Neutron Polarization and Transmission Measurement for the nEDM@SNS Experiment

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nEDM2023 Workshop – Santa Fe

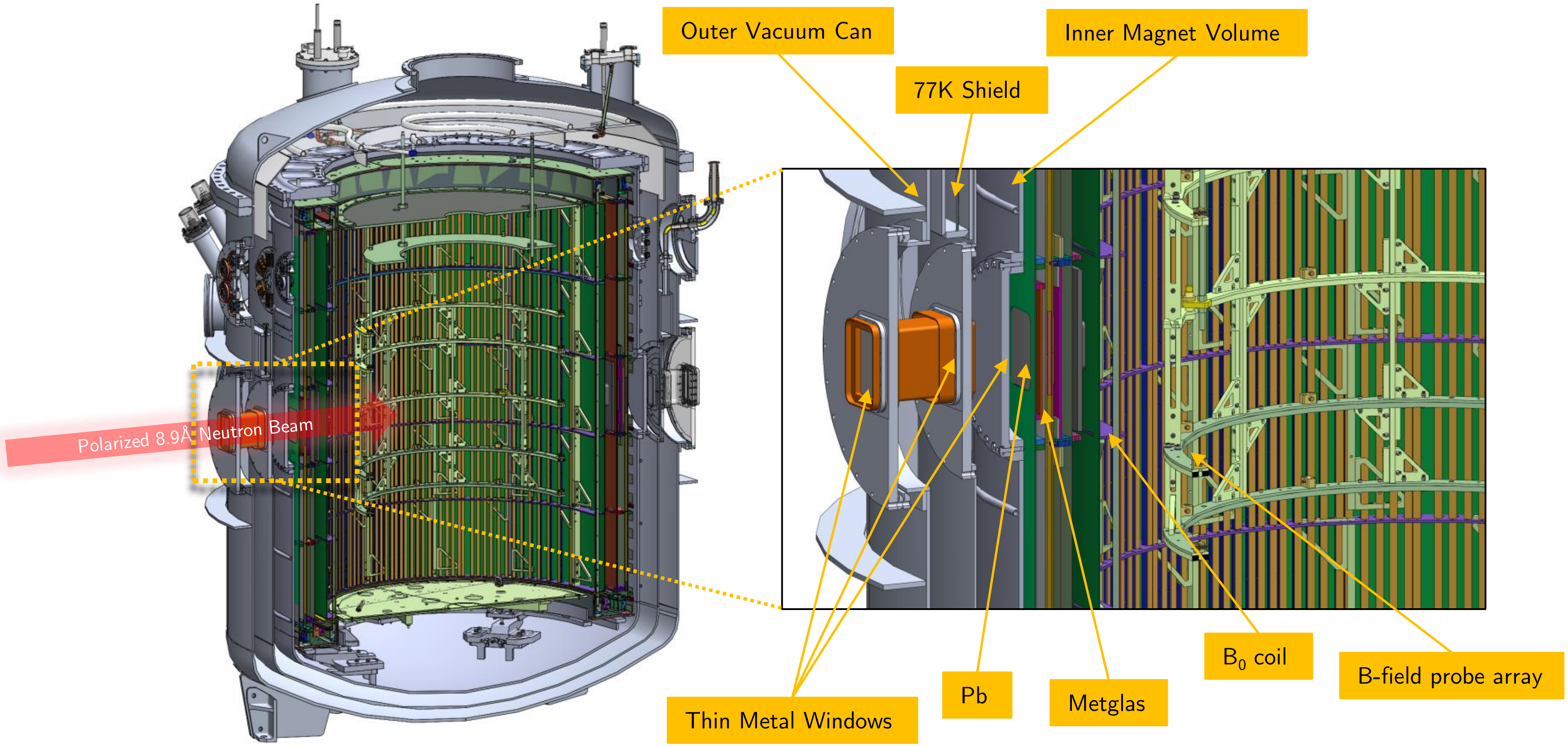
November 8 2023

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Overview

- Neutron Polarization and Transmission Measurements.
- ^{3}He Polarimetry.
- Measurement Results.
- Small Angle Neutron Scattering Measurements.

Cryogenic Magnet & Associated Beam Windows



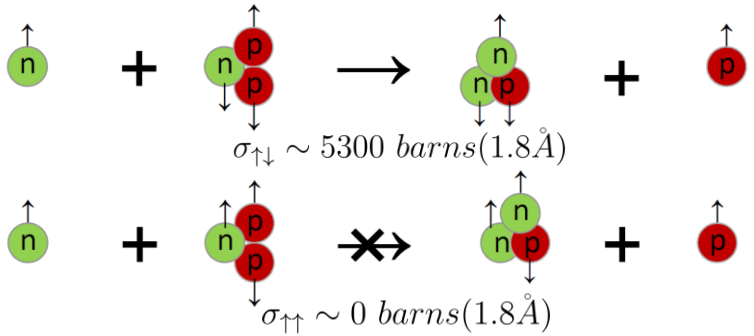
M.W. Ahmed et al., J. Inst. 14 P11017 (2019).

Polarization from ^{3}He Transmission

$$P_n = tanh(\sigma(\lambda) N_{He} L_{He} P_{He})$$

$$T_{pol} = T_0 cosh(\sigma(\lambda) N_{He} L_{He} P_{He})$$

$$T_0 = N_0 e^{-\sigma(\lambda) n_{He} L}$$



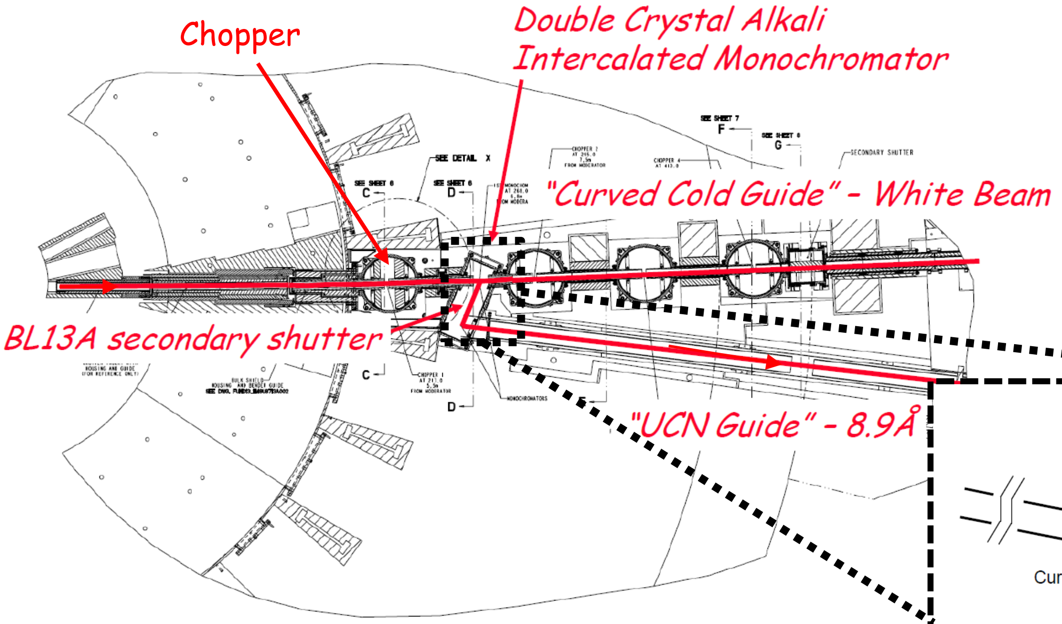
- Very difficult to measure the cell parameters for high precision polarimetry.
- From hyperbolic identities the polarization of a monochromatic neutron beam analyzed by a ^{3}He cell can be expressed in terms of neutron transmission measurements.

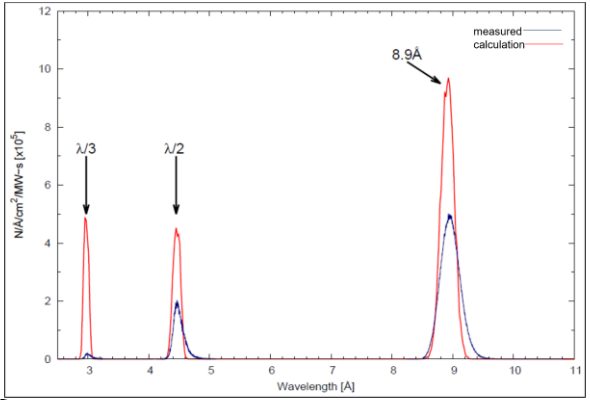
$$P_n = \frac{R - R_{sf}}{\sqrt{[(2\epsilon_{sf} - 1)R + R_{sf}]^2 - 4\epsilon_{sf}^2}}$$

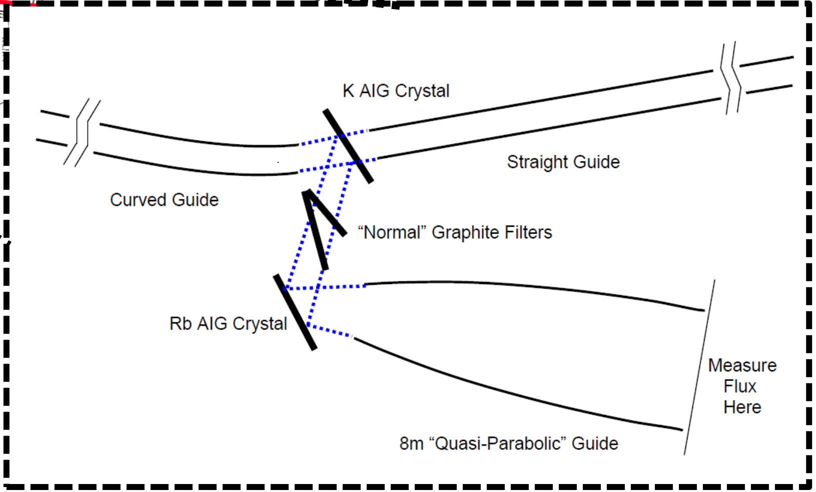
$$R = \frac{T}{T_0} \quad R_{sf} = \frac{T_{sf}}{T_0} \quad \epsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T^{AFP} - T}{T^{AFP} + T}}{\frac{T_{sr}^{AFP} - T_{sf}}{T_{sr}^{AFP} + T_{sf}}}\right)$$

G. L. Greene et. al, Nuc. Inst. Methods A 356 (1995).

Fundamental Neutron Physics Beamline-13



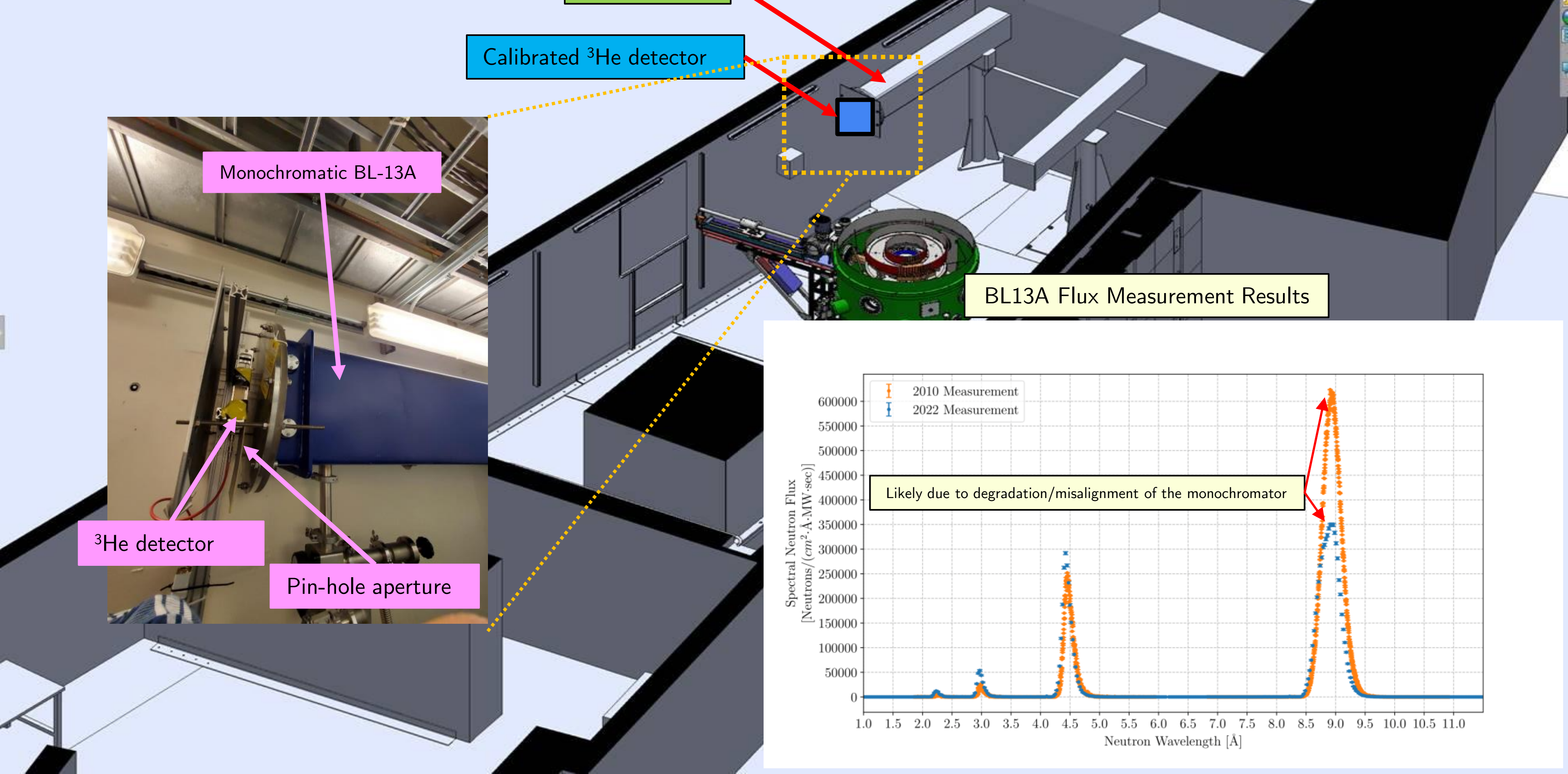




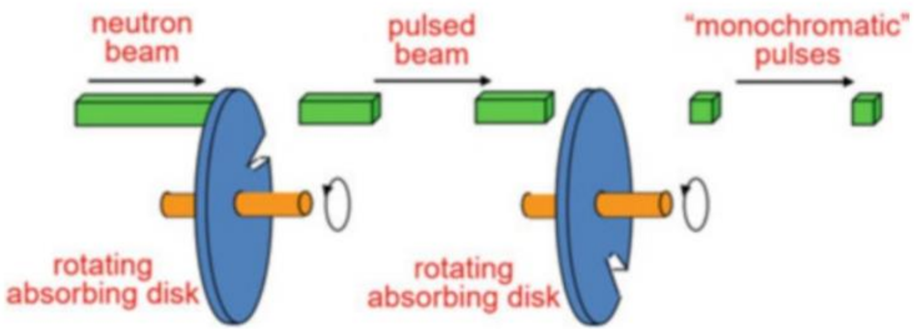
Neutrons that satisfy the Bragg condition of the crystal are reflected.

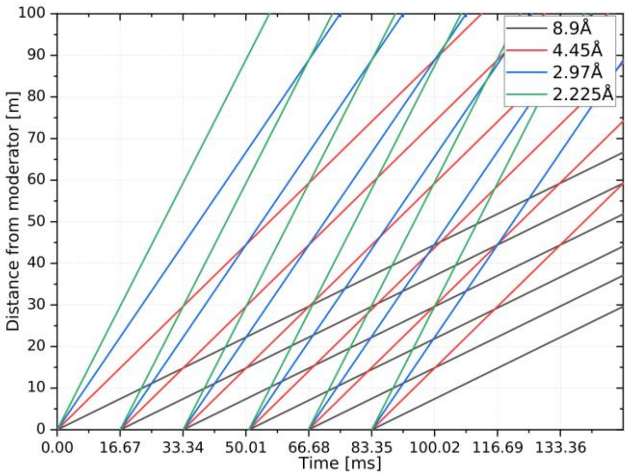
N. Fomin et. al, Nucl. Instrum. Methods A 773 (2015) 45

Beamline 13A

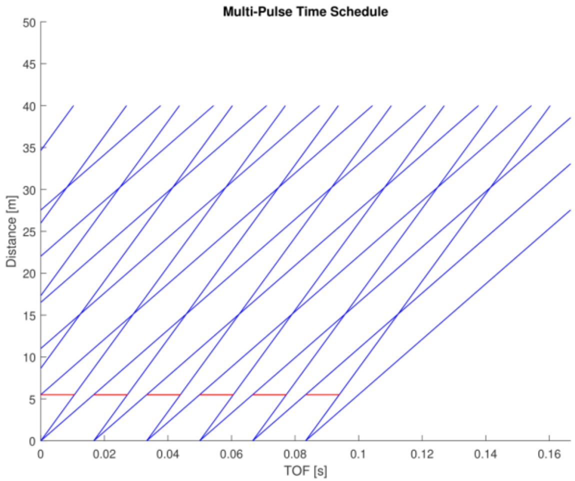


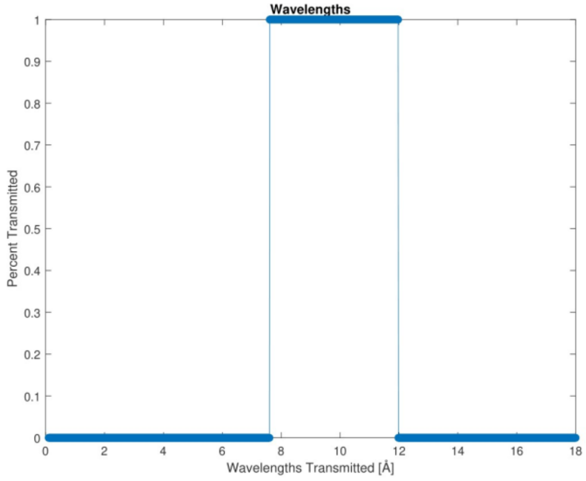
Neutron Time of Flight Choppers



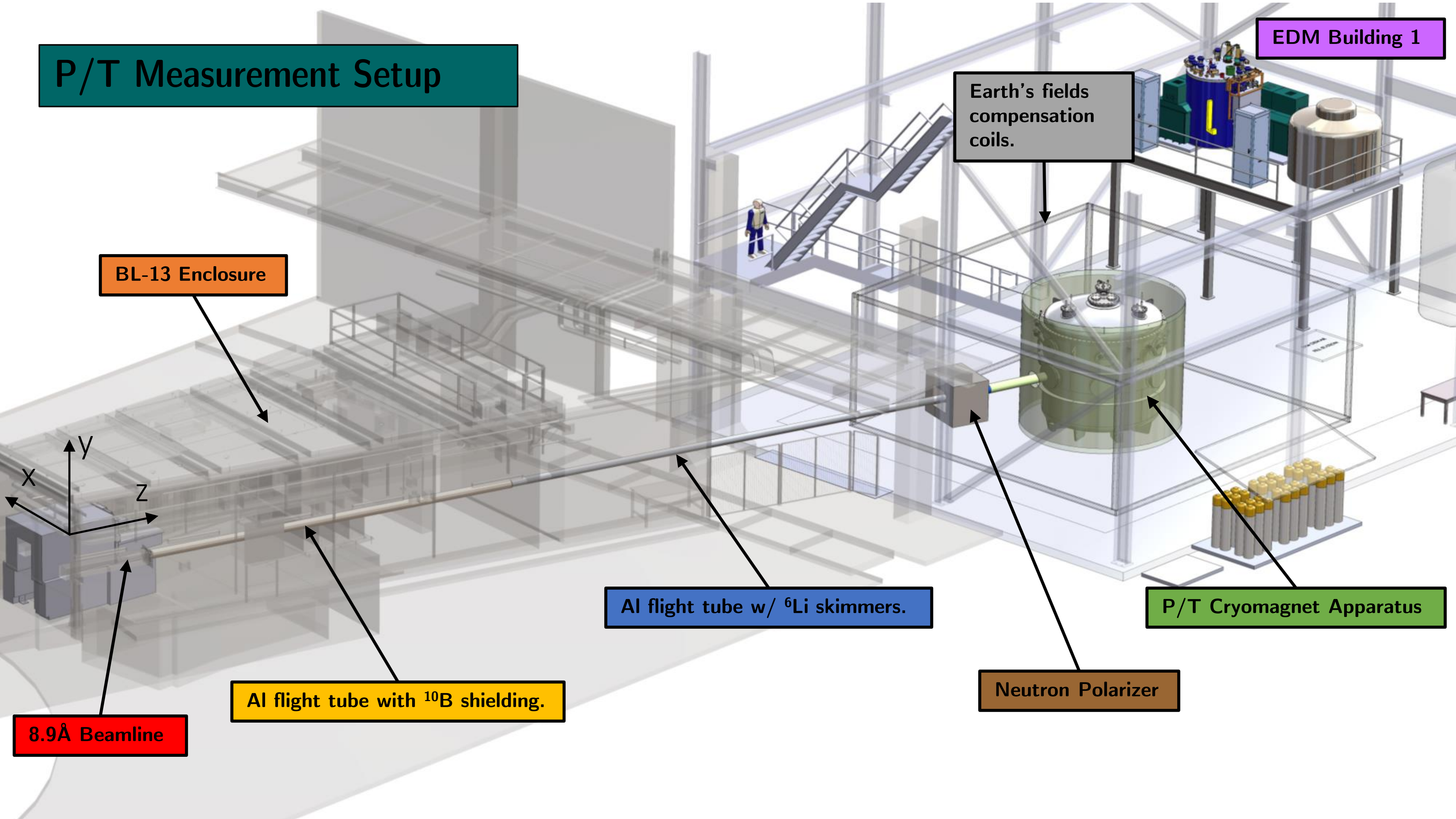


- Frame overlap choppers rotate in sync with the neutron repetition rate.
- Tune the phase of rotation to allow select time of flight neutrons which align with chopper opening.

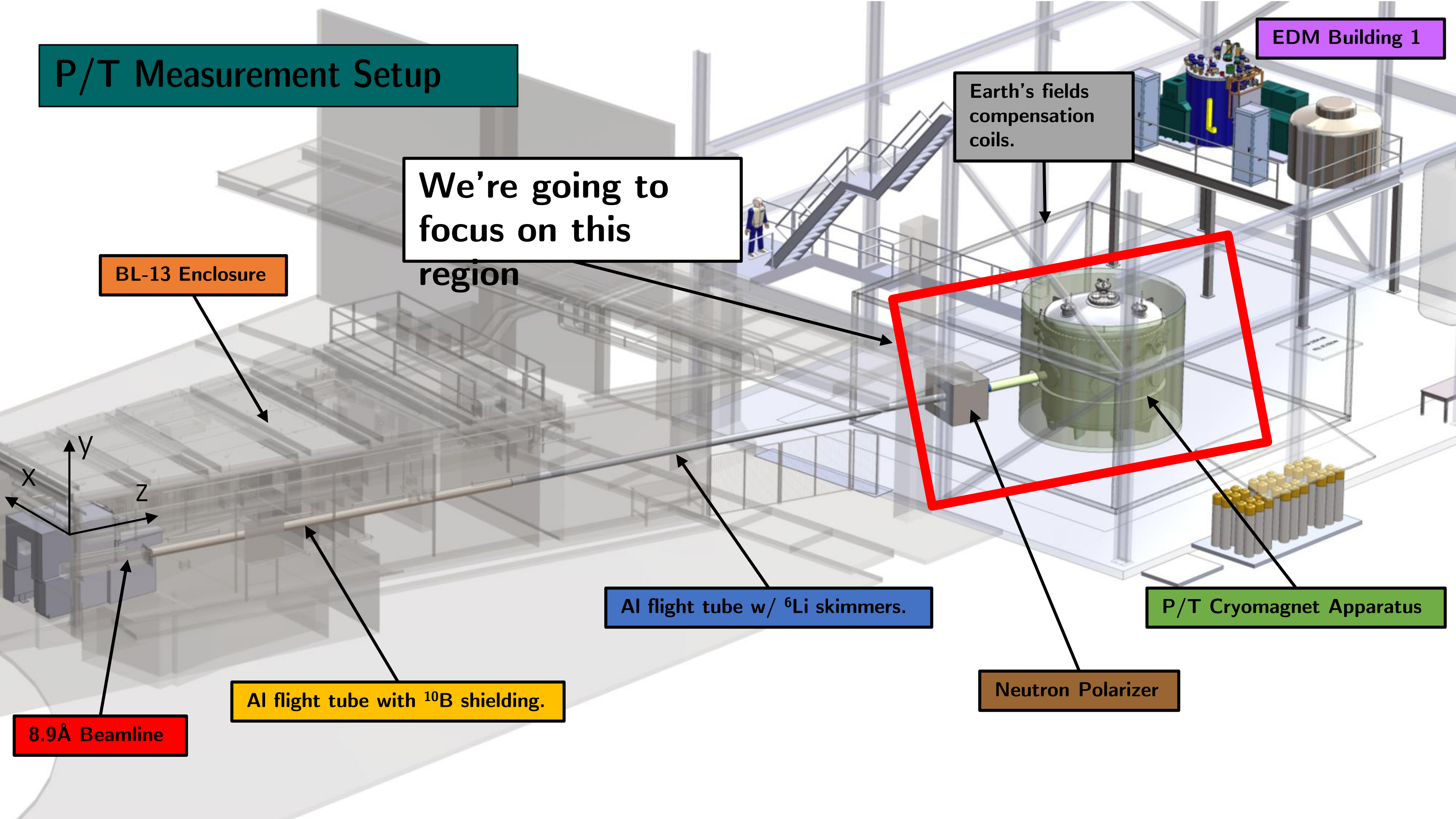




P/T Measurement Setup



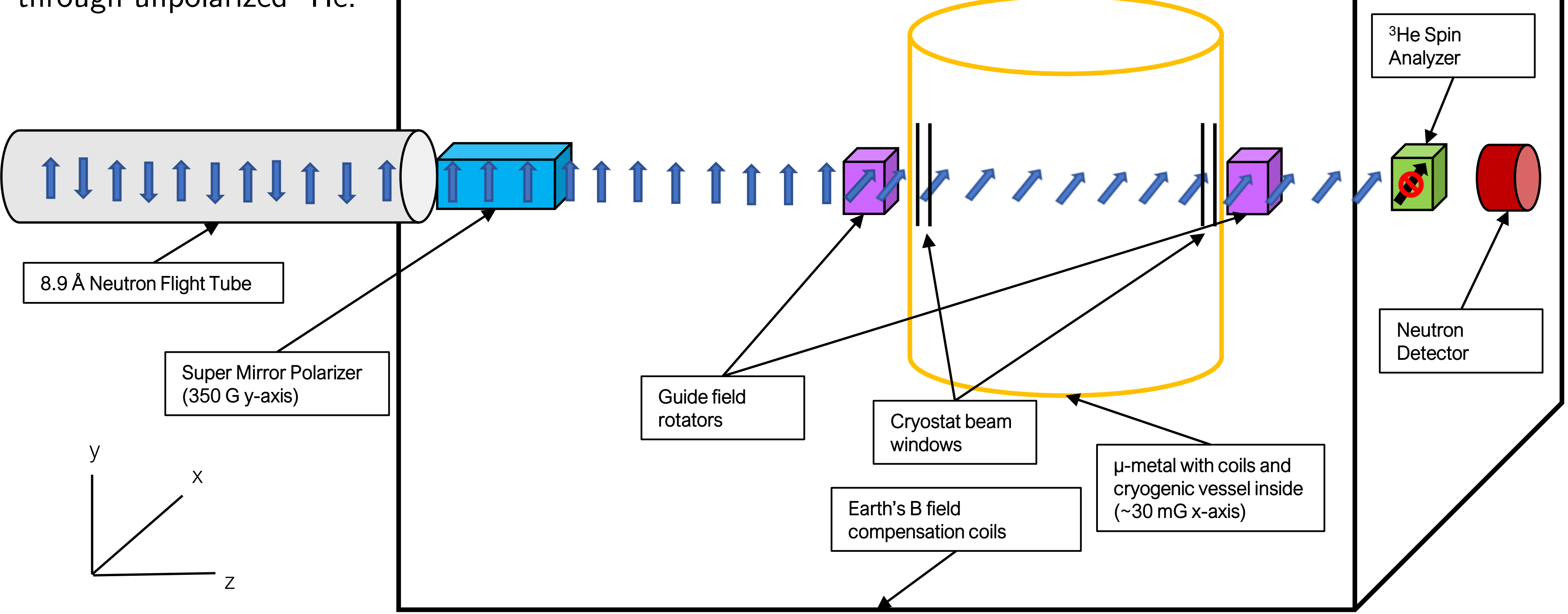
P/T Measurement Setup



P & T Measurement Setup

1) Transmission of polarized neutrons through unpolarized ^{3}He.

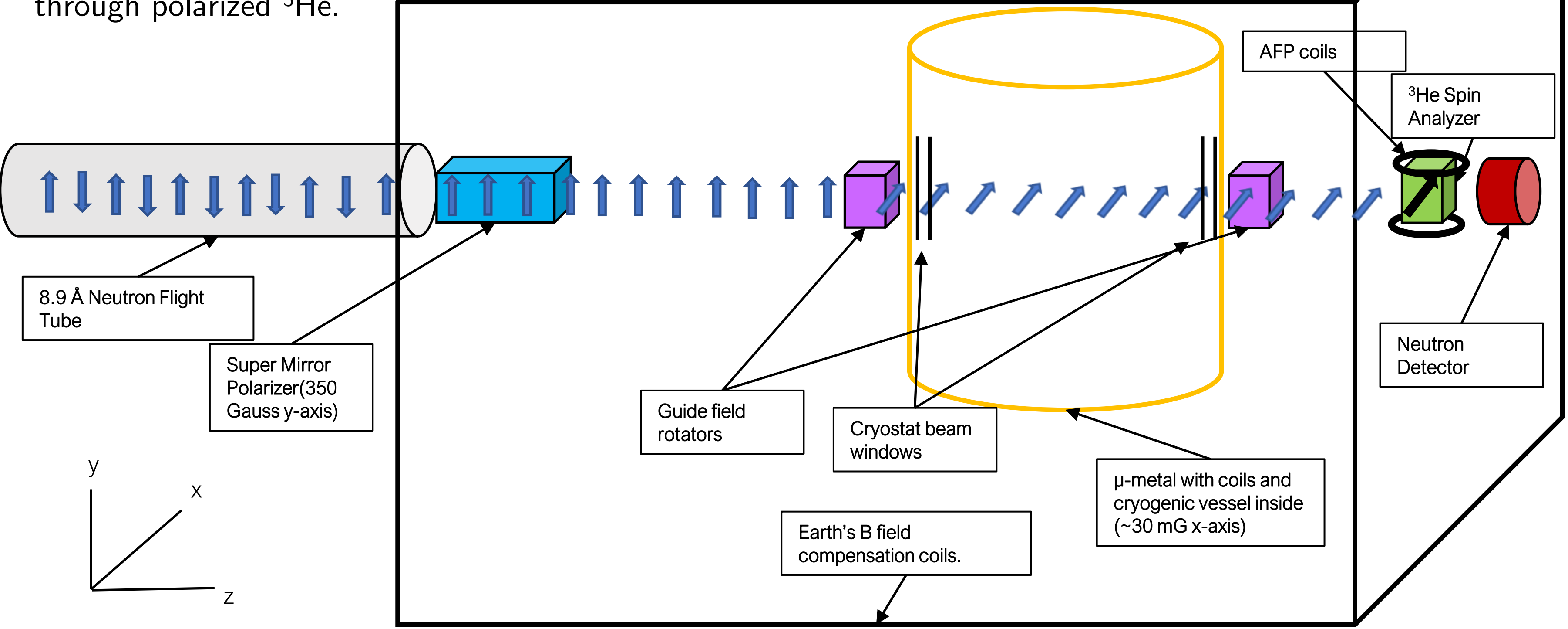
$$R = \frac{T}{T_0}, \; R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$



P & T Measurement Setup

2a) The transmission of polarized neutrons through polarized ^{3}He.

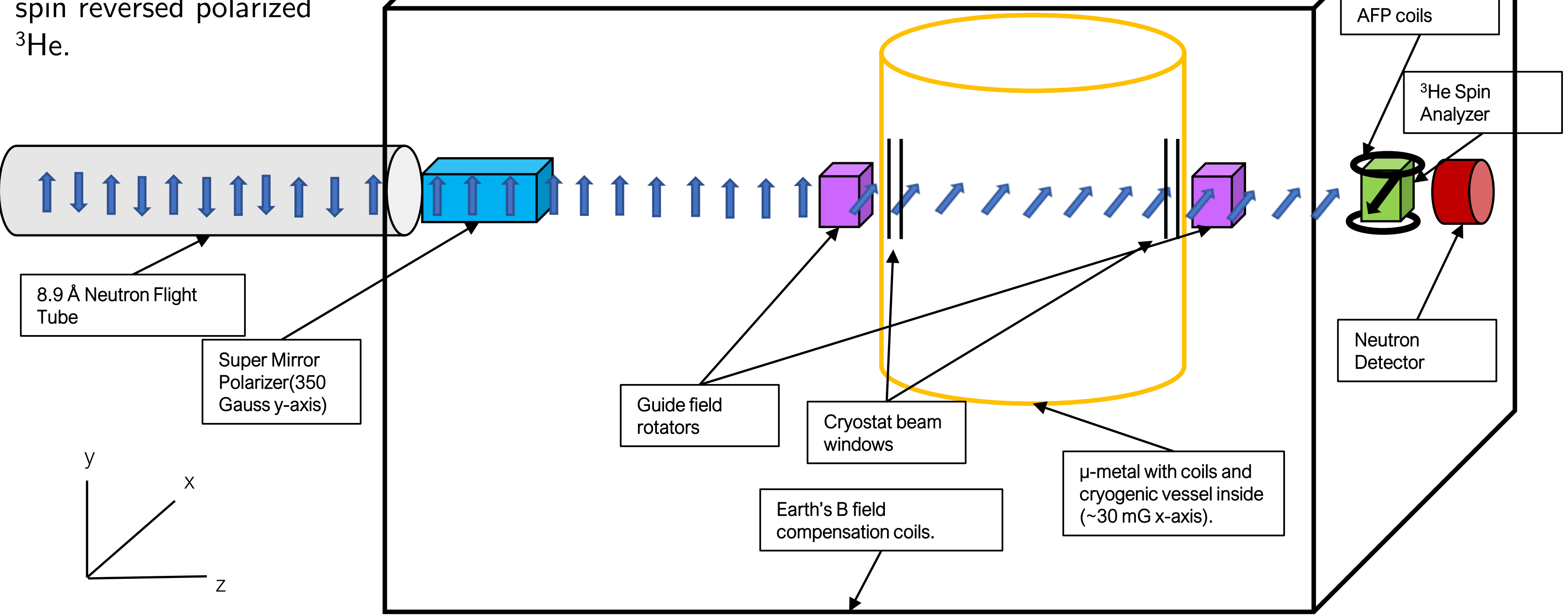
$$R = \frac{T}{T_0}, \; R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$



P & T Measurement Setup

2b) The transmission of polarized neutrons through spin reversed polarized ^3He.

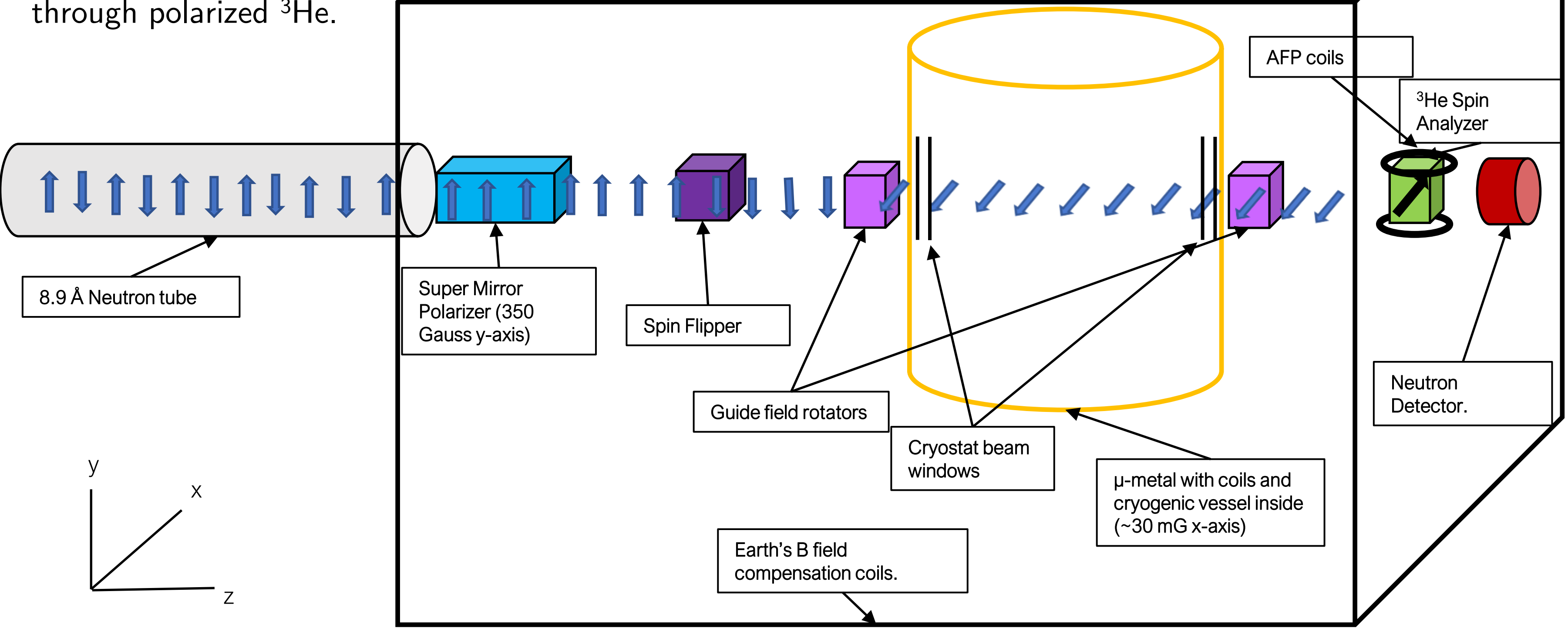
$$R = \frac{T}{T_0}\ ,\ R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$



P & T Measurement Setup

3a) The transmission of spin flipped neutrons through polarized ^{3}He.

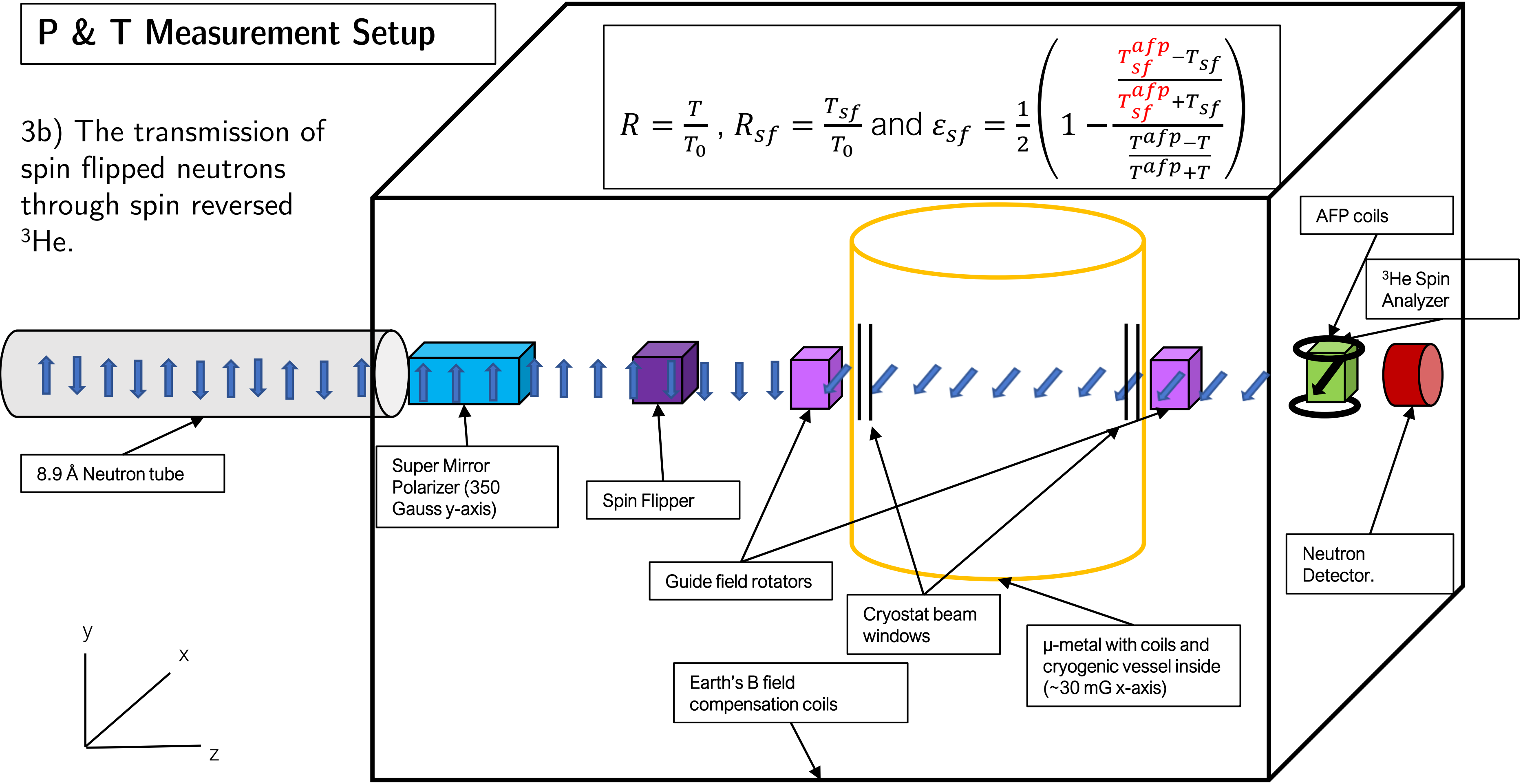
$$R = \frac{T}{T_0}\ ,\ R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$



P & T Measurement Setup

3b) The transmission of spin flipped neutrons through spin reversed ^{3}He.

$$R = \frac{T}{T_0}\ ,\ R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$



Determination of Neutron Polarization

$$P_n = \frac{R - R_{sf}}{\sqrt{[(2\epsilon_{sf} - 1)R + R_{sf}]^2 - 4\epsilon_{sf}^2}}$$

$$R = \frac{T}{T_0}\ ,\ R_{sf} = \frac{T_{sf}}{T_0}\ \&\ \epsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T^{AFP}-T}{T^{AFP}+T}}{\frac{T_{sr}^{AFP}-T_{sf}}{T_{sr}^{AFP}+T_{sf}}}\right)$$

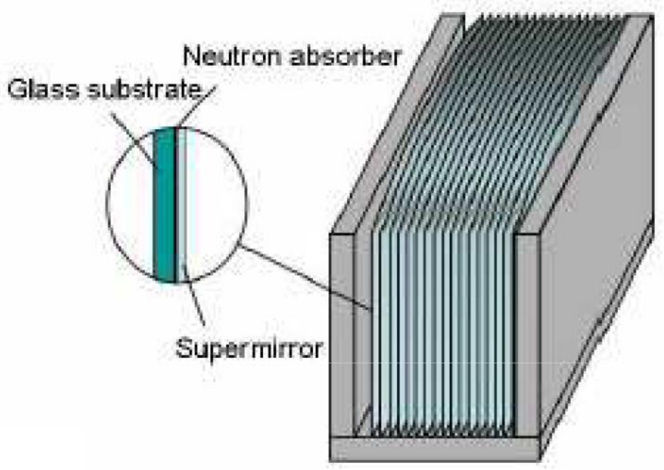
- Neutron polarization can be determined by R and R_{sf} which simply represent ratios of transmissions through ^{3}He analyzer.
- ^{3}He polarization and the physical properties of the ^{3}He cell do not need to be known to determine the neutron polarization.

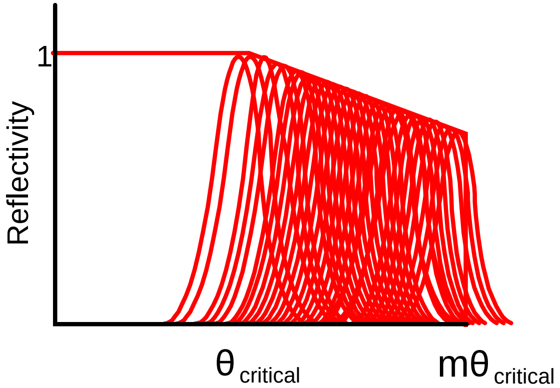
G. L. Greene et. al, Nuc. Inst. Methods A 356 (1995).

Supermirror Neutron Polarizer

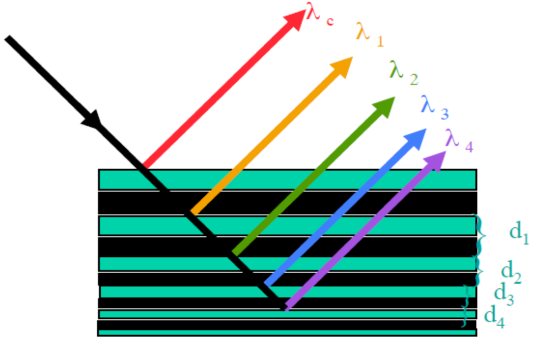
- The spin dependent refractive index of magnetized mirrors for neutrons of wavelength λ.
- One spin state is reflected while the other is absorbed.

$$n = \sqrt{1 - \left(\frac{Nb_{coh}}{\pi} \pm \frac{\mu B}{2\pi^2\hbar^2}\right)\lambda^2}$$





$$\theta = \frac{1.73mrad}{\mathring{A}} \cdot \lambda \cdot m$$



"Super-mirror" system (e.g. Fe/Si bilayers)

- A gradient in the lattice spacing of the multi-bilayers results in a range of effective Bragg angles.
- Reflectivity extends beyond values expected for normal mirror reflections.

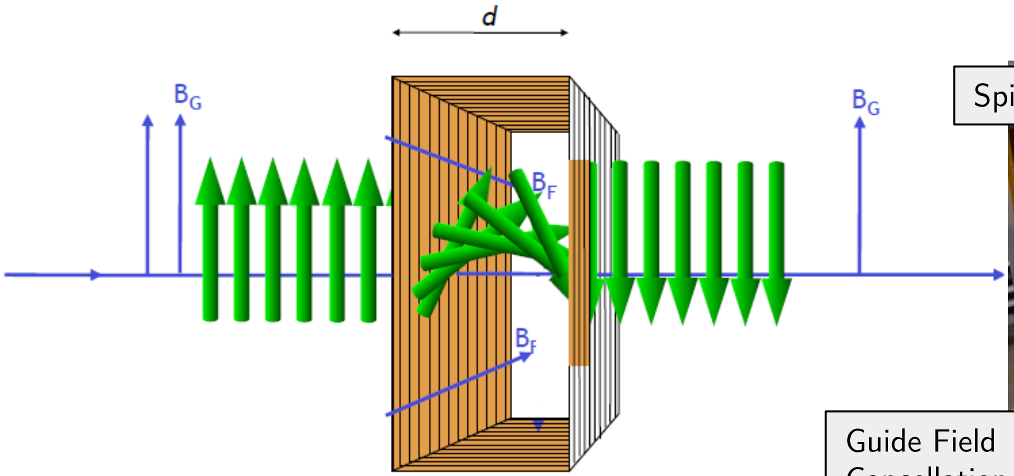
Balascuta et. al, Nuc. Inst. Methods A 671 (2012).

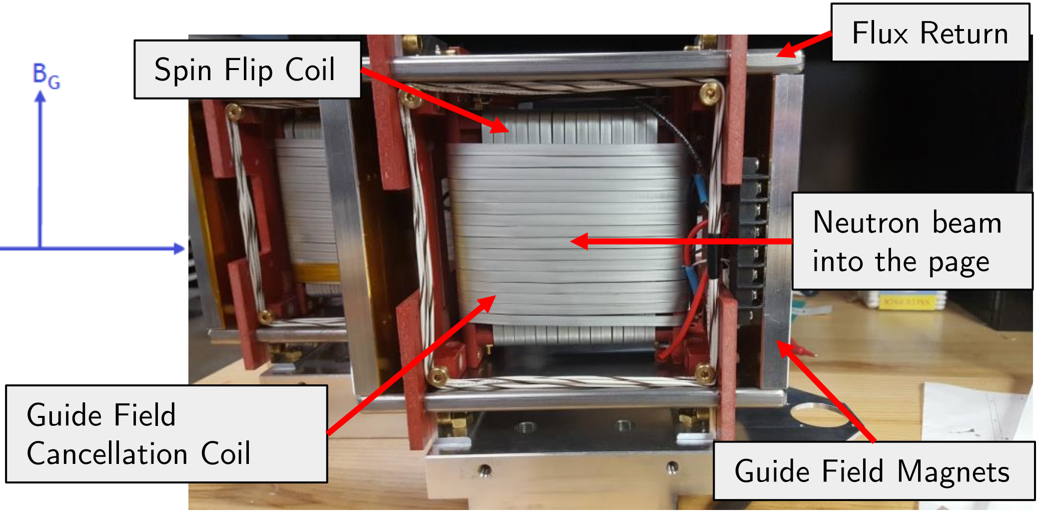
Mezei-type Diabatic Spin Flipper

Diabatic field perpendicular to the guide field change to project the polarization direction of the beam onto any arbitrary field axis.

Useful for monochromatic beams i.e. fixed velocity.

$$d = \frac{\phi v}{\gamma_n B_R}$$





F. Mezei, Z. Physik, 255 (1972) 146.

Mezei-type Diabatic Spin Flipper

- Spin Flipper efficiency measurements at HFIR for 4.2 Å neutrons:

$$\epsilon_{SF} = 0.93 \pm 0.06_{stat}$$

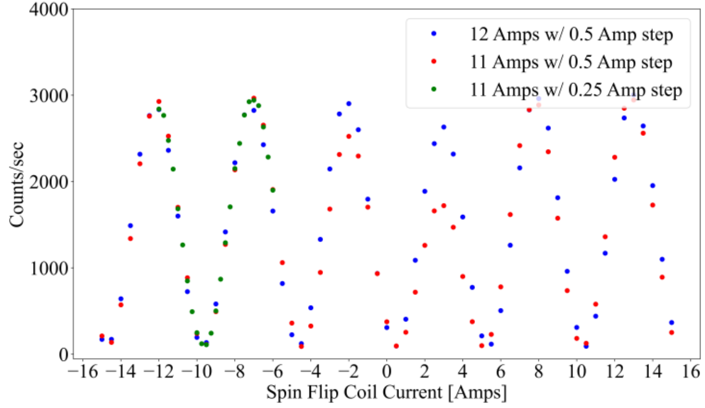
- And at the SNS for 8.9 Å:

$$\epsilon_{SF} = 0.92 \pm 0.03_{stat}$$

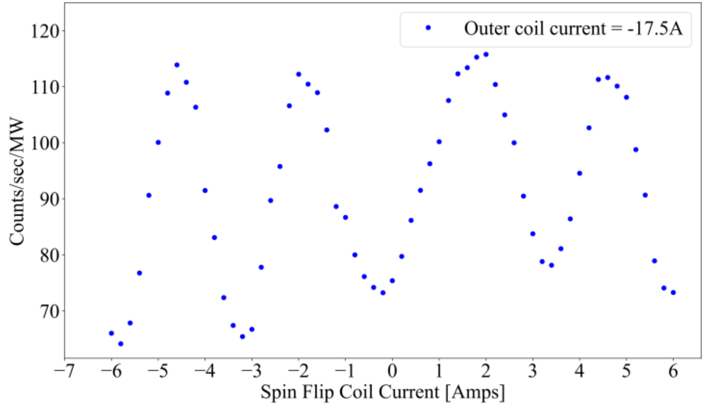
Note:

- Spin flipping contrast is more robust at higher currents.
- The fringe pattern observed for 4.2 Å neutrons is twice as broad as the pattern observed for 8.9 Å neutrons.

SF efficiency for 4.2 Å neutrons

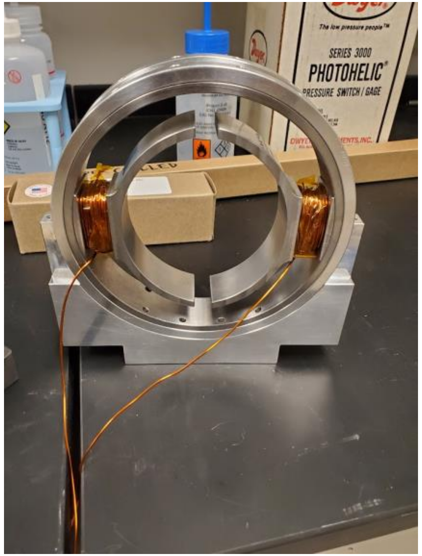


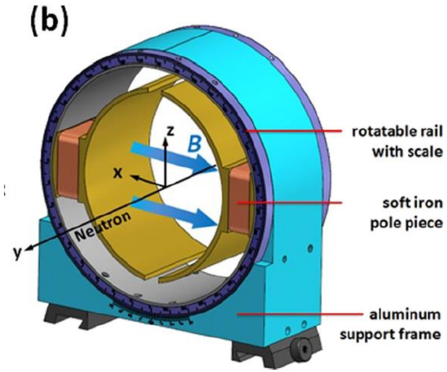
SF efficiency for 8.9 Å neutrons

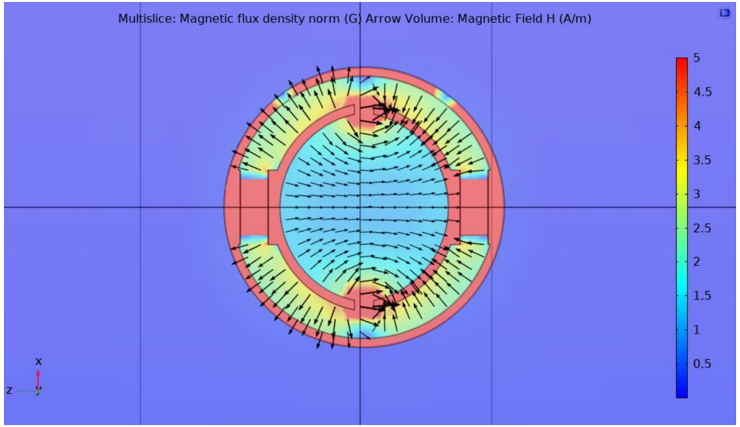


"Neutator"-Guide Field Rotator

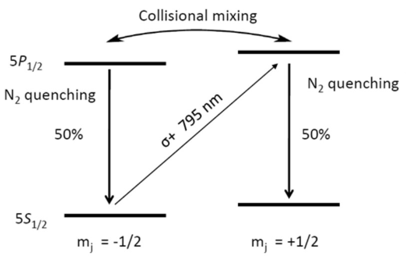
- Fix any depolarization from magnetic field misalignment or "zero-crossing" issues for incoming and outgoing neutron beam from cryo-magnet windows.
- Eliminate the need to rotate the spin flipper and provide the adiabatic rotation after the spin flipper.



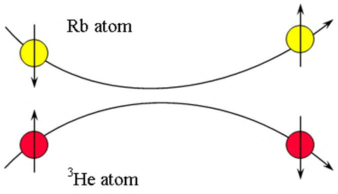




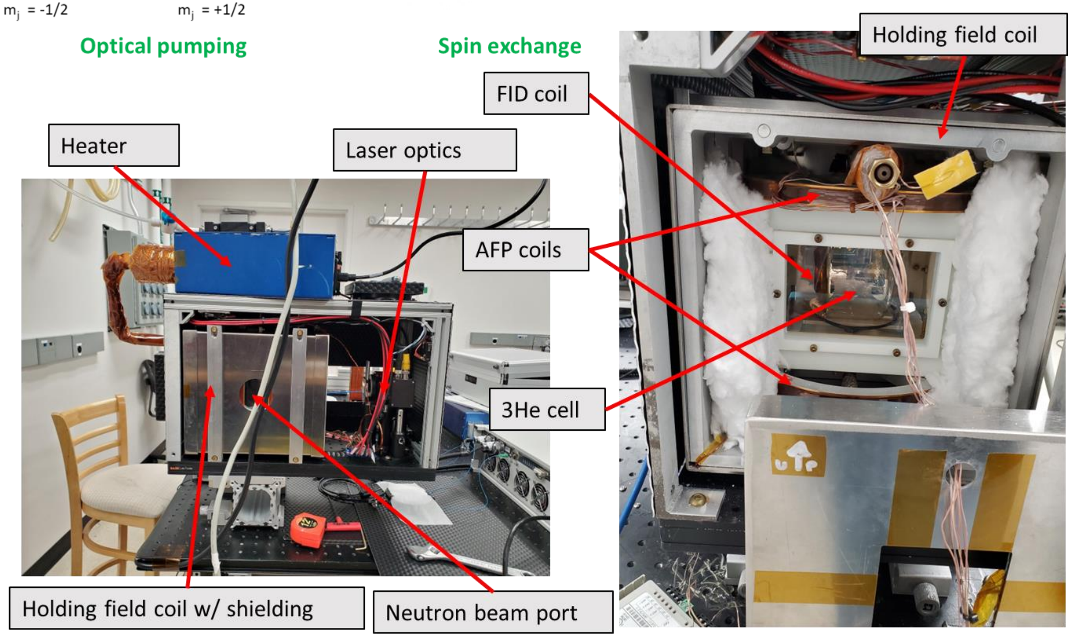
In situ SEOP for ^{3}He Spin Analyzer

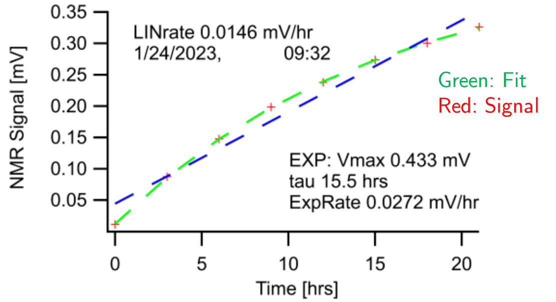


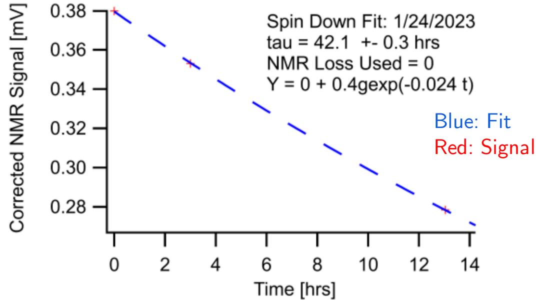
Optical pumping

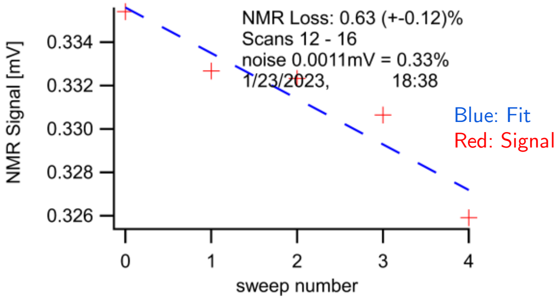


Spin exchange

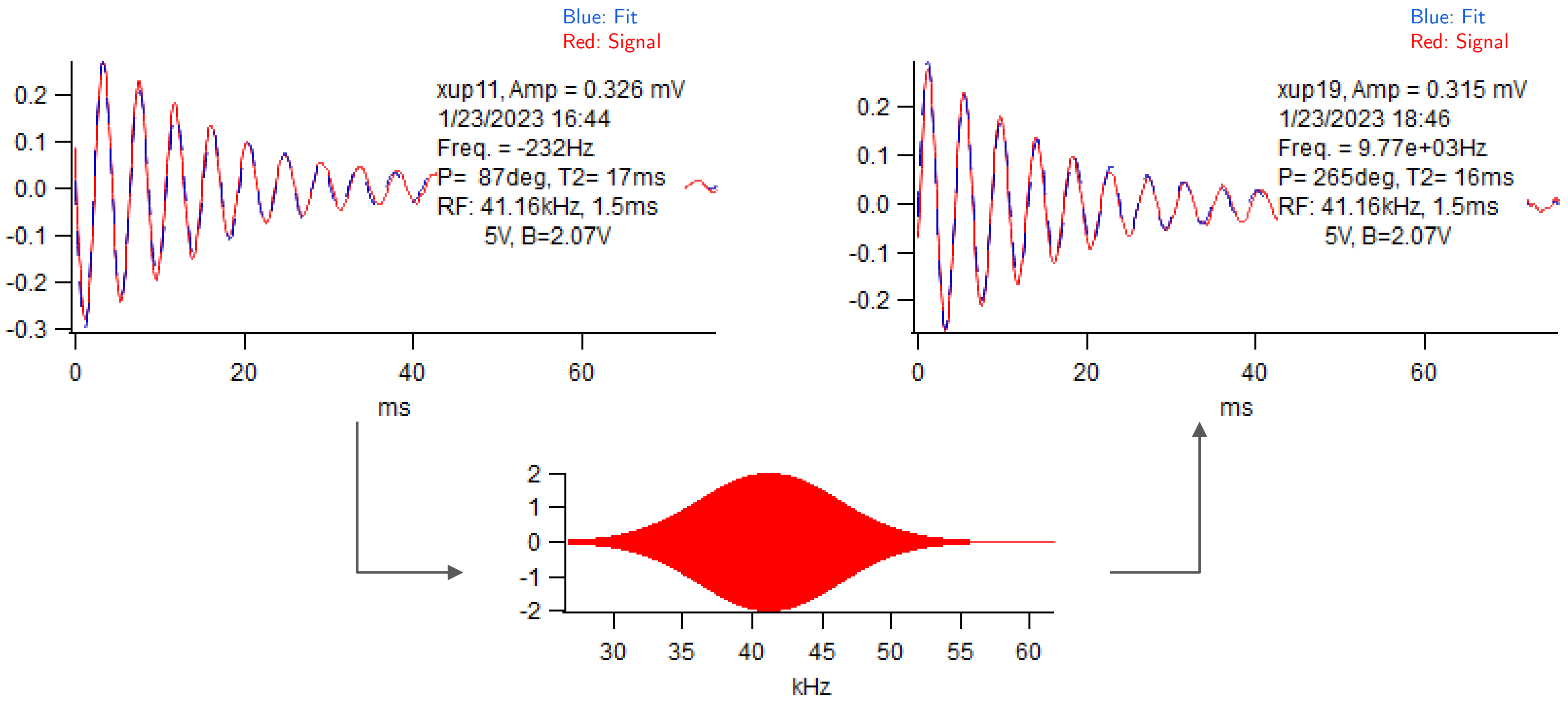








In situ SEOP for ^{3}He Spin Analyzer: Adiabatic Fast Passage



Performed 10 consecutive AFP flips with FID before and after and the AFP NMR loss came out to 0.053%

In situ SEOP for ^{3}He Spin Analyzer: Neutron Transmission

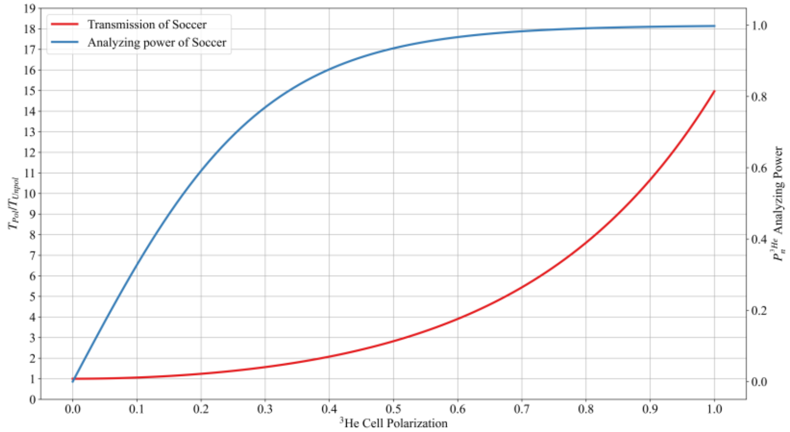
State	Beam Polarization State	Analyzer Polarization State	N/s/MW
N_0	Unpolarized	Not Present	4489
T_{unpol}	Unpolarized	Unpolarized	189
T_{pol}	Unpolarized	Polarized	263

$$T_0 = N_0 e^{-\chi}$$

$$T_{pol} = T_0 cosh(\chi P_{He})$$

$$P_n^{He} = tanh(\chi P_{He})$$

$$\chi = \frac{0.073}{bar * cm * \AA} * P[bar] * l[cm] * \lambda[\AA]$$



T_{unpol} or Cell Transmission = 4.2%

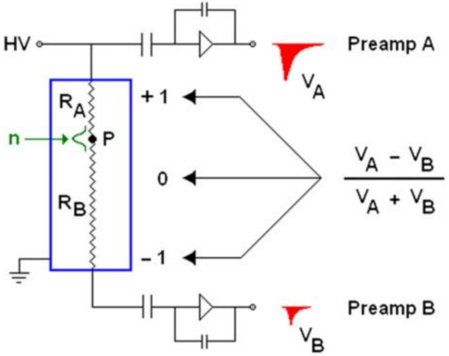
$T_{pol}/T_{unpol} = 1.39$

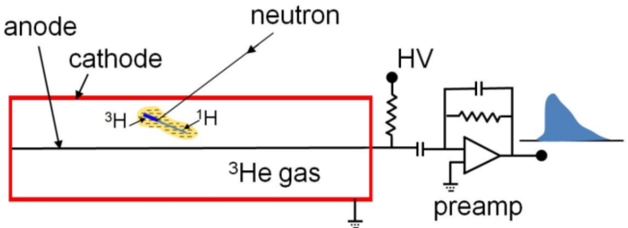
^{3}He Cell Polarization: 27%

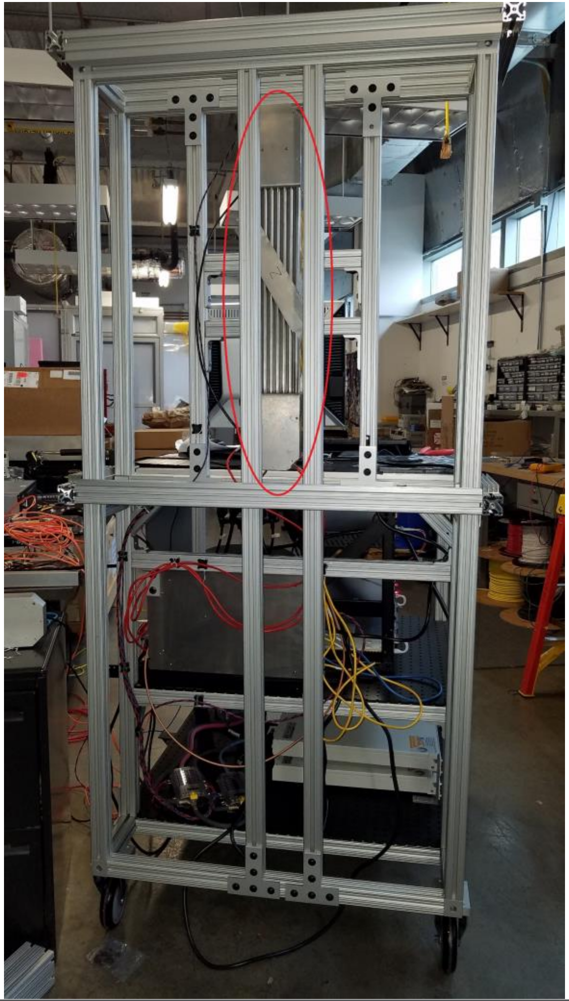
Analyzing Power: 70%

Neutron Detector

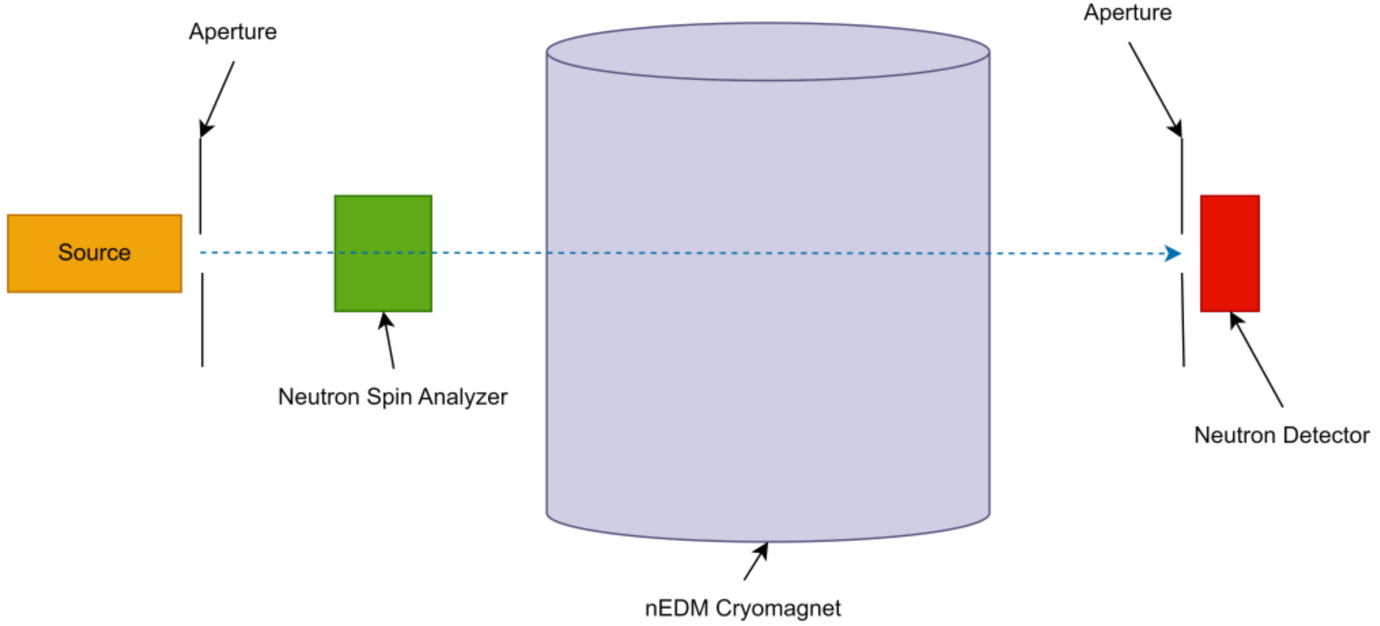
- 8 pack of linear position sensitive ^{3}He gas filled proportional counting detectors.
- Neutron time of flight and positional information.
- Accelerator provides proton t_0 for time of flight triggering and proton charge for beam power.
- Double ended resistive anode charge collection for event position info.







^{3}He Polarimetry with a Polarized Neutron Beam



- Measured polarization upstream of the cryomagnet with the 3He neutron analyzer.

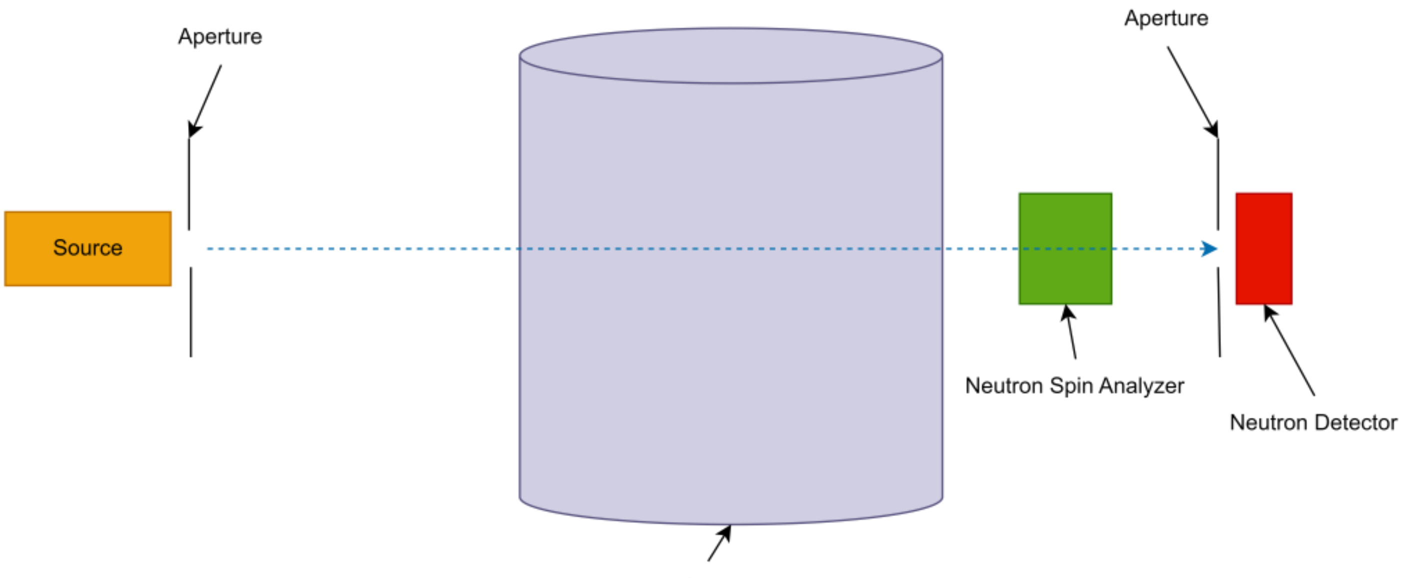
^{3}He Polarimetry with a Polarized Neutron Beam

State	Beam Polarization State	Analyzer Polarization State	Neutrons/MW/s
N_0	Beam Right	Not Present	36.8 ± 0.6
T_0	Beam Right	Unpolarized	1.85 ± 0.04
T	Beam Right	Beam Right	3.57 ± 0.07
T_{sf}	Beam Right	Beam Left	1.34 ± 0.03
T_{sf}^{afp}	Beam Left	Beam Left	3.25 ± 0.06
T^{afp}	Beam Left	Beam Right	1.21 ± 0.03

$$P_n = \frac{R - R_{sf}}{\sqrt{[(2\epsilon_{sf} - 1)R + R_{sf}]^2 - 4\epsilon_{sf}^2}} = 0.83 \pm 0.07_{stat}$$

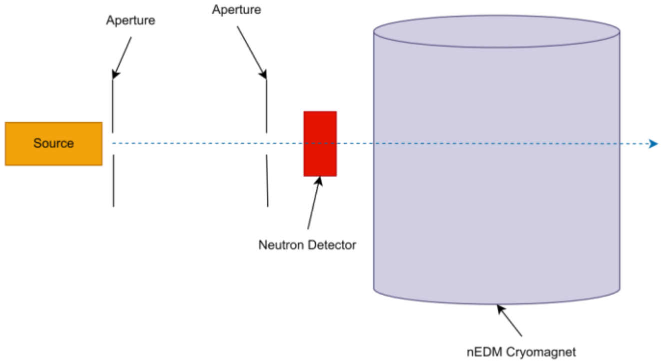
$$R = \frac{T}{T_0} \quad R_{sf} = \frac{T_{sf}}{T_0}$$

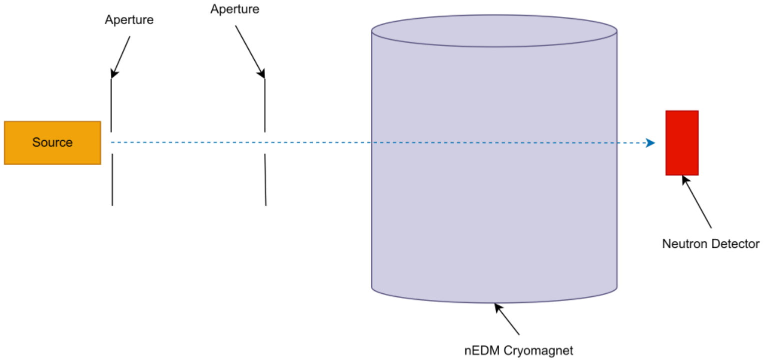
^{3}He Polarimetry with a Polarized Neutron Beam



- Measured polarization downstream of the cryomagnet with the 3He neutron analyzer.
- No significant neutron spin contrast was observed for various settings of the cryomagnet.
- The polarized neutron beam was fully depolarized by the nEDM cryomagnet as well as inefficient neutron spin transport field.
  - Bad neutron spin transport and μ-metal shield misalignment.

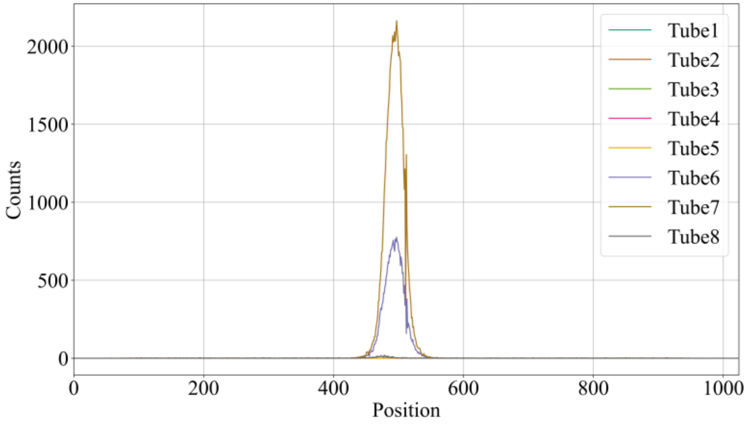
Transmission Measurement



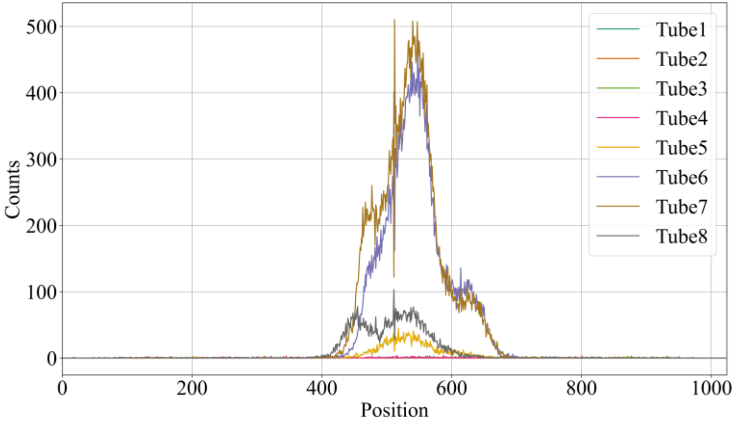


$$T_n^{exp} = 0.62 \qquad T_n = 0.327 \pm 0.001_{stat}$$

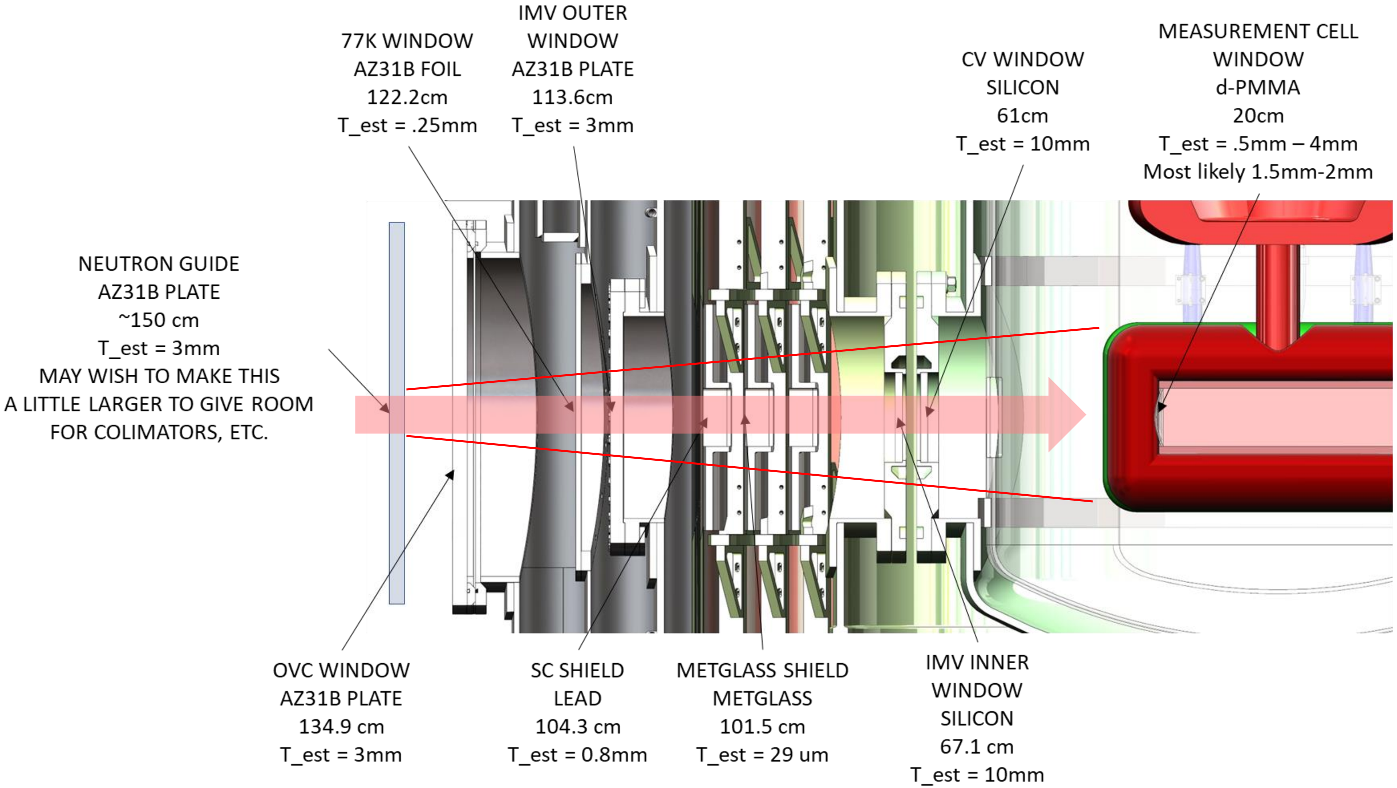
Intensity Upstream of the Cryomagnet



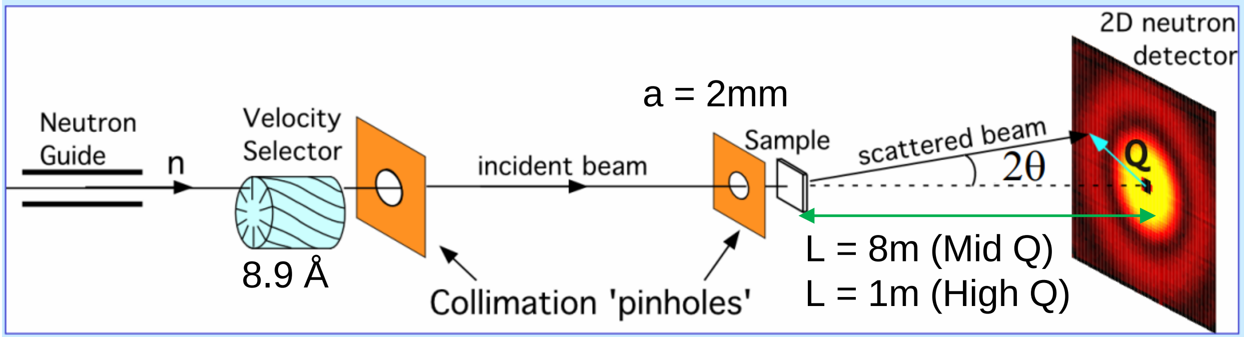
Intensity Downstream of the Cryomagnet



Transmission and Scattering



SANS Studies at HFIR GP-SANS

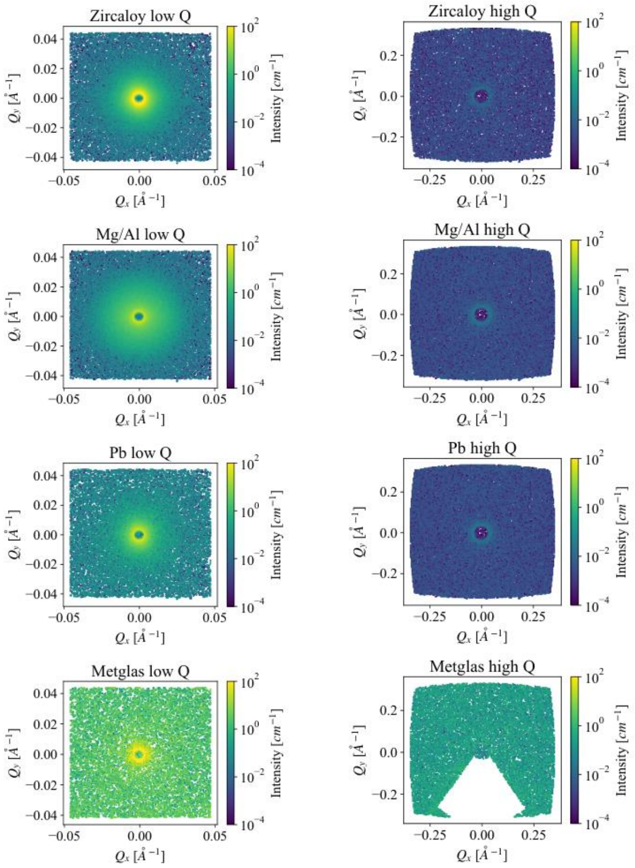


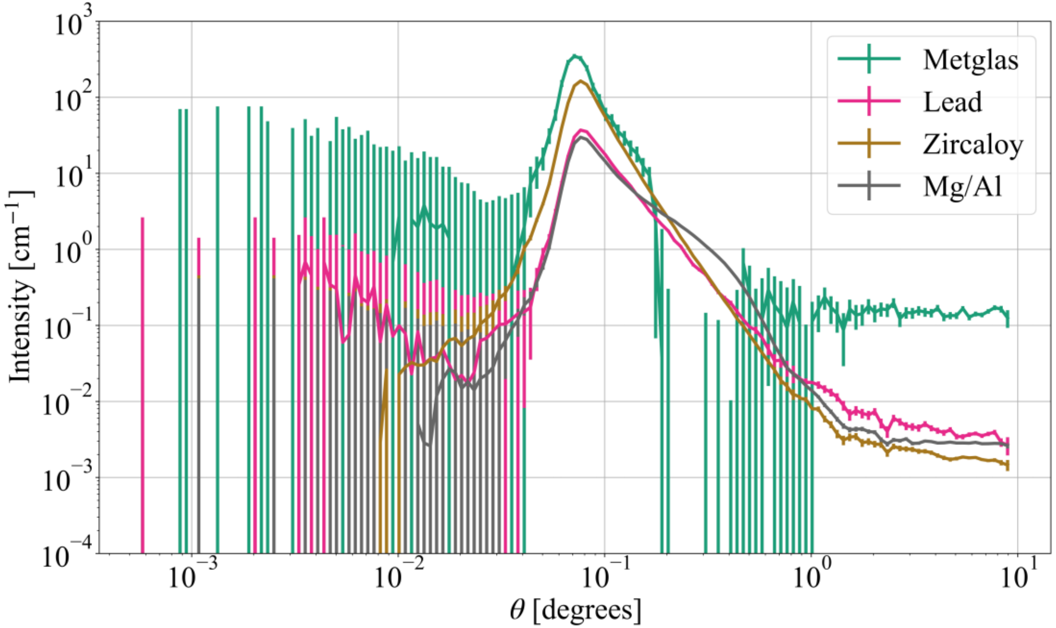
- Scattered neutrons counted as a function of $Q = \frac{4\pi}{\lambda}\sin 2\theta$
- Wavelength is fixed to 8.9Å ($\Delta\lambda/\lambda = 0.13$) and vary θ (i.e Q) by moving the detector along the beam.
- Probe scale d~ λ/θ (small angle approx.)
- Angular resolution $\Delta\theta/\theta \propto a/L$.
- Measure the differential scattering cross section.
- Elastic coherent scattering of neutrons that gives rise to SANS.

$$\frac{d\Sigma(Q)}{d\Omega} = \frac{1}{I_0 \cdot A \cdot d \cdot \Delta\Omega \cdot \epsilon \cdot t} I(Q)$$

diff. cross section → $\frac{d\Sigma(Q)}{d\Omega}$; Scattered Intensity → $I(Q)$; Initial Intensity → I_0; Sample Area → A; Sample thickness → d; Solid angle → $\Delta\Omega$; efficiency → ϵ; time → t

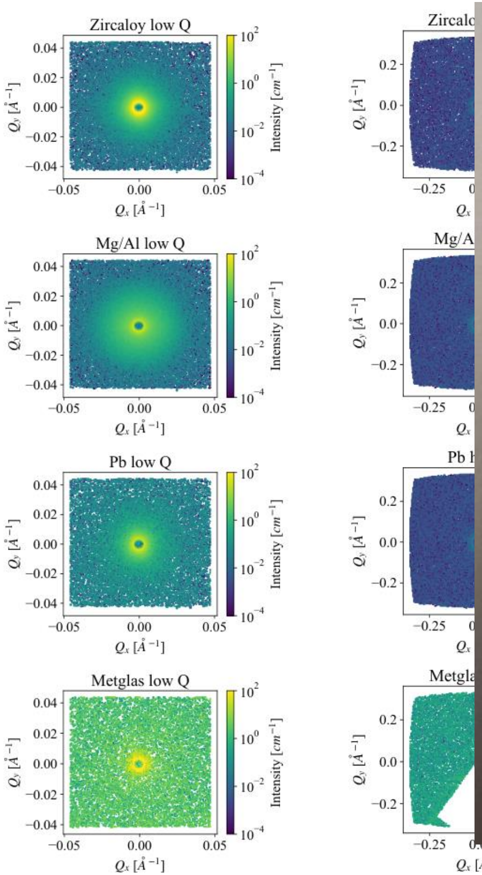
SANS Studies

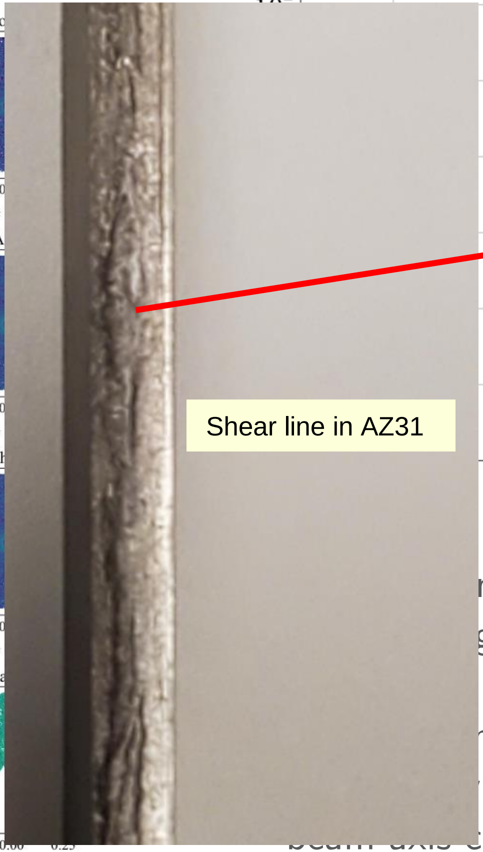


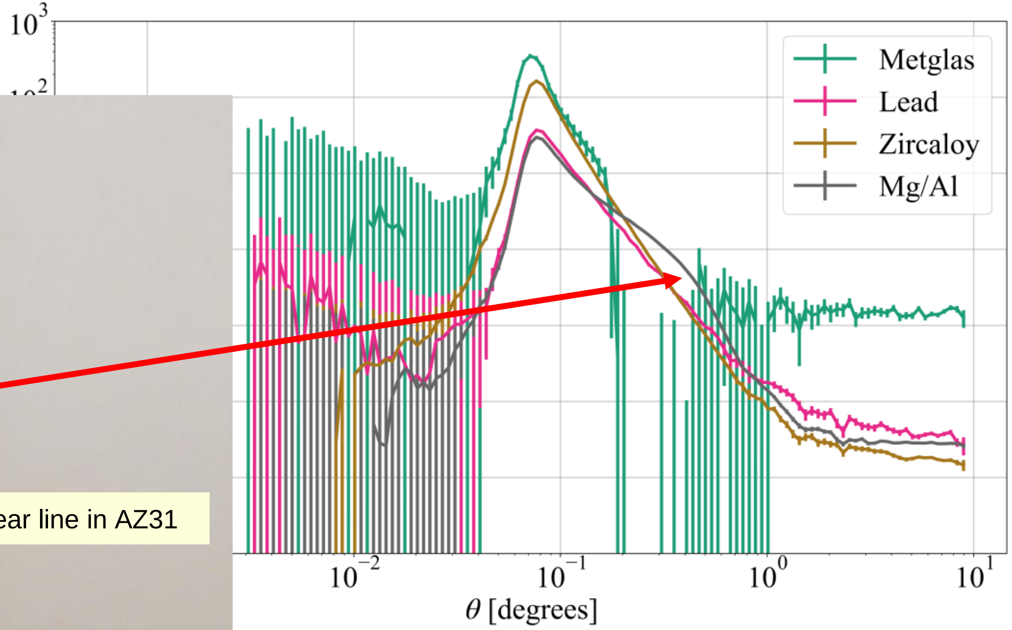


- Measurement cell angle of acceptance = 1.4 deg.
- Beam divergence due to SANS from the window materials was smaller than the angular divergence acceptance of the measurement cell.
- Materials will not cause the neutron beam to interact with off beam axis components of the nEDM@SNS experiment.

SANS Studies



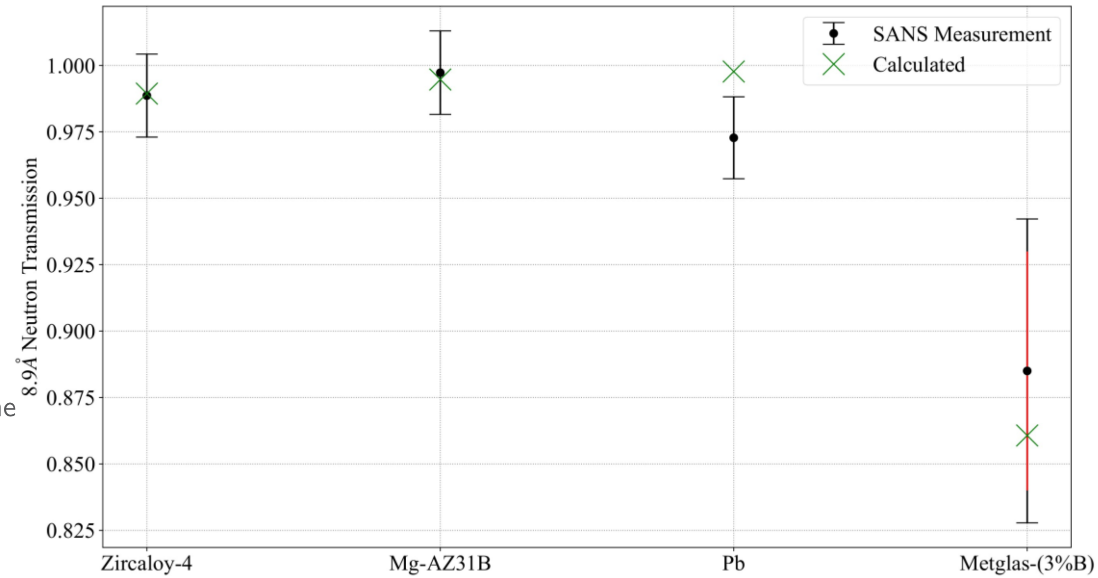




...nt cell angle of acceptance = 1.4 deg.
...gence due to SANS from the window materials
... than the angular divergence acceptance of the
...nt cell.
...ill not cause the neutron beam to interact with off
... components of the nEDM@SNS experiment.

Transmission Measurements via SANS

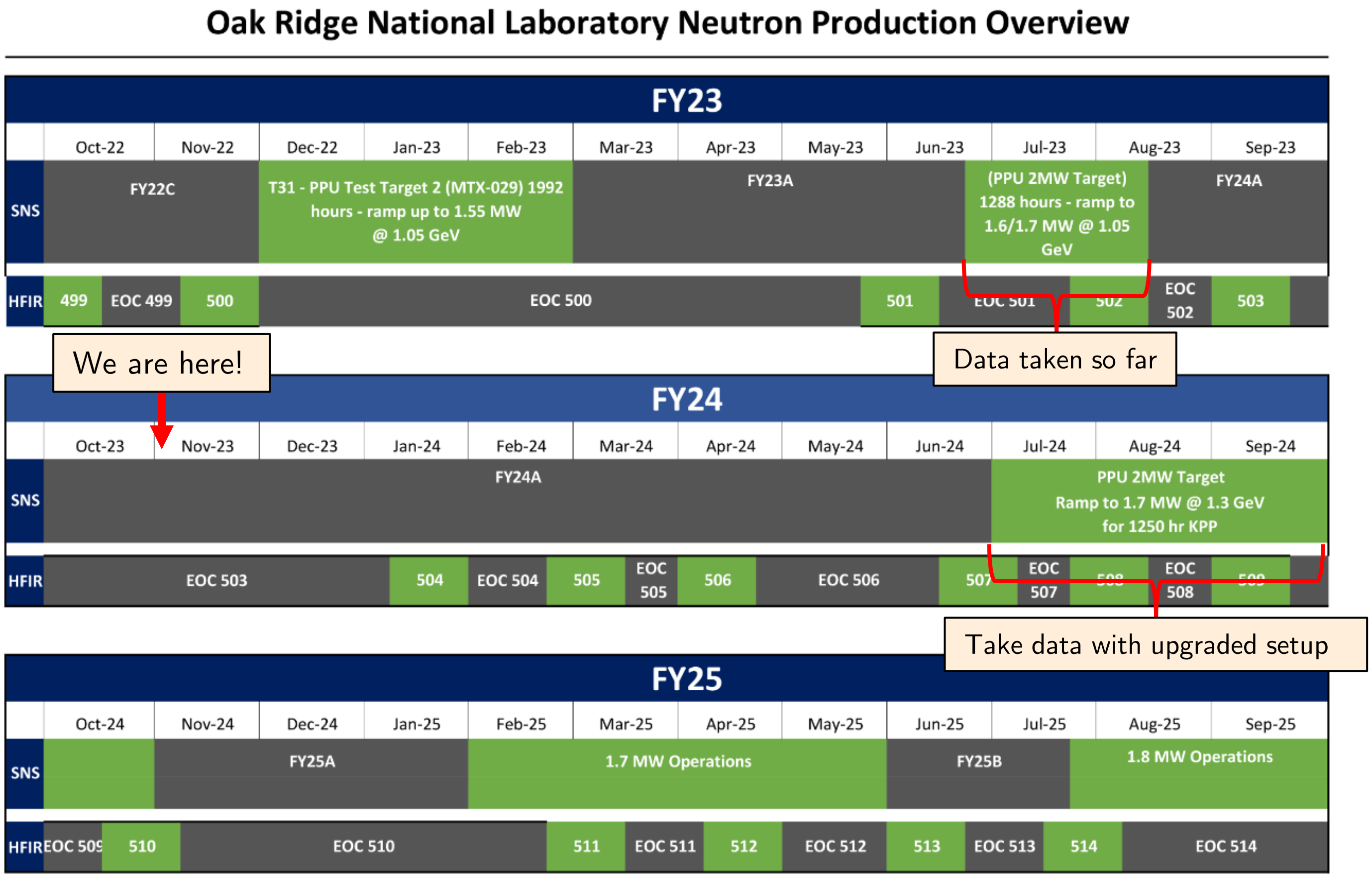
- These measurements also showed that the beam intensity loss from these window materials was small and agreed with the expectation.
- A variation on the neutron beam intensity loss on the Metglas sample was due to neutron beam alignment issues.
  - Difficult to calculate expected loss due to uncertainty in the percent mass composition of the Boron.
- Neutron activation analysis for accurate determination of impurity levels and the mass composition of the window material.



Conclusions

- Measured a large 8.9Å neutron beam polarization loss from the cryomagnet.
  - A high accuracy polarization loss measurement couldn't be conducted due to minimal beam time.
  - Lack of polarization transport magnetic fields and misalignment of the cryomagnet are thought to be the primary culprits.
- Measured a large 8.9Å neutron beam intensity loss from the cryomagnet.
  - Scattering from beam windows due to a diverging beam.
  - Will repeat this study with apertures.
- These preliminary results demonstrate a proof of principle.
  - A new beamline was commissioned.
  - First neutron beam measurement for the nEDM@SNS Experiment.
  - ^{3}He polarimetry components were successfully developed and tested.
- Need to systematically characterize the cause of depolarization and intensity loss before considering the effects on the final nEDM experiment.
  - Can use polarized ^{3}He in the final nEDM experiment to recover the polarization.

SNS Neutron Production Schedule



nEDM@SNS Collaboration

NSF

U.S. DEPARTMENT OF ENERGY

ASU Arizona State University

Bartoszek Engineering

Brown University

Caltech

Duke University

Georgia Tech

Harvard University

Indiana University

Los Alamos National Laboratory

Massachusetts Institute of Technology

Mississippi State University

Montclair State University

NC Central University

NC State University

Oak Ridge National Laboratory

SFU Simon Fraser University

TUNL Triangle Universities Nuclear Laboratory

Tennessee Tech

Universidad Nacional Autónoma de México

University of Illinois Urbana-Champaign

University of Kentucky

The University of Tennessee Knoxville

University of Virginia

Valparaiso University

Yale University

The work presented is in part supported by U.S. D.O.E award number DE-FG02-03ER41258 and D.O.E Office of Science, WDTS-SCGSR program under contract number DE-SC0014664

Back-up Slides

Other Systematic Effects

- Systematic effects are far smaller that the couple % level precision desired for these measurements.
  - Non-Poisson variations of the neutron beam
    - Previous experiments have shown a negligible effect.
  - ^{3}He cell polarization fluctuations:
    - In situ polarization for ^{3}He negated this effect.
  - Moderator fluctuations:
    - No large variations in moderator properties were observed.
  - Humidity fluctuations:
    - Humidity is found to be constant based on literature.
  - Detector efficiency variations
    - Normal pulse height spectra showed no degradation of detector efficiency.

Results and Conclusion

$$\epsilon_{ST} * P_n \rightarrow P_n = \frac{1}{P_n^{He}}\left(1 - \frac{2R_{\uparrow}}{R_{\uparrow} + R_{\downarrow}}\right) = \frac{R_{\downarrow} - R_{\uparrow}}{\sqrt{(R_{\downarrow} + R_{\uparrow})^2 - 4}} = 51.36\% \pm 0.99\%$$

$$R = \frac{T}{T_0} \quad R_{sf} = \frac{T_{sf}}{T_0}$$

- A high accuracy measurement couldn't be conducted due to minimal beam time, .
  - Measured low beam polarization due the fact that the polarimetry components could not be optimized for 8.9Å neutrons.
  - Measured a low ^{3}He analyzer polarization = 33% via neutron beam transmission method (should be 50-60%). Currently verifying this via beam independent method (EPR Spectroscopy).
- These preliminary results shows a proof of principle.
  - A new beamline was commissioned.
  - First neutron beam measurement for the nEDM@SNS Experiment.

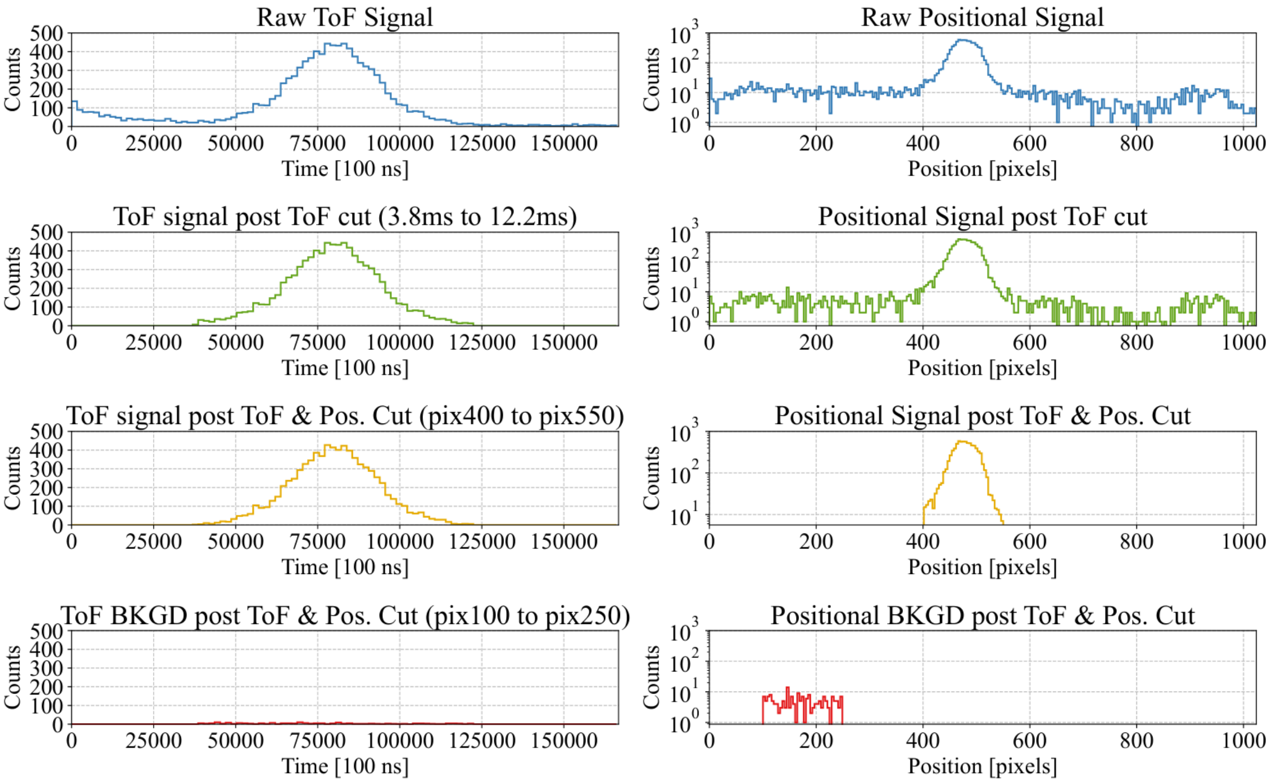
^{3}He Polarimetry with a Polarized Neutron Beam - Analysis

Raw Data

Applied a ToF cut

Applied a Positional cut

Used the flat background region to estimate the background under signal



^{3}He Polarimetry with a Polarized Neutron Beam

The total analyzing power of the Polarizer, Spin flipper and ^{3}He cell:

$$P_n P_3^{AP} \epsilon_{sf} = \frac{R_\uparrow - R_\downarrow}{R_\uparrow + R_\downarrow}$$

Neutron beam polarization as a function of relative neutron transmission measurements:

$$P_n = \frac{R - R_{sf}}{\sqrt{\left[(2\epsilon_{sf} - 1)R + R_{sf}\right]^2 - 4\epsilon_{sf}^2}}$$

$$R = \frac{T}{T_0} \quad R_{sf} = \frac{T_{sf}}{T_0}$$

G. L. Greene et. al, Nuc. Inst. Methods A 356 (1995).

^{3}He Polarimetry with a Polarized Neutron Beam

Beam polarization* as the product of spin flipper efficiency, and the analyzing power of ^{3}He cell, spin transport efficiency and polarizer efficiency:

$$\epsilon_{ST} * \epsilon_{SF} * P_n * P_n^{He} = \frac{R_\uparrow - R_\downarrow}{R_\uparrow + R_\downarrow}$$

Neutron beam polarization as a function of relative neutron transmission measurements:

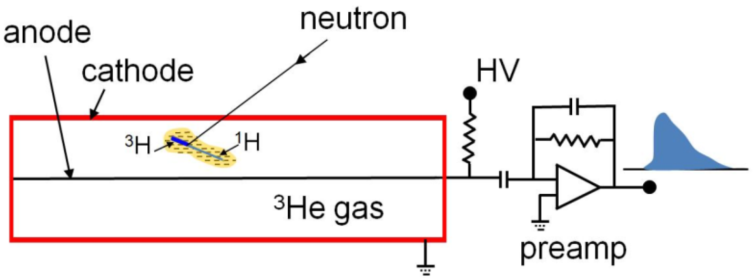
$$P_n = \frac{R - R_{sf}}{\sqrt{\left[(2\epsilon_{sf} - 1)R + R_{sf}\right]^2 - 4\epsilon_{sf}^2}}$$

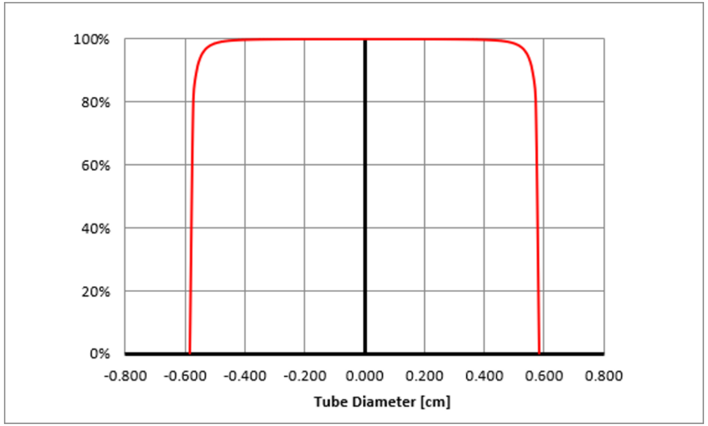
$$R = \frac{T}{T_0} \quad R_{sf} = \frac{T_{sf}}{T_0} \quad \epsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T^{AFP} - T}{T^{AFP} + T}}{\frac{T_{sr}^{AFP} - T_{sf}}{T_{sr}^{AFP} + T_{sf}}}\right)$$

*Cannot separate spin transport efficiency with beam polarization.

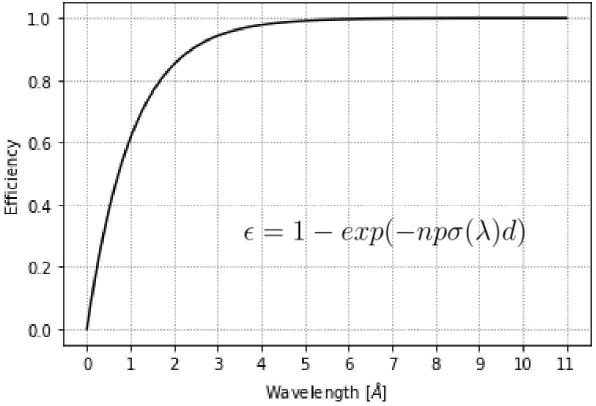
Neutron Detector

- 8 pack of linear position sensitive ^3He gas filled proportional detectors.
- Mobile detector cart from the SNS Detector group. (SNS nED DAQ system)
- Operating in Geiger mode for neutron counting.
- Accelerator provides proton t_0 for time of flight triggering and proton charge for beam power.





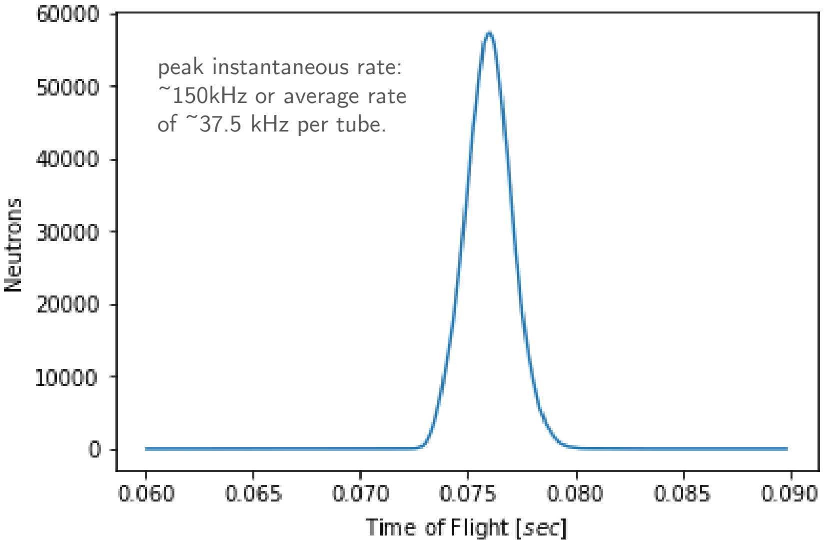
Detection efficiency across a tube diameter



Conversion efficiency for ^3He counters

Neutron Detector-Saturation?

- If the instantaneous neutron rate is too high, then one will saturate the detectors.
- Need to characterize this dead time inefficiency.
  - the DAQ dead time(The detector is set for a 750ns integration time, after which another integration could begin) but from charge transport within the gas itself
- May be able to see this in the pulse height distribution.



Previous Studies

Metglas polarisation measurements on SESAME at LENS

13th April 2014

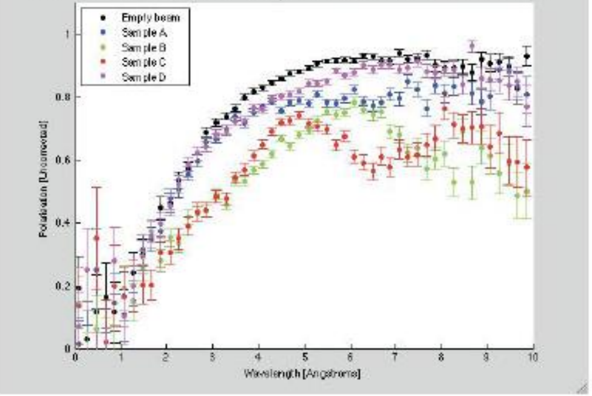
S.R.Parnell, T. Wang, A.L.Washington and R.Pynn

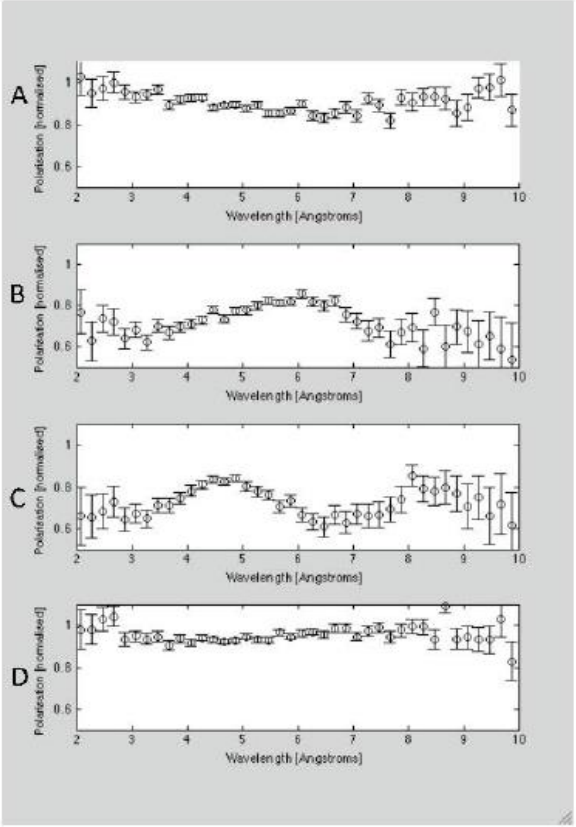
Samples - in approx. 9 G field for neutron spin transport

A - 2826 MB3 – Low-Cobalt
B - 2605 S3A – Low-Cobalt
C - 2605 SA1 – Low-Cobalt
D - 2705 M – High-Cobalt

Note two different parts of D were tested and gave the same results so material seems consistent

Raw data for instrumental polarisation and each sample





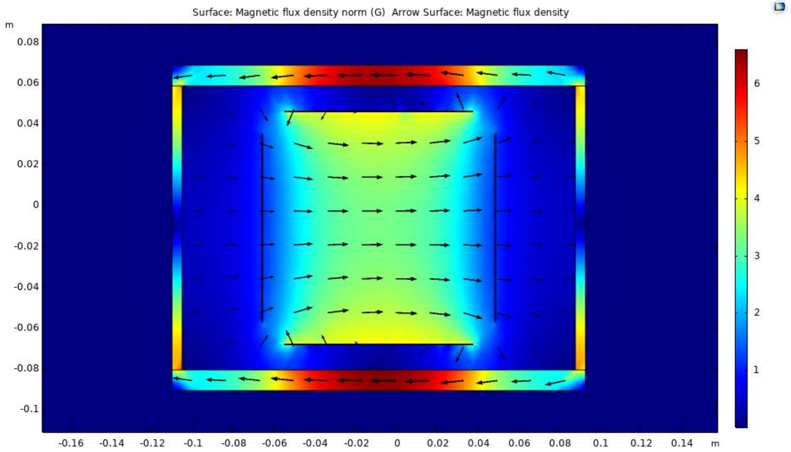
Some studies on superconducting Pb:-

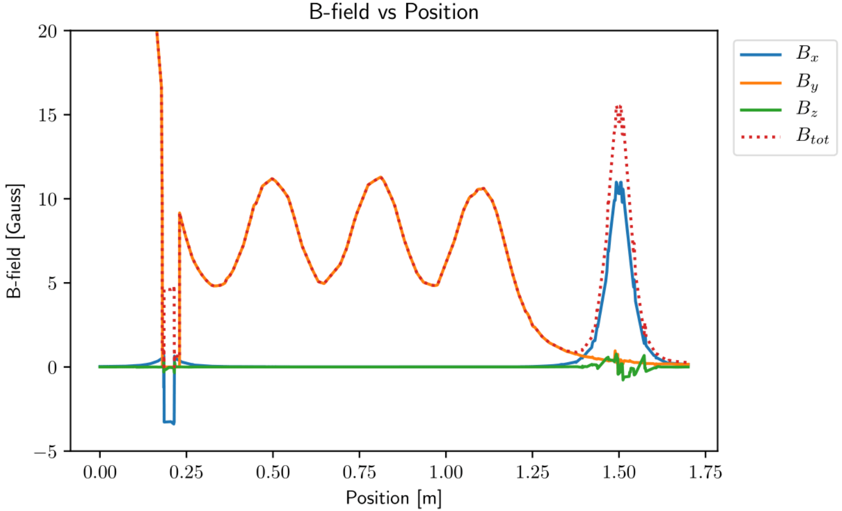
W. Treimer et al., Polarized neutron imaging and three-dimensional calculation of magnetic flux trapping in bulk of superconductors. Phys. Rev. B **85**, (2012) 184522
https://doi.org/10.1103/PhysRevB.85.184522

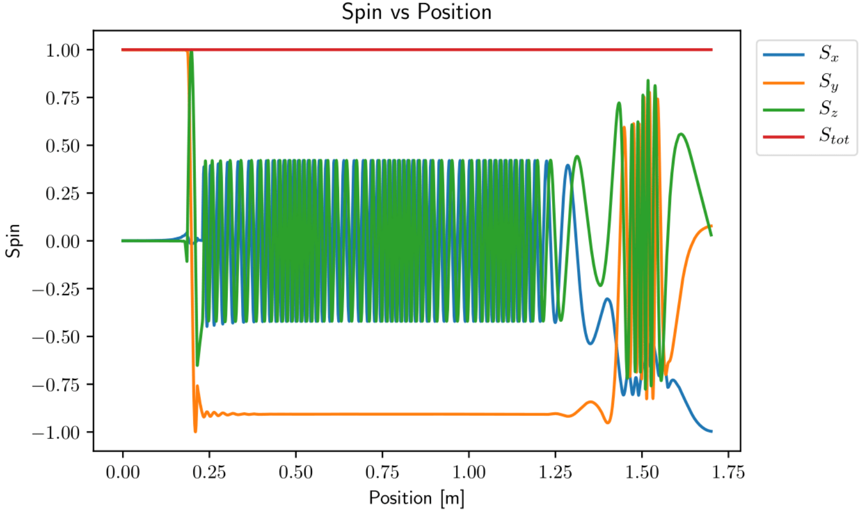
Spin "gymnastics" Simulations

Integrating Bloch's equations to check for spin transport in the magnetic fields of the polarimetry components.

$$\frac{d\vec{S}}{dt} = \gamma_n \vec{S} \times \vec{B}$$







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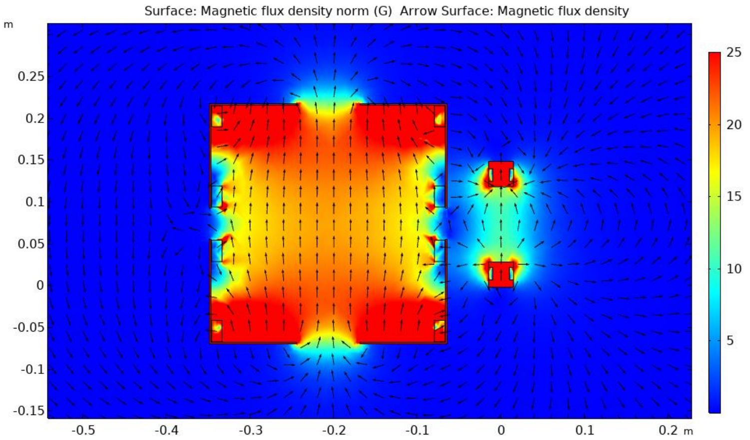
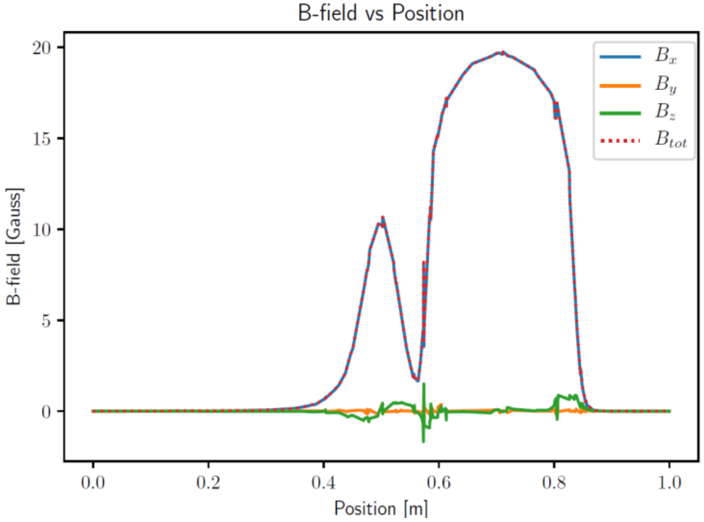
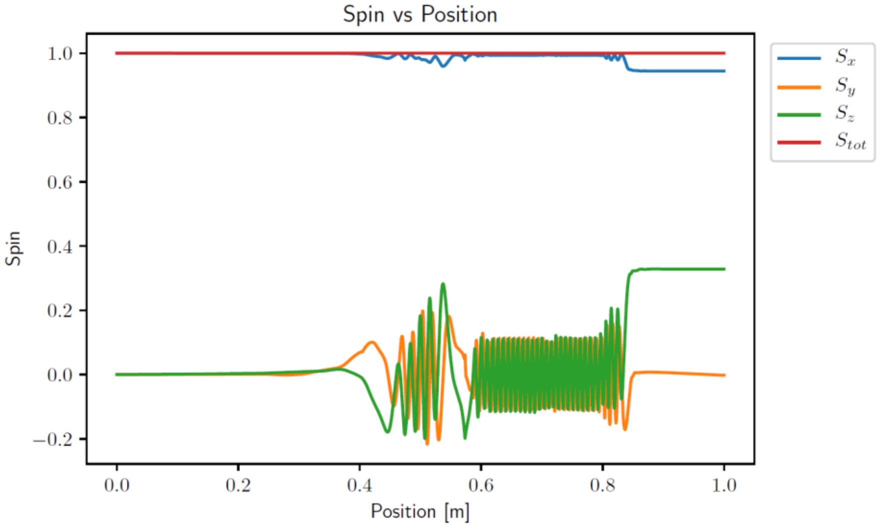






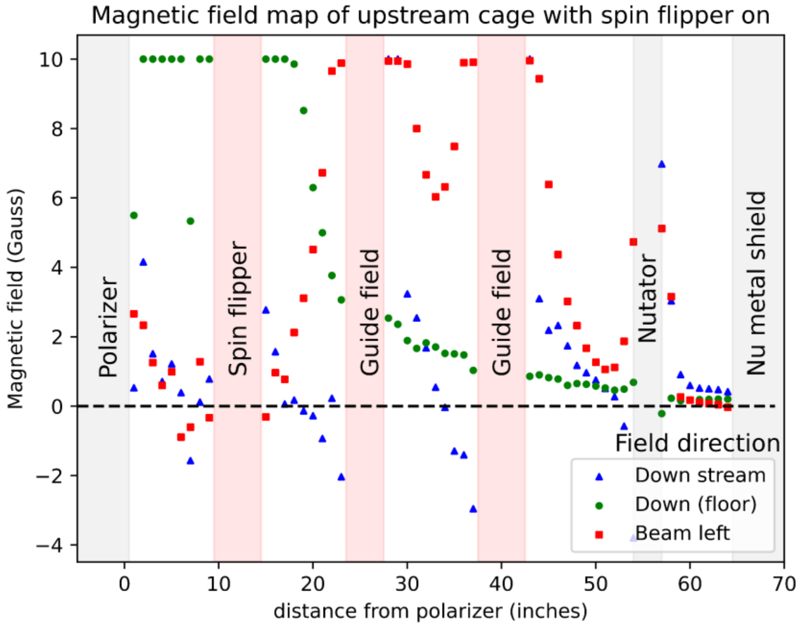
^{3}He Polarimetry with a Polarized Neutron Beam

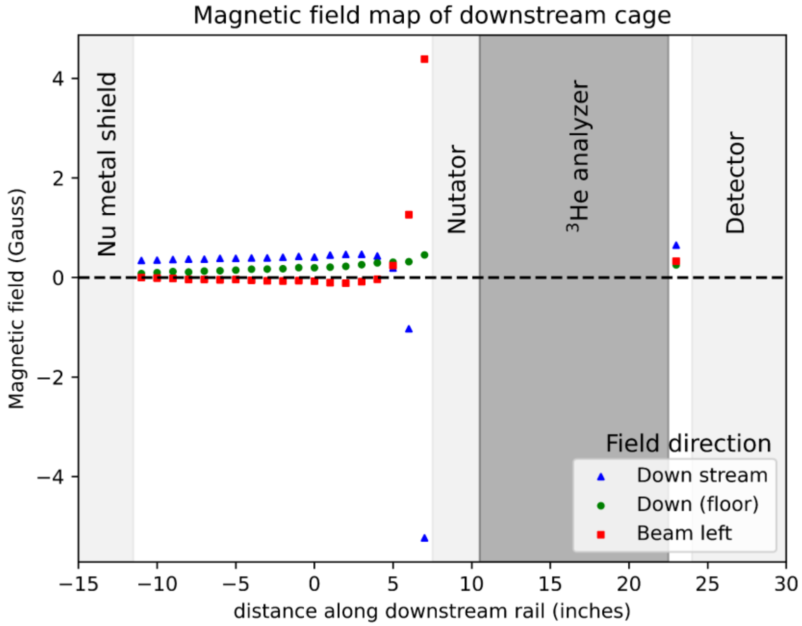
Settings	Neutrons/s/MW
FCS* off, MSE** off	2.73 ± 0.01
FCS off, MSE off, flipper On	2.73 ± 0.01
FCS off, MSE off	2.73 ± 0.01
FCS off, MSE off, flipper On	2.71 ± 0.01
FCS off, MSE on	3.09 ± 0.01
FCS off, MSE on, flipper on	3.05 ± 0.01
FCS off, MSE on	3.03 ± 0.01
FCS off, MSE on (large current)	3.07 ± 0.02
FCS on, MSE on (large current), degauss mu-metal	2.99 ± 0.01
FCS on, MSE on (large current), degauss mu-metal, degauss metglas	3.02 ± 0.02
FCS on, MSE off , degauss mu-metal, degauss metglas	3.07 ± 0.02
FCS on, MSE off , degauss mu-metal, degauss metglas	3.10 ± 0.02

* Earth's Field Cancellation Coil System ** Magnetic Shield Enclosure Coil System

- No significant neutron spin contrast was observed for various settings of the cryomagnet.
- The polarized neutron beam was fully depolarized by the nEDM cryomagnet as well as inefficient neutron spin transport field.

^{3}He Polarimetry with a Polarized Neutron Beam





- μ-metal shield was misaligned with the beam.
  - Polarized neutrons saw an effective diabatic magnetic field region.
- Guide field "dead zones" near μ-metal shield.