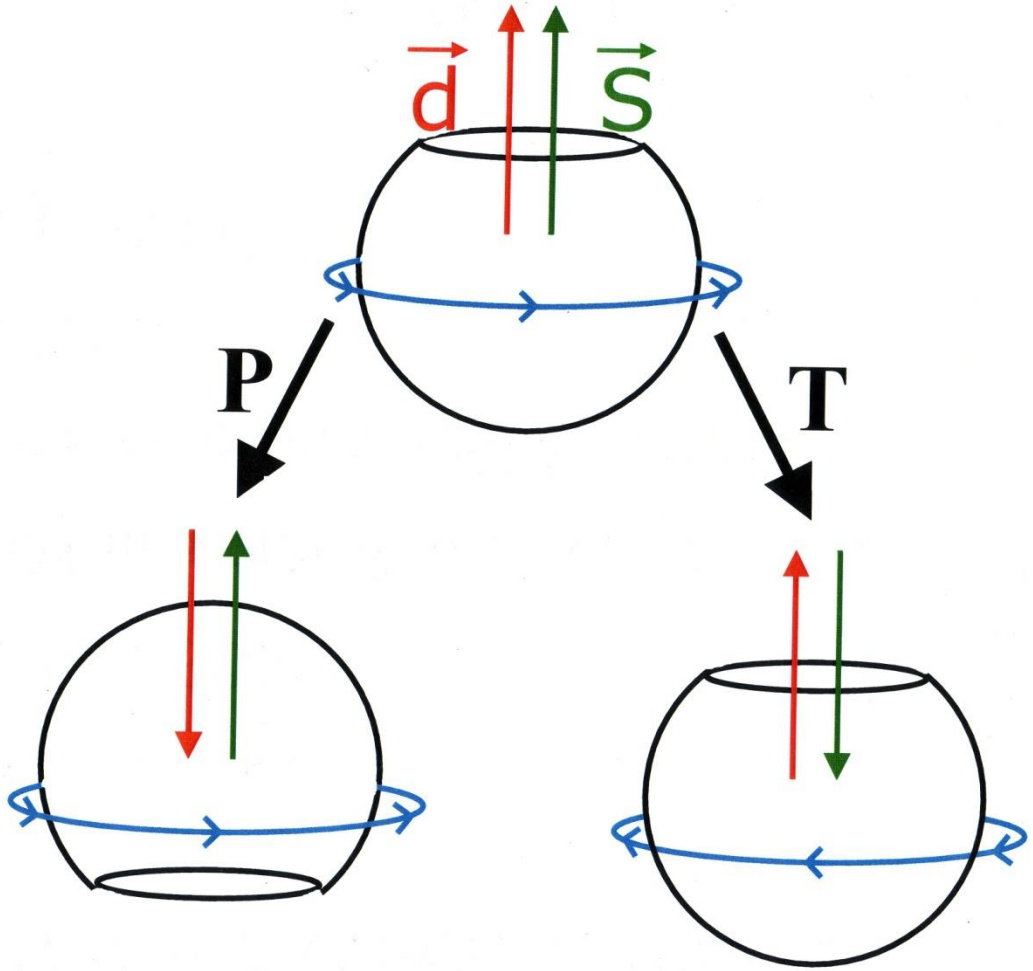
An EDM Violates P and T

Purcell
Ramsey
Landau

$$H_{Magnetic\ dipole} = -\vec{\mu} \cdot \vec{B} = -\mu\vec{\sigma} \cdot \vec{B} \qquad H_{Electric\ dipole} = -\vec{d} \cdot \vec{E} = -d\vec{\sigma} \cdot \vec{E}$$



CPT theorem $\Rightarrow$ T-violation = CP-violation

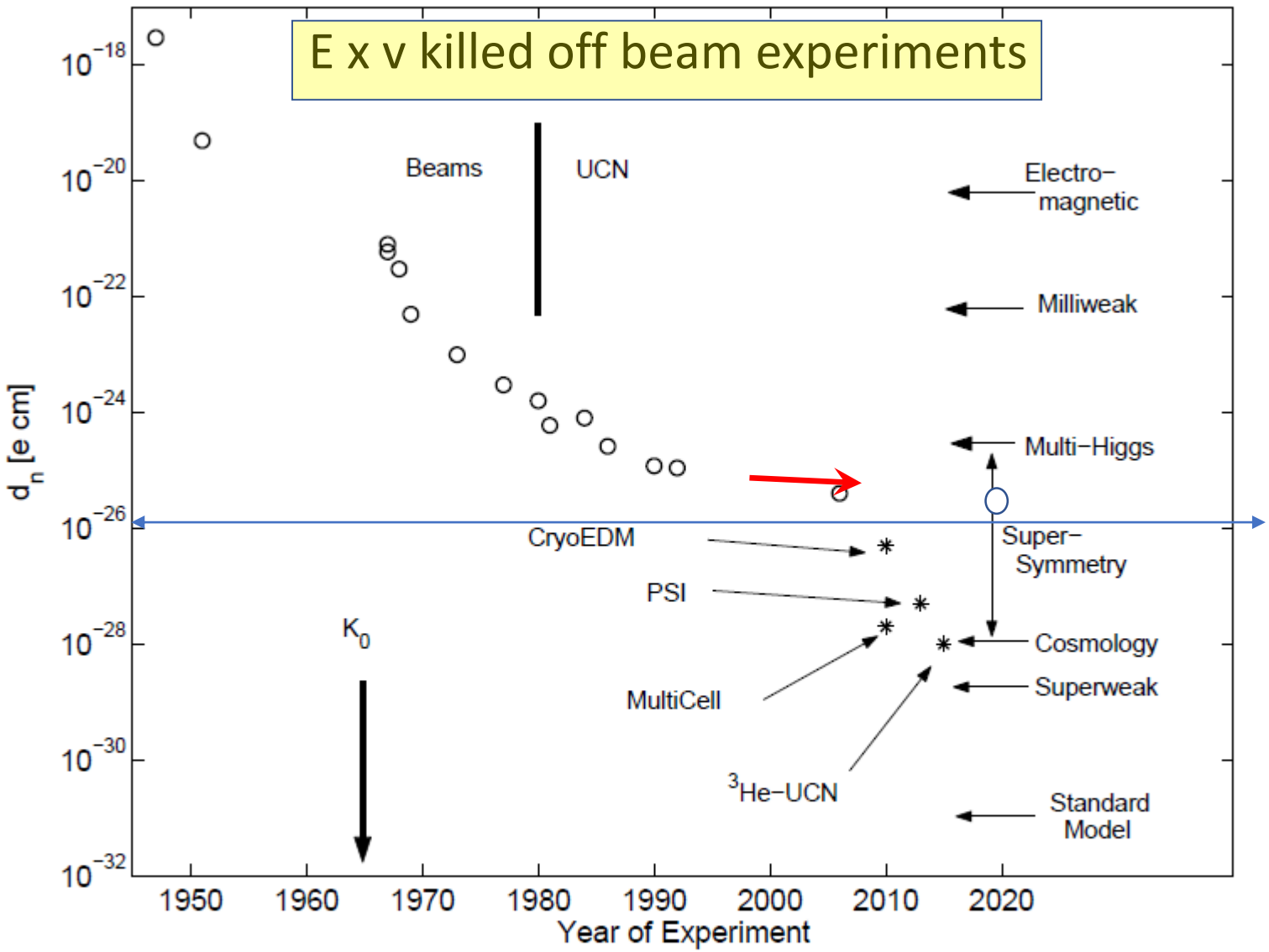


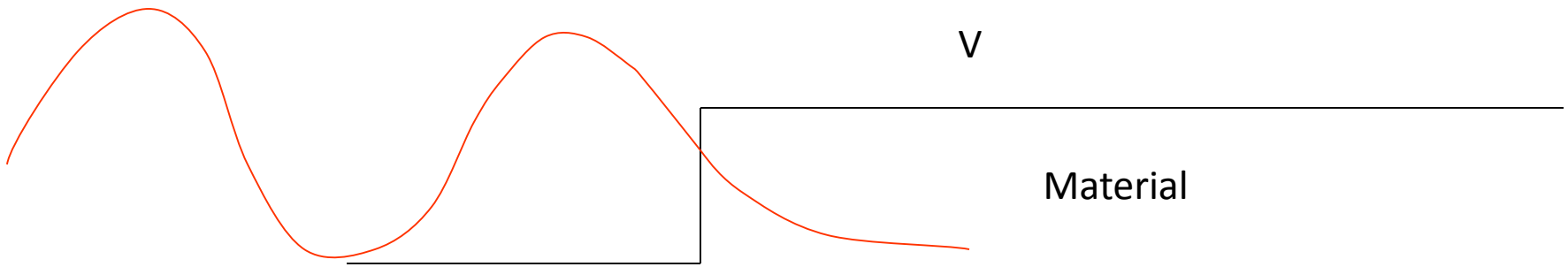
Fig. 1. Historical development of the neutron EDM experimental limit along with expectations from various theoretical models. The points marked with * are experiments presently under development or proposed, and will be discussed in this review.

Ultra-Cold Neutrons (UCN)

- E<Vc critical energy for total refelction
- UCN totally reflected for all angles of incidence

$E \sim 10^2 nev$ $\lambda \sim 500 \overset{o}{A}$ T~1mK h~1m (mgh~E)

B~2 Tesla (uB~E)



Wave fn penetrates material -> wall losses limit storage time

Need for a co-magnetometer

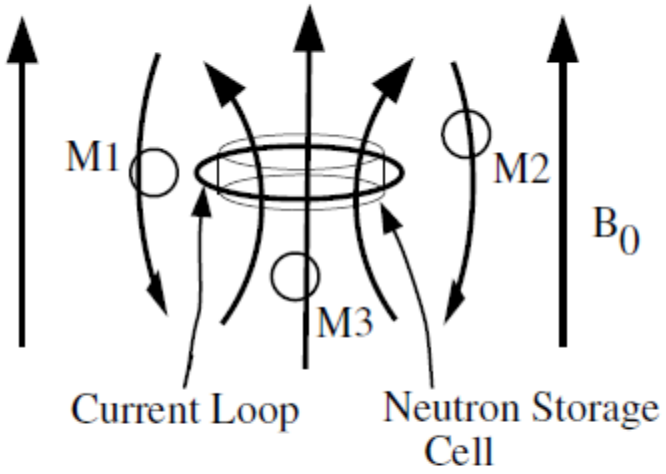


Fig. 3. The external magnetometer problem. Leakage currents associated with the application of a high voltage to the measurement cell can flow in a loop (or some fraction thereof) around the cell, creating a magnetic field that is correlated with the direction of the electric field. Depending on the location of a magnetometer, the field from the loop can add or subtract to the applied static field B_0.

What is Unique About Our Experiment

- Production of ultracold neutrons (UCN) within the apparatus
  – *higher UCN density and longer storage times*

- Use of liquid as a high voltage insulator
  – *higher electric fields*

- Use of a ^{3}He co-magnetometer and superconducting shield
  – *better control of magnetic field systematics*

- Employ two different measurement techniques
  – *oscillation of scintillation rate and dressed spin techniques*

Tackling unknown systematic effects requires unique handles in the experiment that can be varied.

Polarized He3 as:

-Polarizer (partial..beam is polarized
-Magnetometer
-Analyzer
-Detector

Signal in the SNS nEDM Experiment

- Neutron interaction with ^{3}He is spin dependent

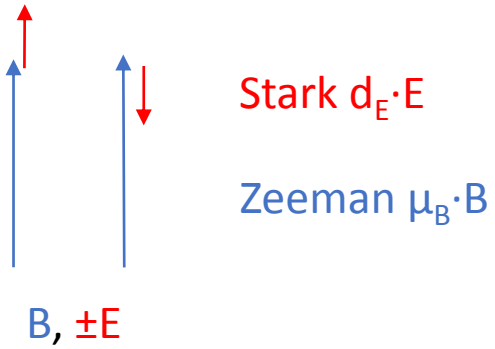
$$n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + {}^1\mathrm{H} \quad 764 \text{ keV}$$

- Interaction is spin dependent, sensitivity to the angle between the neutron and ^{3}He

$$S(t) = \frac{\rho_{UCN} V}{\tau_{^3\mathrm{He}}} \left(1 - P_n P_{^3\mathrm{He}} \cos\theta_{n3}(t)\right)$$

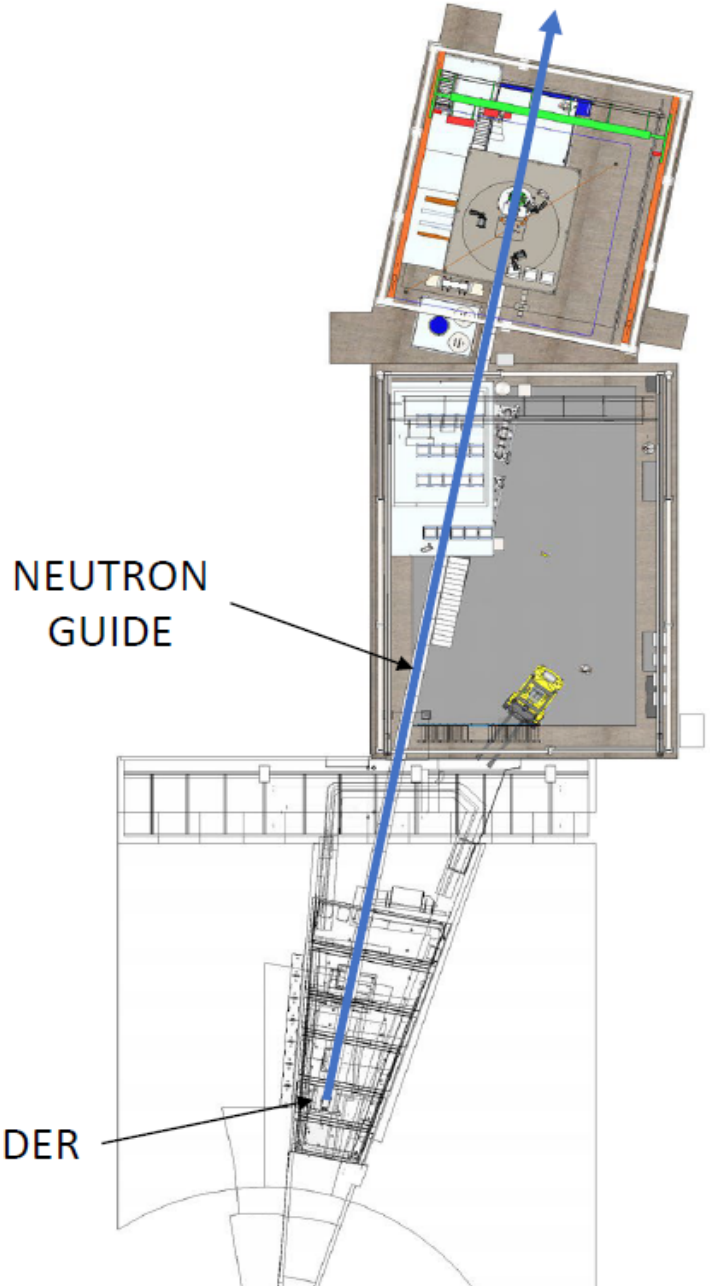
$$\langle \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_3 \rangle$$

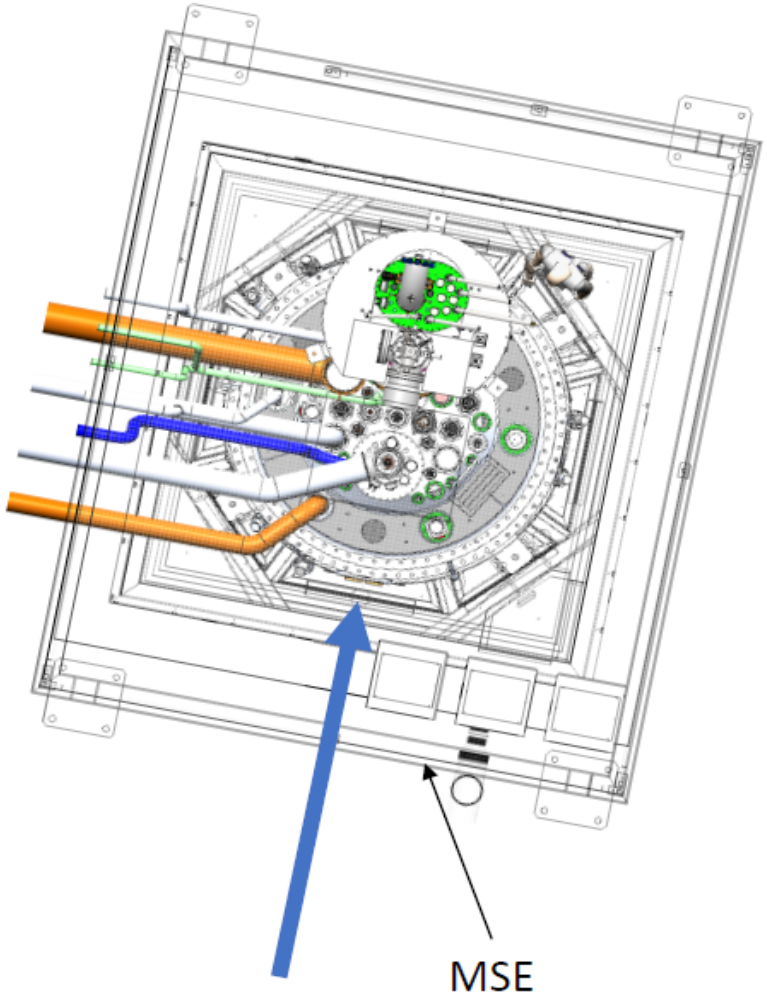
$$\Delta\theta_{\pm} = \frac{4 d_n E T}{\hbar}$$



Beamline

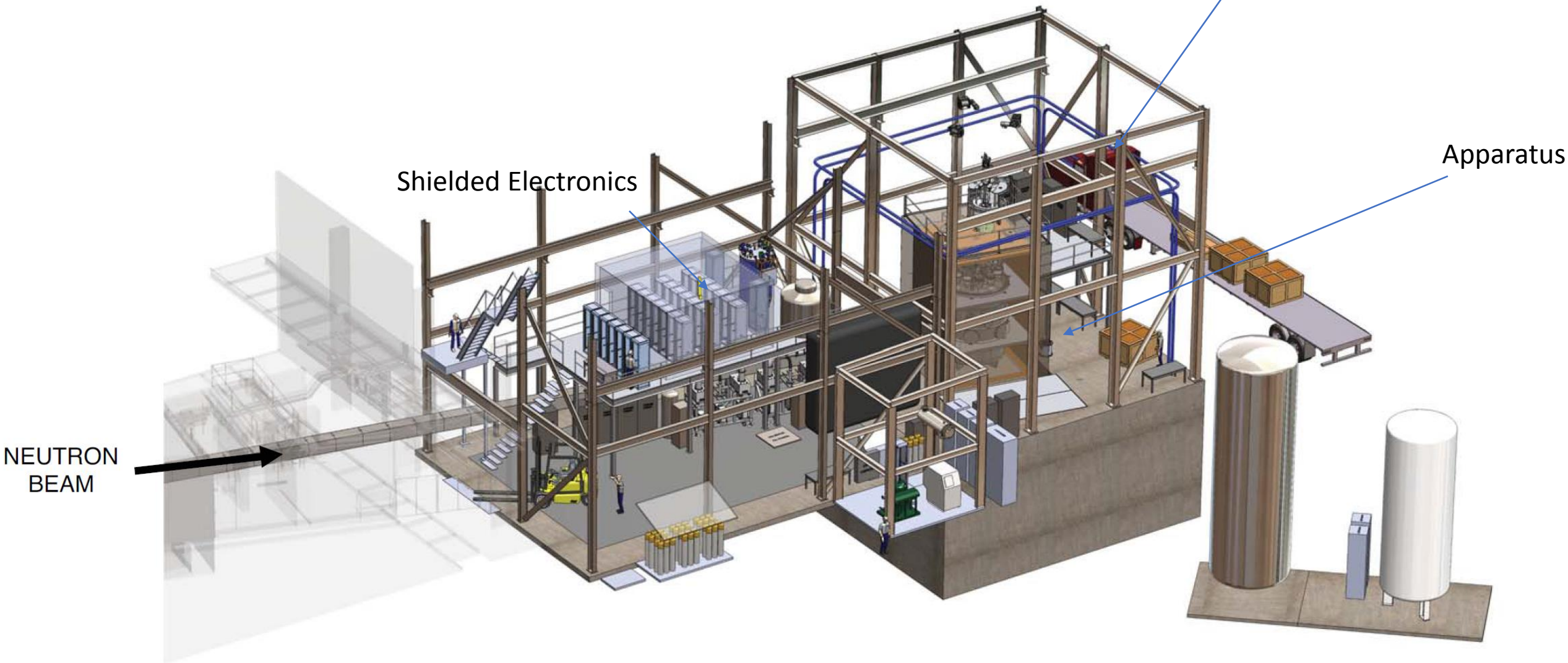
- The beamline direction from the bender
- Preference for beam guide passing perpendicularly through the magnetic shield dictates MSE orientation
- Building should be aligned with the FCS and MSE





SNS Facility Floor plan

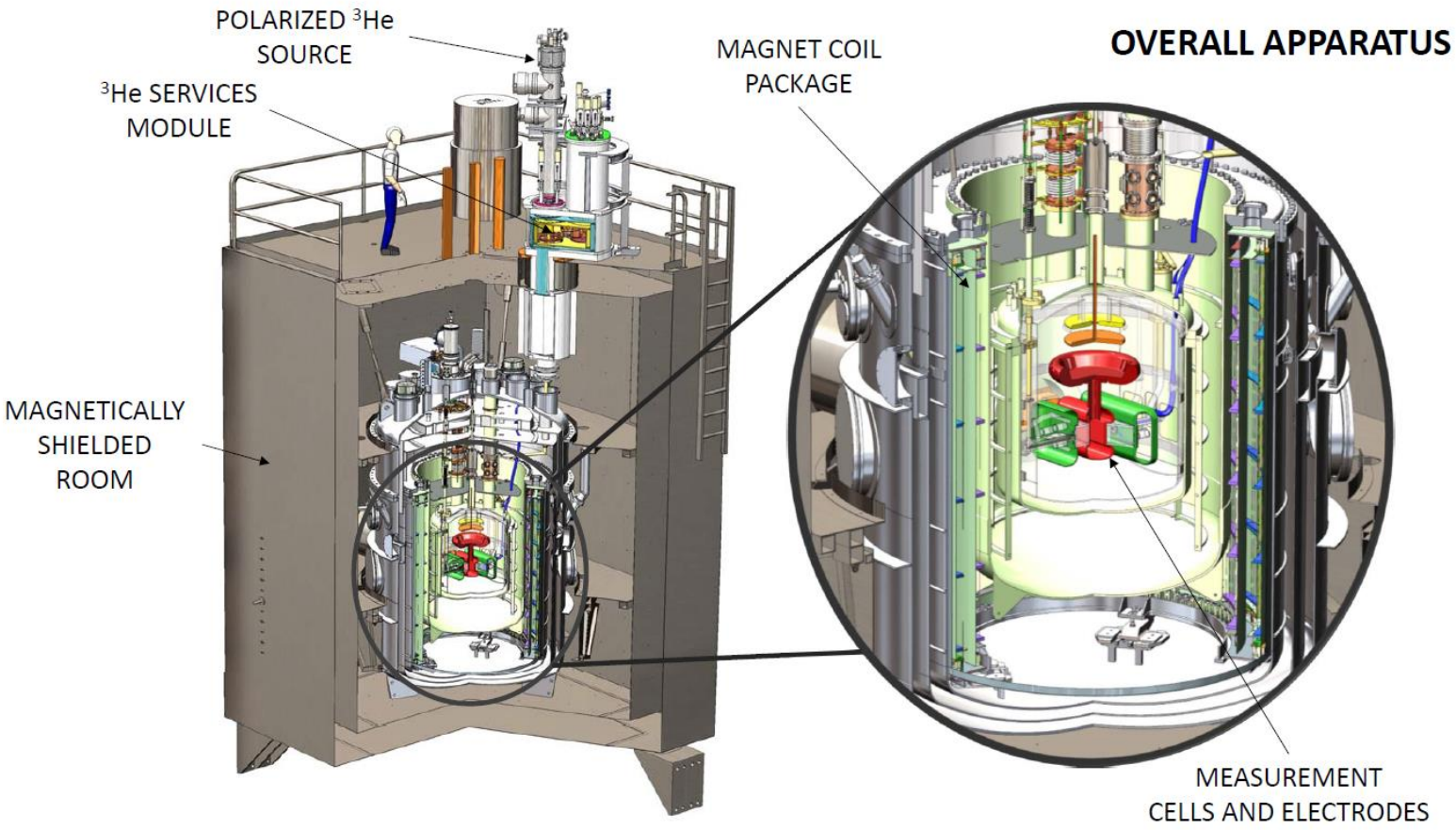
Chris Swank

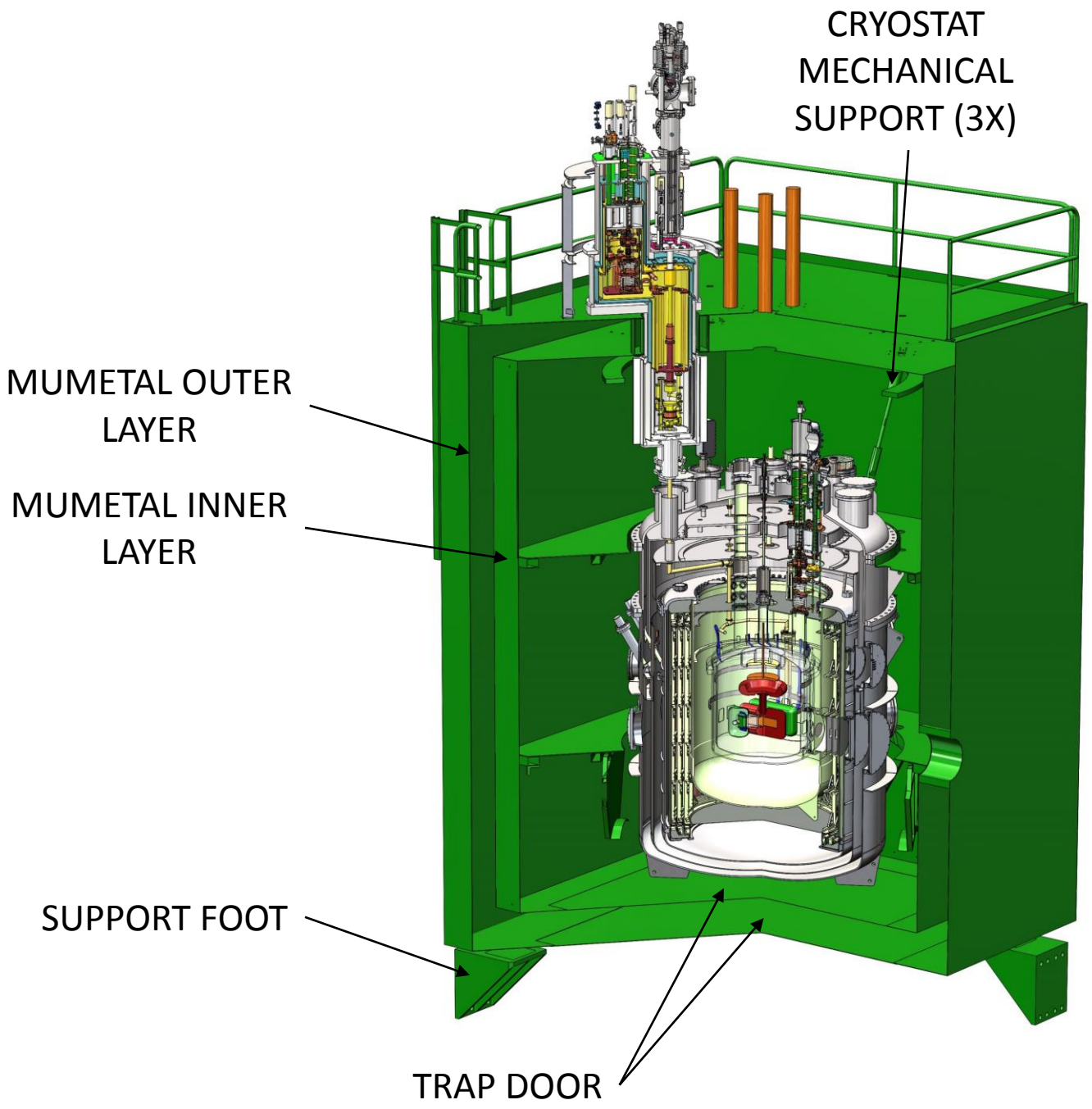


Credit: Brad Filippone, and collaborators, a paper submitted soon to JINST:
A New Apparatus for a Cryogenic Measurement of the Neutron Electric Dipole Moment

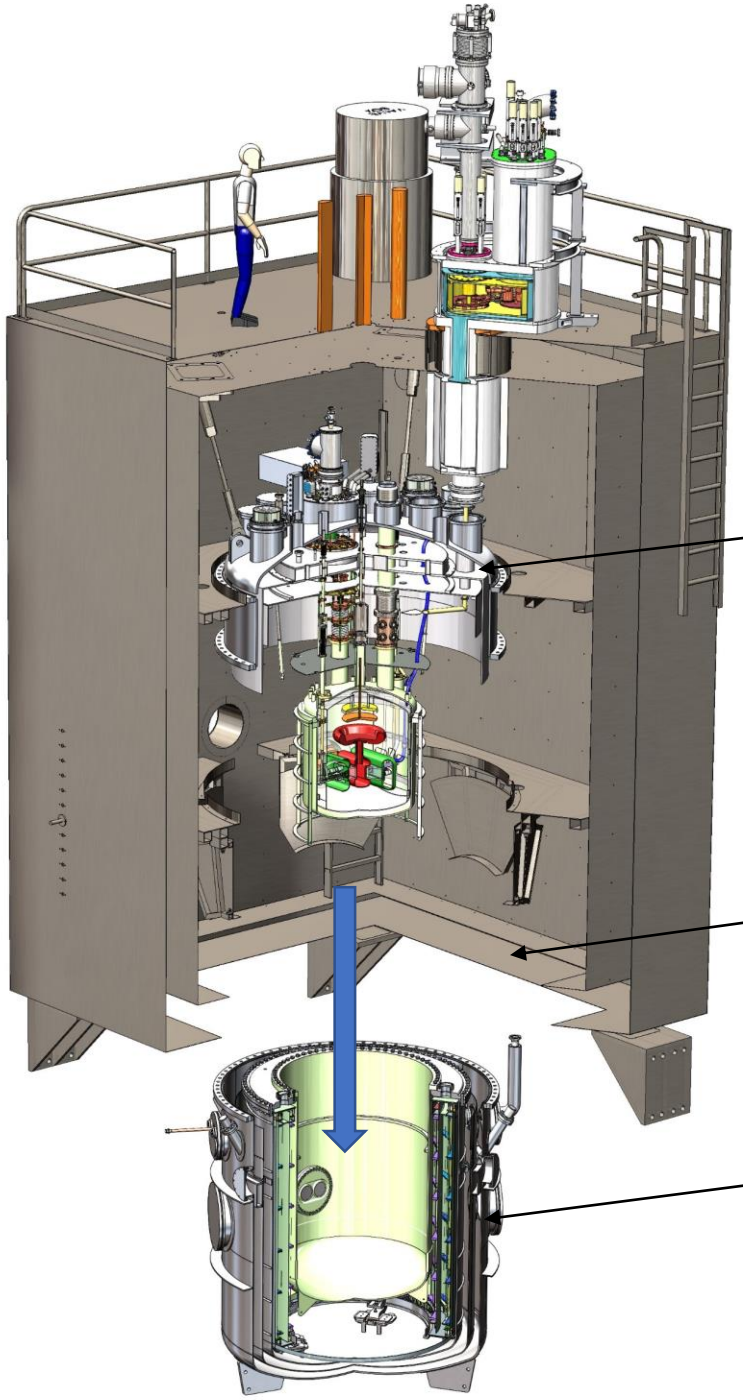
Apparatus Summary

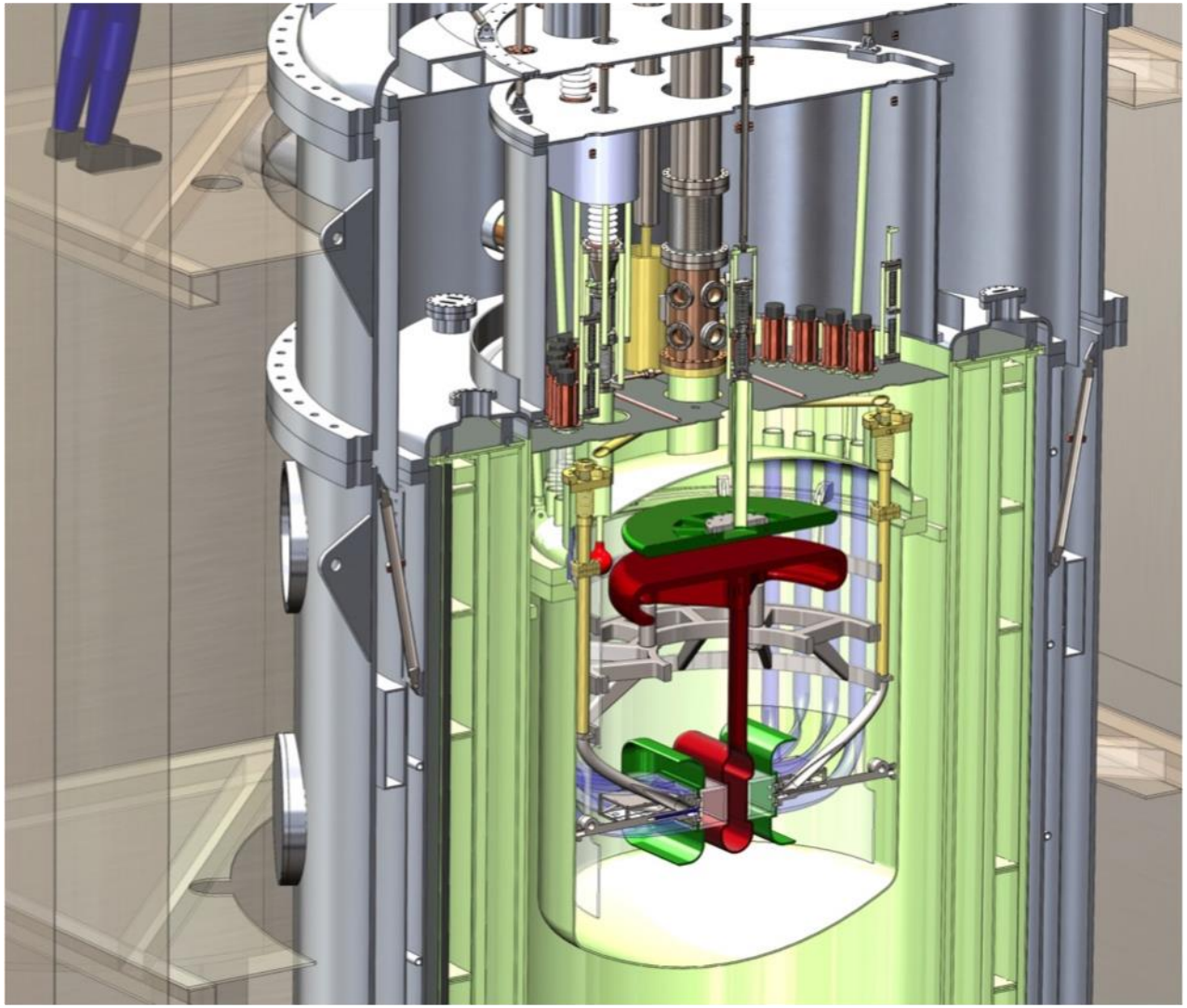
- Magnetic fields
- Helium Transport
- Neutron Transport
- Central Detection
- Systematics
- PULSTAR Systematic Study apparatus




CRYOSTAT MECHANICAL SUPPORT (3X)
MUMETAL OUTER LAYER
MUMETAL INNER LAYER
SUPPORT FOOT
TRAP DOOR

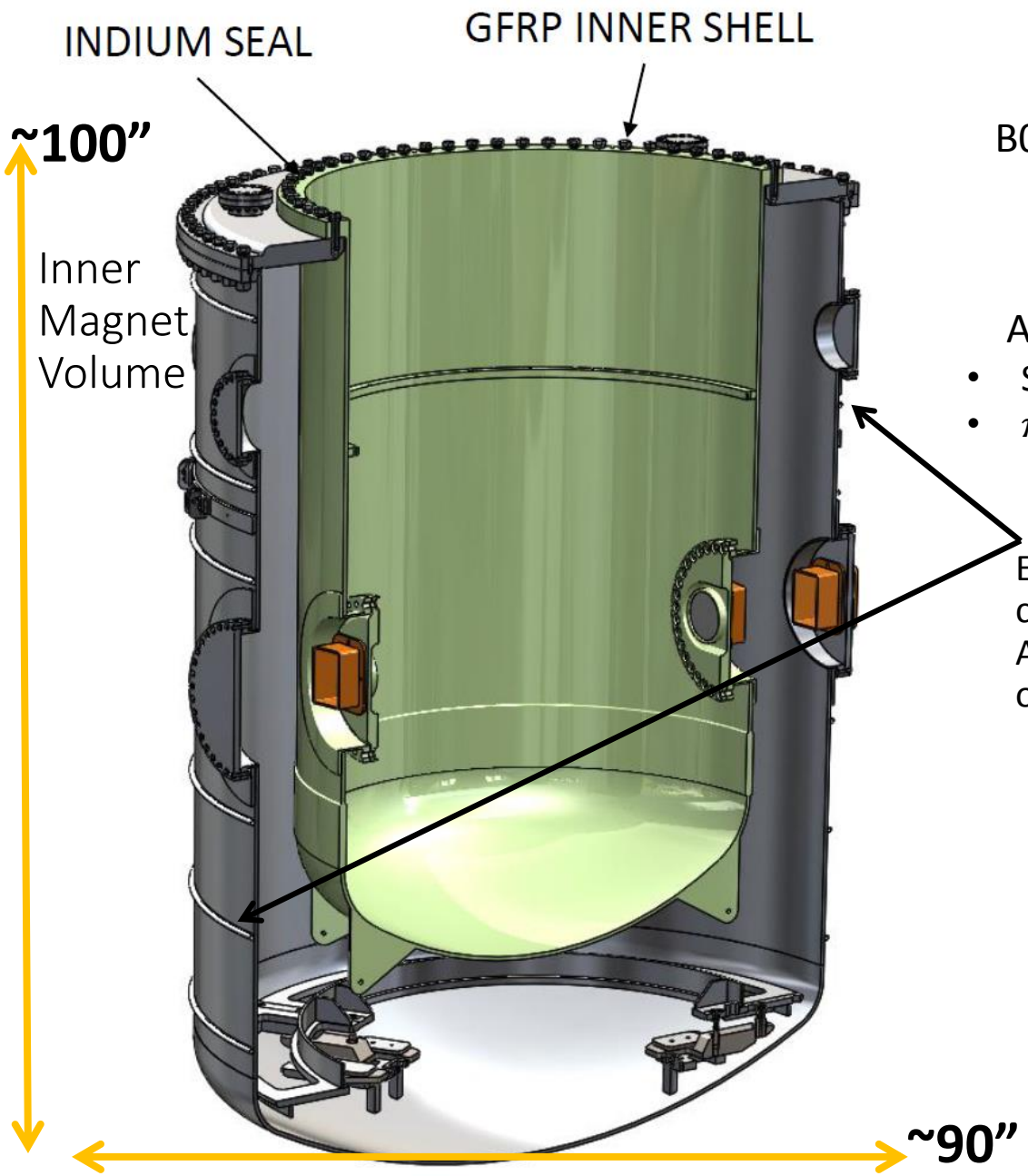
OVERALL APPARATUS
MAGNET EXTRACTED





Commissioning Cryovessel and Outer LN Shield

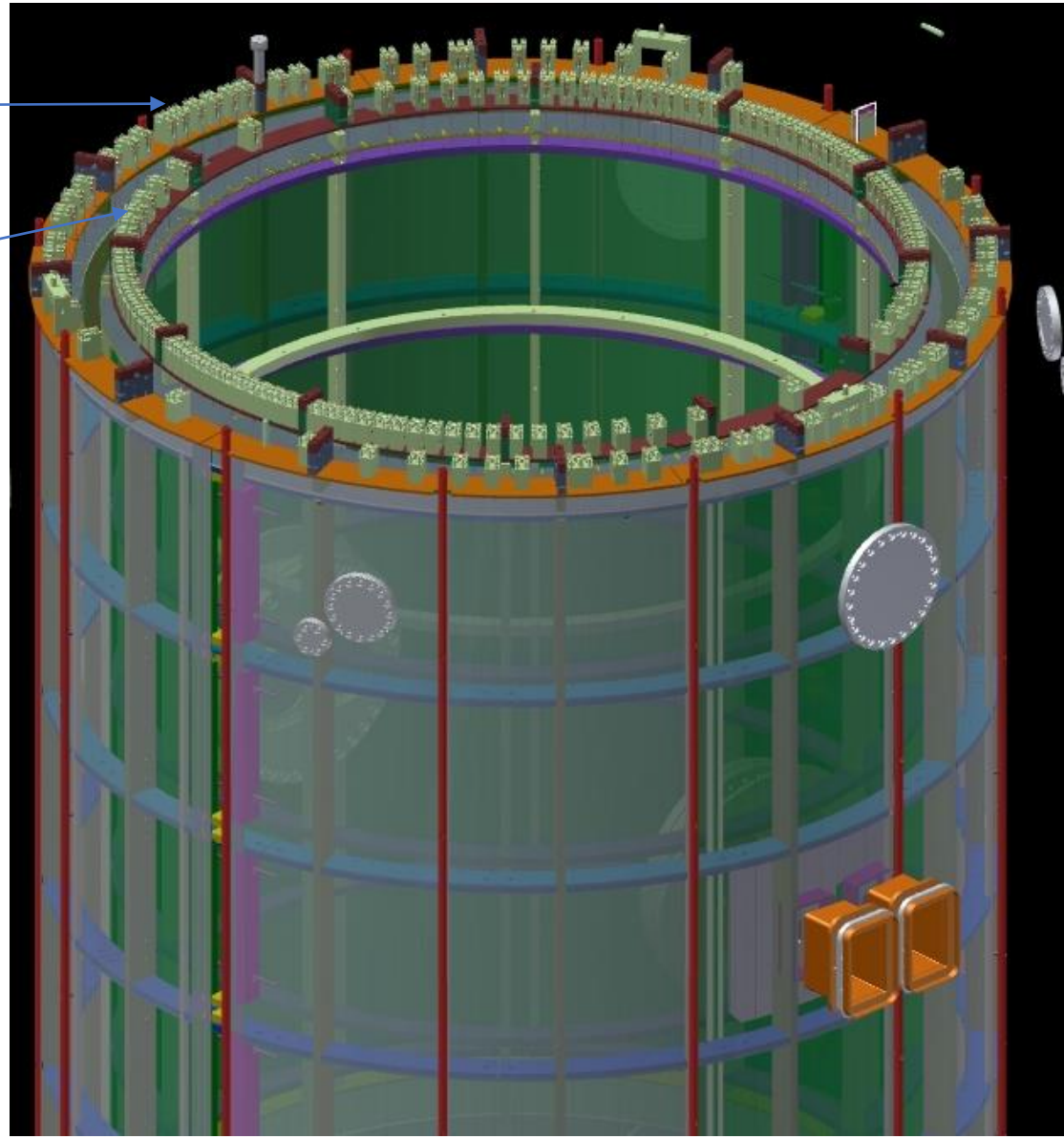
Magnetic Fields



B0 Coil

AC Coil
- Spin Dressing
- $\pi/2$ pulses

Externally cooled Aluminum outer vessel

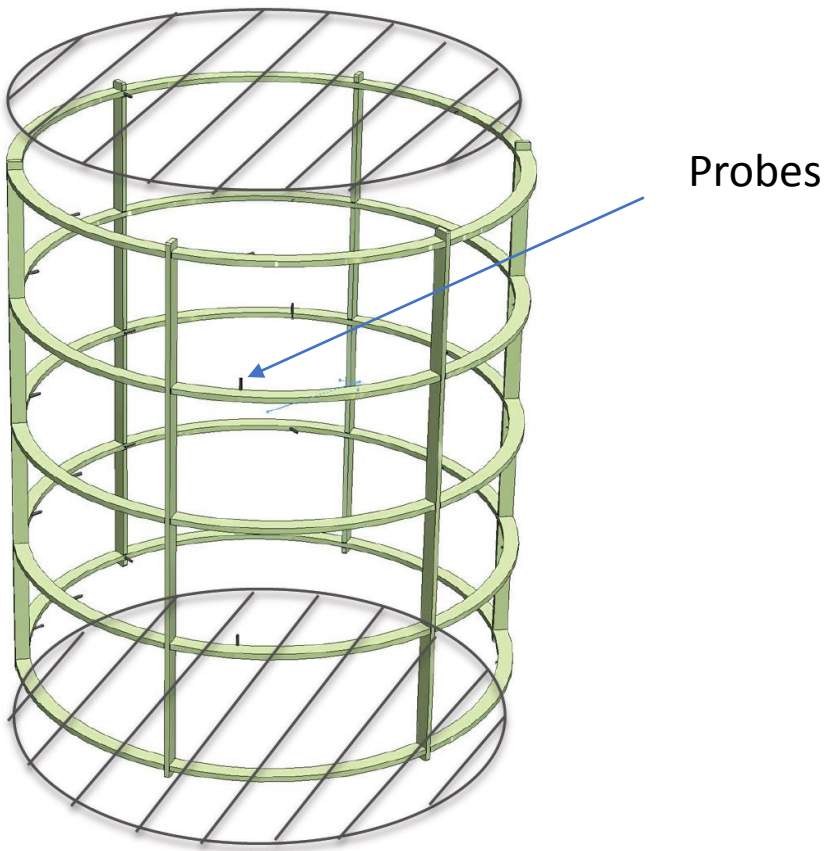


Field Monitoring system

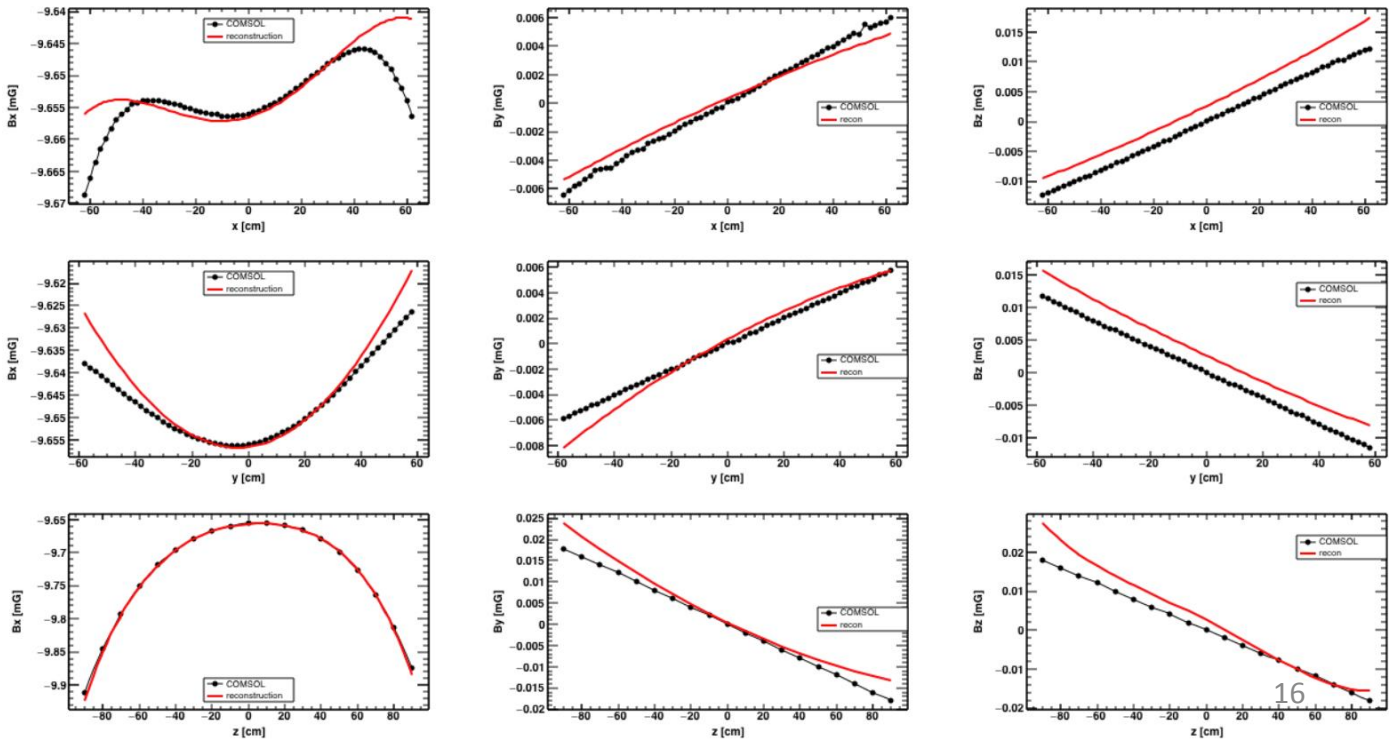
Brad Plaster
Alina Aleksandrova

Field Reconstruction via Scalar potential fitting

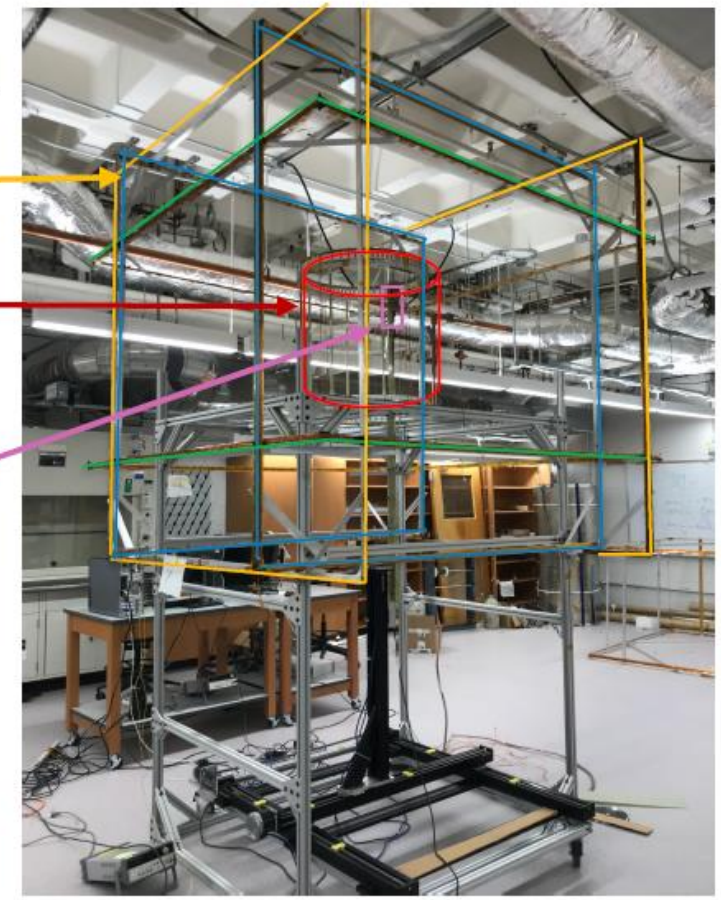
Simulated Sensitivity
~ 1×10^{-4} mG/cm on Axis sensitivity
Can get more with 2 Radii of probes
This is sensitivity enough to shim a good T2



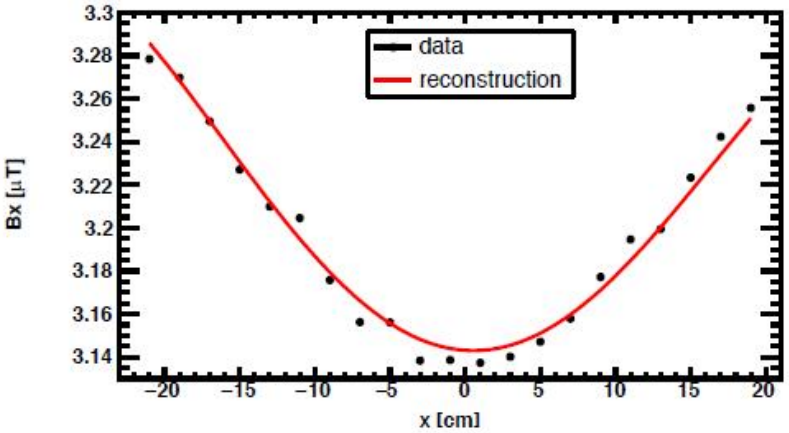
Gradient 3: $a = 0.0001$ mG/cm

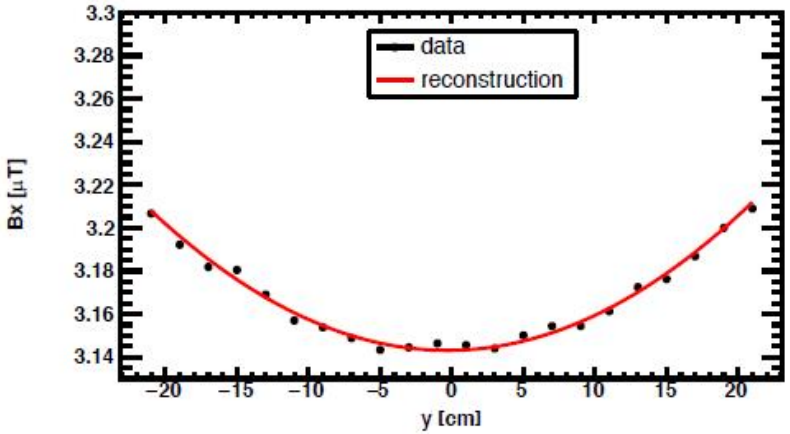


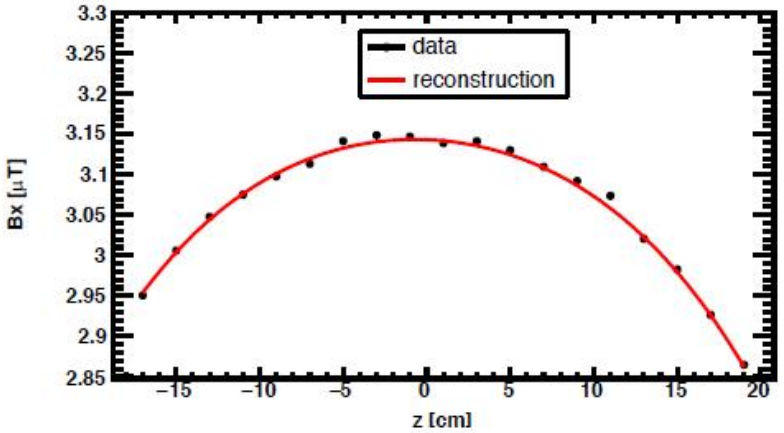
Reconstruction Results of Real Data



Reconstruction with 39 BV







B0 Coil Optimization Chris Swank

- Minimization of conditional density weighted field Fourier coefficients

$$\frac{1}{T_2} \propto S_B(0) = \sum_{l_x,l_y,l_z=-\infty}^{\infty} B_0(l_x,l_y,l_z)B(l_x,l_y,l_z)p\left(\left[\frac{l_x\pi}{L_x},\frac{l_y\pi}{L_y},\frac{l_z\pi}{L_z}\right],\omega\right)$$

$$d\omega \propto \omega Im(S_B)+\langle \boldsymbol{B}_x \boldsymbol{x}\rangle$$

Particle Independent Particle Dependent

$$B(l_x,l_y,l_z) = \int_{-L}^{L} B(\boldsymbol{x})\exp\left(-\frac{i\pi \boldsymbol{l}\cdot\boldsymbol{x}}{L_i}\right)d\boldsymbol{x}$$

^{3}He Diffusion limit

$$p(q,\omega) = 2\,\mathrm{Re}\left(\frac{1}{\frac{kT}{m}q^2\tau_c + i\omega}\right)$$

Thus, minimize

neutrons $$\sum_{l_x,l_y,l_z=-\infty}^{\infty} \frac{B_0(l_x,l_y,l_z)B(l_x,l_y,l_z)}{(l_x^2+l_y^2+l_z^2)^{1/2}}$$

^{3}He $$\sum_{l_x,l_y,l_z=-\infty}^{\infty} \frac{B_0(l_x,l_y,l_z)B(l_x,l_y,l_z)}{l_x^2+l_y^2+l_z^2}$$

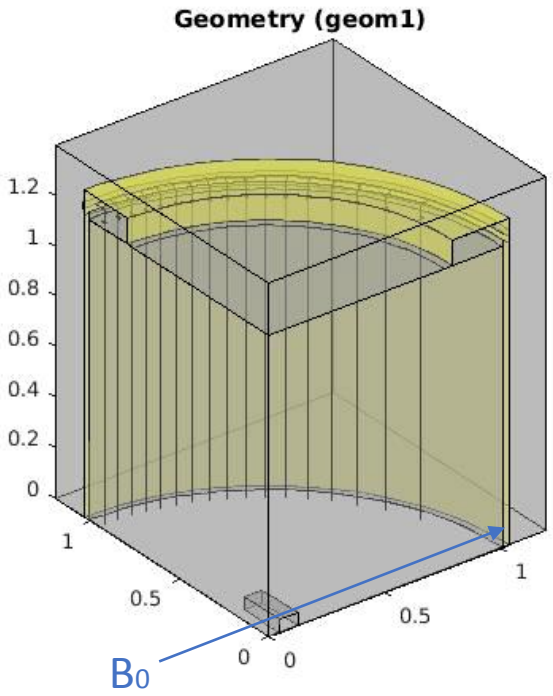
Neutrons
(approximate as ballistic),

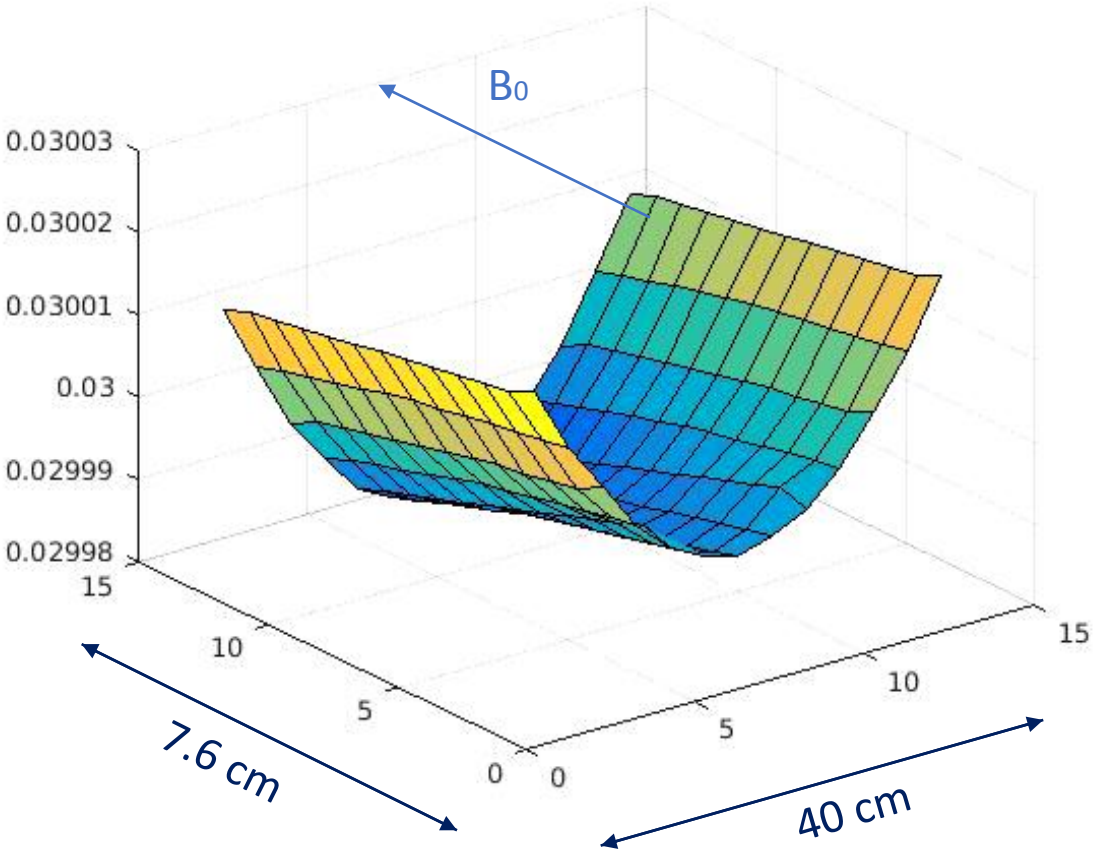
$$p(q,\omega) \propto \frac{1}{|q|}$$

B_0 Field is not parallel to gravity!

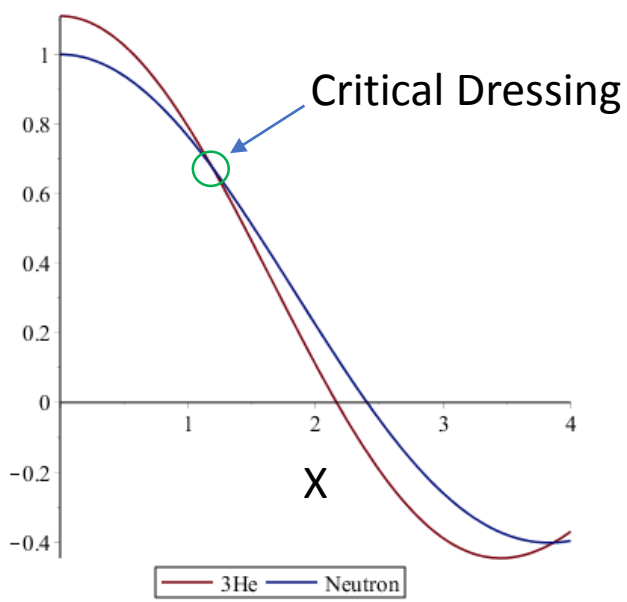
Computationally fast due to modern FFT algorithms.

Optimization Example





Spin Dressing and Critical Dressing



- Spin dressing can be applied so that.

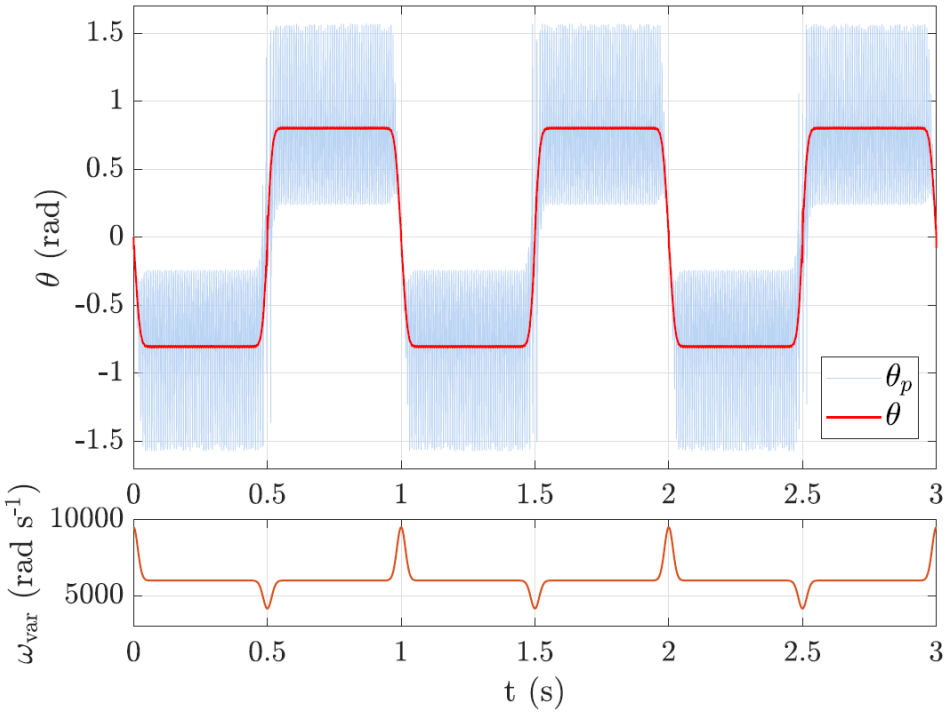
$$J_0(X_c) = \alpha J_0(\alpha X_c) \qquad X_s = \frac{\gamma_s B_{\mathrm{rf}}}{\omega_{\mathrm{rf}}}$$

- For neutrons and ^{3}He α=1.11. And X_c is the critical dressing parameter,
- Dressed with this parameter the two spin species will have the same effective precession.
- With this technique we can set $\langle \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_3 \rangle$ at the optimum and leave it
- Factor 2 improved sensitivity

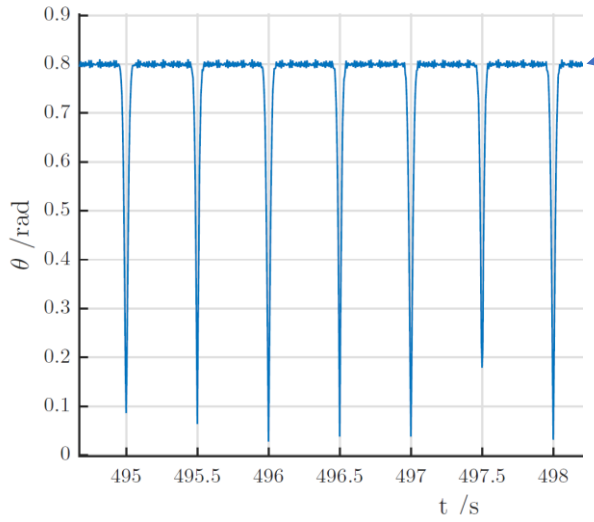
R. Golub and S. K. Lamoreaux, "Neutron electric-dipole moment, ultracold neutrons and polarized ^{3}He," *Physics Reports*, vol. 237, no. 1, pp. 1–62, 1994.

Modulated Critical Dressing.

- Systematic effects can be mitigated by modulation
  - Maintain maximum sensitivity by modulating to maximum sensitivity phase.



$$\langle \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_3 \rangle = \frac{1}{2}\left[1 + J_0(x_n - x_3)\right]\cos\left(\omega_n' t - \omega_3' t - \phi_0\right) + \frac{1}{2}\left[1 - J_0(x_n - x_3)\right]\cos(\omega_n' t + \omega_3' t + \phi_0)$$

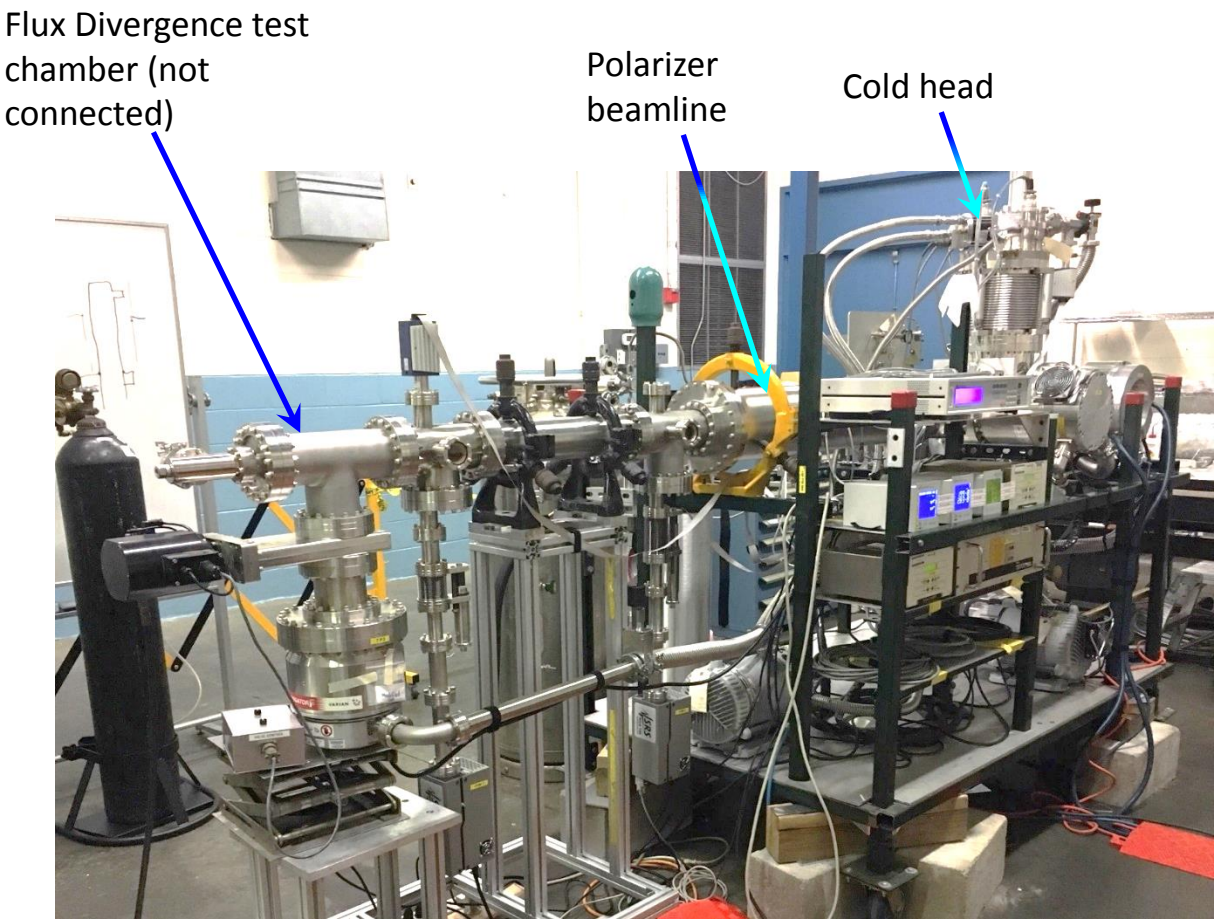


Fast oscillations can be used for diagnostics

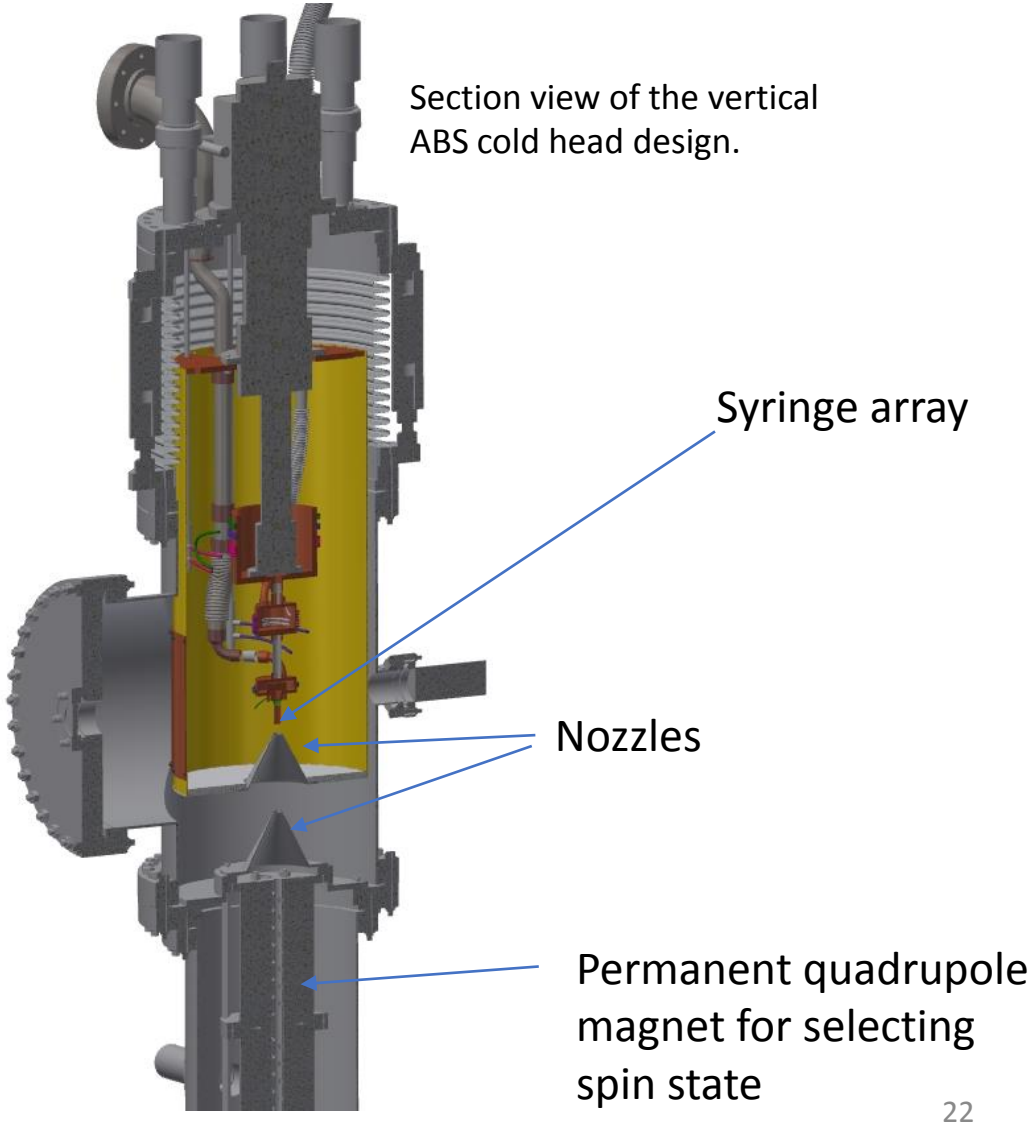
Simulated by Ezra Webb

Polarized ^{3}He Source: Atomic Beam Source (ABS)

ABS installed in the test apparatus



The atomic beam source setup at MIT/Bates



Heat Flush into the measurement cell

- The heat flush can be modeled in different ways.
  - ^{3}He transport determined from convection diffusion

$$\frac{\partial x_3}{\partial t} + \vec{v}_{ph} \cdot \nabla x_3 = \nabla \cdot \left(D_{3,ph} \nabla x_3 \right)$$

  - 1D, phonon velocity determined from heat transport equation

$$\vec{Q} = T S_{ph} \vec{v}_{ph}$$

  - 3D, phonon transport determined from Navier Stokes
    - Required for best accuracy in spin tracking CHANGE TO v_{ph}

$$\rho_{ph} \left(\frac{\partial \mathrm{v}_{ph}}{\partial t} + \mathrm{v}_{ph} \cdot \nabla \mathrm{v}_{ph} \right) = -\nabla p_{ph} + \eta_{ph} \nabla^2 \mathrm{v}_{ph}$$

First heat flush is solved in COMSOL via Navier-Stokes.

$$\rho_n \left(\frac{\partial \mathrm{v_n}}{\partial t} + \mathrm{v_n} \cdot \nabla \mathrm{v_n} \right) = -\nabla p_n + \eta_n \nabla^2 \mathrm{v_n}$$

Temperature derived from pressure

$$\begin{aligned} dp &= S dT \\ S_n(T) &= \frac{2\pi^2 k_B^4}{45\hbar v_T^3} T^3 \\ p(T) &= \frac{2\pi^2 k_B^4}{180\hbar v_T^3} T^4, \end{aligned}$$

Viscosity and density are given by

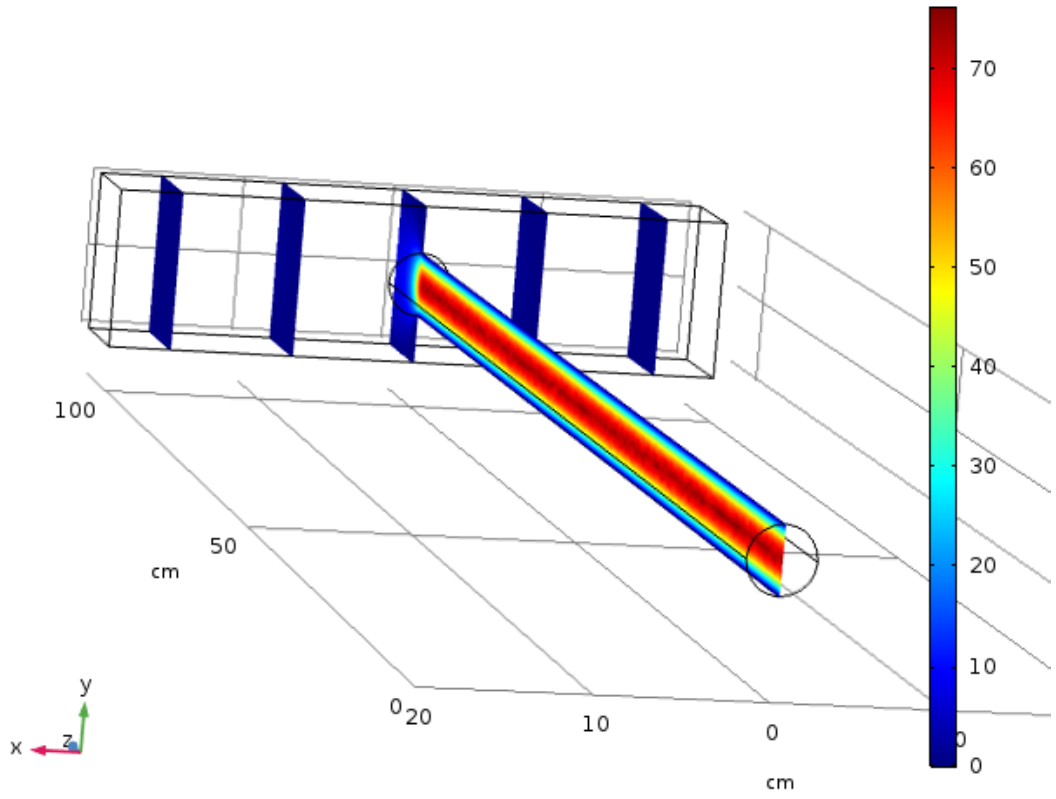
$$\begin{aligned} \eta &= \rho_n \frac{\lambda\, \mathrm{u}}{3} \\ \rho_n &= \frac{2\pi^2 k_B^4}{45\hbar^3 u^5} T^4 \\ u &= 24000 \frac{\mathrm{cm}}{\mathrm{s}} \\ \lambda &= \left(1.28 \times 10^{-5} T^{-9} + 3.80 \times 10^{-3} T^{-4}\right) \ [\mathrm{cm}]. \end{aligned}$$

For those interested (cgs):
$p=2492.2T^4$ (dyn/cm^2),
$\rho_n=1.7305e\text{-}5T^4$ (g/cc)

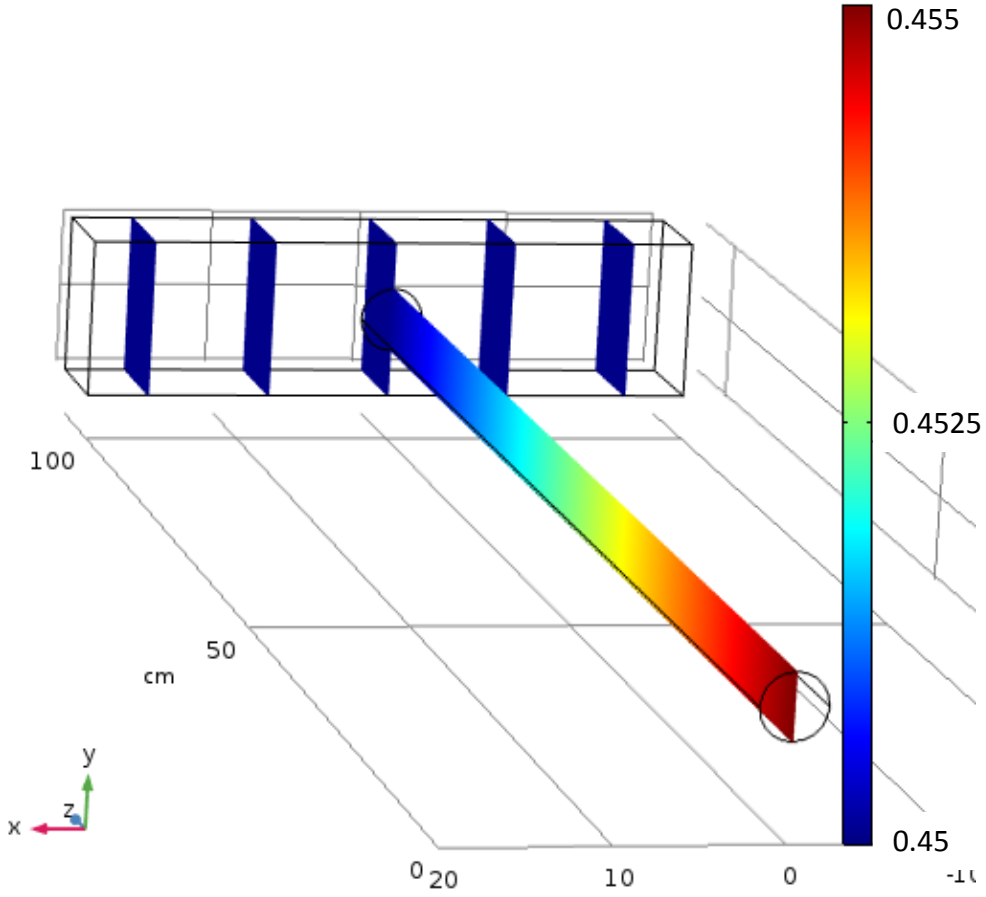
Visualization of COMSOL Navier Stokes Solution.

This example is steady state, time can be included (4D quad-cubic spline, more time to solve)

Velocity field (cm/s)



Temperature (K)



Rectangular mesh data file is imported into c++, tri-cubic spline built for data interpolation.

Building 2 Non-magnetic Dilution Refrigerators

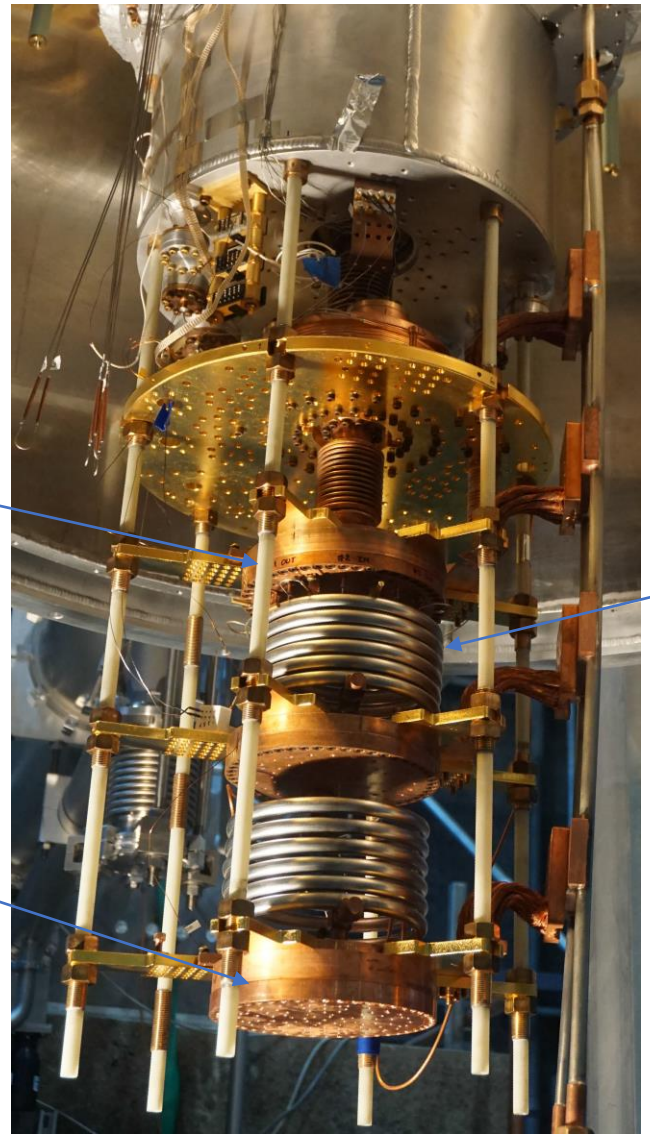
Chris Swank

Design Goal:

80 mW at 300 mK

Still

Mixing Chamber



Currently Stainless Steel heat exchangers (a little mangetic)

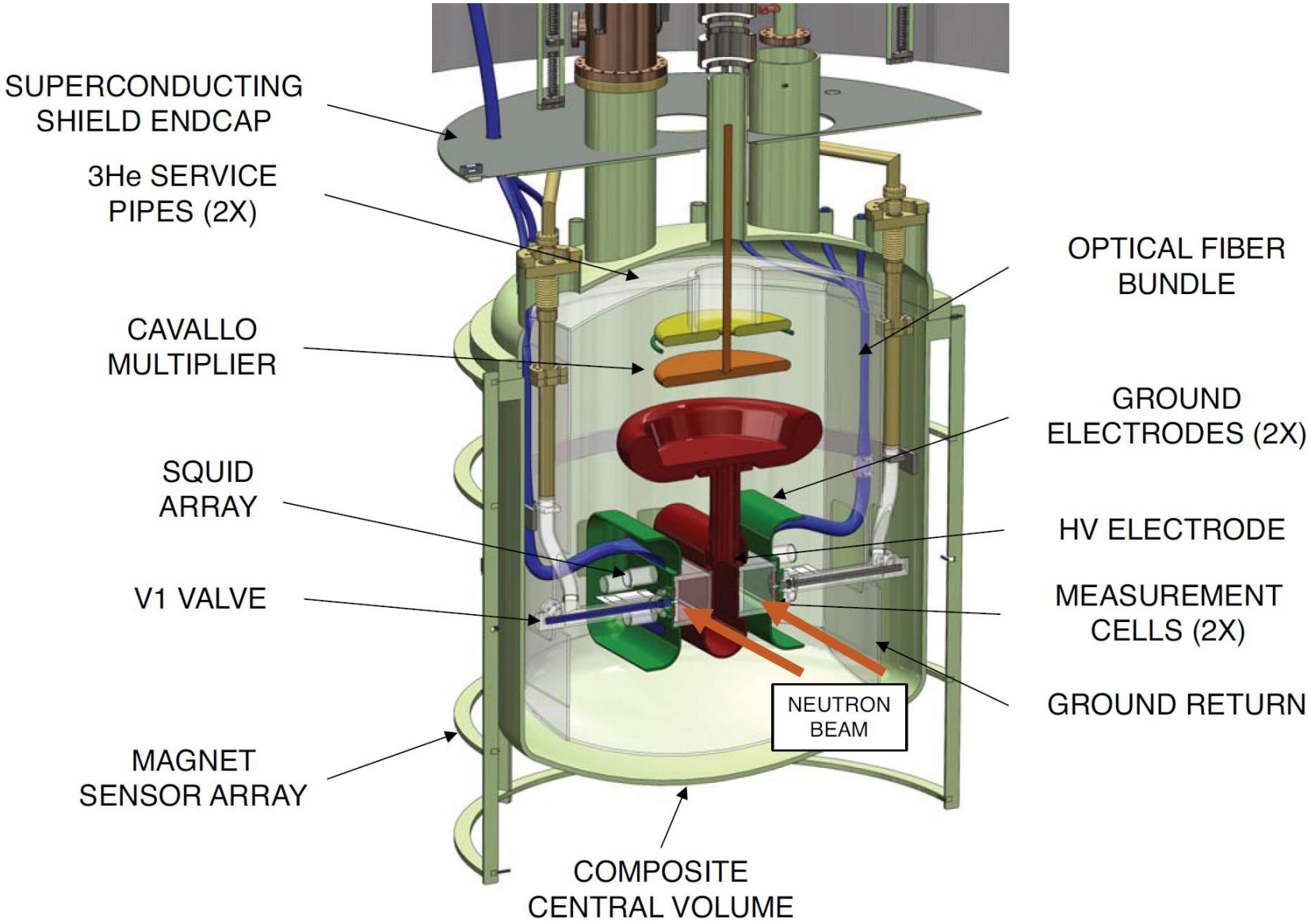
2nd Fridge will be German Sivler (non Magnetic)

Credit: Weijun Yao

Central Detection System

Highlights

- 75 kV/cm Electric field
- Cavallo's Multiplier
- Squid Magnetometer
- 1600 L of super fluid helium
- Light collection



Cavallo Refresher: Marie Blatnik

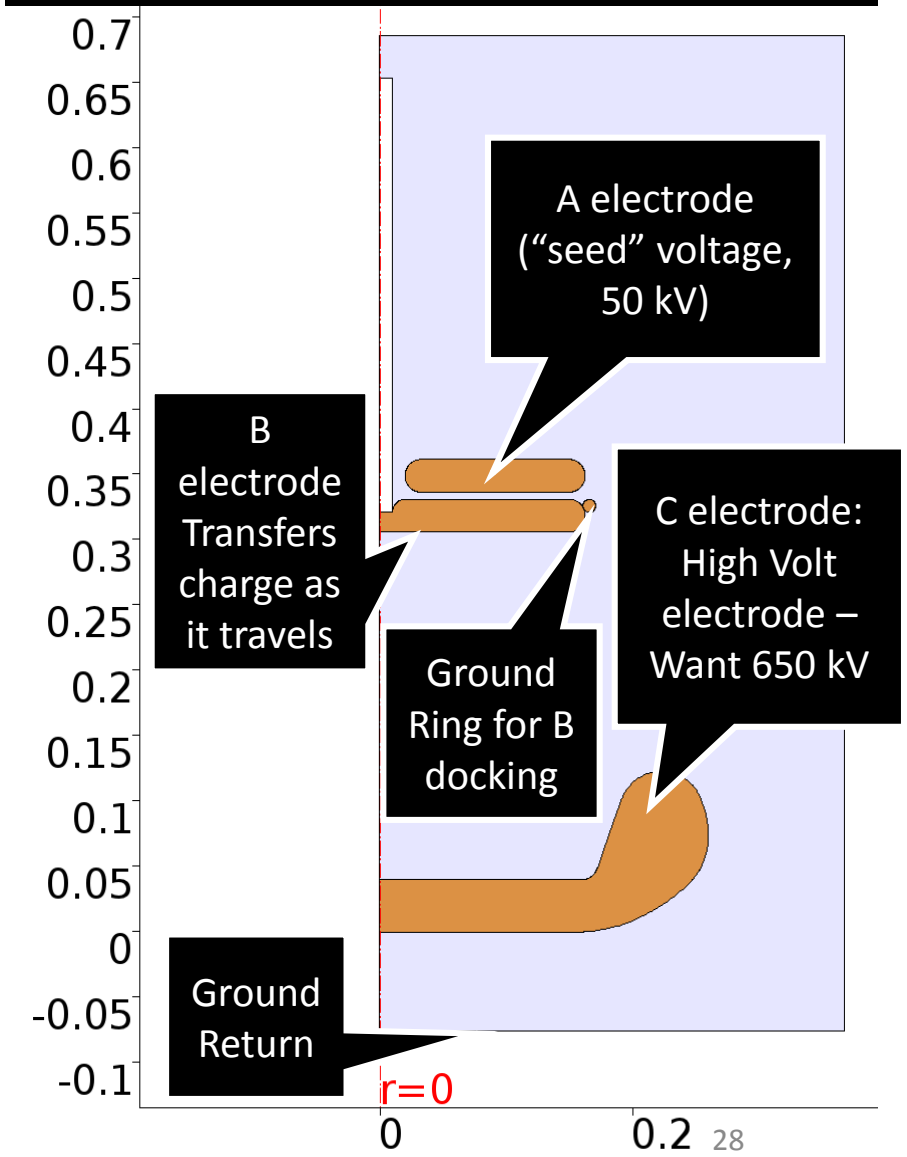
Cavallo Electrode Simulation Constraints:

1. Maximize Output Voltage (at least 650 kV).
2. E fields < ~100 kV/cm.
3. Small input voltage V_A (50 kV).
4. Restricted Diameter (~30’’) with length to spare.

Cavallo Electrode Reality:

Endeavor to fabricate this design and test them in the Caltech dewar.

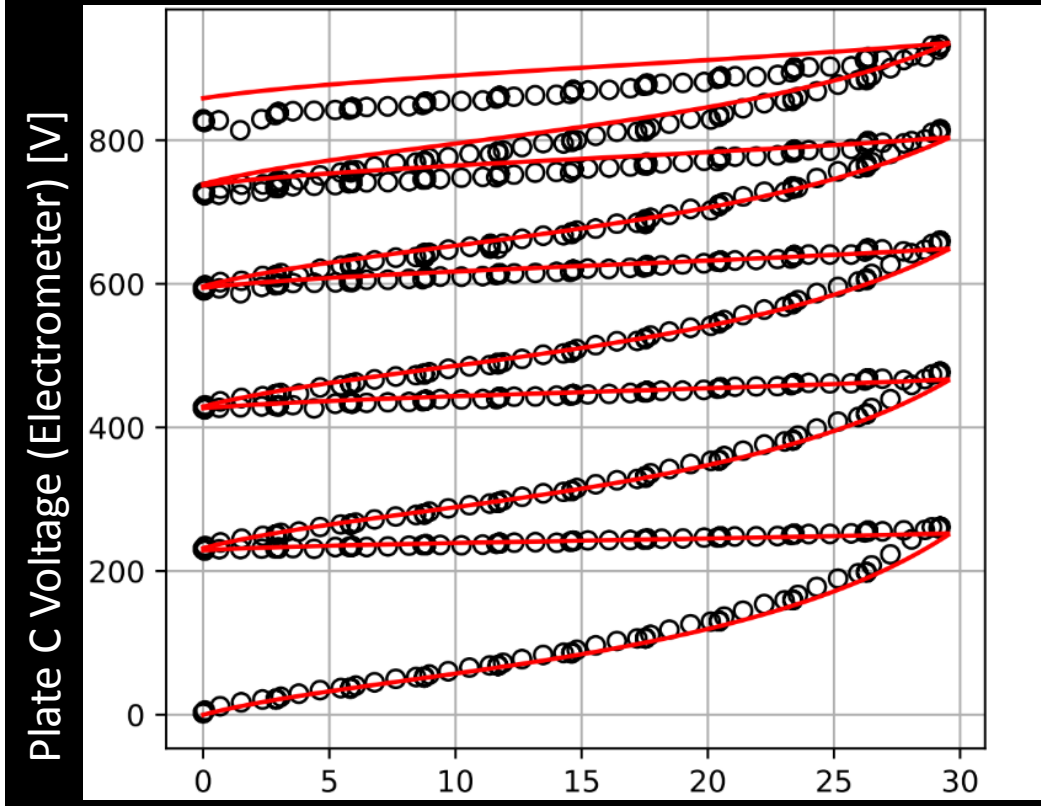
2-D Axisymmetric Model:



ROOM TEMPERATURE APPARATUS

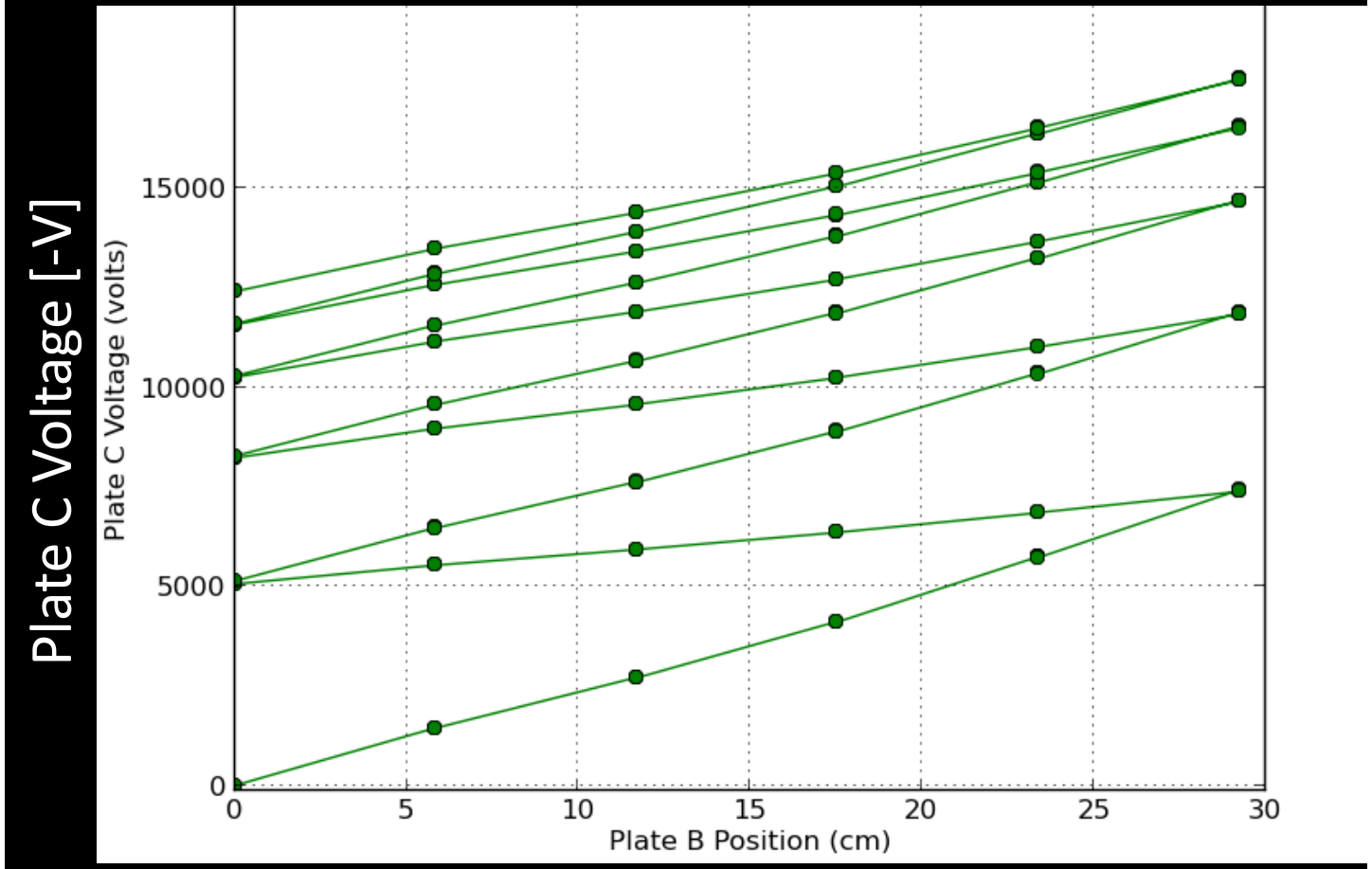
Marie Blatnik

C Electrode Voltage vs B Position



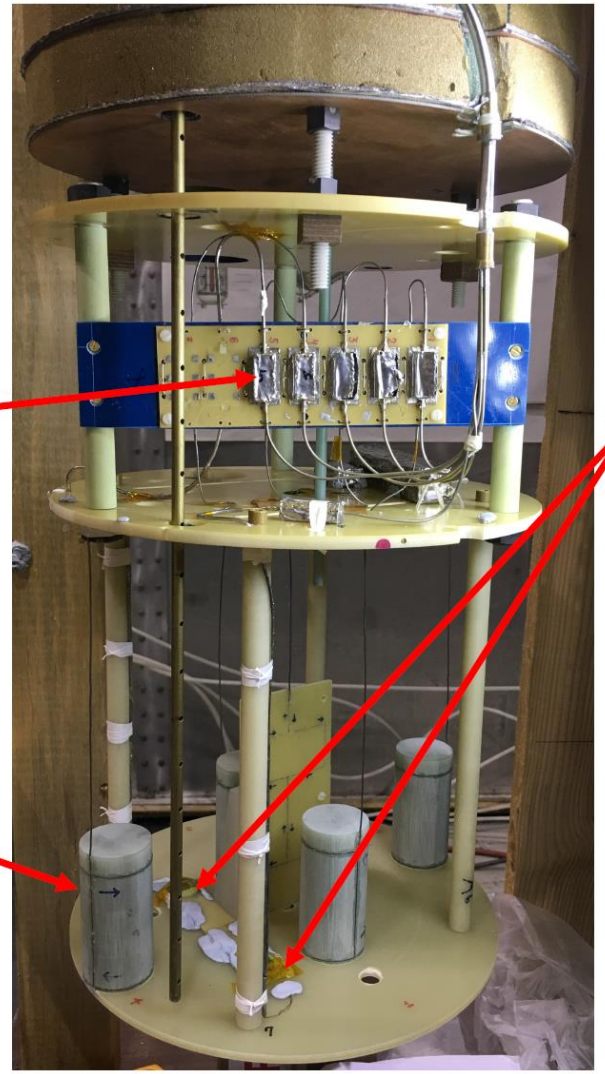
We can use the PD410 from PI to wiggle cryogenically

C Electrode Voltage vs B Position



SQUID System

SQUIDs Multichannel Prototype



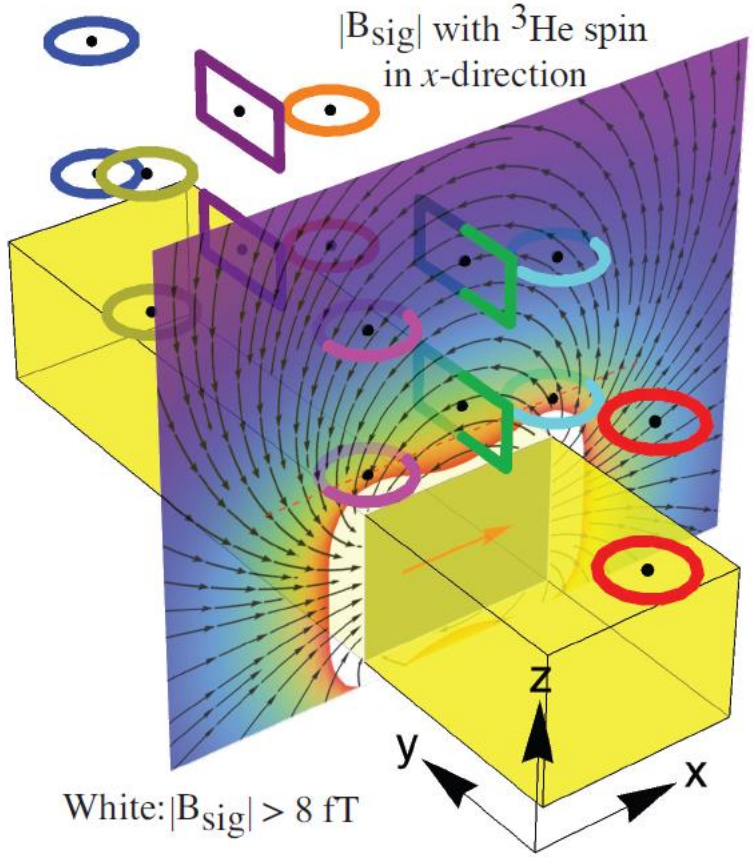
SQUIDs in Pb boxes

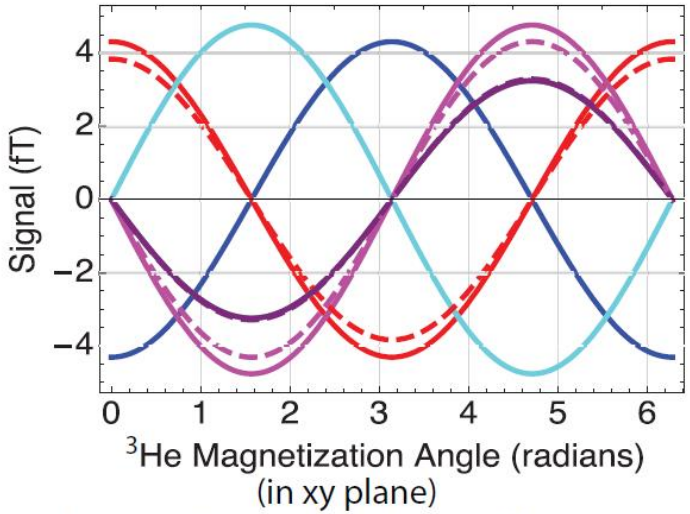
Axial pickup loop

Integrated magnetometers from Supracon/Jena

Distance between inside bottom of dewar (4 K) and outside (RT): 24 mm

"AC defluxing" coils will be installed on the integrated magnetometer chips for this test. Matlashov et al., IEEE TAS, **27**, no. 4, June 2017.





Squid System Expected SNR≈6

Steven Clayton
Young-Jin Kim, LANL

PULSTAR Systematic Apparatus

Relatively agile apparatus compared to SNS nEDM (short turn around time)

Perform Systematic Studies

- Correlation function measurements
- Predictions of Geometric Frequency shift

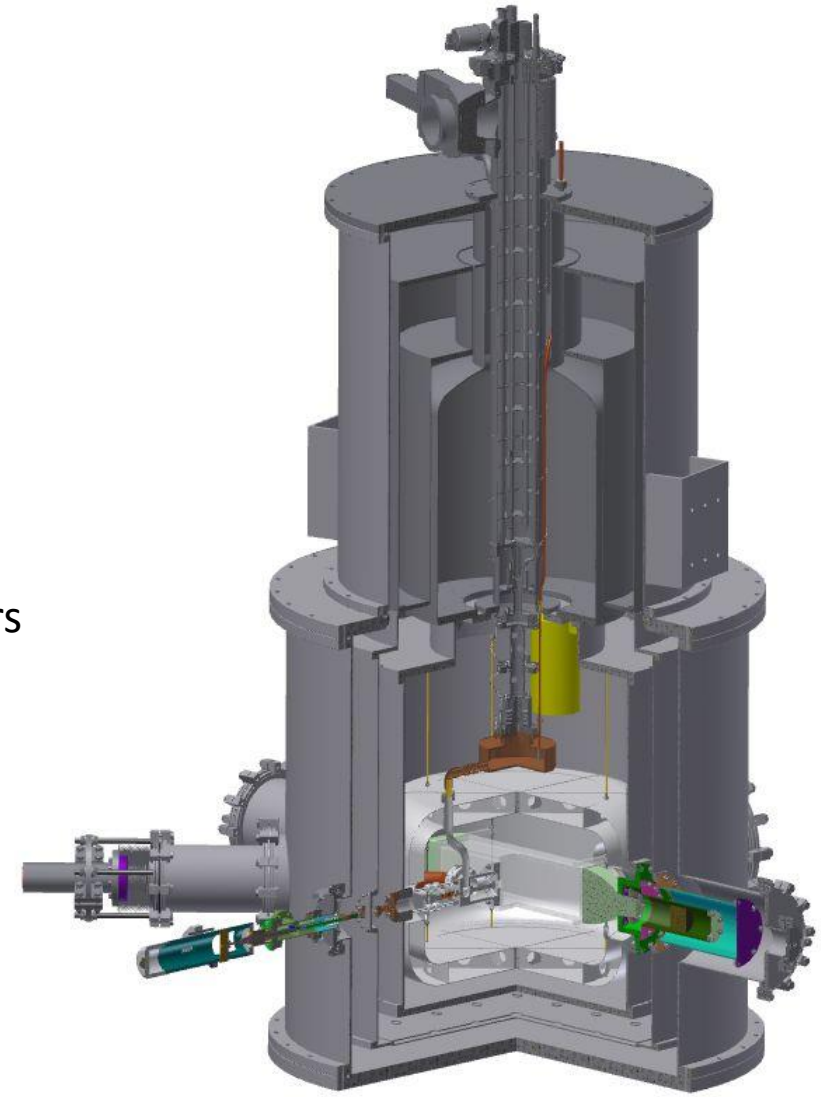
NMR/Spin Dressing pulse optimization

- $\pi/2$ pulses, critical dressing parameters

Cell Storage Studies

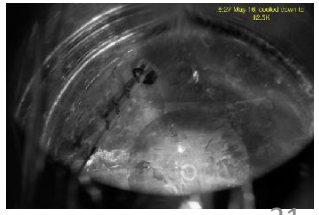
- Determine cell quality prior to implementation into SNS nEDM apparatus.

- Estimated to reduce time to data taking by more than 1 year.



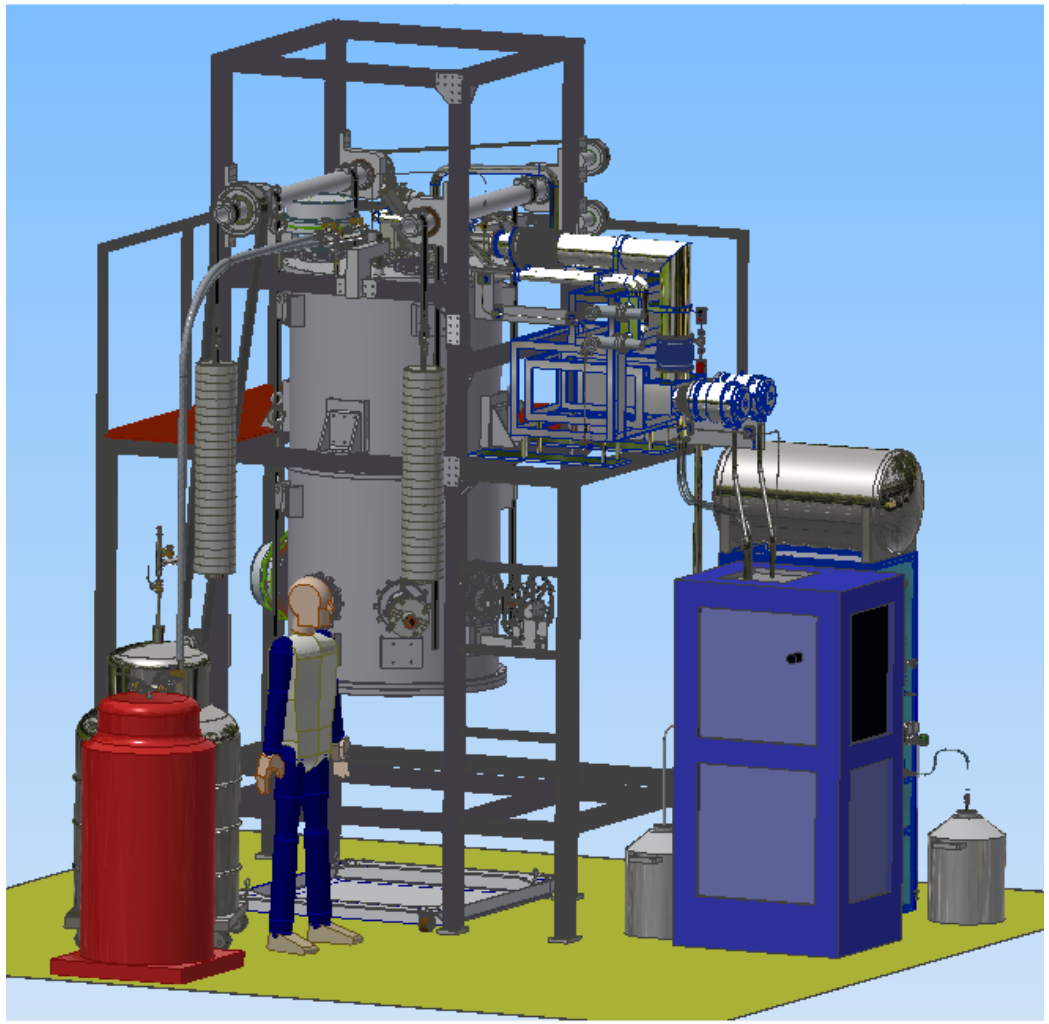
Commissioning

Solid Deuterium Source



Overview

- Test bed for SNS nEDM
- Contains many similar systems to nEDM
- Is being constructed at Triangle Universities Nuclear Laboratory (TUNL) in Durham NC on Duke campus
- Once commissioning is complete, a study of the Correlation Function (Barry Shift) will be conducted with 3He
- The cryostat will then be moved to the PULSTAR reactor on NC State campus, where UCN will be placed inside the measurement cell with polarized 3He



Comparing SOS to nEDM

Similarities

- Experiments conducted at 0.4K
- Nuclear Magnetic Resonance (NMR)
- Superfluid Helium
- Polarized 3He
- Ultra-cold Neutrons (UCN)
- LHe scintillation
- Light collection with Silicon Photomulitipliers (SiPM)
- Superconducting QUantum Interference Devices (SQUIDs)
- Critical spin dressing
- Same size measurement cell

Differences

- No electric field
- Meta-stability optical pumping for polarized 3He (SOS) vs Atomic beam source (nEDM)
- SQUIDs in vacuum (SOS) vs LHe (nEDM)
- Single measurement cell (SOS) vs Two measurement cells (nEDM)
- 1 week to cool (SOS) vs 6 months to cool (nEDM)

SOS Operation

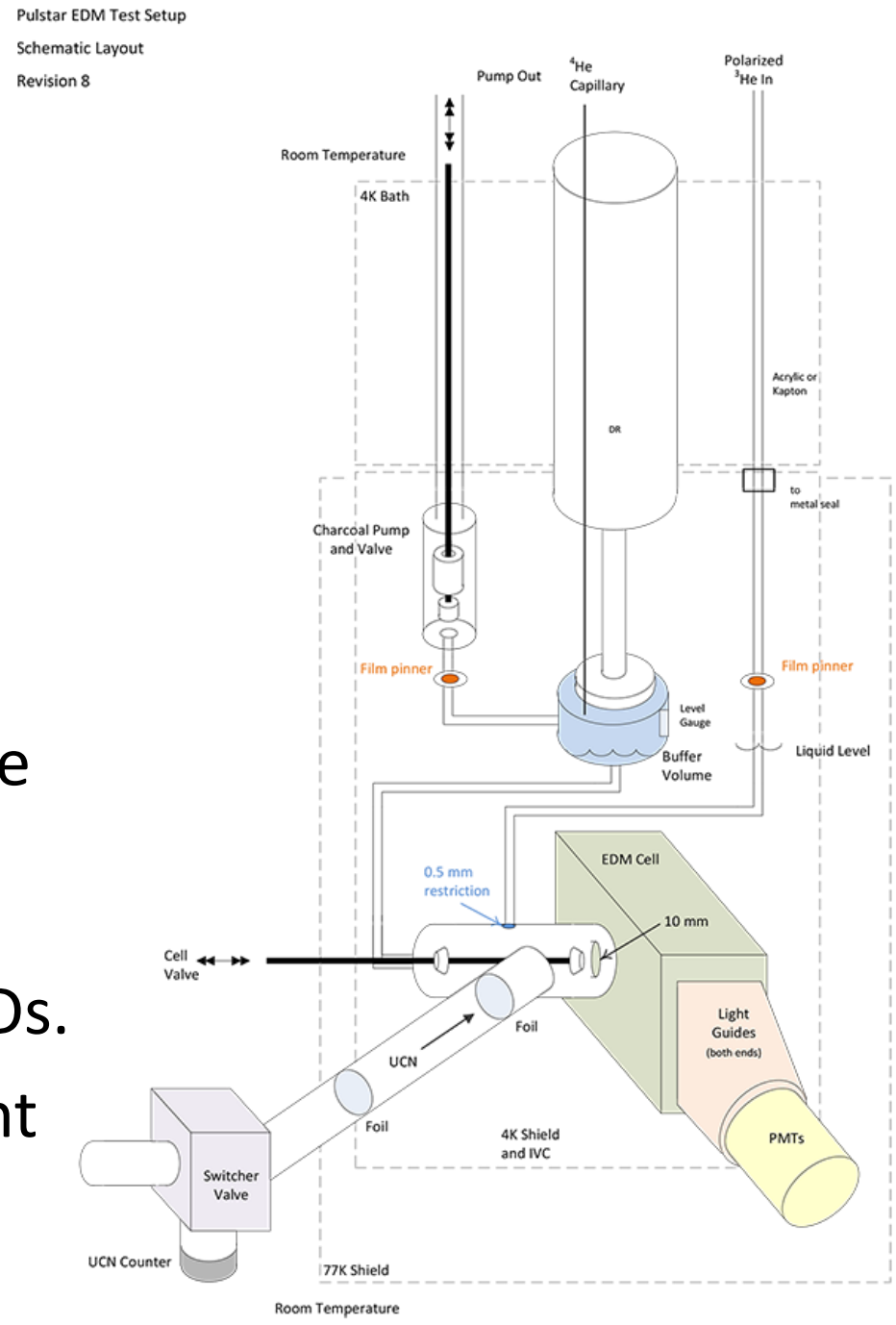
- Measurement cell is filled with 4He at 0.4K
- UCN are delivered from PULSTAR reactor
- Polarized 3He and UCN are placed in measurement cell

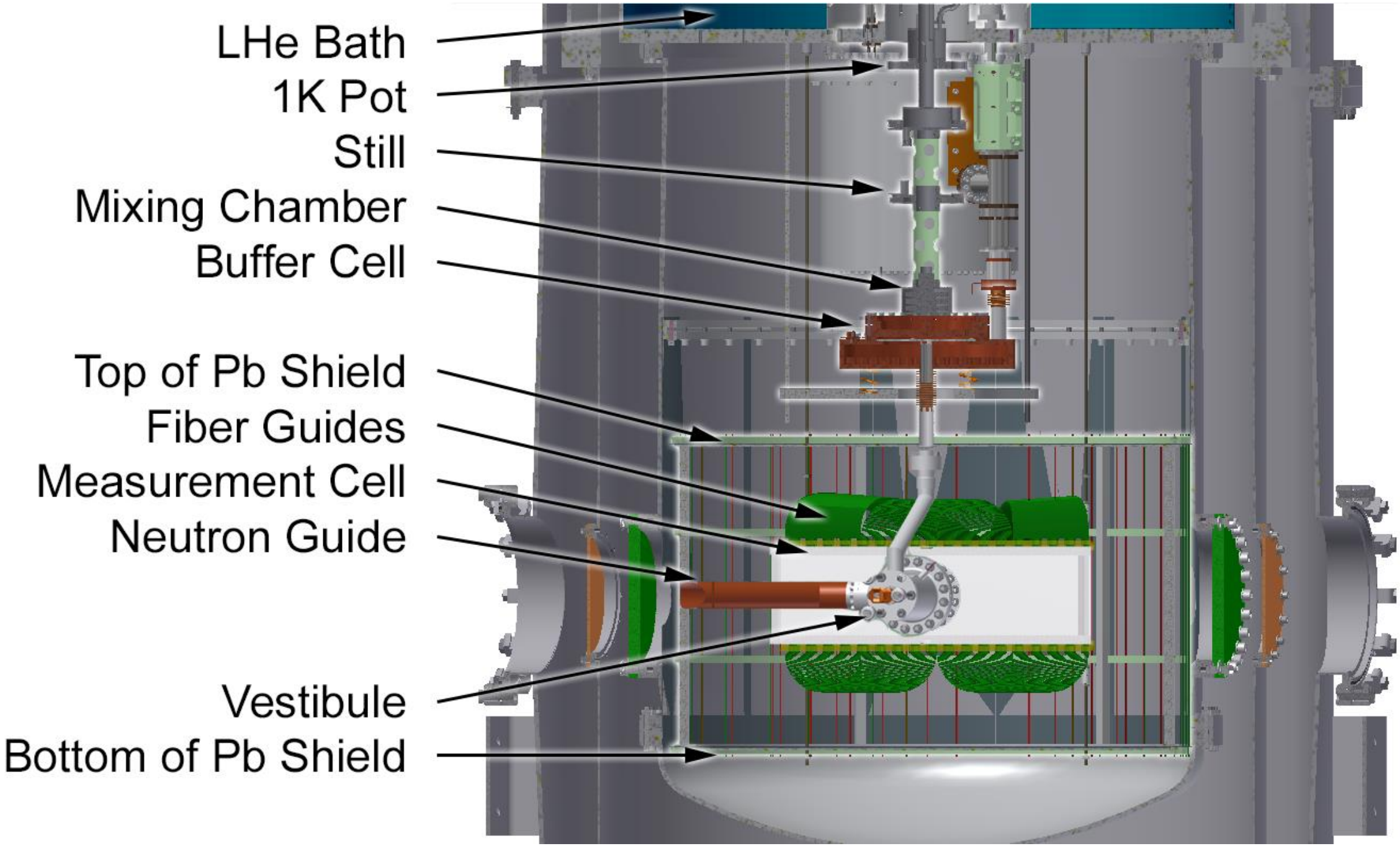
$$3He + n \rightarrow T + p + \gamma$$

- This is a spin dependent interaction with rate

$$S(t) = \frac{\rho_{UCN} V}{\tau_{3He}} (1 - PnP_{3Hecos} \theta_{n.\,3He}(t))$$

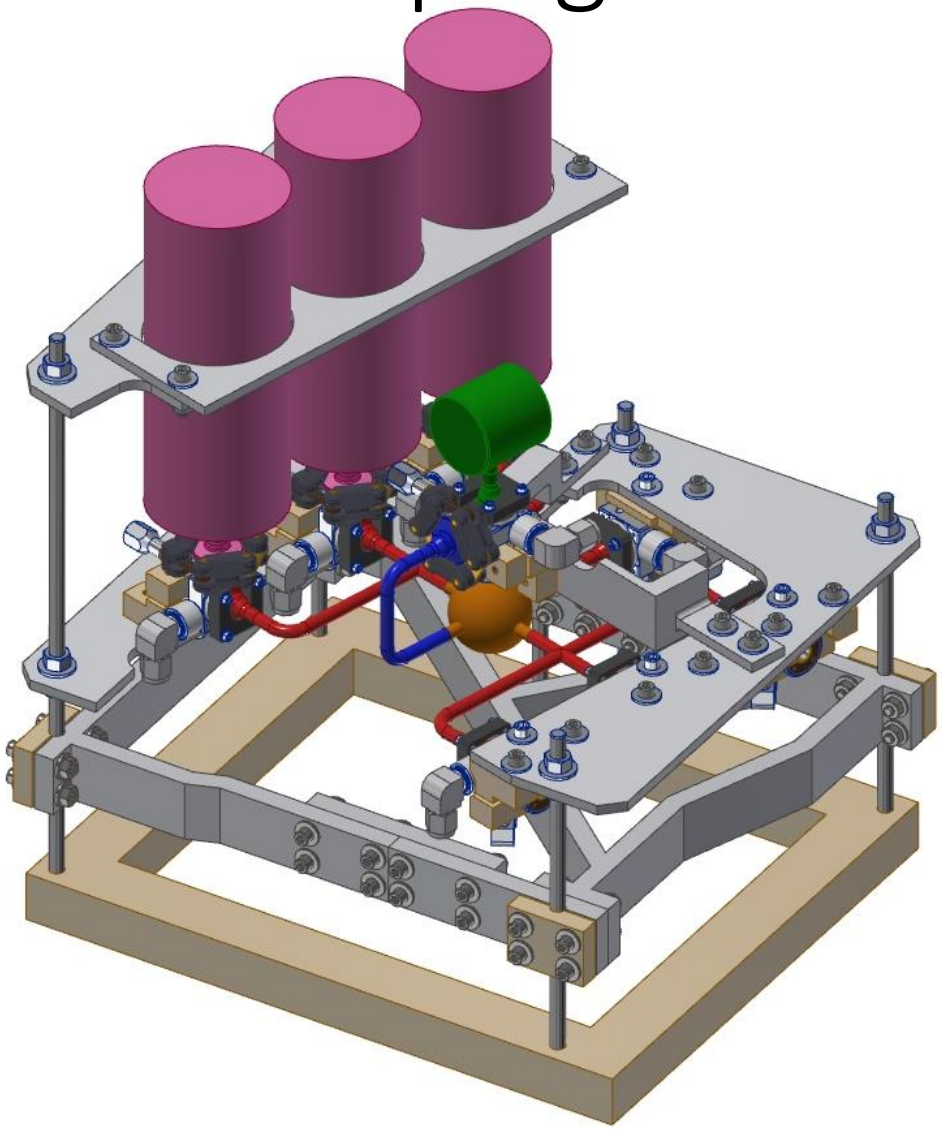
- Orientation of 3He is monitored using SQUIDs.
- Rate of interaction is monitored through light collection.




LHe Bath
1K Pot
Still
Mixing Chamber
Buffer Cell
Top of Pb Shield
Fiber Guides
Measurement Cell
Neutron Guide
Vestibule
Bottom of Pb Shield

MEOP - Meta-stability Optical Pumping

- Polarizes 3He at 1 mbar using electric RF, magnetic field, and laser
- Has three 1 liter dilution volumes for dilution down to desired concentration of [4He:3He] = 10^{-9}
- Polarized 3He friendly valves - ILL design
- Once 3He is polarized and rarified, 4He will be added to increase the pressure (0.5 bar) before being transported to the measurement cell. This will overcome the LHe vapor pressure.



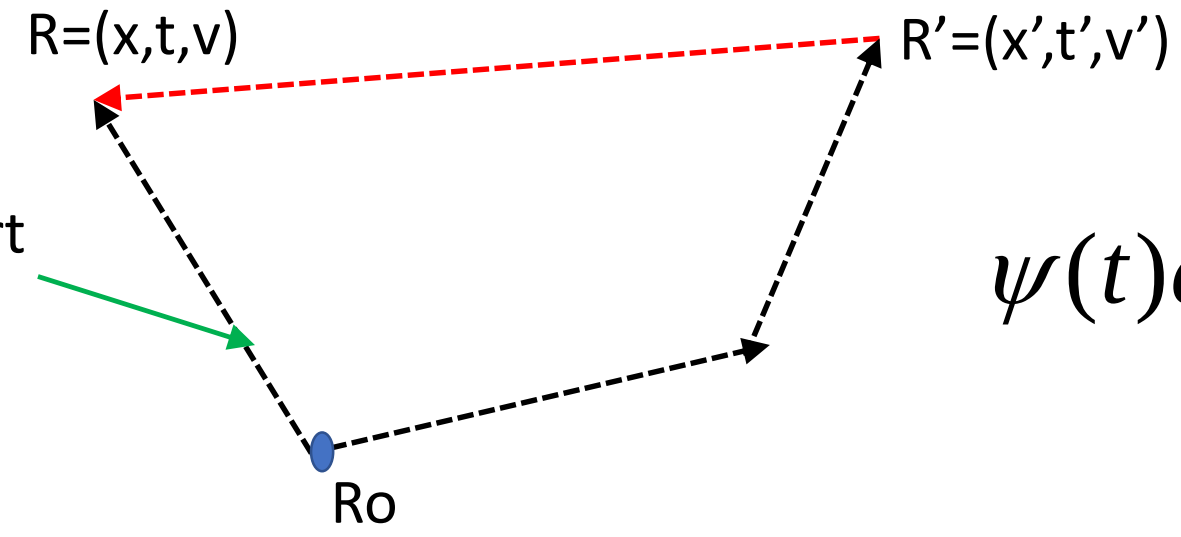
Thermalizing gas collsions

Velocity change kernel

Scattering density

$$\rho(\mathbf{x},t,\mathbf{v}) = \boxed{f(\mathbf{x},t,\mathbf{v})\alpha(\mathbf{v})\psi(t)} + \underbrace{\int d^3\mathbf{x}'dt' f(\mathbf{x}-\mathbf{x}',t-t',\mathbf{v})\psi(t-t')\int d^3\mathbf{v}'\boxed{\beta(\mathbf{v}|\mathbf{v}')}\rho(\mathbf{x}',t',\mathbf{v}')}_{\text{Previous scattering}}.$$

Direct tranport



$\psi(t)dt$ Probability of scattering between t and t+dt

$$\int d^3\mathbf{v}'\beta(\mathbf{v}|\mathbf{v}')\alpha(\mathbf{v}') = \alpha(\mathbf{v}),$$

Condition for thermal equilibrium

$$\psi(t) = \frac{1}{\tau_c} = e^{-t/\tau_c}$$

g(x,t,v)

$$\rho(\mathbf{x},t,\mathbf{v}) = \alpha(\mathbf{v})\boxed{f(\mathbf{x},t,\mathbf{v})\psi(t)} + \alpha(\mathbf{v})\int d^3\mathbf{x}'dt' f(\mathbf{x}-\mathbf{x}',t-t',\mathbf{v})\psi(t-t')\rho(\mathbf{x}',t'),$$

$$p(\mathbf{x},t,\mathbf{v}) = \alpha(\mathbf{v})\boxed{f(\mathbf{x},t,\mathbf{v})\Psi(t)} + \alpha(\mathbf{v})\int d^3\mathbf{x}'dt' \boxed{f(\mathbf{x}-\mathbf{x}',t-t',\mathbf{v})\Psi(t-t')}\rho(\mathbf{x}',t').$$

G(x,t,v)

Convolution

Use Fourier transform

$$\Psi(t) = \int_t^\infty \psi(t)dt$$

Prob of not scattering between t=0 and t

$$g(\mathbf{x}-\mathbf{x}', t-t', \mathbf{v}) = f(\mathbf{x}-\mathbf{x}', t-t', \mathbf{v})\psi\left(t-t'\right),$$

$$G(\mathbf{x}-\mathbf{x}', t-t', \mathbf{v}) = f(\mathbf{x}-\mathbf{x}', t-t', \mathbf{v})\Psi\left(t-t'\right),$$

$$p(\mathbf{q}, s) = \frac{\int \alpha(\mathbf{v}) G(\mathbf{q}, s, \mathbf{v}) d^3\mathbf{v}}{1 - \int \alpha(\mathbf{v}) g(\mathbf{q}, s, \mathbf{v}) d^3\mathbf{v}}.$$

$$p(\mathbf{q}, s) = \frac{\alpha(\mathbf{v}) G(\mathbf{q}, s, \mathbf{v})}{1 - \alpha(\mathbf{v}) g(\mathbf{q}, s, \mathbf{v})}.$$

Single velocity

$$p(q,\omega) = 2\mathrm{Re}\left[\frac{\sqrt{\frac{m\pi}{2kT}}\frac{1}{q}\mathrm{e}^{z^2}\mathrm{erfc}(z)}{1-\sqrt{\frac{m\pi}{2kT}}\frac{1}{q\tau_c}\mathrm{e}^{z^2}\mathrm{erfc}(z)}\right] = 2\mathrm{Re}\left[\tau_c\left(\frac{1}{1-\sqrt{\frac{m\pi}{2kT}}\frac{1}{q\tau_c}\mathrm{e}^{z^2}\mathrm{erfc}(z)}-1\right)\right]$$

$$z(q,s) = \sqrt{\frac{m}{2kT}}\frac{1}{\tau_c}\frac{(1+s\tau_c)}{q}. \quad (s = i\omega)$$

$$S_{xx}(\omega) = \frac{8{L_x}^2}{\pi^4}\sum_{n=1,3\ldots}^{\infty}\frac{p(q_n,\omega)}{n^4},$$

$$q_n = \frac{n\pi}{L_x}. \qquad S_{vv}(\omega) = \omega^2\sum_{n=\mathrm{odd}}\frac{4L_x^2}{\pi^4 n^4}p\left(\frac{\pi|n|}{L_x},\omega\right).$$

Same for 1 ,2 and 3 dimensions

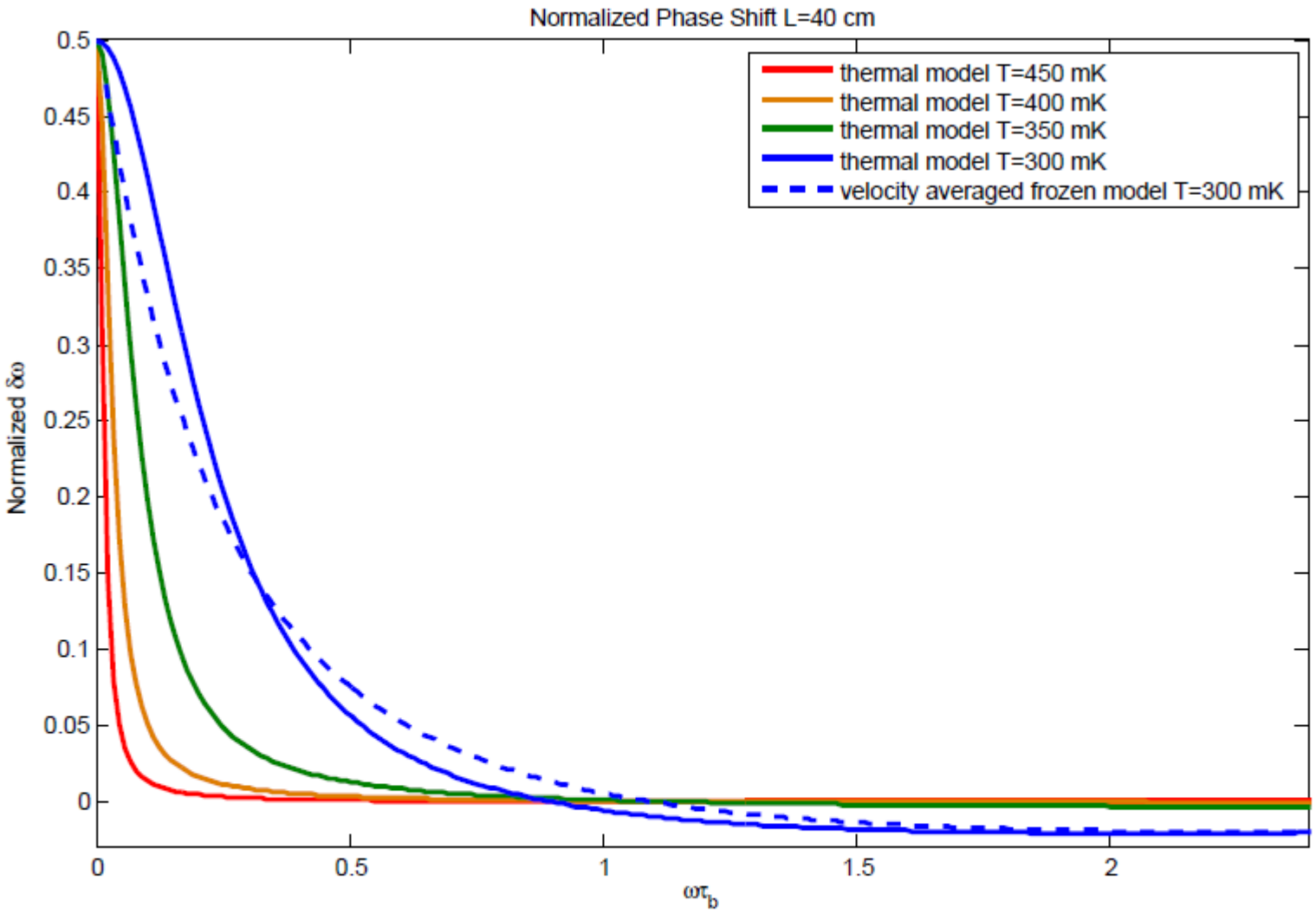


FIG. 7. The normalized spectrum of the linear in E phase shift for dilute ^{3}He dissolved in superfluid ^{4}He, with temperature as a parameter. All the solid curves are derived from the thermalization

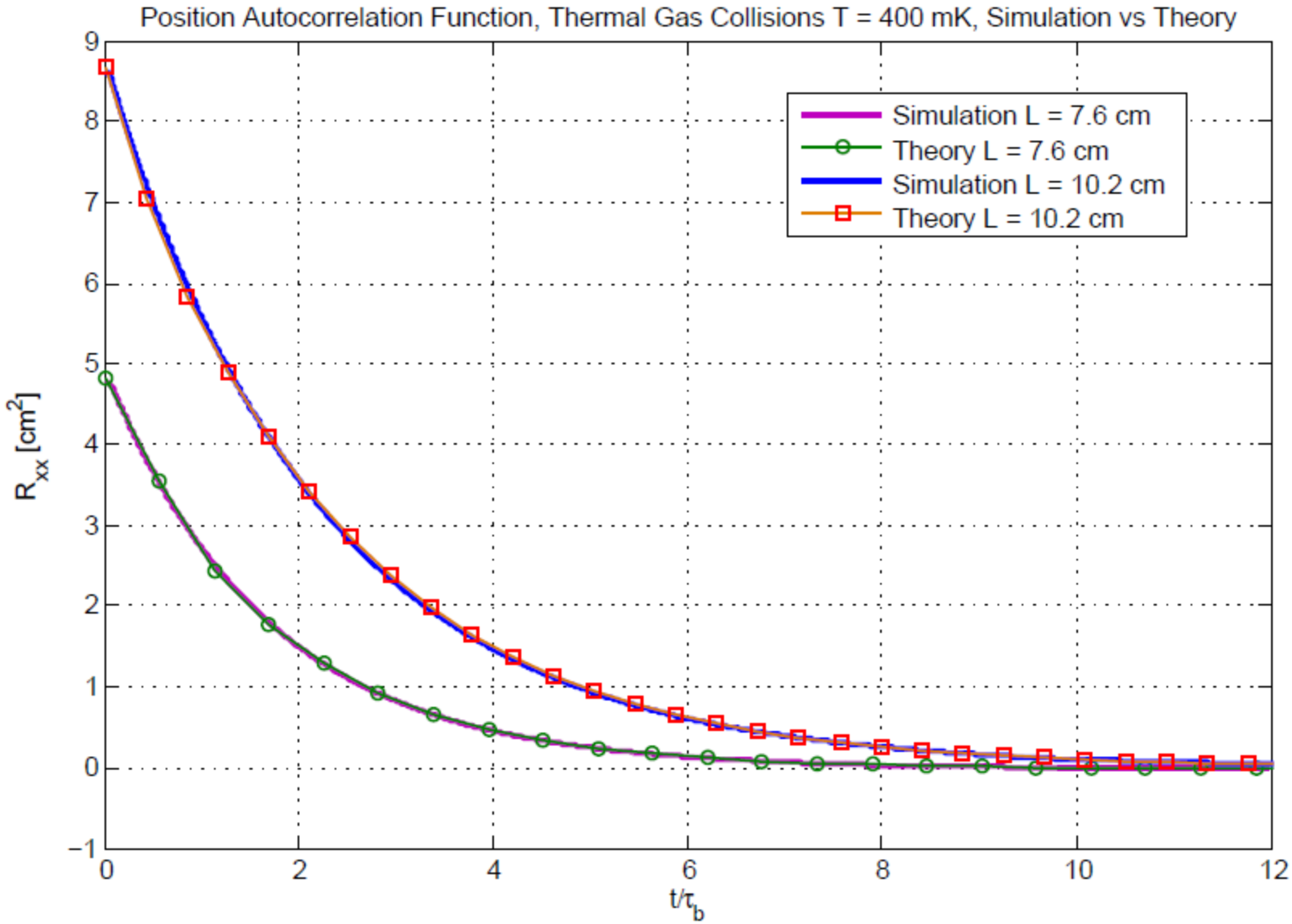


FIG. 10. The position autocorrelation function. The 3D Simulation is compared to thermalizatic theory. Good agreement is observed.

THEORY WITH THERMALIZING COLLISIONS He3