The Development of Polarized ^{3}He Neutron Spin Filters at the Oak Ridge National Laboratory

Chenyang Jiang (Peter)

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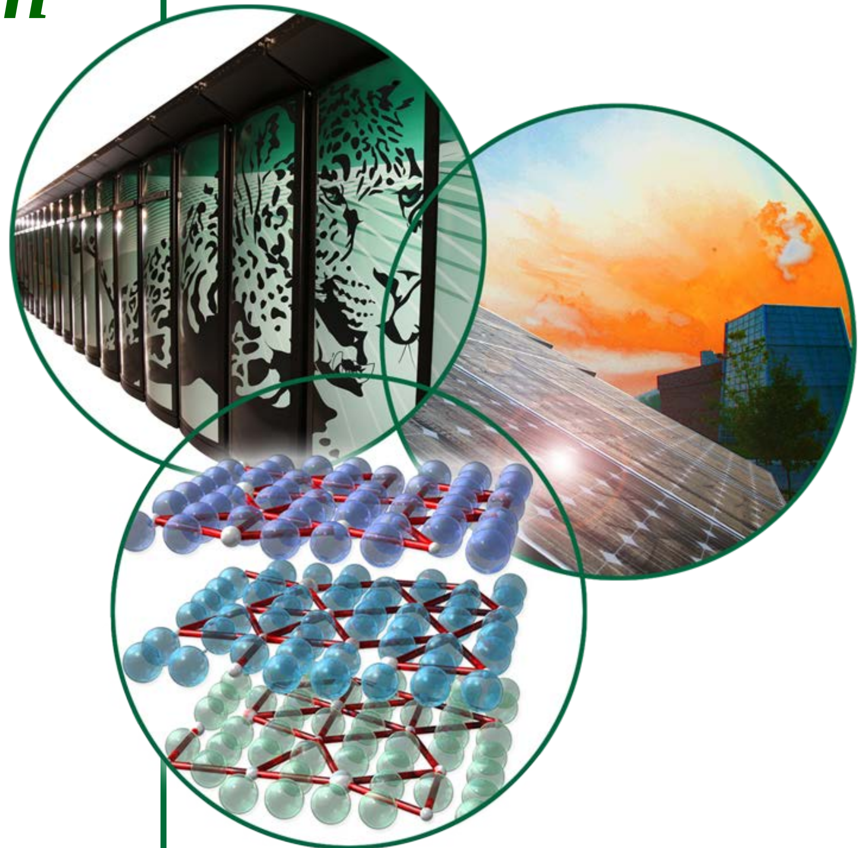


HFIR

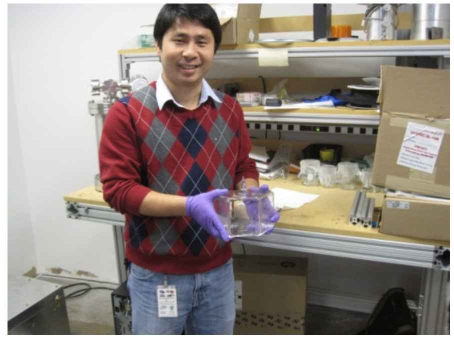
SNS
SPALLATION NEUTRON SOURCE

U.S. DEPARTMENT OF ENERGY

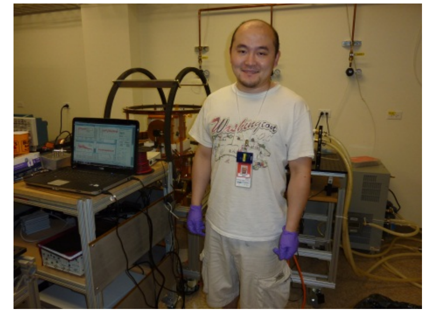
OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

^{3}He Team at ORNL

Lee Robertson



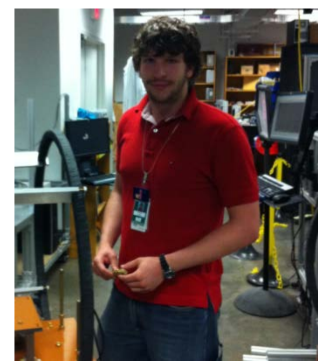
Tony Tong



Peter Jiang

Mike Fleenor

Dan Brown

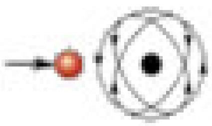


Benjamin Kadron

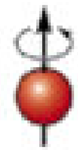
Outline:

- Neutron Scattering in general
- Polarized Neutron Scattering
- Polarized ^{3}He in general
- *ex situ* polarized ^{3}He system
- *in situ* polarized ^{3}He system
- Polarized ^{3}He filling station

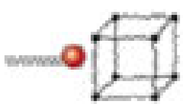
Neutron Properties

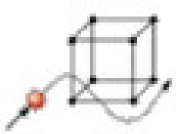


- Neutral
- Penetrating, probe nuclei
- Non-destructive



- Spin 1/2
- Magnetic moment
- Can be polarized

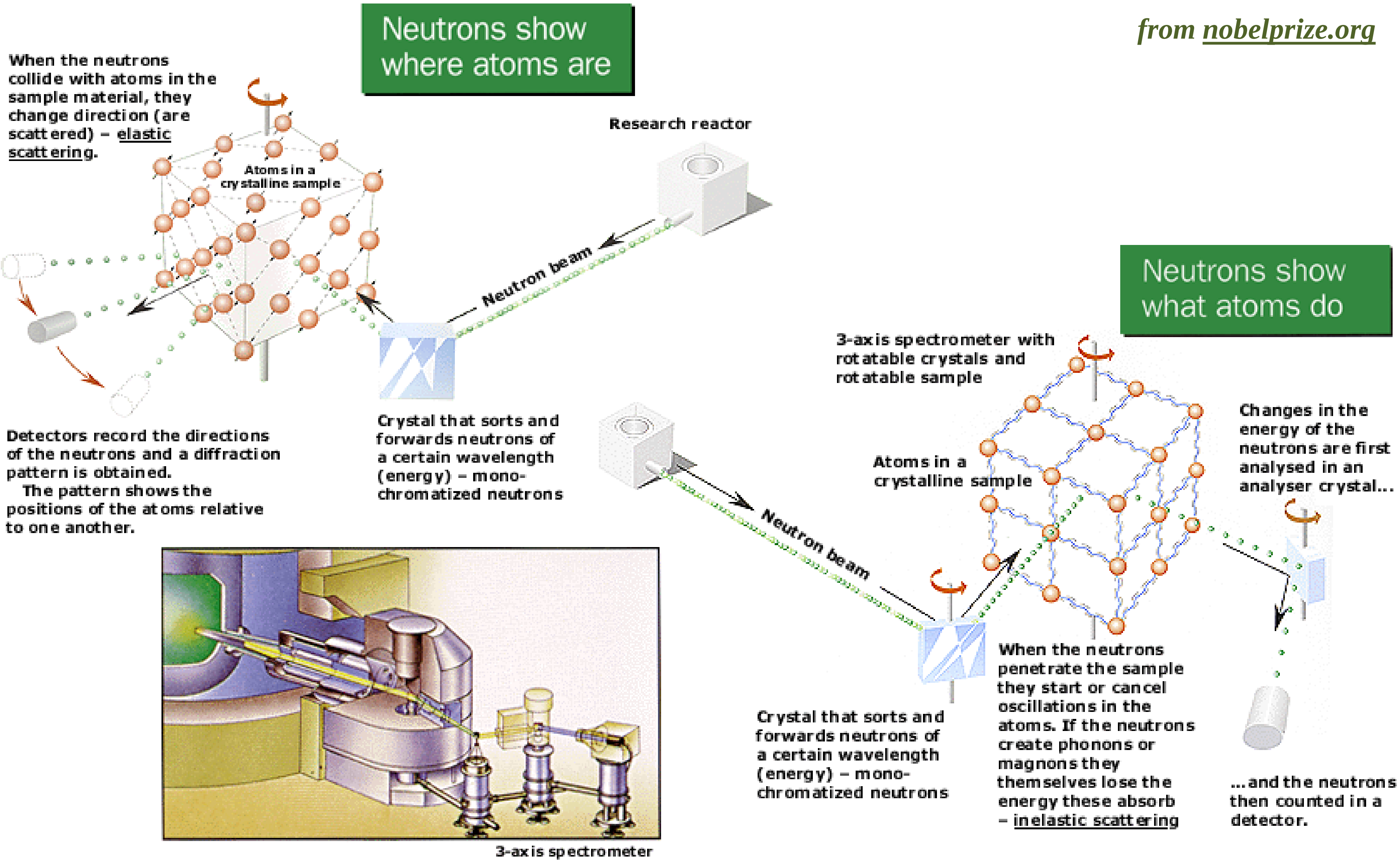




- Energy similar to excitations in solids
  - ➢ Molecular vibrations
  - ➢ Atomic motion
  - ➢ Lattice modes
- Wavelengths similar to interatomic spacings
  - ➢ Crystal structures
  - ➢ Huge probe range from 10^{-13} to 10^{-4} cm

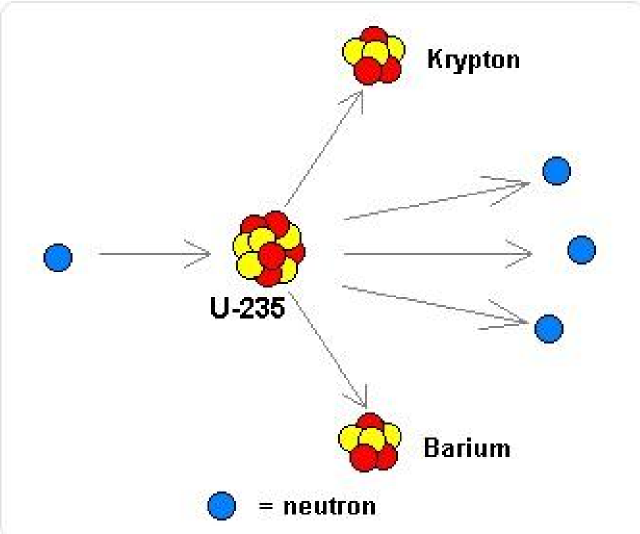
The 1994 Nobel Prize in Physics –Shull & Brockhouse

from nobelprize.org

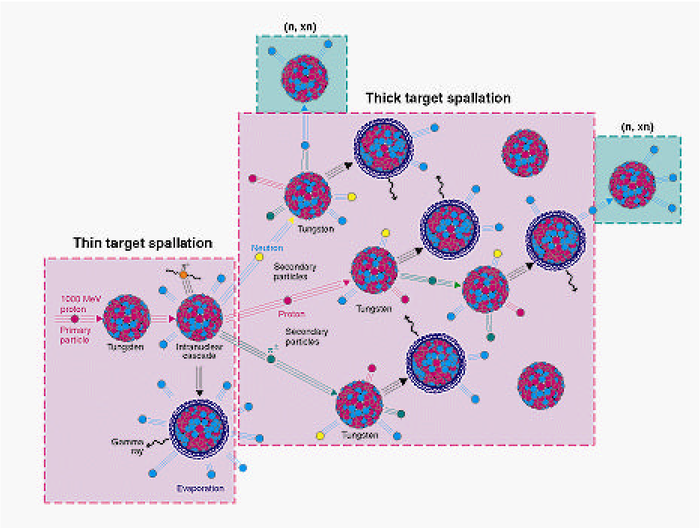


http://www.nobelprize.org/nobel_prizes/physics/laureates/1994/illpres/neutrons.html

Neutron Sources – how do we get neutrons

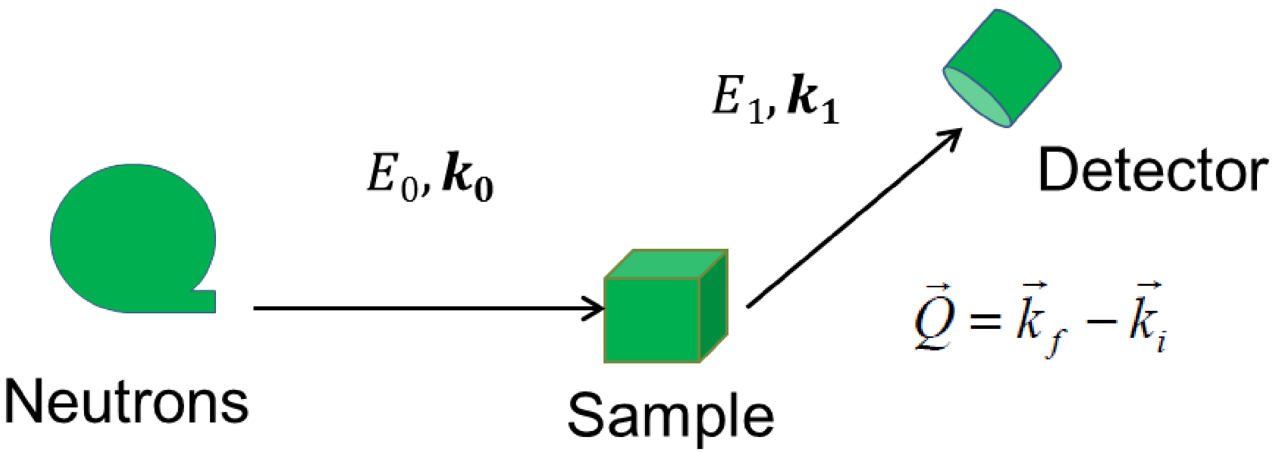


High Flux Isotope Reactor(HFIR)



Spallation Neutron Source(SNS)

A Typical Neutron Scattering Experiment



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

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{h/_{mv}}$$

$$E = \frac{1}{2}mv^2$$

- **Elastic scattering**
- **Inelastic scattering**

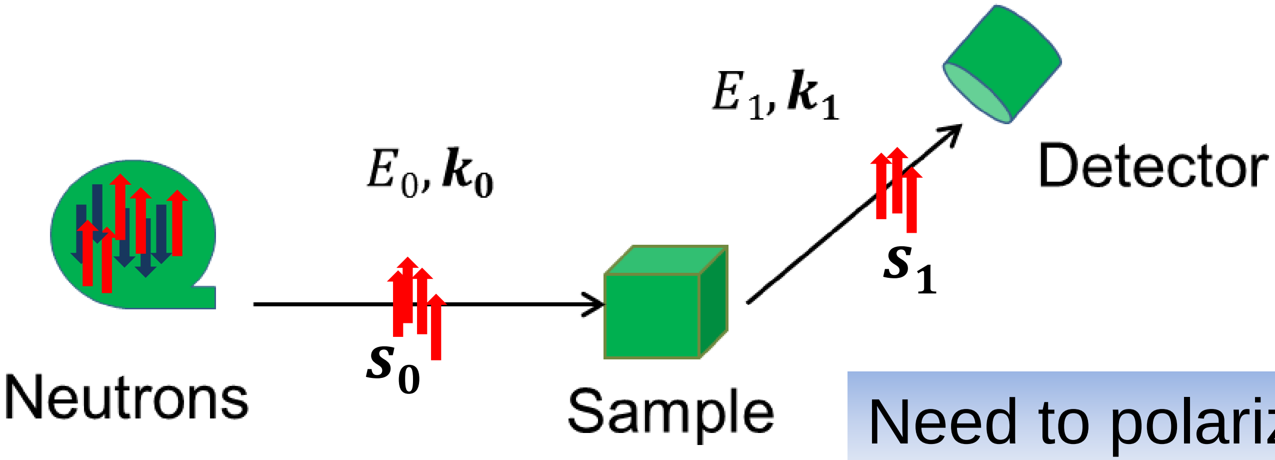
- Lots of neutrons – neutron source
- Determine incident wavevector $\boldsymbol{k_0}$
- Sample
- Determine scattered wavevector $\boldsymbol{k_1}$
- Neutron detctor

$$\left(\frac{d^2\sigma}{d\Omega dE_1}\right)_{\lambda\to\lambda_1} = \left(\frac{m}{2\pi\hbar^2}\right)^2 \frac{k_1}{k_0} |\langle k_1|V|k_0\rangle|^2 \delta(\hbar\omega + E_0 - E_1)$$

Polarized Neutron Scattering

- Determination of magnetic structures and spin densities
- Identification of magnetic fluctuations and excitations
- Separation of coherent scattering from incoherent scattering
- Separation of magnetic scattering from nuclear scattering
- Improve the energy resolution of spin echo spectrometer

A Typical Polarized Neutron Scattering Experiment



$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{h/_{mv}}$$

$$E = \frac{1}{2}mv^2$$

Need to polarize neutrons

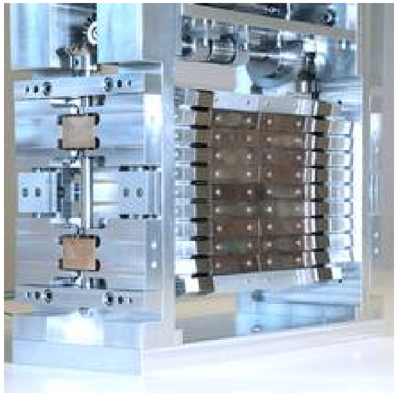
- **Polarizer**
- **Analyzer**
- **Guide field**
- **Flipper**

- Lots of neutrons – neutron source
- Determine incident wavevector $\boldsymbol{k_0}$
- Sample
- Determine scattered wavevector $\boldsymbol{k_1}$
- Neutron detctor

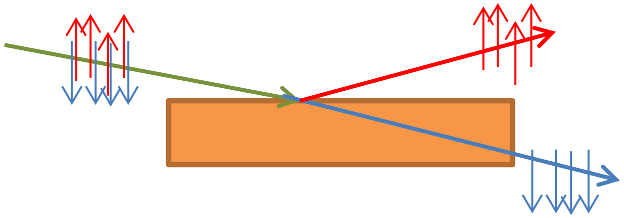
$$\left(\frac{d^2\sigma}{d\Omega dE_1}\right)_{\lambda\to\lambda_1} = \left(\frac{m}{2\pi\hbar^2}\right)^2 \frac{k_1}{k_0} |\langle k_1 s_1 | V | k_0 s_0 \rangle|^2 \delta(\hbar\omega + E_0 - E_1)$$

How to polarize neutrons

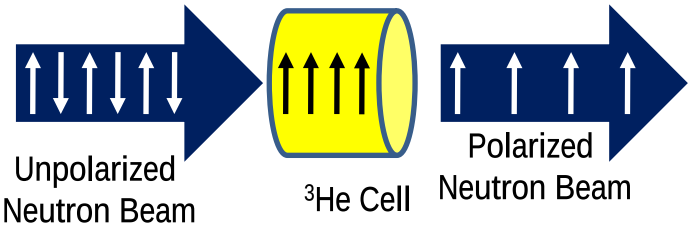
- Polarizing monochromators
  - Usually Heusler alloy (Cu2MnAl)
  - Using preferential **Bragg diffraction**



- Supermirrors
  - Very efficient polarizers
  - Using **total reflection**
  - Disadvantage is that small angular beam divergence required



- Polarizing filters
  - Usually polarized ^{3}He
  - Using **preferential absorption cross section**
  - Good for polarizing large, divergent neutron beams
  - broadband

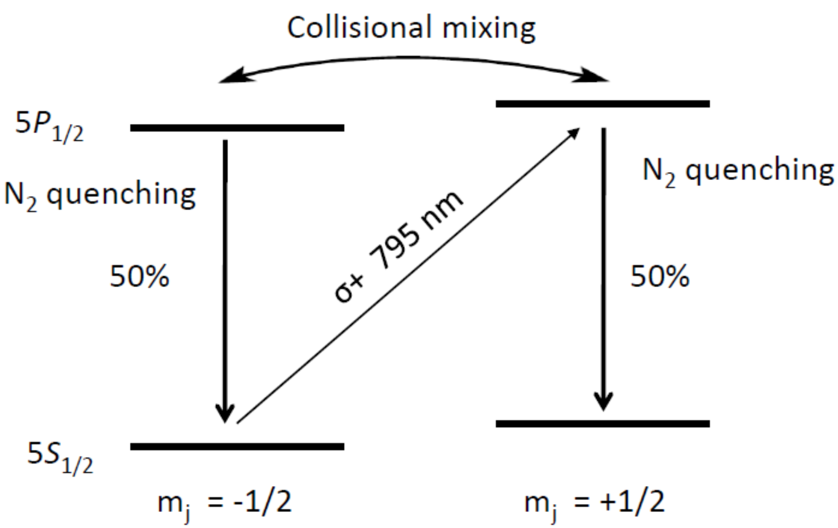


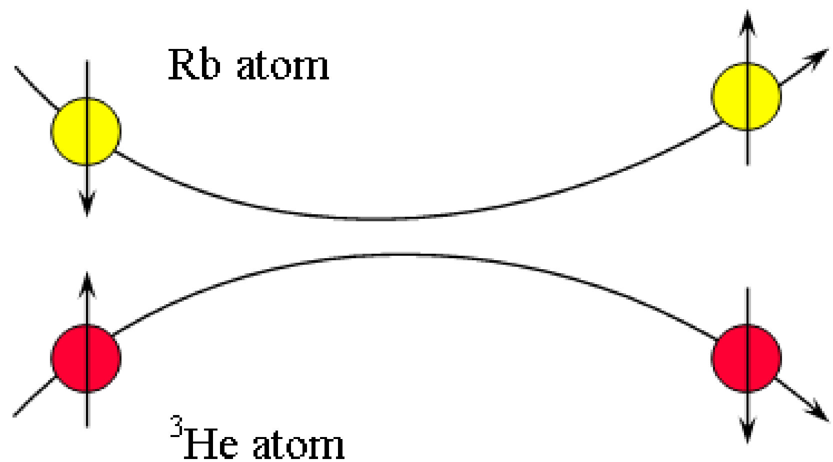
^{3}He is like a honey badger, it doesn't care, it just polarizes

Production of Polarized ^{3}He

- **Spin-exchange Optical Pumping (SEOP)**
- **Use high power diode lasers to polarize**

- GE180 glass
- ^{3}He
- N_2
- Rb & K





Polarized ^{3}He as neutron spin filter

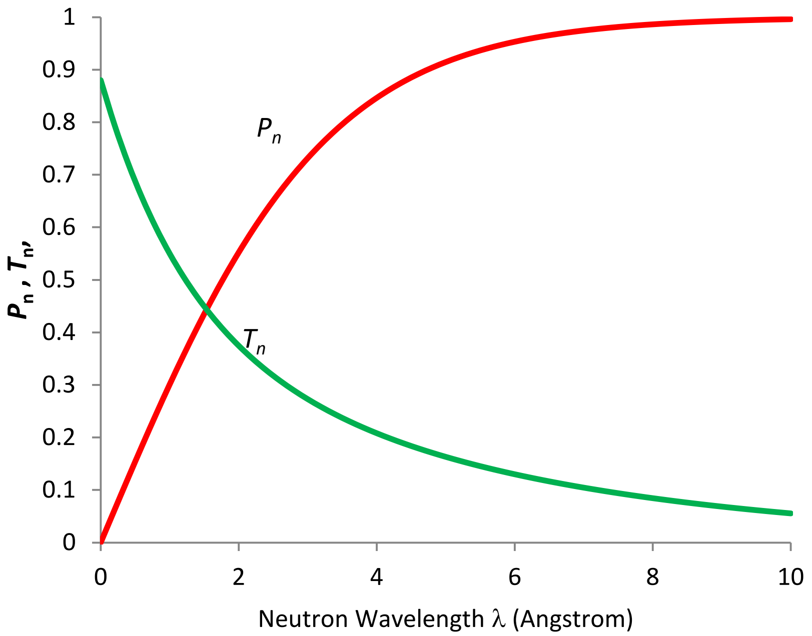
P_{3He}: ^{3}He polarization 70%-75%
T_e: Glass transmission

Cell thickness:

$$A = n\sigma_0 l \propto pressure * length$$

where:

n: number density
σ_0: absorption cross section for $\lambda = 1Å$
l : cell length

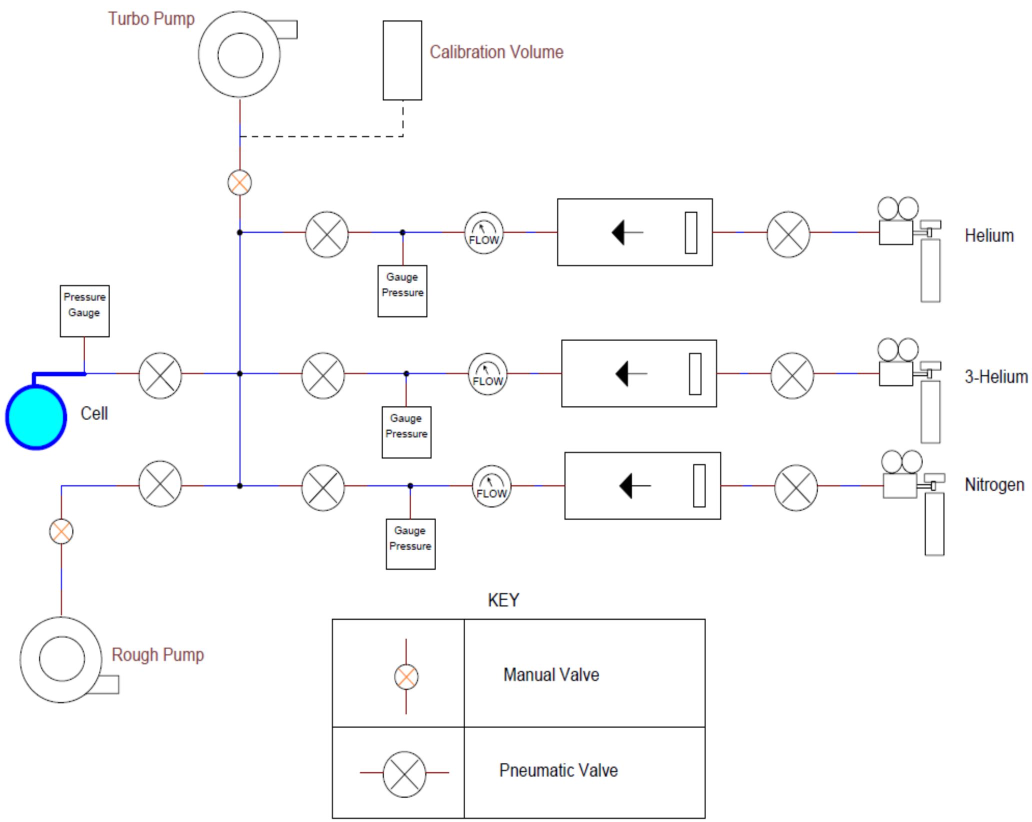


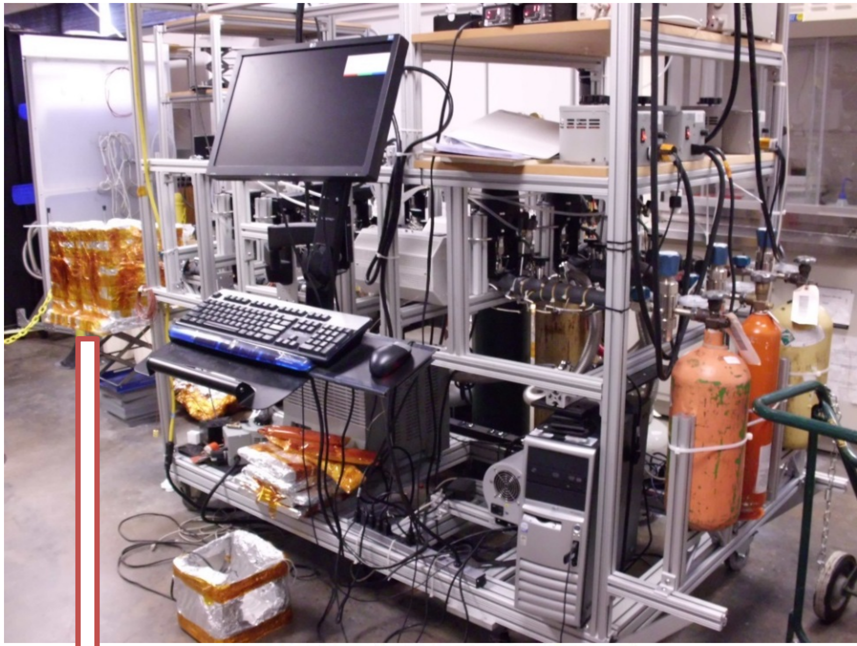
$$P_{neutron}(\lambda) = \tanh(A\lambda P_{3He})$$

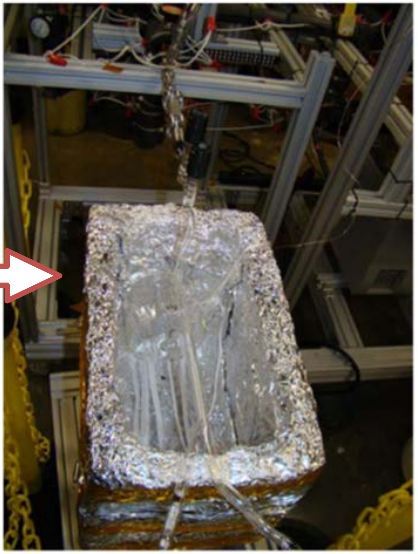
$$T_{neutron}(\lambda) = Te\exp(-A\lambda)\cosh(A\lambda P_{3He})$$

- **Compromise between polarization and transmission**
- **Improving ^{3}He polarization can increase both neutron polarization and transmission**

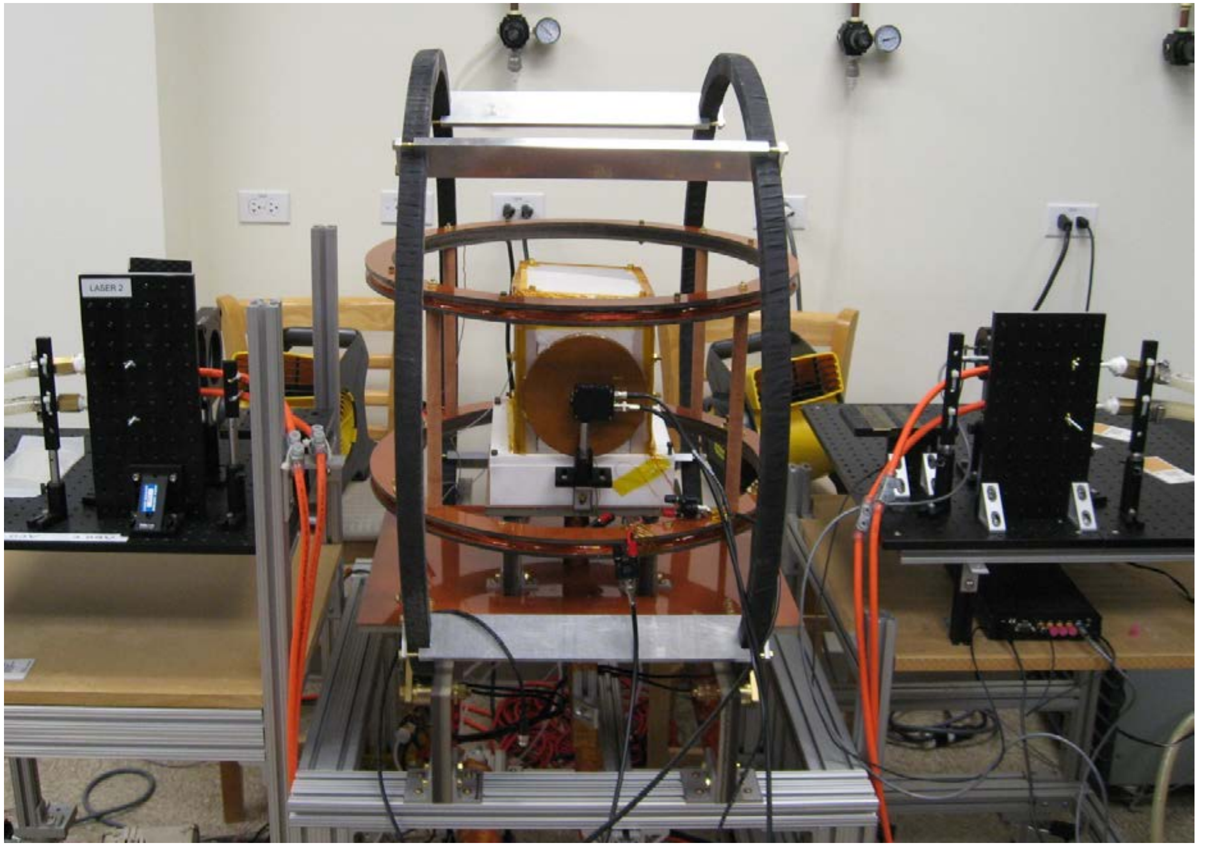
Lab-based Filling Station







ex situ Optical Pumping Station

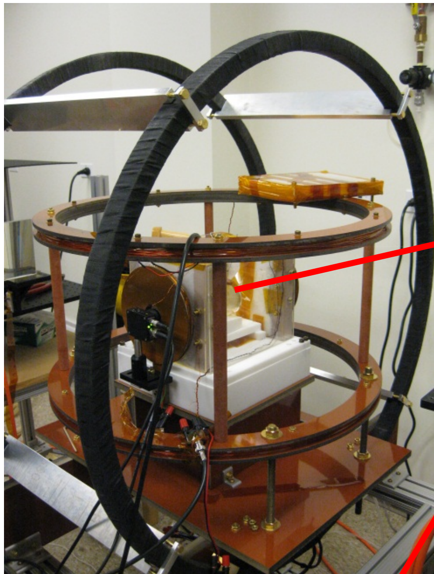


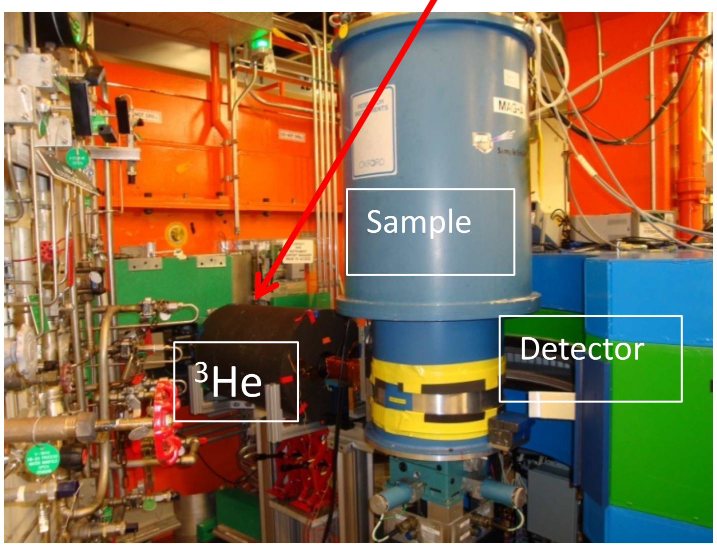
Monitor ^{3}He polarization

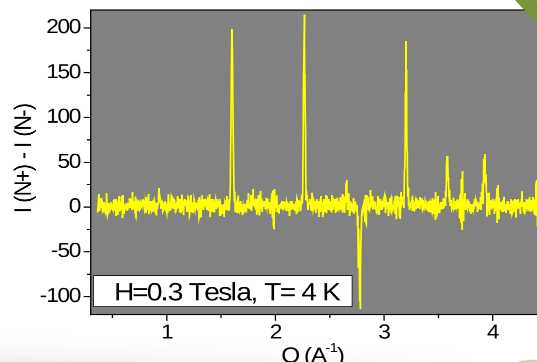
- FID NMR
- AFP NMR
- EPR

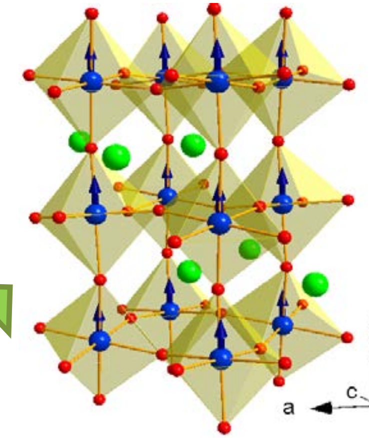
- 2 pumping stations at SNS lab C-241
- 2 pumping stations at HFIR (being built)
- 1-2 days of pumping time

ex situ Optical Pumping Station – HB2A, as polarizer

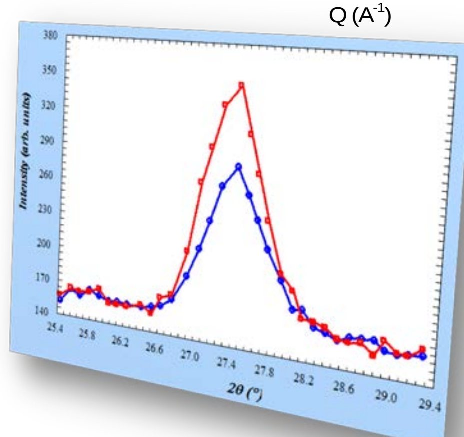


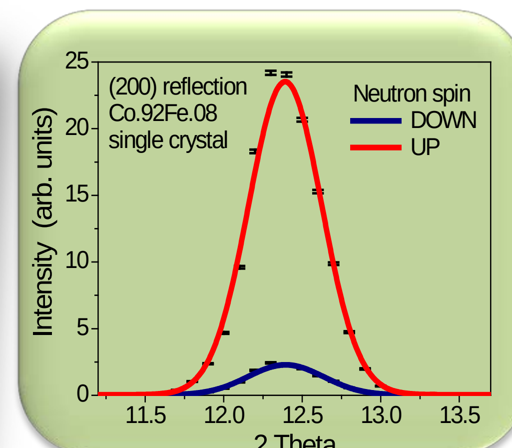






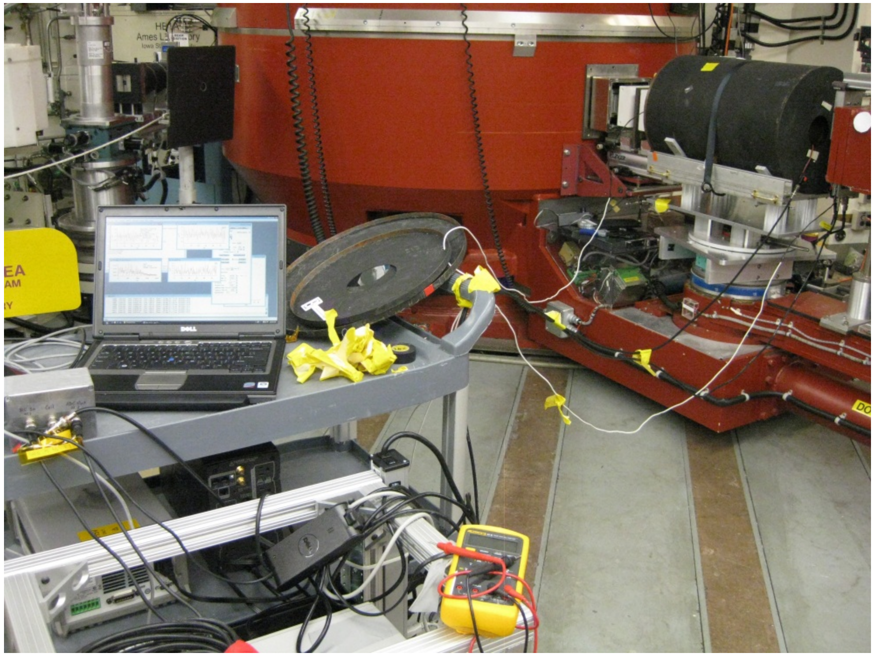
Magnetic order of thermally quenched K-Co-Fe Prussian blue analog photomagnet

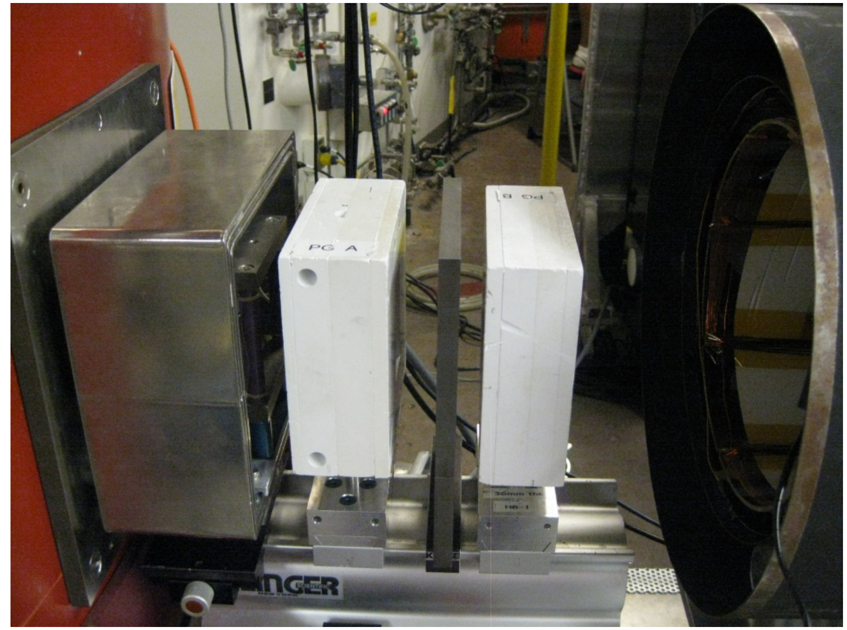


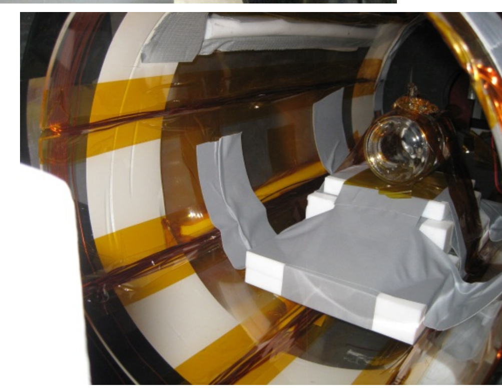


D. M. Pajerowski, V. O. Garlea, et al, PHYSICAL REVIEW B **86**, 054431 (2012)

ex situ Optical Pumping Station –HB1, as analyzer





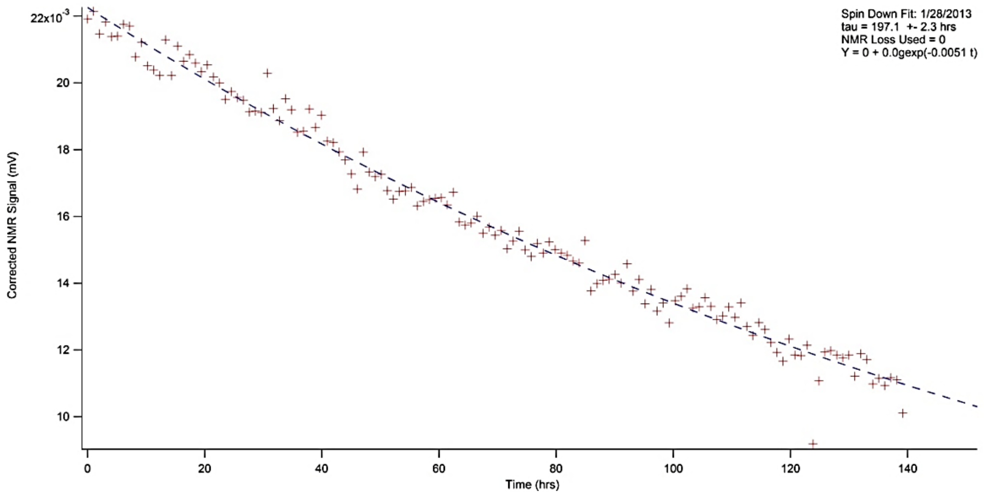


$$P_{He} \sim 70\%$$

Energy(meV)	Heusler flipping ratio	Polarized 3He FR
13.5	20.3	67.4
30.5	6.65	16.7
50	2.52	8.93

ex situ Optical Pumping Station – disadvantages

- The ^{3}He polarization relaxes once removed from the laser beam



$$P(t) = Pi\exp\left(-\frac{t}{T_1}\right)$$

- May need to repolarize 3He for a lengthy experiment
- Data analysis may be complicated

in situ Polarized ^{3}He Pumping station

Why *in situ*?

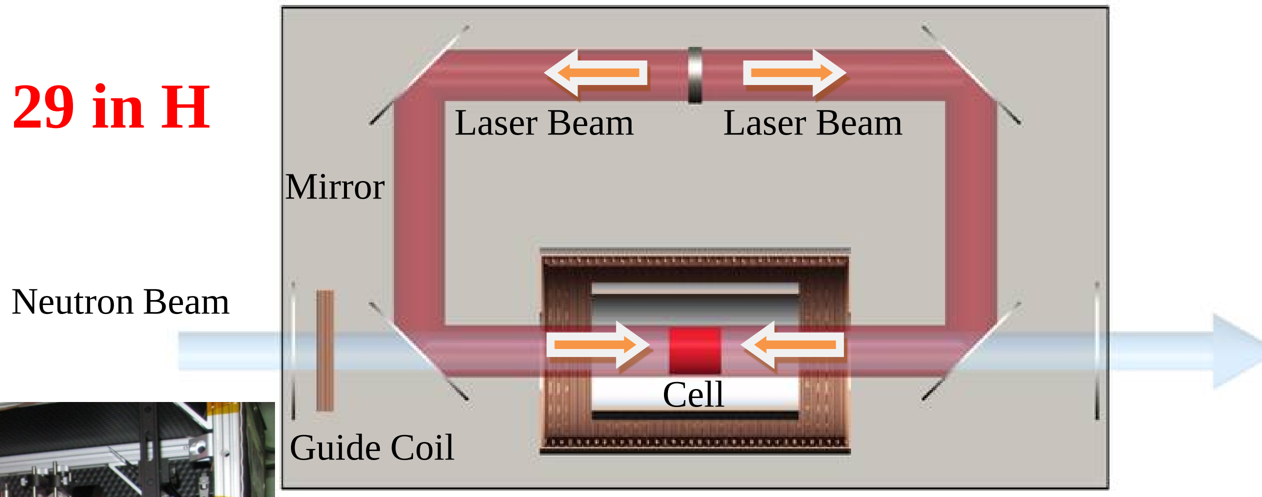
- Constant Polarization
- Lower field gradient requirement
- user friendly

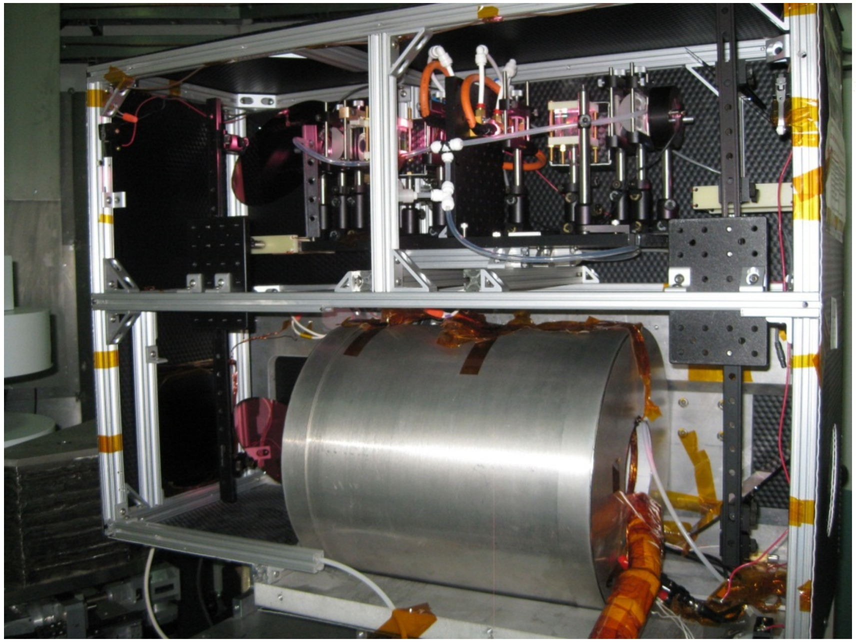
Difficulties?

- Tight space confinement
- Laser safety
- Over heating issue
- Ambient field invasion

in situ ^{3}He Analyzer for Magnetism Reflectometer at SNS

39 in L x 15 in W x 29 in H





- Two 250W laser pumping
- System enclosed with laser interlock
- Remote operating and controlling
- Built-in ^{3}He spin flipper
- High ^{3}He polarization achieved

X. Tong, C. Y. Jiang, et al, Rev. Sci. Instrum. 83, 075101 (2012)

The measurements

Unpolarized neutron measurement

- ^{3}He polarization
- ^{3}He cell thickness
- Neutron transmission through ^{3}He

Polarized neutron measurement

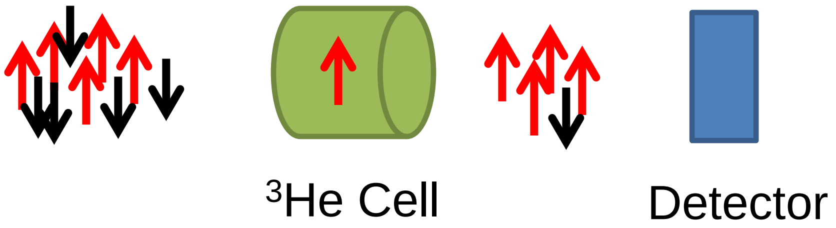
- ^{3}He as analyzer
- Measured supermirror bender polarization

Reference sample measurement

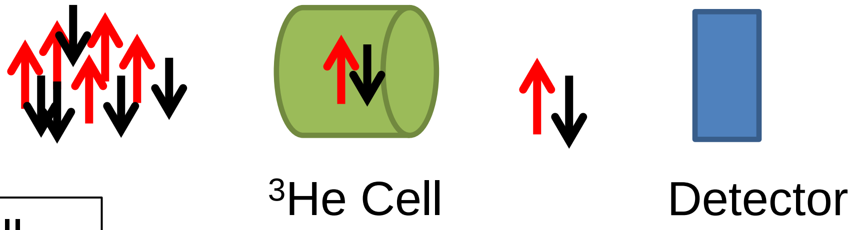
- Full polarization analysis on a reference sample
- Four cross-sections measured

Unpolarized neutron measurements

$$T_n(\lambda) = T_e \mathrm{exp}(-n\sigma_0 l\lambda)\cosh(n\sigma_0 l\lambda P_{He})$$



$$T_0(\lambda) = T_e \mathrm{exp}(-n\sigma_0 l\lambda)$$



T_e : empty transmission through glass wall
n : number density of ^{3}He gas
σ_0 : absorption cross section per wavelength
l : cell length
λ : neutron wavelength

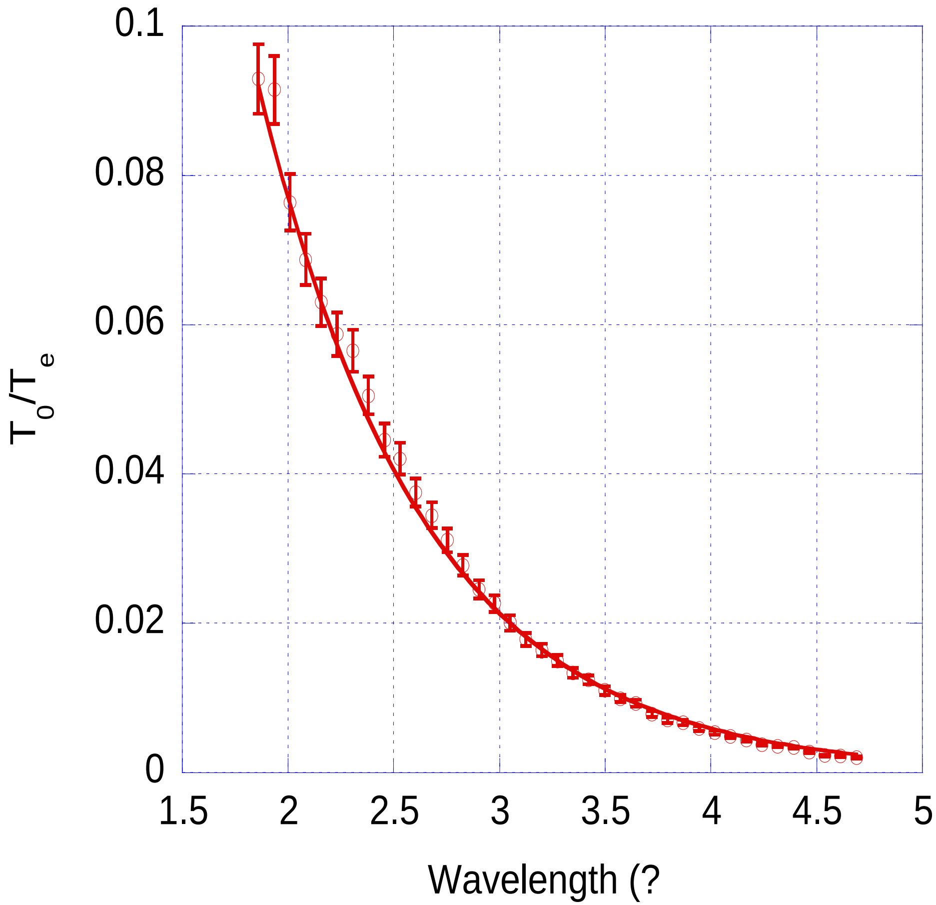
Unpolarized neutron measurements -- results

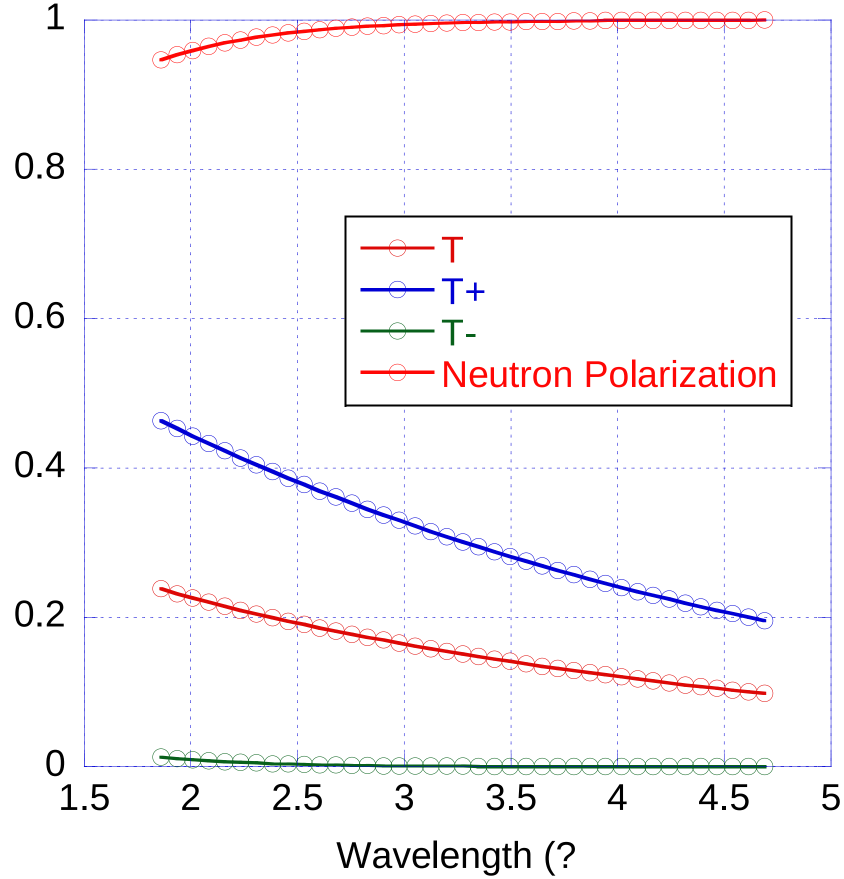
$$A = n\sigma_0 l = 1.270 \pm 0.013$$
$$T_e \sim 82\%$$
$$P_{3He} = 76\% \pm 1\%$$

$$T_0(\lambda) = Te\exp(-A\lambda)$$

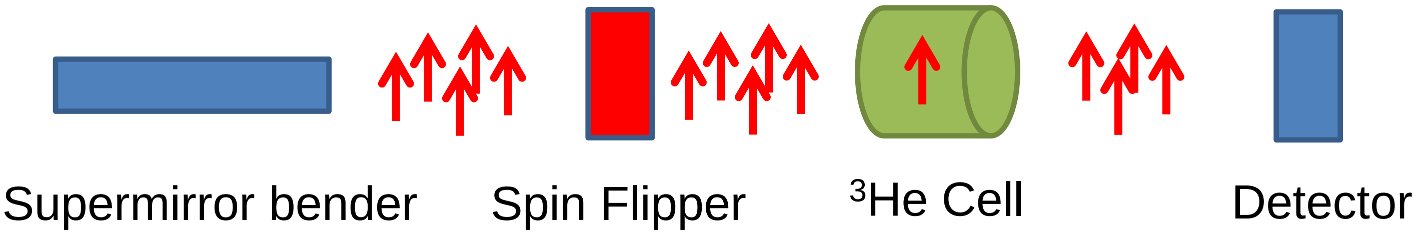
$$P_{neutron}(\lambda) = \tanh(A\lambda P_{3He})$$

$$T_{neutron}(\lambda) = Te\exp(-A\lambda)\cosh(A\lambda P_{3He})$$

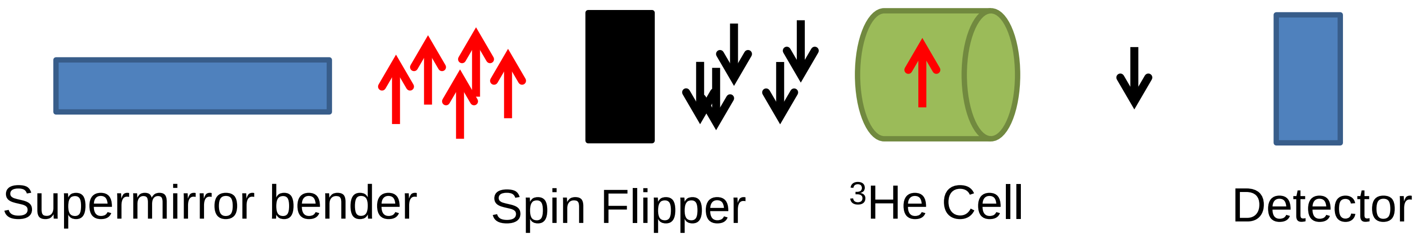




Polarized neutron measurements – Flipping Ratios



$$T_+(\lambda)$$



$$T_-(\lambda)$$

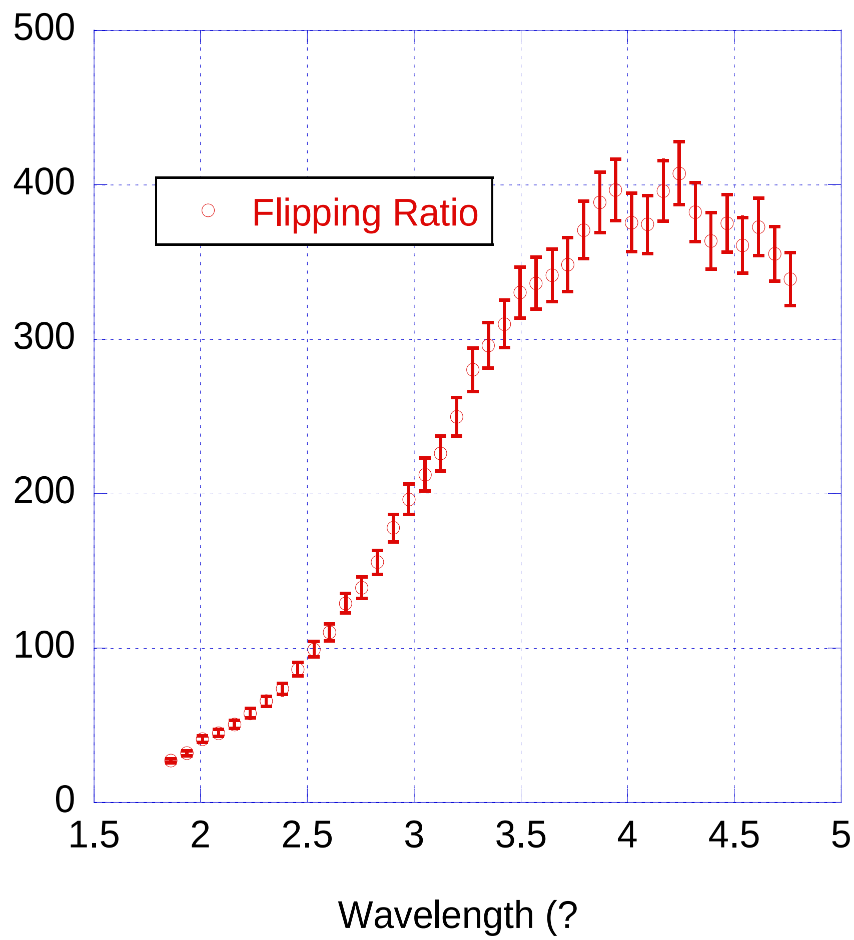
$$F(\lambda) = \frac{T_+(\lambda)}{T_-(\lambda)}$$

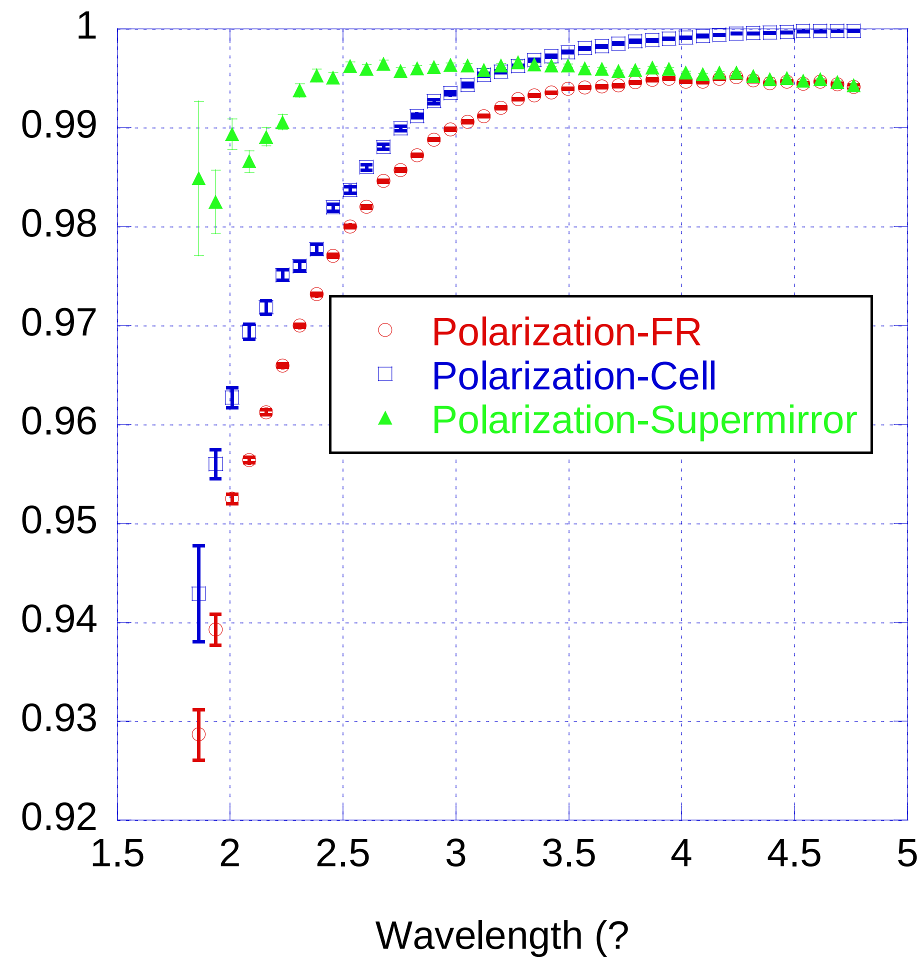
$$P_{SM}P_{3He}P_{ST}P_{SF} = \frac{F-1}{F+1}$$

SM: Supermirror
ST: Spin transport
SF: Spin flipper

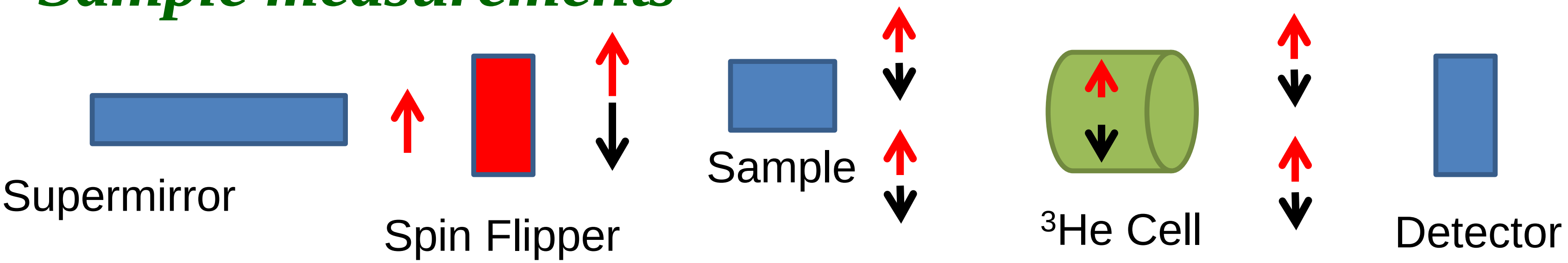
Polarized neutron measurements -- results

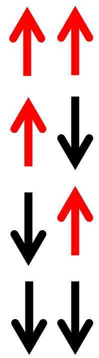
$$P_{SM}P_{3He} = P_{FR} = \frac{F-1}{F+1}$$, assume perfect spin transport and spin flip efficiency





Sample measurements



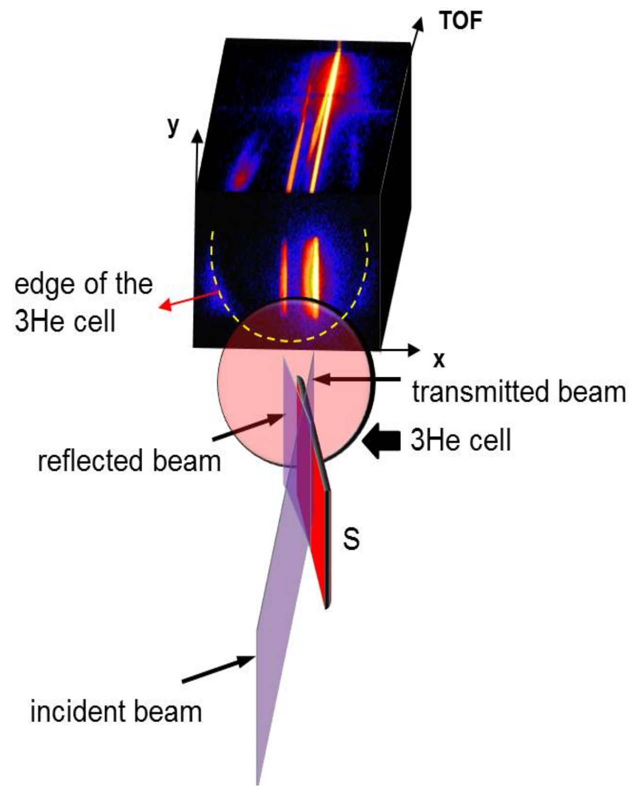


σ_{++}

σ_{+-}

σ_{-+}

σ_{--}

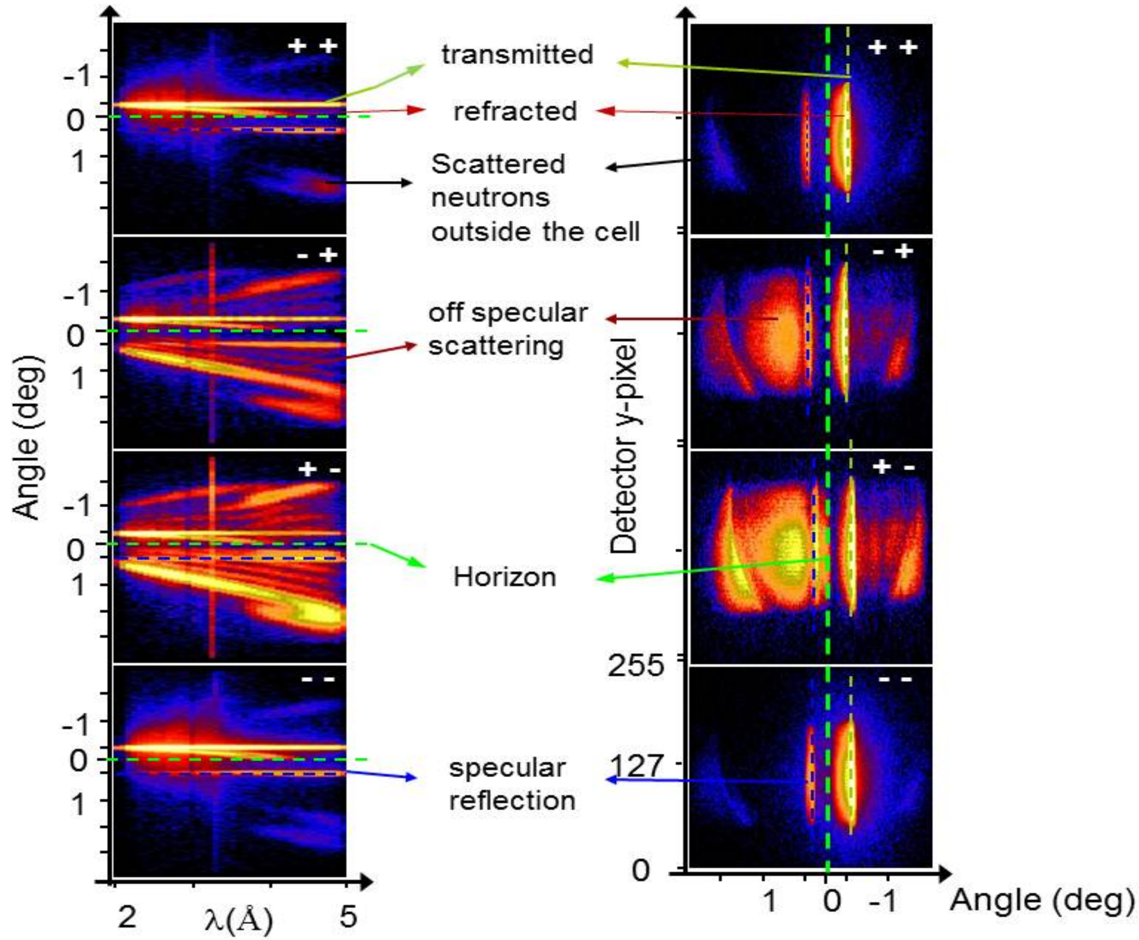


^{57}Fe(6.7 nm)/Cr(-1.2 nm)

anti-ferromagnetic inter-layer exchange coupling and an in-plane magnetic domain structure

L.-P. V, H. J. Lauter, B. P. Toperverg, L. Romashev and U. V, Phys Rev Lett **89** (16) (2002).

Sample measurements -- results



The wavelength dependence of the specularly reflected, off-specularly scattered and transmitted intensities for the four spin-states.

In the coordinates of the PSD and being integrated over the TOF.

Summary for BL4A's in-situ setup

Performance

- 76% ^{3}He polarization achieved
- 98% neutron polarization for wavelength 2.5 Å and above (96% at 2 Å)
- 25% average transmission (40% at 2 Å and 18% at 4.5 Å)

Uniqueness

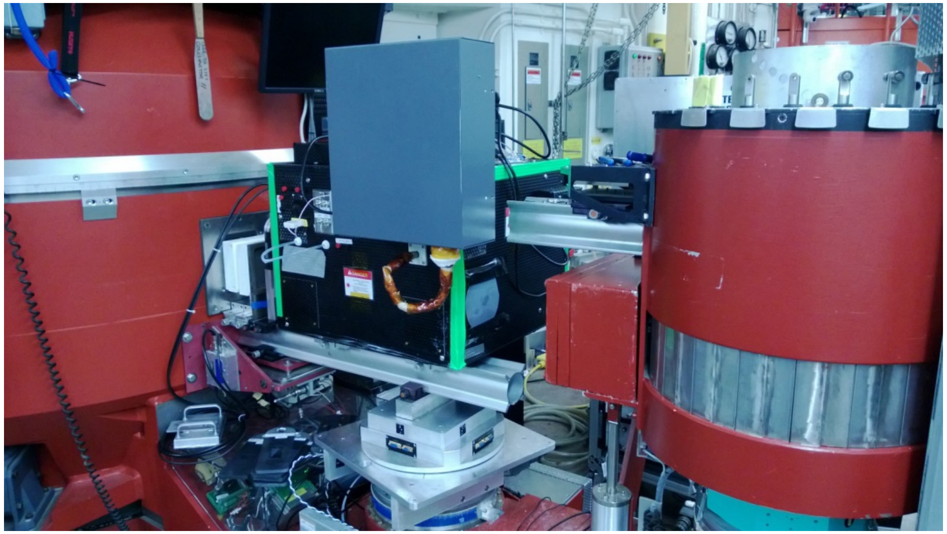
- Motor controlled, can be moved in and out of the beam
- All ^{3}He setup computer controlled
- Class 1 laser certification, user friendly

Stability

- 3 weeks of running without interruption

It's so easy that  can operate it!

Compact in situ Analyzer for HB1 at HFIR

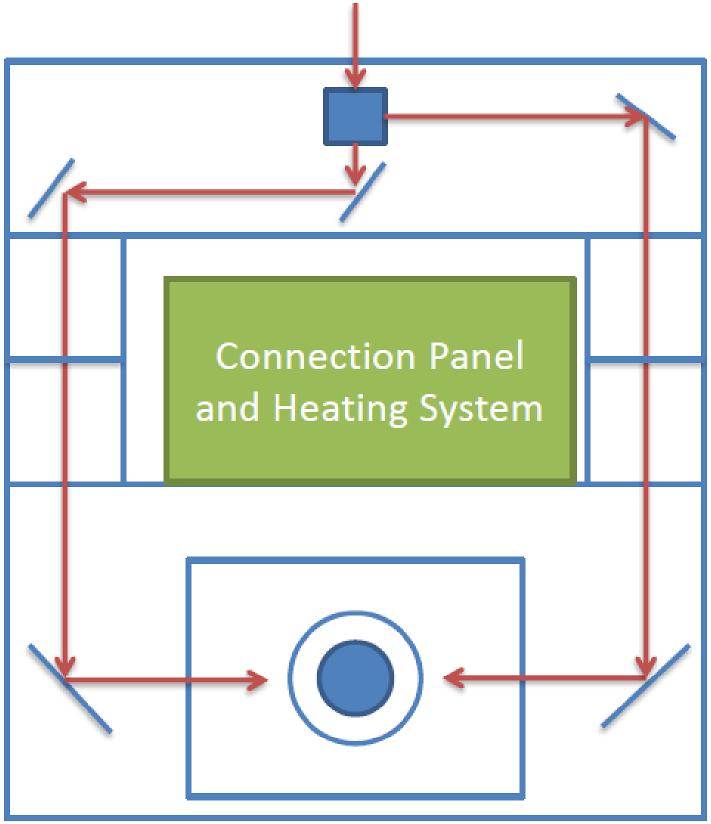


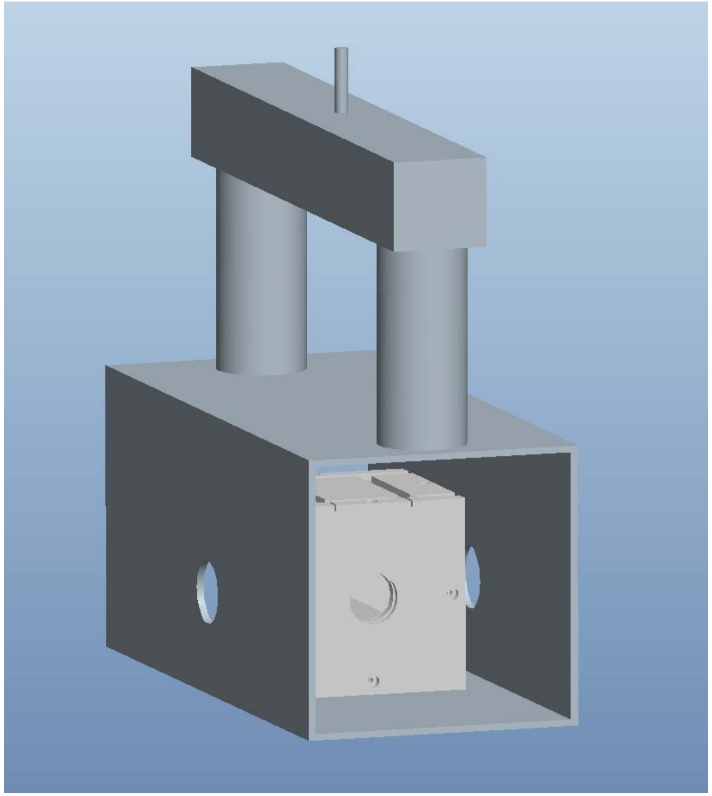
24 in L x 22 in W x 18 in H

- One 70W fiber-coupled laser pumping
- System enclosed with laser interlock
- Built-in ^{3}He spin flipper
- ^{3}He polarization (54%) achieved

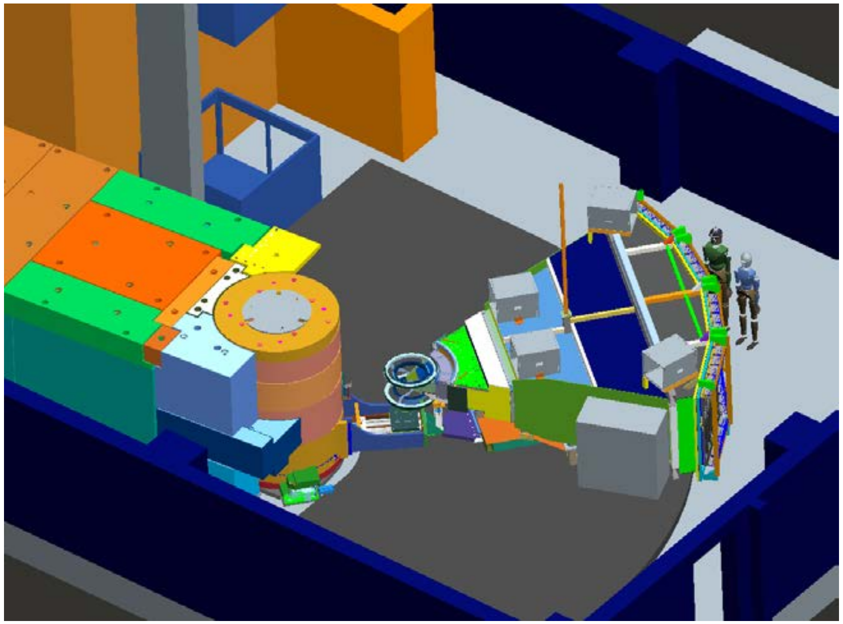
Future Development

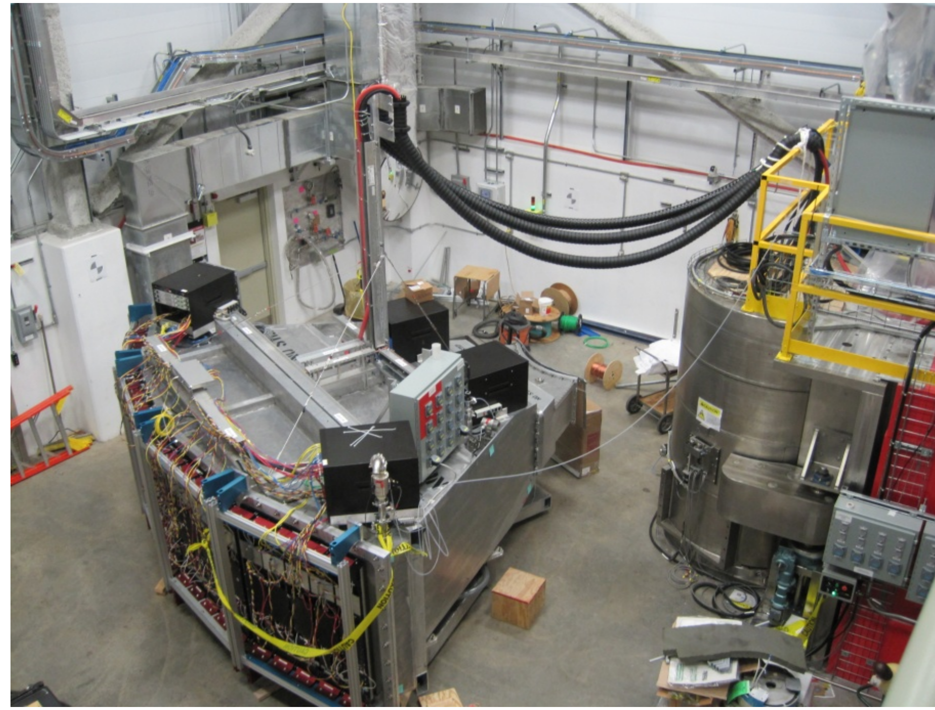
- Super compact *in situ* system
  - 1 ft long in the direction of neutron beams
  - can fit into most neutron beam lines at SNS and HFIR





The Hybrid Spetrometer - HYSPEC





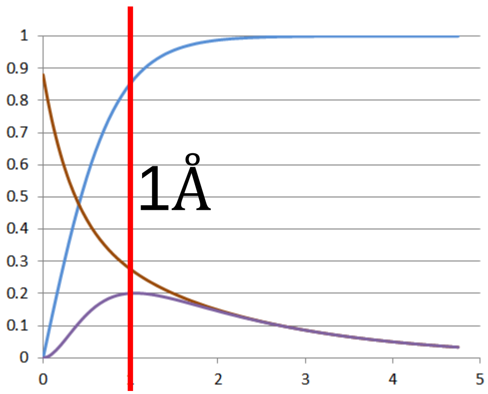
- High flux by trick of tall guide & vertical focusing with crystals (~6x)
- Located in external building – space around beamline, very flexible, low background
- Curved guide & vertical axis T0 chopper – background reduction
- $3.6 < E_I < 90$ meV, $0.9Å < \lambda < 4.7Å$
  $10^5 - 10^7$ n/cm^2/s $\Delta E / E_I$ – 2% → 10%

Huge neutron wavelength/energy span!

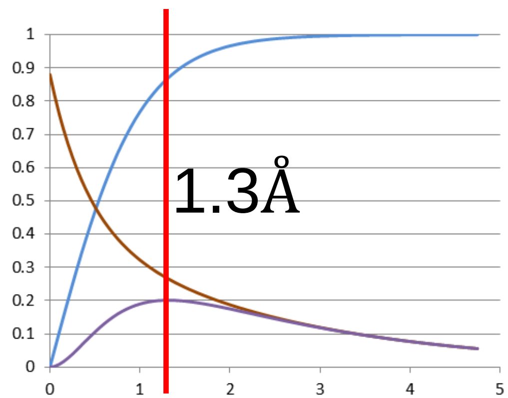
Choosing the Right 3He Pressure – Max Figure of Merit

$$FOM(\lambda) = P_{neutron}(\lambda)^2 T_{neutron}(\lambda)$$

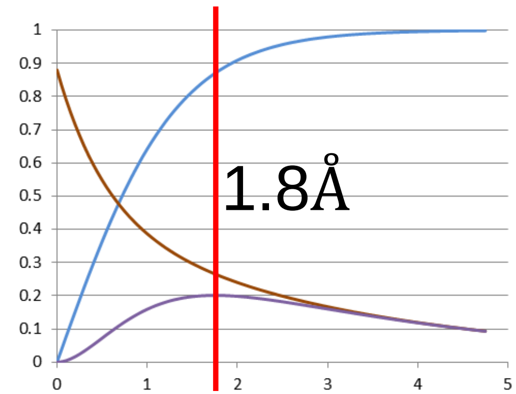
Assume 70% P_{3He}



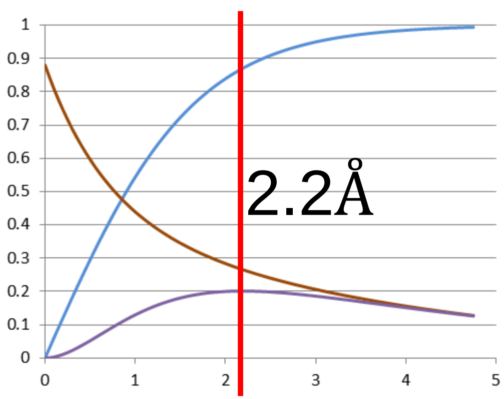
25 bar * cm



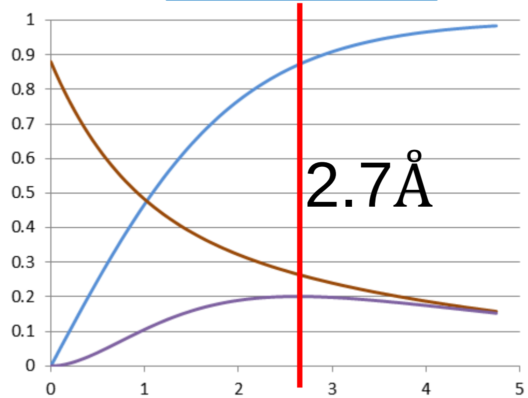
20 bar * cm



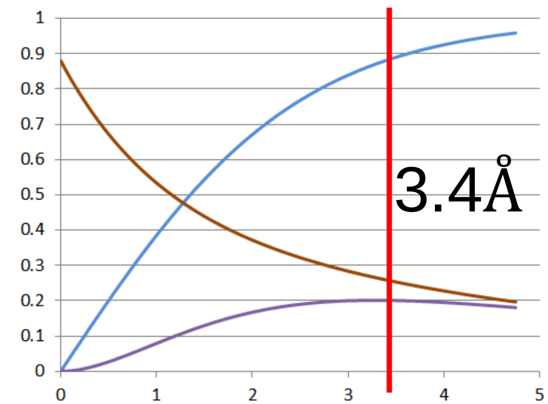
15 bar * cm



12 bar * cm

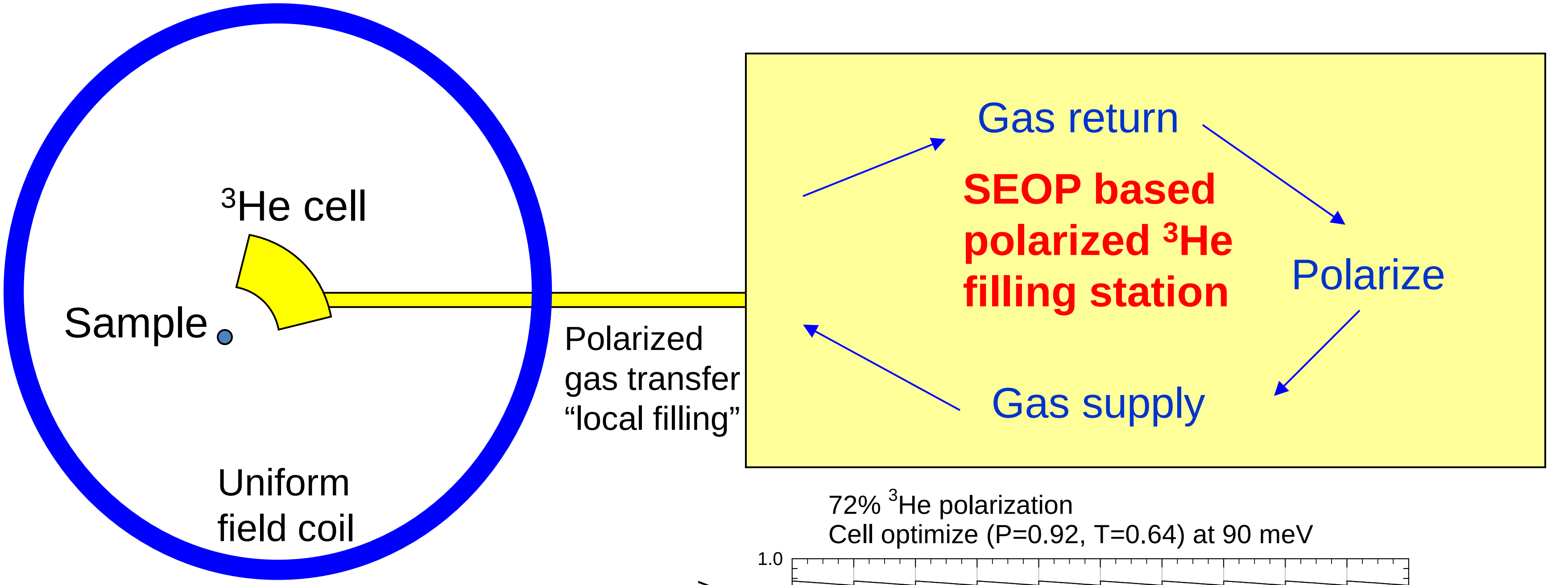


10 bar * cm

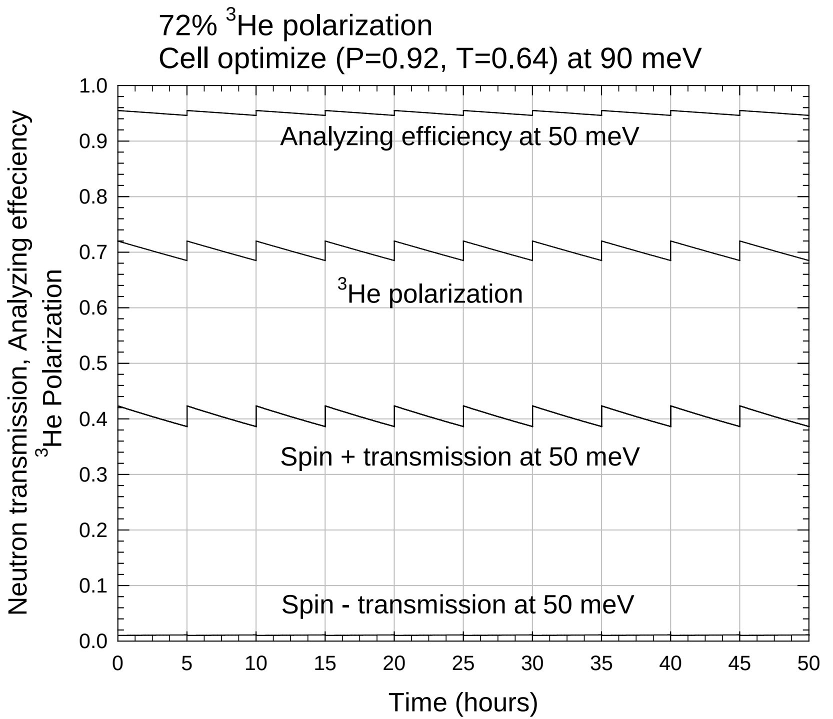


8 bar * cm

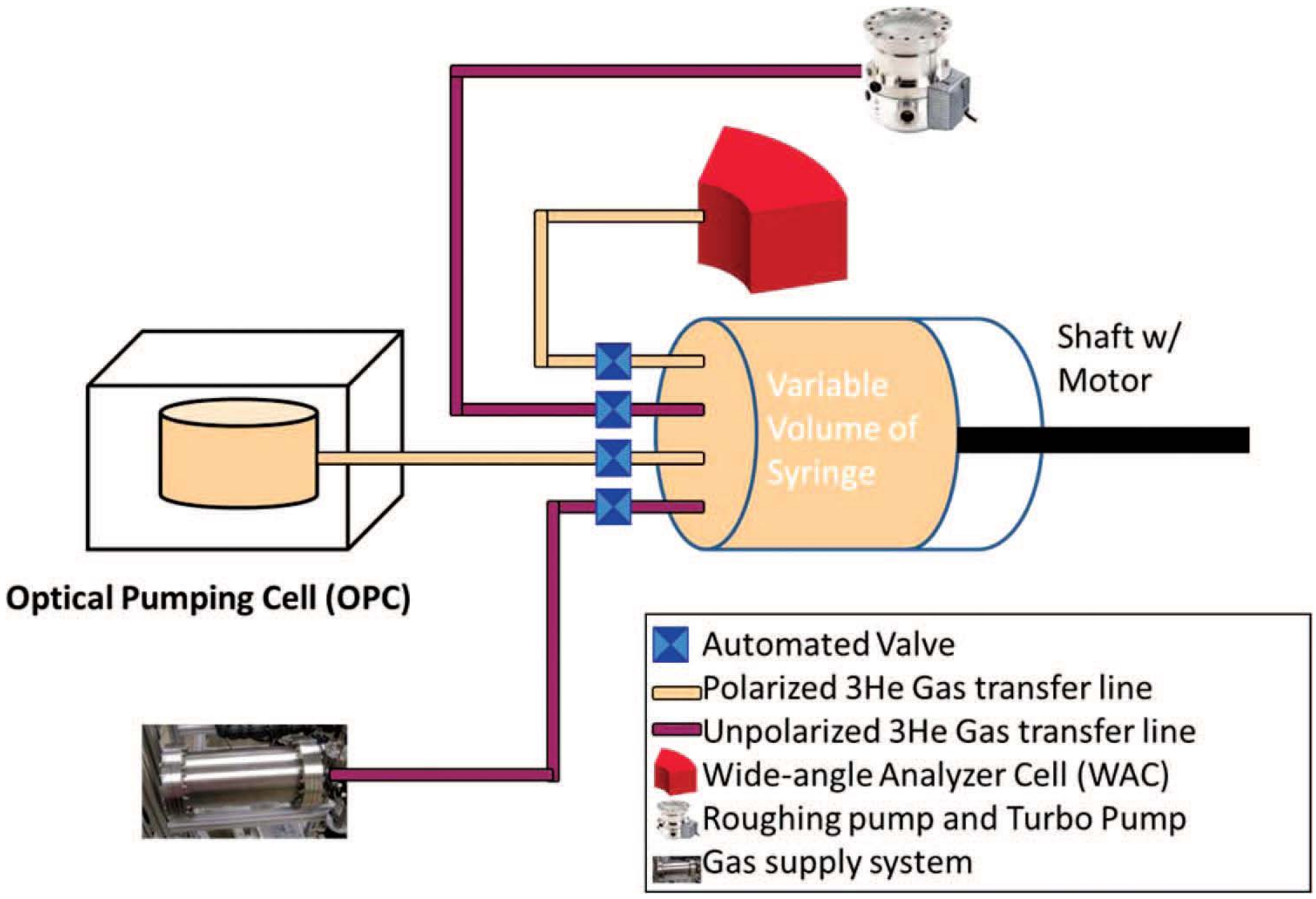
Polarized 3He Filling Station - Concept



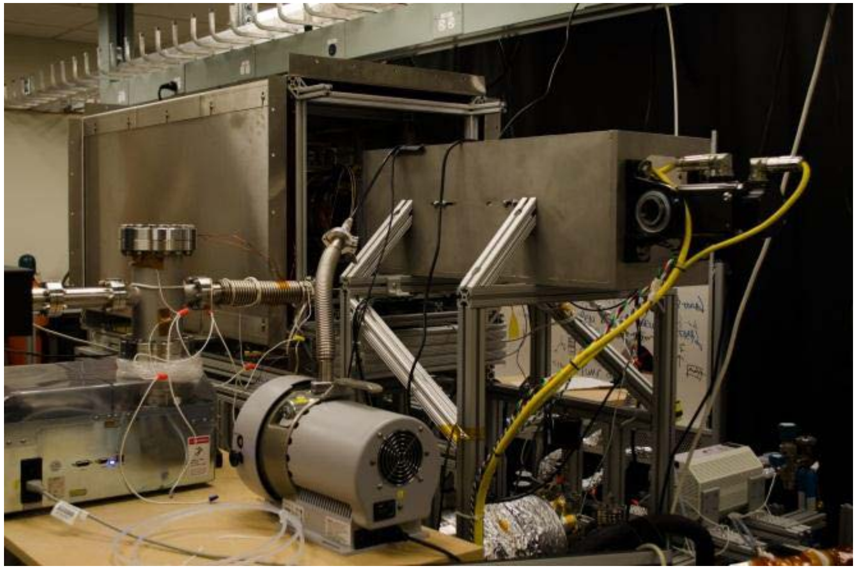
Example: Max. ^{3}He polar. =72%, optimized at 90 meV. T_1=100 hours, exchange all the gas every 5 hours. (Plot: for 50 meV neutrons)



Polarized 3He Filling Station - Blueprint



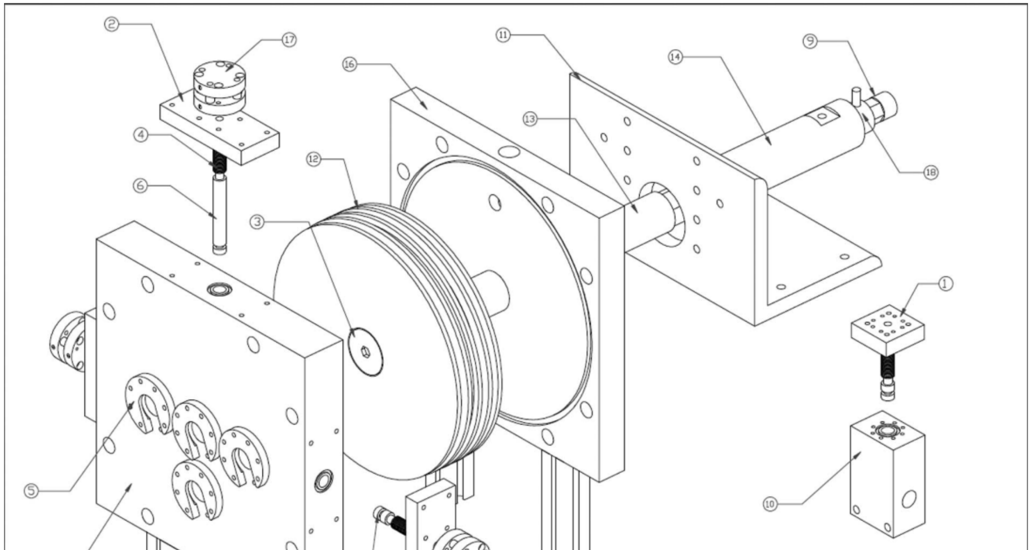
Polarized ^{3}He Filling Station – Prototype Assembled



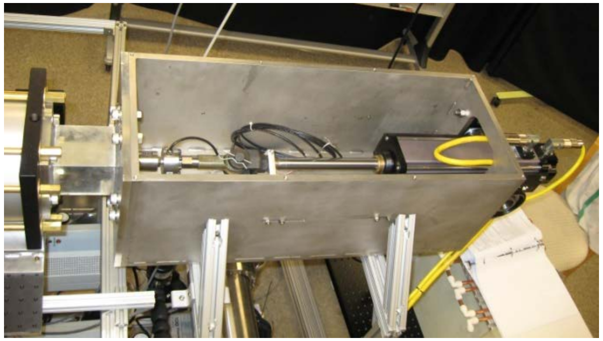
first of its kind in the world

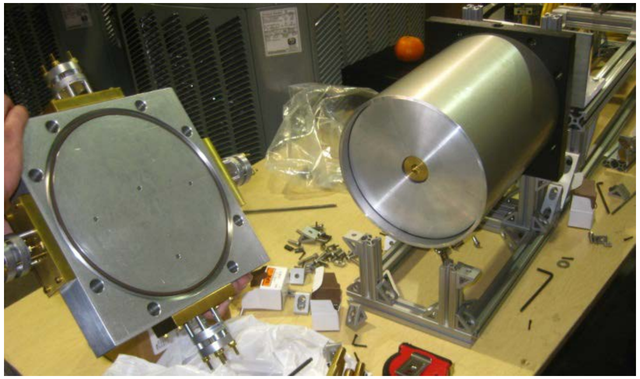
- ❑ A 1045 turn rectangular solenoid was built to create the magnetic field necessary to keep the polarization of the 3He cell aligned
- ❑ This is designed to slide over the laser system, oven, and gas syringe cylinder on the upper left-hand side of the cart
- ❑ The gradient of the field was measured to be 4.42×10^{-4} cm^{-1} which leads to reasonable polarization relaxation times for this application

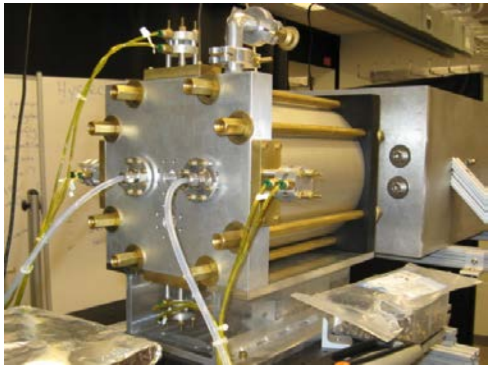
The Syringe System



ITEM NO	QTY	DESCRIPTION	DWG	MATERIAL
1	3	INDIVIDUAL BELLOWS FLANGE	1	BRASS
2	4	CAP END BELLOWS FLANGE	2	BRASS
3	1	BRASS PILOT	3	BRASS
4	7	BELLOWS	4	BE-CU
5	4	KF-CLAMP	5	ALUMINUM
6	1	ELONGATED VALVE STOPPER	6	COPPER
7	1	CAP END HEAD	7	ALUMINUM
8	8	80/20 SUPPORT	N/A	ALUMINUM
9	1	FEMALE-MALE HEX BOLT	9	BRASS
10	3	INDIVIDUAL VALVE BODY	10	BRASS
11	1	L-BRACKET	11	ALUMINUM
12	1	PISTON	12	ALUMINUM
13	1	DRIVE SHAFT - PISTON END	13	TITANIUM
14	1	DRIVE SHAFT - MOTOR END	14	TITANIUM
15	6	VALVE STOPPER	15	COPPER
16	1	ROD END HEAD	16	ALUMINUM
17	7	FABCO PANCAKE CYLINDER	N/A	VARIES
18	1	FORCE SENSOR	N/A	VARIES

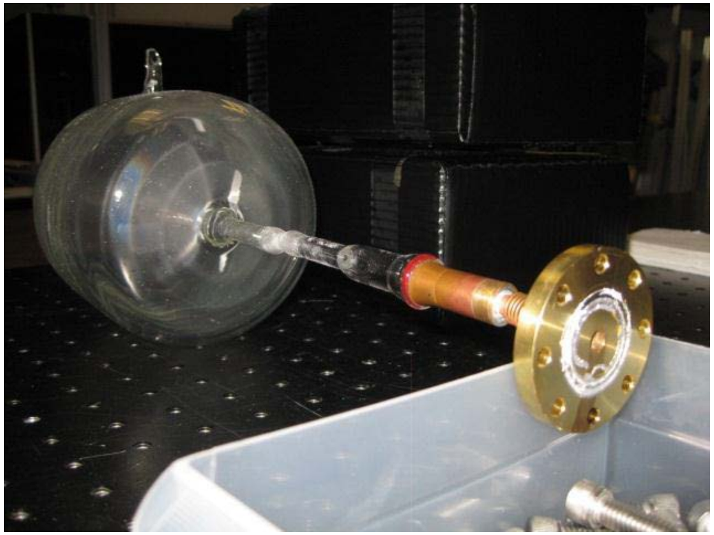


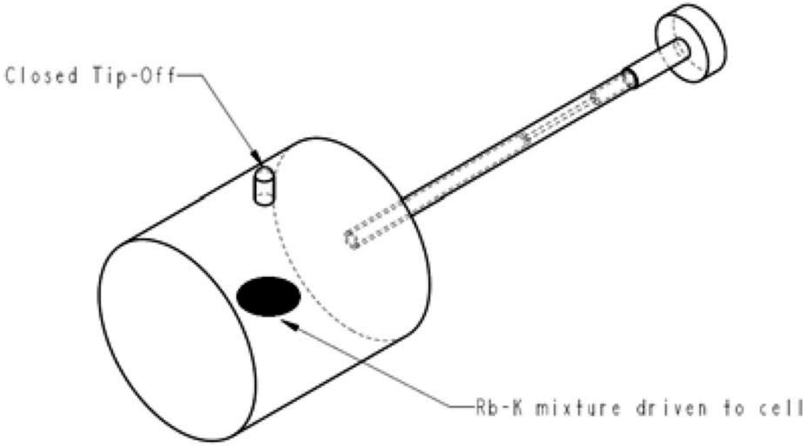


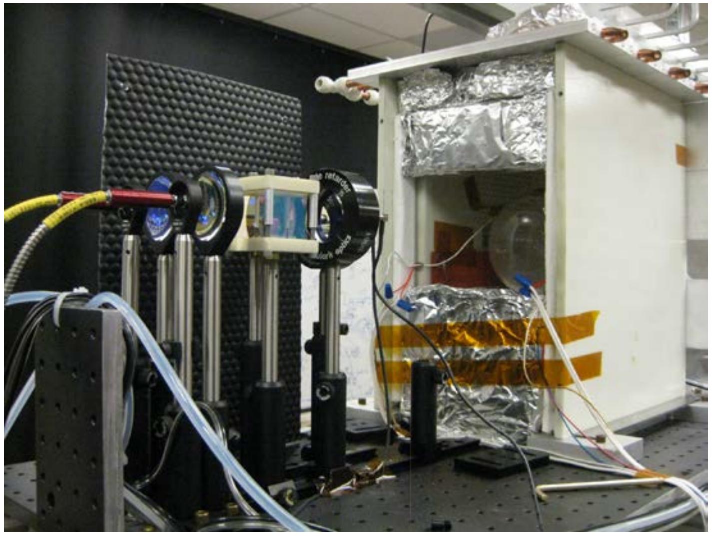


- ❑ The gas syringe was manufactured out of non-magnetic material (Brass, Aluminum, and Titanium)
- ❑ This syringe has four air-controlled valves that connect it to the vacuum pump, gas supply system, pump-up cell, and analyzer cell
- ❑ A linear actuating motor controls a piston within the syringe moving the gas

Pump Up Station and Cell

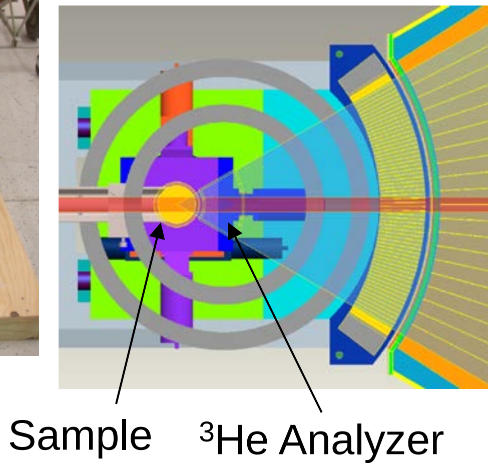






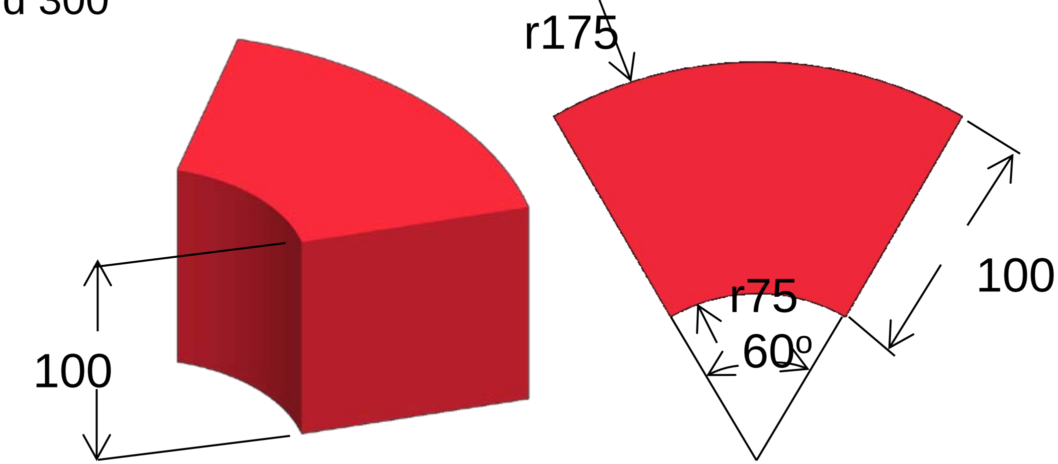
- The pump-up cell is made of GE180 glass
- The end flange is made of brass.
- In the middle is pyrex capillary tubing connecting the cell and the end flange.
- Electrical heating

Wide-angle Cell & Coils



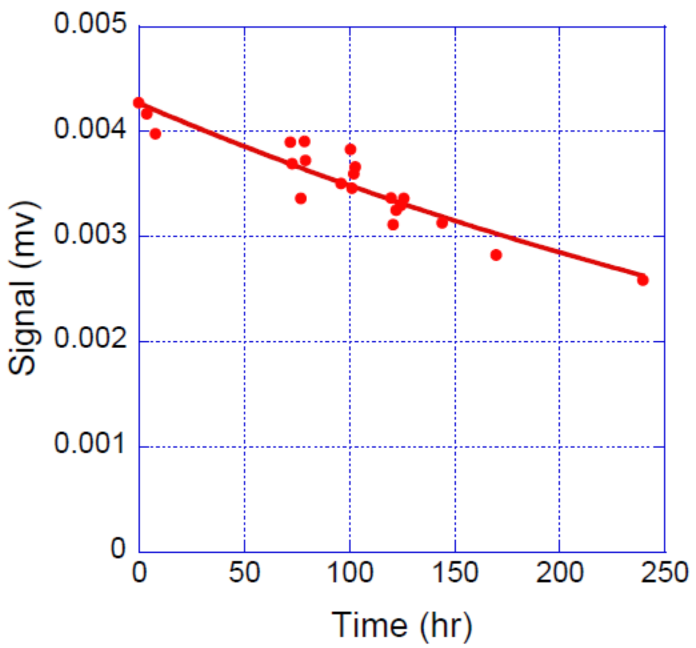
Wide-angle analyzer cell

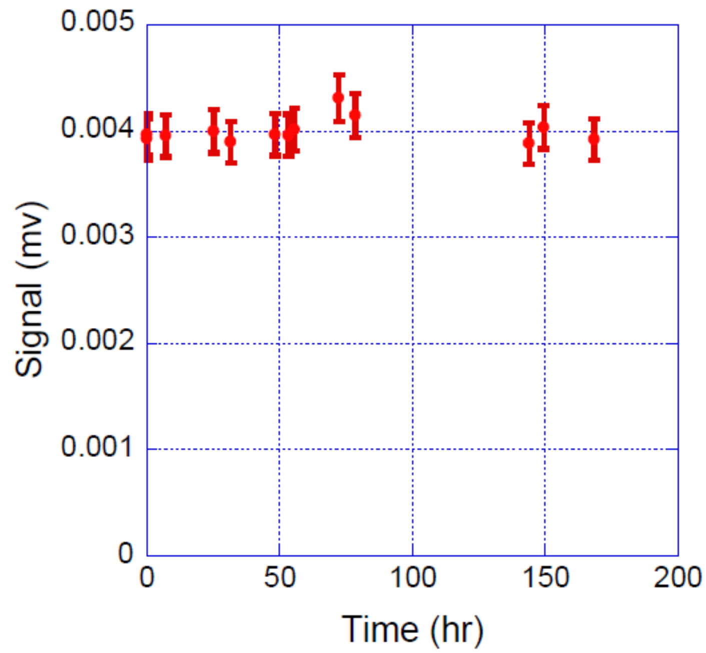
- Analyzer sits in the center of the coils
- Analyzer converges to the center of the sample stage
- Wall thickness is about 4mm, pressure tested to 35 psi (2.4 bar)
- The cell was filled with 50 Torr of N_2 and 300 Torr of ^{3}He. T1=70.1 hr +/- 0.6 hr



Tests and Results

❑ Saturated Polarization Measurement

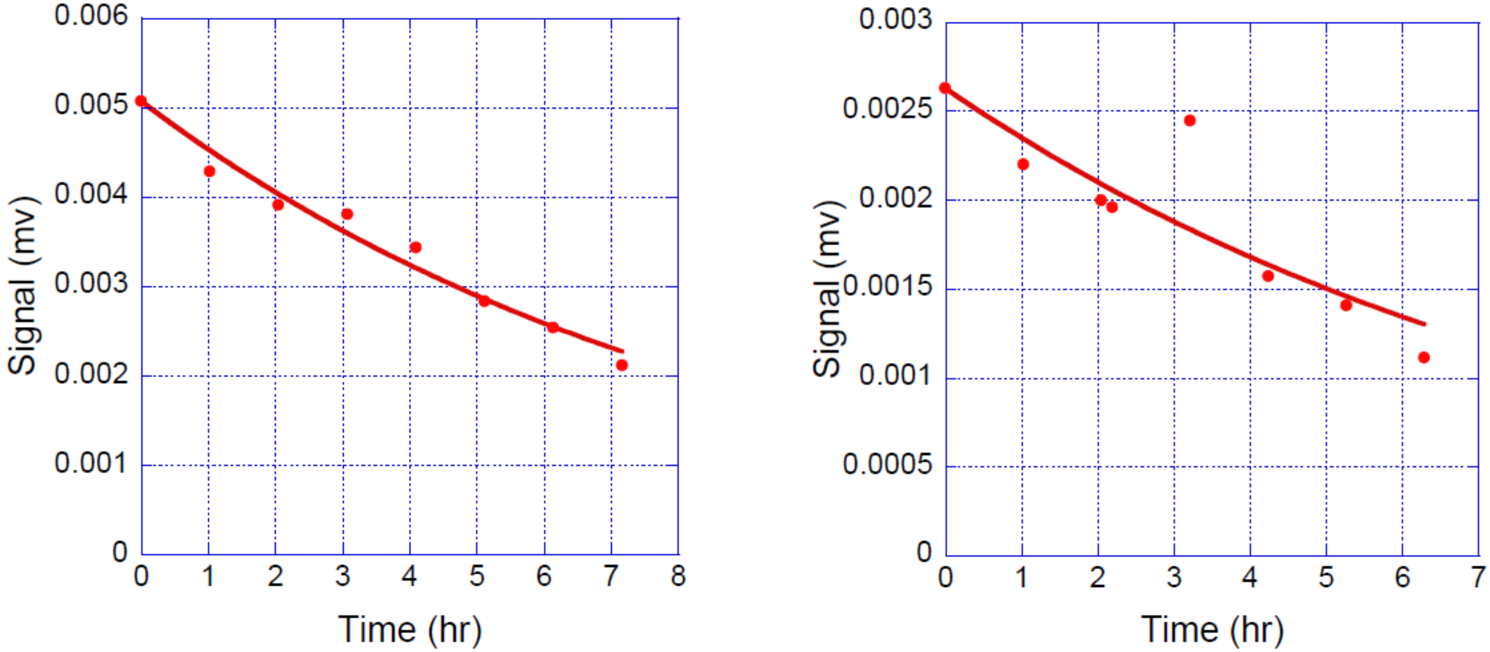




- **Left, the saturated 3He polarization slowly decayed with time.**
- **Right, after we drove Rb to the capillary tubing to separate the optical pumping cell from the valve, the 3He polarization stayed constant for more than a week, indicating a small gas leakage from the valve.**

Tests and Results

❑ Cell Lifetime Measurement



- **Left, the OPC decay measurement, the fit gives 8.7 ± 0.4 hours of lifetime**
- **Right, the OPC is blocked from capillary using Rb, the fit gives 10.5 ± 1.6 hours of lifetime**

Tests and Results

- ❑ Unpolarized gas transfer between the optical pumping cell and the recycle tank shows a negligible loss

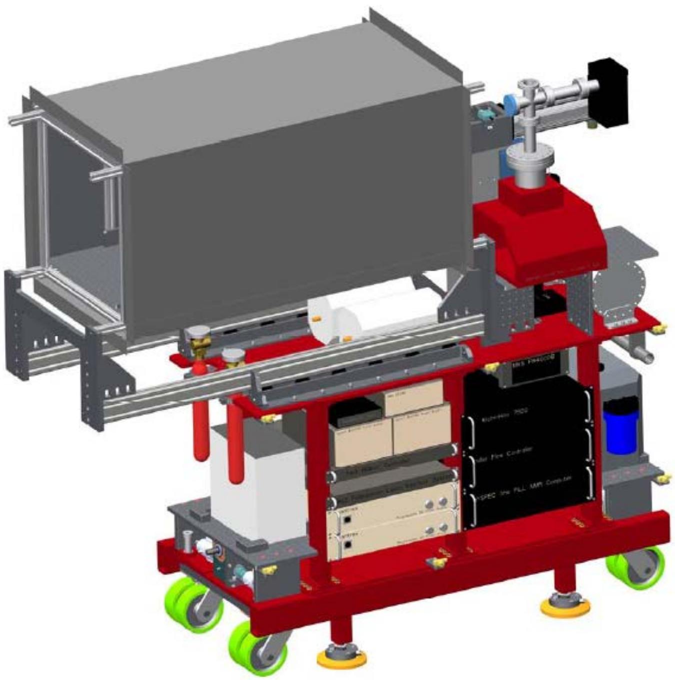
- ❑ Polarized ^{3}He transfer between the optical pumping cell and the syringe shows ~ 15% polarization loss per transfer

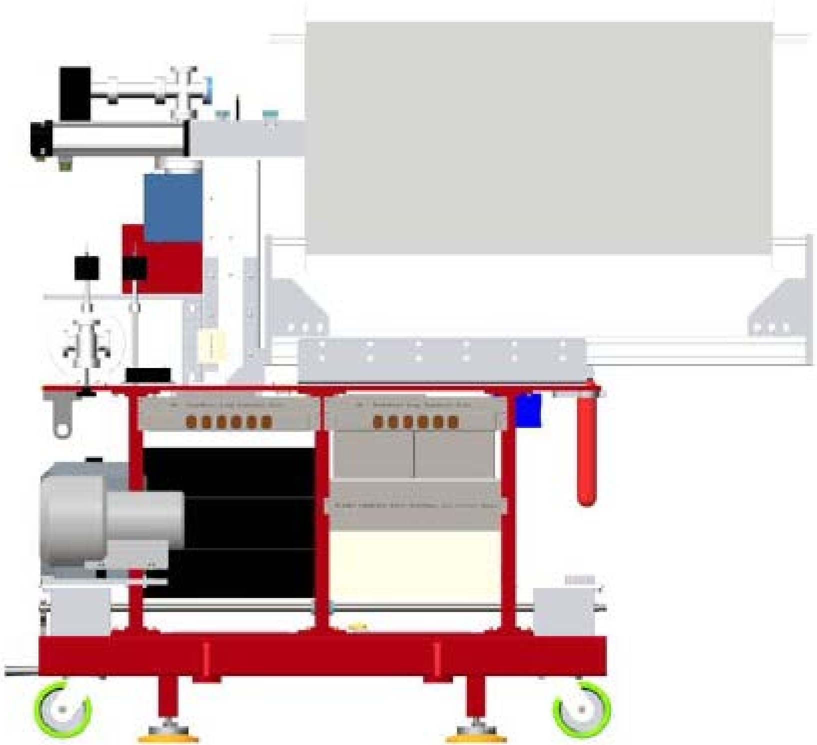
- ❑ EPR measurements show ~ 20% ^{3}He polarization achieved

Showed proof of principle
Next version is underway

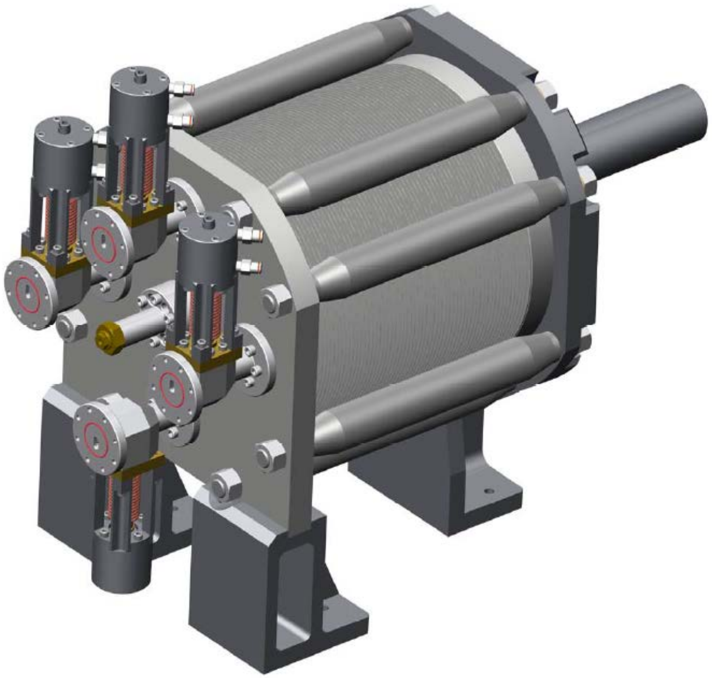
Future Improvements

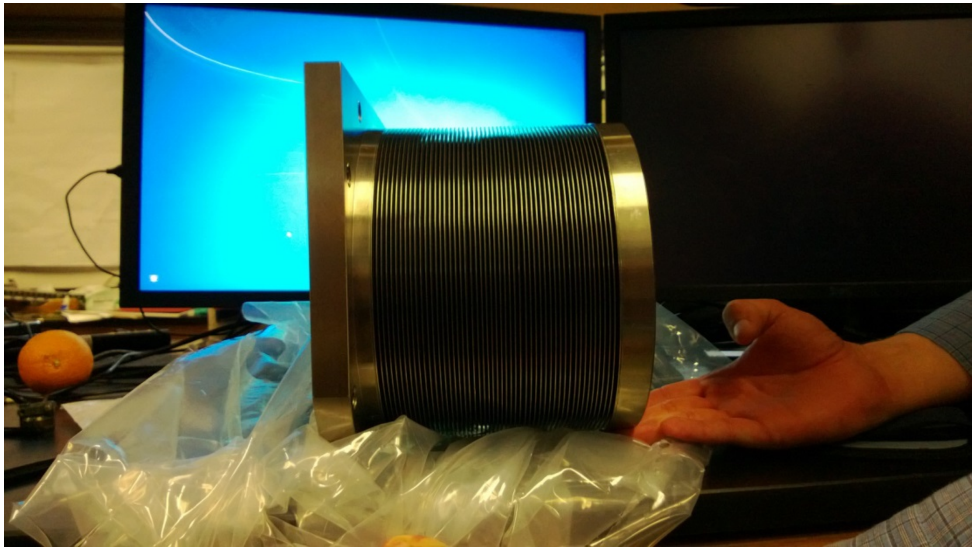
- **A Higher power fiber-coupled laser (200W)**
- **A completely redesigned cart, more compact**





- **A titanium bellow system to replace the current syringe**



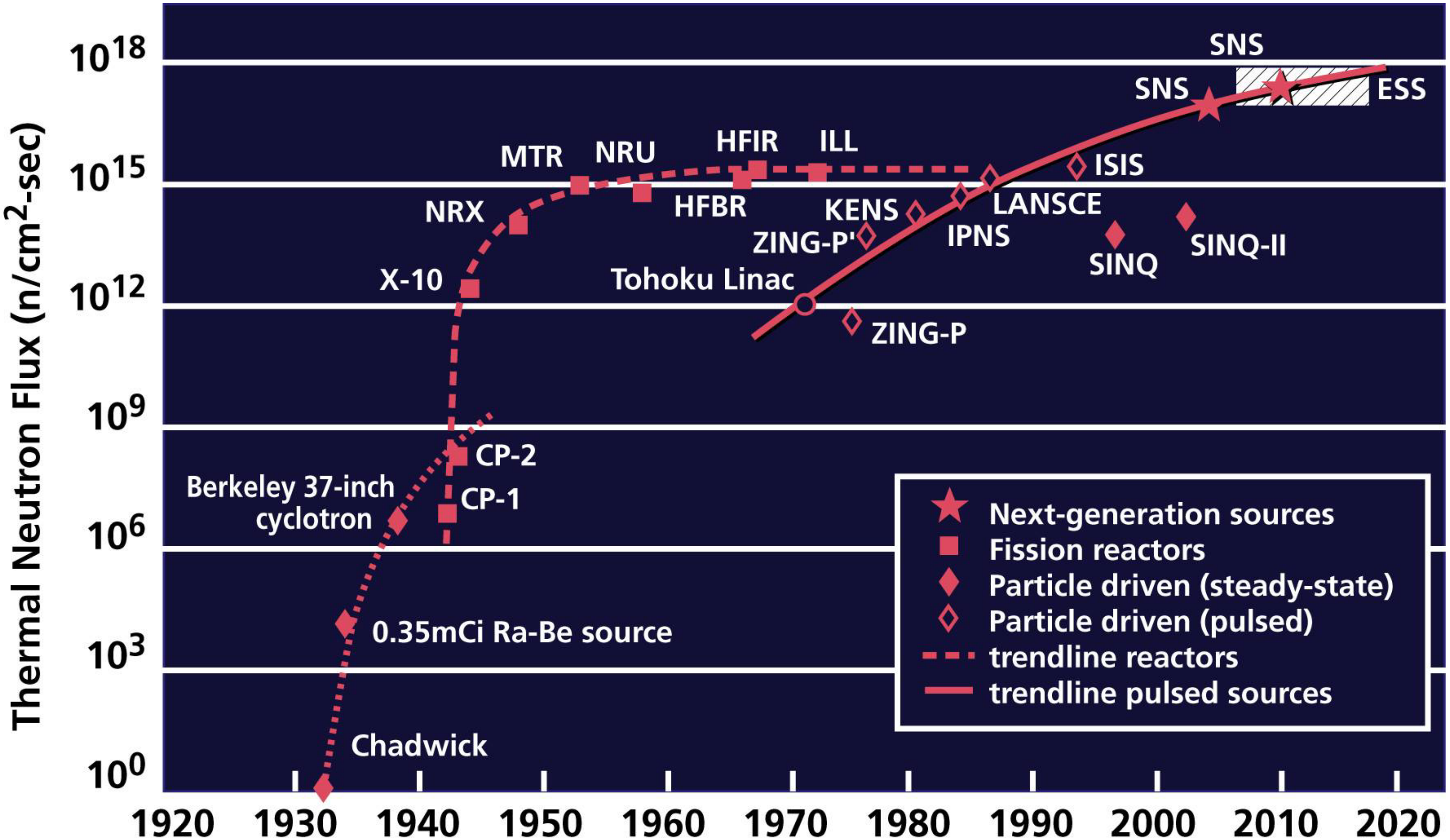


Summary

- ^{3}He cells of long lifetime and high polarization
  - 70%+ ^{3}He polarization
  - 100+ hours of decay time
- drop-in ^{3}He cells as polarizer or analyzer
  - 95%+ neutron polarization (wavelength dependent)
  - 40% neutron transmission (wavelength dependent)
  - Fast turn-around time
- *in situ* ^{3}He pumping systems
  - Maintains steady ^{3}He polarization
  - Permanent installation with minimum maintenance required
- online ^{3}He filling system for HYSPEC
  - The world's first polarized gas transfer system using SEOP

Thanks

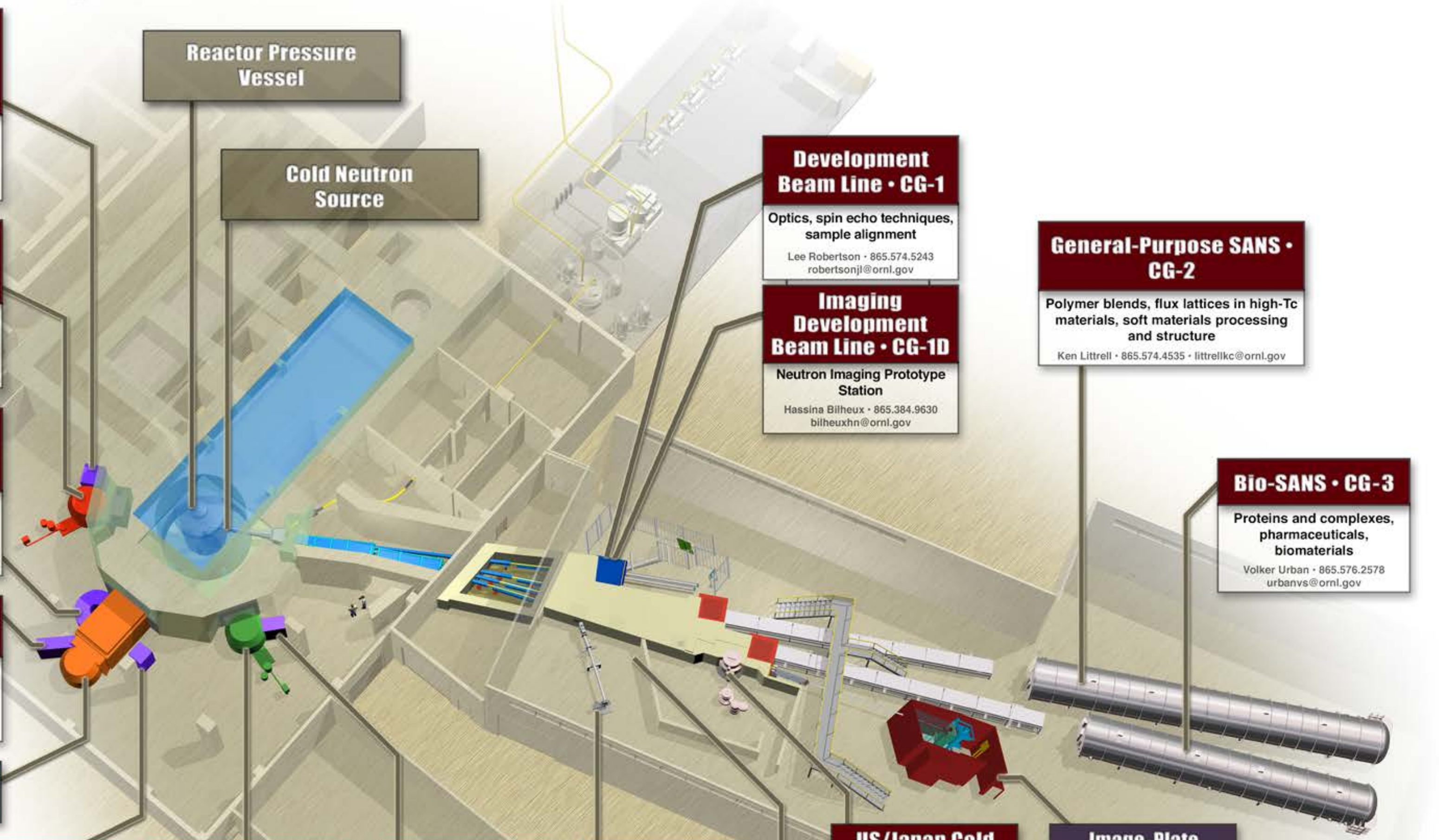
Where do we get the neutrons to do the scattering?



High Flux Isotope Reactor at Oak Ridge National Laboratory

The United States' highest flux reactor-based neutron source

HFIR



Fixed-Incident-Energy Triple-Axis Spectrometer • HB-1A
Low-energy excitations, magnetism, structural transitions
Jerel Zarestky • 865.574.4951
zarestkyjl@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
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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

Reactor Pressure Vessel

Cold Neutron Source

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
Huibo Cao • 865.241.9428
caoh@ornl.gov

Development Beam Line • CG-1
Optics, spin echo techniques, sample alignment
Lee Robertson • 865.574.5243
robertsonjl@ornl.gov

Imaging Development Beam Line • CG-1D
Neutron Imaging Prototype Station
Hassina Bilheux • 865.384.9630
bilheuxhn@ornl.gov

General-Purpose SANS • CG-2
Polymer blends, flux lattices in high-Tc materials, soft materials processing and structure
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urbanvs@ornl.gov

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Future Development • CG-4B

US/Japan Cold Neutron Triple-Axis Spectrometer • CG-4C
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hongt@ornl.gov

Image-Plate Single-Crystal Diffractometer (IMAGINE) • CG-4D (2012*)
Chemical, organic, metallo-organic, protein single crystals
Flora Meilleur • 865.241.2897
meilleurf@ornl.gov

* Scheduled commissioning date.

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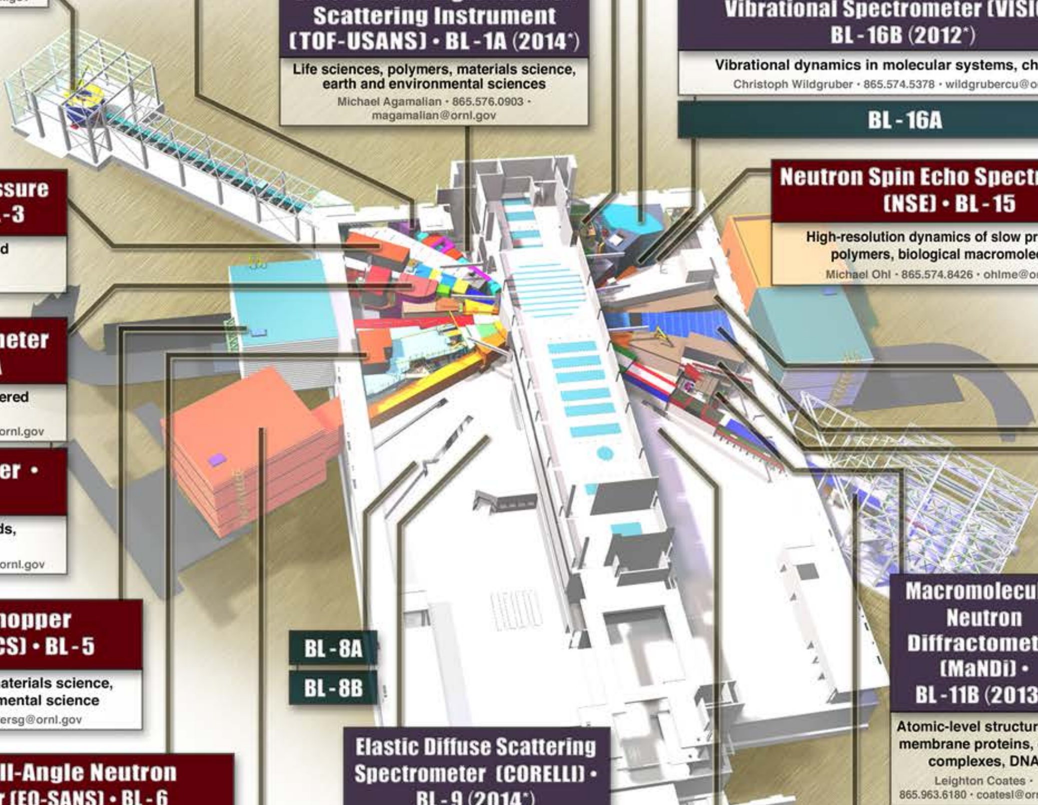
Spallation Neutron Source at Oak Ridge National Laboratory

The world's most intense pulsed, accelerator-based neutron source

SNS SPALLATION NEUTRON SOURCE



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

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Joerg Neuefeind • 865.241.1635 • neuefeindjc@ornl.gov

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

Doug Abernathy • 865.576.5105 • abernathydl@ornl.gov

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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

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Vibrational dynamics in molecular systems, chemistry

Christoph Wildgruber • 865.574.5378 • wildgrubercu@ornl.gov

BL-16A

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

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Chris Tulk • 865.576.7028 • tulkca@ornl.gov

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Barry Winn • 865.809.6819 • winnbl@ornl.gov

BL-14A

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Valeria Lauter • 865.576.5389 • lauterv@ornl.gov

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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

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BL-8A

BL-8B

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Christina Hoffmann • 865.576.5127 • hoffmanncm@ornl.gov

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BL-10

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Engineering Materials Diffractometer (VULCAN) • BL-7

Mechanical behaviors, materials science, materials processing

Ke An • 865.919.5226 • kean@ornl.gov

* Scheduled commissioning date

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