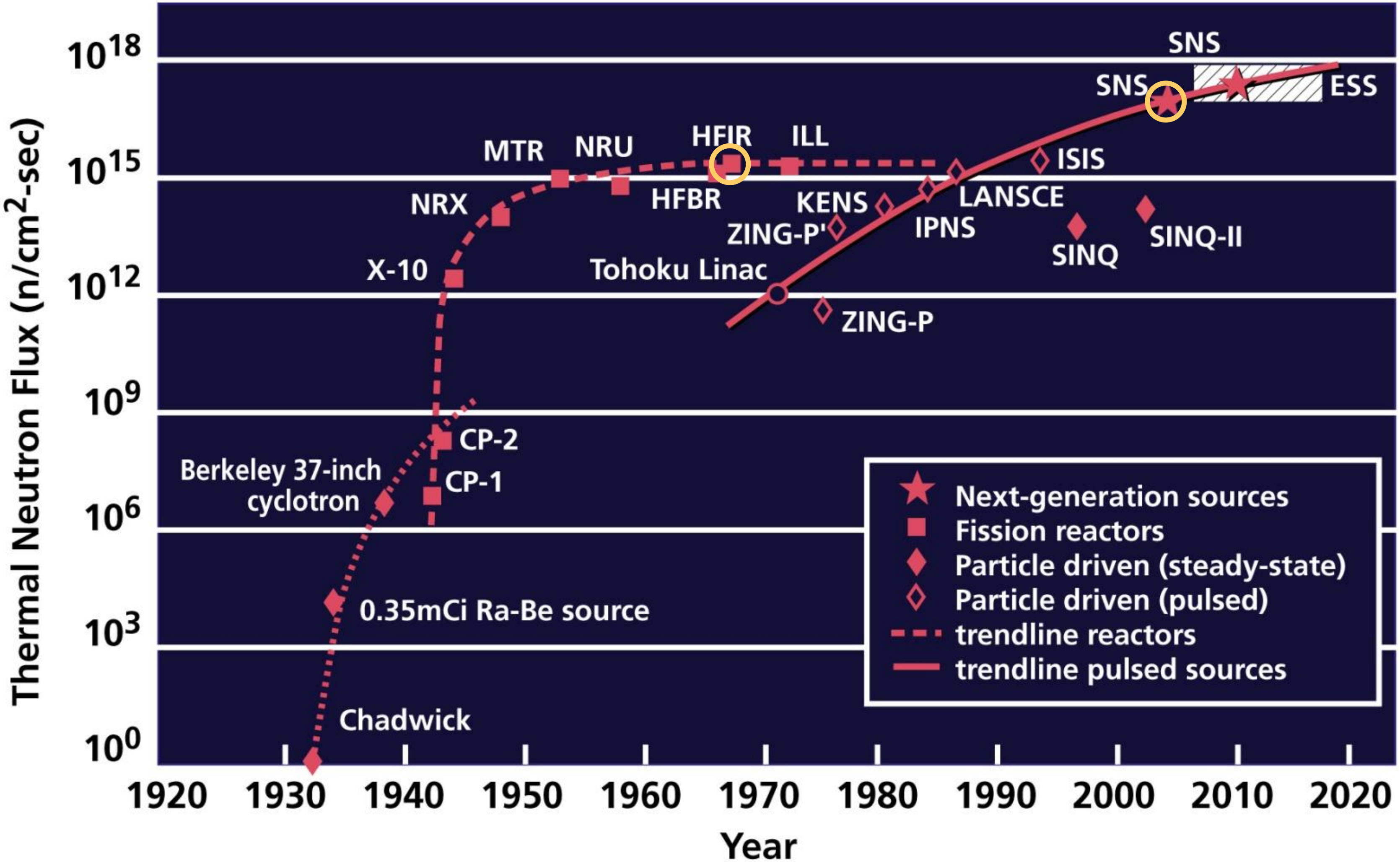
- chain reaction
- continuous flow
- 1 excess neutron/fission
- 180 MeV/neutron



Spallation

- no chain reaction
- pulsed operation
- 40 neutrons/proton
- 30 MeV/neutron

Neutron Source Trends



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

The High Flux Isotope Reactor

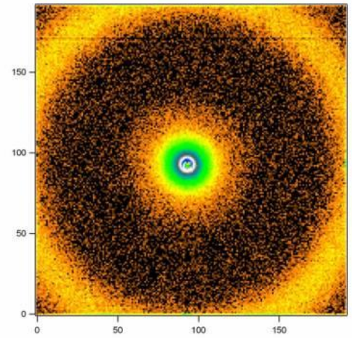
- **Constructed in 1965**
- **Operating power: 85 MW**
- **Steady-state thermal neutron flux: 1.0×10^{15} neutrons/(cm²•s) (among the world's highest)**
- **$70M upgrade completed in 2007**
  - **State-of-the-art instruments**
  - **World class cold neutron source**

The 85MW High Flux Isotope Reactor World class cold and thermal beams

- Nine instruments in the user program
  - **4 Triple axis Spectrometers**
  - **2 SANS**
  - **Powder diffraction**
  - **Single Crystal Diffraction**
  - **Strain Scanner (HTML)**

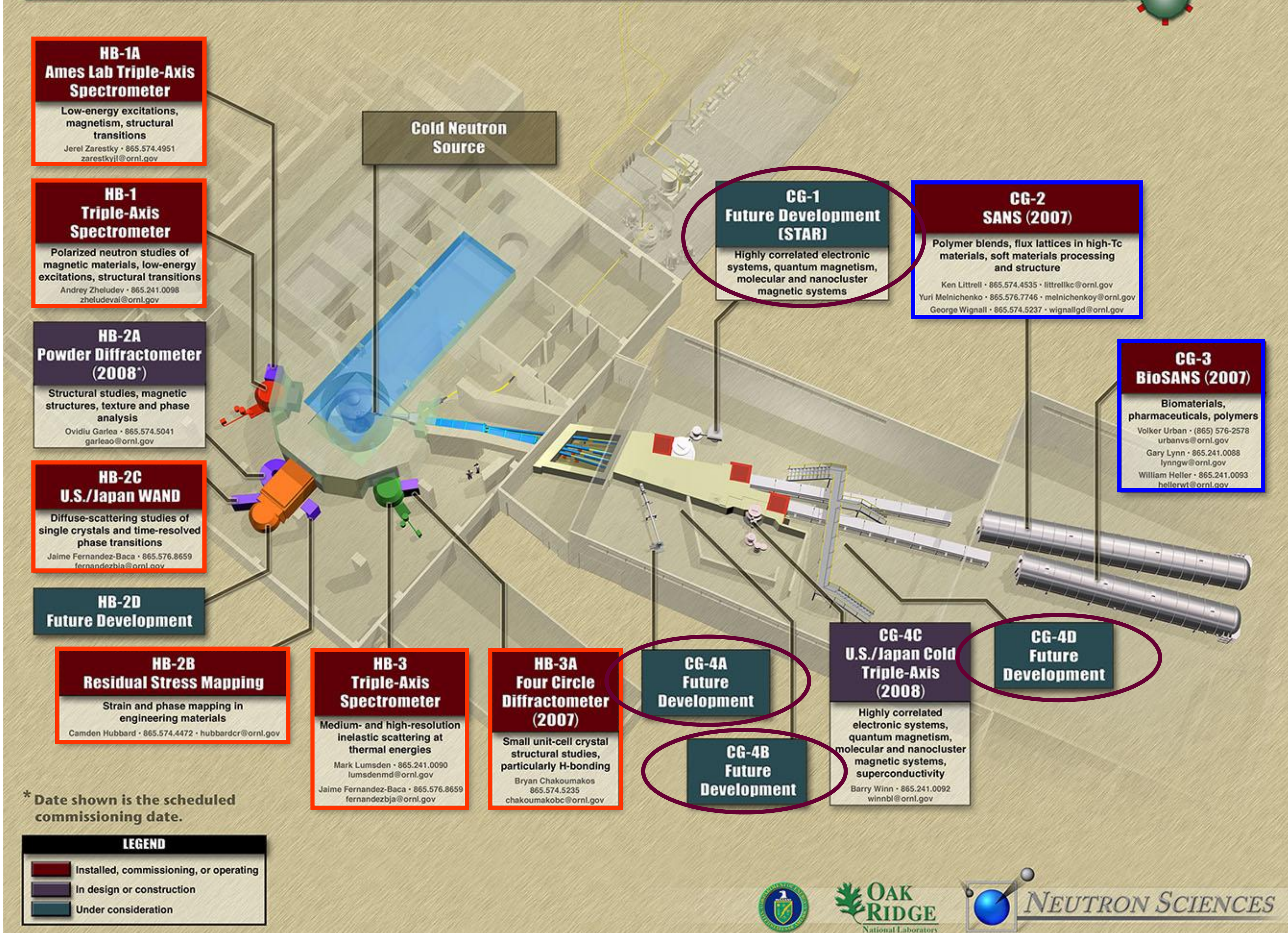
- Commissioning two new instruments in 2010

- Full User program underway

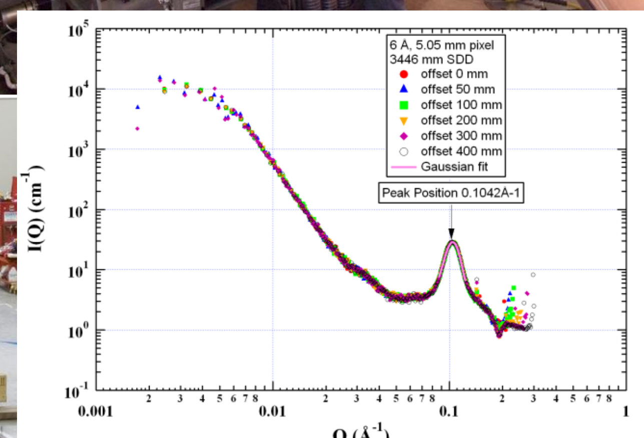


Two-dimensional scattering pattern of a polymer blend taken on the new HFIR SANS instrument

High Flux Isotope Reactor - Capacity for Growth



HFIR Cold Instrument Guidehall



The Spallation Neutron Source

- **Construction completed May 2006**
- **User operations began in 2007**
- **At 1.4 MW (in 2010): the world's most powerful pulsed spallation source**
- **Room for 25 instruments spanning physics, chemistry, biology, and materials science**
- **Upgradable to higher power and a second target station**

Full Energy linac and Accumulator Ring

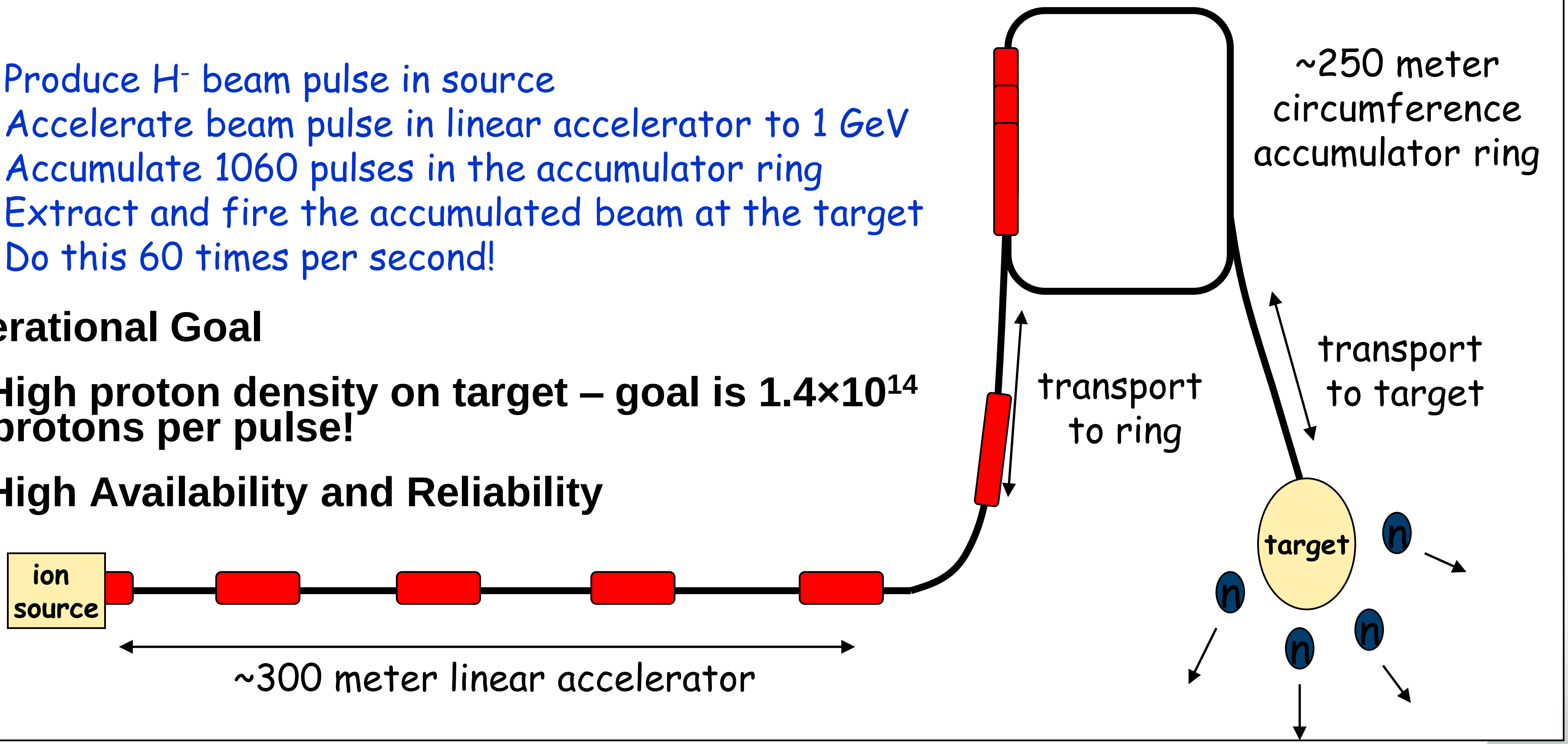
Design Criteria

1) Produce H^- beam pulse in source
2) Accelerate beam pulse in linear accelerator to 1 GeV
3) Accumulate 1060 pulses in the accumulator ring
4) Extract and fire the accumulated beam at the target
5) Do this 60 times per second!

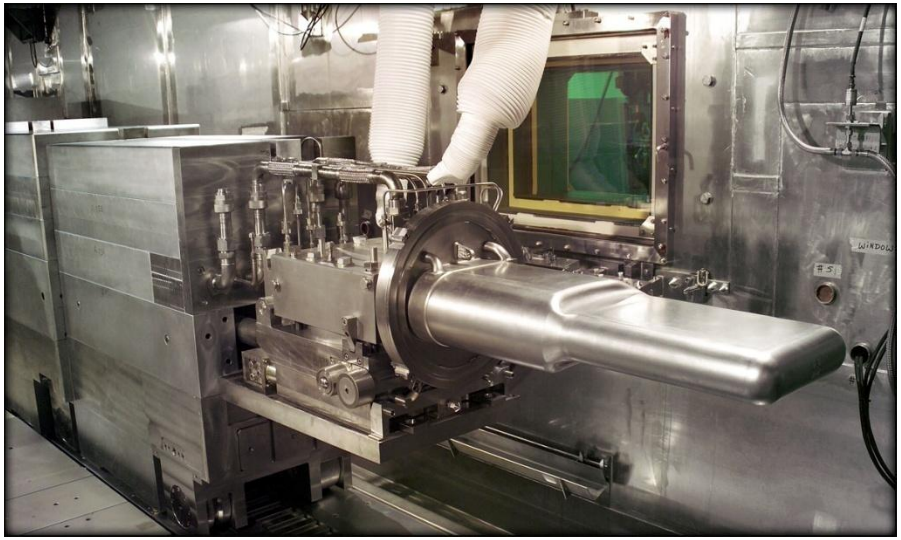
Operational Goal

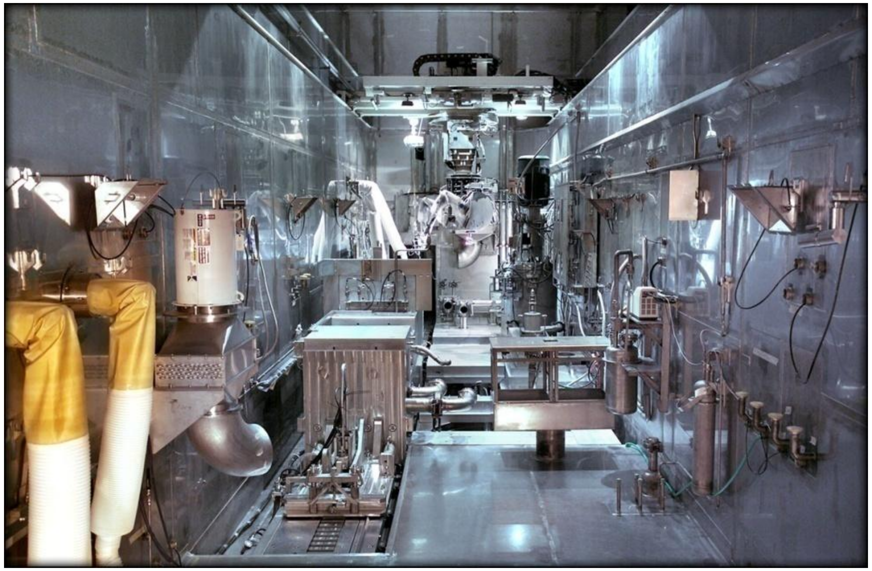
High proton density on target – goal is 1.4×10^{14} protons per pulse!

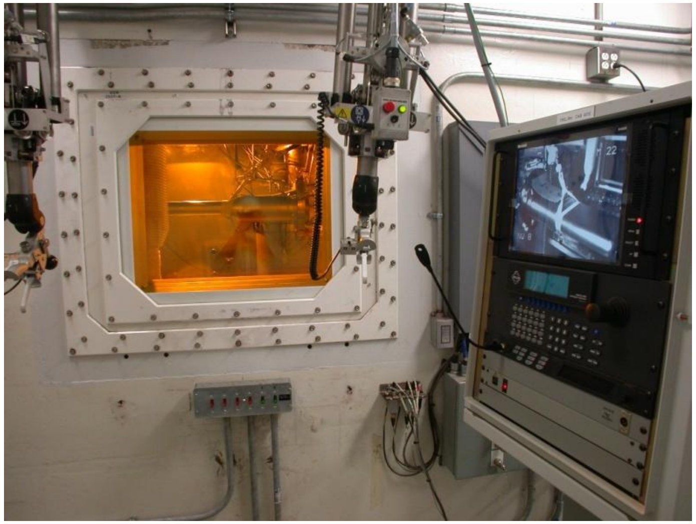
High Availability and Reliability

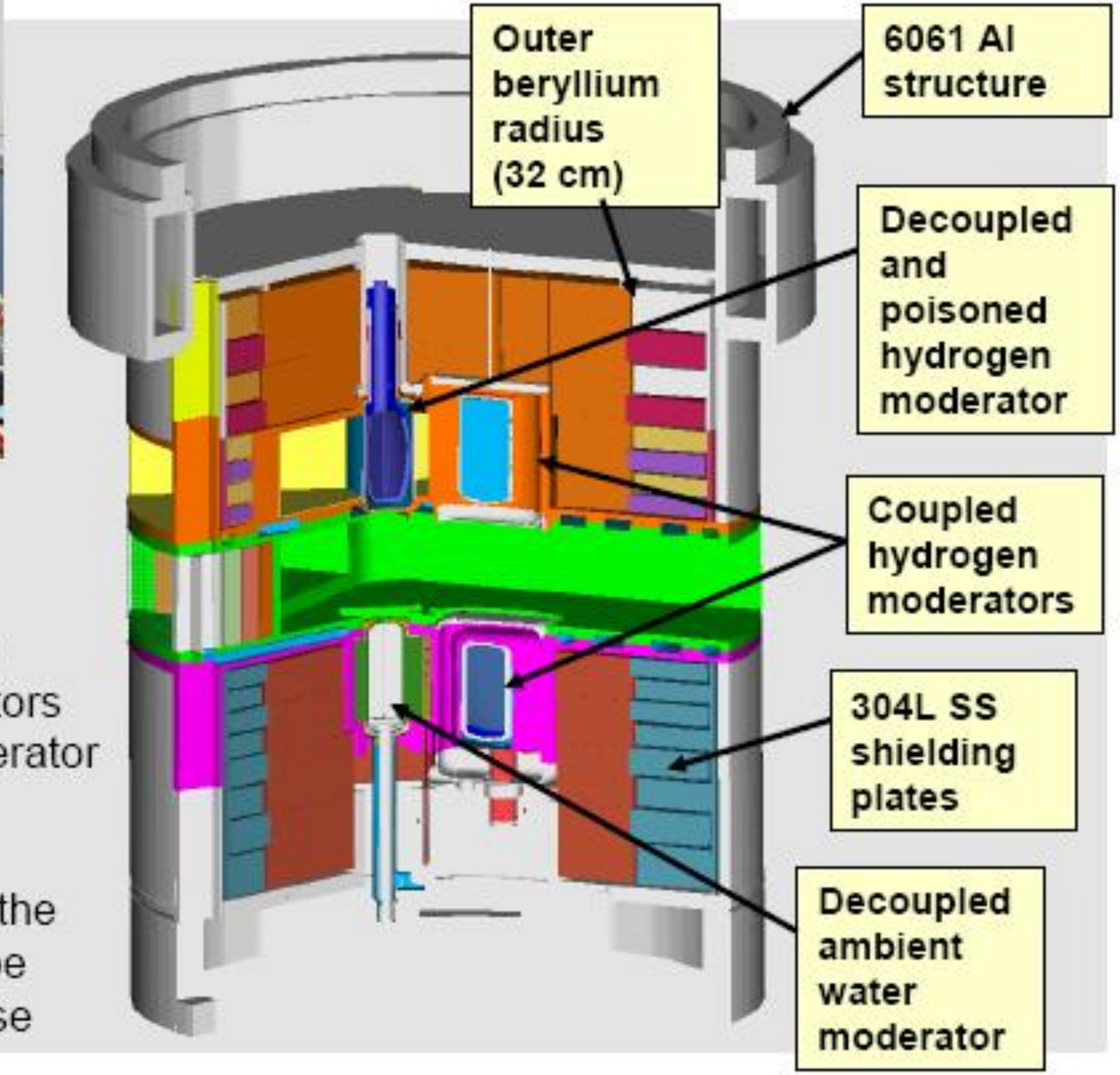


Mercury Target





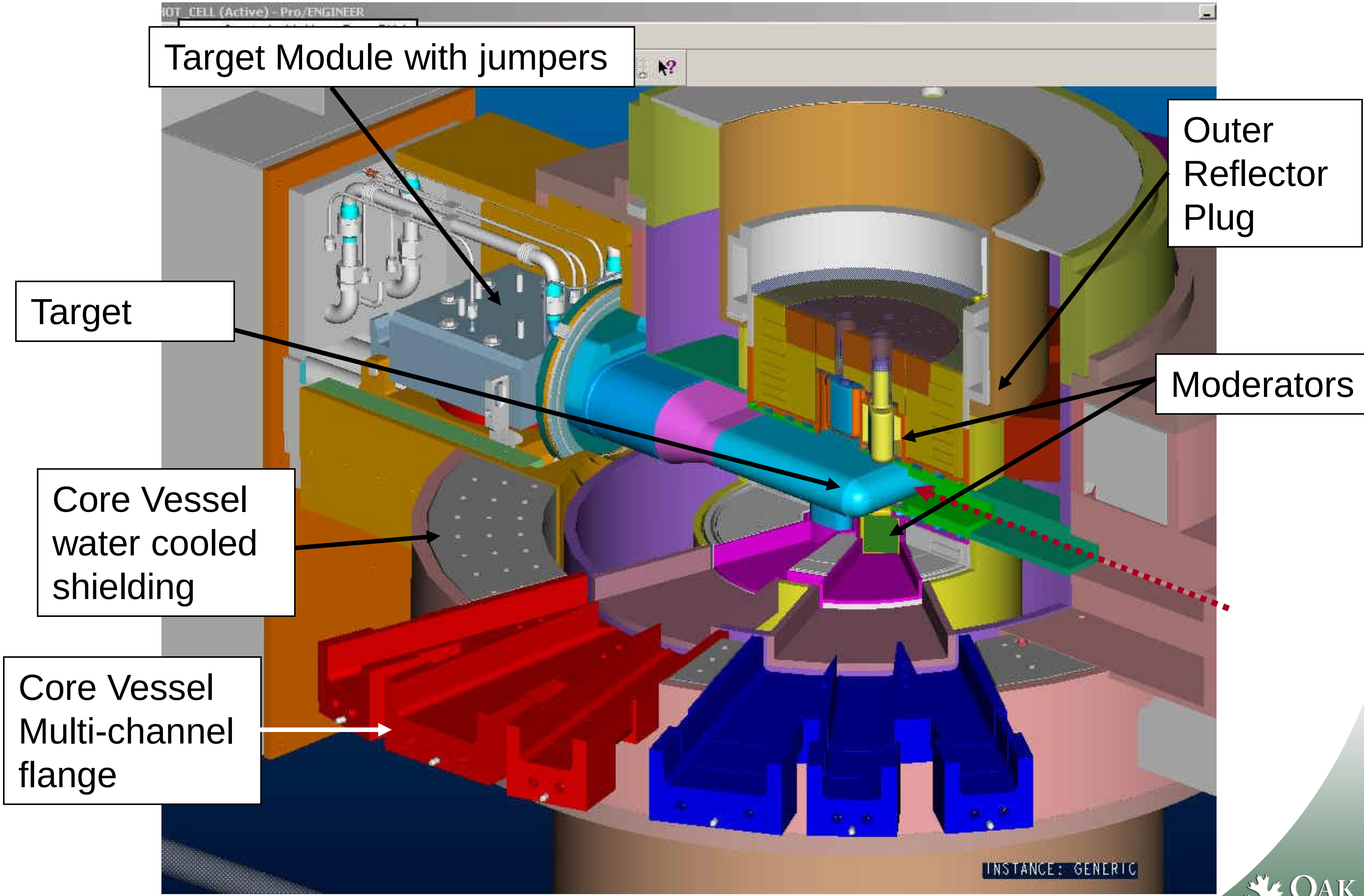




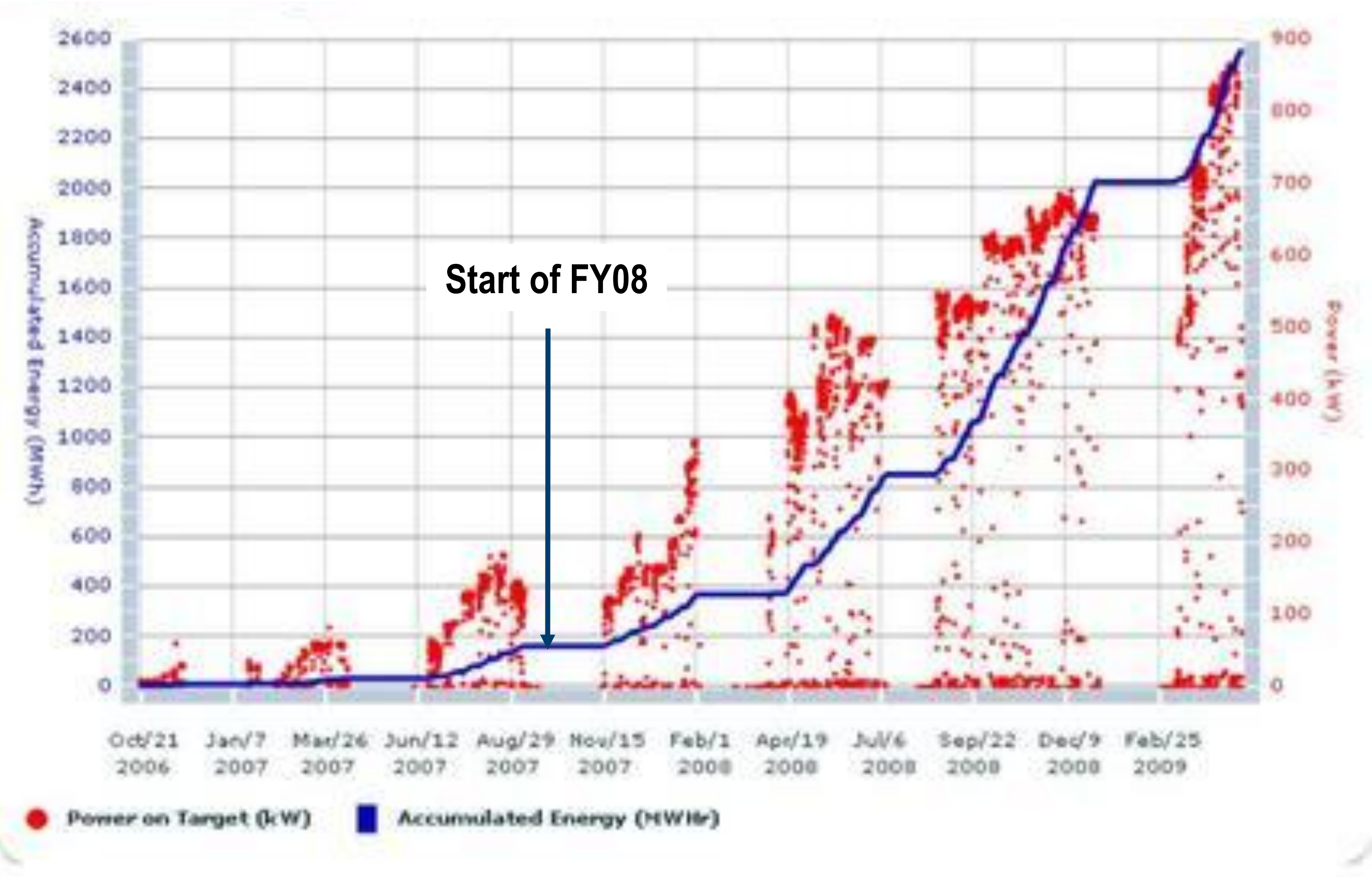
Inner Reflector Plug

- Contains moderators and reflectors around the target. Three H moderators running at ~20K and one H_2O moderator running at 290K
- Neutrons produced by spallation in the Hg are high energy, ~1GeV, must be cooled to 1meV → 1eV range for use in thermal neutron scattering

Target Region Within Core Vessel

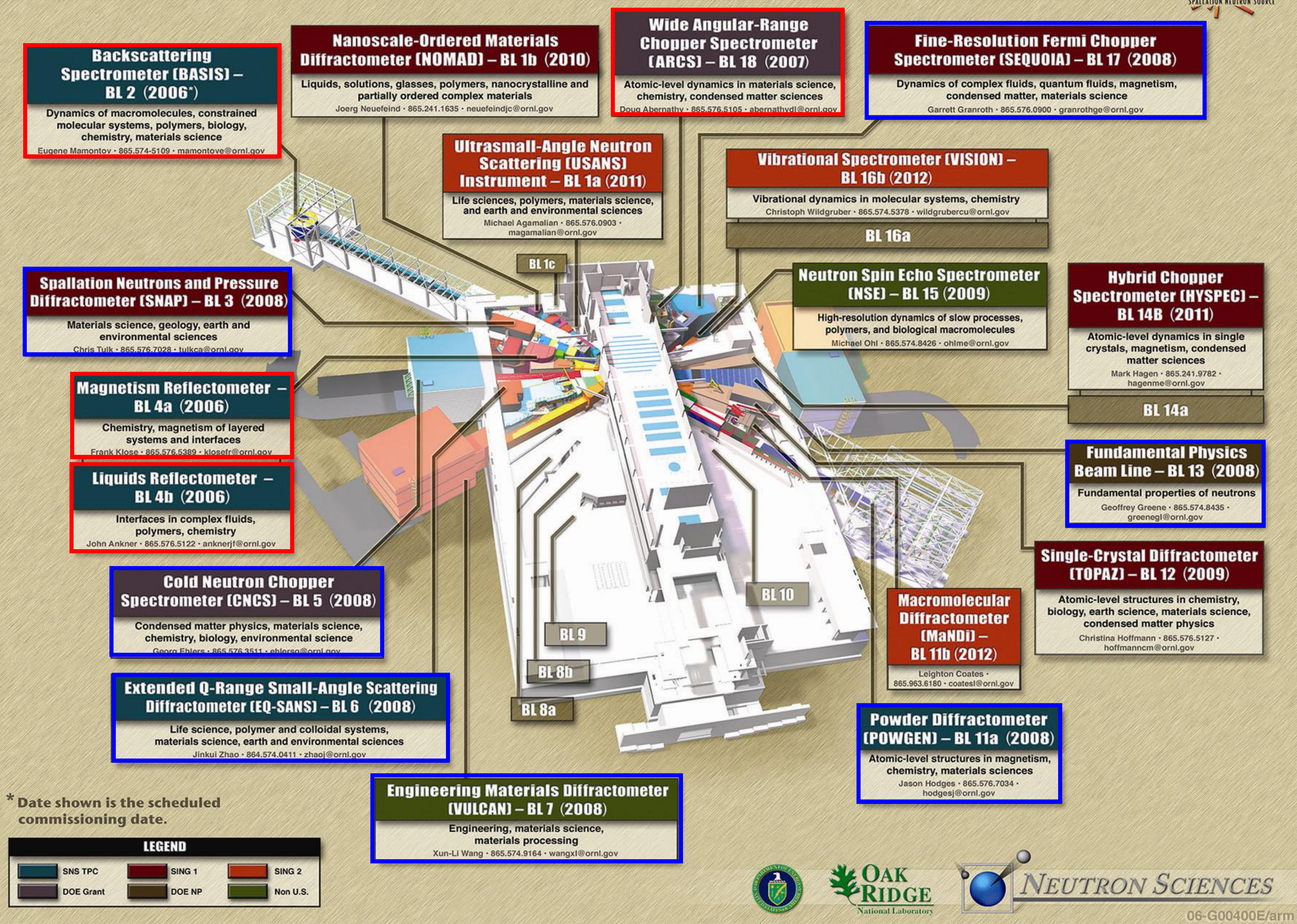


We've reached 800 kW; ultimate goal is 1.4 MW in FY 2010

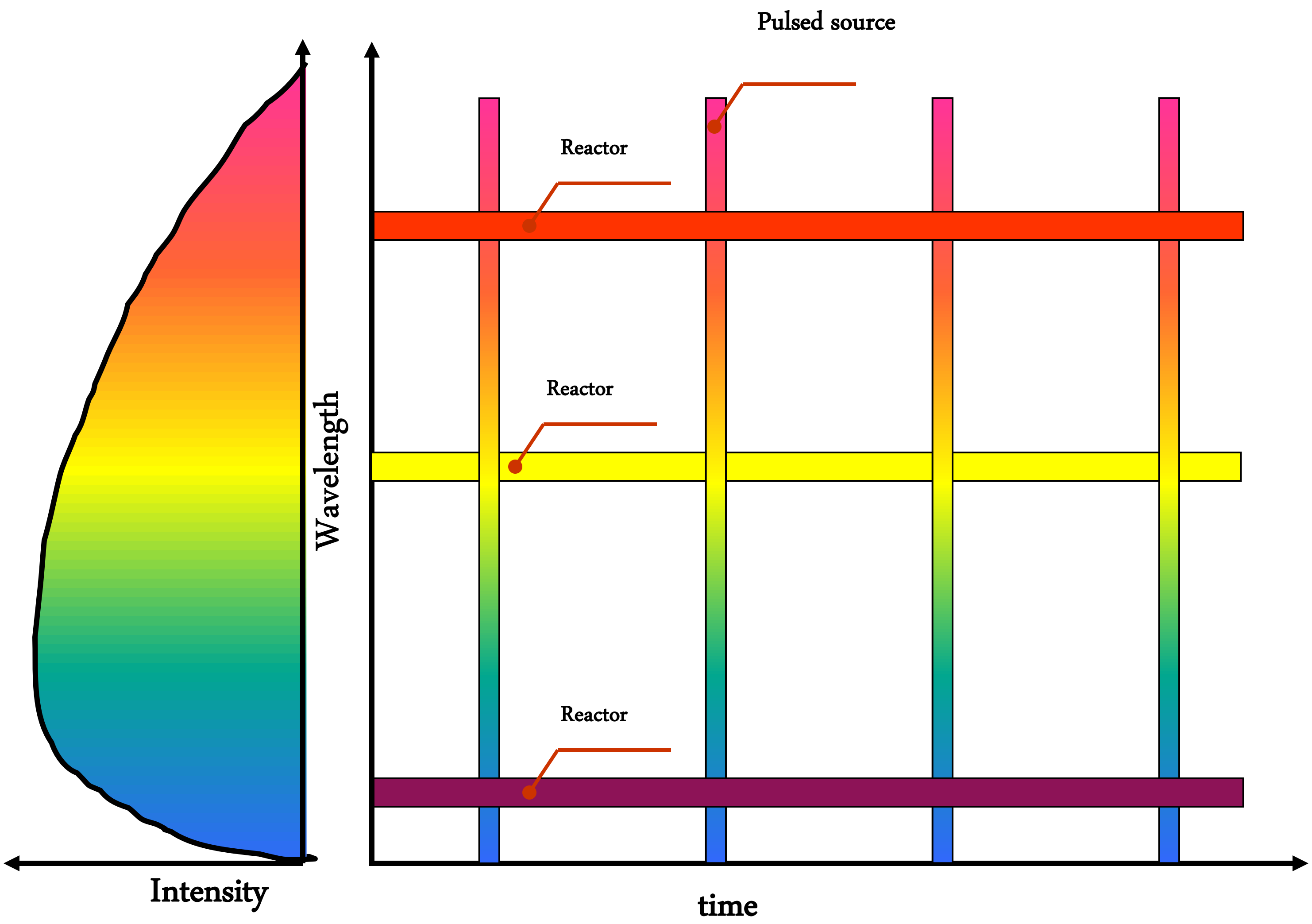


SNS beam power has more than tripled since Oct 2007

Spallation Neutron Source

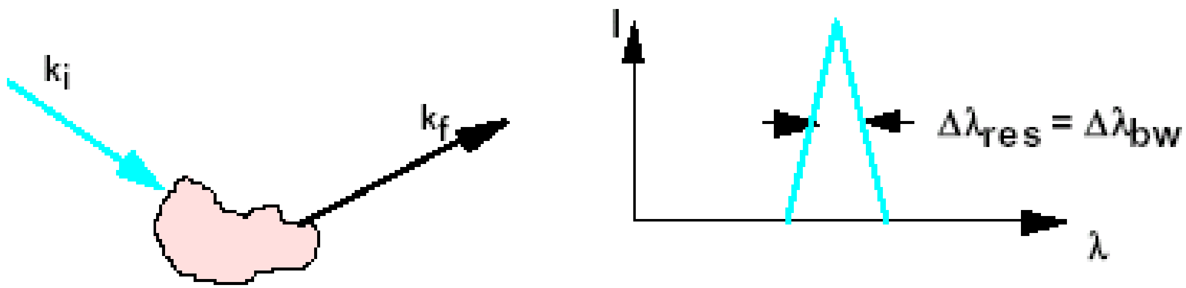


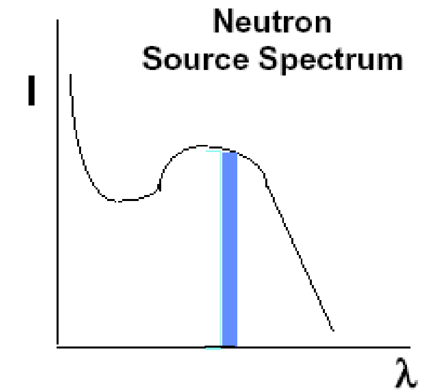
Reactor or pulsed source?



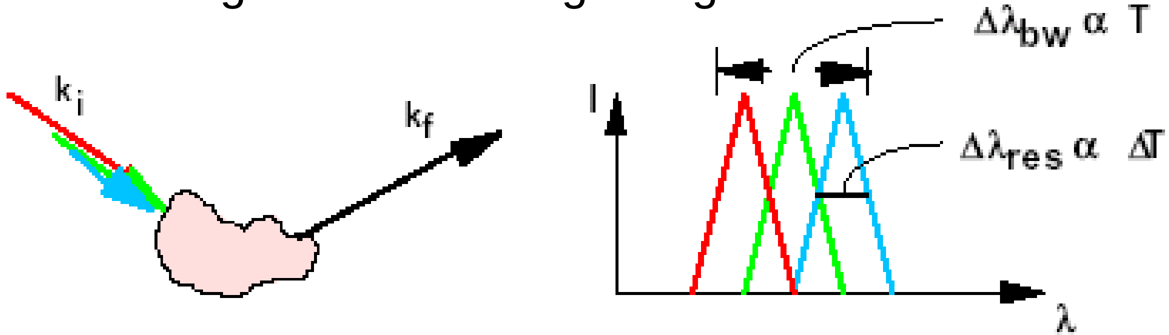
Differences between TOF and steady-state

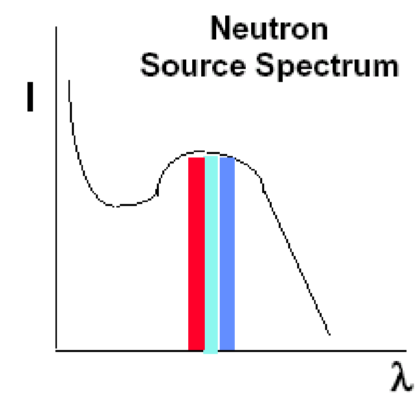
Steady-state
- uses single wavelength
- bandwidth (bw) = resolution width (res)
- range of data requires multiple angles





TOF
- uses range of wavelengths
- bandwidth (bw) >> resolution width (res)
- range of data at single angle





Neutrons have both Particle-like and Wave-like Properties

- Mass: $m_n = 1.675 \times 10^{-27}$ kg
- Charge = 0; Spin = ½
- Magnetic dipole moment: $\mu_n = -1.913\ \mu_N$
- Kinetic energy (E), Velocity (v), Wavelength (λ), Wavevector (k)

$$E = m_n v^2/2 = k_B T = (hk/2\pi)^2/2\ m_n;\ k = 2\pi/\lambda = m_n v/\ (h/2\pi)$$

	Energy (meV)	Temperature(k)	Wavelength (nm)
Cold	0.1 – 10	1 – 120	0.4 – 3
Thermal	5 – 100	60 – 1000	0.1 – 0.4
Hot	100 - 500	1000 - 6000	0.04 – 0.1

Room temperature ~ 25 meV ~ 0.18 nm ~ 2200 m/s

Neutron Instrumentation

Essentially 2 types of Instrument:

Diffractometers: - measure Elastic Scattering

Structure:

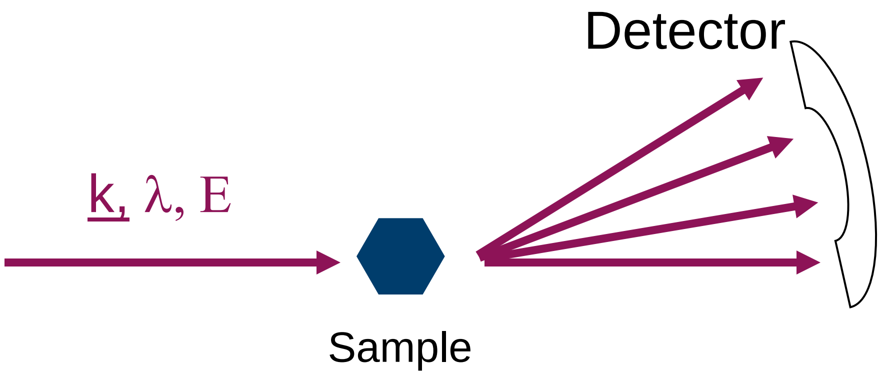
- **Neutrons as waves**
- **Based on Bragg's Law**
- **No change of energy detected**

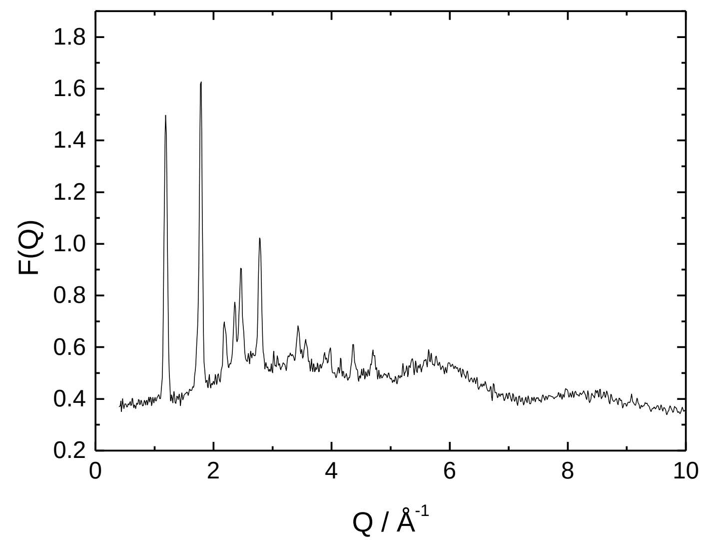
Spectrometers: - measure Inelastic Scattering

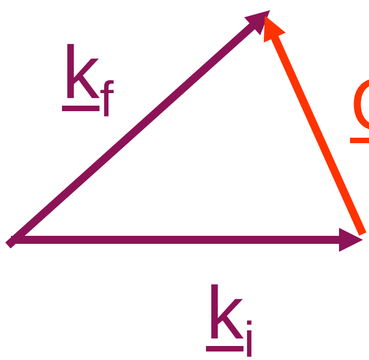
Dynamics

- **Neutrons as particles**
- **Based upon Newton's laws**
- **Change of energy detected**

Diffractometers: - Elastic Scattering







$\underline{Q} = \underline{k}_f - \underline{k}_i$ Wavevector transfer

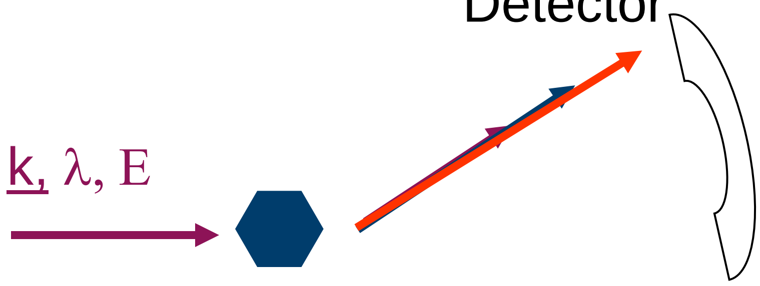
$|k_f| = |k_i|$ "Elastic" scattering $I(\underline{Q})$

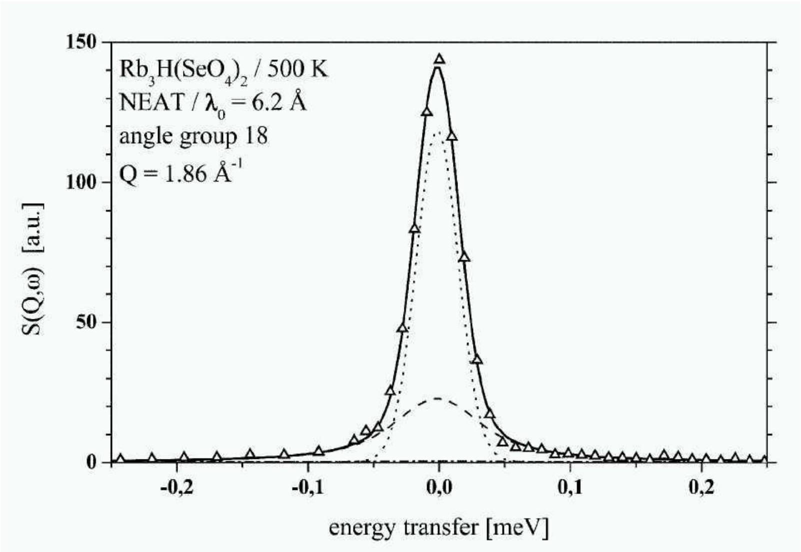
$|\mathbf{Q}| = 2|\boldsymbol{k}| \sin\theta$

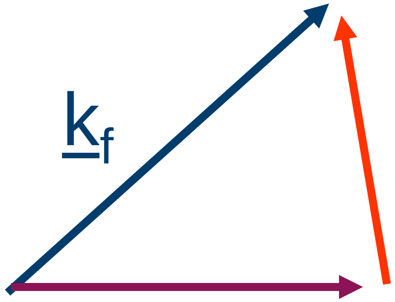
Since $|\boldsymbol{k}| = 2\pi/\lambda$; where $\lambda = h/(mnv)$ {de Broglie}

Then $|Q| = Q = (4\pi/\lambda) \sin\theta$

Spectrometers: Inelastic Scattering







$\underline{Q} = \underline{k}_f - \underline{k}_i$ Wavevector transfer

$\hbar\omega = \underline{E}_f - \underline{E}_i$ Energy transfer

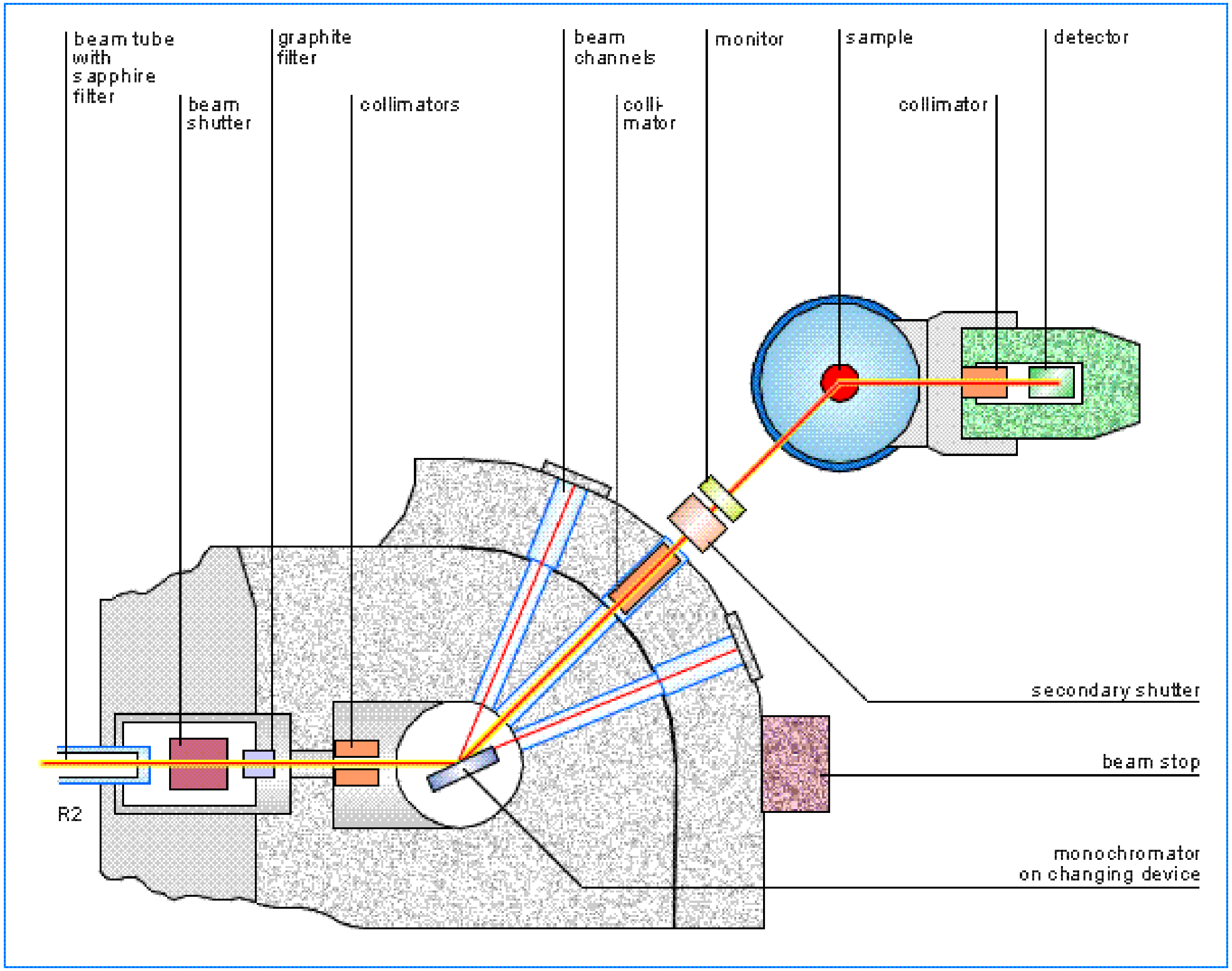
$|k_f| \neq |k_i|$ "Inelastic" scattering $I(\underline{Q}, \omega)$

$$\hbar\omega = E_i - E_f = \frac{\hbar^2}{2m}(k_i^2 - k_f^2)$$

Some Typical Components of Neutron Scattering Instruments

- **Monochromators**
  - Monochromate or analyze the energy of a neutron beam using Bragg's law
- **Collimators**
  - Define the direction of travel of the neutron
- **Guides**
  - Allow neutrons to travel large distances without suffering intensity loss
- **Choppers**
  - Define a short pulse or pick out a small band of neutron energies
- **Detectors**
  - Neutron is absorbed by ^3He and gas ionization caused by recoiling particles is detected
- **Spin turn coils**
  - Manipulate the neutron spin using Lamor precession
- **Shielding**
  - Minimize background and radiation exposure to users

Diffractometers - Elastic scattering



Single Crystal Diffractometer

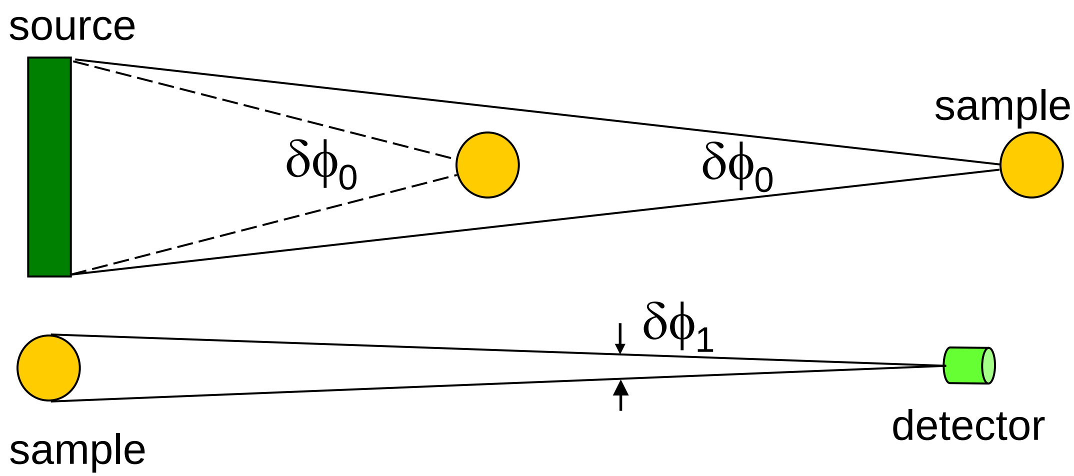
(Continuous source)

Angular Resolution - Collimation

Natural Collimation

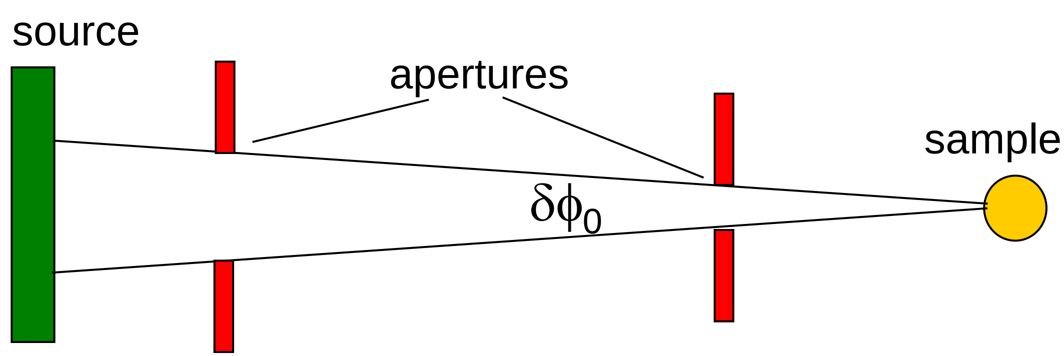
Angular uncertainties are determined by source-sample and sample-detector distance.

Uncertainties increase as the distance decreases.



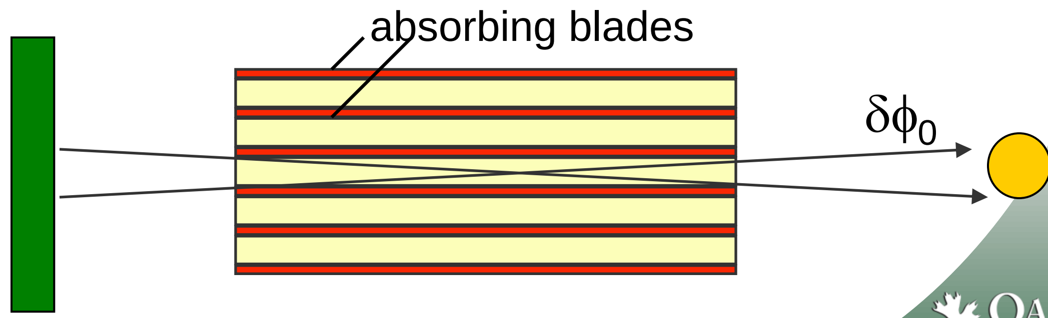
Pinhole Collimation

Angular uncertainty is determined by apertures.

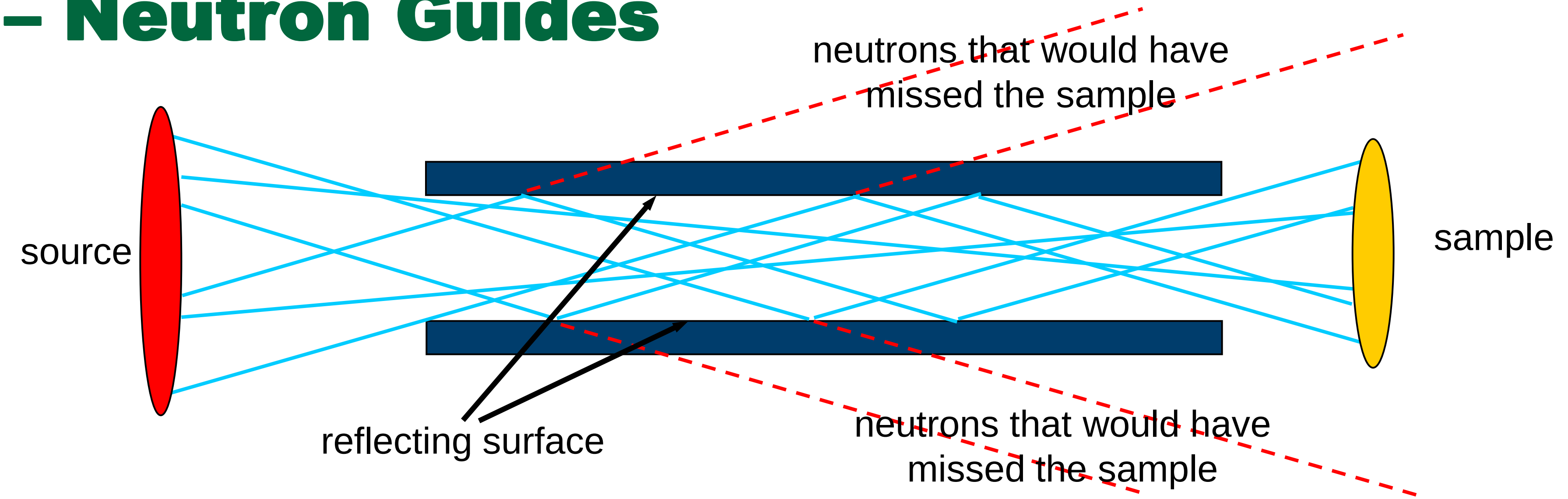


Soller Collimation

Angular uncertainty and aperture decoupled.



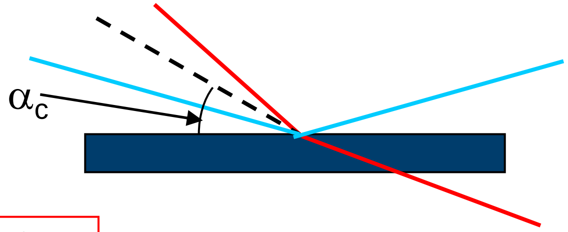
Beam delivery over long distances – Neutron Guides



Index of refraction $n = 1 - \lambda^2\rho/2\pi$

ρ = Nb = scattering length density

n < 1 for most materials, so there is a critical angle α_c for total external reflection



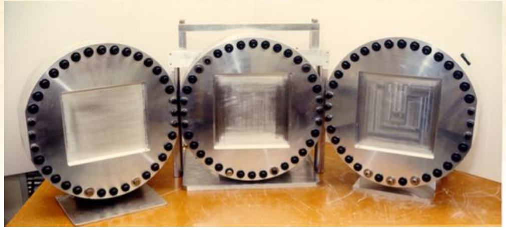
For Nickel $\alpha_c\,(^o) = 0.1\,\lambda$ (Å)

Beam delivery – Neutron Guides

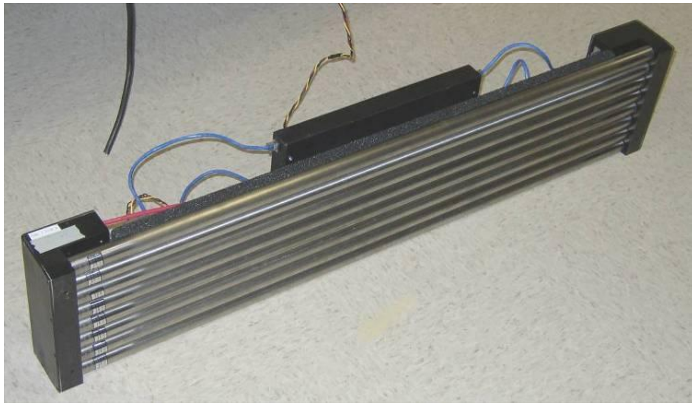
Detection of neutrons

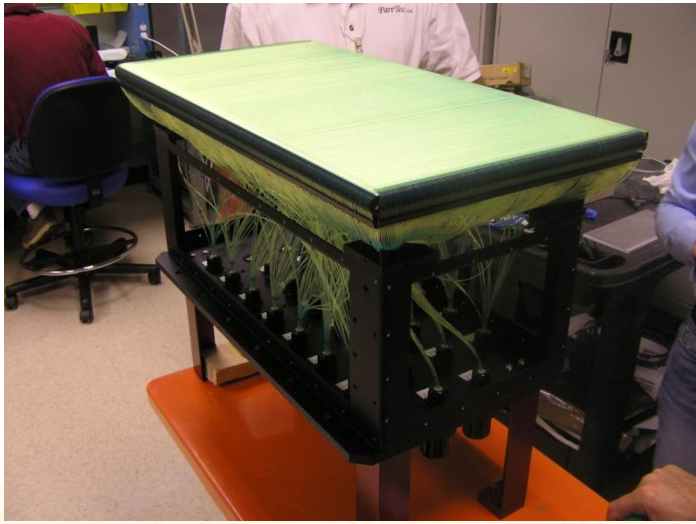
- **Since neutrons have zero charge they cannot be detected directly, instead a charge particle needs to be produced and then detected.**
- Counters:
  - BF_3 ${}^{10}B_5 + {}^{1}n_0 \rightarrow {}^{7}Li_3 + {}^{4}He_2 + 2.7$ MeV
  - ${}^{3}He$ ${}^{3}He_2 + {}^{1}n_0 \rightarrow {}^{3}He_1 + {}^{1}H_1$
- Film/scintillators:
  - ${}^{6}Li_3 + {}^{1}n_0 \rightarrow {}^{3}H_1 + {}^{4}He_2$
- Most detectors need bulky shielding as they are sensitive also to γ-rays

Neutron Detectors



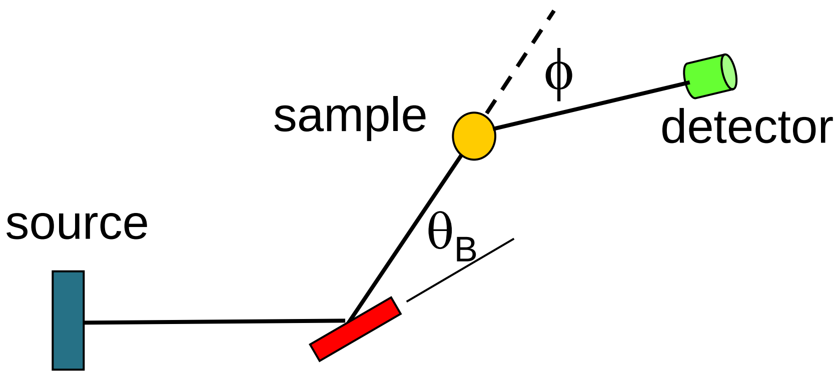
- We are using four detector types:
  - Multiwire proportional chambers
  - Position sensitive proportional tubes
    - Commercially available tubes
    - Electronics and packaging done in house
  - Scintillation detectors with wavelength shifting fiber readout
    - New development
  - Anger cameras with position sensitive PMTs
    - New development

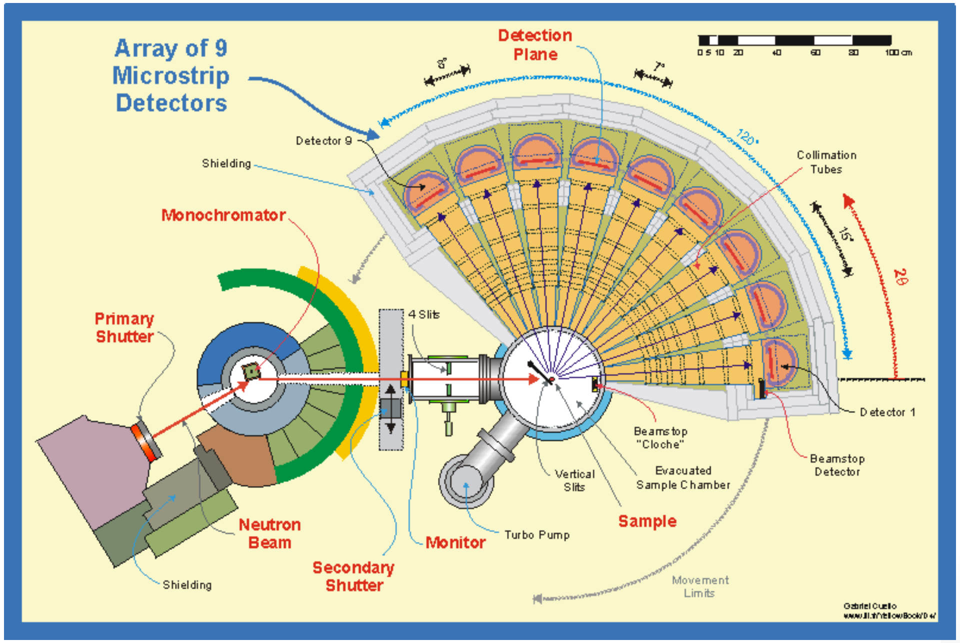




Determining the Wavelength – reactor (continuous) source

crystal monochromator
(Bragg diffraction)



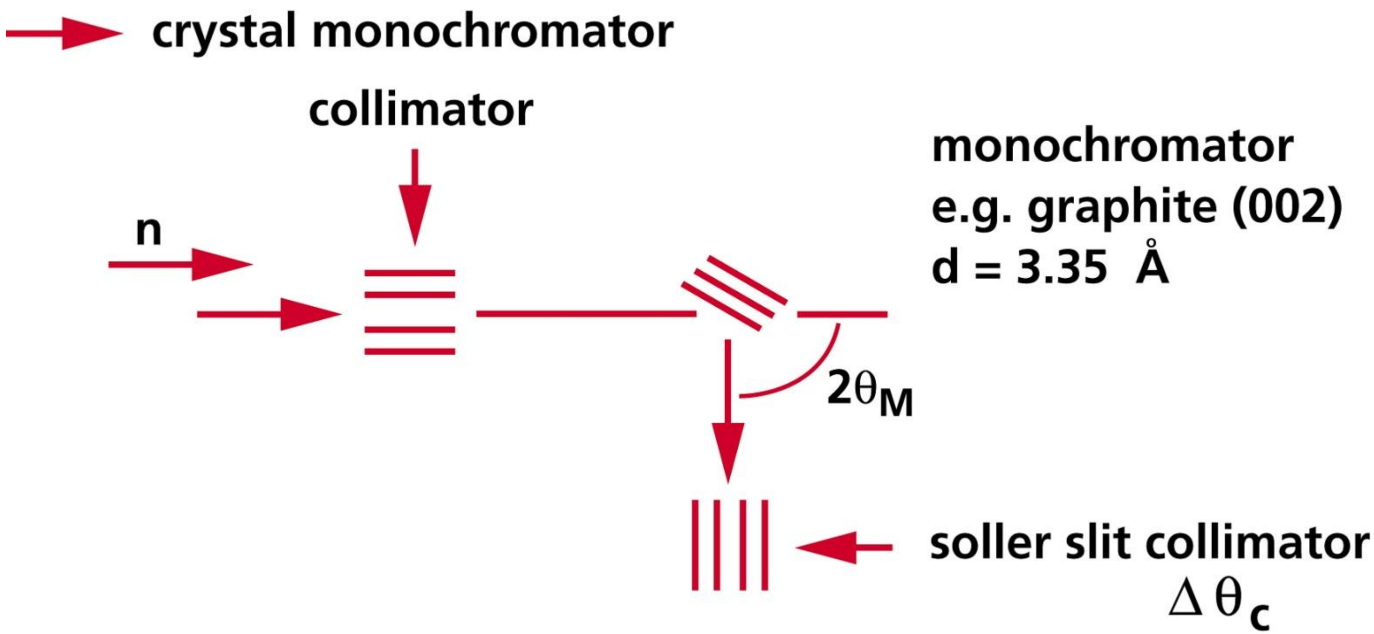


$$\lambda = \frac{2d_c \sin(\theta_B)}{n}$$

$$\Delta\lambda/\lambda \sim \delta d/d + \cot(\theta)\delta\theta$$

Oak Ridge National Laboratory

Resolution



use Bragg's Law $\lambda = 2d \sin\theta$

resolution $1/2 \, \frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda} \sim \cot\theta \, \Delta\theta_c$

•98-6254 uc/trh

Put in some numbers:

so if $2\theta_M = 74.14$ (5 meV) PG002

$$\cot \frac{2\theta_M}{2} = 1.6$$

and for $\Delta\theta_c = 0.5° = 0.0087$ rad

and $\frac{\Delta\lambda}{\lambda} \sim 1\%$

advantages: high $\frac{\Delta\lambda}{\lambda}$

disadvantages: high $\frac{\Delta\lambda}{\lambda}$

poorer reflectivity (transmission)

$\frac{\lambda}{n}$ contamination

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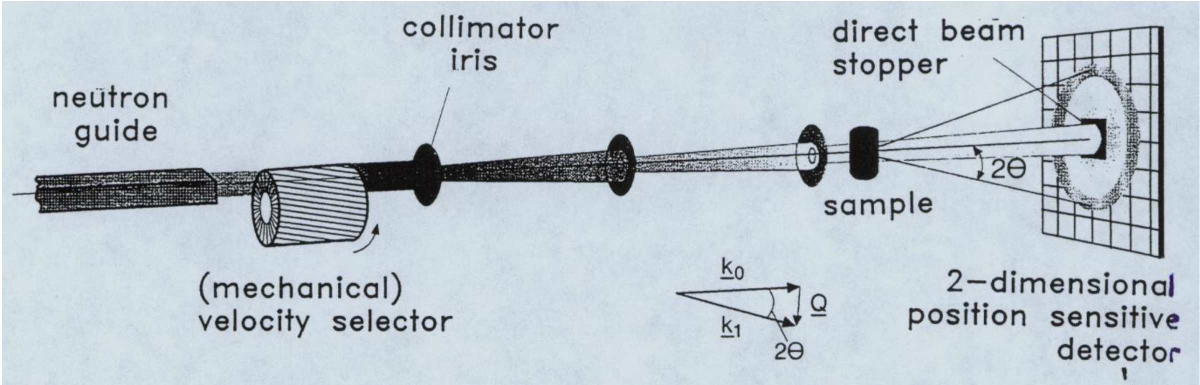
Small Angle Scattering – a special case

$$\lambda = 2d_c \sin(\theta_B)$$

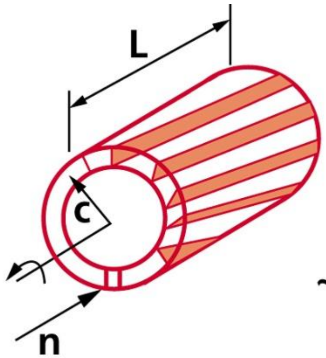


$$Q = 4\pi \sin\theta/\lambda; \ (\delta Q/Q)^2 = (\delta\lambda/\lambda)^2 + (\cot\theta \ \delta\theta)^2$$

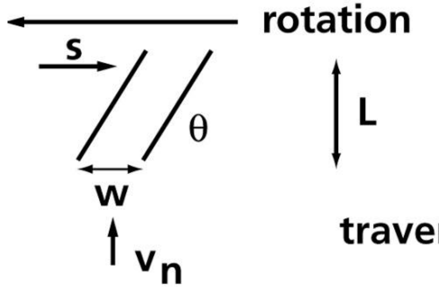
- **Small diffraction angles to observe large objects => long (20 m) instrument**
- **poor monochromatization ($\delta\lambda/\lambda$ ~ 10%) sufficient to match obtainable angular resolution (1 cm² pixels on 1 m² detector at 10 m => $\delta\theta \sim 10^{-3}$ at $\theta \sim 10^{-2}$))**

Mechanical Velocity selector provides large Δλ/λ

⇒ velocity selector



typically
~1000 rpm



traverse time for n

$$t = \frac{L}{v_n}$$

$$\text{and } s = v_s t = 2\pi r\,\omega \cdot t = \frac{2\pi r\,\omega L}{v_n}$$

w controls $\frac{\Delta v_n}{v_n}$ and transmission

advantages:

high transmission
coarse (5% - 30%) $\frac{\Delta v}{v} = \frac{\Delta\lambda}{\lambda}$

disadvantage:

coarse $\frac{\Delta v}{v} = \frac{\Delta\lambda}{\lambda}$

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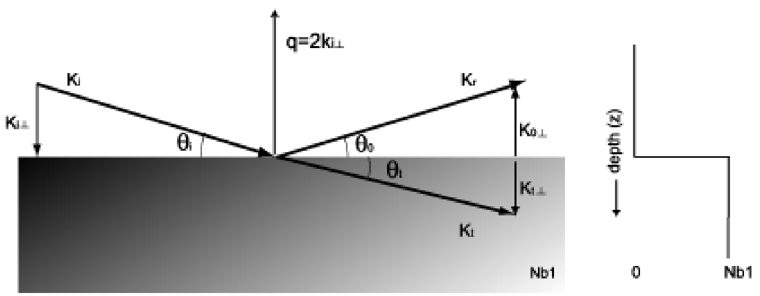
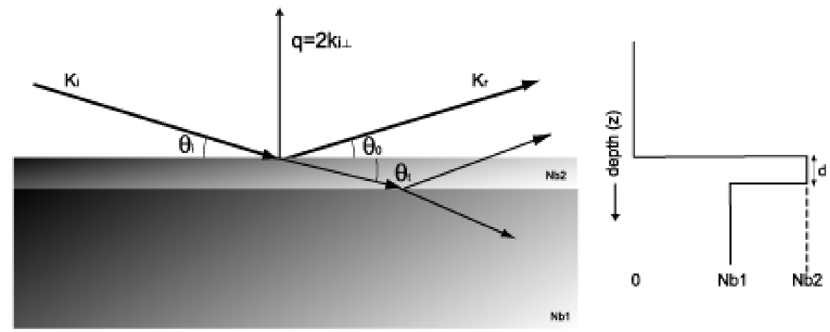
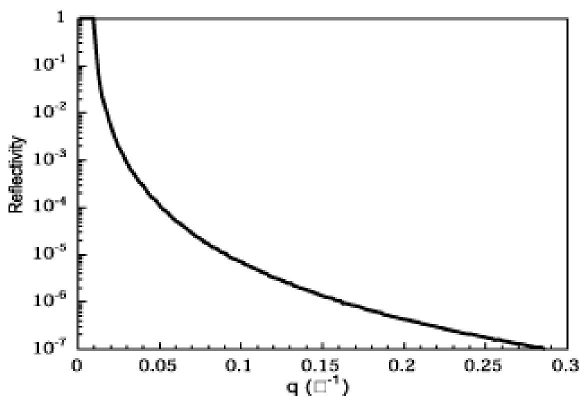
Reflectometry – another special case - also can use large Δλ/λ

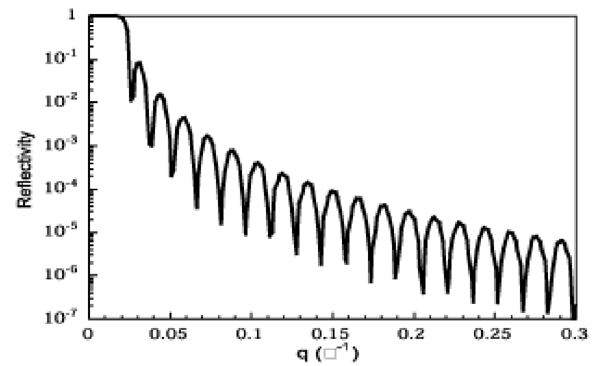
- ***refractive index*** $n = 1 - \delta - i\beta$
- ***x-rays*** $\delta = \dfrac{\lambda^2}{2\pi} r_e \rho$
- ***neutrons*** $\delta = \dfrac{\lambda^2}{2\pi} N_b$

- **Total external reflection** will occur for grazing angles of incidence $\theta_{in} < \theta_c = (2\delta)^{1/2}$ since *n<1*
- For $\theta_{in} < \theta_c$ only an ***evanescent wave*** propagates below the surface (depth *~nm*) and surface sensitivity is greatly enhanced

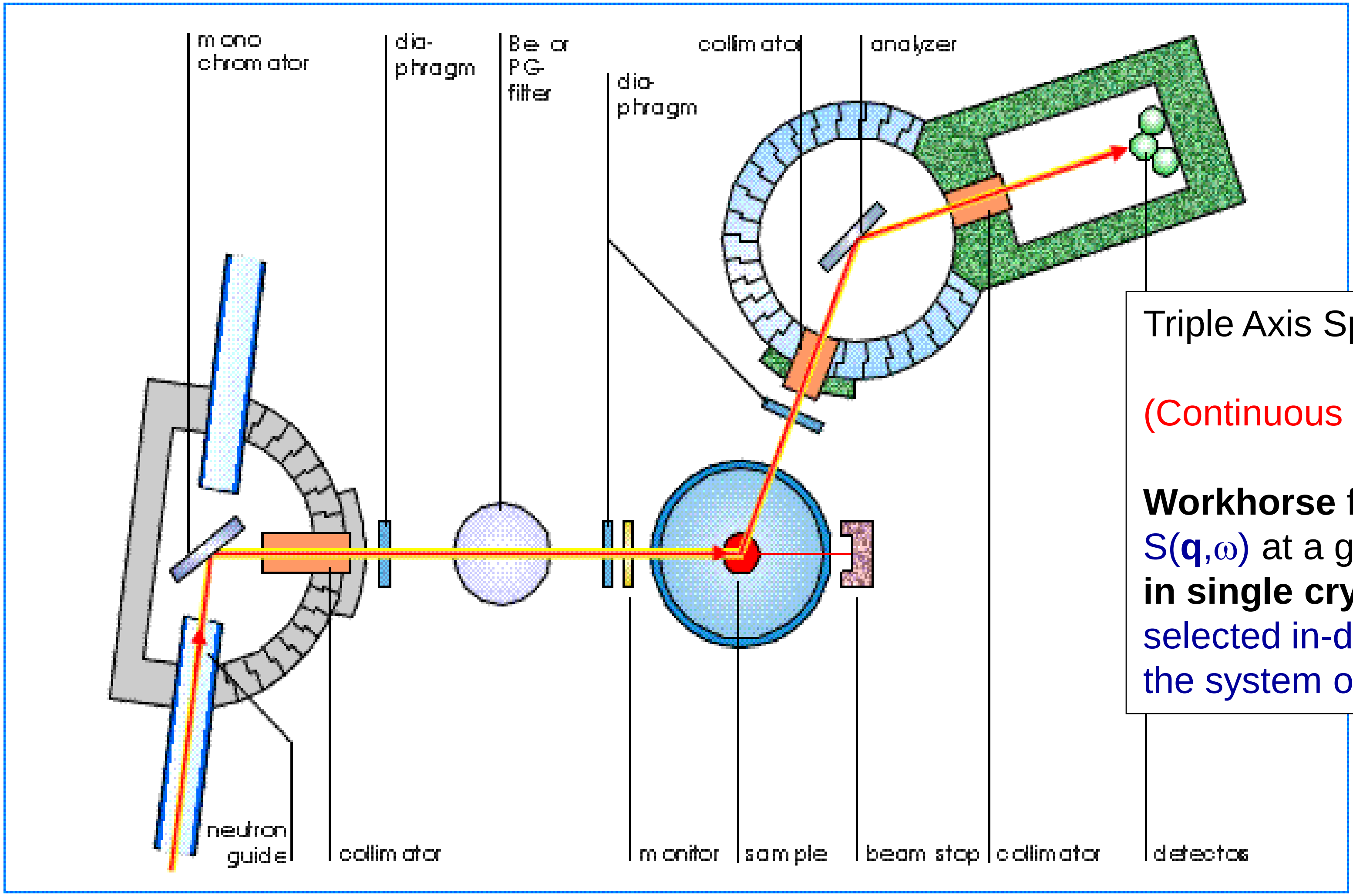








Inelastic scattering - Spectrometers

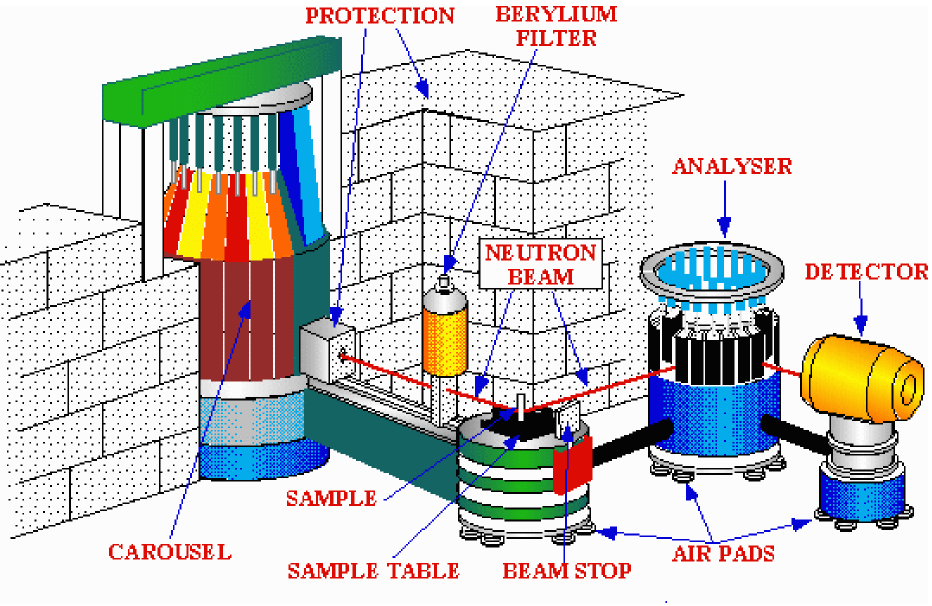


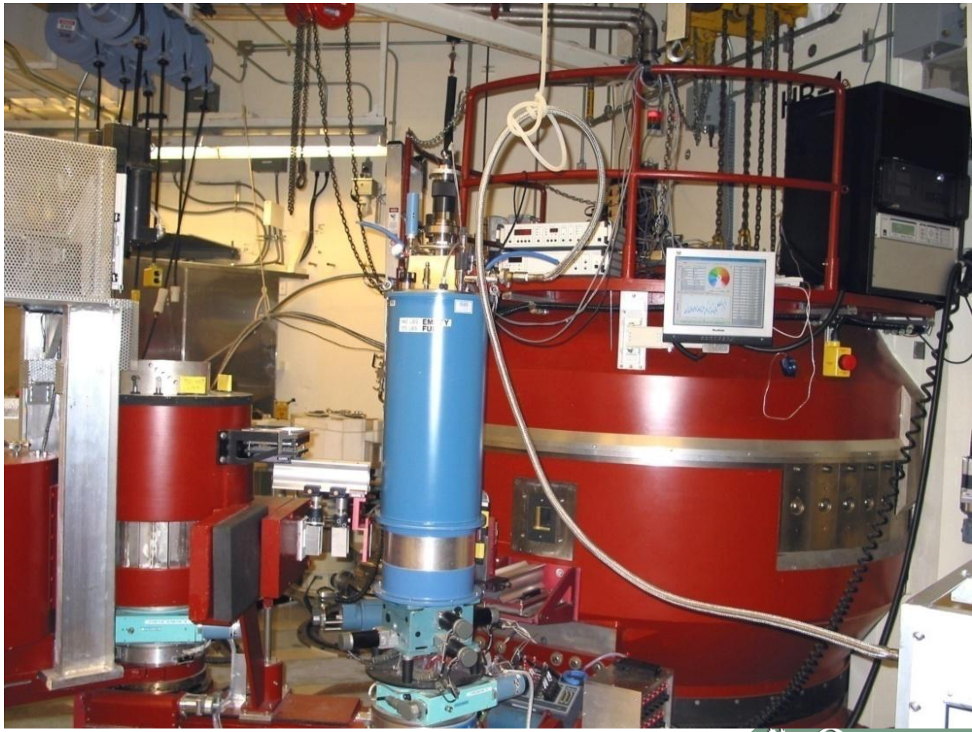
Triple Axis Spectrometer

(Continuous source)

Workhorse for the study of $S(\mathbf{q},\omega)$ at a given **q** vector **in single crystals**: **k** and **k'** selected in-dependently in the system of sample

The Triple Axis Spectrometer





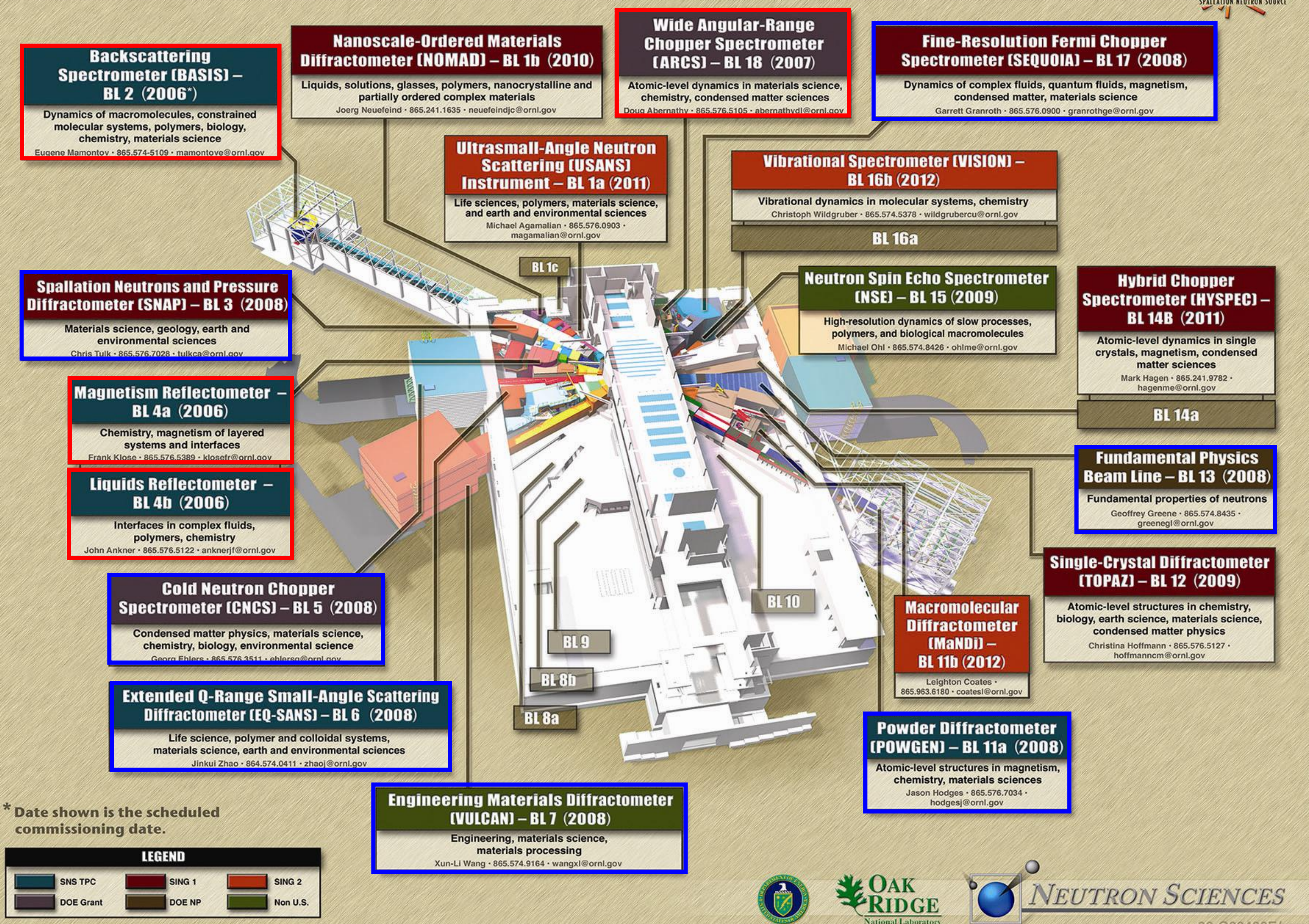
HFIR TAS

HB1a – Fixed Ei (14.6 meV) triple-axis, Resolution typical ~1 meV, 0.5 meV (Be analyzer),

HB1 – Polarized (soon) triple-axis, vertical focusing

HB3 – triple-axis, three available monochromators, vertical focusing

Spallation Neutron Source



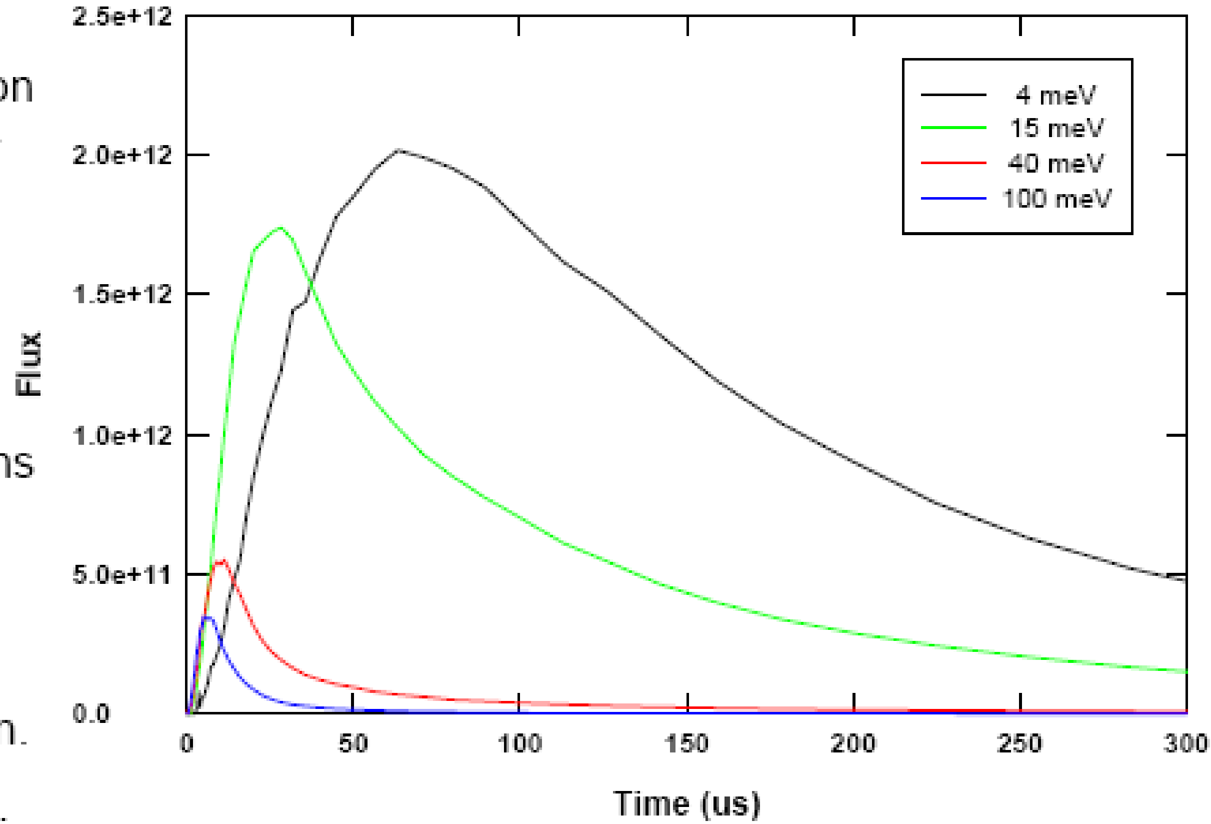
Oak Ridge National Laboratory

Neutron Sciences

06-G00400E/arm

Slowing down time or T0(λ) or T0(E)

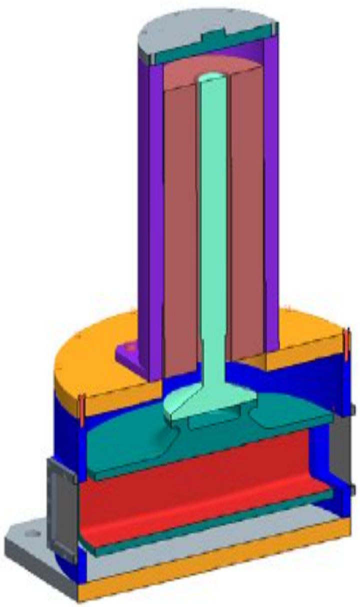
- Neutrons emerging from moderators have a distribution of energies = a Maxwellian + a 1/E (epithermal) tail.
- But different neutron energies (wavelengths) emerge from the moderator with different time distributions (see example on right).
- Need to calibrate a T0(E) function for each moderator and use this in data reduction.
- Now the neutrons are emerging out of the monolith and into the beamlines for the neutron scattering instruments…..

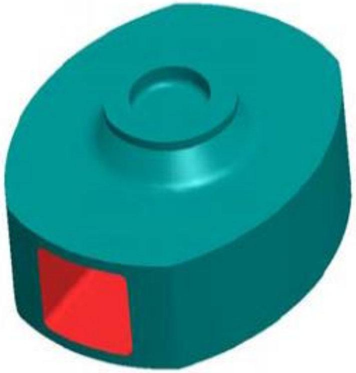


Example: MCNPX results for coupled cryogenic H_2 moderator on SNS target station 1

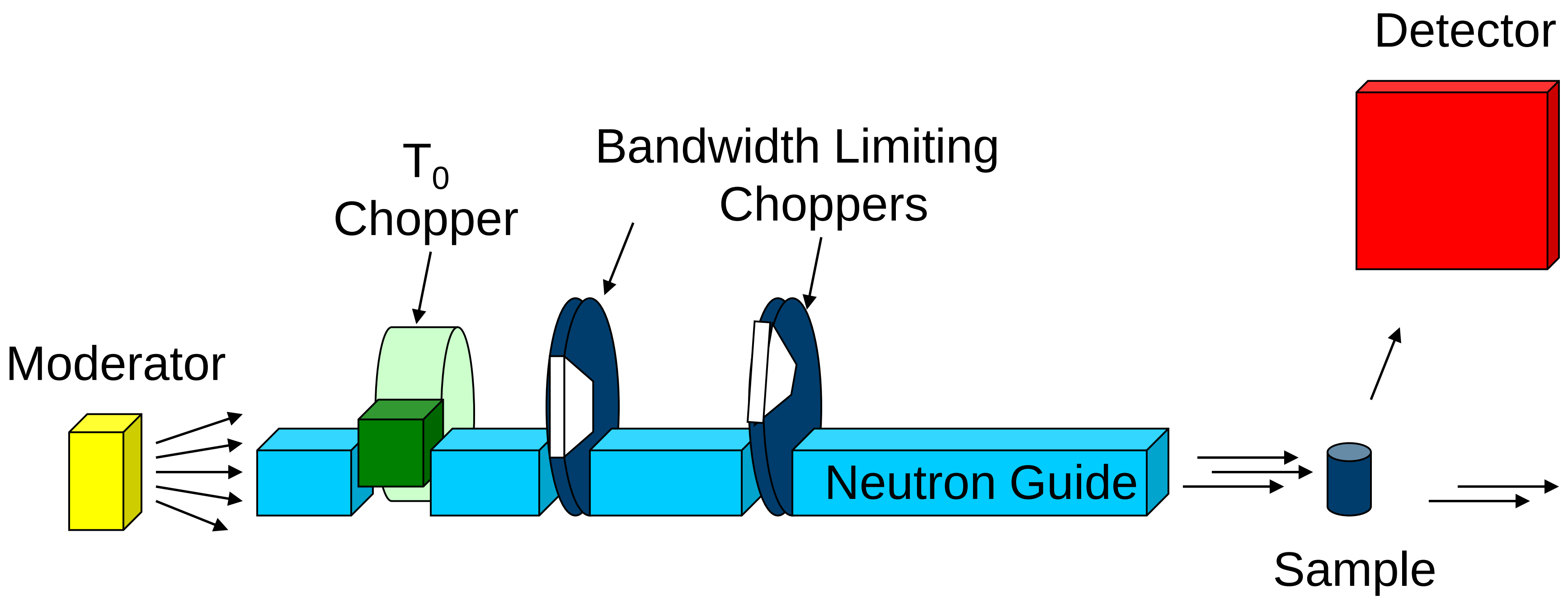
Beam Selection/conditioning T0 Choppers and Curved Guides

- When the proton beam strikes the target (time T0) a burst of ~1GeV neutrons and a flash of gamma rays are produced. Some are neutrons are moderated but some emerge into the beamlineat time T0. Have to get rid of the fast neutrons and gamma rays.
- Two methods -T0 chopper or curved guide
- T0 chopper –rotating plug of Inconel(200 →300mm) that blocks the beam at time T0.
- Curved guide, low energy neutrons are reflected but not higher energies. The guide is curved so that final sample position does nothave a line of sight to the source and fast neutrons must collide/be absorbed in, shielding around beamline. BASIS, CNCS and HYSPEC have curved guides.
- Note T0 choppers are phased (electronically) to the source“T0”signal.

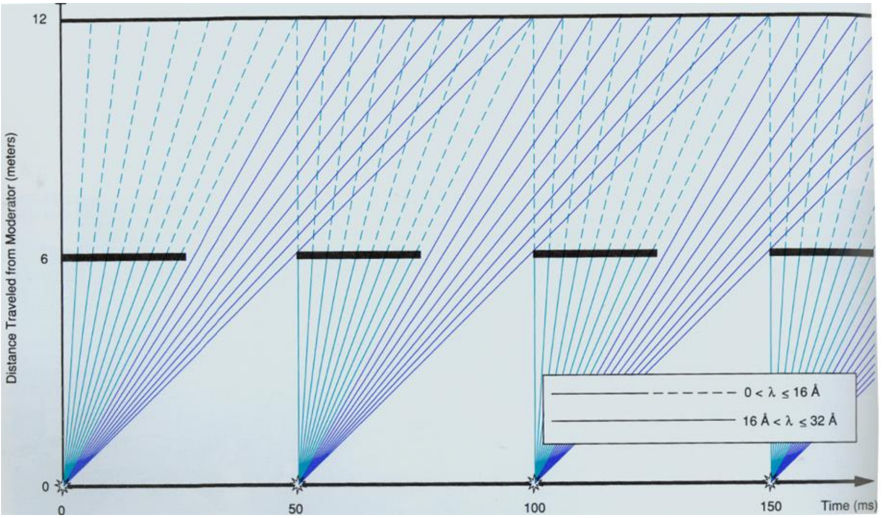




A Generic Pulsed Source Instrument – introducing choppers



Rotating Choppers Are Used to Tailor Neutron Pulses



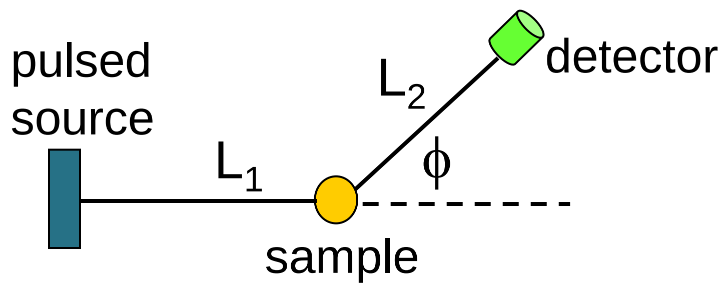
Fast neutrons from one pulse can catch-up with slower neutrons from a succeeding pulse and spoil the measurement if they are not removed.

This is called “frame-overlap”

- **T-zero choppers are used at spallation sources to absorb the prompt high-energy pulse of neutrons**
- **Cd is used in frame overlap choppers to absorb slower neutrons**

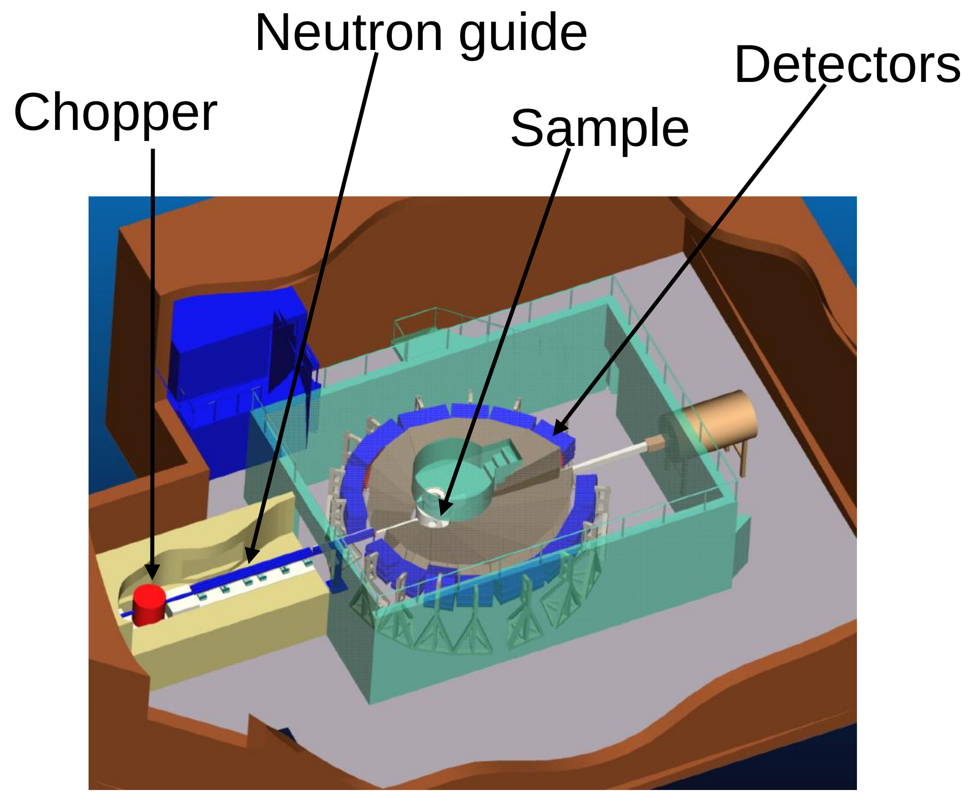
Determining the wavelength – pulsed source

time-of-flight (TOF)



$$\lambda = \frac{4000}{v} = \frac{4000\,(t-t_0)}{L}$$

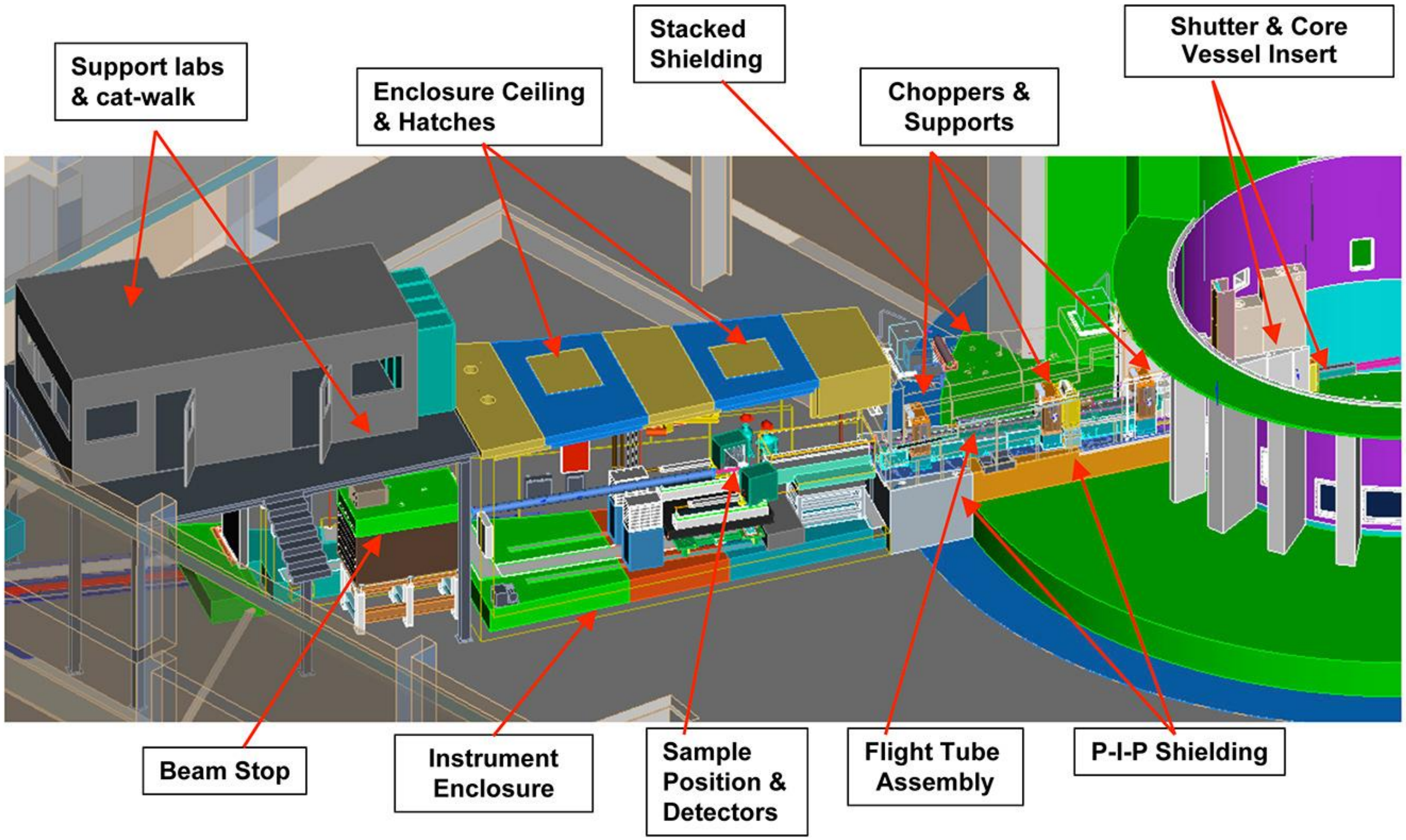
$$\delta\lambda \sim \delta t_0, \delta t, \delta L$$



Powgen3 at SNS

L = 60 m

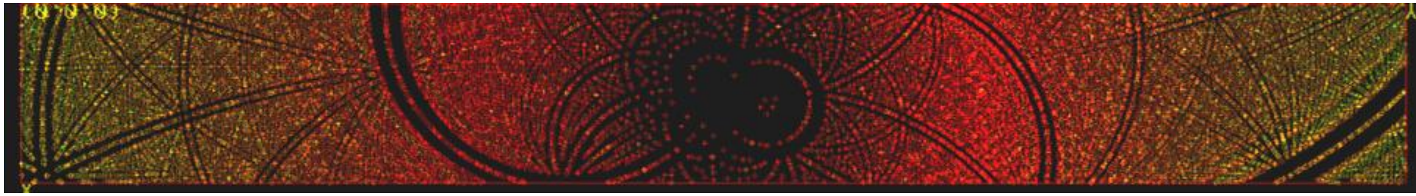
SNAP – Single Crystal Diffractometer for high pressures (>50 Gpa)

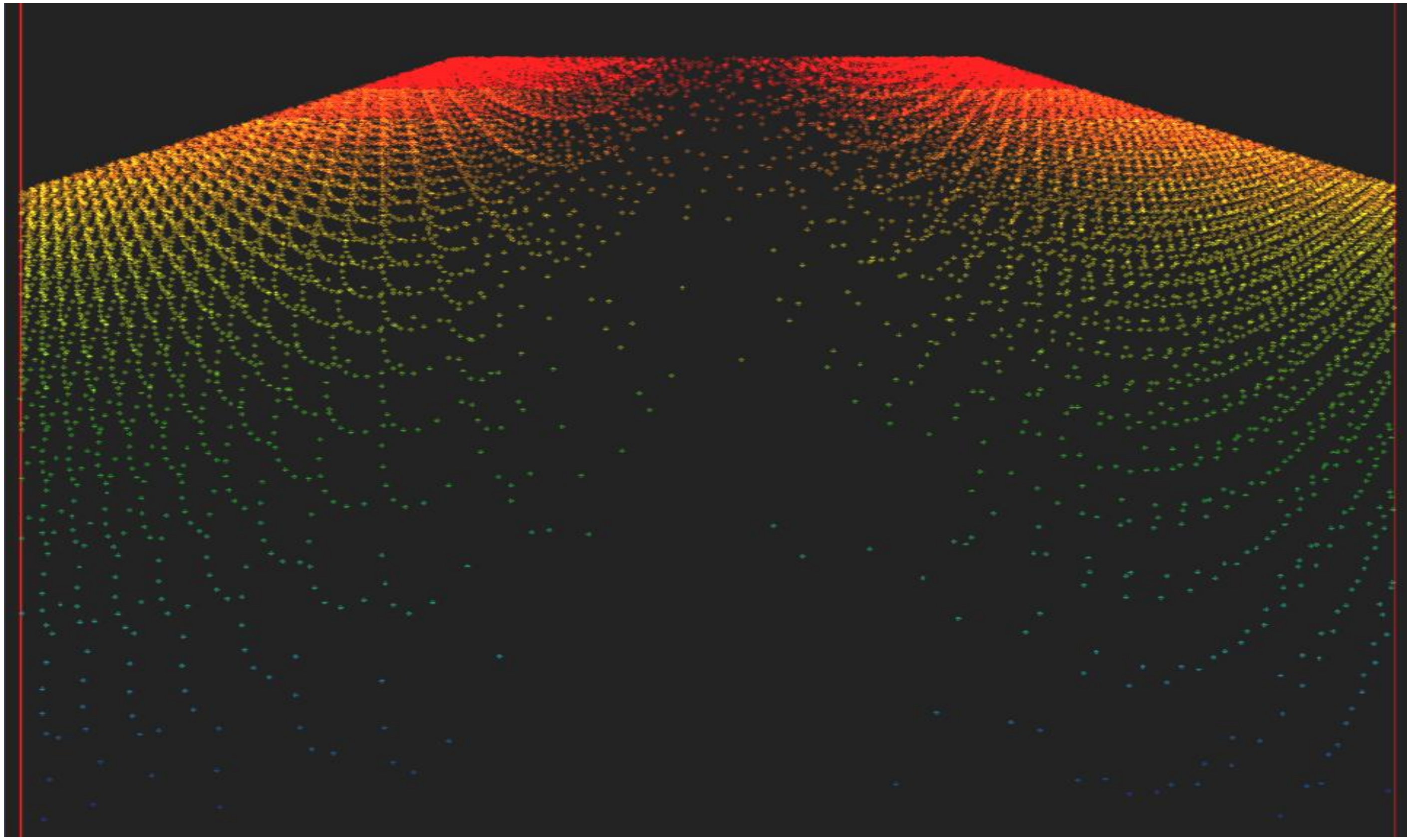


SPECIFICATIONS

Moderator	Decoupled poisoned supercritical hydrogen
Source to sample distance	15 m
Sample to detector distance	50 cm
Angular coverage	38-142° \ 98-150° horizontal ±34° vertical
Wavelength range (bandwidth)	
Frame 1	0.5 – 3.65 Å
Frame 2	3.7 – 6.5 Å
Pressure range	From ambient pressure to >50 GPa (500 kbar)
Focused beam size	From 1 cm to <100 μm

Wavelength-resolved Laue Data in Detector Space





Diffraction patterns are 3D: (x,y,λ)

Reduced reflection overlap.

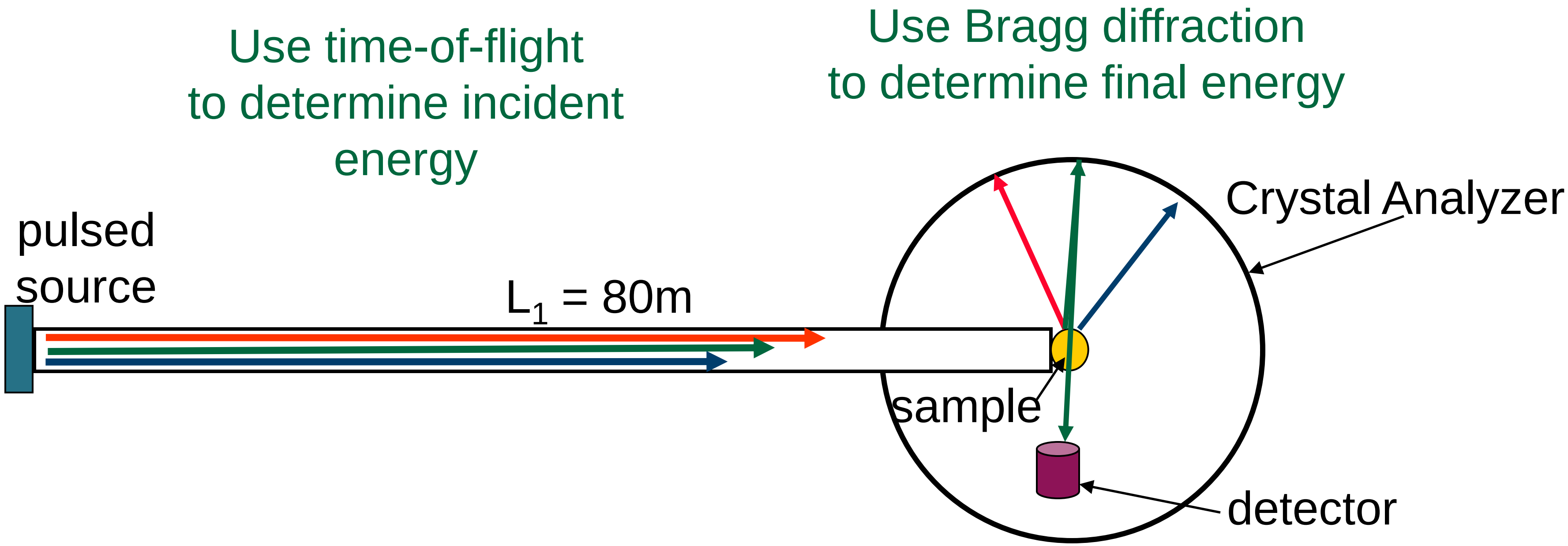
Reduced background

Enhanced signal-to-noise

Red-Blue: 0.6A-6A

Backscattering spectrometer at SNS

Want high resolution, BASIS has ΔE = 3.5ueV



$$\lambda = \frac{4000}{v} = \frac{4000\,(t-t_0)}{L}$$

$$\lambda = \frac{2d_c \sin(\theta_B)}{n}$$

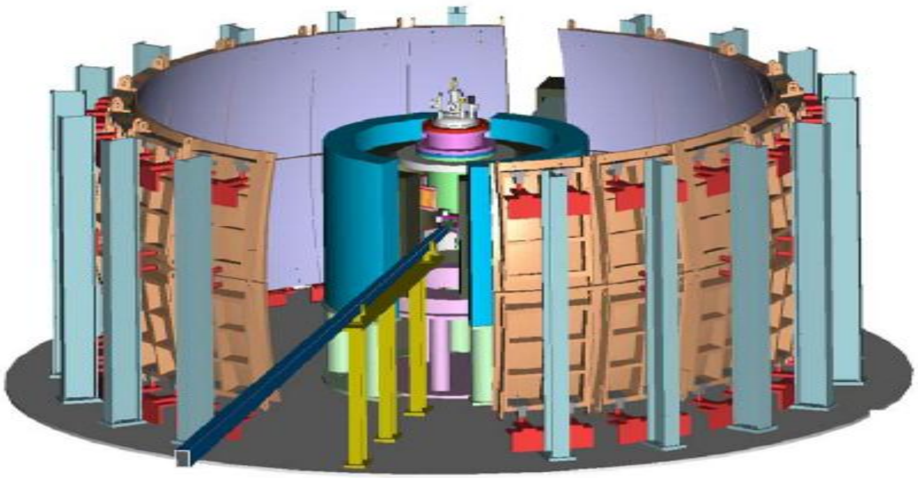
$\delta\lambda \sim \delta t_0, \delta t, \delta L$

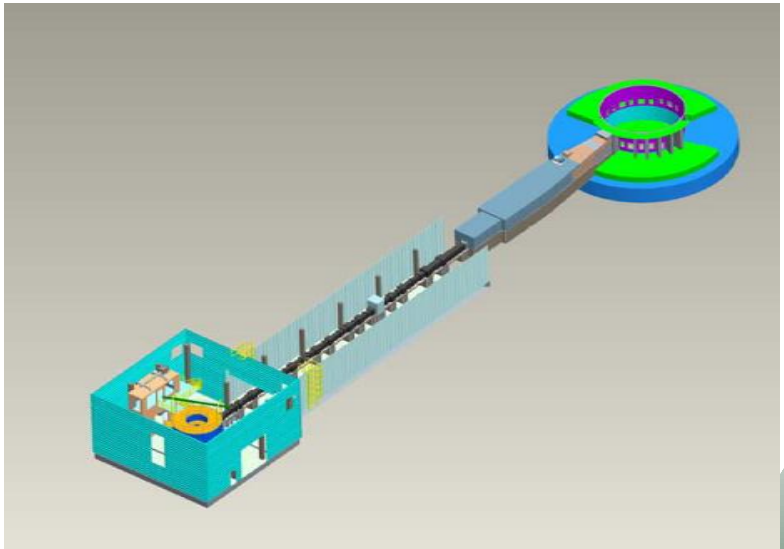
$\Delta\lambda/\lambda \sim \delta d/d + \cot(\theta)\delta\theta$

BASIS –backscattering spectrometer

- Source/Moderator
  - Decoupled supercritical Hydrogen, centerline poisoned
- Incident Flight Path -84 m moderator-sample position
  - Curved Guide: 10 cm wide x 12 cm tall, 1000 m radius of curvature, line-of-sight at 31 m
  - Straight Guide: 10 cm wide x 12 cm tall
  - Converging Funnel exit: 3.25 cm x 3.25 cm, stops 27.5 cm from sample
- Chopper System -3 bandwidth/frame overlap choppers
- Sample –nominal dimensions 3 x 3 cm^2
- Radial Collimator –restricts analyzer view of the sample, Final Flight Path -2.5 m sample - analyzer, ~2 m analyzer –detector
- Detector Choice – ^{3}He LPSD tubes, peak count rate (elastic, 30% scatterer) 4000 counts/cm2 /sec
- Analyzer Crystals

  Si (111): λf= 6.267 Å, δd/d~3.5 x 10^{-4}, 2.03 ster, 12.5 m^2, bandwidth 0.785 Å





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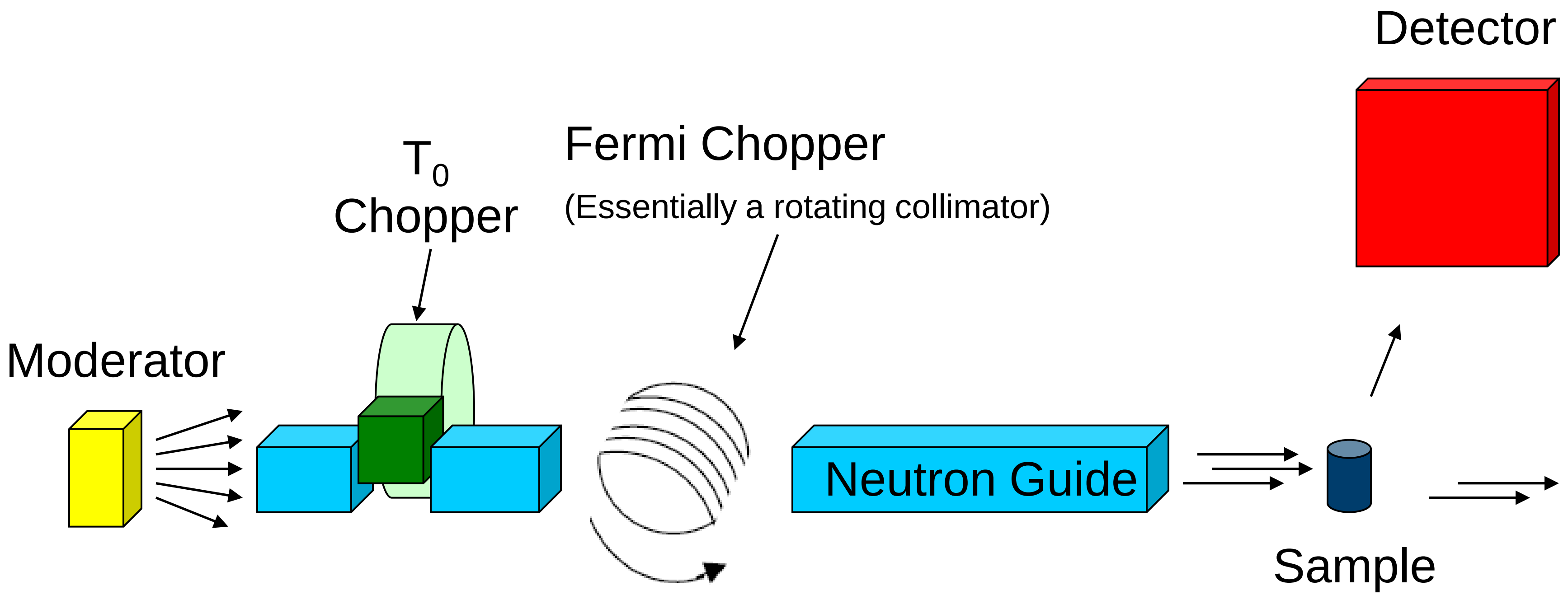
A generic TOF spectrometer - again, but with a twist

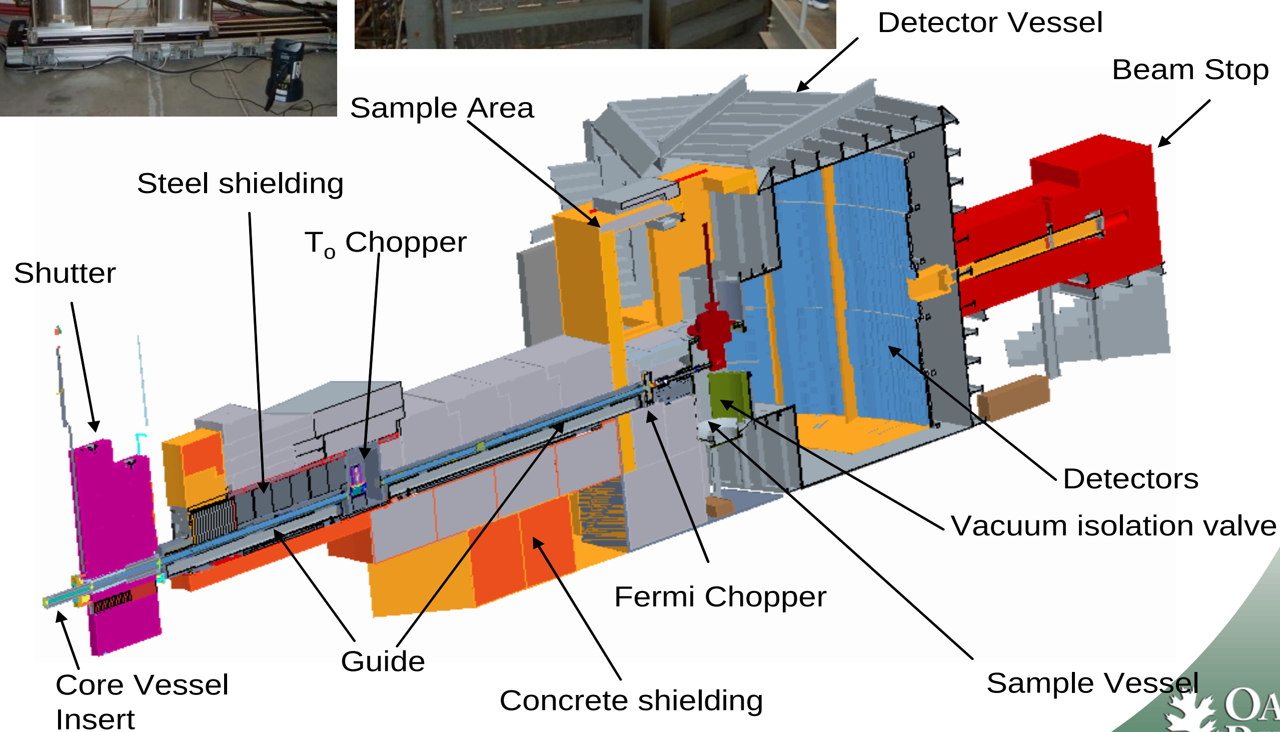


SEQUOIA – high resolution chopper spectrometer

optimized for magnetic inelastic scattering (in forward direction), which falls off with increasing Q (angle).

SPECIFICATIONS

Moderator	Decoupled ambient water
Source to Fermi chopper distance	18 m
Chopper to sample distance	2.0 m
Sample to detector distance	5.5 – 6.3 m cylindrical geometry
Incident energy range	10 – 2000 meV
Resolution (elastic)	1 – 5% E_i
Vertical detector coverage	-30 – 30°
Horizontal detector coverage	-30 – 60°
Minimum detector angle	3°

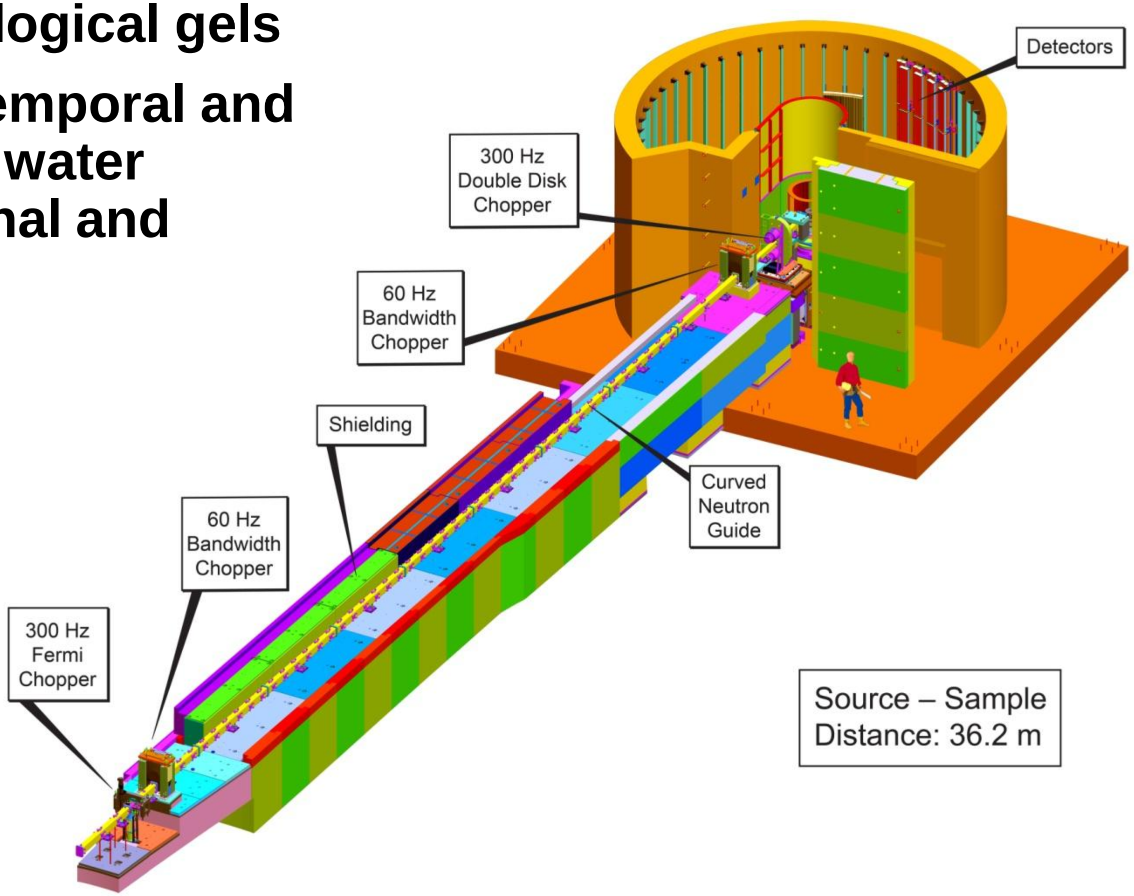


Detector Vessels: vacuum tanks – ARCS & SEQUOIA

- Air scatters neutrons strongly, over long flight paths want to remove the air → vacuum
- Wallpaper the detector vessel with LPSD tubes

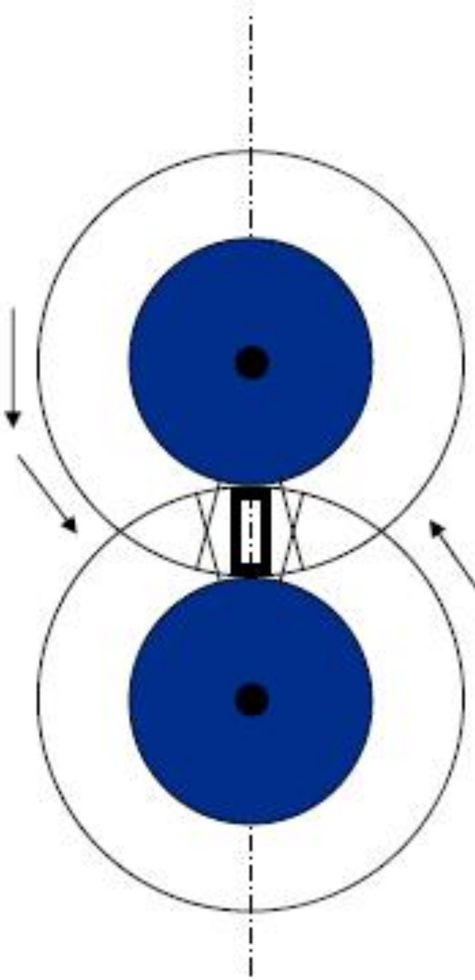
CNCS (Cold Neutron Chopper Spectrometer)

- **Designed for rapid data collection using a large position-sensitive detector array.**
- **Flexible chopper system can adapt the resolution to the problem of interest**
- **Example: Diffusion in biological gels**
  - **CNCS can study the temporal and spatial correlations of water undergoing translational and rotational motions.**



High Speed Double Disk Choppers - CNCS

- In order to get high final energy resolution we need a short burst time for the chopper.
- If the 2 disks are rotating at 300Hz each then the effective frequency of the 2 choppers is 600Hz is this "counter-rotating" mode.
- Opening time is phased to T0 signal.



Polarized Neutron Beams

Each individual neutron has spin s=½ and an angular momentum of ±½ħ

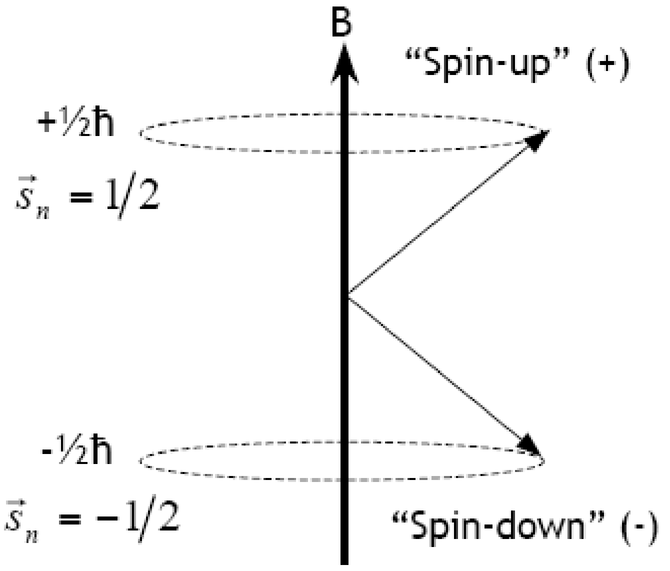
Each neutron has a spin vector $\vec{s}_n$ and we define the polarization of a neutron beam as the ensemble average over all the neutron spin vectors, normalised to their modulus

$$\vec{P} = \langle \vec{s}_n \rangle / \tfrac{1}{2} = 2\langle \vec{s}_n \rangle$$

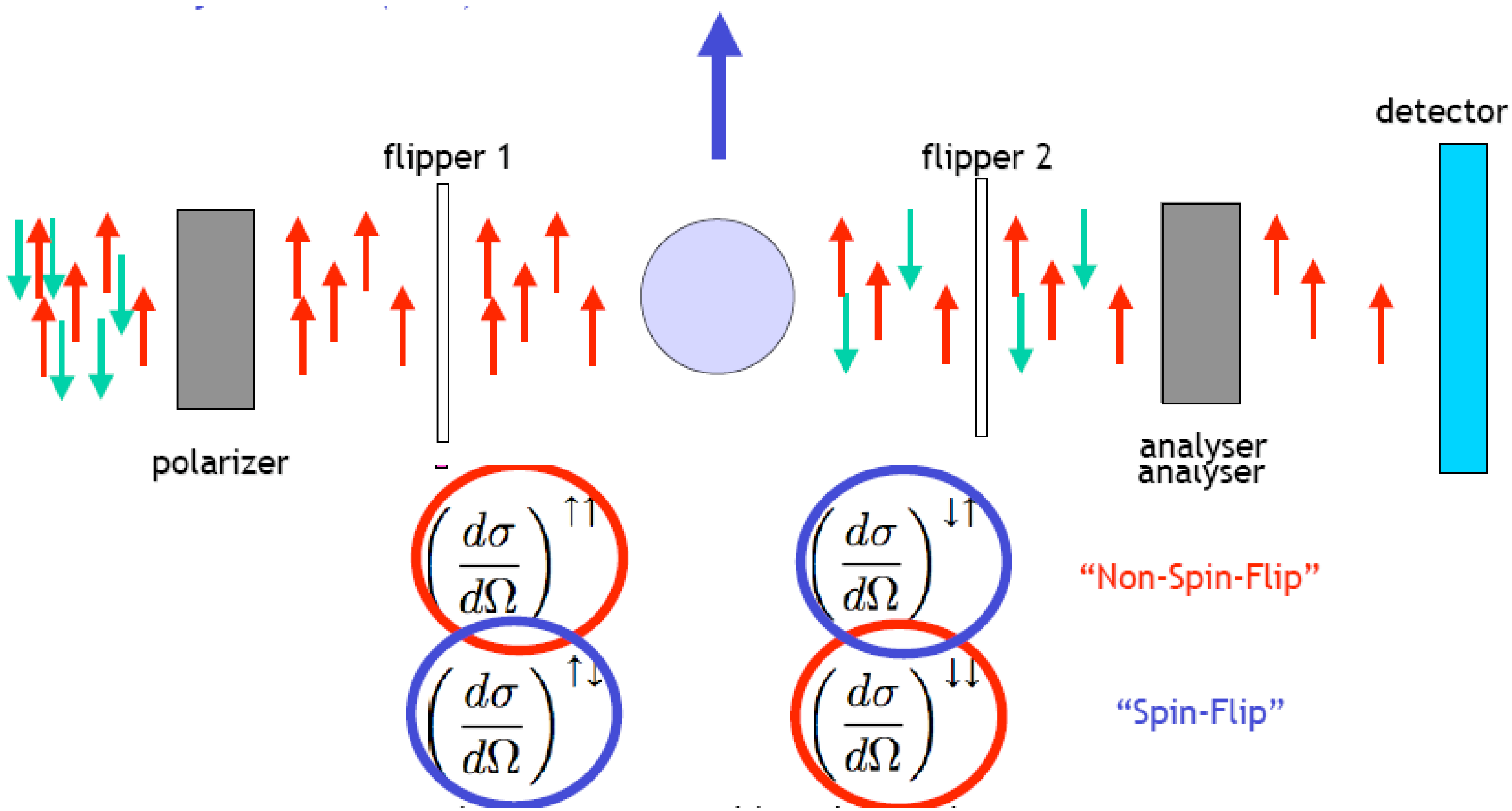
If we apply an external field (quantisation axis) then there are only two possible orientations of the neutrons: parallel and anti-parallel to the field. The polarization can then be expressed as a scalar:

$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

where there are N_+ neutrons with spin-up and N_- neutrons with spin-down

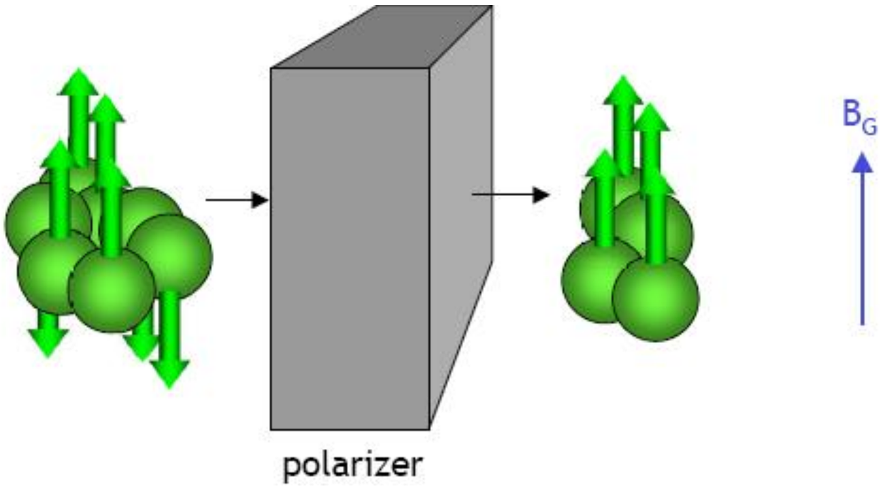


A Uniaxial PA Experiment



First attempted by Moon, Riste and Koehler (1969)
Phys Rev. 181 (1969) 920

Production of polarized beams



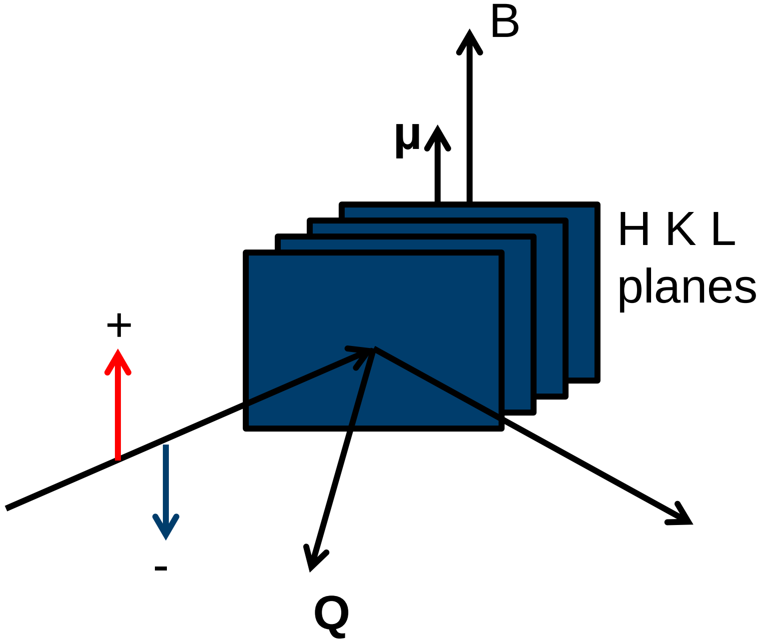
There are three principal (passive) methods of beam polarization, each with specific advantages in particular experimental situations

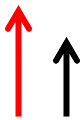
1. polarizing crystals (e.g. $Co_{92}Fe_8$, Heusler crystals (Cu_2MnAl)) using preferential Bragg reflection)
2. polarizing mirrors and supermirrors (using preferential reflection)
3. polarizing filters (e.g. preferential absorption by polarized ^3He nuclei)

See, e.g. Williams in Polarized Neutrons, Oxford

Polarizing monochromators

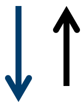
Reflected intensity I ~ $d\sigma/d\Omega = F_N(\mathbf{Q})^2 + F_M(\mathbf{Q})^2 + 2F_N(\mathbf{Q}).\ F_M(\mathbf{Q}).(\mathbf{P}.\boldsymbol{\mu})$





$(\mathbf{P}.\boldsymbol{\mu}) = 1$

Intensity ~ $(F_N + F_M)^2$



$(\mathbf{P}.\boldsymbol{\mu}) = -1$

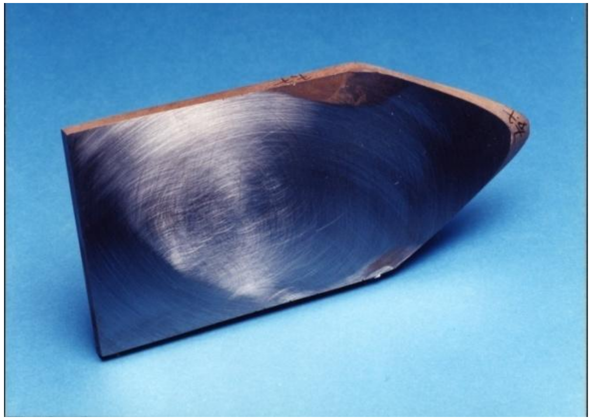
Intensity ~ $(F_N - F_M)^2$

Polarization = $(I_+ - I_-)/(I_+ + I_-) = \pm 2F_N(\mathbf{Q}).\ F_M(\mathbf{Q})/[F_N(\mathbf{Q}) - F_M(\mathbf{Q})]^2$

Polarizing crystal monochromators

Heusler alloy

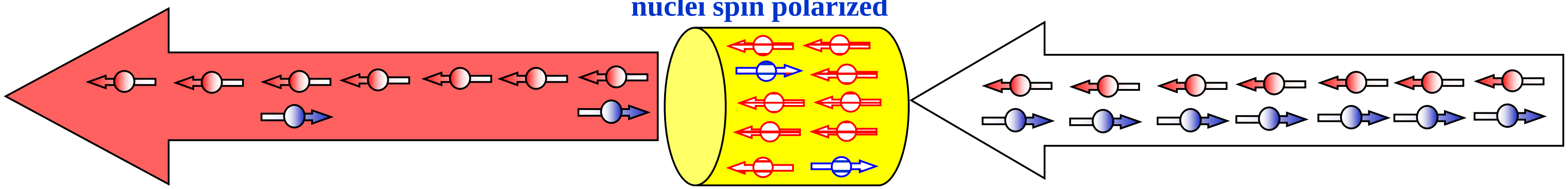
	$Co_{0.92}Fe_{0.08}$	Cu_2MnAl	Fe_3Si	^{57}Fe:Fe	$HoFe_2$
Matched reflection $\lvert F_N\rvert \sim \lvert F_M\rvert$	(200)	(111)	(111)	(110)	(620)
d-spacing (Å)	1.76	3.43	3.27	2.03	1.16
Take-off angle $2\theta_B$ at 1 Å (deg)	33.1	16.7	17.6	28.6	50.9
Cut-off wavelength, λ_{max} (Å)	3.5	6.9	6.5	4.1	2.3

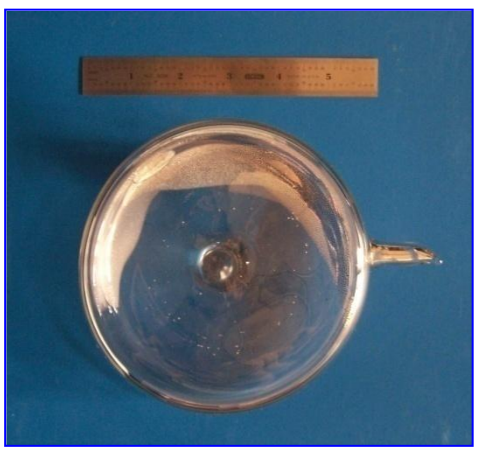


Polarized ^{3}He based neutron spin filter

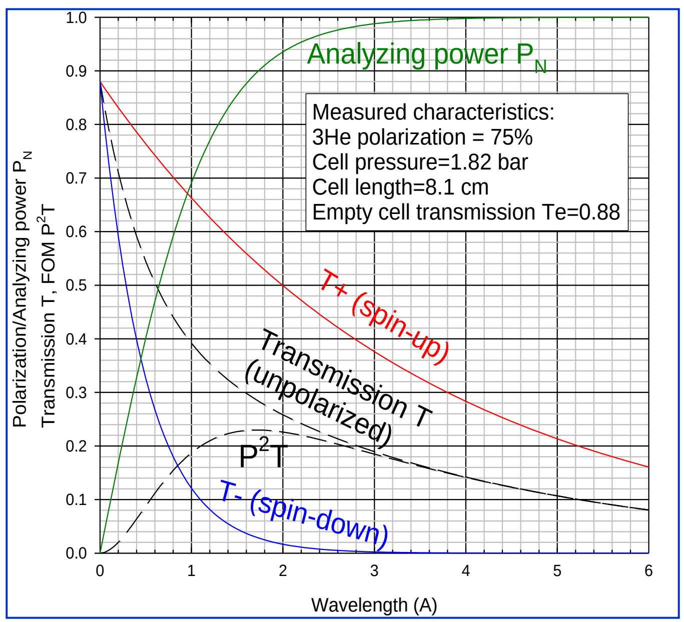
Polarized ^{3}He neutron spin filter is based on the spin-dependence of the neutron absorption of ^{3}He. If the ^{3}He nuclear spin and the neutron spin are anti-parallel, the absorption is very strong: σ_a (↑↓) = 5931 b for λ=1 Å neutrons. If the spins are parallel, there is virtually no absorption. σ_a (↑↑) ~ 0. The absorption cross-section is proportional to the neutron wavelength λ.

A beam of polarized neutrons | **A cell of ^{3}He with their nuclei spin polarized** | **A beam of unpolarized Neutrons**





A ^{3}He spin filter cell



$$T_+ = T_{glass} e^{-(1-P_{He})n\sigma\lambda l}$$

$$T_- = T_{glass} e^{-(1+P_{He})n\sigma\lambda l}$$

$$P_n = \tanh(P_{He} n\sigma\lambda l)$$

T = transmission

P_n = neutron polarization

P_{He} = ^{3}He polarization

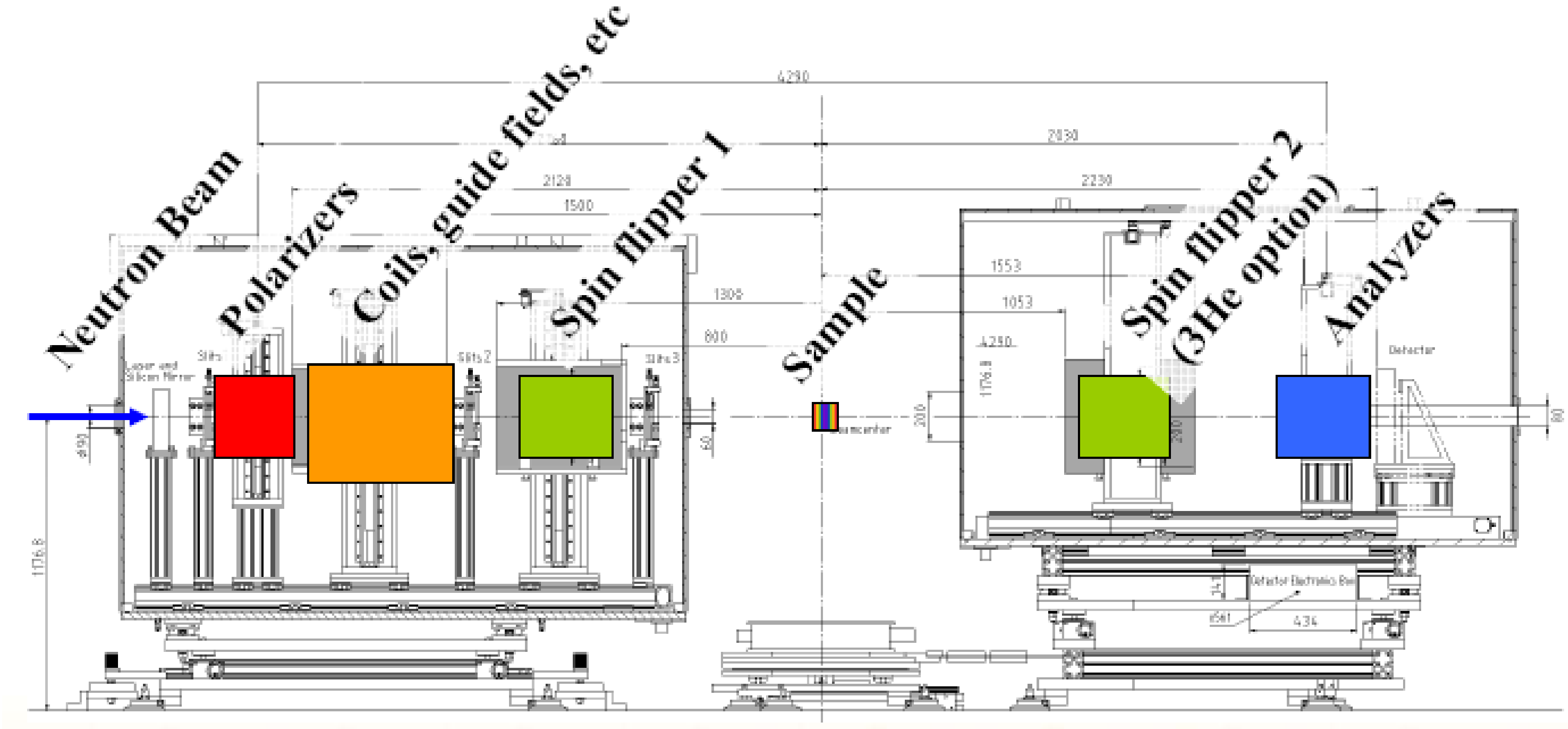
n = number density of ^{3}He

l = cell length

σ = absorption cross-section at 1 Å

λ = neutron wavelength

Polarized Neutron Technology: The Magnetism Reflectometer at SNS



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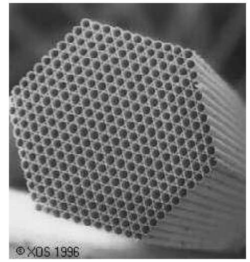
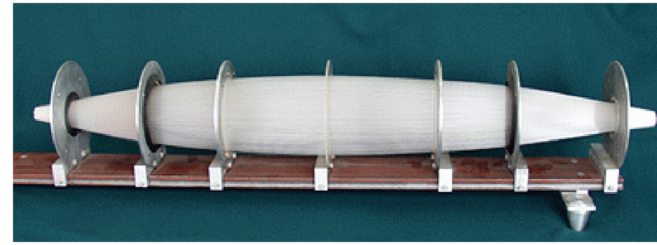
Polarized Neutron Technology: The Magnetism Reflectometer at SNS

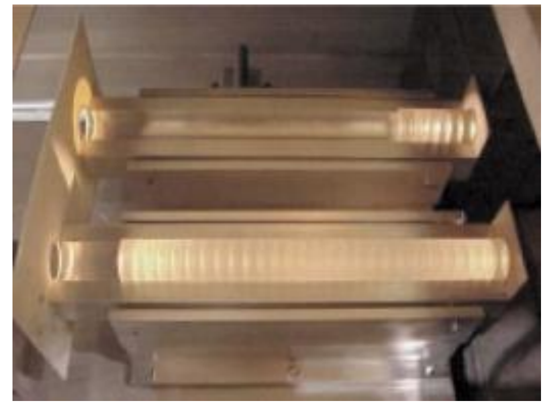
Some things we didn't talk about: but others will

- Capillary Optics

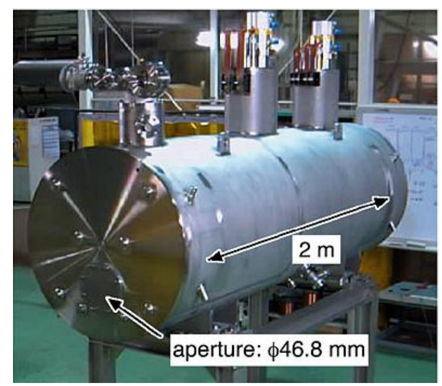




- Compound Refractive Lens



- Magnetic Lens
- Polarized Neutrons



- Neutron Spin Echo

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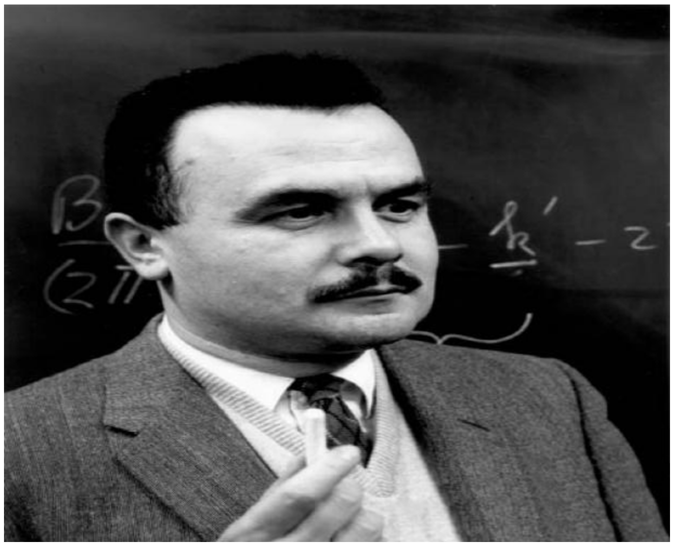
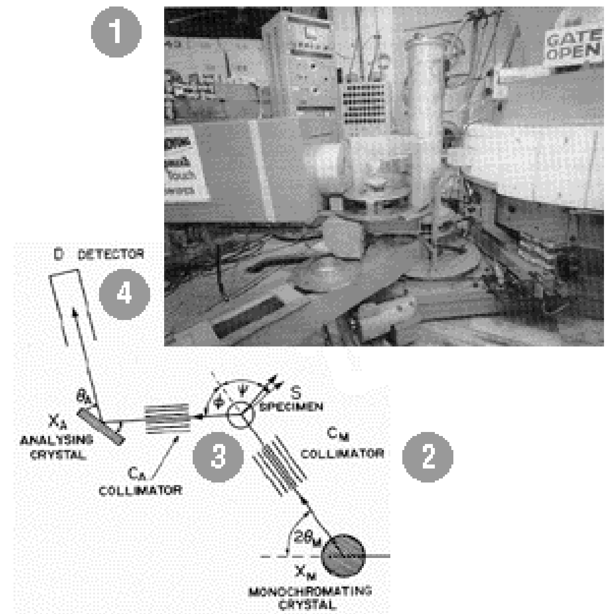
The beginnings of neutron spectroscopy

Bertram Brockhouse, Chalk River, Canada, 1950's





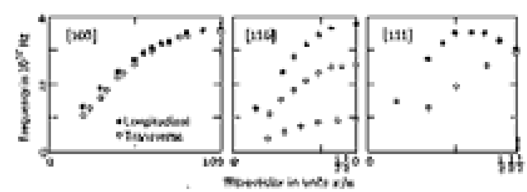


Figure 11 The dispersion curves of sodium for phonons propagating in the [001], [110], and [111] directions at 90 K, as determined by inelastic scattering of neutrons. [Woods, Brockhouse, March and Bowers, Proc. Phys. Soc. London 79, pt. 2, 440 (1962).]

"If the neutron did not exist, it would need to be invented."
-B. Brockhouse