Neutron Generation and Detection
Neutron Optics and Instrumentation

Lee Robertson
Neutron Technologies Division
Oak Ridge National Laboratory

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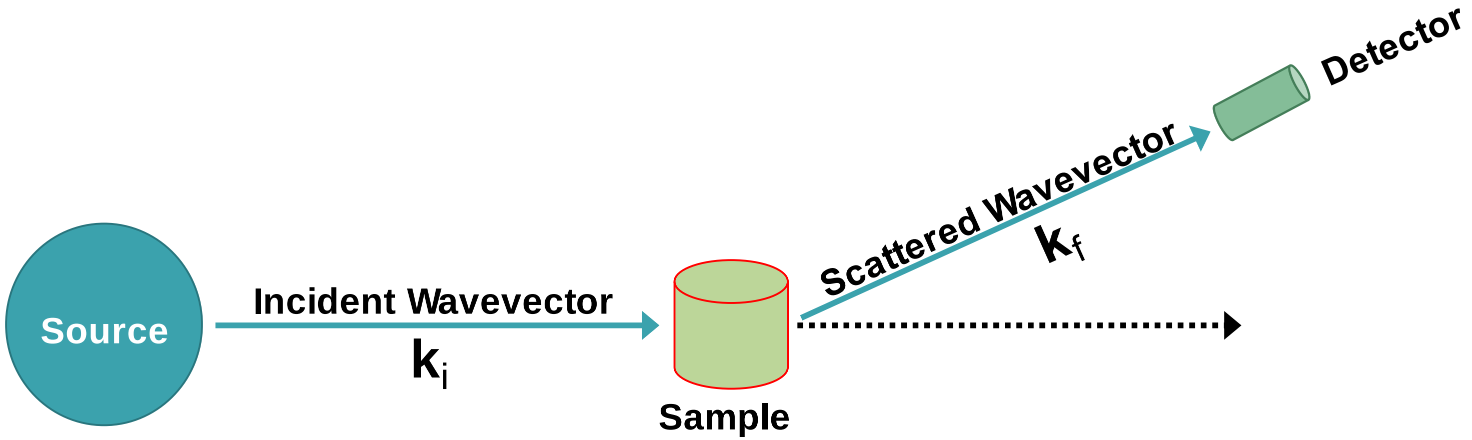
What is a Neutron Scattering Instrument?

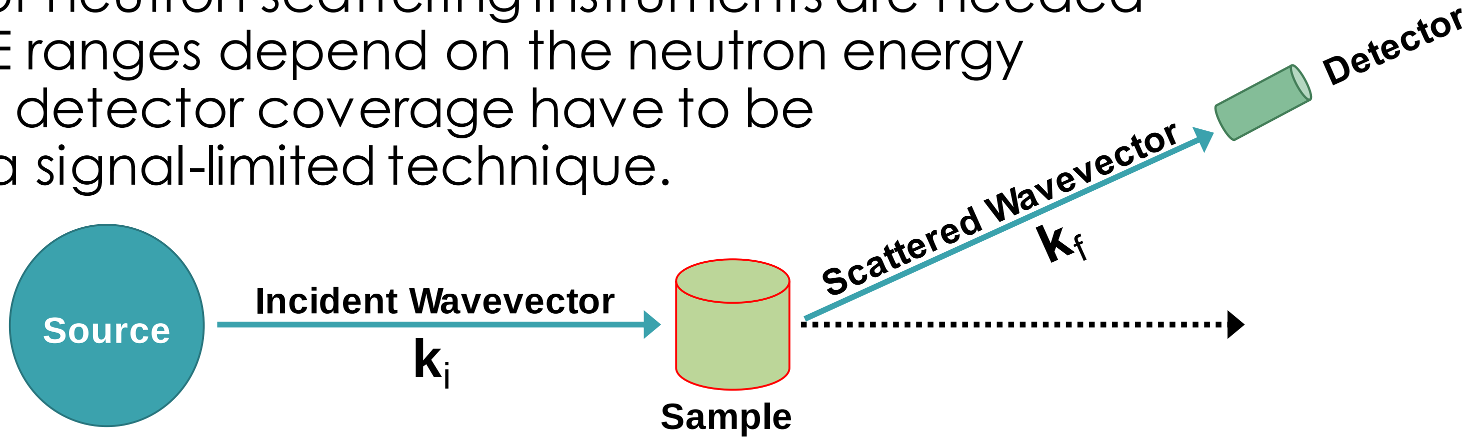
- Neutron scattering experiments measure the number of neutrons scattered by a sample as a function of the wavevector change (Q) and the energy change (E) of the neutron.

- What do we need to accomplish this?
  1) A source of neutrons
  2) A method for selecting the wavevector of the incident neutrons (ki)
  3) A very interesting sample
  4) A method for determining the wavevector of the scattered neutrons (kf)
  5) A neutron detector

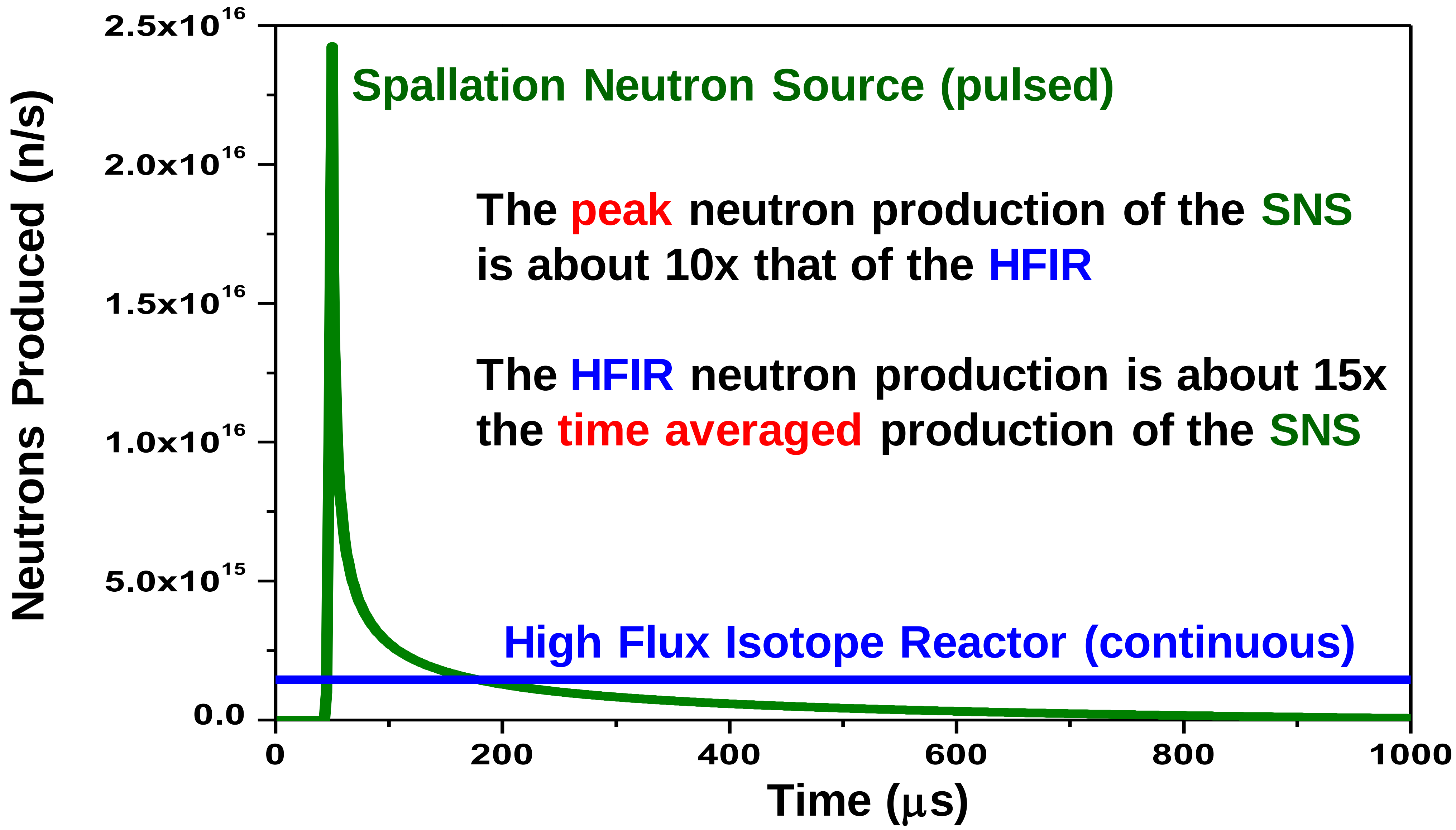


Why Not Just Build a Universal Neutron Scattering Instrument That Can Do Everything We Need?

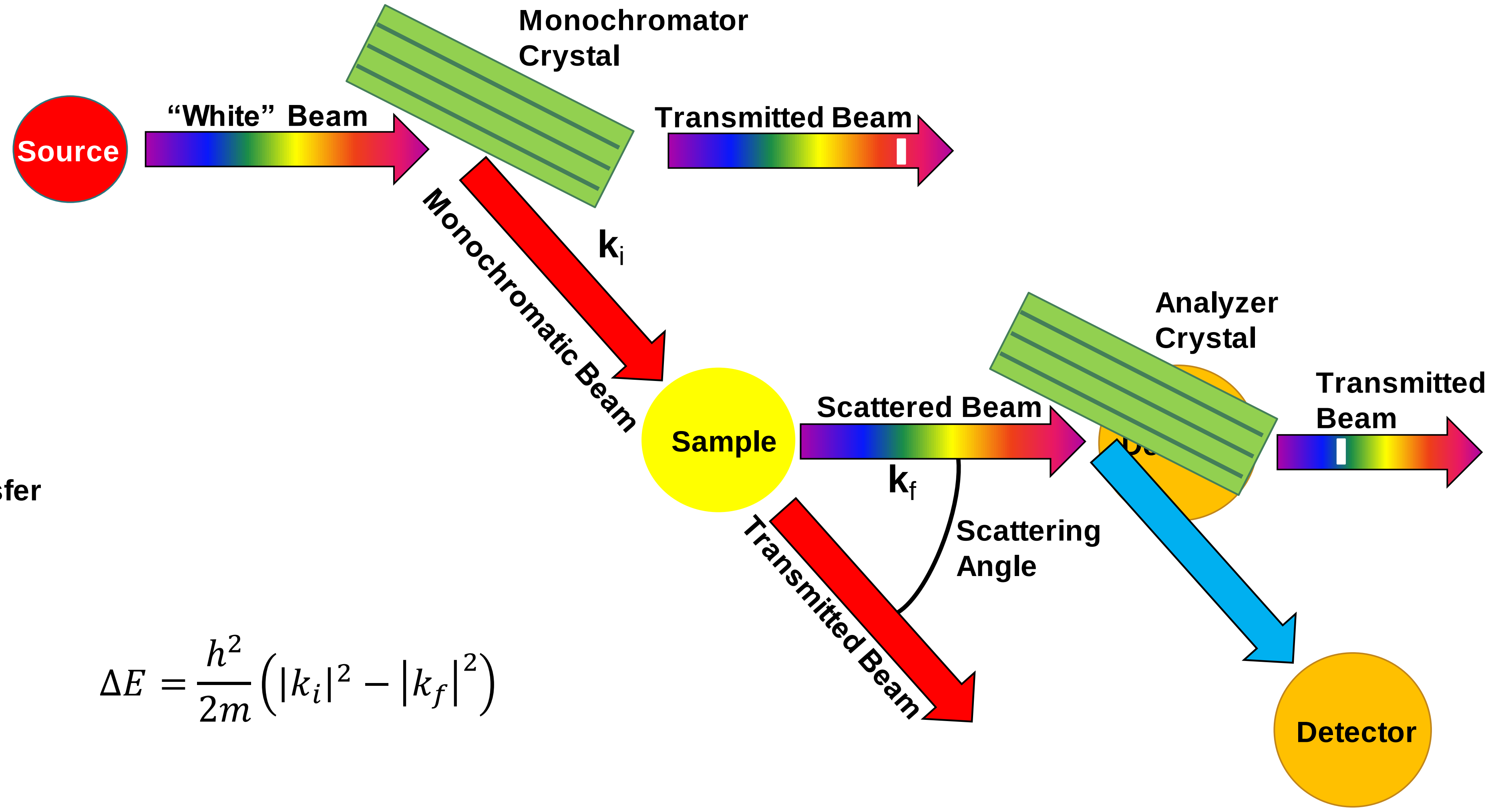
- Two types of sources (continuous and pulsed)
- Two methods for determining the neutron wavevector, k (time-of-flight and diffraction)
- Two types of scattered neutrons (elastic and inelastic)
- Two types of interactions between the neutrons and the sample (nuclear and magnetic)
- Wide range of length scales driven by the science
- The energy of the neutron is coupled to its wavelength and velocity:
  $\lambda^2(\text{Å}^2) \sim 81.81/E(\text{meV})$ and $v^2(m^2/s^2) \sim 191313 \times E(\text{meV})$
- S(Q,E) the scattering properties of the sample depend only on Q and E, not on the neutron wavelength(λ)
- Message: Many different types of neutron scattering instruments are needed because the accessible Q and E ranges depend on the neutron energy and because the resolution and detector coverage have to be tailored to the science for such a signal-limited technique.



Pulsed vs Continuous Neutron Sources



Neutron Scattering Instruments at Continuous Sources Are Typically Based on Diffraction Techniques



Bragg's Law

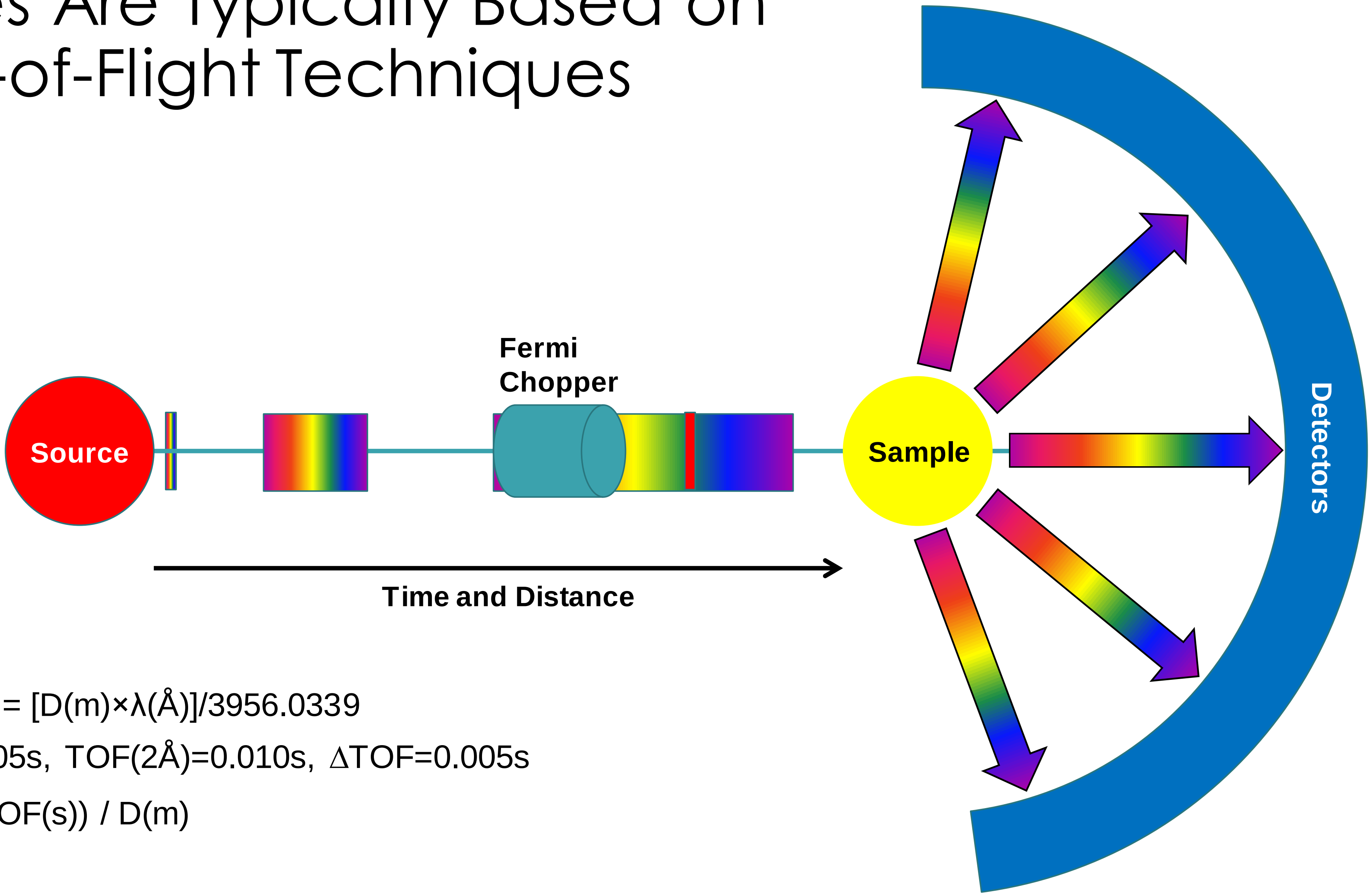
$$n\lambda = 2d \sin\theta$$

Momentum Transfer

$$\vec{\boldsymbol{Q}} = \vec{\boldsymbol{k}}_i - \vec{\boldsymbol{k}}_f$$

$$\Delta E = \frac{h^2}{2m}\left(|k_i|^2 - |k_f|^2\right)$$

Neutron Scattering Instruments at Pulsed Sources Are Typically Based on Neutron Time-of-Flight Techniques



v(1.8Å) = 2187m/s

TOF(s) = D(m)/v(m/s) = [D(m)×λ(Å)]/3956.0339

D=20m, TOF(1Å)=0.005s, TOF(2Å)=0.010s, ΔTOF=0.005s

λ(Å) = (3956.0339 * TOF(s)) / D(m)

Neutron Optics

The following neutron optical components are typically used to construct a neutron scattering instrument

- **Monochromators / Analyzers:** Monochromate or analyze the energy of a neutron beam using Bragg's law
- **Choppers:** Define a short pulse of neutrons or select a small band of neutron energies
- **Guides / Mirrors:** Allow neutrons to travel large distances without suffering intensity loss
- **Polarizers / Spin Manipulators**: Filter and manipulate the neutron spin
- **Collimators:** Define the direction of travel of the neutrons
- **Detectors:** Neutron position (and arrival time for TOF) is recorded. Neutrons are typically detected via secondary ionization effects.

Instrument Resolution

- Uncertainty in the neutron wavelength and direction limit the precision that Q and E can be determined
- For scattering, the uncertainty comes from how well k_i and k_f can be determined
- For TOF, the uncertainty primarily comes from not knowing the exact start time for each neutron
- The total signal observed in a scattering experiment is proportional to the phase space volume within the elliptical resolution volume – the better the resolution, the lower the count rate

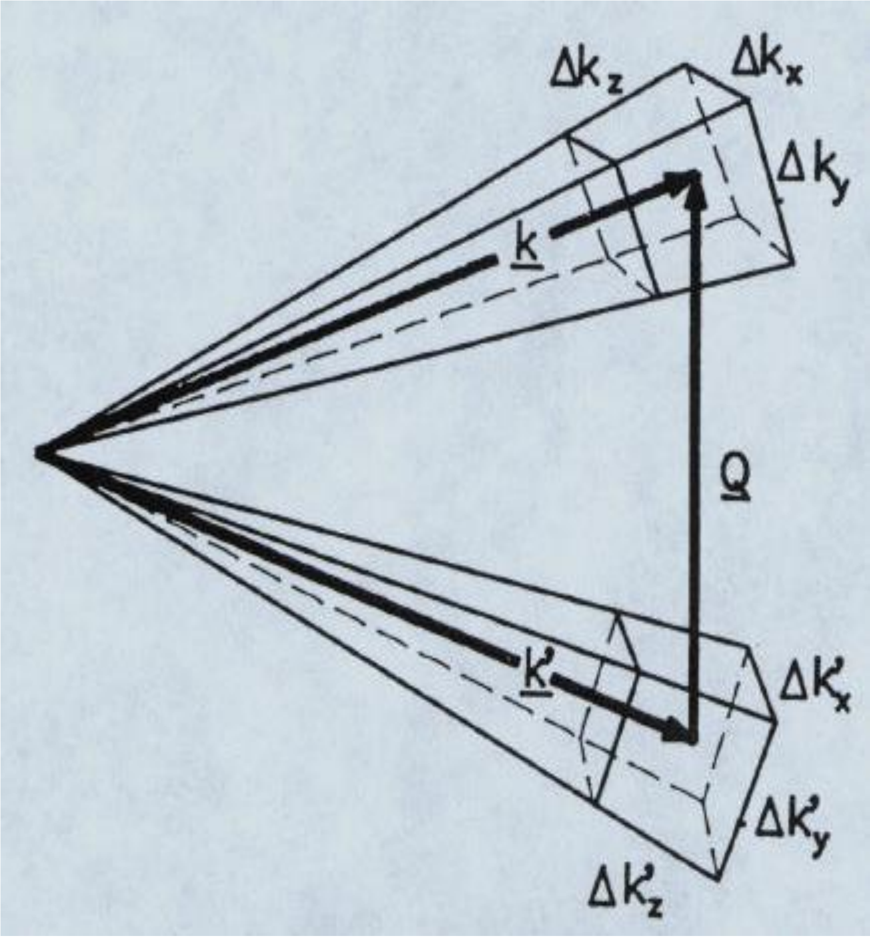
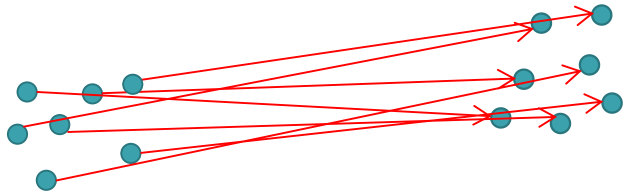
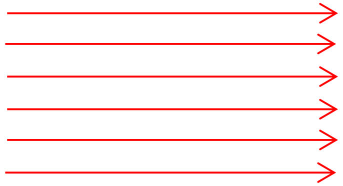


Figure borrowed from Roger Pynn

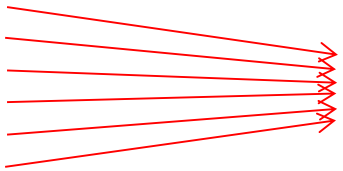
Liouville's Theorem

- In the geometrical-optics the propagation of neutrons can be represented as trajectories in a six-dimensional **phase space** (p, q), where the components of q are the generalized coordinates and the components of p are the conjugate momenta.
- Simply stated, Liouville's Theorem says that phase space volume is conserved.
- Translation: It costs flux to increase resolution and it costs resolution to increase flux.
- There is no way to win!





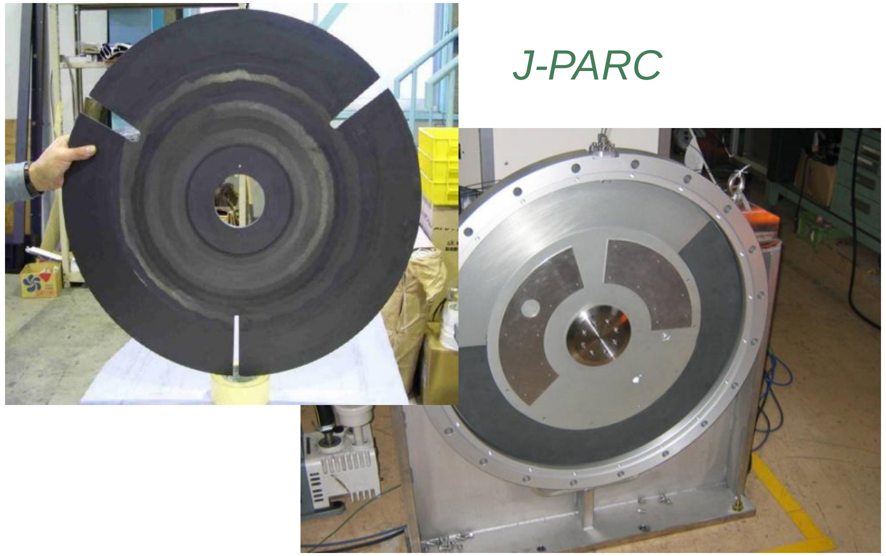
Parallel



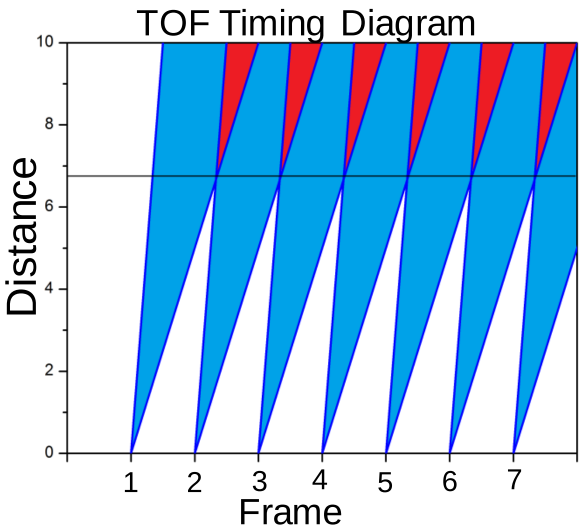
Converging

Choppers and Velocity Selectors

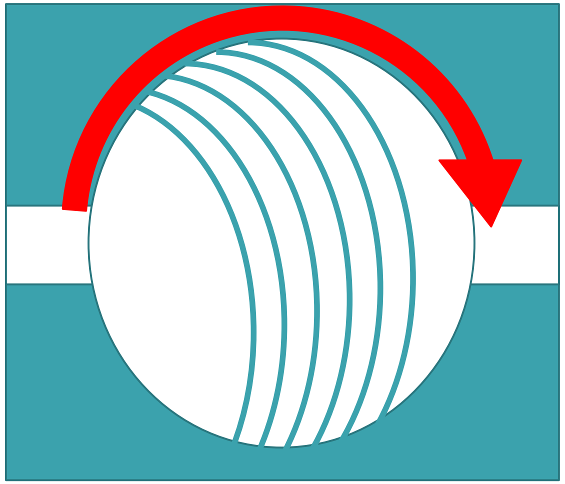
Disk Chopper



J-PARC



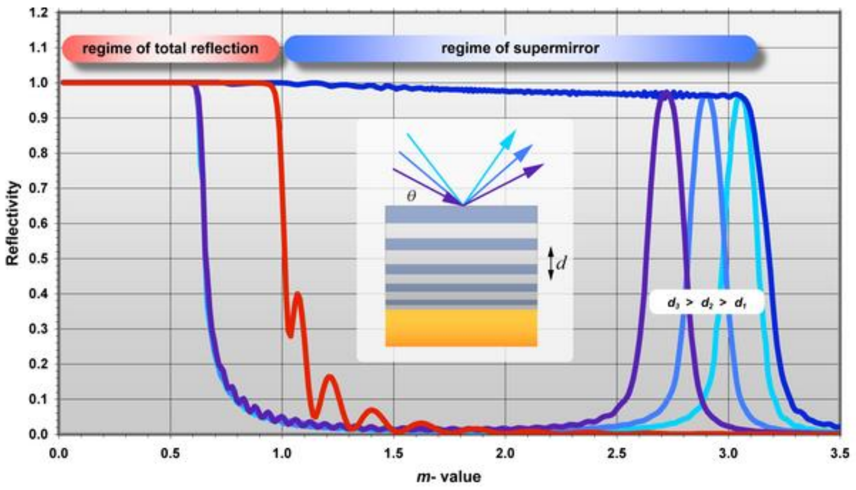
Fermi Chopper

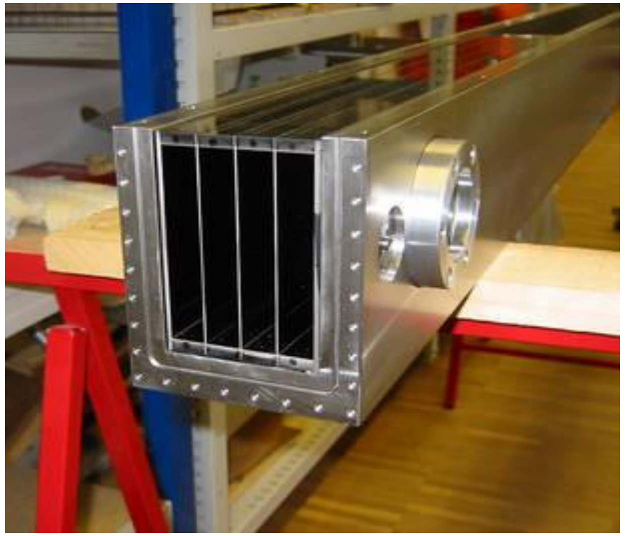


Velocity Selector

Astrium

Neutron Mirrors and Supermirrors / Neutron Guides



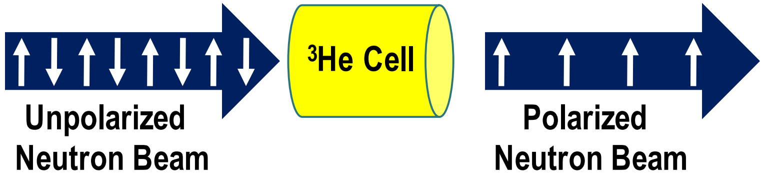


Multichannel Curved Guide
Fabricated by Swiss Neutronics

80m Guide for HRPD at J-PARC
Fabricated by Swiss Neutronics

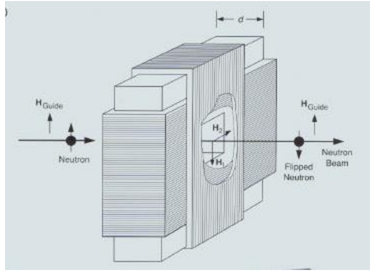
Guide Installation at ISIS

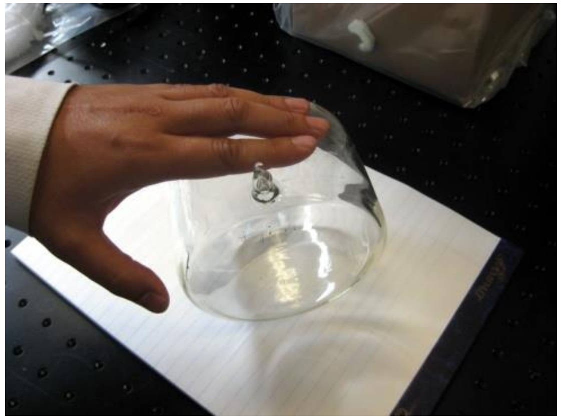
Polarizers and Spin Manipulators



Heussler Monochromator
AlCuMn

Larmor Precession Flipper



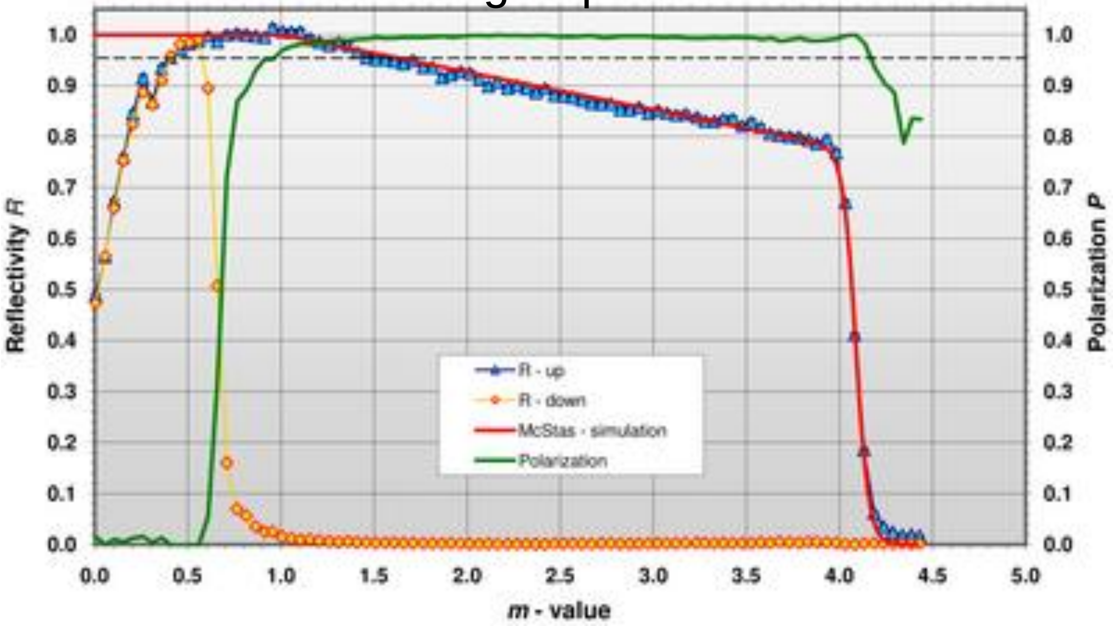


^{3}He Spin Filters

Spherical Neutron Polarimetry

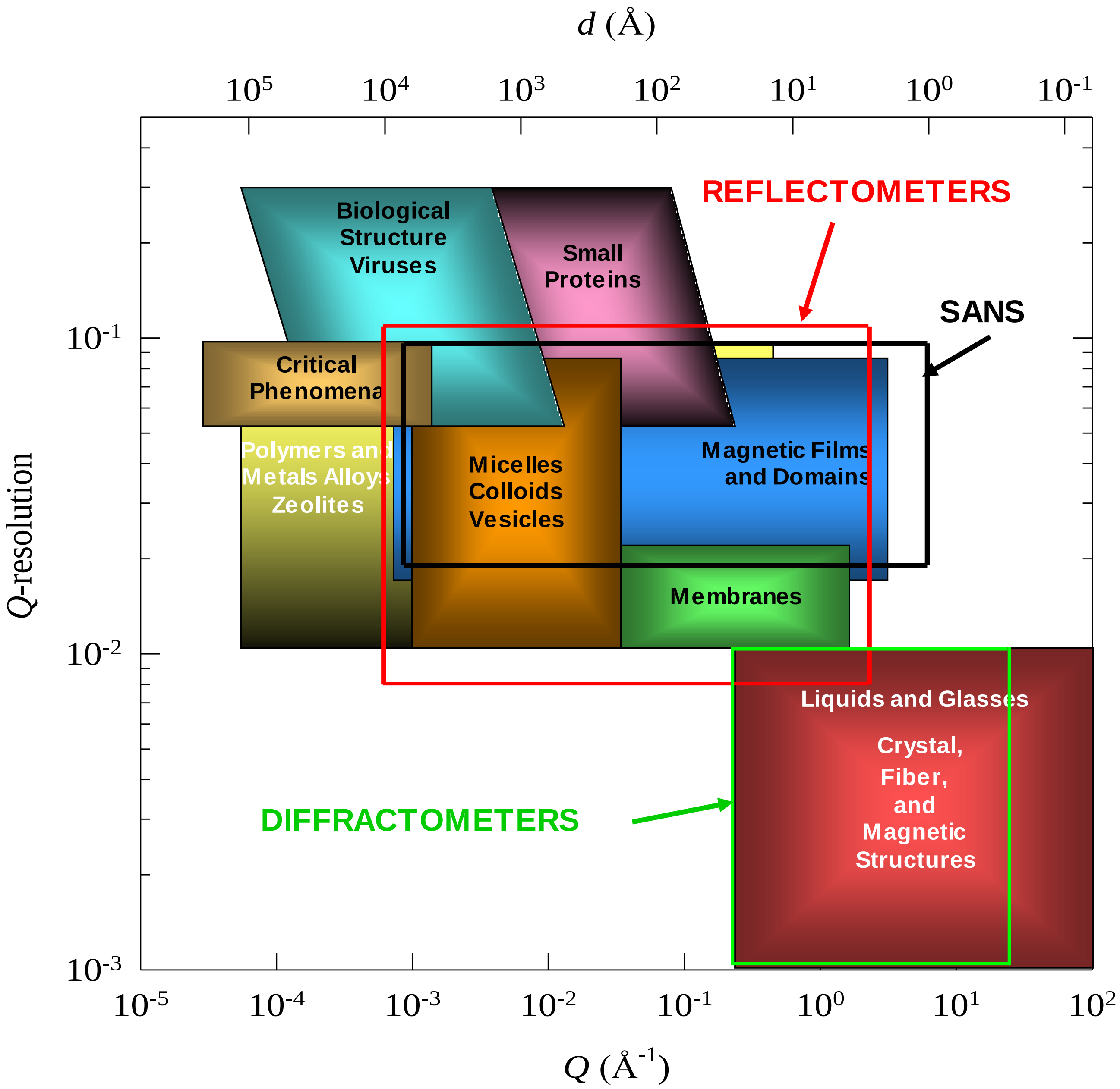
POLI-HEiDi at FRMII

Polarizing Supermirrors

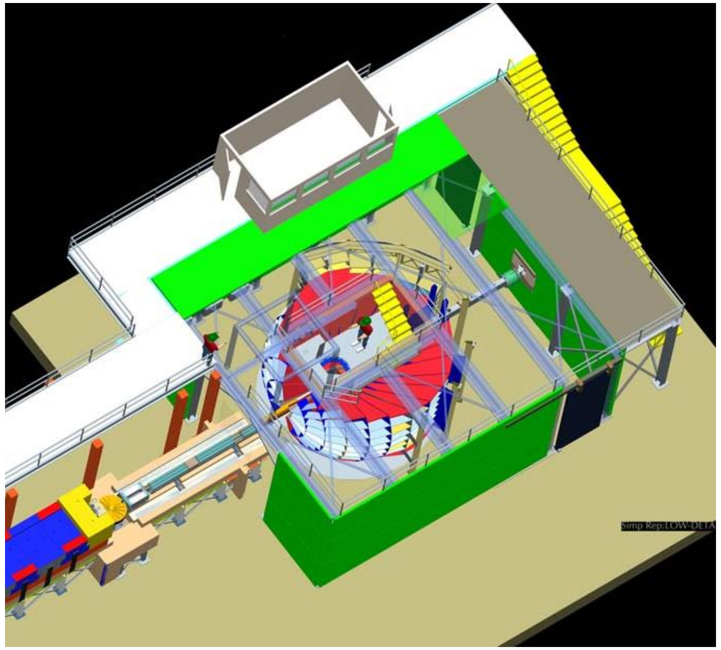


Elastic Neutron Scattering Instruments

- Elastic instruments include:
  - Powder diffraction
  - Single Crystal diffraction
  - SANS (typical)
  - Reflectometry
- Used to determine the average structure of materials (i.e. how the atoms are arranged)



TOF Powder Diffractometer: POWGEN (SNS)

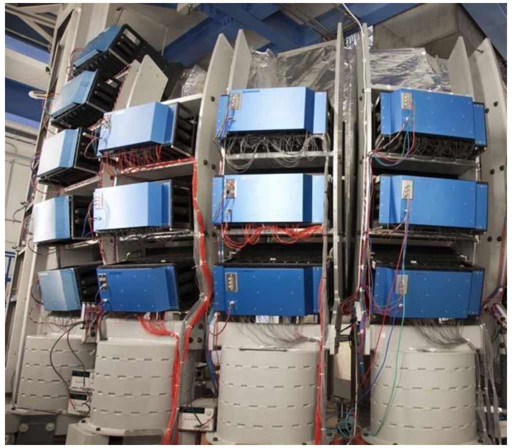


$$d = \frac{\lambda}{2\sin\theta} = \frac{2\pi}{Q}$$

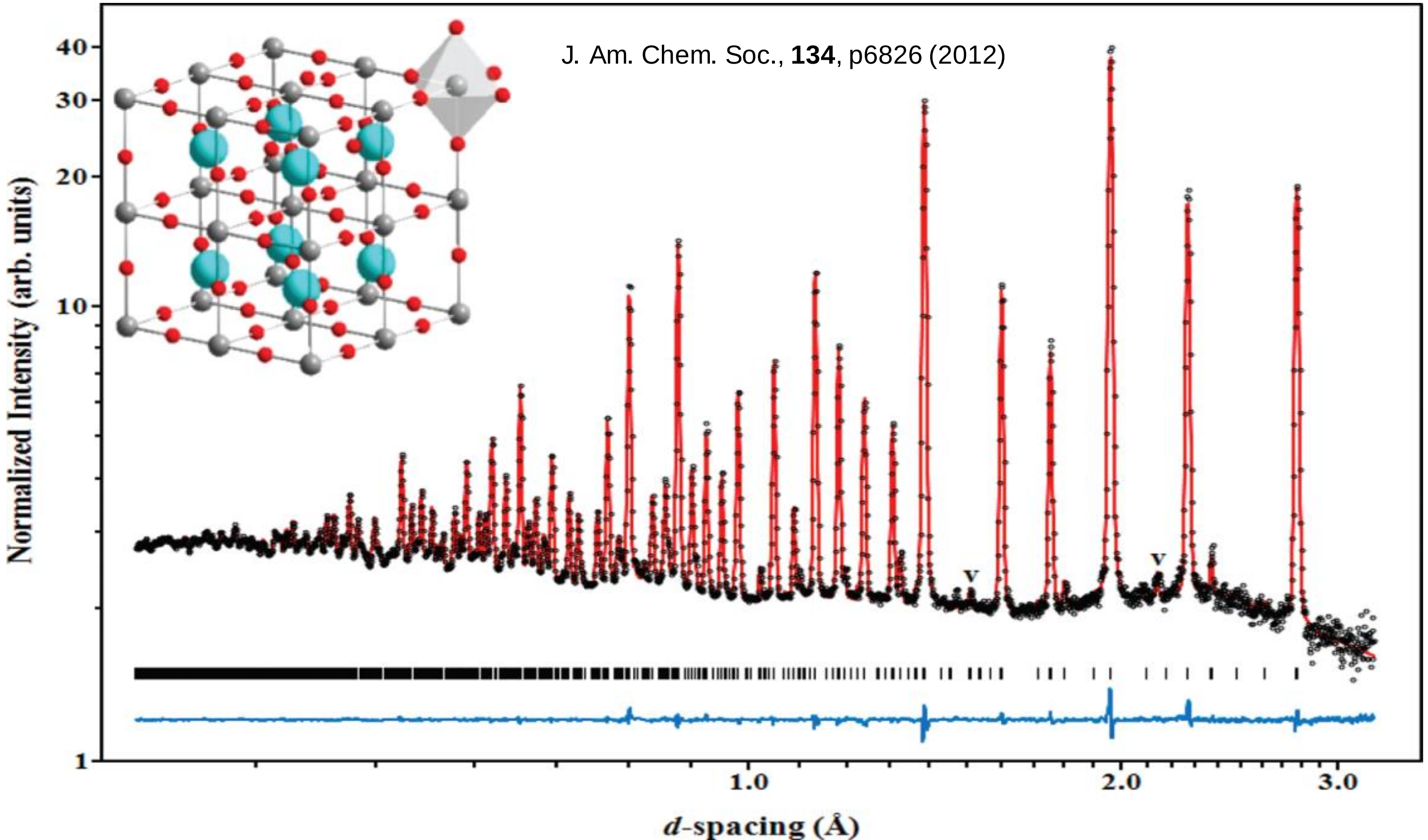
$$d = \frac{(3956.0339 * TOF)/D}{2\sin\theta}$$

$$\lambda(\text{Å}) = (3956.0339 * TOF(s)/D(m)$$

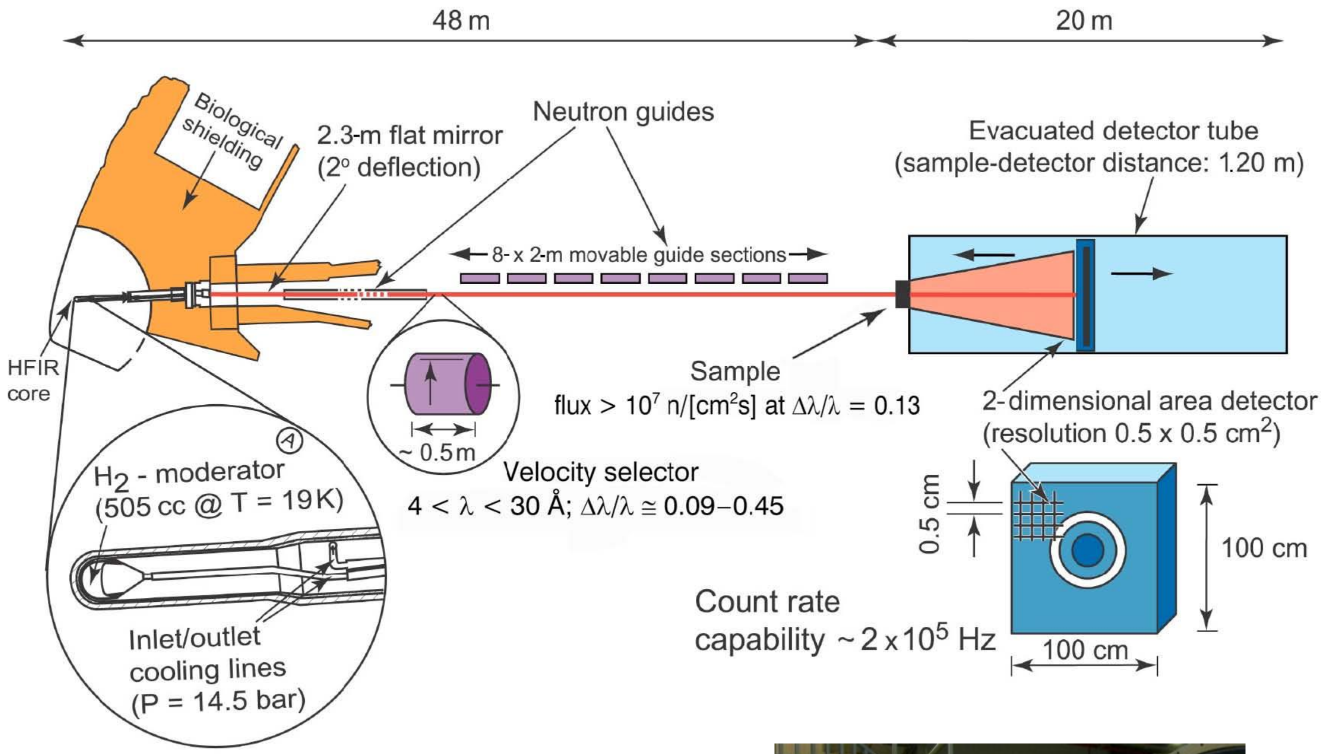
For POWGEN D = 64.5m

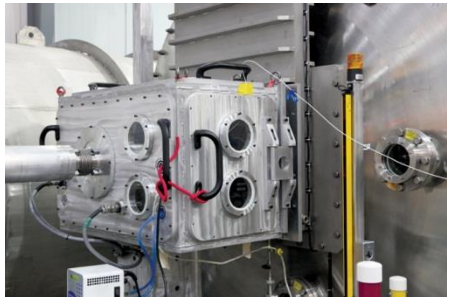


$Sr_2Fe_{1.5}Mo_{0.5}O_6$, Electrode Material for Solid Oxide Fuel Cells

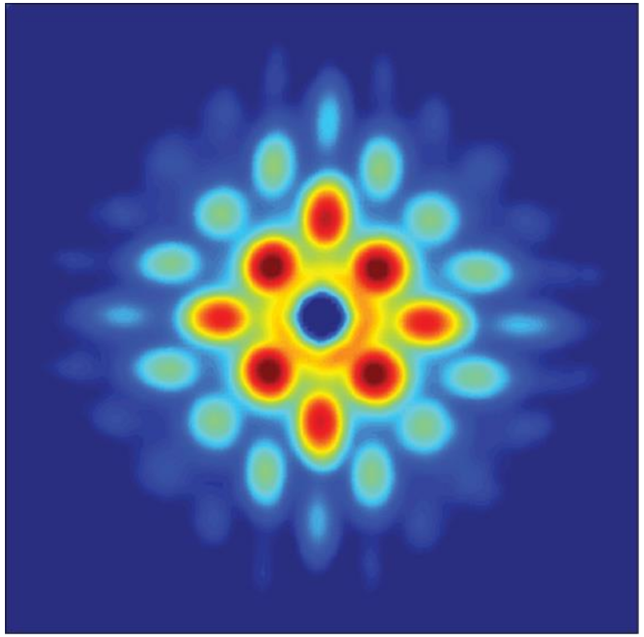


Small Angle Neutron Scattering (SANS)



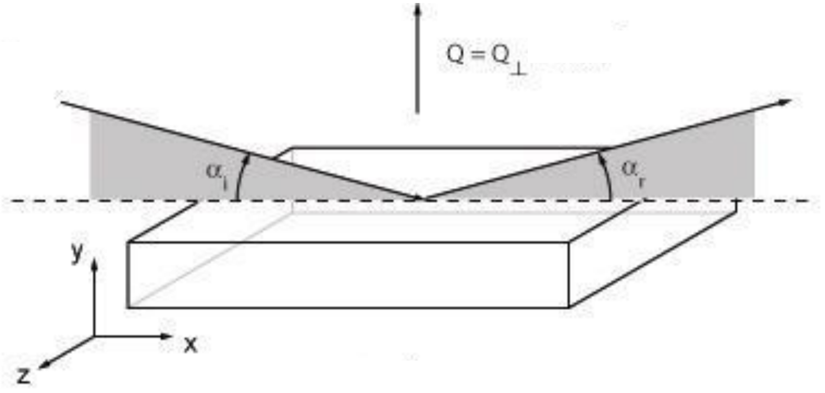


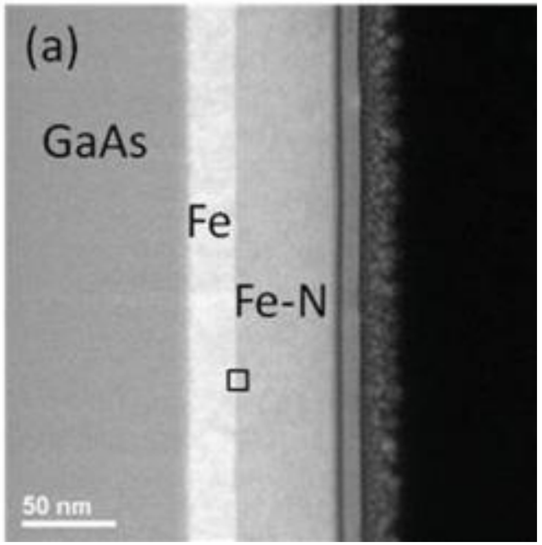
$TmNi_2B_2C$ Vortex Lattice



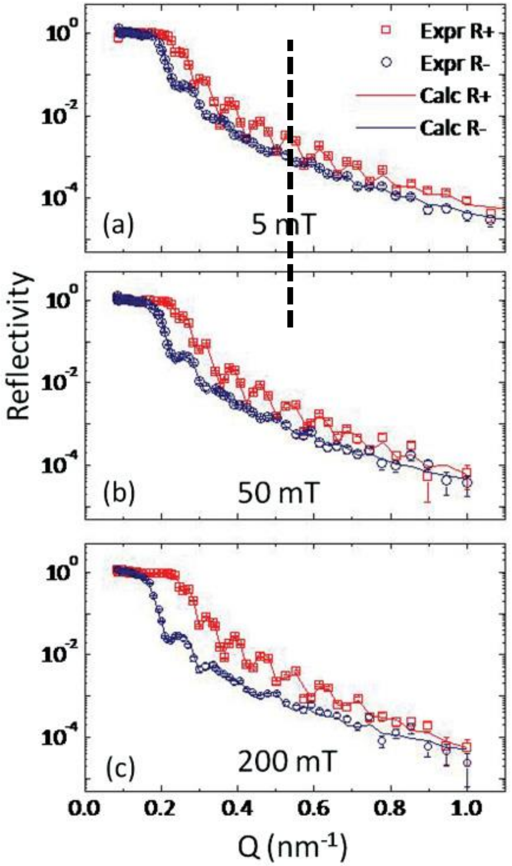
PHYS REV B **86**, 144501 (2012)

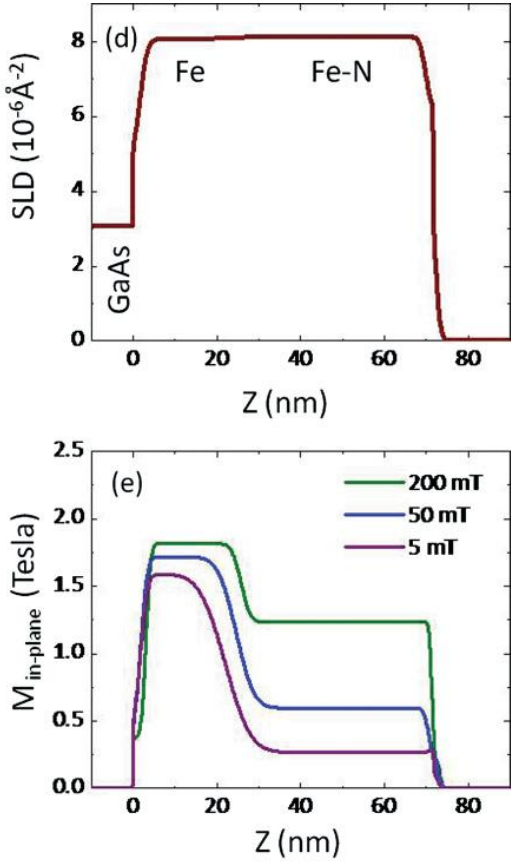
Magnetism Reflectometer (SNS)



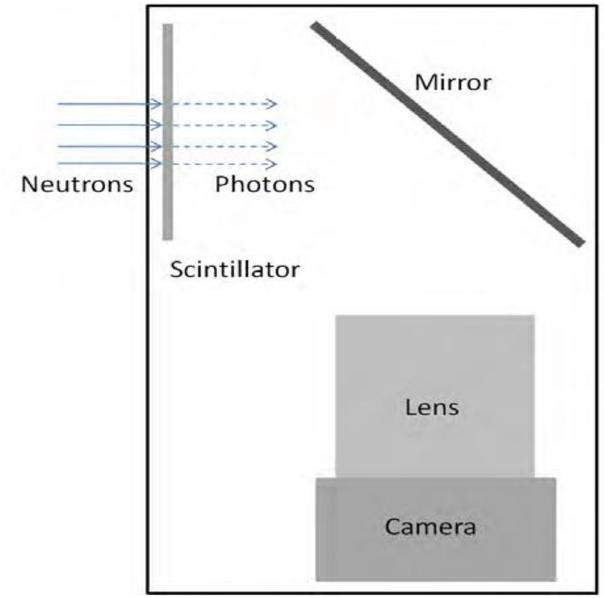


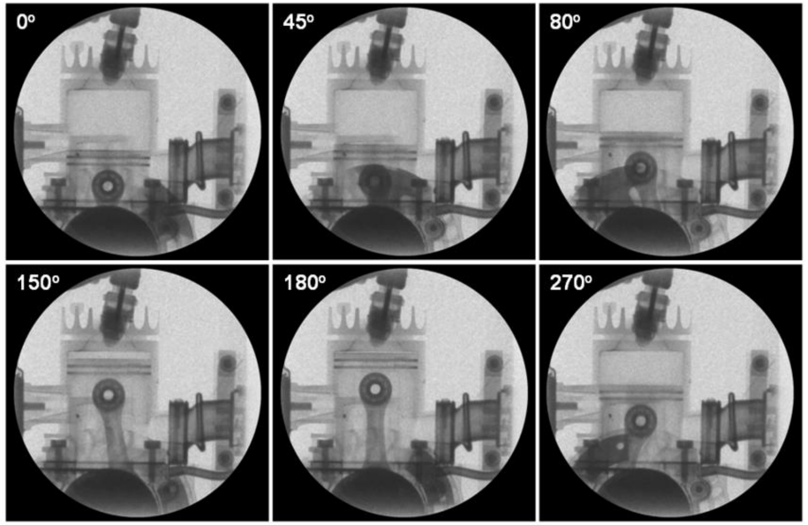
PHY REV B **84**, 245310 (2011)

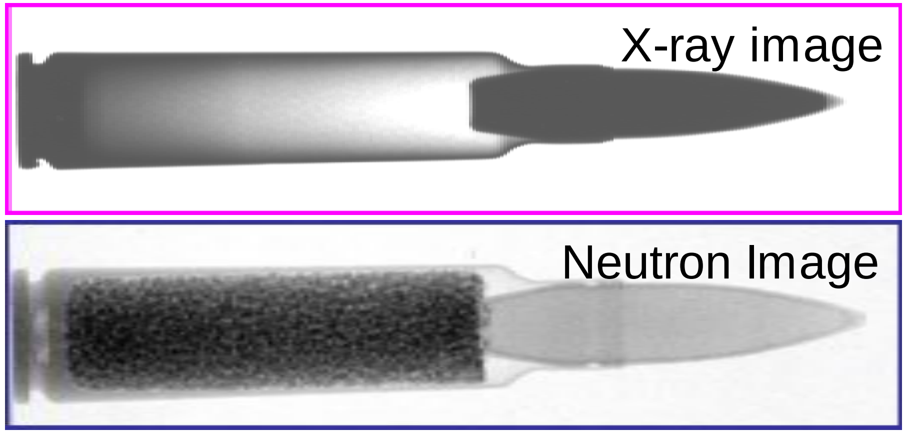




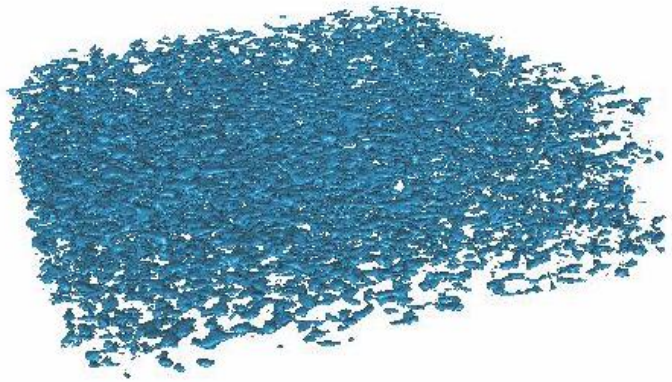
Neutron Imaging





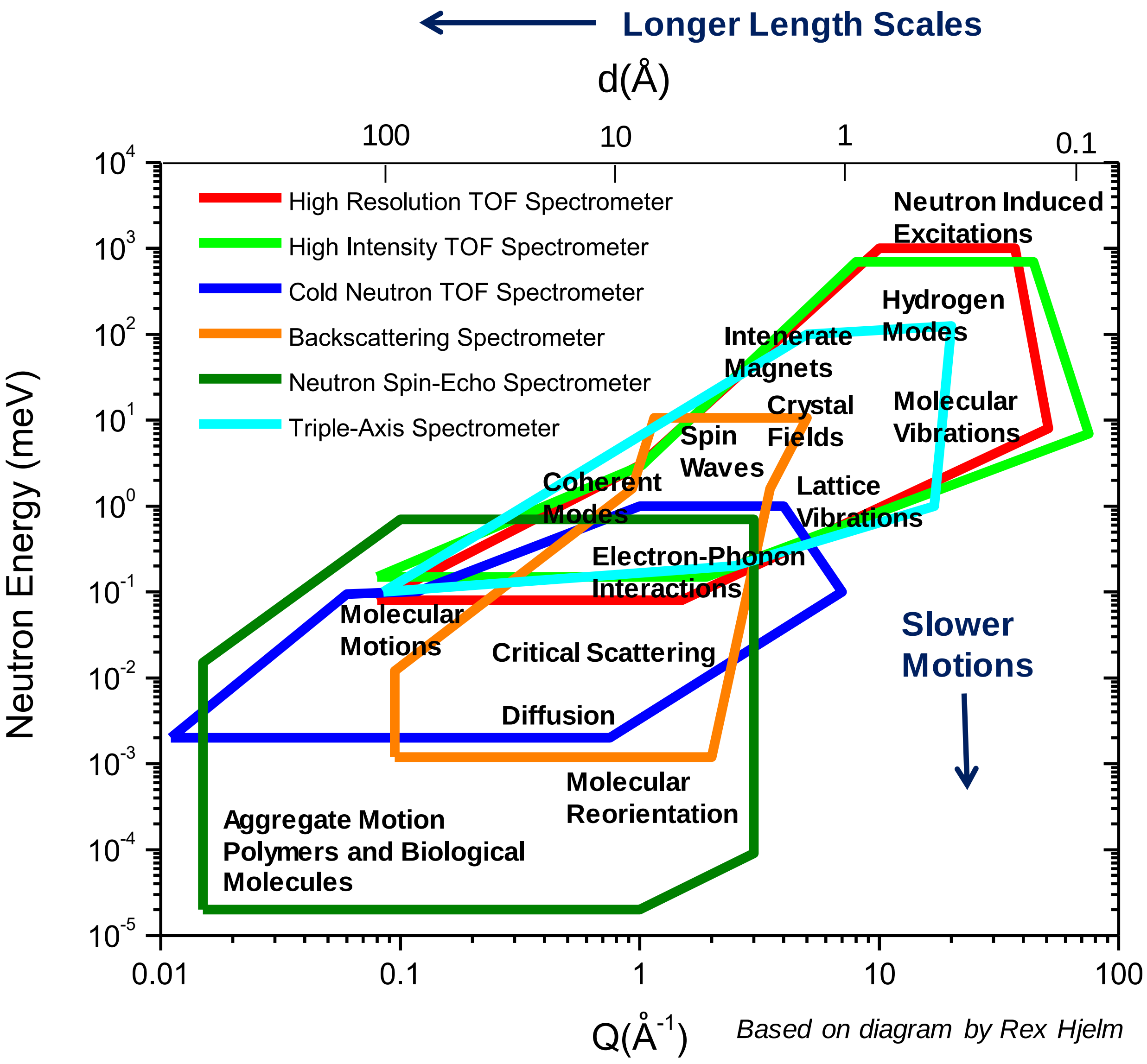


Carbon foam matrix in a Li battery (H. Bilheux and S. Voisin)



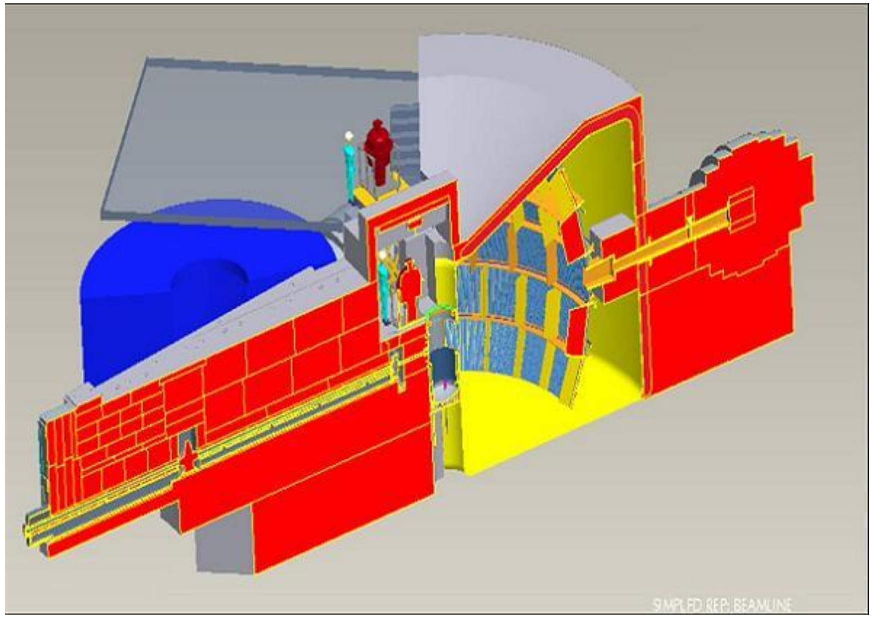
Inelastic Neutron Scattering Instruments

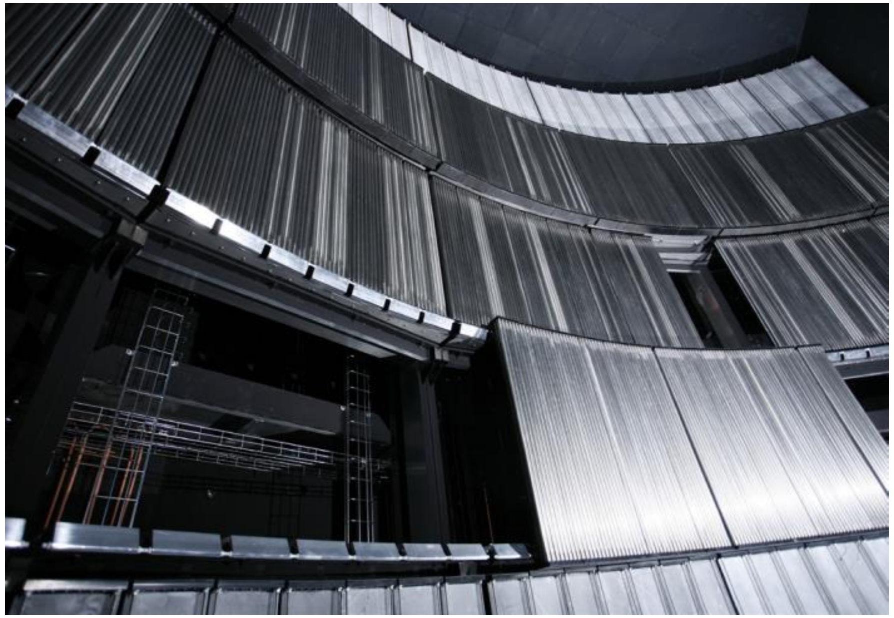
- Inelastic instruments include:
  - Direct Geometry TOF Spectrometers
  - Indirect Geometry TOF Spectrometers
  - Triple-Axis Spectrometers
  - Backscattering Spectrometers
  - Neutron Spin-Echo Spectrometers
- Used to study dynamics such as phonons, magnons, and diffusion (i.e. what the atoms are doing)



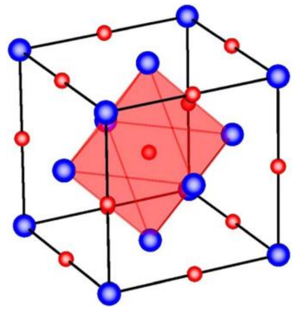
Based on diagram by Rex Hjelm

SEQUOIA: A Direct Geometry TOF Spectrometer at the SNS

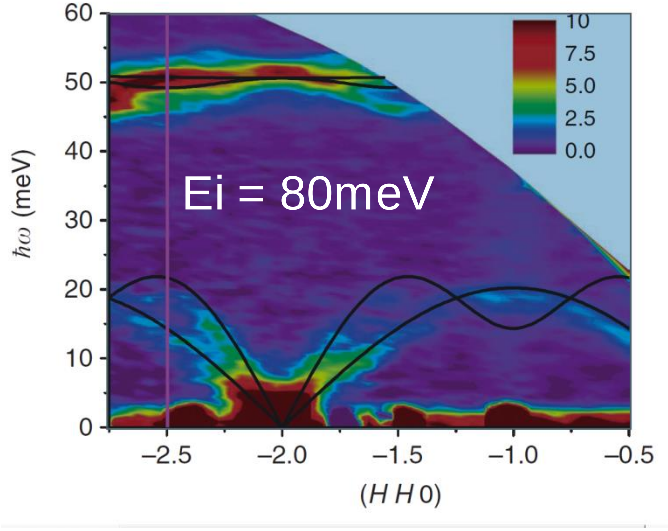


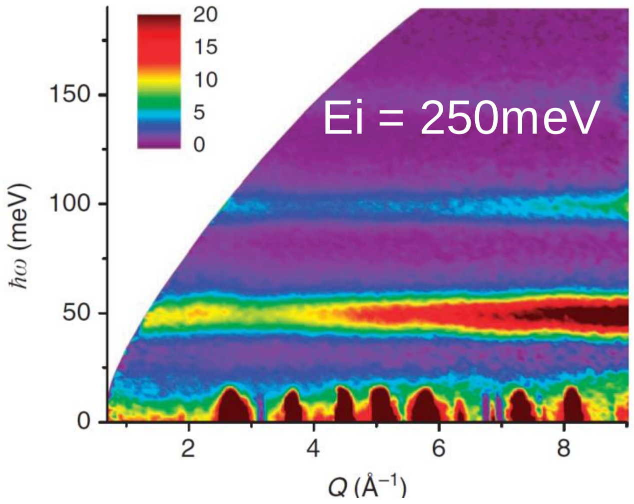


Quantum oscillations of nitrogen atoms in uranium nitride

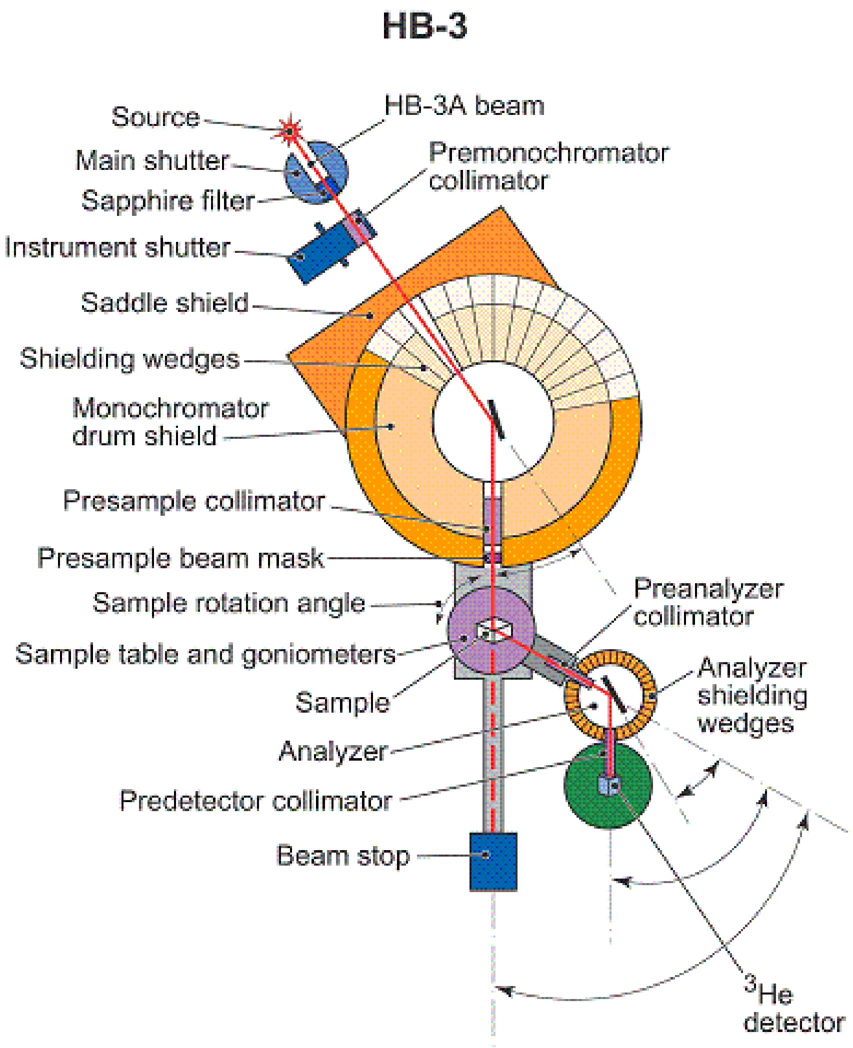


Nature Communications v**3**, p1124 (2012)

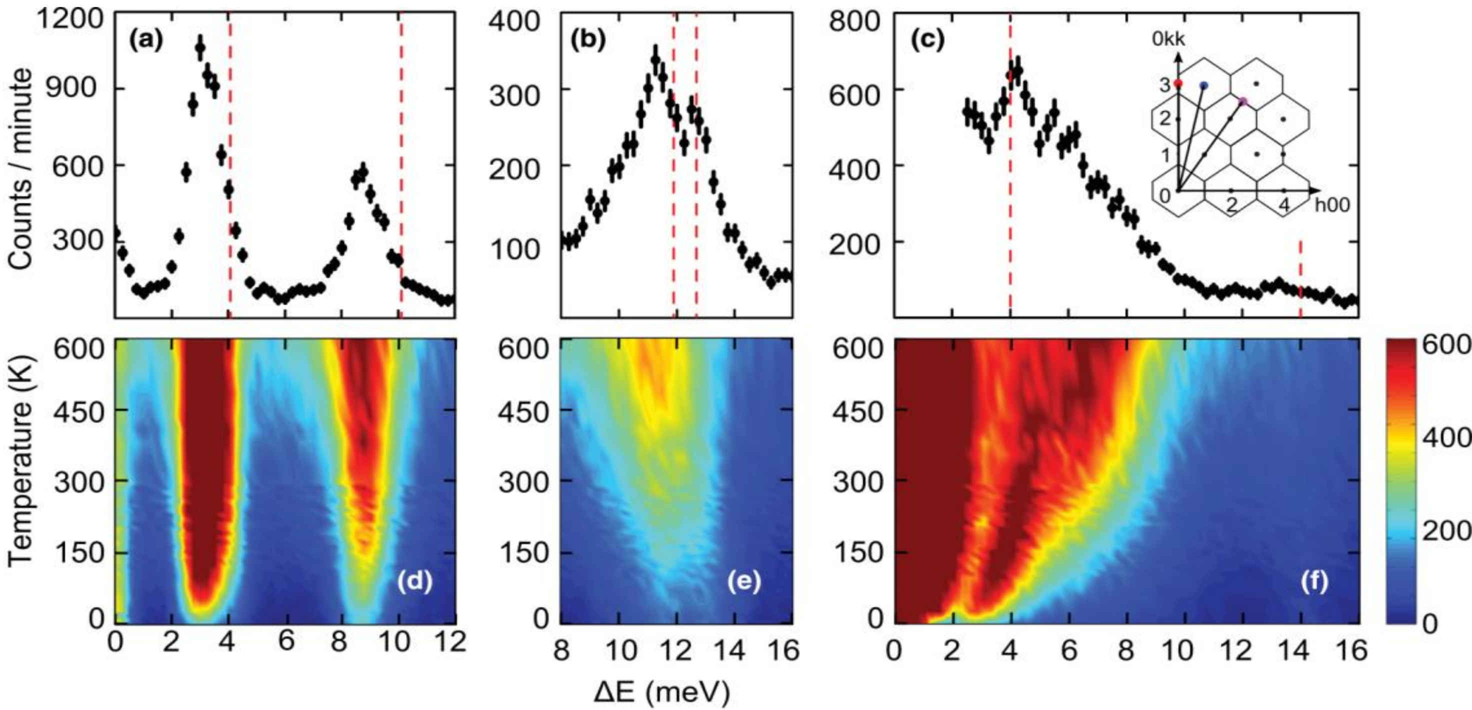




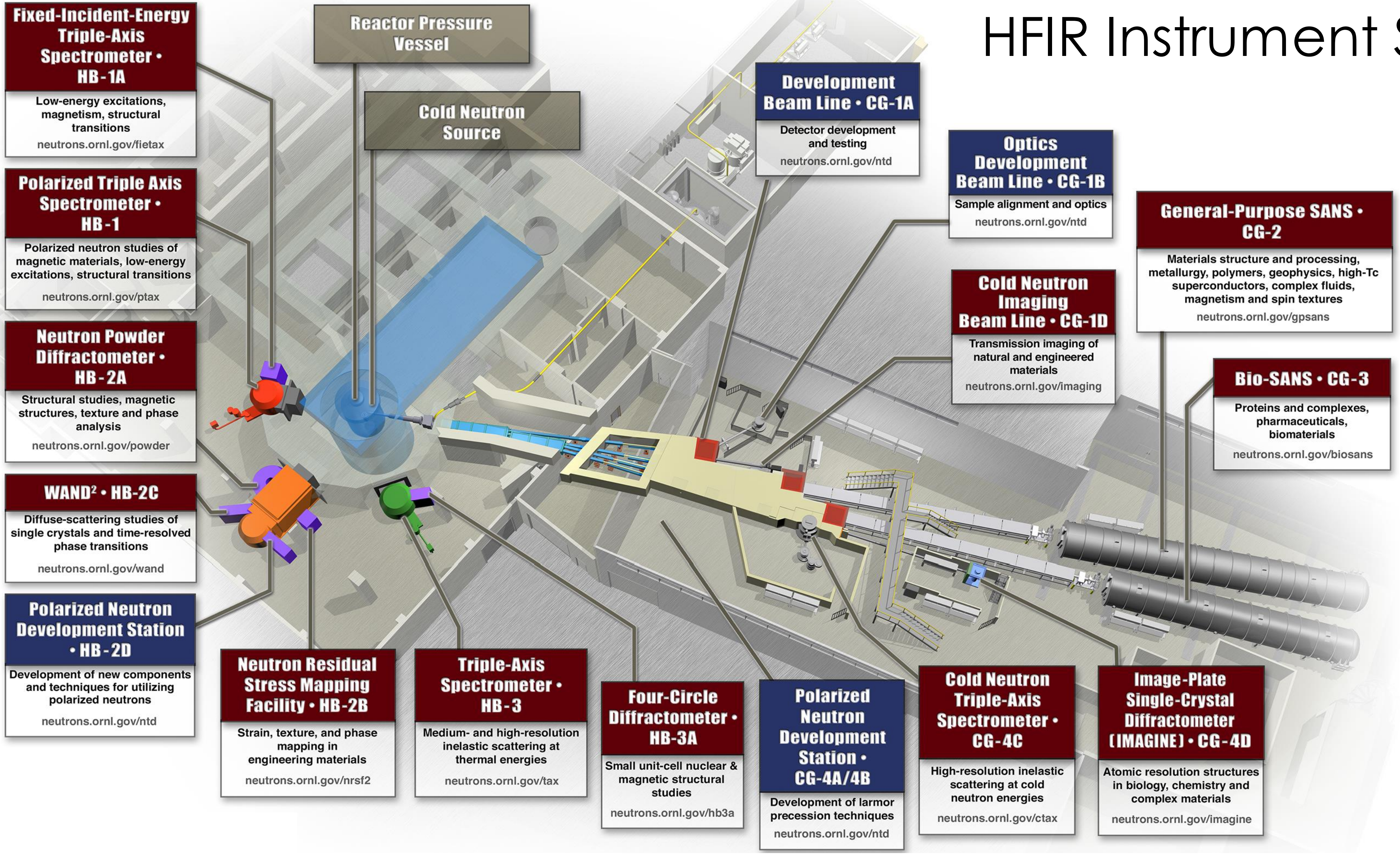
Triple-Axis Spectrometer



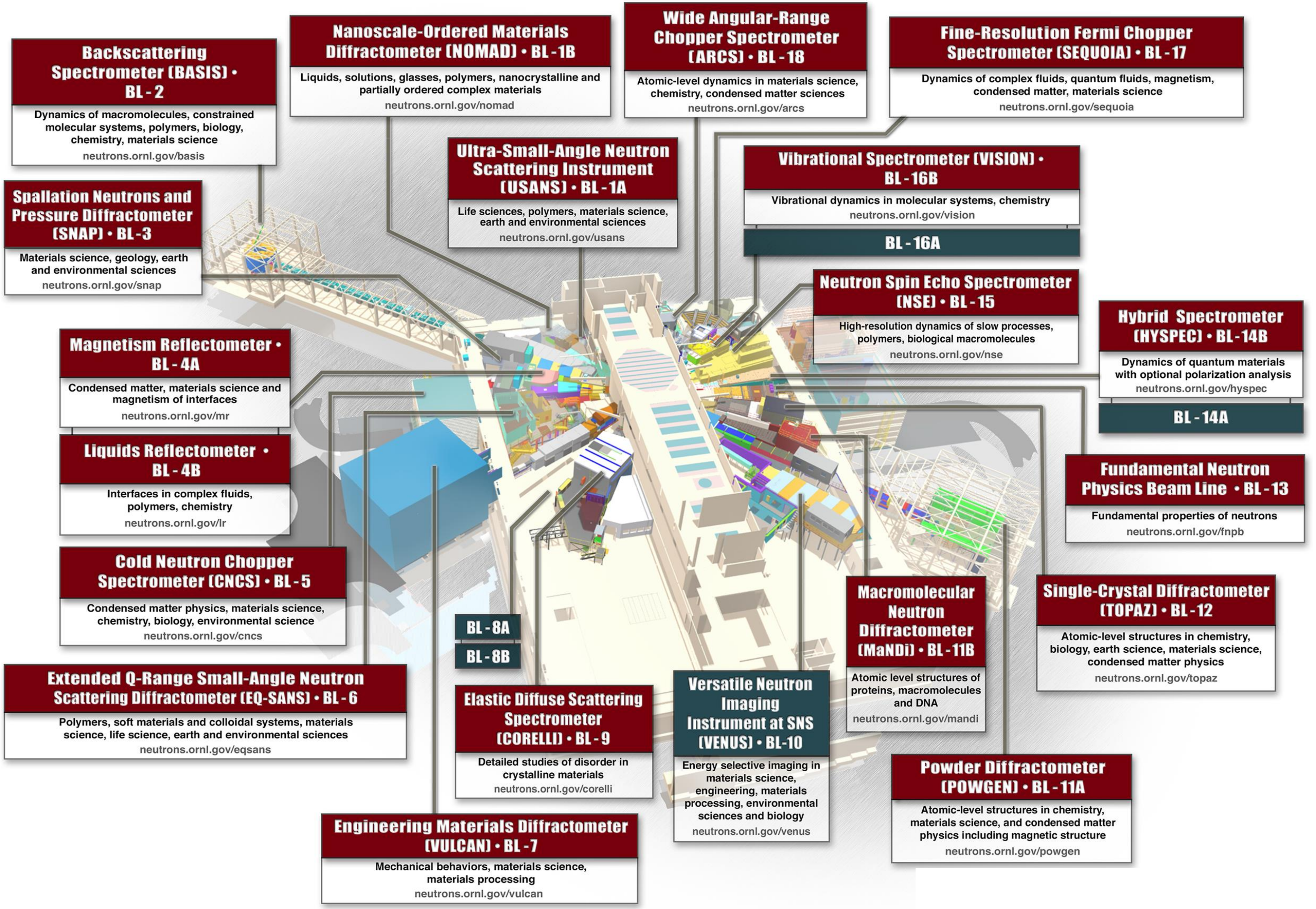
Lattice Dynamics of PbTe PHYS REV B **86**, 085313 (2012)



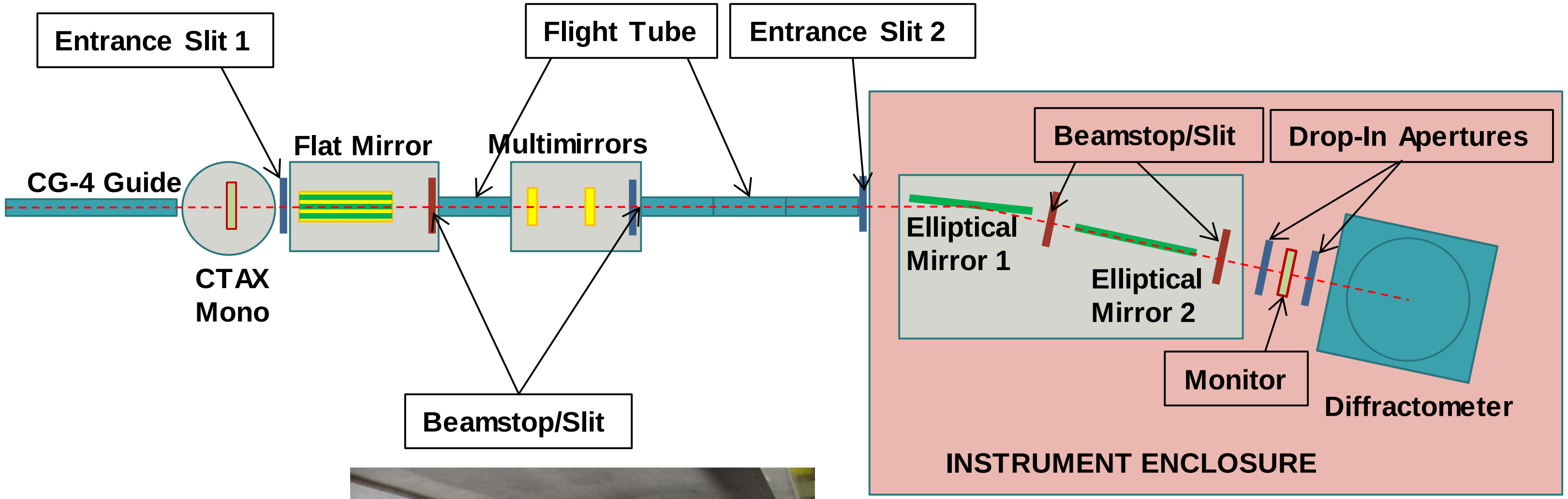
HFIR Instrument Suite



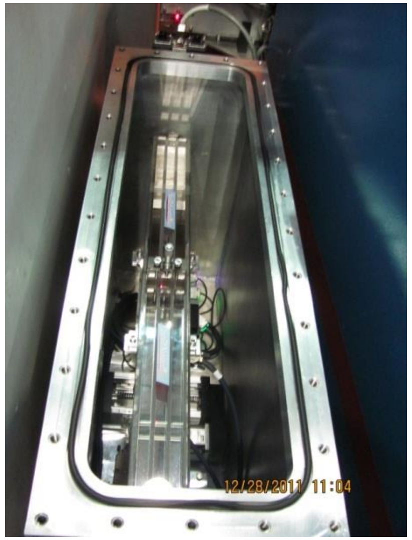
SNS Instrument Suite

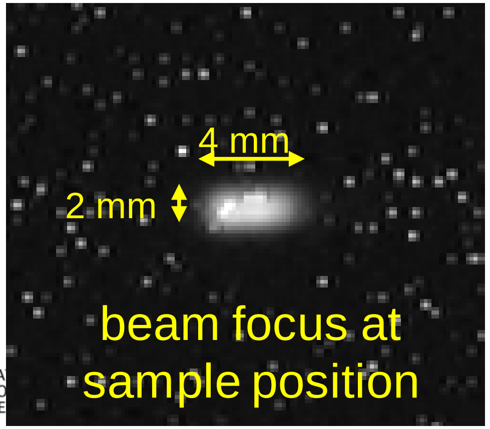


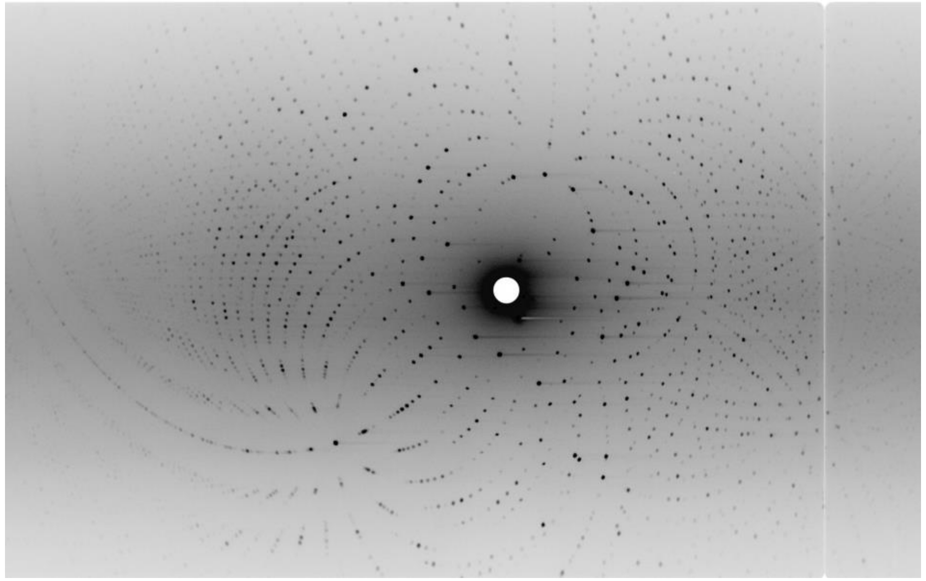
Advanced Neutron Optics: IMAGINE



Short wavelength filter @ 2.0, 2.78, and 3.33 Å
Long wavelength filter @ 3.0, 4.0, and 4.5 Å
Elliptical mirrors for focusing the beam



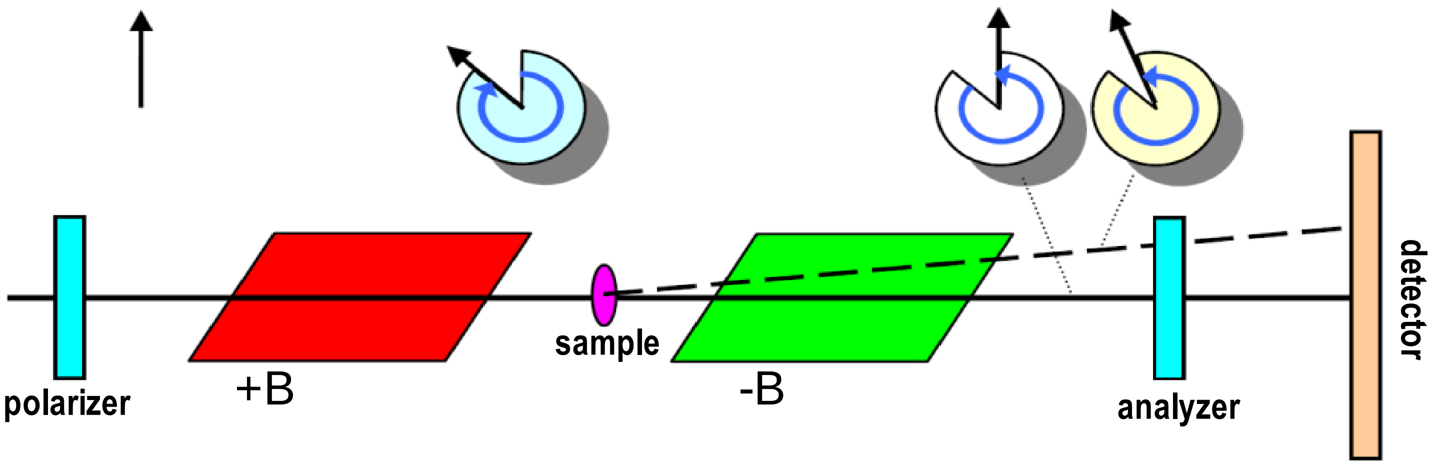




Future Instruments: Larmor Pression

Spin-Echo Scattering Angle Measurement:

The neutron spin precesses through two magnetic regions with opposite field directions. For scattered neutrons the path-length through the two regions is different resulting in a net change in the spin procession.



- Real space correlation lengths up to 20 microns (and beyond?)
- Does not require tight collimation for high resolution
- Can be used to probe the in-plane correlations of thin films and interfaces.

Concluding Remarks

- Instrument design is driven by the needs of the scientific community coupled with the source capabilities along with advances in neutron optics and detectors.
- In the near term instrument development will be primarily focused on:
  - Focusing optics
  - Neutron transport
  - Polarization
  - Detectors
  - Instrument development infrastructure (computer simulations)
  - New techniques and applications