Neutron Polarization and Transmission Measurement for the nEDM@SNS Experiment

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2021 International Workshop on Searches for a Neutron Electric Dipole Moment

THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

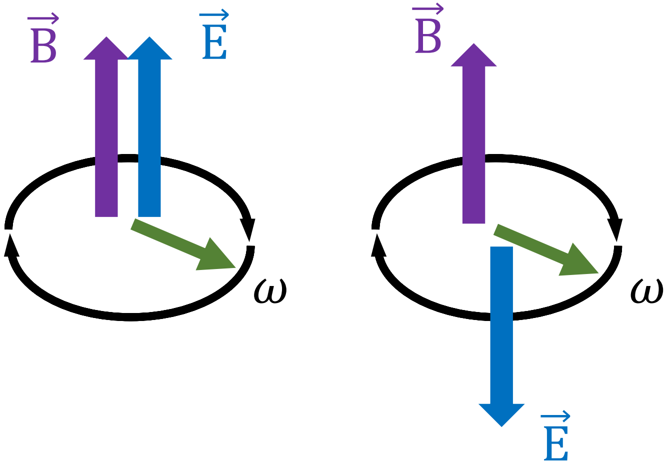
Principle of EDM Measurement

Existence of EDM will change the precession frequency of Neutron

$$\omega = \frac{2(\mu_n B_0 \pm d_n E_0)}{\hbar}$$

$$\Delta\omega = \frac{4 d_n E_0}{\hbar}$$

Sensitivity $$\sigma_{d_n} \simeq \frac{1}{E_0 \tau \sqrt{N_{UCN}}}$$



nEDM@SNS is aiming at a sensitivity of $\simeq 10^{-28} e \cdot cm$ (current limit $d_n < 1.8 \times 10^{-26}\ e \cdot cm\ (90\%\ CL)$[PDG])

- Ultracold Neutrons (UCN) production via superthermal scattering in superfluid He.
- B field of 30 mG and field uniformity of 3 ppm/cm and E field of 75 kV/cm.
- Free precession method
  - ^{3}He co-magnetometry to monitor B field via SQUIDS.
  - Scintillation rate via spin dependent n-^{3}He reaction.

$$n \uparrow + {}^3He \downarrow \rightarrow {}^3H + p + 765\ keV$$

- Critical spin dressing method for better sensitivity and cross check on systematics

R. Golub and S.K. Lamoreaux, Physics Reports 237, 1 (1994).

Cryogenic Magnet Package and its associated windows

See A. Aleksandrova (B-field production)

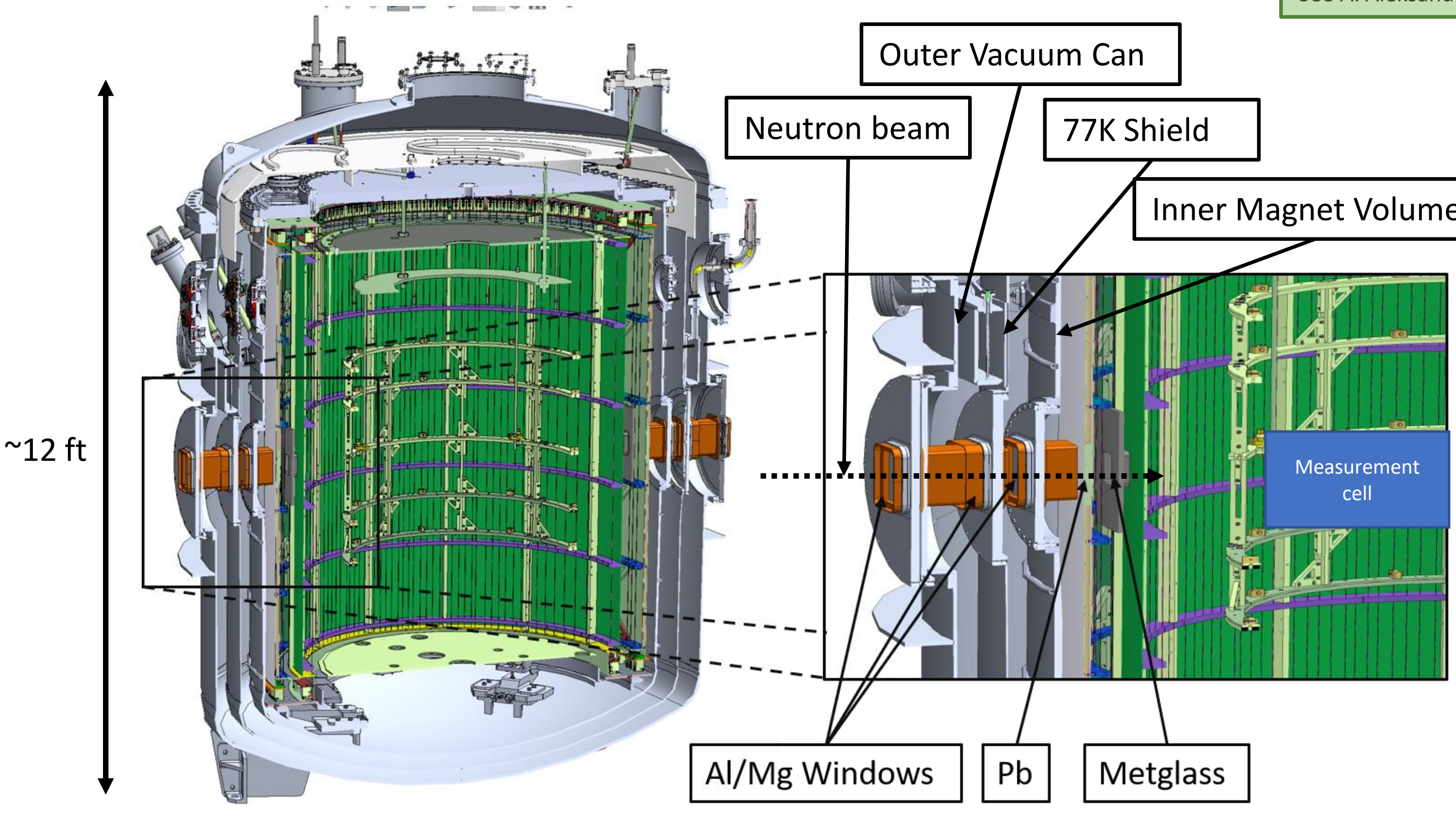
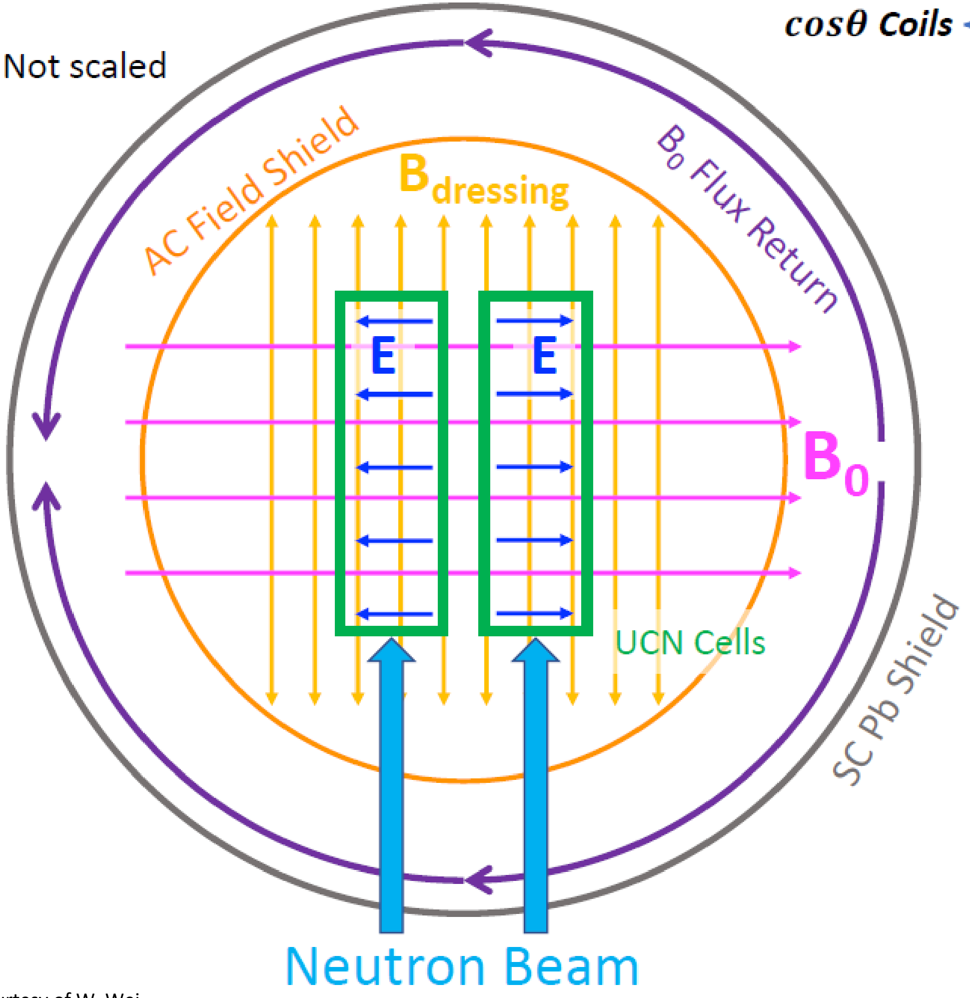


Image courtesy of J. Ramsey

Illustration of the Magnetic Fields



B_0 Coil: (Superconducting Cu-clad NbTi wire)

30 mG and uniformity of 3 ppm/cm

uniformity is crucial for the transverse coherence time T_2 of UCN and helium-3

Dressing Coil: (Superconducting Ti/Pb Solder Wire)

AC field < 0.5 G and uniformity of 45 ppm/cm

also used as $\pi/2$ spin flip

Superconducting Pb Shield:

Further shield the ambient environmental magnetic fields and stabilize the magnetic drifts over the measurement time

B_0 Flux Return:

Metglas 2826M, location accuracy < 1 mm

improve field uniformity, mitigating the effect of errors in wire placement and reducing field distortions due to the cylindrical superconducting shield just outside of this shield

AC Field Shield:

A copper film shields the Metlas from heating of the dressing field

Image courtesy of W. Wei

Cryogenic Magnet Package and its associated windows

See A. Aleksandrova (B-field production)

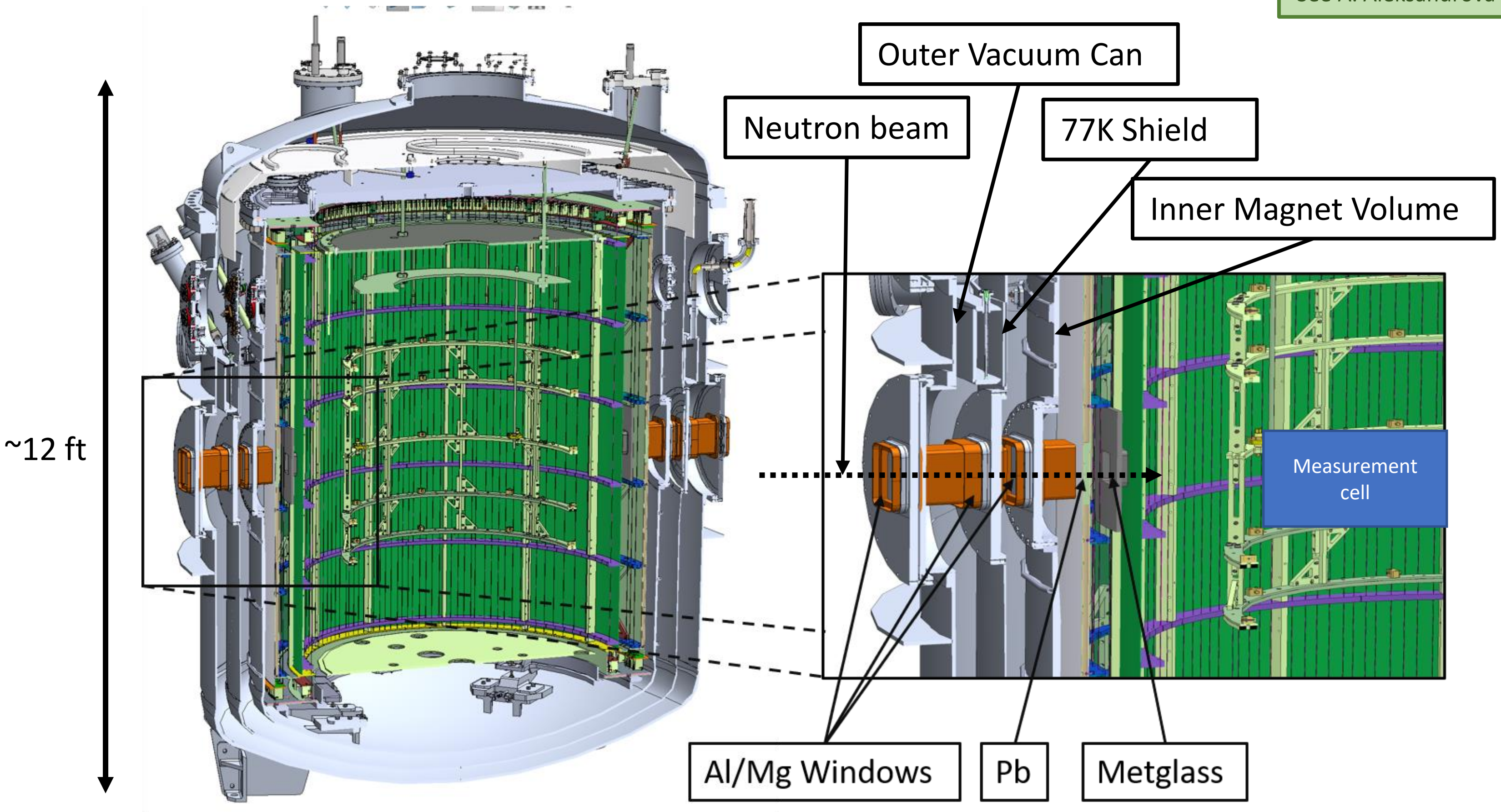


Image courtesy of J. Ramsey

Polarization and Transmission of Neutrons

- Need to measure the transmission and polarization loss of monochromatic neutrons from nEDM cryostat magnet windows.
- Especially superconducting Pb shielding and ferromagnetic flux-return Metglas.
- Presence of microscopic magnetic domains and the fact that windows can act as current sheets can cause diabatic transitions in the magnetic fields leading polarization loss.
- Difficult to simulate diabatic transitions so need to measure polarization loss experimentally in a magnetic field environment similar of that of the final experiment.

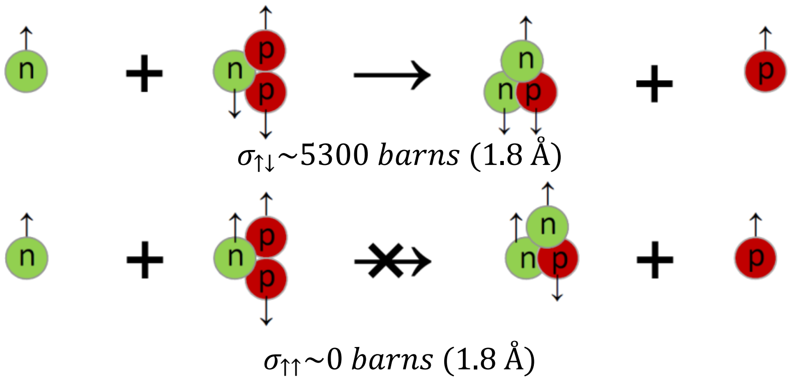
^{3}He Polarimetry

Takes advantage of the spin dependence in the capture cross section of neutrons on polarized ^{3}He.

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

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

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



^{3}He analyzer cell parameters are difficult to accurately measure.

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

Determination of Neutron Polarization

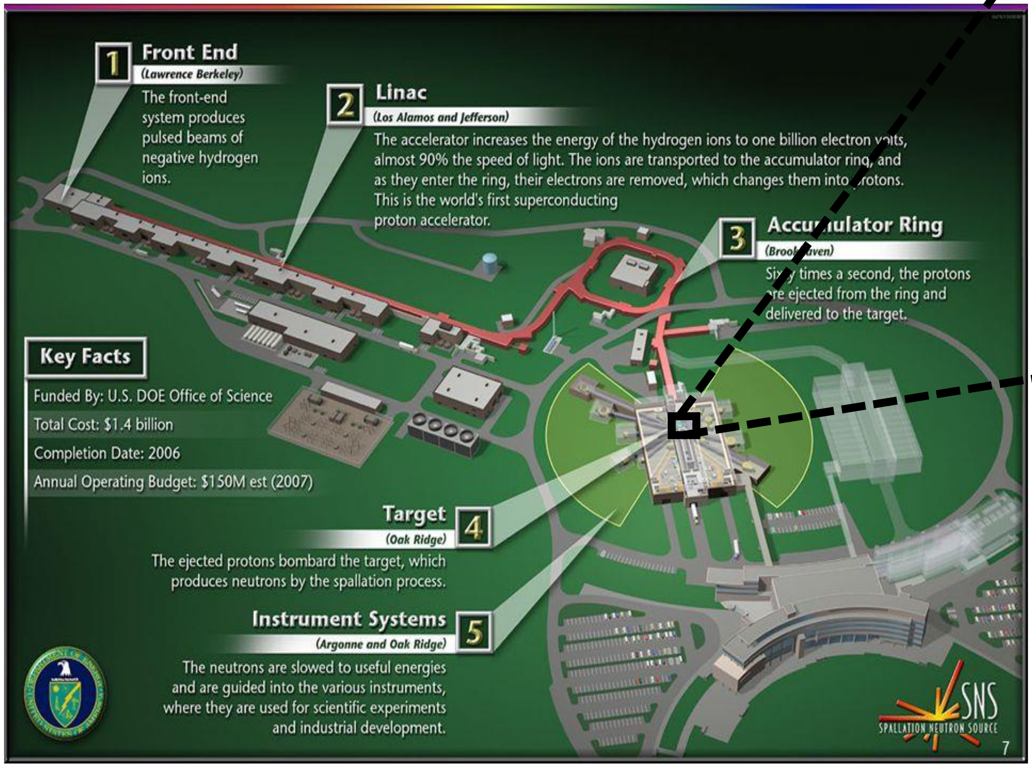
$$P_n = \frac{R - R_{sf}}{\sqrt{\left[\left(2\varepsilon_{sf} - 1\right)R + R_{sf}\right]^2 - 4\varepsilon_{sf}{}^2}}$$

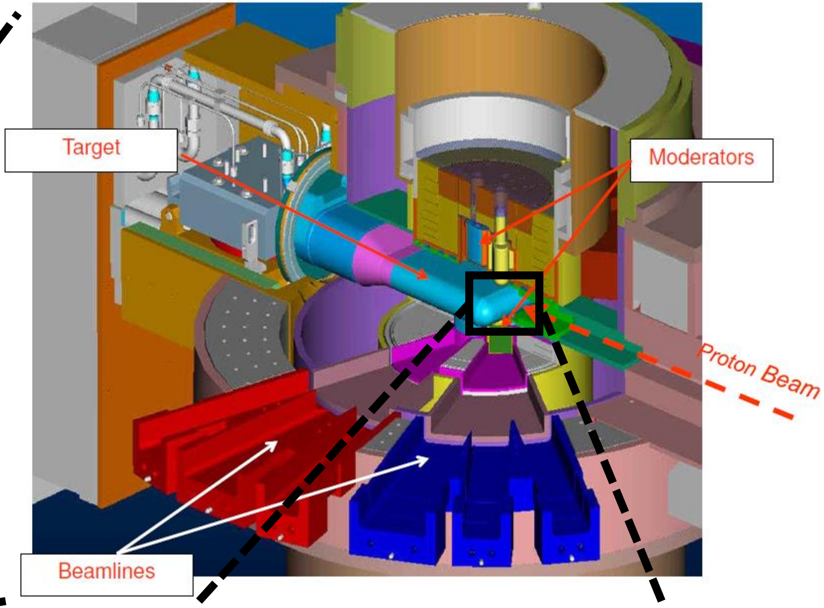
$$R = \frac{T}{T_0},\ R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$

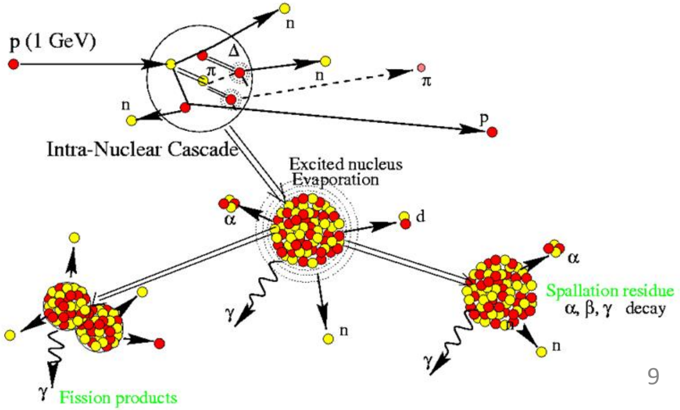
- Neutron polarization can be determined by R and R_{sf} which simply represent ratios of transmissions through ^{3}He analyzer.
- ^{3}He polarization and the physical properties of the ^{3}He cell do not need to be known to determine the neutron polarization.

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

Spallation Neutron Source

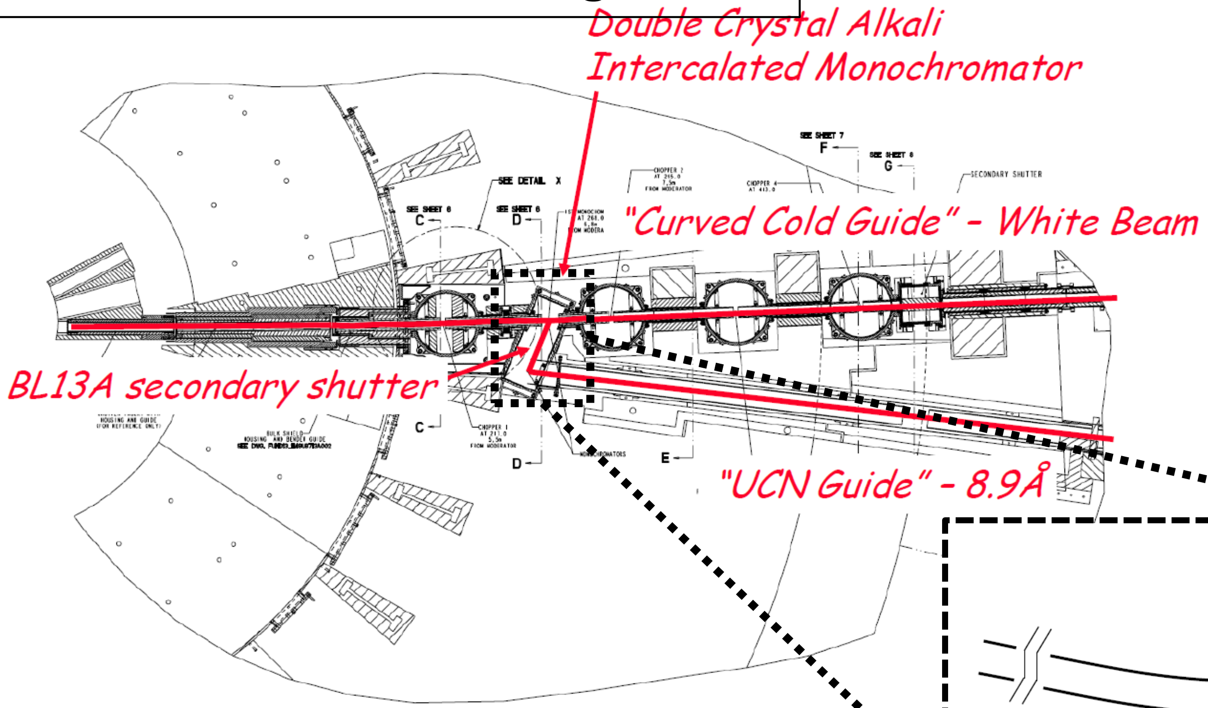


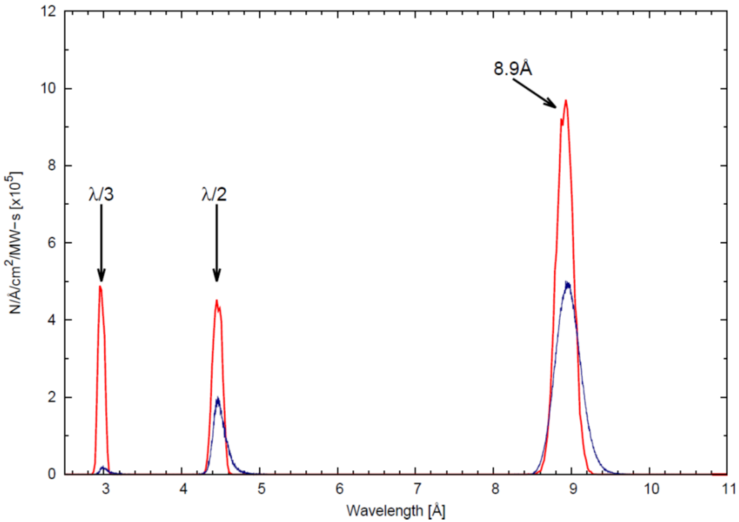


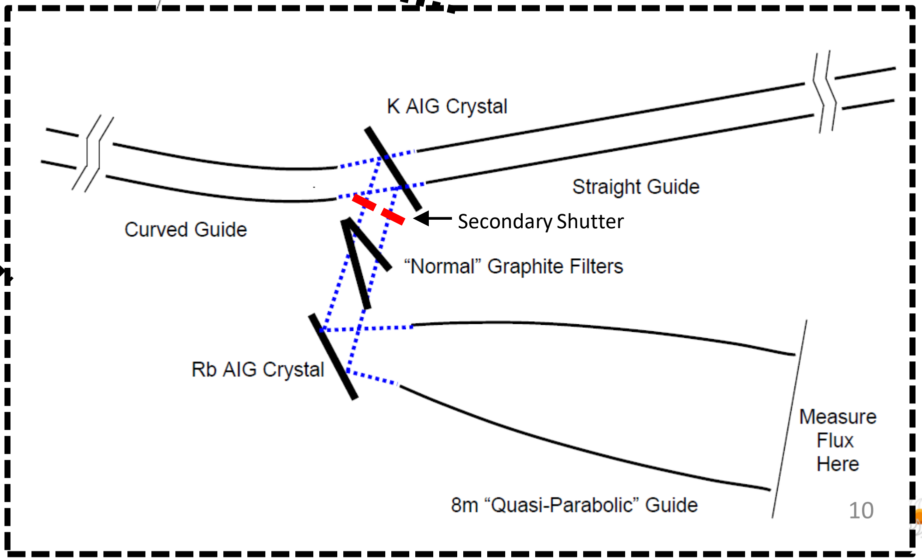


N. Fomin et. al, Nucl. Instrum. Methods A 773 (2015) 45

Beamline 13 Schematic Diagram

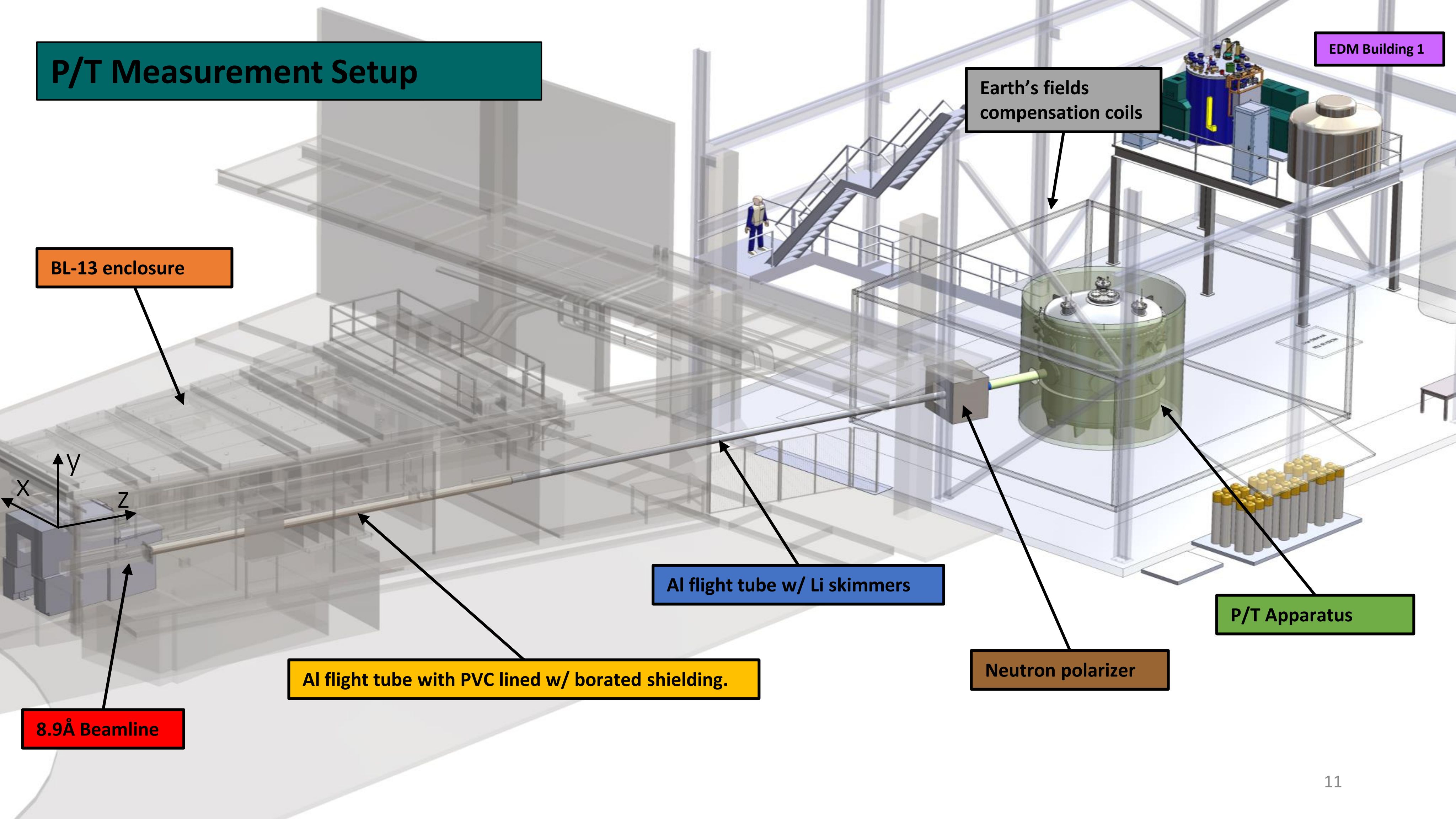






N. Fomin et. al, Nucl. Instrum. Methods A773 (2015) 45

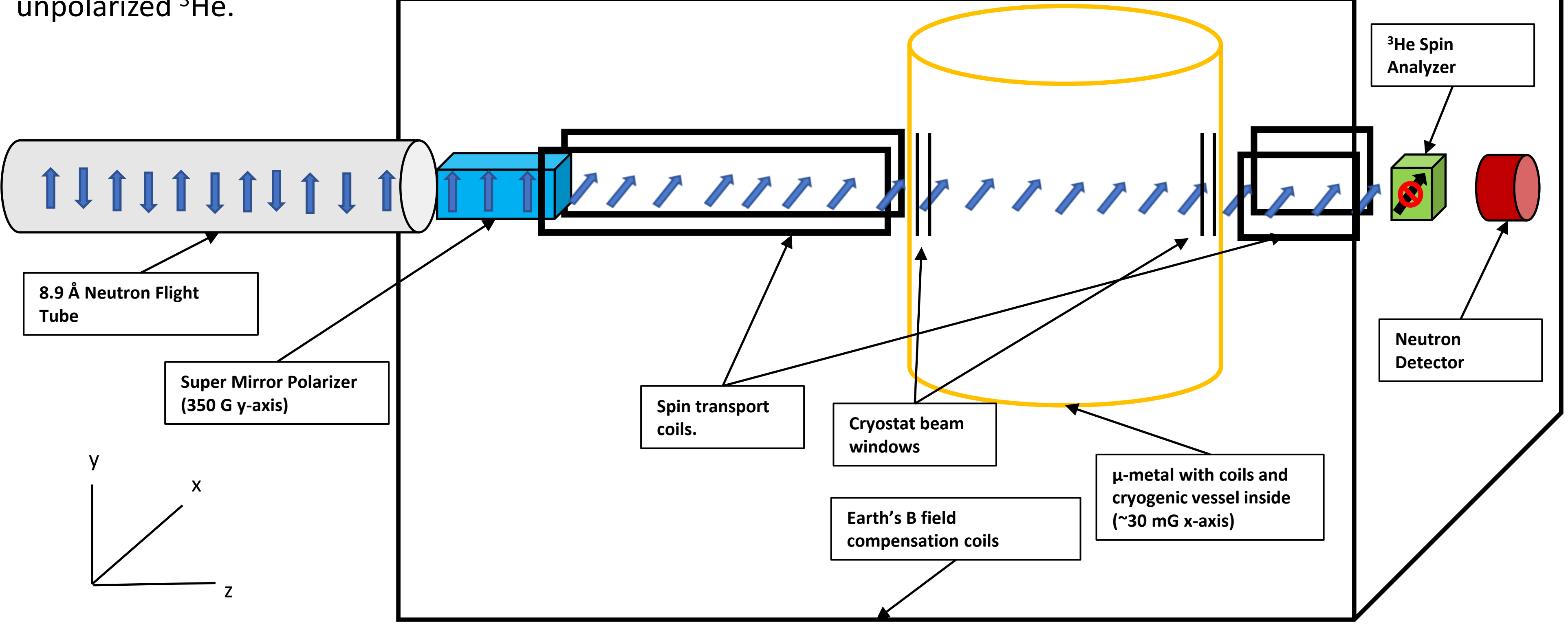
P/T Measurement Setup



P & T Measurement Setup

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

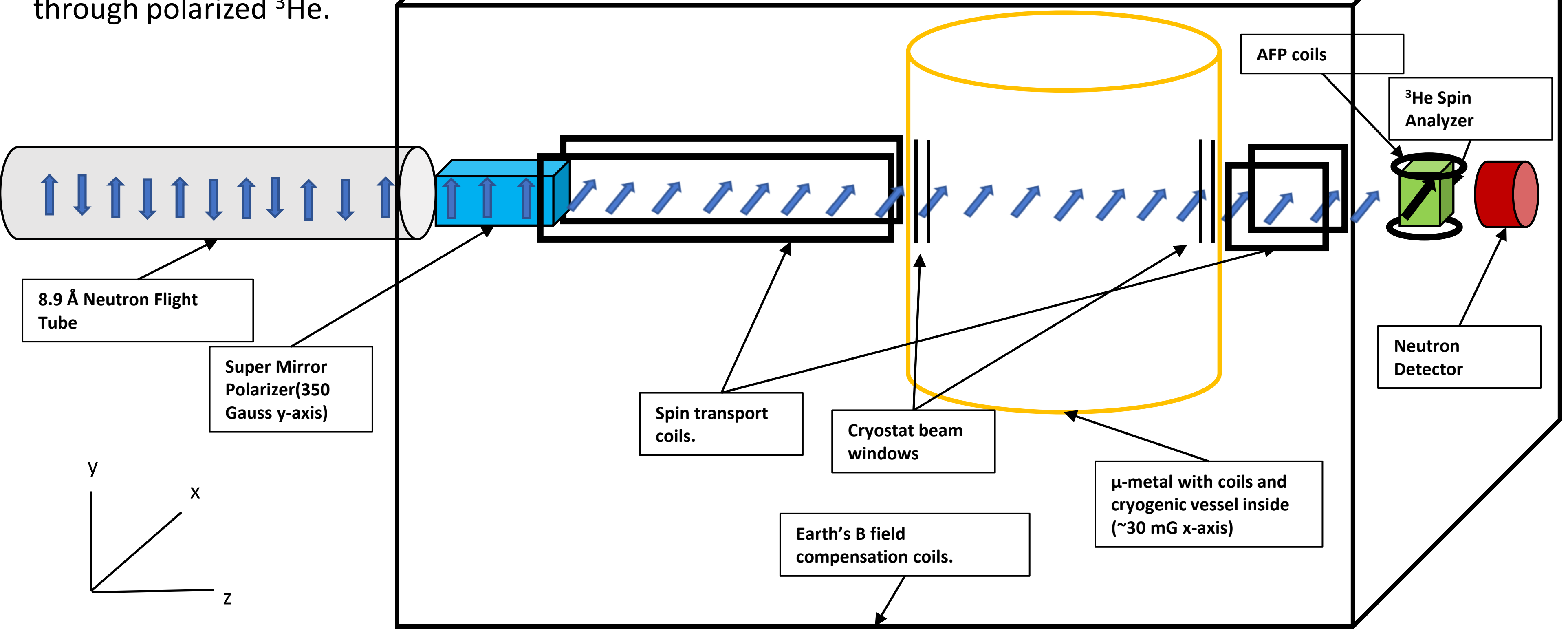
1) Transmission of polarized neutrons through unpolarized ^{3}He.



P & T Measurement Setup

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

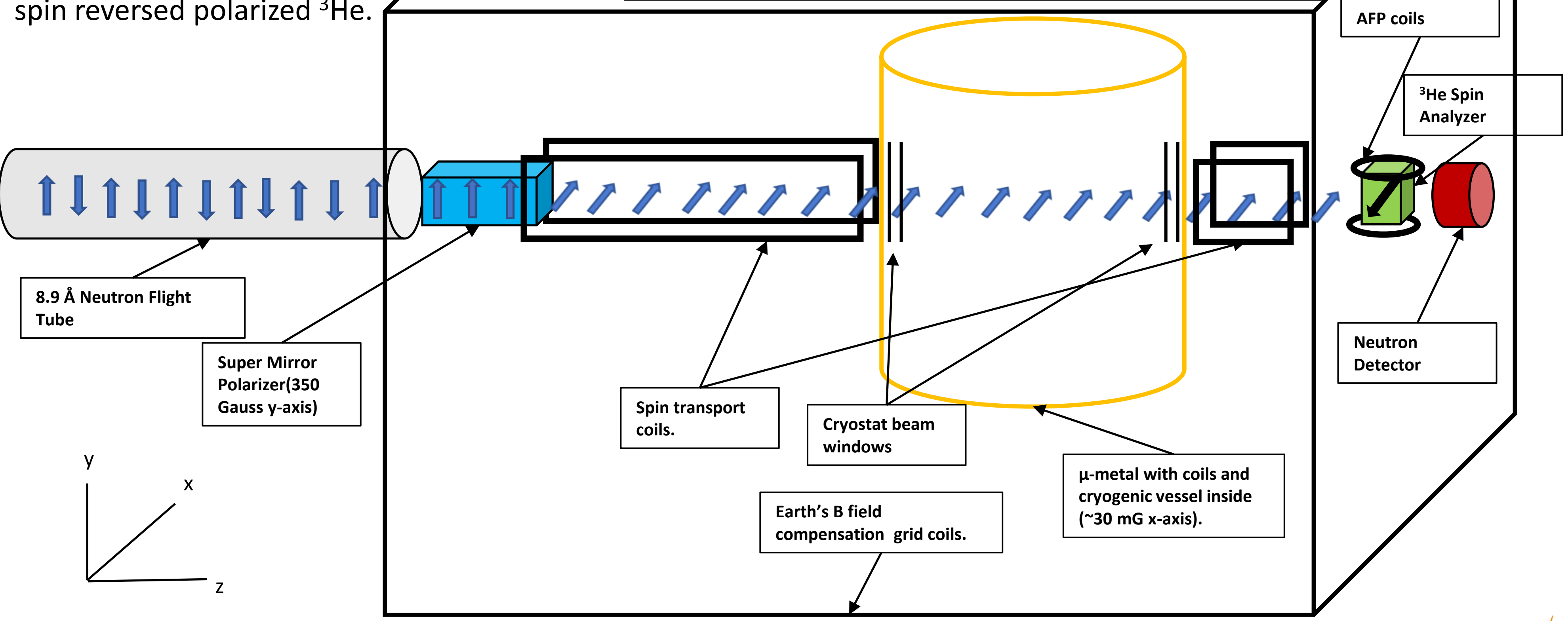
$$R = \frac{T}{T_0}, \; R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$



P & T Measurement Setup

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

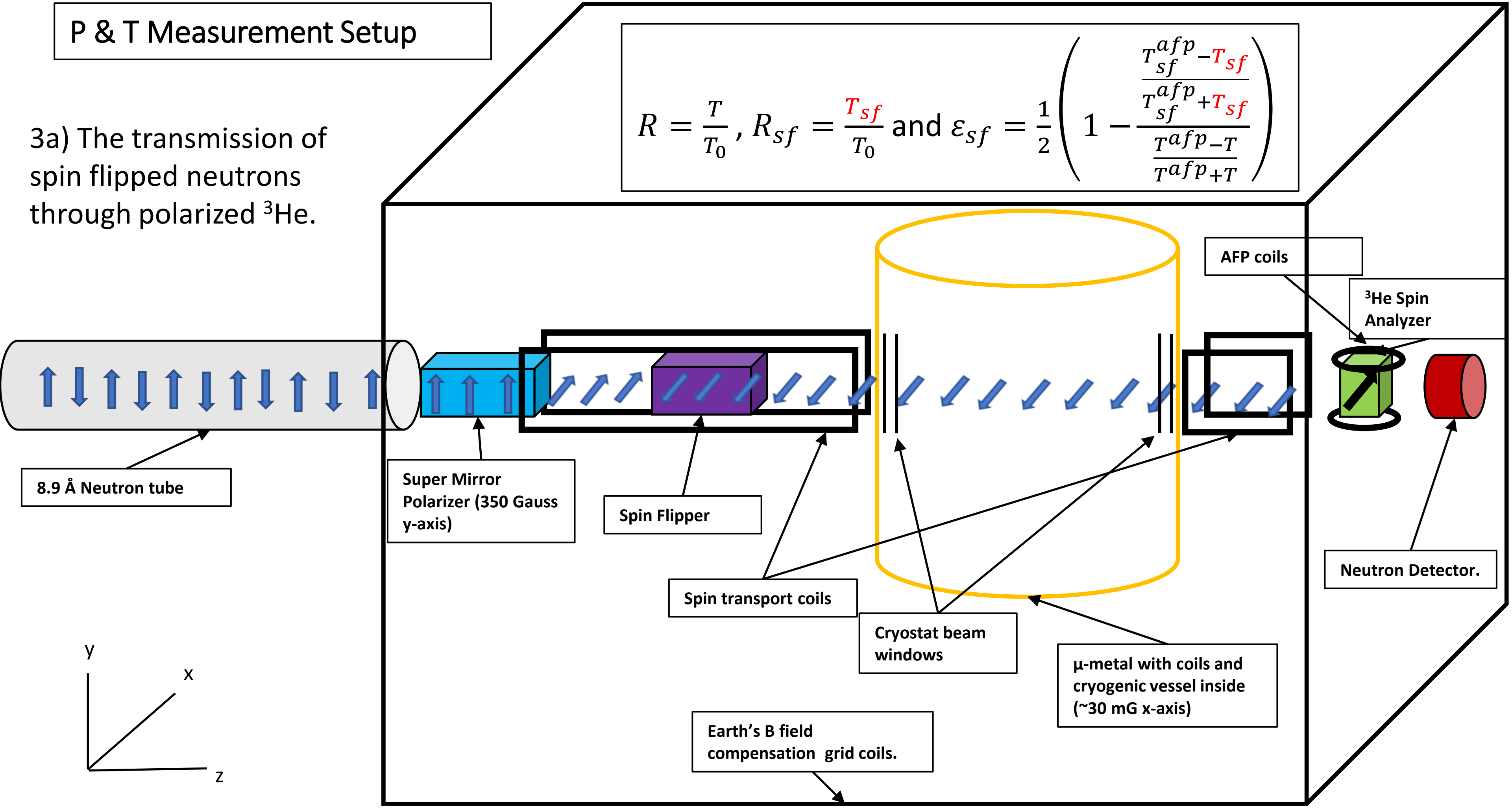
$$R = \frac{T}{T_0},\ R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$



P & T Measurement Setup

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

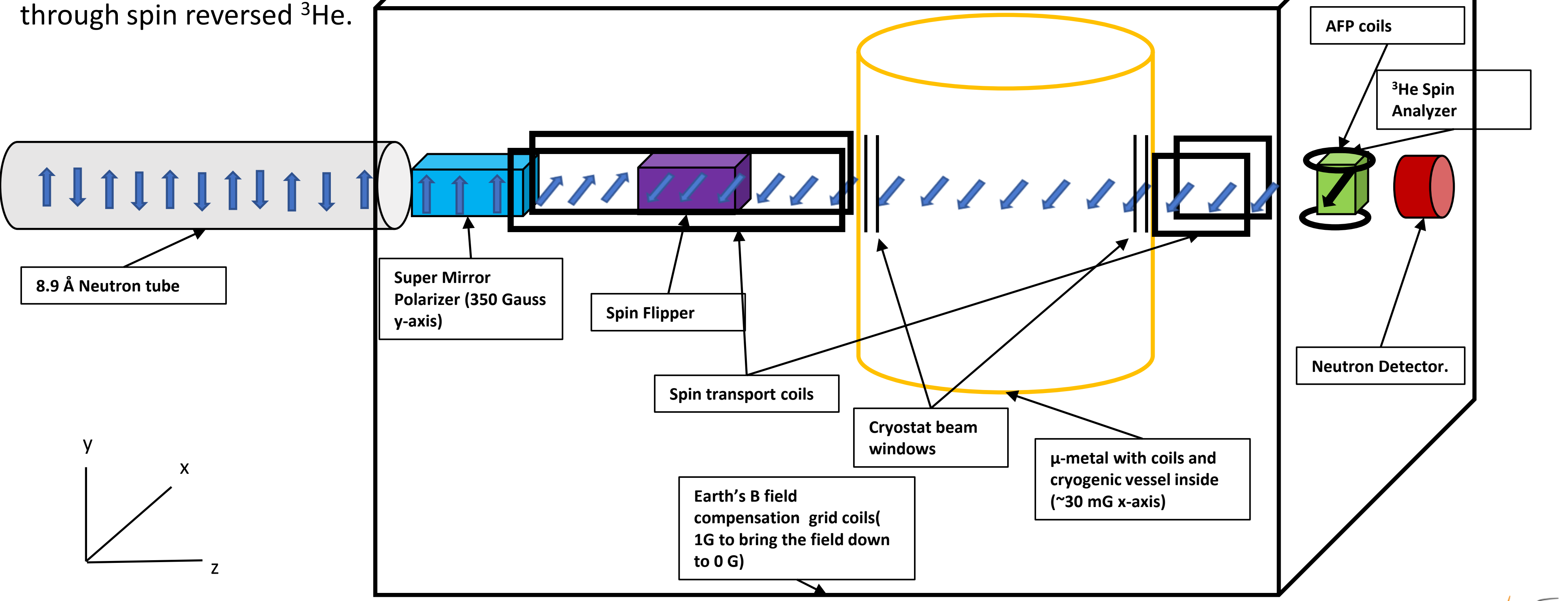
$$R = \frac{T}{T_0},\ R_{sf} = \frac{T_{sf}}{T_0} \text{ and } \varepsilon_{sf} = \frac{1}{2}\left(1 - \frac{\frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}}}{\frac{T^{afp} - T}{T^{afp} + T}}\right)$$



P & T Measurement Setup

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

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



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

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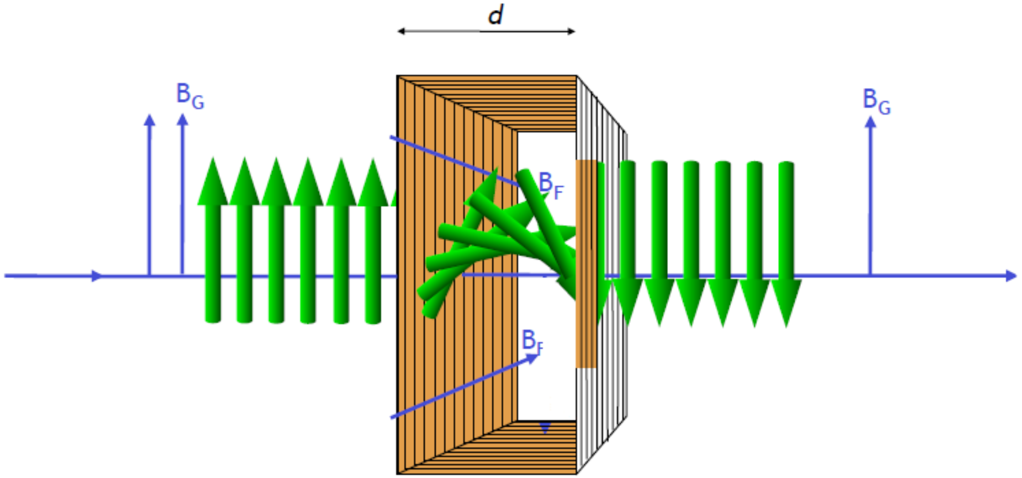
- ^{3}He polarization and the physical properties of the ^{3}He cell do not need to be known to determine the neutron polarization.

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

Mezei coil spin flipper

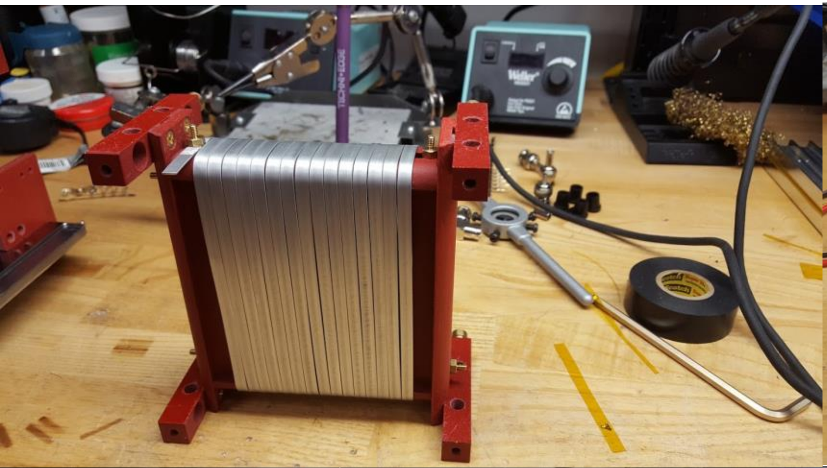
The Mezei flipper uses a diabatic field perpendicular to the guide field change to project the polarization direction of the beam onto any arbitrary field axis.

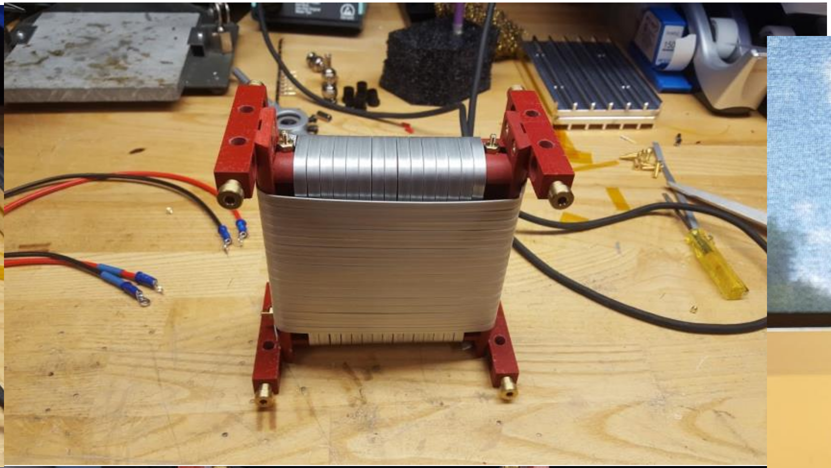
Useful for monochromatic beams i.e. fixed velocity

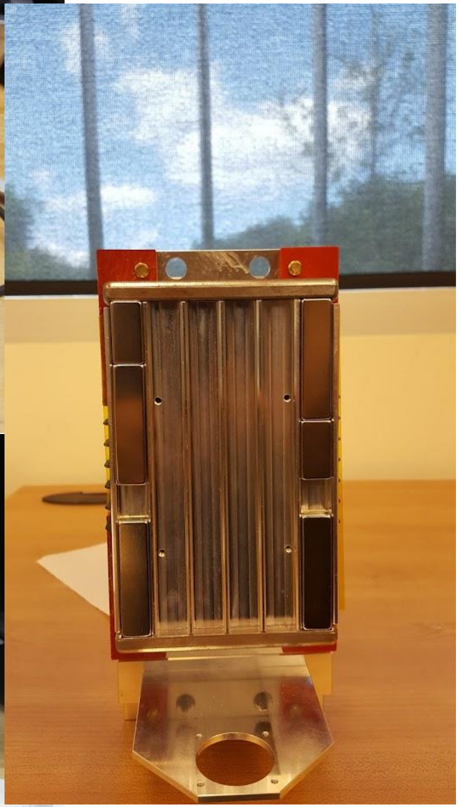


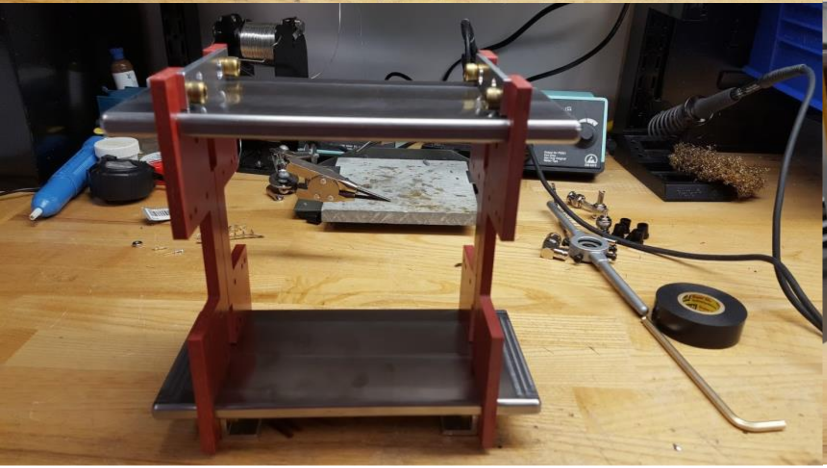
A flip of ϕ radians with respect to the guide field can be achieved if the resultant field within the coil, B_F, is perpendicular to B_G and

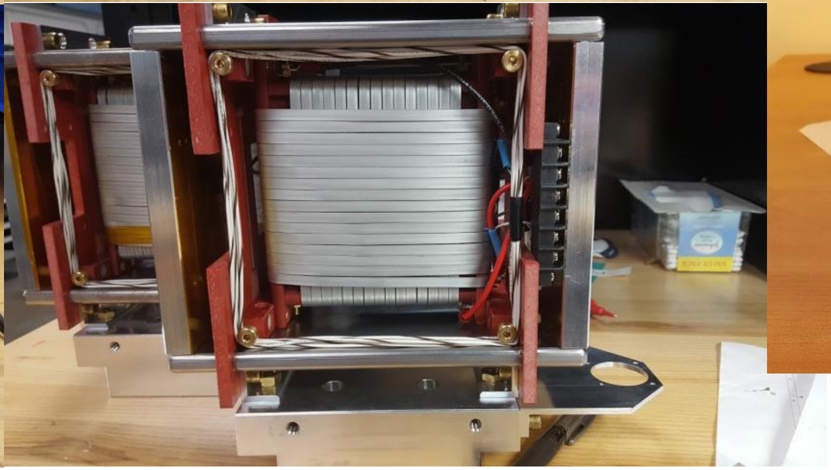
$$d = \frac{\phi v}{\gamma_n B_R}$$





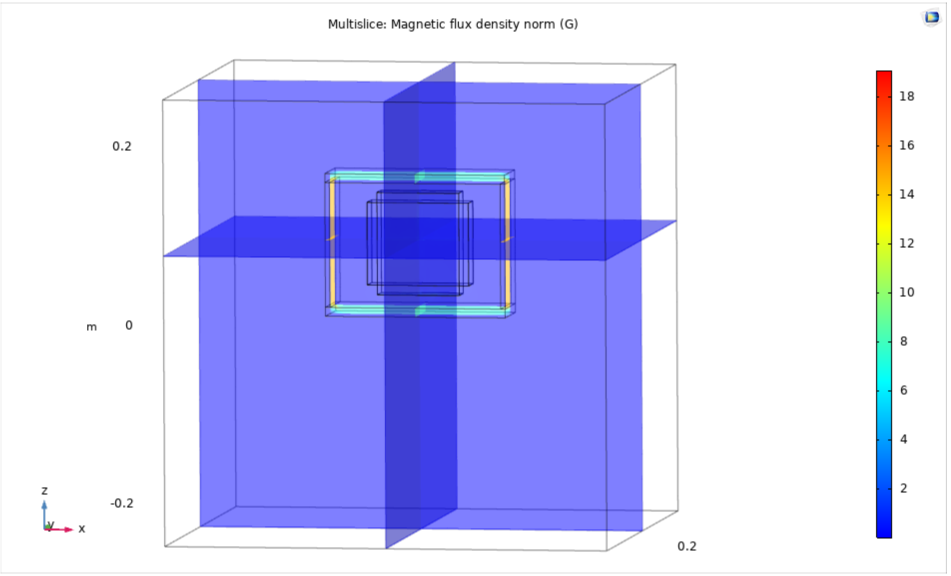


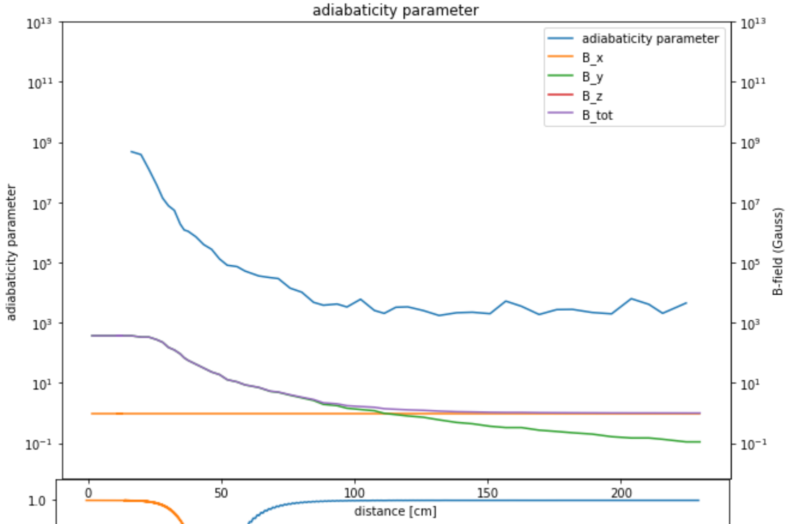


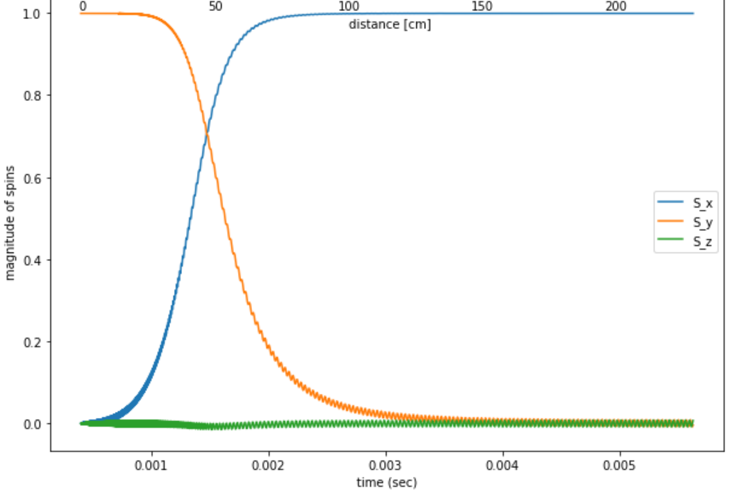


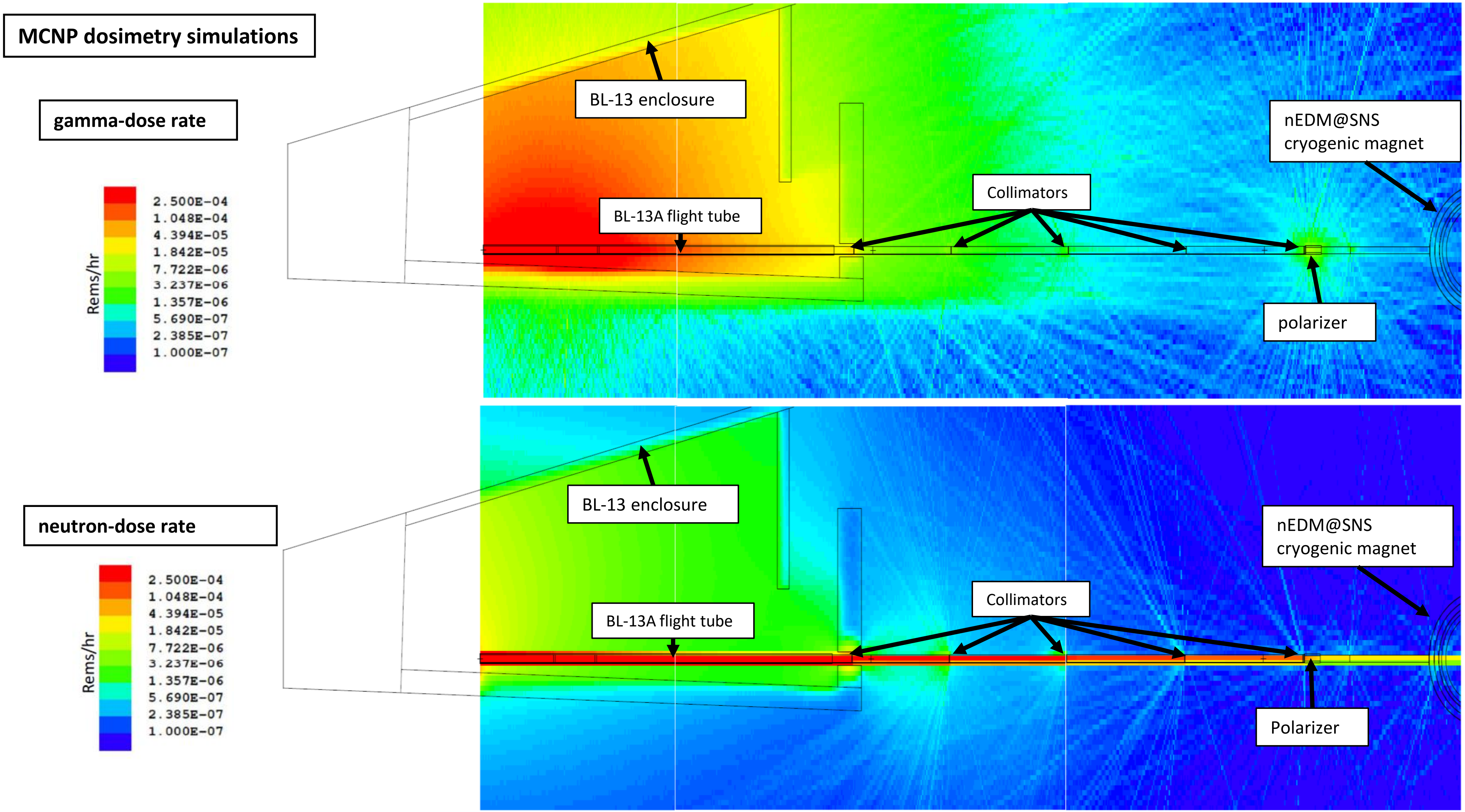
Spin “gymnastics” simulations

- Integrating Bloch’s equations to check for spin “gymnastics” transport in the magnetic field for the polarimetry components.








MCNP dosimetry simulations
gamma-dose rate
Rems/hr
2.500E-04
1.048E-04
4.394E-05
1.842E-05
7.722E-06
3.237E-06
1.357E-06
5.690E-07
2.385E-07
1.000E-07
BL-13 enclosure
BL-13A flight tube
Collimators
nEDM@SNS
cryogenic magnet
polarizer
neutron-dose rate
Rems/hr
2.500E-04
1.048E-04
4.394E-05
1.842E-05
7.722E-06
3.237E-06
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5.690E-07
2.385E-07
1.000E-07
BL-13 enclosure
BL-13A flight tube
Collimators
nEDM@SNS
cryogenic magnet
Polarizer

Ongoing work…

- Cryogenic Magnet is being commissioned at Caltech and is expected to arrive at SNS early 2022.
- Flight tube is undergoing engineering design and construction will begin 2021.
- Polarimetry components are being developed and tested.
- Magnetic field simulations are being performed to check for spin transport.
- Dosimetry calculations have been performed and reviewed for approval.

nEDM @SNS Collaboration

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

Metglas polarisation measurements on SESAME at LENS

13th April 2014

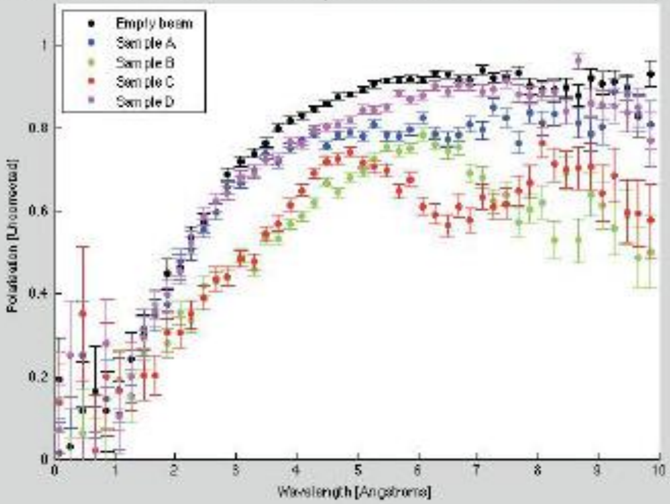
S.R.Parnell, T. Wang, A.L.Washington and R.Pynn

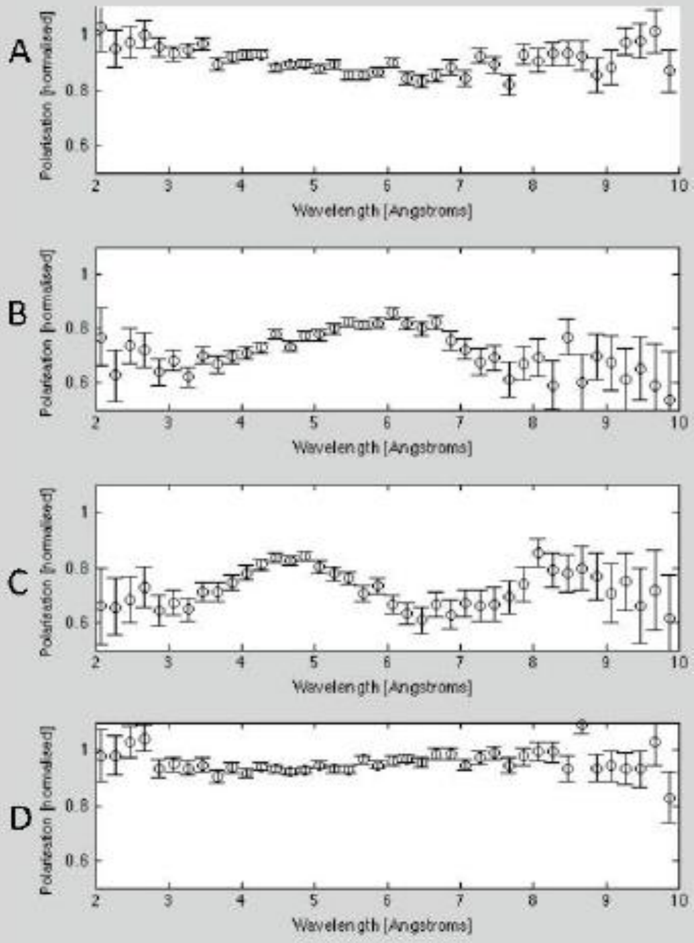
Samples - in approx. 9 G field for neutron spin transport

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



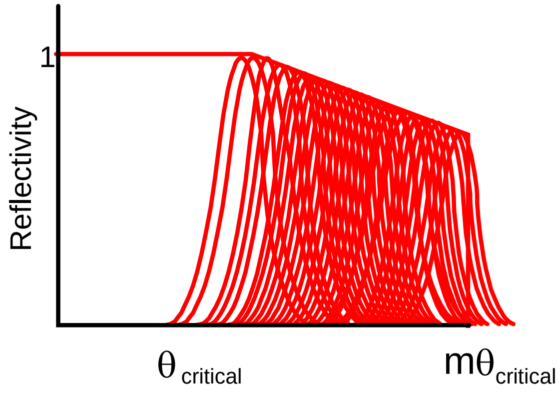


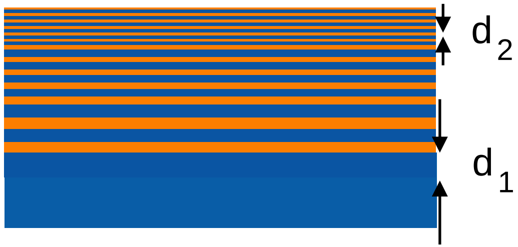
W. Treimer et al., Polarized neutron imaging and three-dimensional calculation of magnetic flux trapping in bulk of superconductors. Phys. Rev. B **85**, (2012) 184522 https://doi.org/10.1103/PhysRevB.85.184522

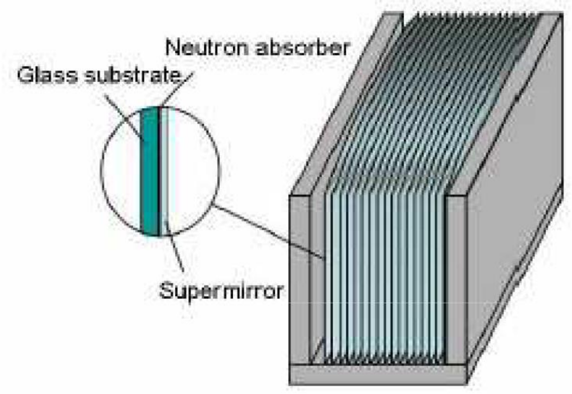
Supermirror Polarizer

The supermirror polarizer spin filters the neutron beam by preferentially reflecting one neutron spin state. The other spin state is absorbed in the Borofloat glass substrate.

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







^{3}He Analyzer Cell

- In collaboration with SNS polarimetry group.
- Offsite polarization using SEOP.
- Transport to site using transport coils.

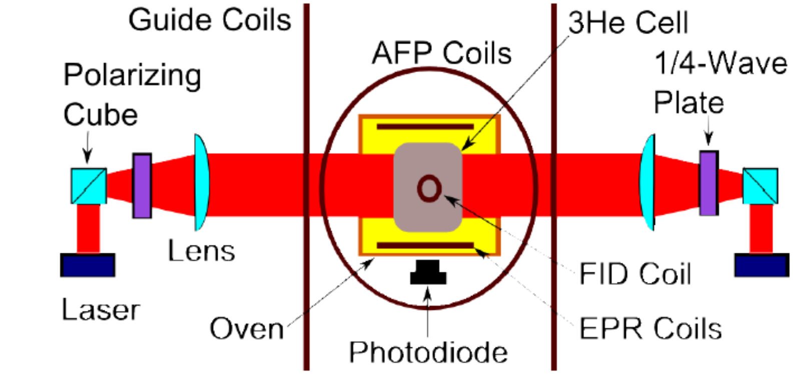
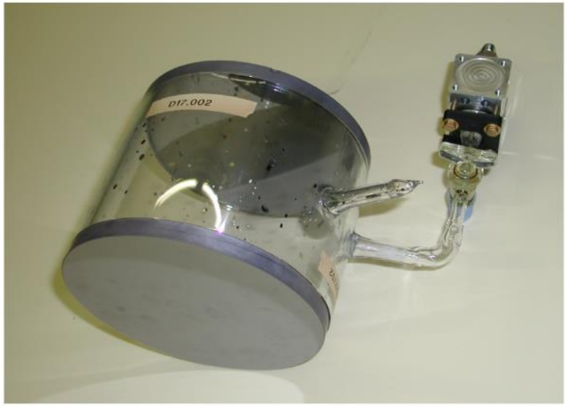
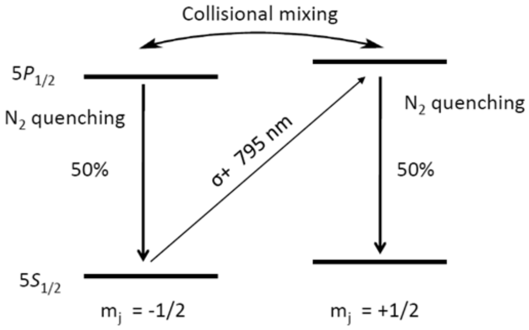
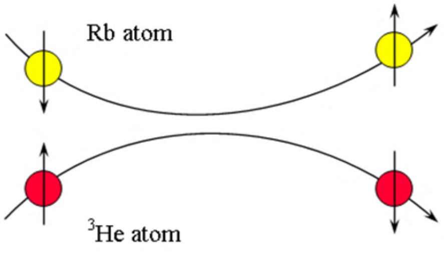


Figure 4.7: Schematic of the optical pumping station used to polarize ^{3}He cells.





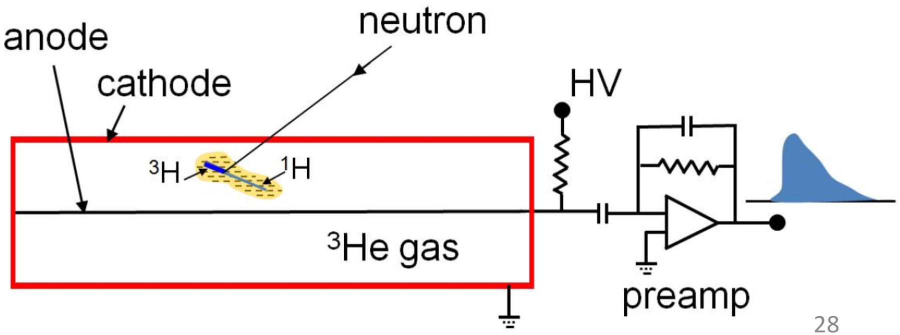
Optical pumping



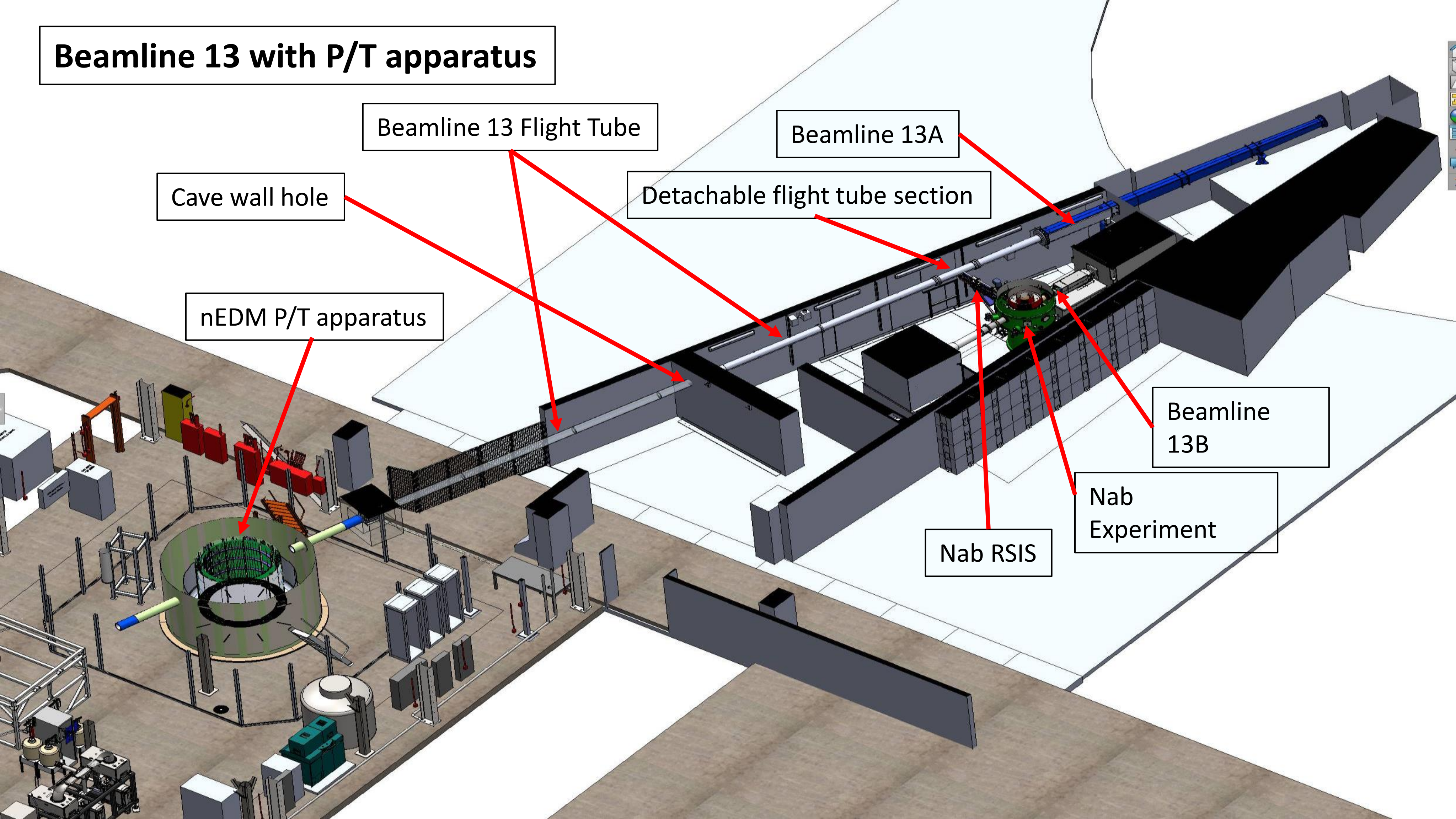
Spin exchange

Neutron Detector

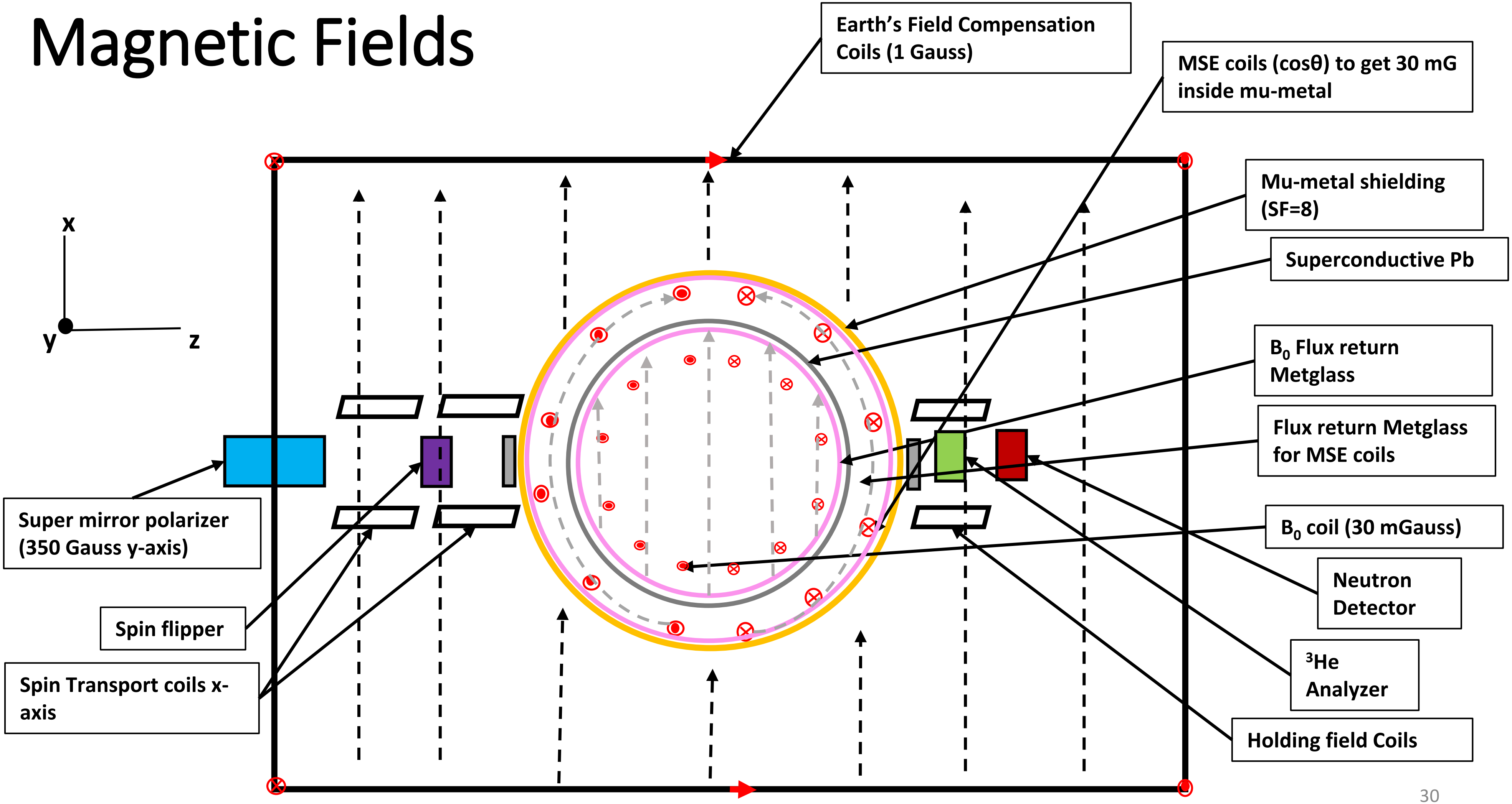
- 8 or 6 pack of Reuter Stokes ^{3}He Gas Filled Proportional Detectors.
- Borrow these from the SNS polarimetry group.
- ^{3}He counter($n + ^3He \rightarrow ^3H + p$)
  - Proton and triton create avalanche multiplication
  - Proportional counters operating in Geiger mode.



Beamline 13 with P/T apparatus

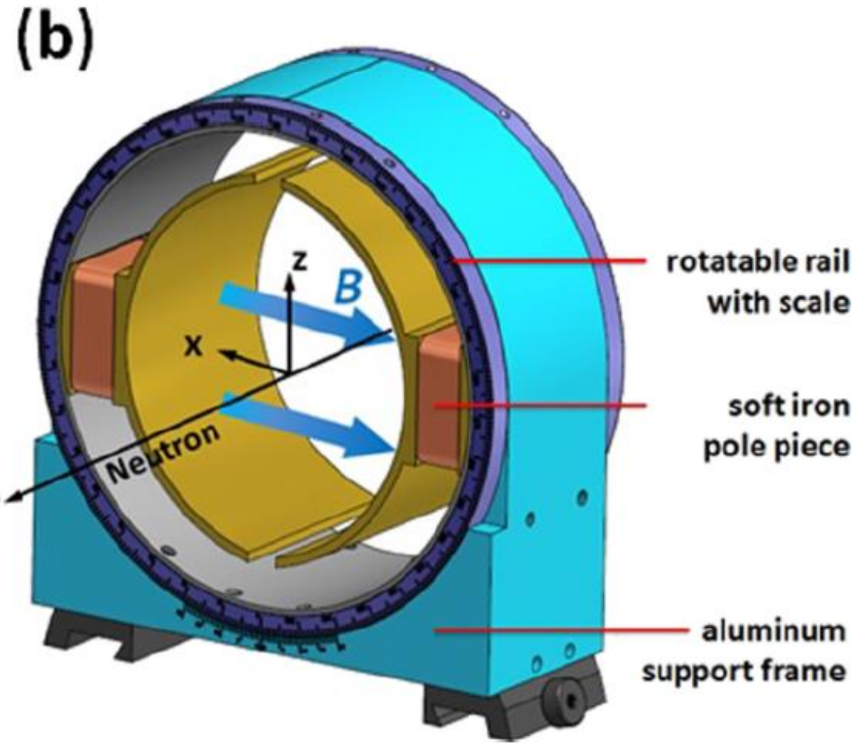


Magnetic Fields



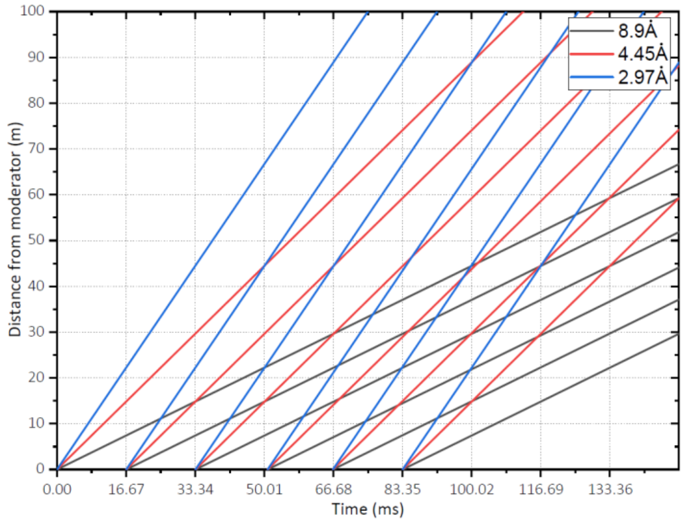
“Neutator”-guide field rotator

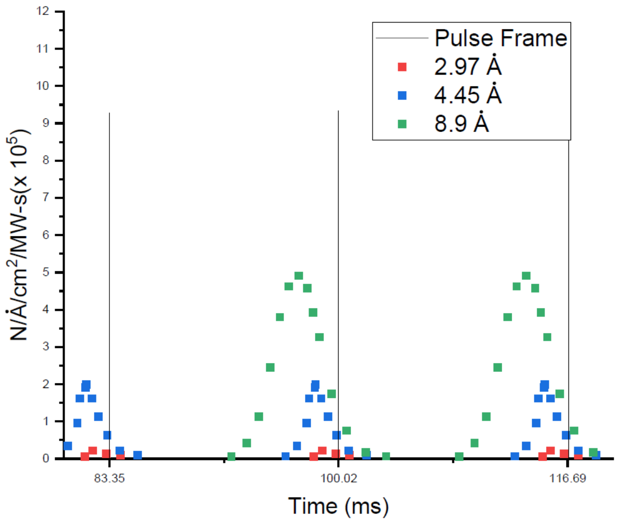
- Neutron guide field rotator -“neutator”.
  - Fix any magnetic field misalignment issues.
  - This will eliminate the need to rotate the spin flipper
  - provide the adiabatic rotation after the spin flipper.
  - In collaboration with SNS polarimetry group.



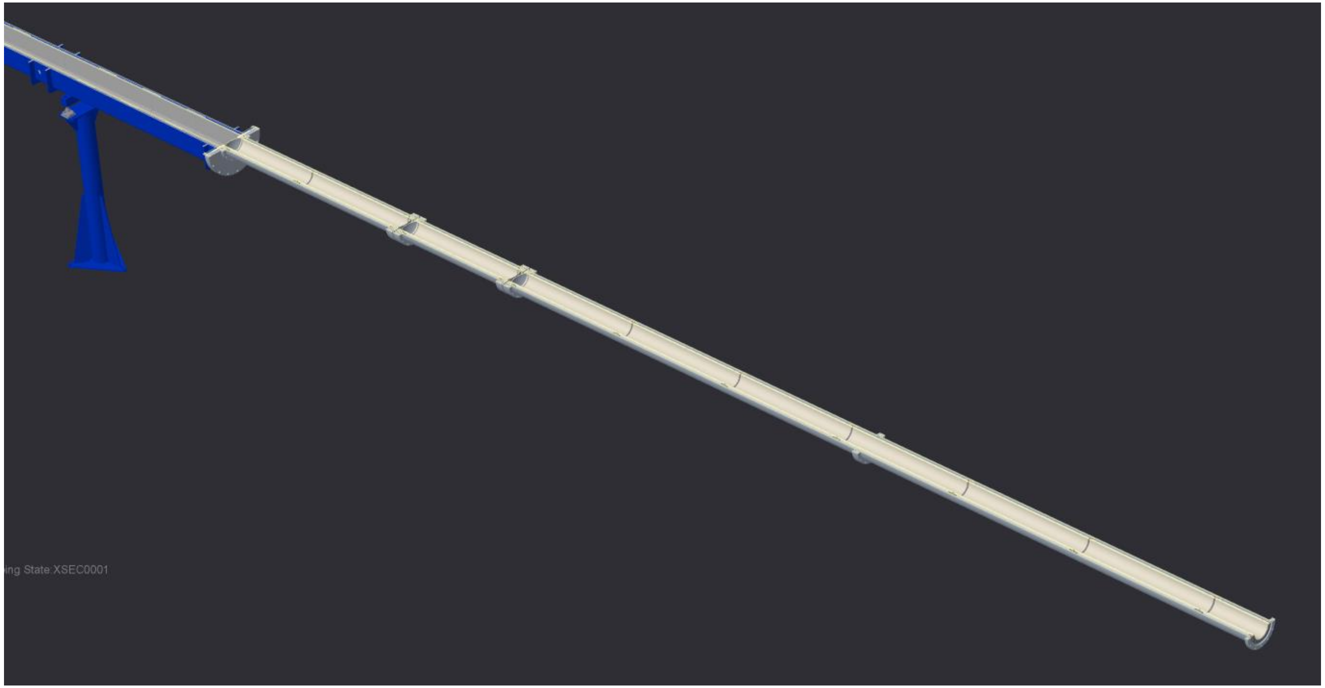
Frame Overlap

- Graphite filters do not fully filter out the 4.45Å and 2.97Å neutrons.
- These neutrons could overlap with the 8.9Å neutrons in time.
- This will lead to a systematic effect for the polarimetry experiment since the neutron detector will be counting the 8.9Å and the overlap neutrons.





Measured spectrum as a function of time of flight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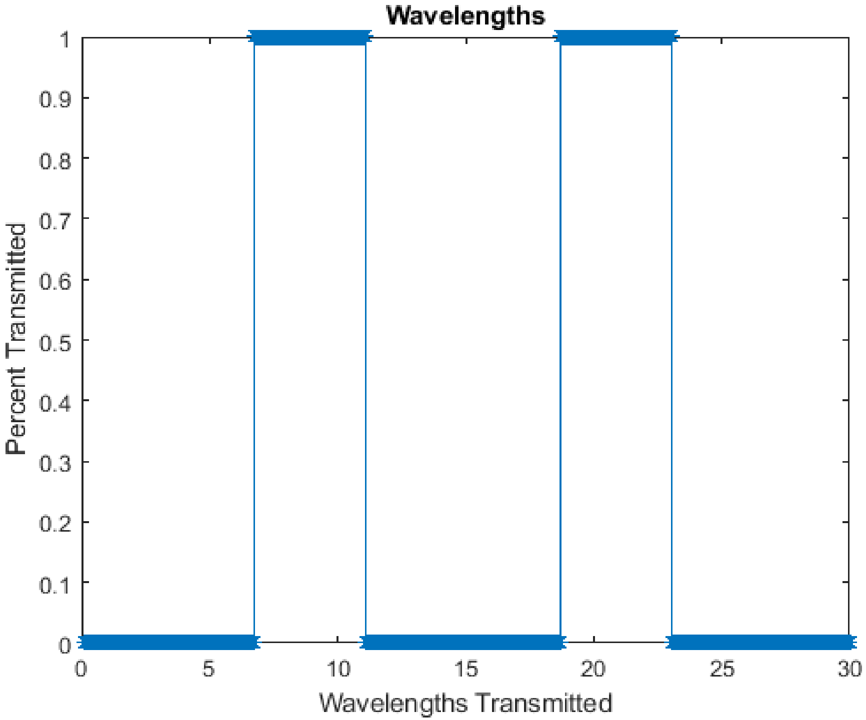
T13_CT102

Chopper solution:



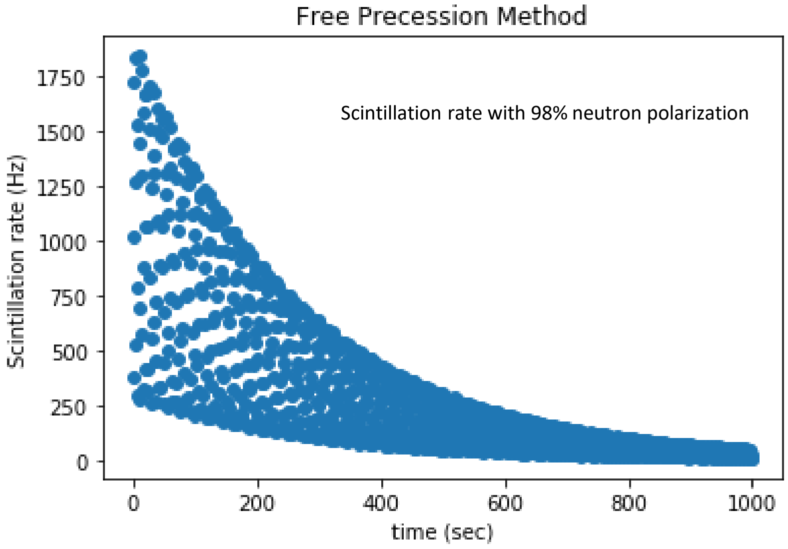
Chopper opening angle: 133 deg
Chopper phase: 267.25 deg
Chopper length: 5.5 m from source
Pulse frequency: 60 Hz
Path length to detector: 42.88 m from source

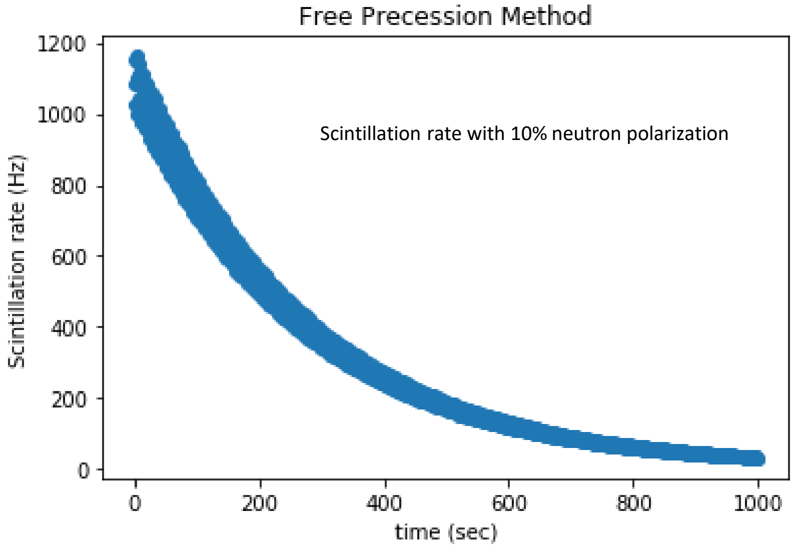
Effect of polarization loss on scintillation rate

$$\dot{N}(t) = \dot{I}_0 e^{-t/\tau}\left[1 - F\cos\left(\theta_{n3}\right)\right] + \dot{N}_B$$
$$= \dot{I}_0 e^{-t/\tau}\left[1 - F\cos\left(\omega t + \phi_0\right)\right] + \dot{N}_B$$

$$\frac{1}{\tau_{UCN}} = \frac{1}{\tau_{cell}} + \frac{1}{\tau_\beta} + \frac{1}{\tau_{up}} + \frac{1}{\tau_3}$$

$$\dot{I}_0 = N_0\left(\frac{\epsilon_\beta}{\tau_\beta} + \frac{\epsilon_3}{\bar{\tau}_3}\right); \quad F = \frac{\epsilon_3 P_3 P_n}{\bar{\tau}_3\left(\frac{\epsilon_\beta}{\tau_\beta} + \frac{\epsilon_3}{\bar{\tau}_3}\right)}$$



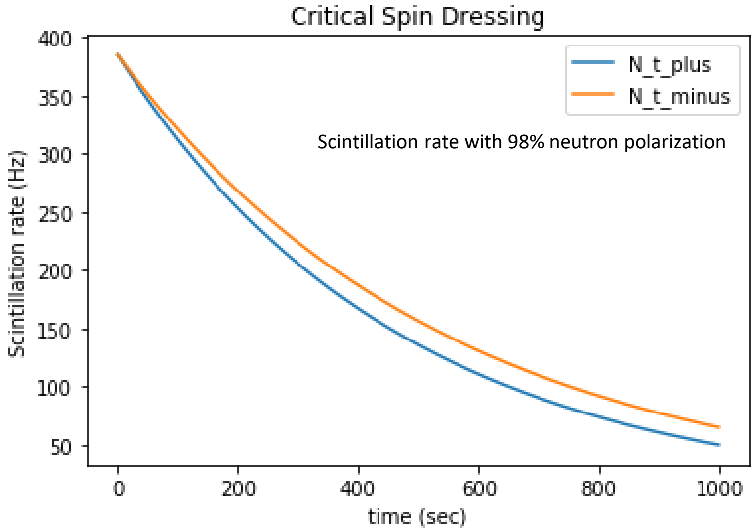


Effect of polarization loss on scintillation rate

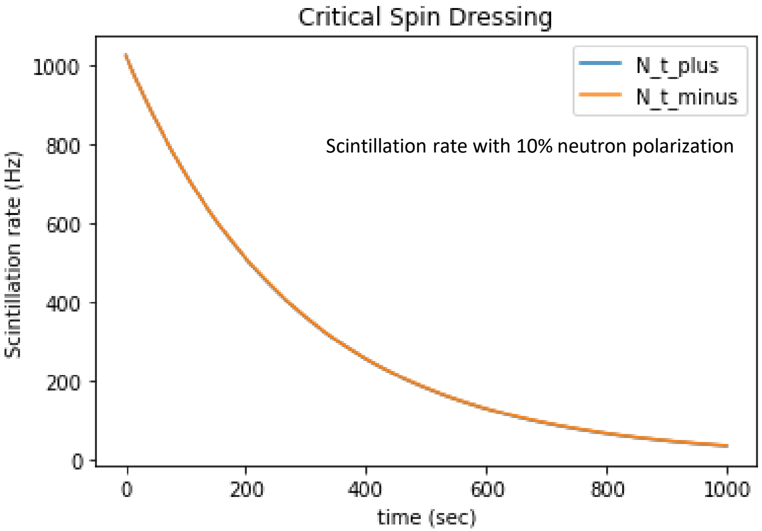
$$N_{\pm}(t_i) = \left(\frac{N_0\epsilon_\beta}{\tau_\beta}\right) e^{-\Gamma t_i}\Delta t + \dot{N}_B \Delta t$$
$$+ \left(\frac{N_0\epsilon_3}{\bar{\tau}_3}\right)\left(1 - P\cos\phi_0 \mp \frac{2J_0(x_c)d_n|\vec{E}|t_i P\sin\phi_0}{\hbar}\right) e^{-\Gamma t_i}\Delta t$$

$$P = P_3 P_n \quad \text{and} \quad \Gamma = \frac{1 - P\cos\phi_0}{\bar{\tau}_3} + \frac{1}{\tau_\beta} + \frac{1}{\tau_{cell}} + \frac{1}{\tau_{up}}$$

Assume d_n : 10^{-24} e·cm

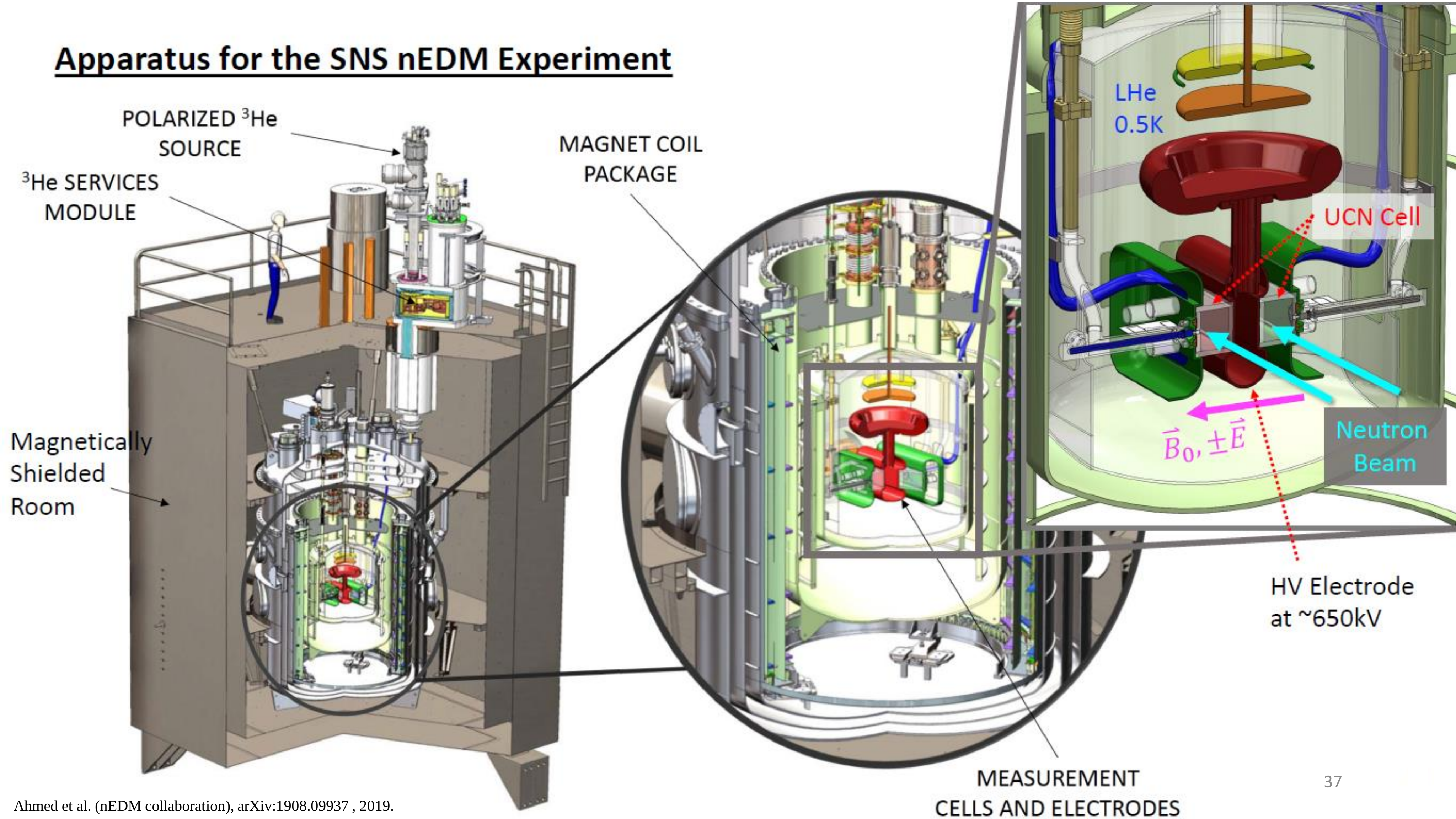


Scintillation rate with 98% neutron polarization

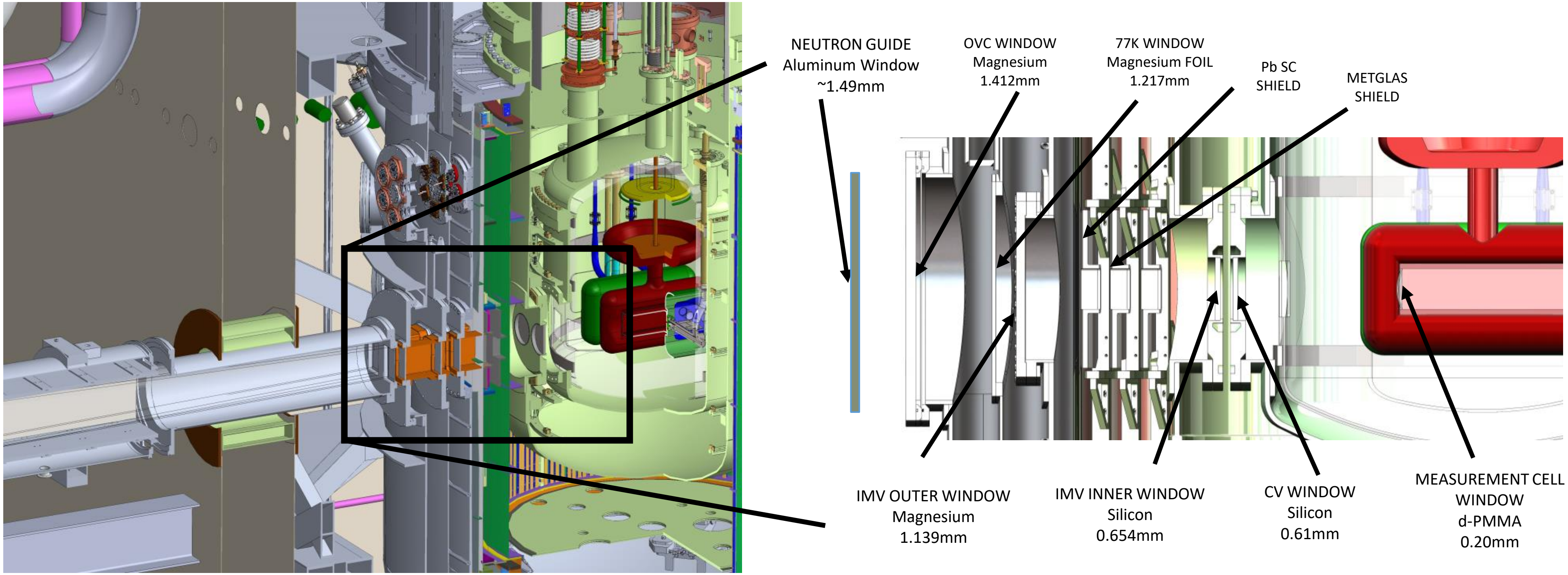


Scintillation rate with 10% neutron polarization

Apparatus for the SNS nEDM Experiment



Ahmed et al. (nEDM collaboration), arXiv:1908.09937 , 2019.



NEUTRON GUIDE
Aluminum Window
~1.49mm
OVC WINDOW
Magnesium
1.412mm
77K WINDOW
Magnesium FOIL
1.217mm
Pb SC
SHIELD
METGLAS
SHIELD
IMV OUTER WINDOW
Magnesium
1.139mm
IMV INNER WINDOW
Silicon
0.654mm
CV WINDOW
Silicon
0.61mm
MEASUREMENT CELL
WINDOW
d-PMMA
0.20mm