PULSTAR systematics studies apparatus of SNS nEDM experiment

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On behalf of the SNS nEDM Collaboration

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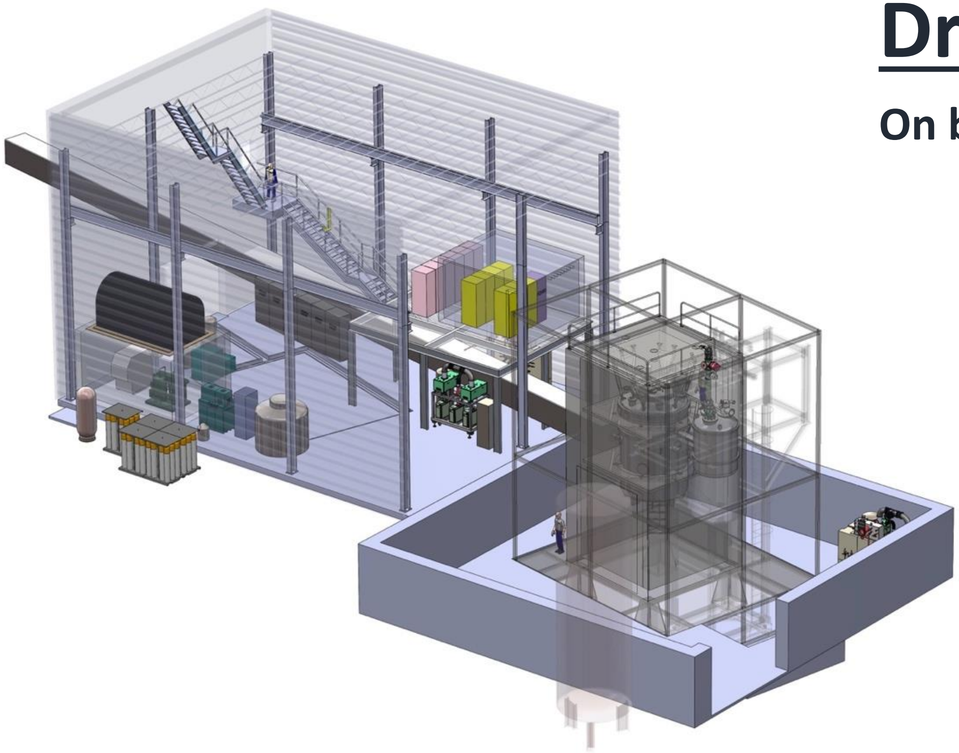
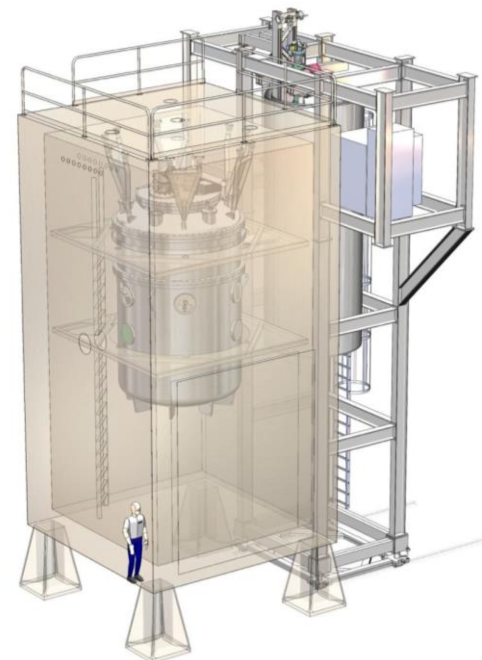


PULSTAR systematics studies apparatus summary

- Provide a test bed with one full-sized cell at final temperature (0.3 K) with no electric field
- Use external source of ultracold neutrons rather than neutron beam from NCSU PULSTAR UCN source (1MW reactor + solid D_2)
- System will have shorter cooldown and turnaround times
- Study how to manipulate the spins of polarized ultracold neutron and polarized ^{3}He spins.
- Measure the correlation functions that describe UCN and ^{3}He motion, which are used to analytically calculate false EDM effects such as ("geometric phase")

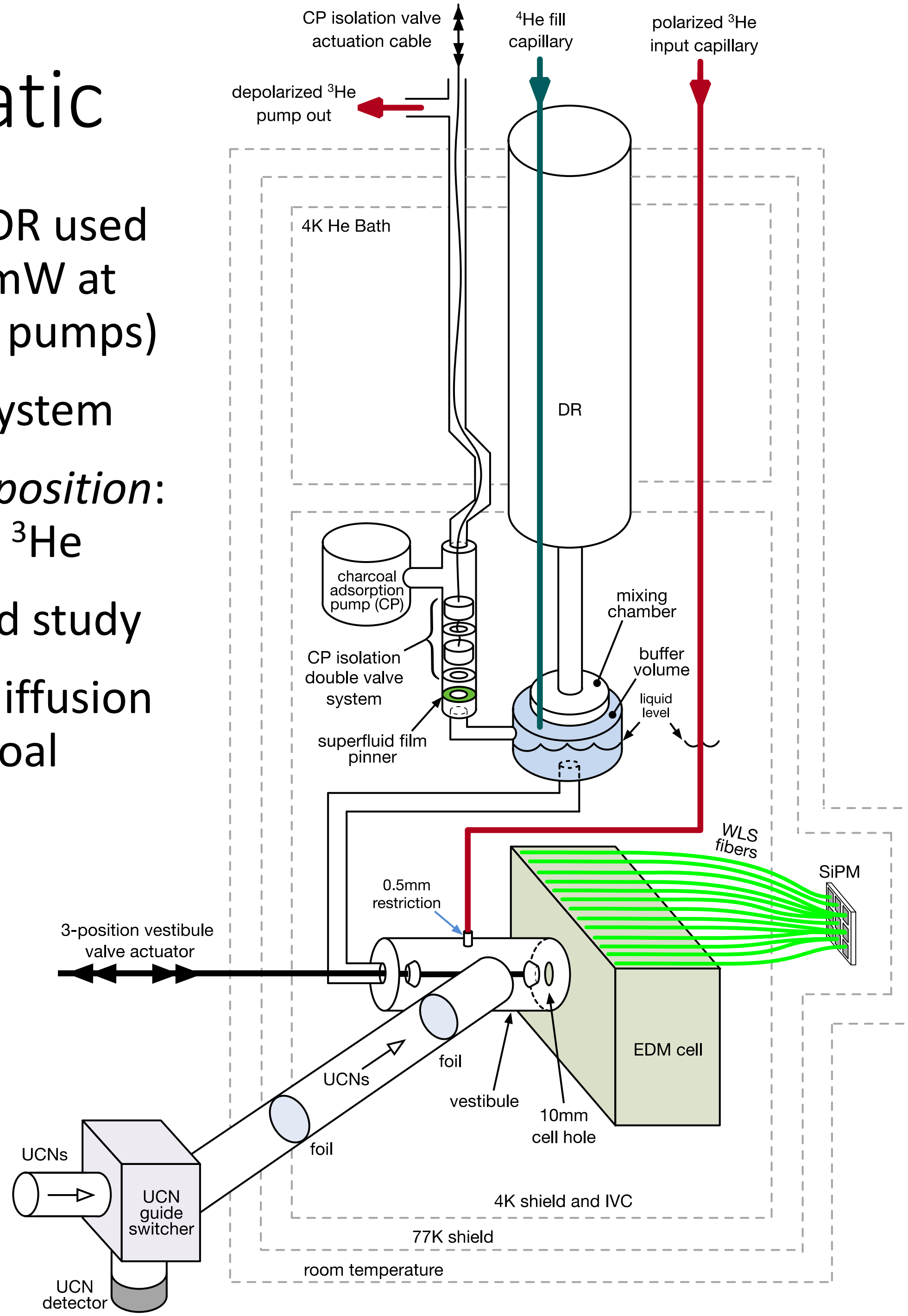
SNS nEDM



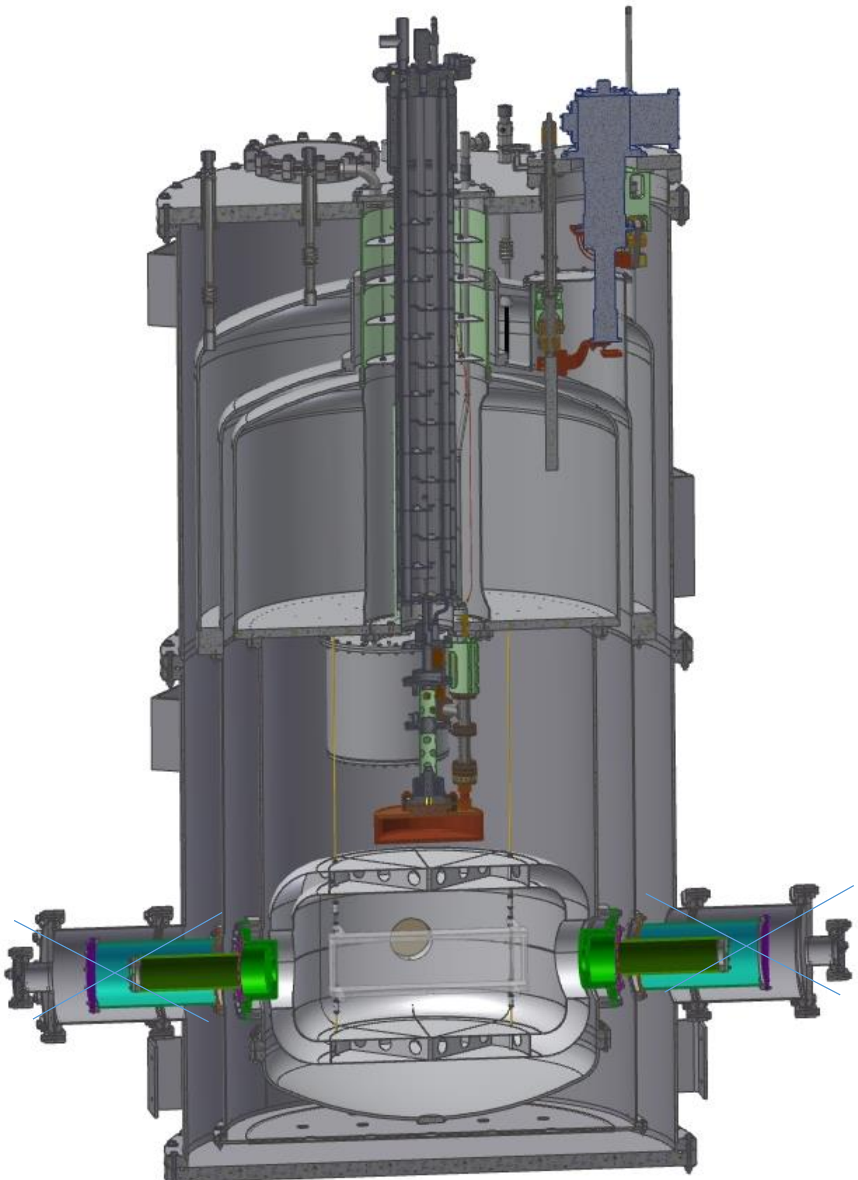
PULSTAR apparatus

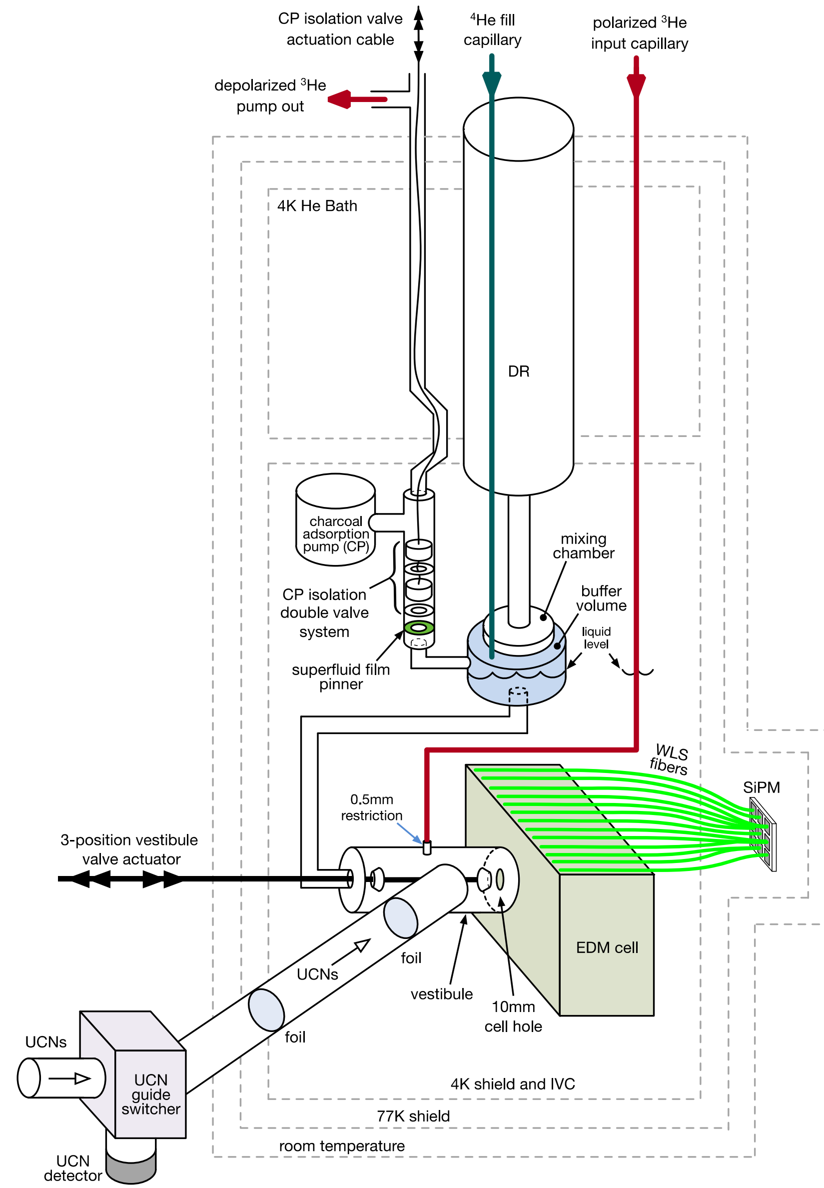
Experiment schematic

- Ultracold neutrons from The ”HMI” DR used tested in June 2016 to provide 1500mW at 0.3K (will increase with newly added pumps)
- Polarized ^{3}He produced by a MEOP system
- 3-position “vestibule valve”. *Far-left position*: load in polarized UCNs and polarized ^{3}He
- *Far-right*: hold UCNs in ^{3}He in cell and study
- *Middle*: unload depolarized ^{3}He via diffusion and differential evaporation to charcoal adsorption pump (CP)
- CP isolation double valve system for when heating CP for purging
- Scintillation light read out with wavelength shifting (WLS) fibers with silicon photomultipliers (SiPMs)



Apparatus Design





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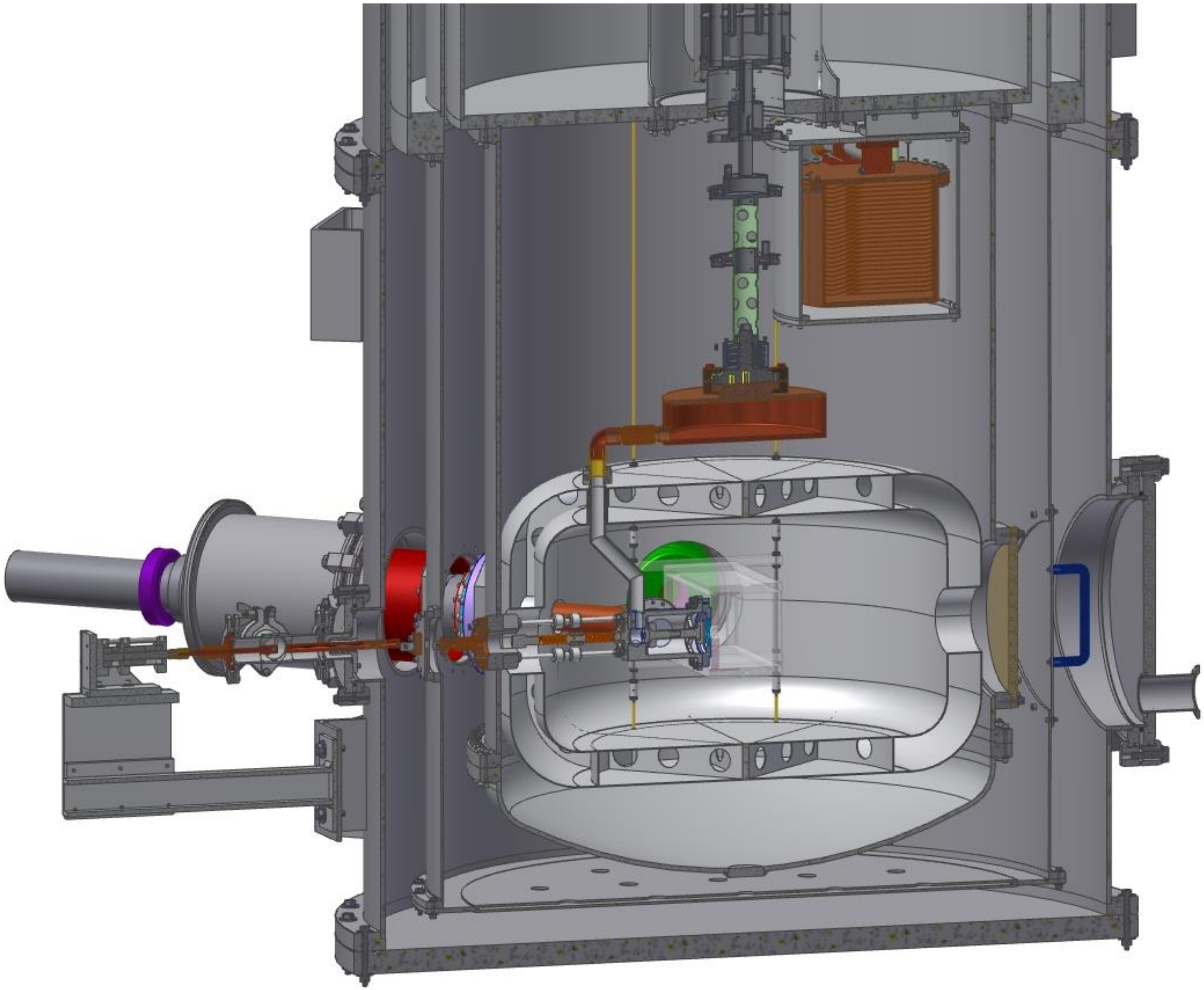

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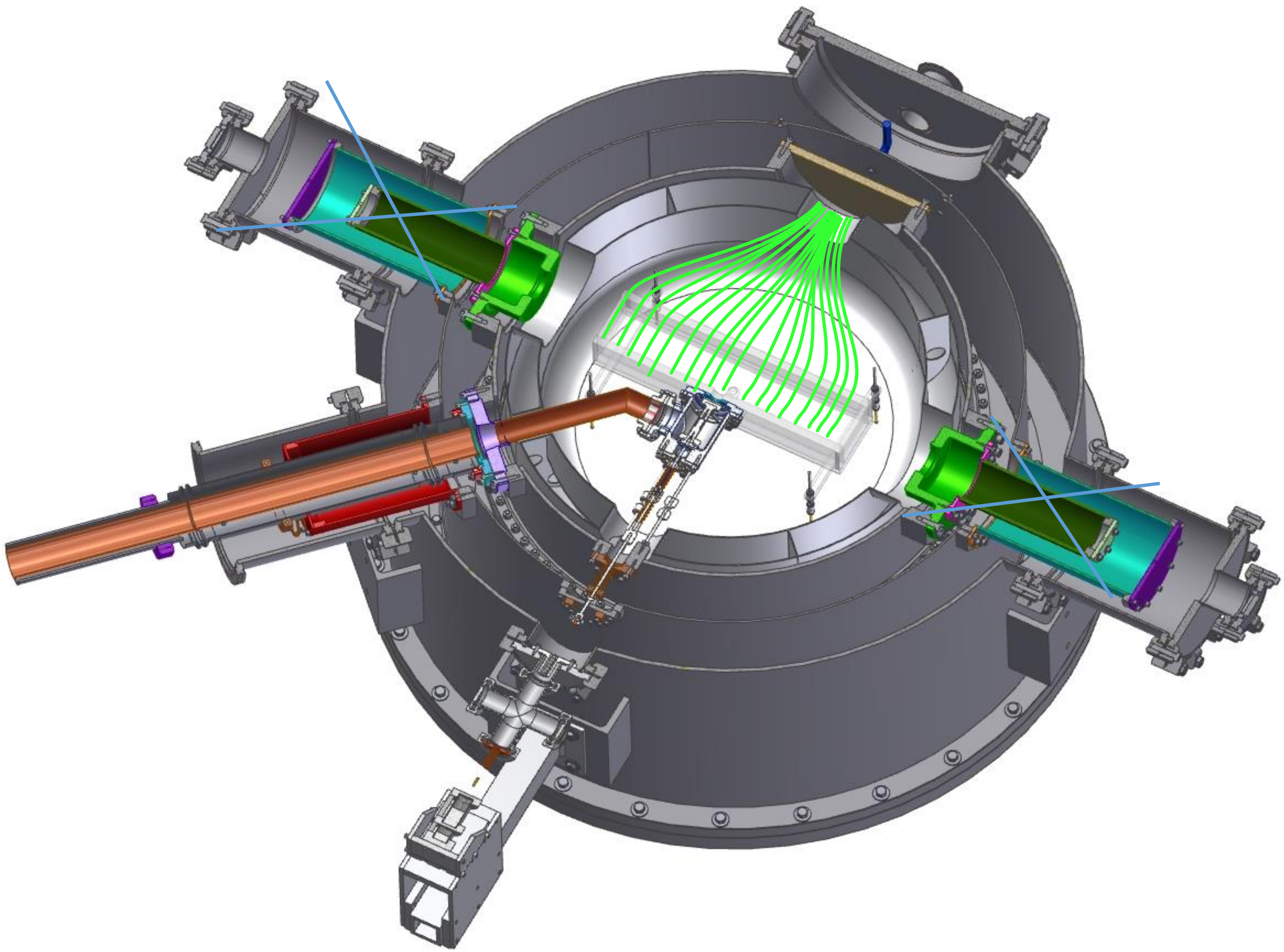


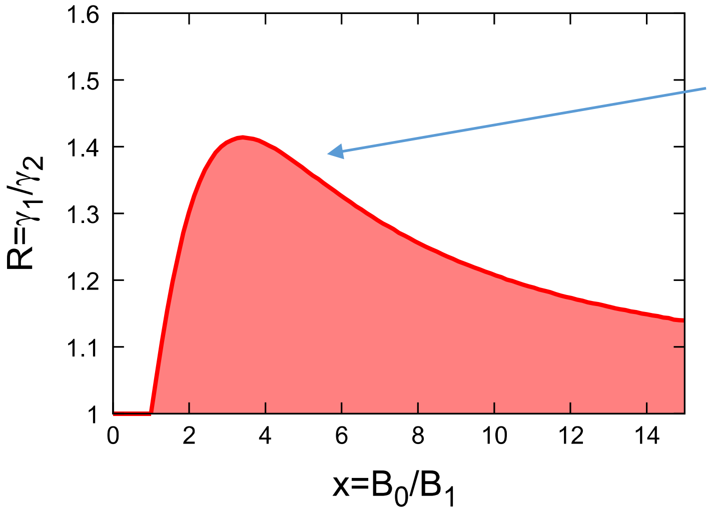
Experimental Program

To study the various systematic and test spin "gynmastics" of n-^{3}He-superfluid ^{4}He scheme [*Golub & Lamoreaux, Physics Reports 237, 1-62 (1994)*]

- Simultaneous $\pi/2$ flip of ^{3}He and neutron
- Pseudomagnetic field
- Measurement of ^{3}He correlation functions => allow analytic calculations of false EDM systematic effects
- Study techniques for Critical Spin-Dressing
- ^{3}He imaging
- Measurement cell deuterated plastic coating ultracold neutron storage properties and ^{3}He T_1 and T_2 before installation in full SNS nEDM apparatus

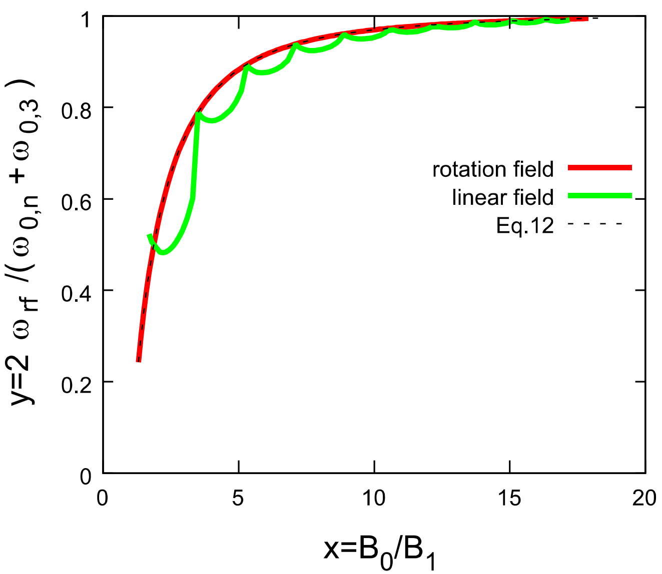
Simultaneous π/2 flip of ^{3}He and n

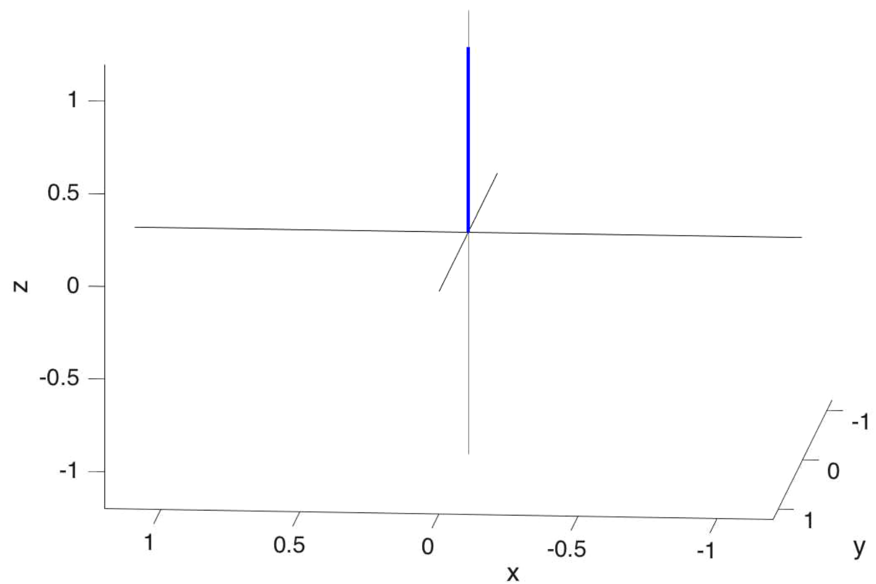
- Two species have different: γ_3 = 20.37894 Hz/mG , γ_n = 18.32472 Hz/mG , γ_3 / γ_n = 1.112



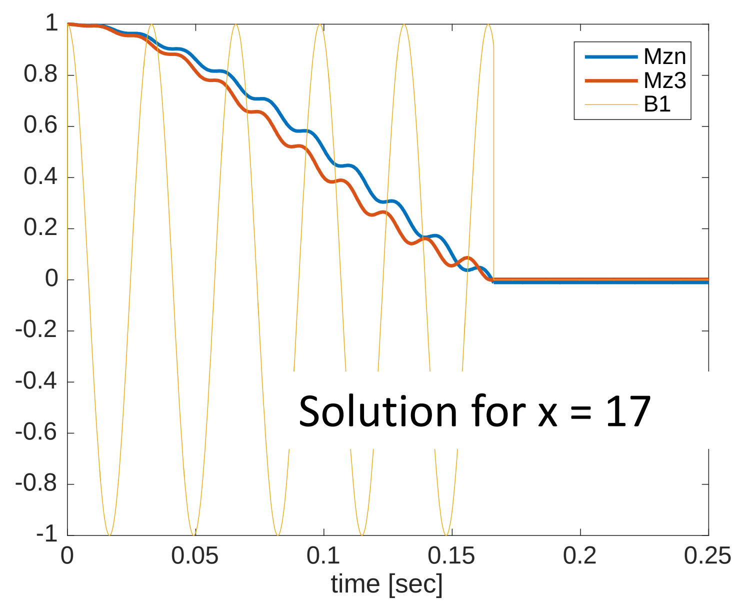
Chu & Peng, *NIM A 795* (2015): off-resonance simultaneous π/2 pulse for two species only exists if ratio x = $B_0/B_1 < 1.4$

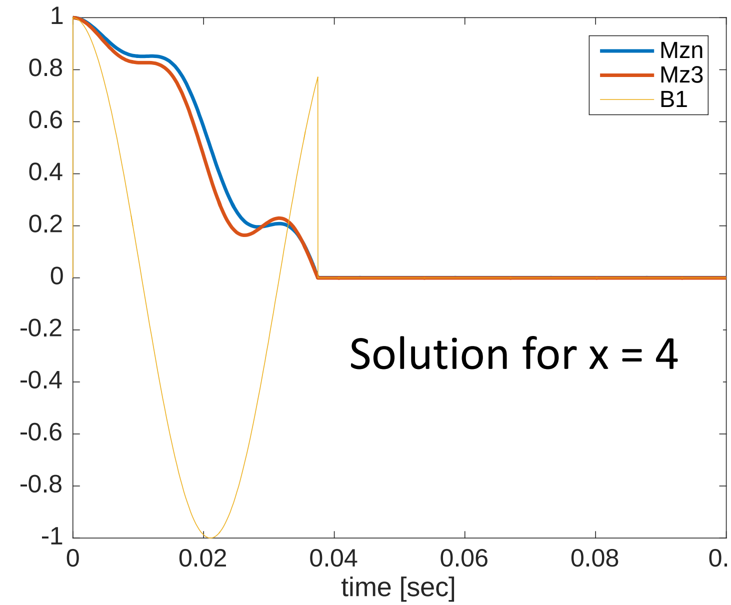
Solution for x = 17 , B_0 = 10mG, $\omega_{0,3}$ = 203.7Hz
$\omega_{0,n}$ = 183.2Hz, $\omega_{\pi/2}$ = 191.5Hz, $T_{\pi/2}$ = 166 ms



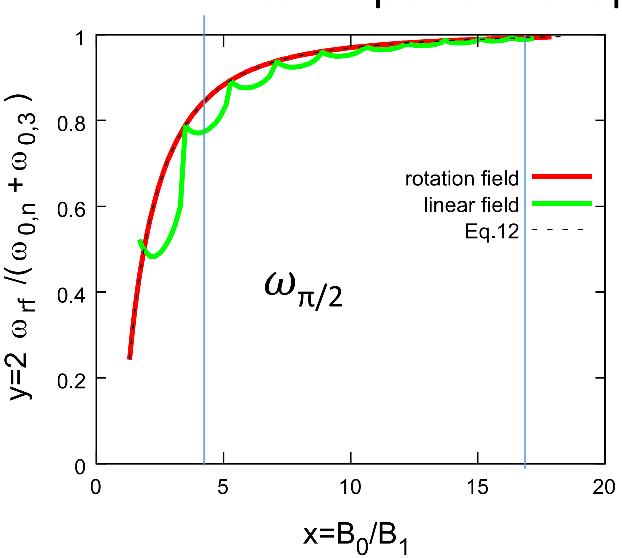


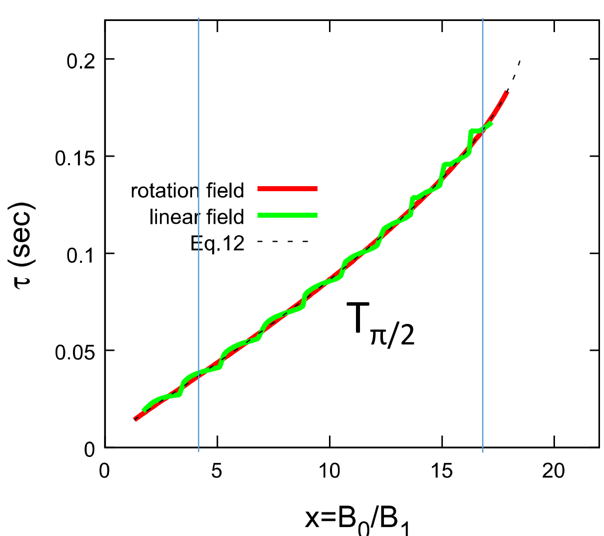
Simultaneous $\pi/2$ flip of ^{3}He and n

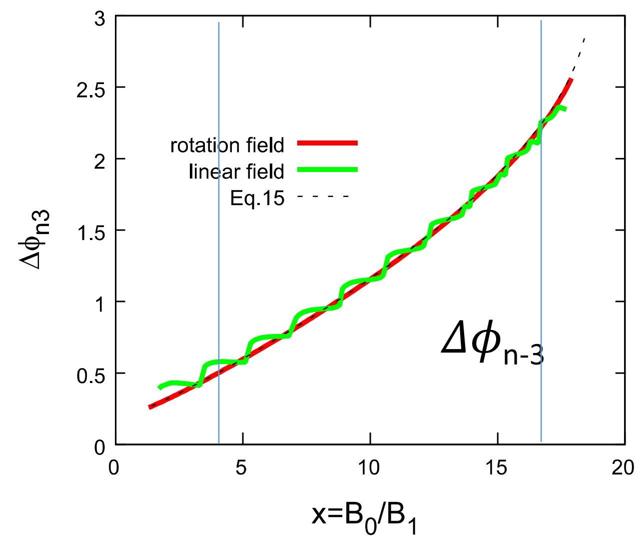




Most important is reproducibility and knowledge of angle $\Delta\phi_{n\text{-}3}$ (next slide)







Scintillation signal from n-^{3}He capture

$$y_i(t_i) = I_0 e^{-t/\bar{\tau}_{tot}} \left[1 - F\cos(\omega t_i + \phi_0)\right] \Delta t + R_{BG} \Delta t$$

$$I_0 = N_0 \left(\frac{\epsilon_\beta}{\tau_\beta} + \frac{\epsilon_3}{\tau_3} \right)$$

Light from $\boldsymbol{\beta}$-decay & ^{3}He abs

$$F = \frac{\epsilon_3 P_3 P_n}{\tau_3 \left(\frac{\epsilon_\beta}{\tau_\beta} + \frac{\epsilon_3}{\tau_3} \right)}$$

polarizations

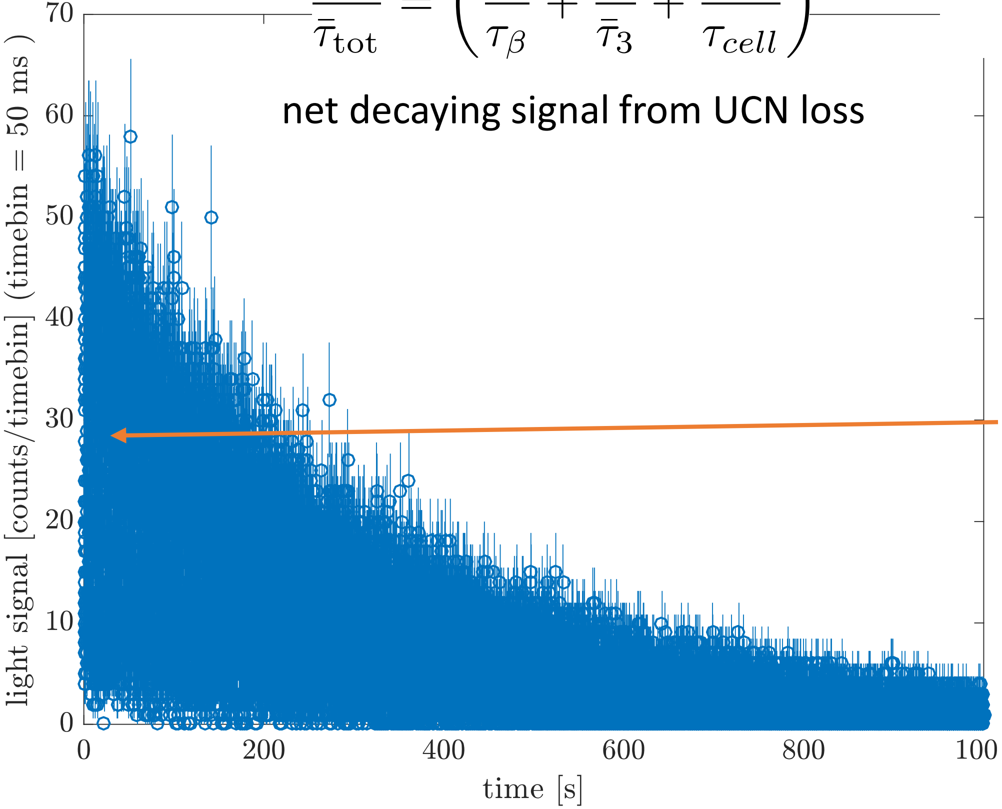
$$\omega = (\gamma_3 - \gamma_n) B_0 \pm \frac{2 e d_n E}{\hbar}$$

magnetic precession

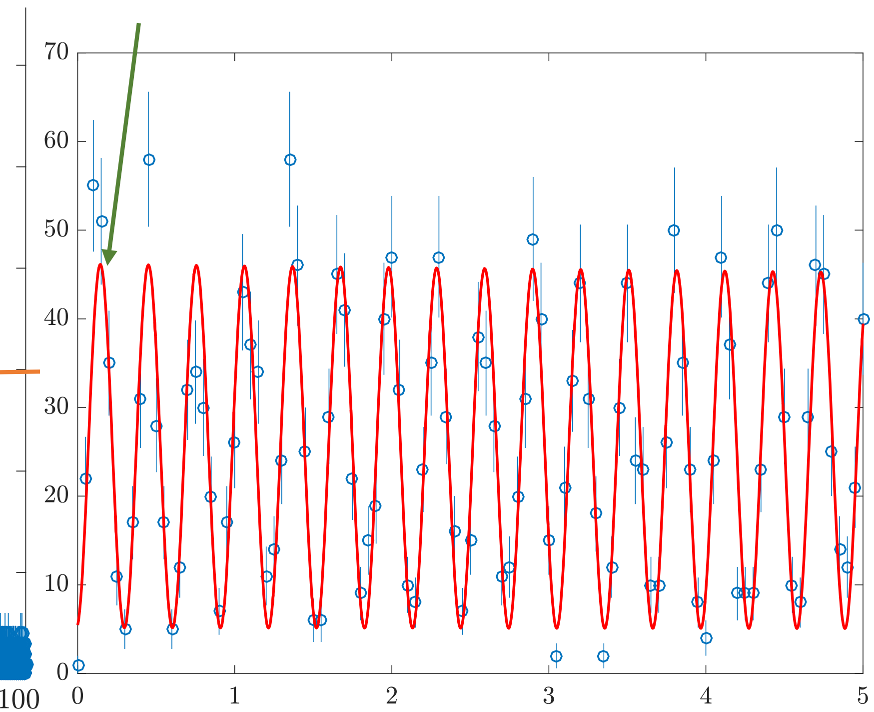
From EDM!

$$\frac{1}{\bar{\tau}_{tot}} = \left(\frac{1}{\tau_\beta} + \frac{1}{\bar{\tau}_3} + \frac{1}{\tau_{cell}} \right)$$

net decaying signal from UCN loss



ϕ_0 needs to be measured separately and fixed otherwise σ_ω from fit increases by ~1.5x



Systematic effects

Extracted frequency from one cell:

$$\omega = (\gamma_3 - \gamma_n)B_0 \pm \frac{2ed_nE}{\hbar}$$

Determine B_0 from precession of ^{3}He comagnetometer with SQUIDs (i.e. measure $\gamma_3 B_0$) so can determine d_n . $\sigma_\omega \sim 3$ μHz per cycle.

$$\omega = \gamma_3 B_{0,3} - \gamma_n B_{0,n} \pm \frac{2ed_nE}{\hbar}$$

What if the average field seen by the ^{3}He is different to that seen by neutron? i.e. $B_{0,3} \neq B_{0,n}$

Not possible to detect UCNs' NMR signal ($\rho_{UCN} < 1000$ cm^{-3}, ^{3}He:^{4}He = 10^{-10}, $\rho_3 = 10^{12}$ cm^{-3}) so no knowledge of $B_{0,n}$ is possible.

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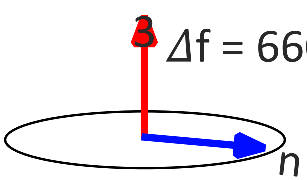
What can cause $B_{0,3} \neq B_{0,n}$?

Pseudomagnetic effect

Neutron optical potential in a medium = Σ (spin-dependent coherent scattering length x ρ)

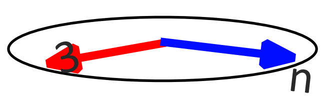
Polarized neutron and polarized ^{3}He:

$$b_{\uparrow\uparrow} = 4.29\,\text{fm} \;\&\; b_{\uparrow\downarrow} = 10.07\,\text{fm}.$$



Δf = 660 µHz

Δf average = 0



5% π/2 pulse inaccuracy → Δf = 33 µHz

^{3}He average position different

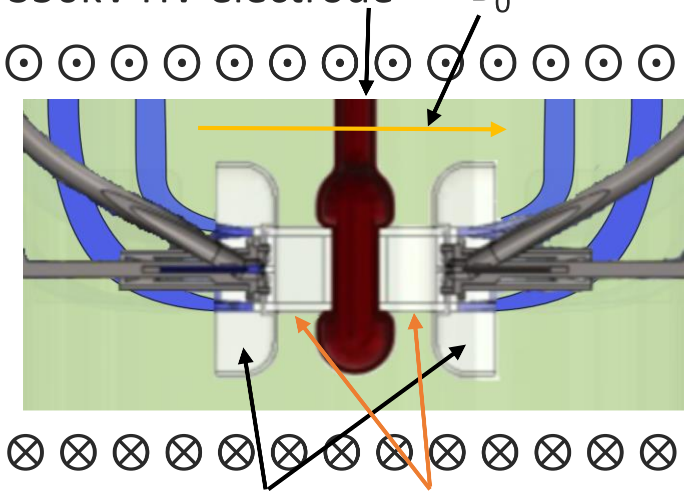
$$\bar{v}_{^3\text{He}} = \sqrt{\frac{2k_BT}{m^*}} \approx 30\ \text{m/s} \quad \bar{v}_{\text{UCN}} \approx 4\ \text{m/s}$$

effective mass

Gravitational offset $\Delta h \approx 1$ mm . Only a problem if there's a spurious B_0 field gradient in vertical direction

Study both in PULSTAR apparatus!
Scan ρ_3 with MEOP + introduce gradient fields with additional coils

Double cell systematic effect cancellation



$$\omega = \gamma_3 B_{0,3} - \gamma_n B_{0,n} \pm \frac{2ed_n E}{\hbar}$$

Simultaneously measure with 2x cells with opposite E-field but same B_0 and take frequency difference:

$$\Delta\omega = \omega_+ - \omega_-$$

$$= (\gamma_3 B_{0,3})^+ - (\gamma_3 B_{0,3})^- + (\gamma_n B_{0,n})^+ - (\gamma_n B_{0,n})^- + \frac{4ed_n E}{\hbar}$$

This cancels out most systematics and drifts.

- For pseudomagnetic effect, if ρ_3 the same in both cells and π/2 pulse similar then

  $(\gamma_n B_{0,n})^+ = (\gamma_n B_{0,n})^-$ → subtraction cancels

- If spurious magnetic fields product a non-constant B_0 within each cell but same or horizontally symmetric B_0 in both cells:

  $(\gamma_3 B_{0,3})^+ = (\gamma_3 B_{0,3})^-$ & $(\gamma_n B_{0,n})^+ = (\gamma_n B_{0,n})^-$ → subtraction cancels

- If spurious magnetic fields produce different B_0 within each cell and/or not-symmetric between two cells: use SQUID signal for: $B_{0,3}^+$ & $B_{0,3}^-$ to correct $B_{0,n}^+$ & $B_{0,n}^-$

  → cancels at low orders

False EDM from interaction B0 gradient & E x v motional field

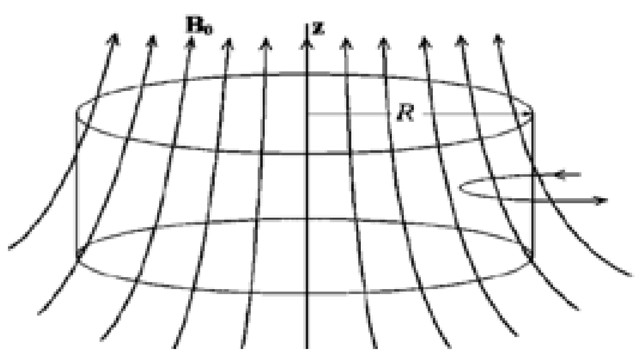
$$\Delta\omega = \omega_+ - \omega_-$$

Subtraction between two cells fails if frequency shift changes with E-direction

Pendlebury PRA A 70, 032102 (2004)

Assume a B_0 field gradient along axis of cylindrical cell → produces a radial field

interaction of B gradient with E x v field:



$$B_r = \frac{\partial B_0}{\partial z}\frac{r}{2} = ar$$

False EDM from interaction B_0 gradient & E x v motional field example

Pendlebury et al, PRA A 70, 032102 (2004)

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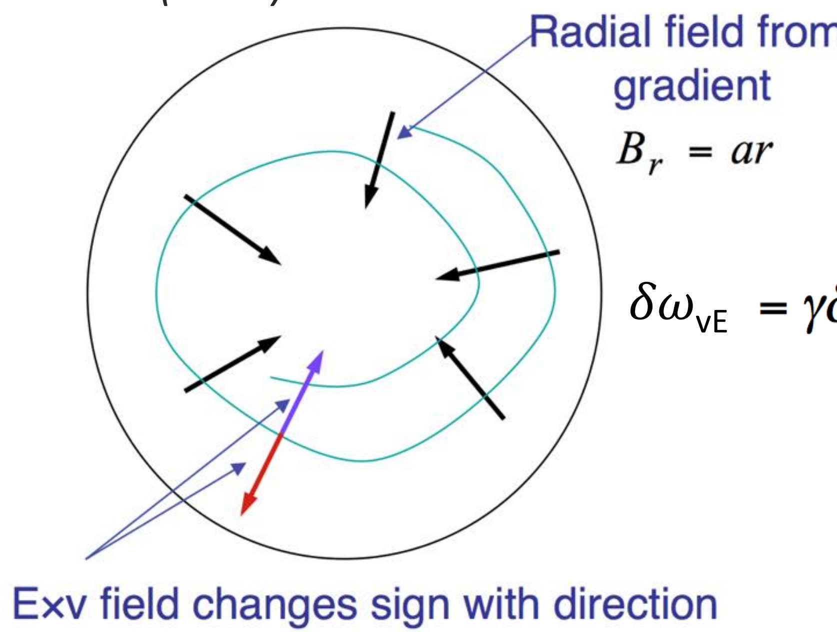

$$\delta\omega_{vE} = \gamma\delta B = -\frac{\gamma^2 a v^2 E}{c(\omega_0{}^2 - \omega_r{}^2)}$$

Effect linear in E!

- On average particle population are 50% in each clockwise/counter-clockwise
- E⊗, E x v field adds with B-radial for clockwise motion → clock-wise rotating B field

False EDM from interaction B_0 gradient & E x v motional field example

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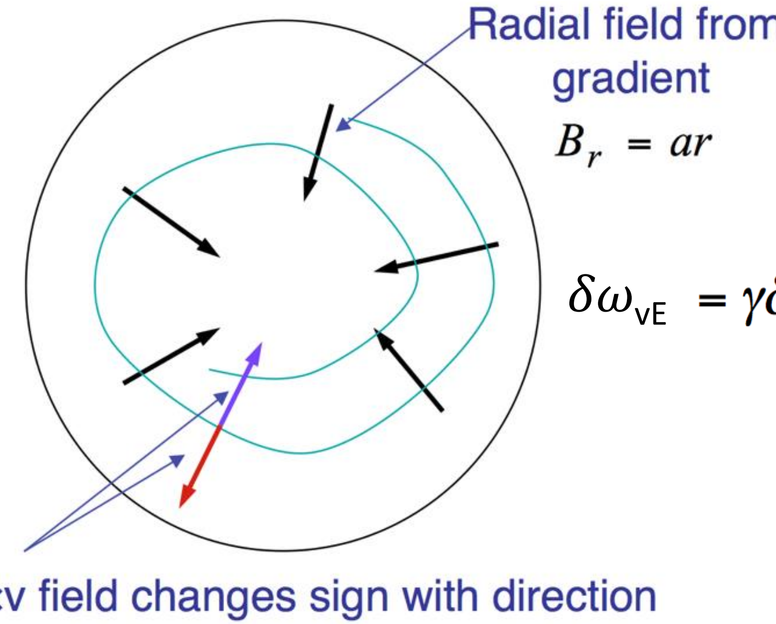

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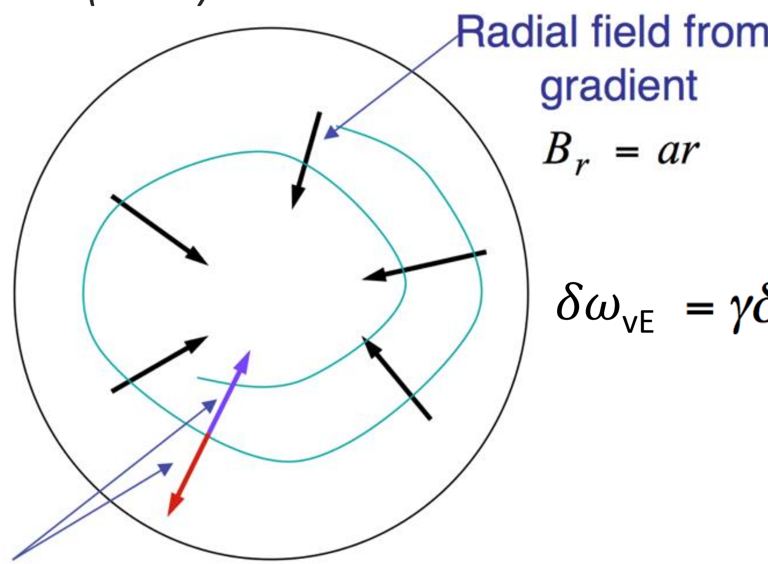

$$\delta\omega_{\mathrm{vE}} = \gamma\delta B = -\frac{\gamma^2 a v^2 E}{c(\omega_0^{\,2} - \omega_r^{\,2})}$$

Effect linear in E!

E×v field changes sign with direction

- On average particle population are 50% in each clockwise/counter-clockwise
- E⊗, E x v field adds with B-radial for clockwise motion → clock-wise rotating B field
- E⊙, E x v field adds with B-radial for counter-clockwise motion → counter clock-wise field
- Occurs for both ^{3}He and UCN but different in size in general due v differences and motion difference: ^{3}He has with mean-free-path λ = 0.77 (0.45K/T)$^{15/2}$ [cm], while UCNs are ballistic)
- Must be controlled for 10-^{28} e.cm level experiments

T_1 and T_2 measurements → $\delta\omega_{vE}$

The density matrix contains orientation of spin: $$\rho = \begin{pmatrix} 1+\rho_z & \frac{\rho_x}{2} + i\frac{\rho_y}{2} \\ \frac{\rho_x}{2} - i\frac{\rho_y}{2} & 1-\rho_z \end{pmatrix}$$

Time evolution governed by: $\frac{d\rho}{dt} = -i[H_0 + H_1(t), \rho]$ where $H_1(t) = \sum_{x,y,z} \frac{\omega_{x,y,z}(t)}{2}\sigma_{x,y,z}$

The ^{3}He polarization relaxation times are derived from the same density matrix as $\delta\omega_{vE}$:

$$\frac{1}{T_1} = \frac{\gamma^2}{2}\left(\int_{-\infty}^{\infty} B_x(t)B_x(t+\tau)e^{-i\omega_0\tau}d\tau + \int_{-\infty}^{\infty} B_y(t)B_y(t+\tau)e^{-i\omega_0\tau}d\tau\right)$$

$$\delta\omega_{vE} = \frac{\gamma^2 E}{c^2}\int_0^{\infty} d\tau\,\cos(\omega_0\tau)\langle B_x(0)v_x(\tau) + B_y(0)v_y(\tau)\rangle$$

For a linear gradients
$$\frac{\partial B_{x,y}}{\partial x, y} = -\frac{1}{2}\frac{\partial B_z}{\partial z} = -a$$

$$\frac{1}{T_1} = \frac{\gamma^2 a^2}{2}[S_r(\omega_0)] \qquad \delta\omega_{vE} - \frac{ab}{2\pi}\int_{-\infty}^{\infty}\frac{\omega^2 S_r(\omega)}{(\omega_0^2 - \omega^2)}d\omega$$

Power spectrum of position autocorrelation function

Lamoreaux & R. Golub, PRA **71**, 032104 (2005)
Pignol & Roccia PRA **85**, 042105 (2012)
R. Golub et al. PRA **92**, 062123 (2015)
Chris Swank, PhD thesis

→ measure T1 and T2 times without E-field and known added B gradients in PULSTAR to derive $[S_r(\omega_0)]$, which can then be used predict size of $\delta\omega_{vE}$.
→ Do this for full-sized measurement cells with same wall conditions (the actual final cells).

Critical spin-dressing

- Spin-dressing involves application of a transverse RF-field, which produces an effective (high frequency limit $\omega_{\text{dress}} \gg \gamma B_0$):

$$\gamma' = \gamma J_0\left(\frac{\gamma B_{\text{dress}}}{\omega_{\text{dress}}}\right)$$

0th order Bessel function

Chu et al. PRC 84, 022501 (2011): demonstrated for ^{3}He gas room temperature gas, higher fields

- "Critical dressing" $\gamma_n' = \gamma_3'$ occurs when: $\dfrac{\gamma_3 B_{\text{dress}}}{\omega_{\text{dress}}} \approx 1.323$
- For f_{dress} = 2 kHz (c.f. $\gamma_3 B_0 \approx \gamma_n B_0 \approx$ 200Hz) need B_{dress} = 0.812 G

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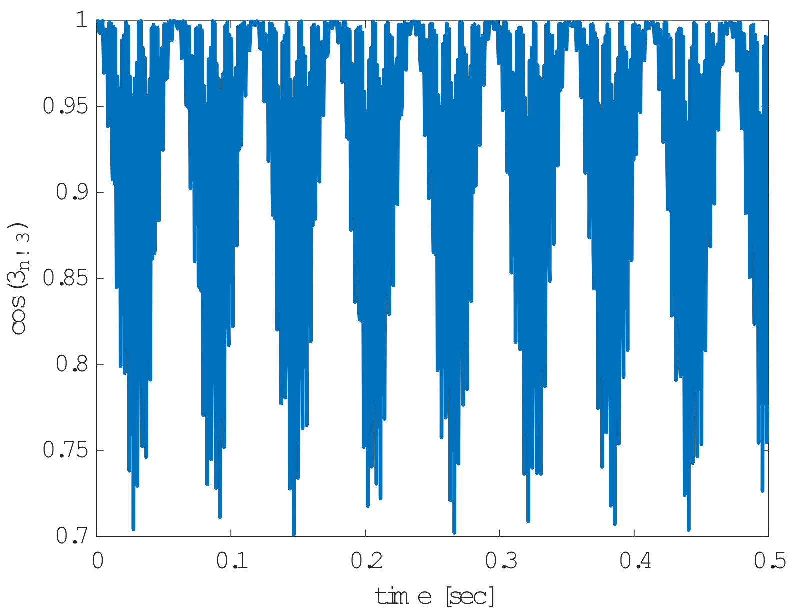
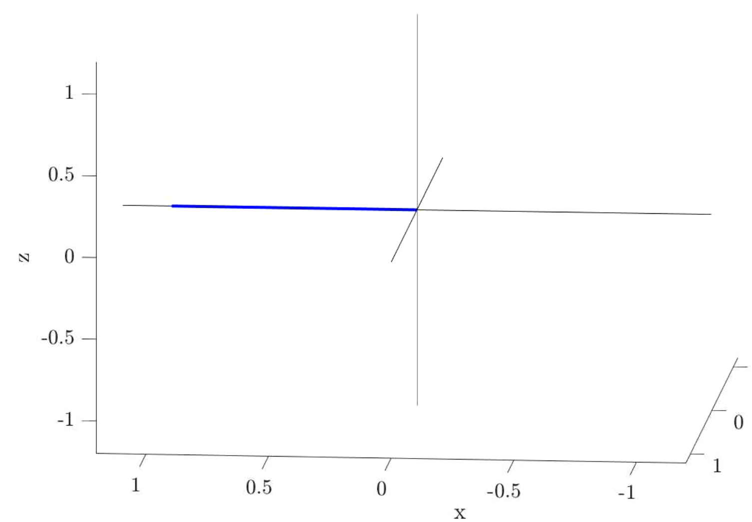


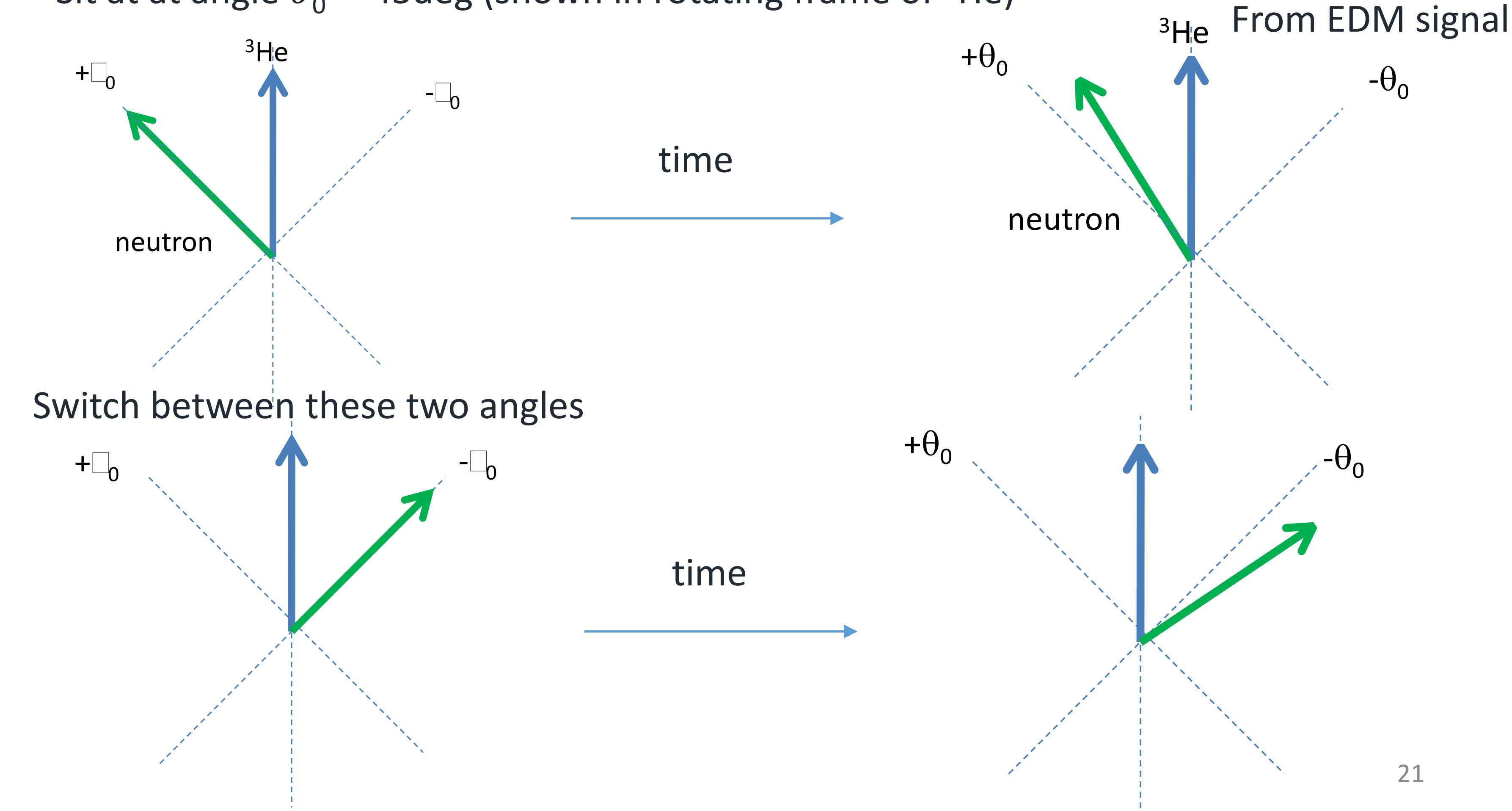


Critical dress-spin mode

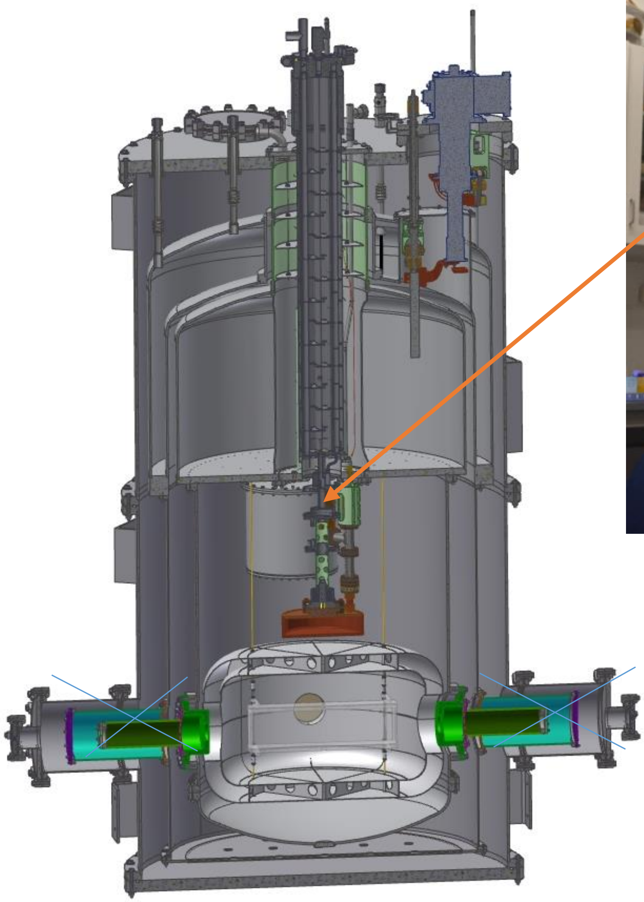
$$\theta_{\mathrm{n3}} = \cancel{|\gamma_n - \gamma_3| B_0 t} \pm \frac{e d_n |E|}{\hbar} t$$

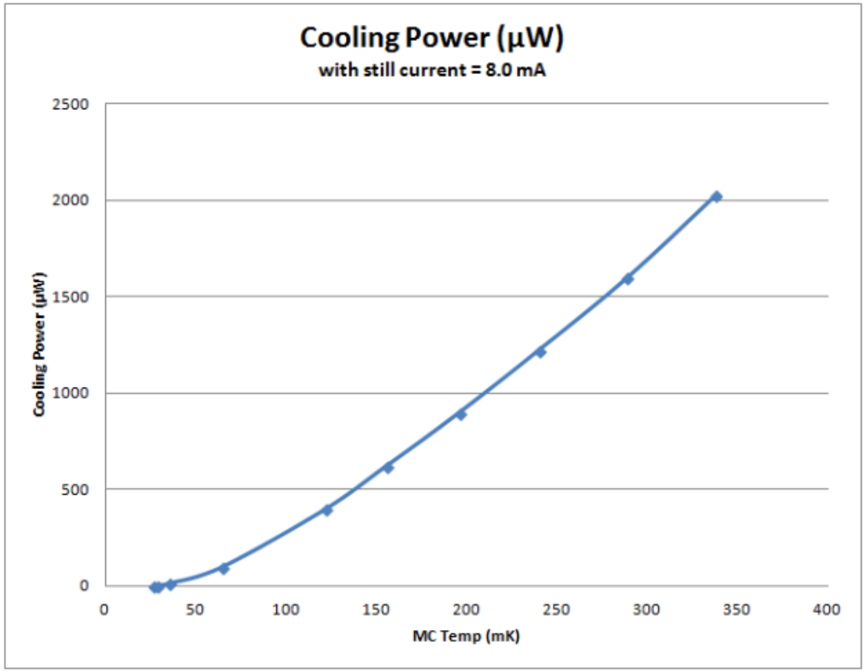
EDM signal changes with time as 1^{st} harmonic.

- Sit at at angle θ_0 ≈ 45deg (shown in rotating frame of ^{3}He)



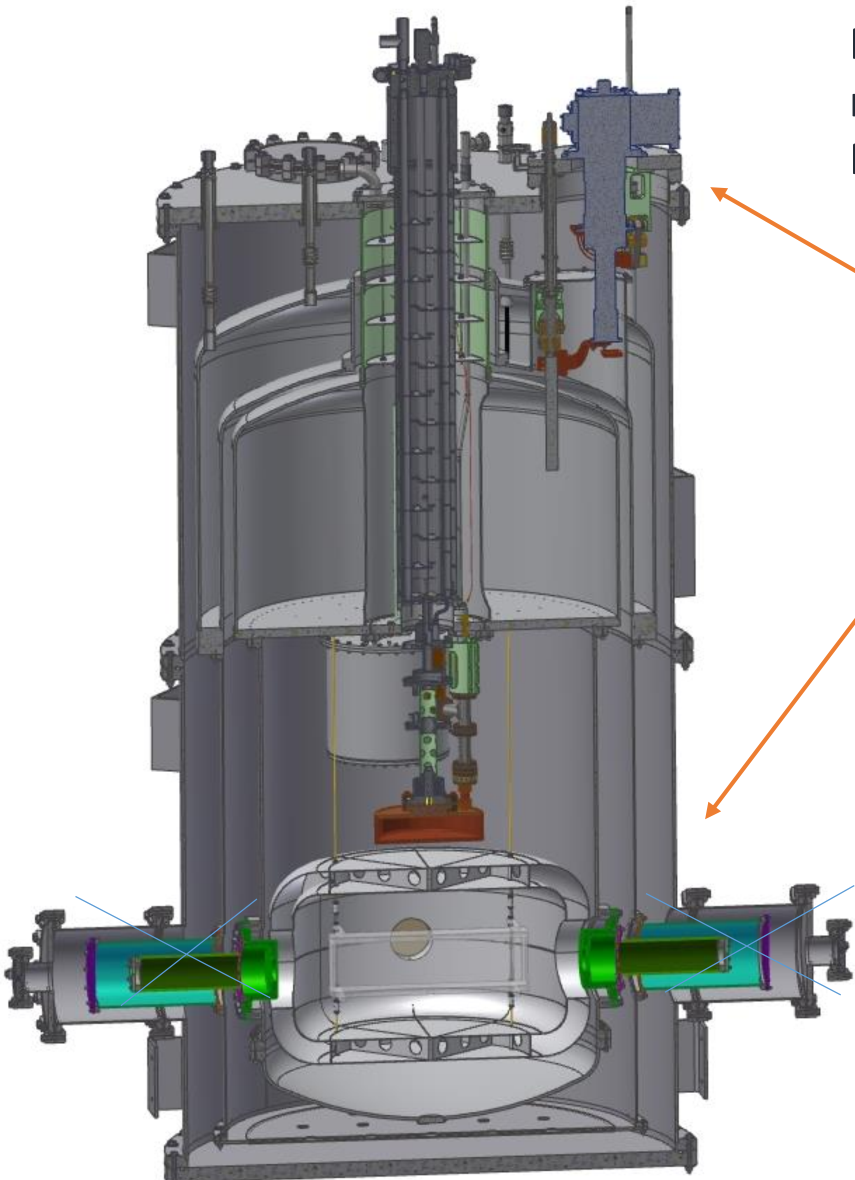
Dilution Refrigerator





Dilution Refrigerator we have and was cooled recently (June) to check cooling power.
Adding turbopumps for more cooling

Cryostat

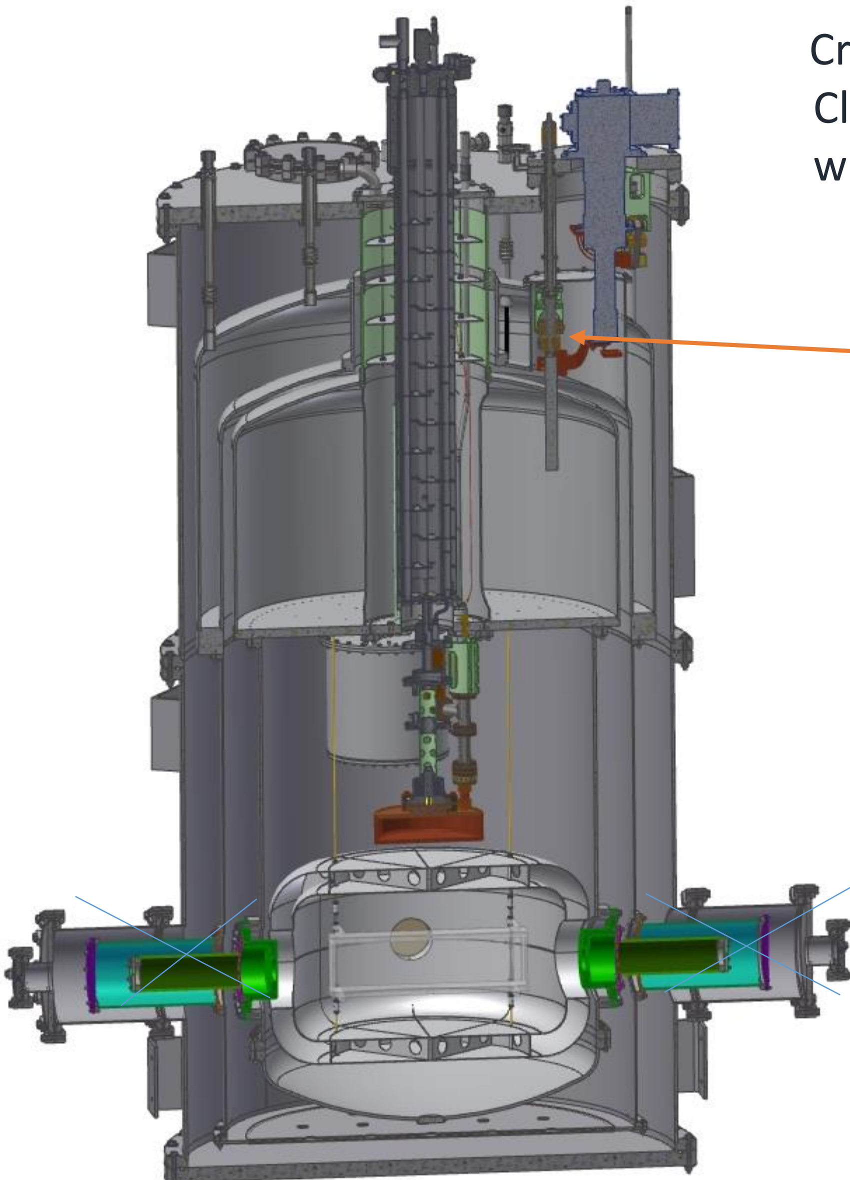


New Aluminum non-magnetic cryostat to have more space and better magnetic conditions. Manufacturer will ship in 1-2 weeks.

Fibers not shown

Cryostat

Cryocooler creates vibration and magnetic noise
Clamp mechanism for detachable thermal link with cryocooler



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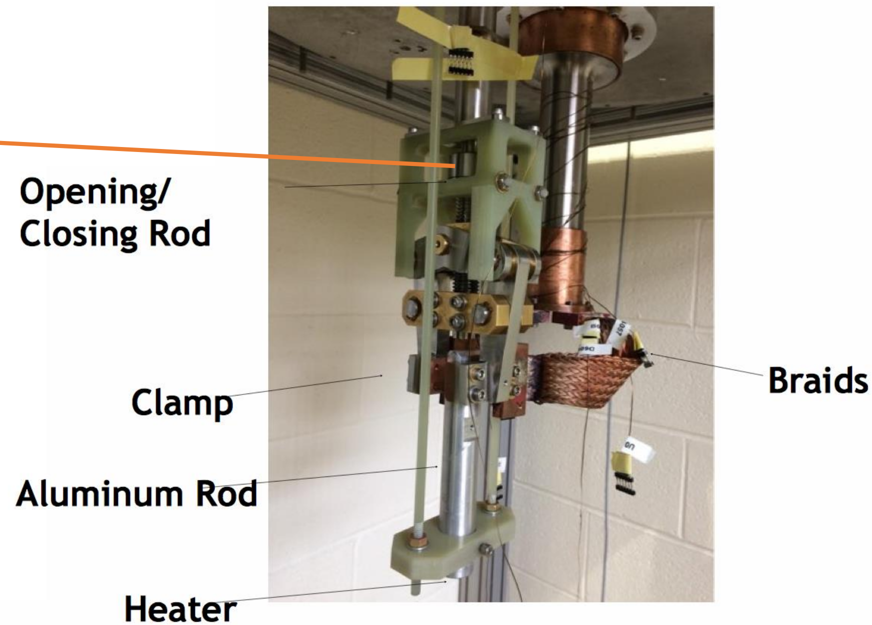
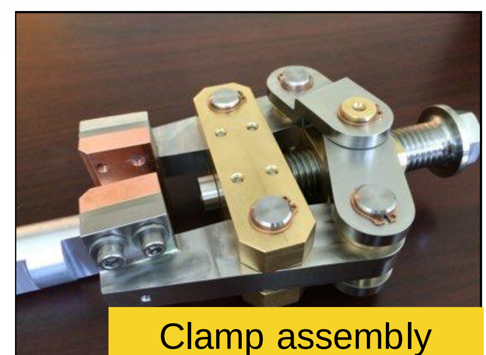
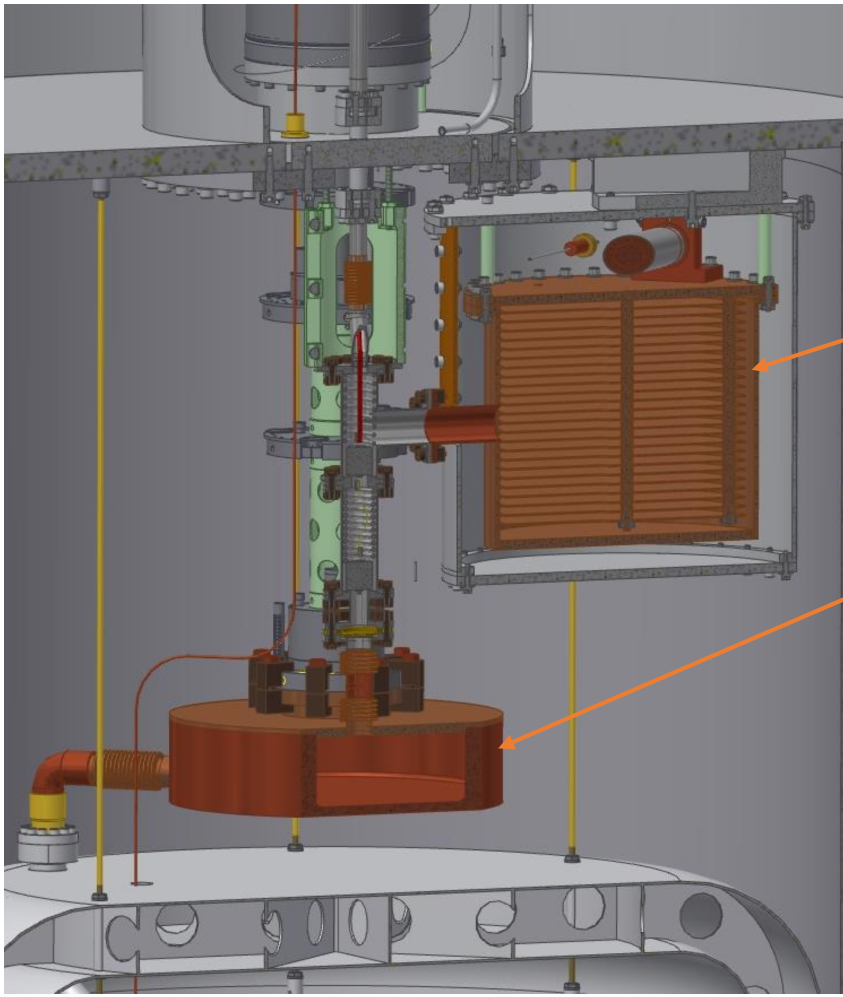


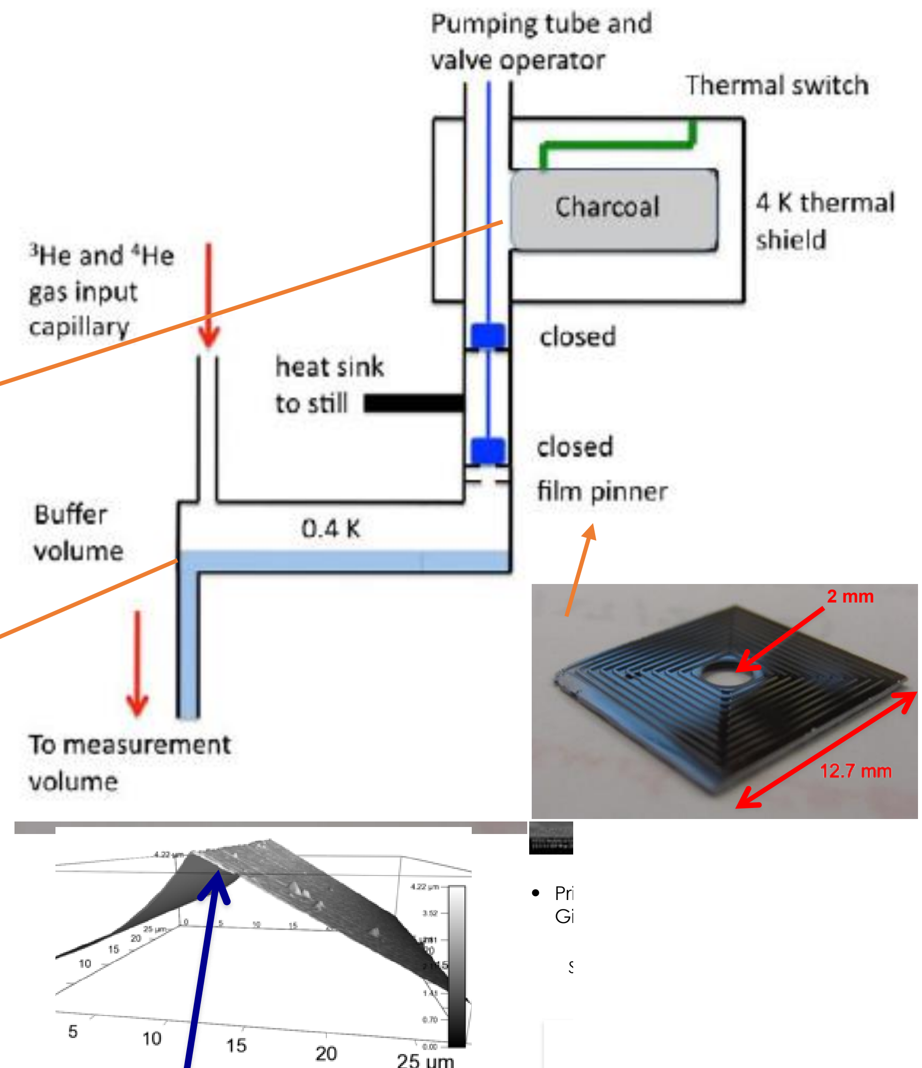


3He removal system

3He removal system: Charcoal pump + thermal isolation double valve + film pinner.

Relies on diffusion and differential evaporation

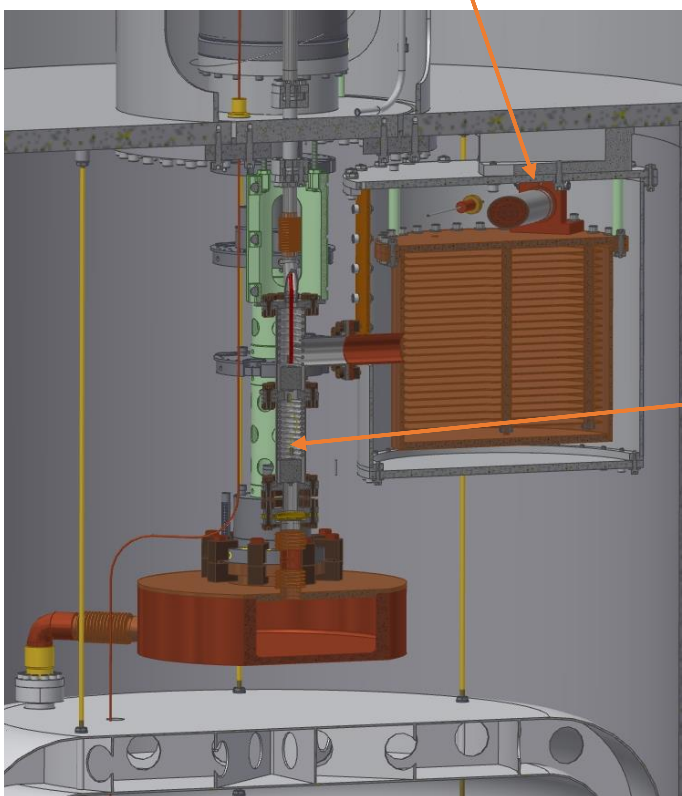




Radius of curvature < 10 nm

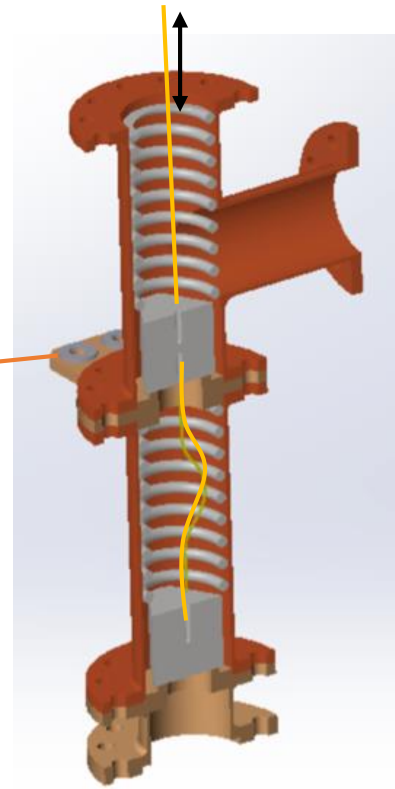
Charcoal Pump Isolation System

Gas heat switch for cooling and heating charcoal pump

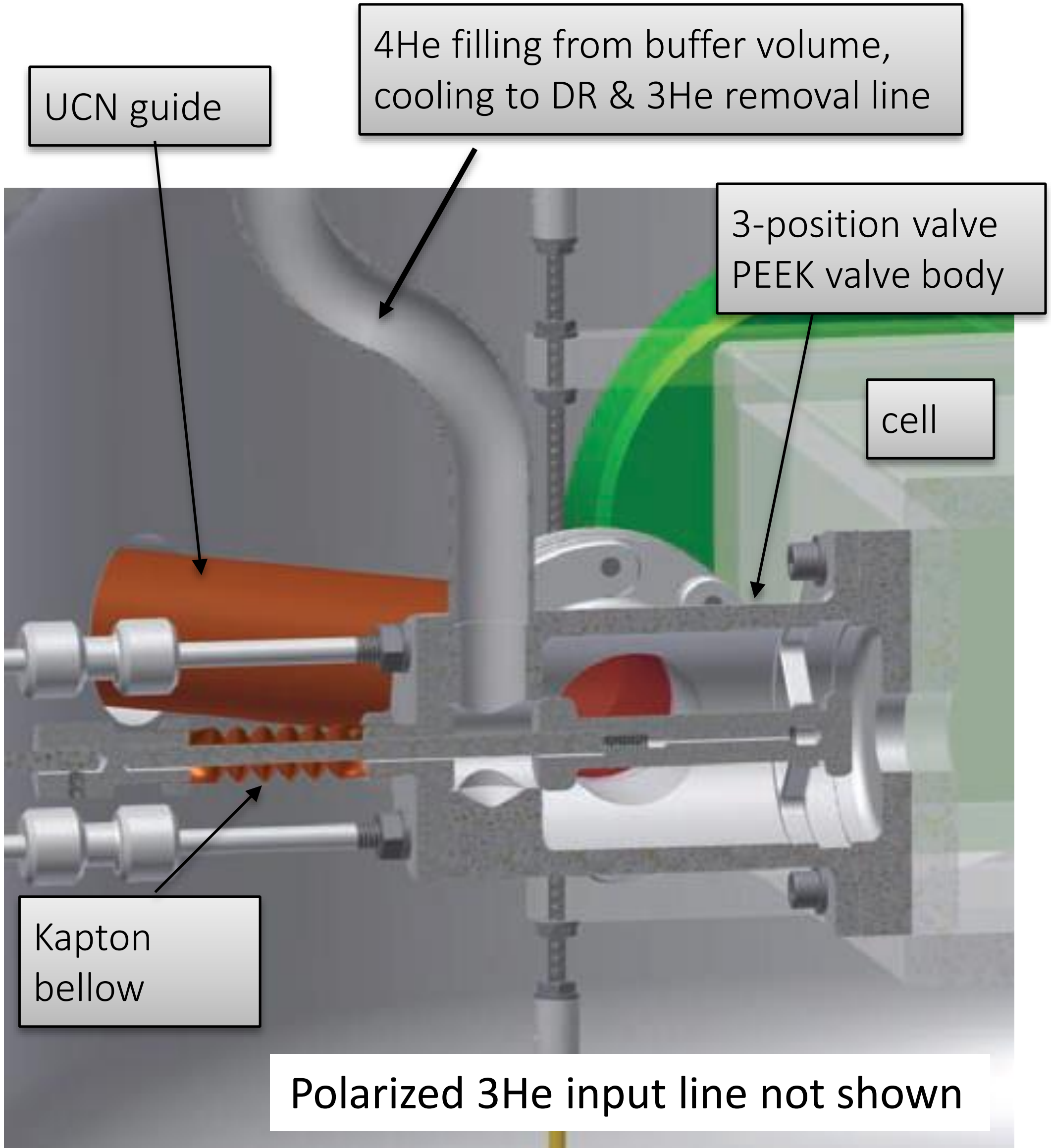


Non-magnetic double valve design actuated by rope at room temperature.

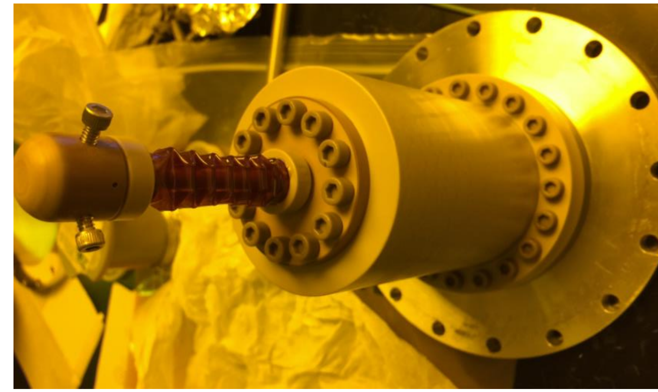
- Could not have direct line
- Lower rope to close bottom valve first, wait for pump out volume between valves, and then lower rope more to close top valve.
- Pumped volume provides thermal isolation when purging Charcoal pump valve when is heated to ~10K



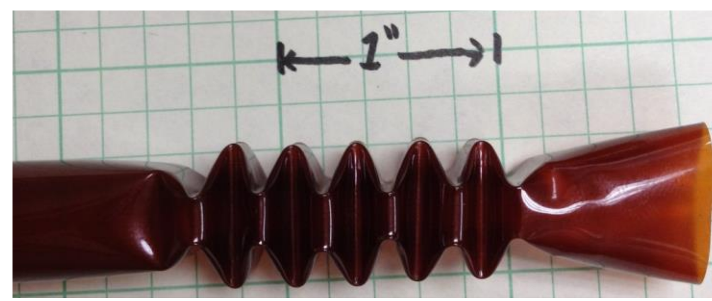
3-position vestibule valve



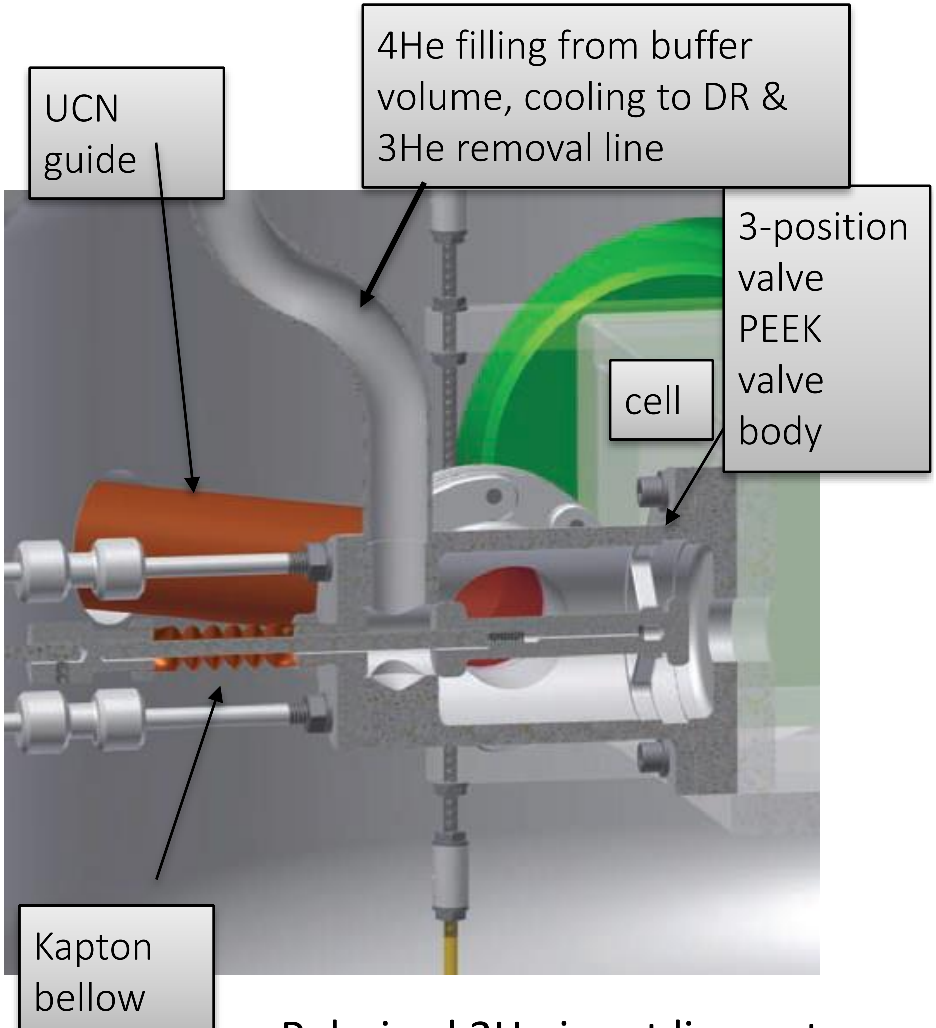
Testing leakage through valve



Kapton Origami Bellows: Have now increased diameter to 0.7” and length to 4”

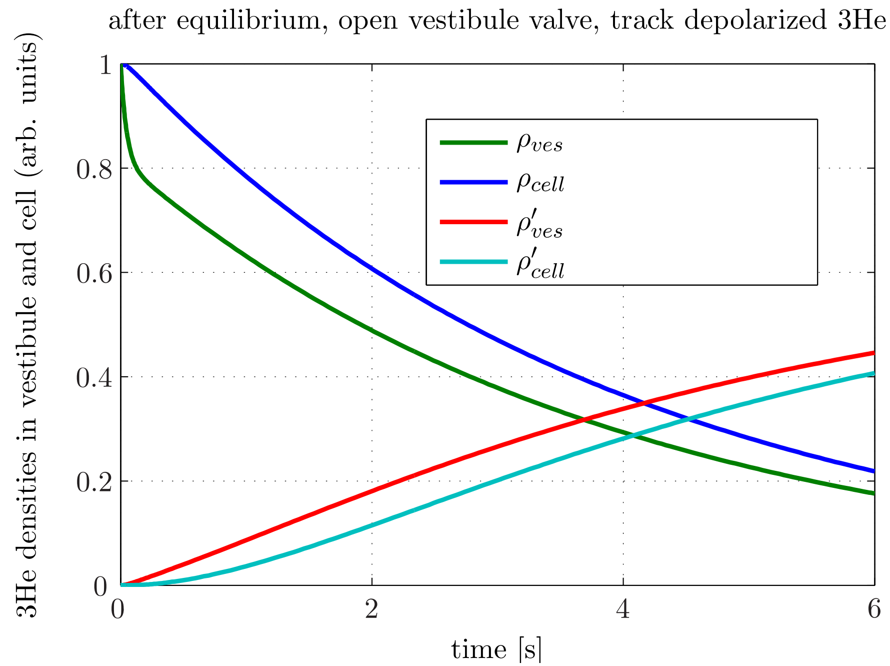


3-position vestibule valve



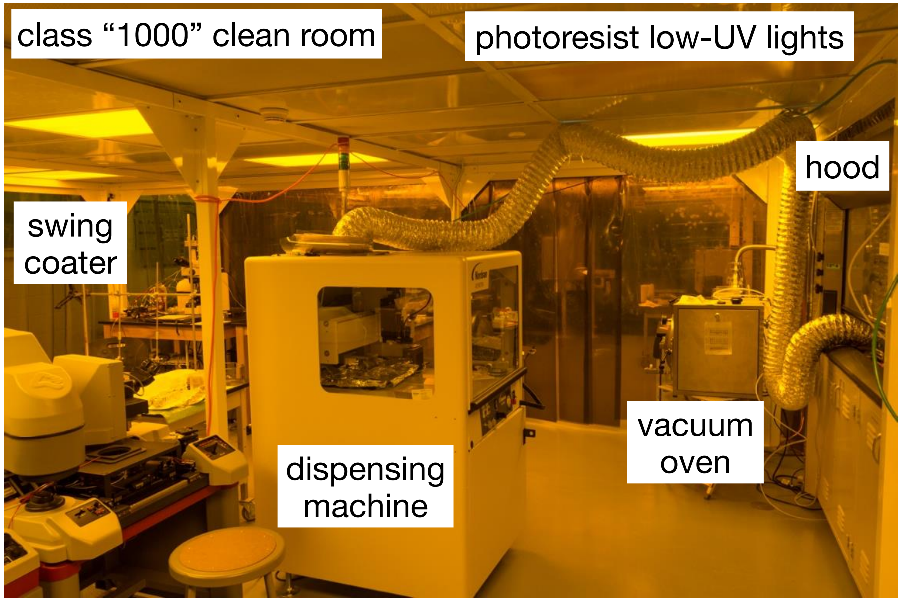
Polarized 3He input line not shown

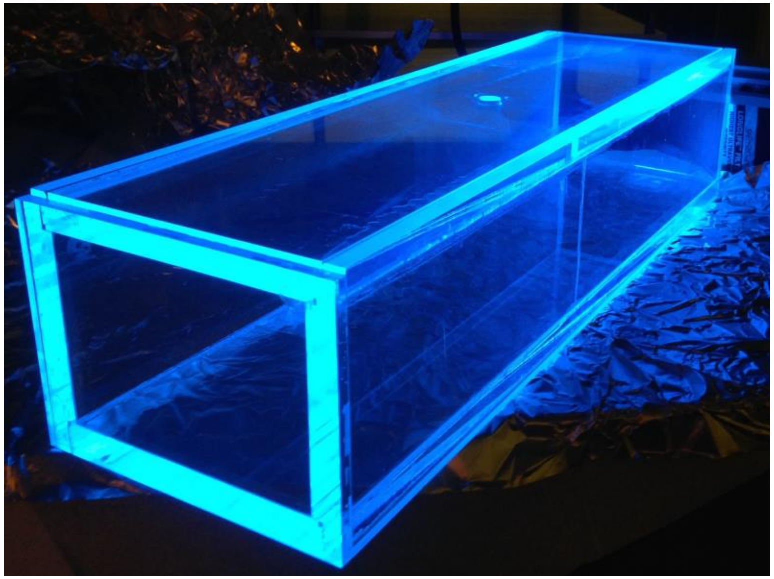
Pessimistic kinetic theory shows need to move valve from far left (filling 3He) and far right (close cell) within 1sec



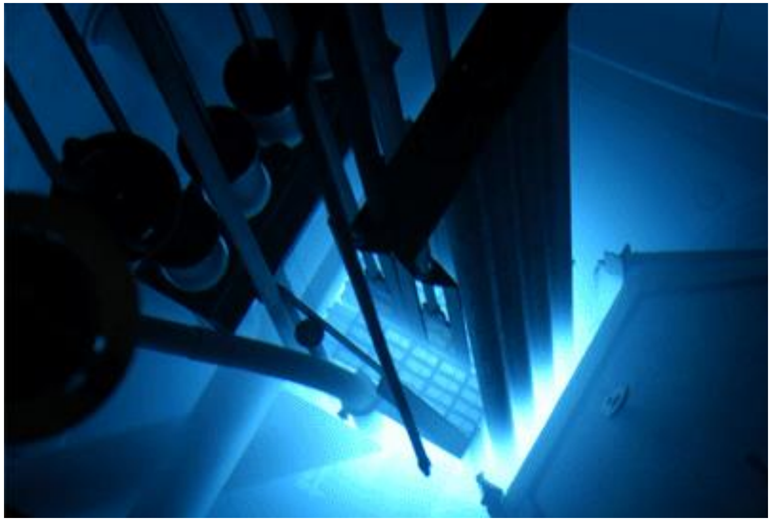
Bellows tested and shown can handle this for >1000 cycles at room temperature

Measurement cell production @NCSU

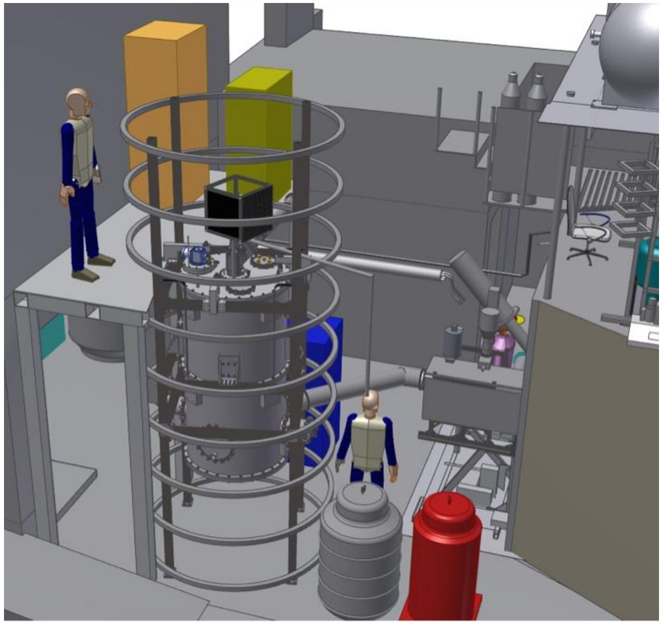


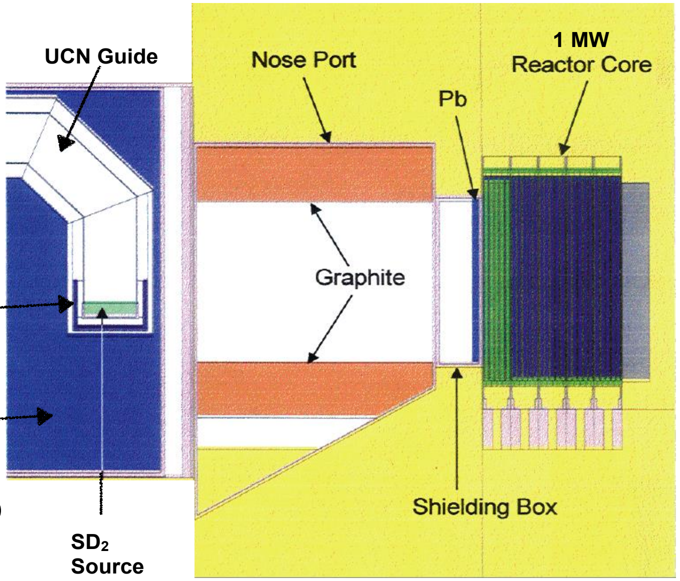


PULSTAR UCN source



@ NCSU's 1MW PULSTAR Reactor



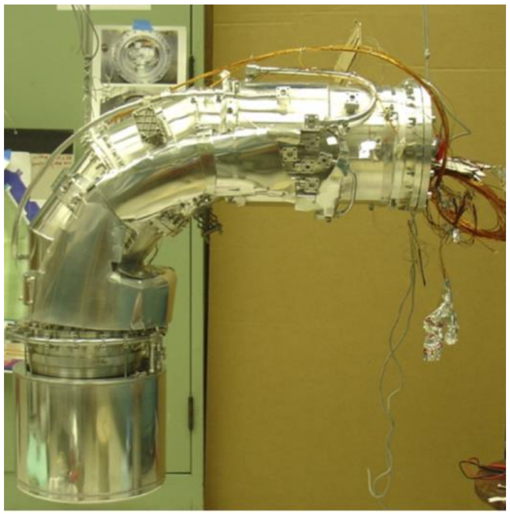


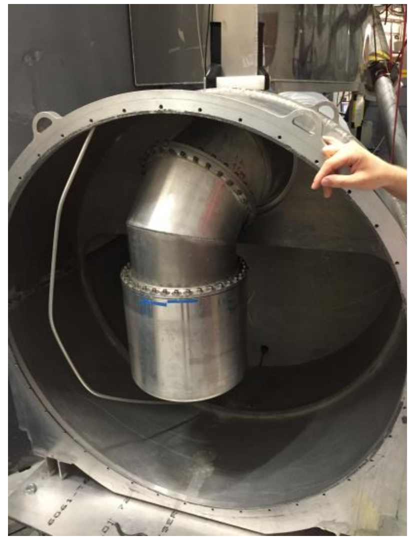
D2O tank

)16

PULSTAR UCN source

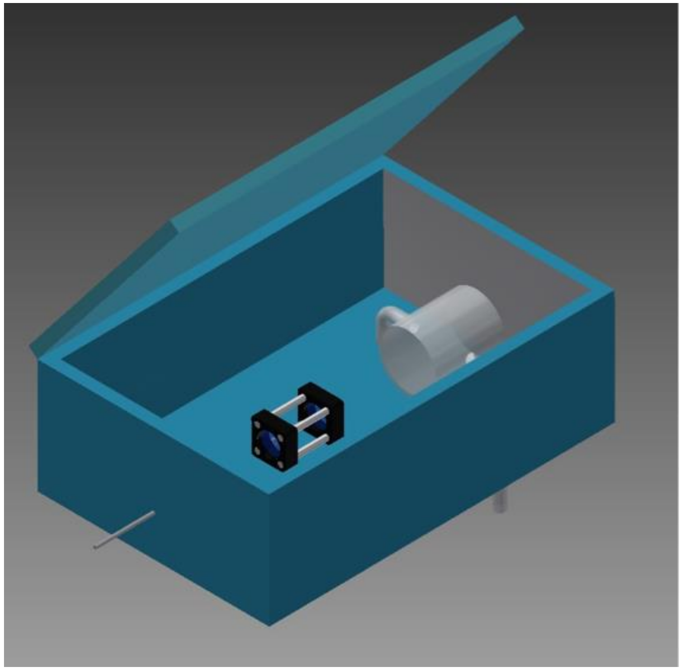
Methane and solid D2 insert

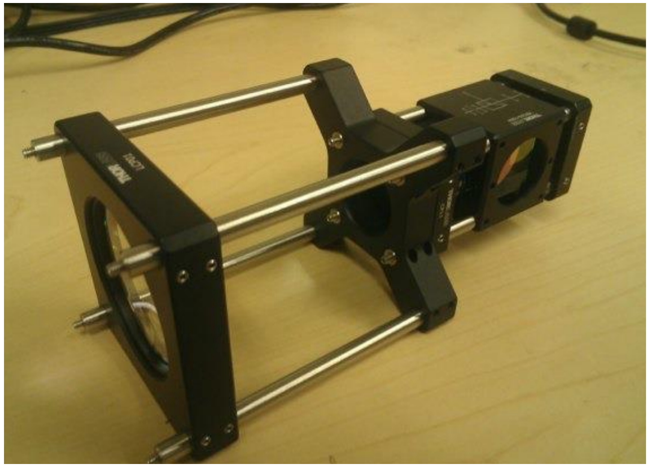


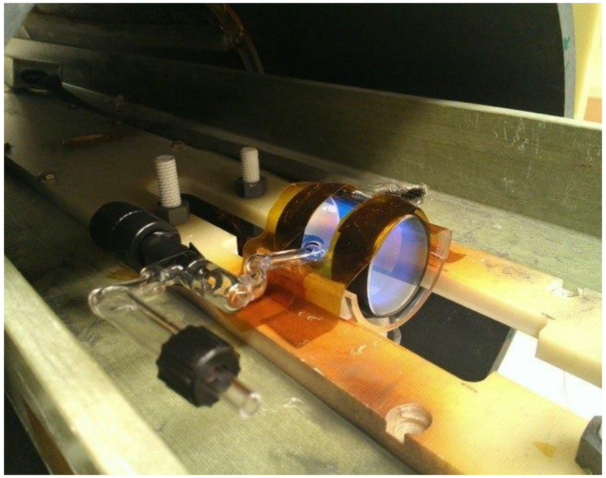


Outside of core, condensed Flammable gasses and grown sD2 crystal this year

MEOP system







10W fiber laser

PULSTAR collaboration

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SNS nEDM collaboration

THANK YOU!

Arizona State University

Brown University

Boston University

UC Berkeley

California Institute of Technology

Duke University

Harvard University

Indiana University

University of Illinois Urbana-Champaign

University of Kentucky

Los Alamos National Laboratory

Massachusetts Institute of Technology

Mississippi State University

North Carolina State University

Oak Ridge National Laboratory

Simon Fraser University

University of Tennessee

Valparaiso University

University of Virginia

Yale University

Backup Slides

Phase shift derived from Redfield Theory

$$\delta\omega = -\frac{1}{2}\int_0^t d\tau\,(\cos\omega_0\tau)\langle \omega_x(t)\omega_y(t-\tau) - \omega_x(t-\tau)\omega_y(t)\rangle$$

For linear in E shift

$$\omega_x = ax + bv_y \qquad a = \gamma\frac{G_z}{2}$$

$$\omega_y = ay + bv_x \qquad b = \gamma\frac{E}{c}$$

- Keeping only terms linear in E

R is a position-velocity Correlation Function

$$\delta\omega = \frac{ab}{2}\int_0^\infty R(\tau)\cos(\omega_0\tau)d\tau \qquad R(\tau) = \left\langle \begin{matrix} y(t)v_y(t-\tau) - y(t-\tau)v_y(t) \\ x(t)v_x(t-\tau) - x(t-\tau)v_x(t) \end{matrix} \right\rangle$$

[1] S. K. Lamoreaux and R. Golub. Phys. Rev. A, 71:032104, 2005.

$R(\tau)$ correlation function can be written in terms of the position autocorrelation function.

$$\delta\omega = \frac{\gamma^2 G_z E}{4c} \int_0^\infty d\tau \cos\omega_0\tau \frac{\partial}{\partial\tau} \langle 2x(t)x(t+\tau) + 2y(t)y(t+\tau)\rangle$$

Which can be written in terms of the Fourier transform for an arbitrary B field

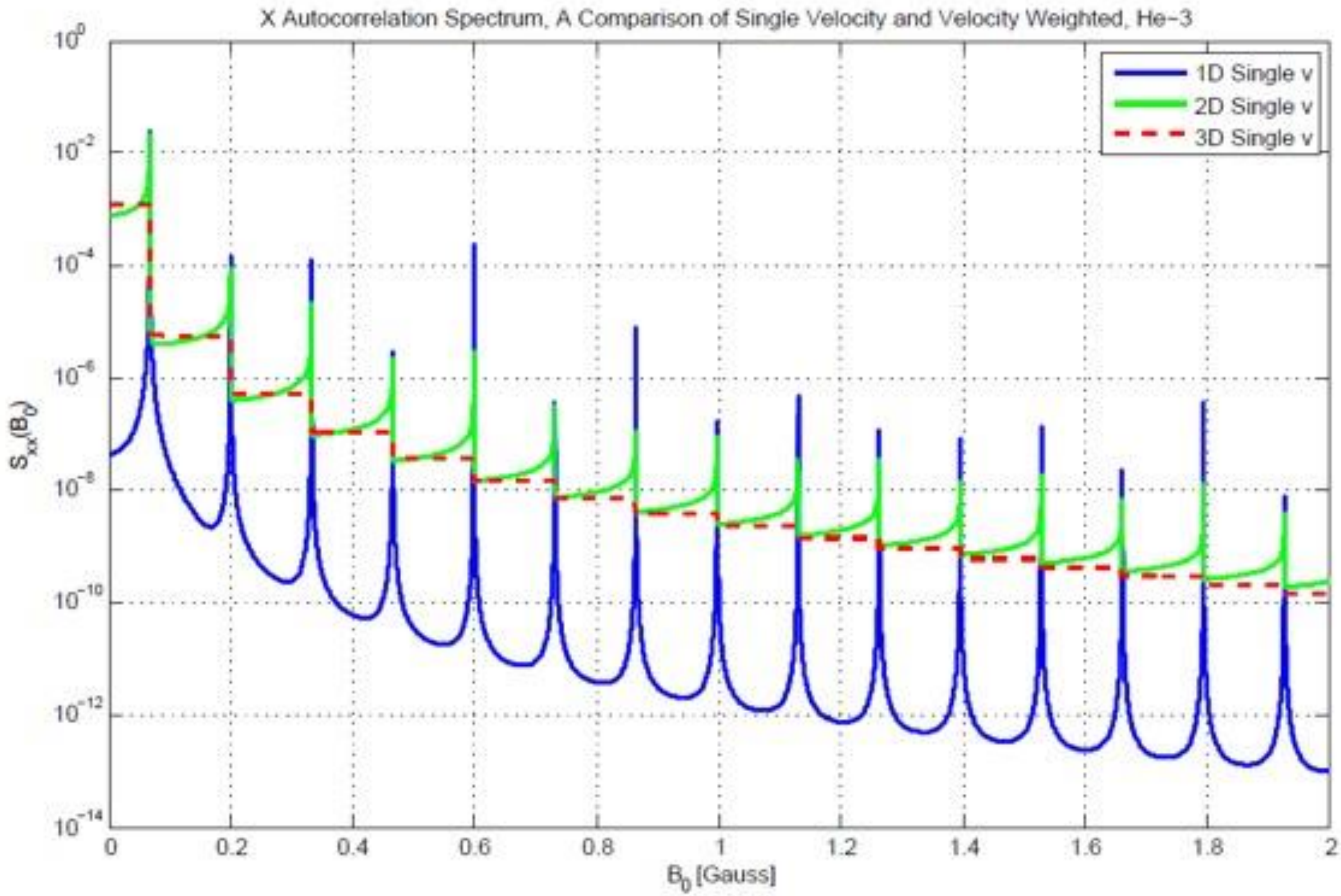
$$\delta\omega = \omega_0 \frac{\gamma^2 E}{2c} \Im\left\{\int_{-\infty}^{\infty} d\tau \mathrm{e}^{-i\omega_0\tau} \langle B_x(t)x(t+\tau) + B_y(t)y(t+\tau)\rangle\right\} - \frac{\gamma^2 E}{c}\langle B_x x + B_y y\rangle$$

$R(\tau)$ correlation function can be written in terms of the position autocorrelation function.

$$\delta\omega = \frac{\gamma^2 G_z E}{4c} \int_0^\infty d\tau \cos\omega_0\tau \frac{\partial}{\partial\tau} \langle 2x(t)x(t+\tau) + 2y(t)y(t+\tau)\rangle$$

Which can be written in terms of the Fourier transform for an arbitrary B field

$$\delta\omega = \omega_0 \frac{\gamma^2 E}{2c} \Im \left\{ \int_{-\infty}^{\infty} d\tau \mathrm{e}^{-i\omega_0\tau} \langle B_x(t)x(t+\tau) + B_y(t)y(t+\tau)\rangle \right\} - \frac{\gamma^2 E}{c} \langle B_x x + B_y y\rangle$$


X Autocorrelation Spectrum, A Comparison of Single Velocity and Velocity Weighted, He-3
1D Single v
2D Single v
3D Single v
$S_{xx}(B_0)$
B_0 [Gauss]
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

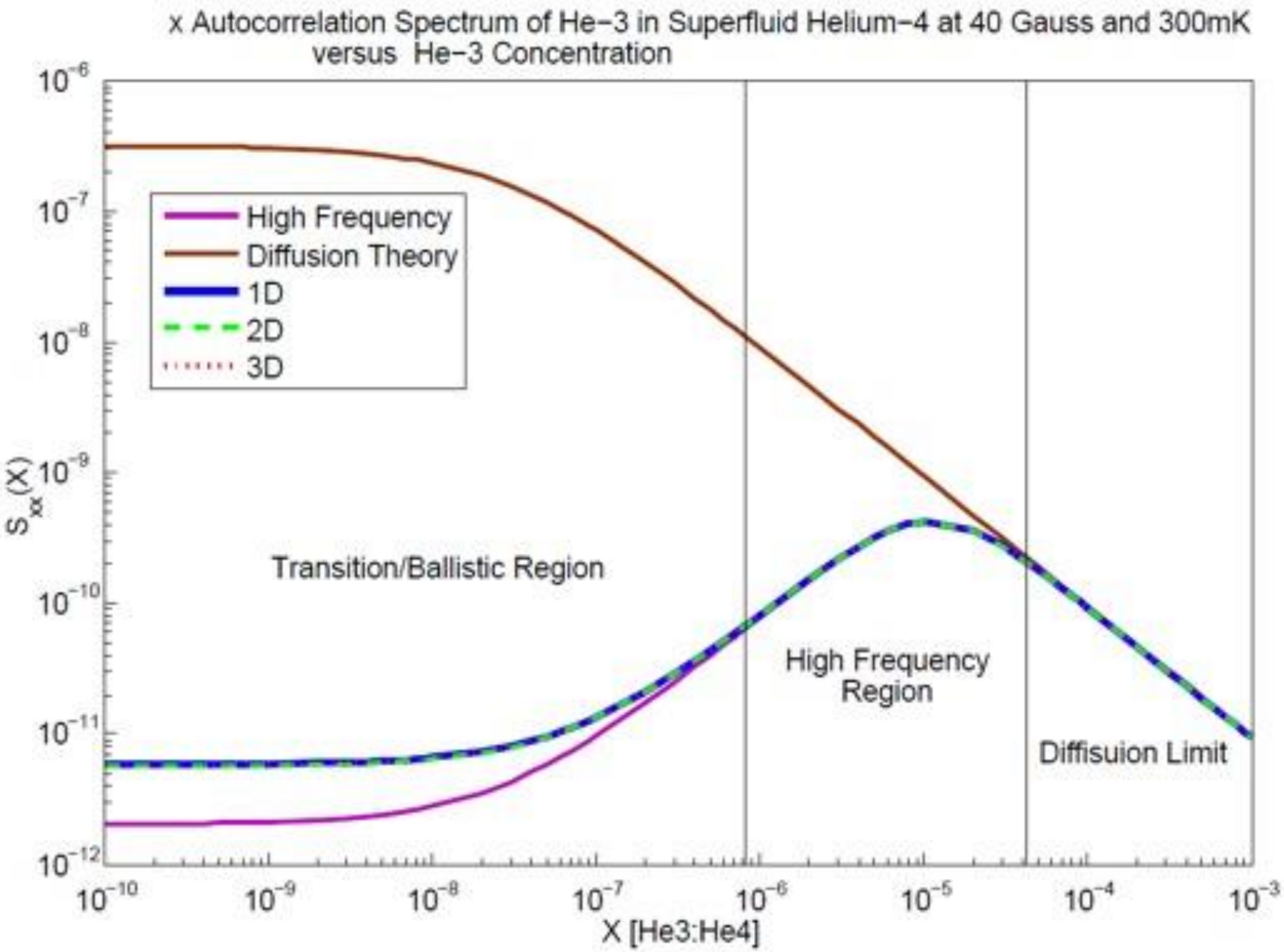
Spectrum of the correlation funtion is measured by gradient induced relaxation.

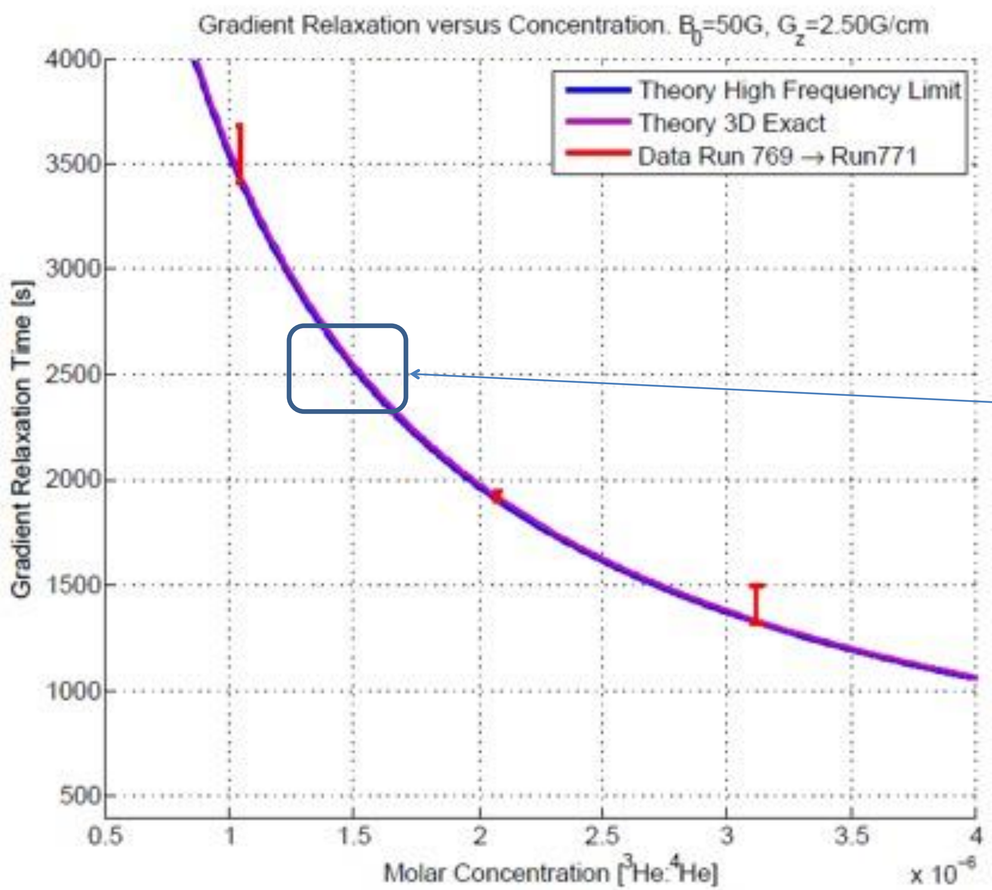
Longitudinal Relaxation

$$\frac{1}{T_1} = \frac{\gamma^2}{2}\left(\int_{-\infty}^{\infty} B_x(t)B_x(t+\tau)e^{-i\omega_0\tau}d\tau + \int_{-\infty}^{\infty} B_y(t)B_y(t+\tau)e^{-i\omega_0\tau}d\tau\right)$$

In a linear gradient the position autocorrelation function spectrum is proportional to the relaxation rate, therefore we can measure the spectrums used to predict the geometric phase.

$$\frac{1}{T_{1gradient}} = \frac{\gamma^2 G_z^{\ 2}}{4}\left(S_{xx}(\omega_0) + S_{yy}(\omega_0)\right)$$


x Autocorrelation Spectrum of He−3 in Superfluid Helium−4 at 40 Gauss and 300mK
versus He−3 Concentration
High Frequency
Diffusion Theory
1D
2D
3D
Transition/Ballistic Region
High Frequency Region
Diffisuion Limit
$S_{xx}(X)$
X [He3:He4]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}



$$\frac{1}{T_{1gradient}} = \frac{\gamma^2 G_z^{\ 2}}{4}\left(S_{xx}(\omega_0) + S_{yy}(\omega_0)\right)$$

$$\frac{\lambda}{L} \approx 0.03$$

Expected $\frac{\lambda}{L}$ parameter range for the nEDM apparatus