nEDM at SNS

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for the nEDM collaboration

nEDM workshop

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Outline

- Method of the nEDM experiment
- Design of the experiment
- R&D
- Projected sensitivity
- Systematic controls
- Schedule
- Summary

nEDM Experiment Method Overview

Experimental Concept: Golub& Lamoreaux, Physics Reports **237**,1,1994

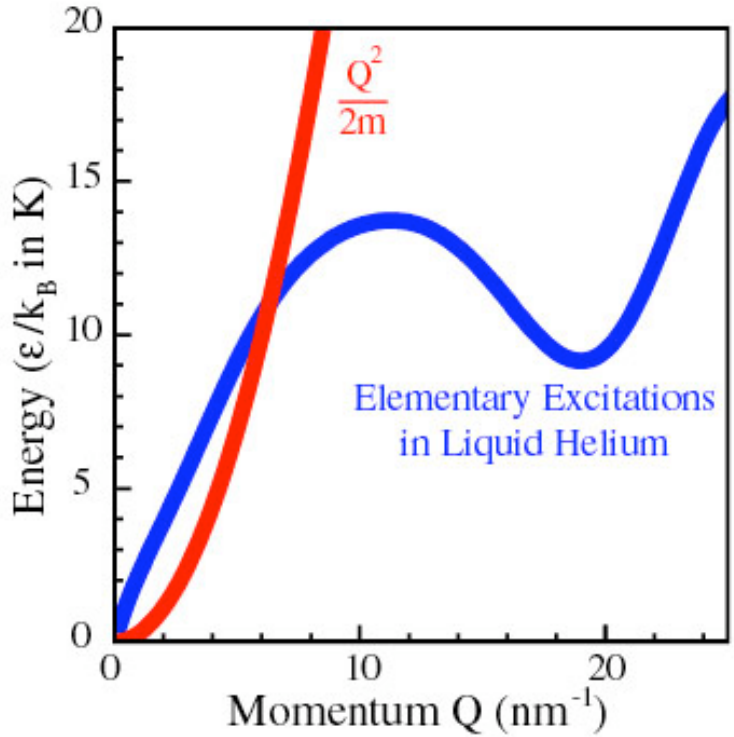
- In situ production of UCN from 8.9 A cold neutron beam via superthermal process
- Higher electric fields expected to be achievable in LHe
- Use of ^{3}He as comagnetometer
- Use of ^{3}He as spin analyzer for the neutron
- Two complementary approaches to looking for the neutron EDM signal (effect of **d•E**)
  - Free precession method
  - Dressed spin method

Two techniques provide critical crosscheck of the EDM results with different challenges and systematics.

Superthermal Production of UCN

R.Golub and J.M.Pendlebury, Phys.Lett.A **62**,337,(77)

- 8.9 Å cold neutrons get down-scattered in superfluid ^{4}He by exciting elementary excitation
- Up-scattering process is suppressed by a large Boltzman factor
- No nuclear absorption



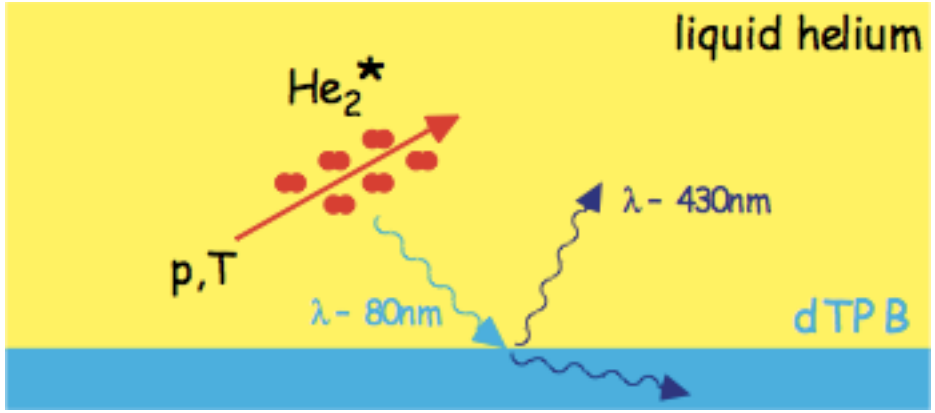
- Expect a production of ~ 0.2-0.3 UCN/cc/s
- With a 500 second lifetime, ρ_{UCN}~100-150/cc and N_{UCN}~3-4x10^5 for each of the two 3 liter cells

Comagnetometer

- We use polarized ^{3}He atoms as comagnetometer.
- A comagnetometer is a polarized atomic species within the same storage volume as the neutrons that provides a nearly exact spatial and temporal average of the magnetic field affecting the neutrons over the storage period.
- Requirements for a comagnetometer:
  - It does not have an EDM of its own.
  - Short diffusion time (rapid sampling of the entire cell)
- ^{3}He as used in this experiment meets both requirements:
  - ^{3}He atomic EDM: $d_{atm}(^3\text{He}) \sim d_{atm}(^{199}\text{Hg})/3000 < 10^{-32}\ e$ cm, Dzuba, et al. PRA 76, 034501 (2007). (See also Stetcu et al., PLB 665, 168 (2008).)
  - ^{3}He diffusion in SFL^{4}He: Lamoreaux et al. Europhys. Lett. 58, 781 (2002)

^{3}He as spin analyzer

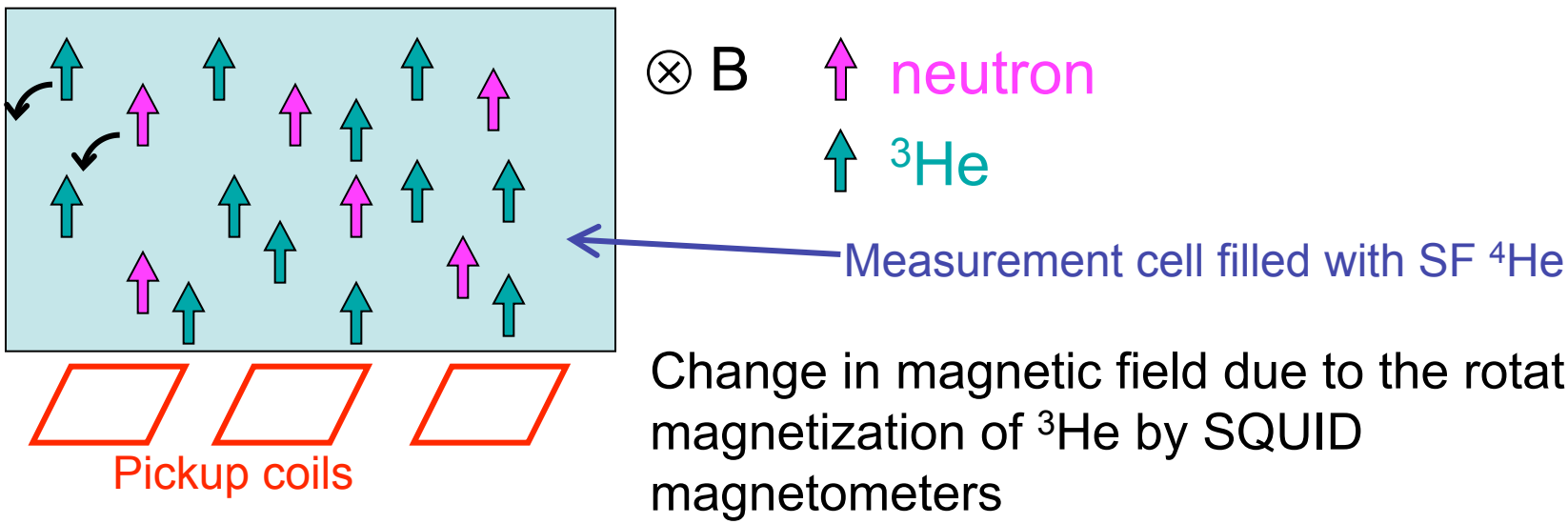
- ^{3}He's gyromagnetic ratio is larger than neutron's by ~ 10% (γ_3/γ_n ~ 1.1)
- Neutron absorption on ^{3}He is highly spin dependent ($\sigma_{\uparrow\downarrow} >> \sigma_{\uparrow\uparrow}$)
  - $n + {}^3He \rightarrow p + t$
- Reaction products of $n + {}^3He \rightarrow p + t$ generates UV scintillation light (80 nm) in LHe.
- The UV light will be downconverted by a wavelength shifter and detected by PMTs.



Spin dependent n-^{3}He absorption reaction provides a measurement of the difference of the neutron precession frequency and the ^{3}He precession frequency.

Free precession method

A dilute admixture of polarized ^{3}He atoms is introduced to the bath of SF ^{4}He ($x = N_3/N_4 \sim 10^{-10}$ or $\rho_{3He} \sim 10^{12}$/cc) as comagnetometer



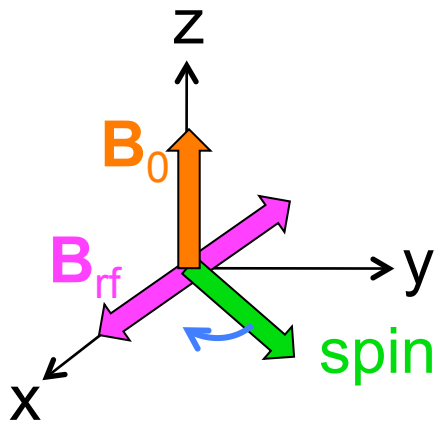
Change in magnetic field due to the rotating magnetization of ^{3}He by SQUID magnetometers

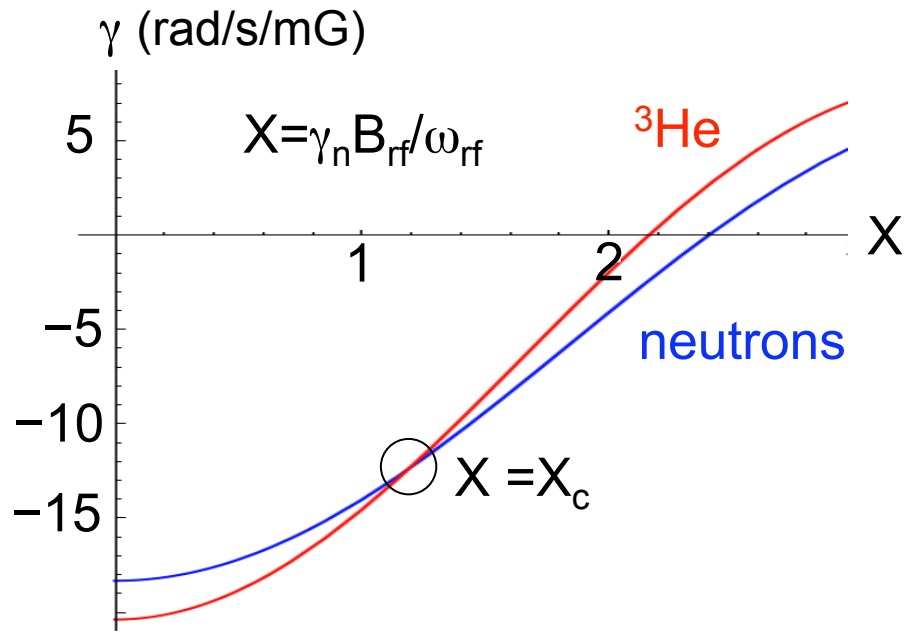
Signature of EDM appears as a shift in ω_3-ω_n corresponding to the reversal of ***E*** with respect to ***B*** with no change in ω_3

3He concentration needs to be adjusted to maximize the sensitivity

- Low concentration ➔ small BR for capture events, weak SQUID signals
- High concentration ➔ short storage time

Dressed spin method





A strong non-resonant RF field

$\mathbf{B_{rf}}$ $\mathbf{B_0}$, $B_{rf} >> B_0$, $_{rf} >>$ $_0$

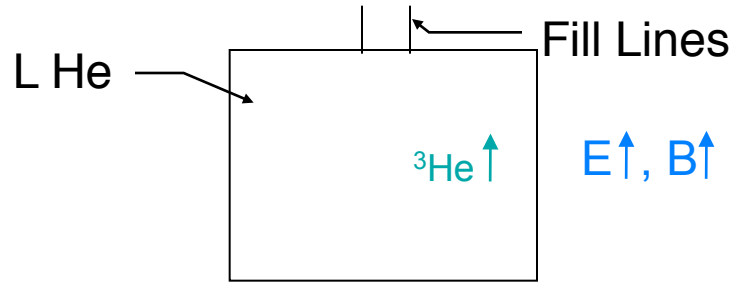
- By applying a strong non-resonant RF field, the gyromagnetic ratio can be modified or "dressed"

$$\gamma' = \gamma J_0\left(\gamma B_{rf}/\omega_{rf}\right) = \gamma J_0\left(X\right)$$

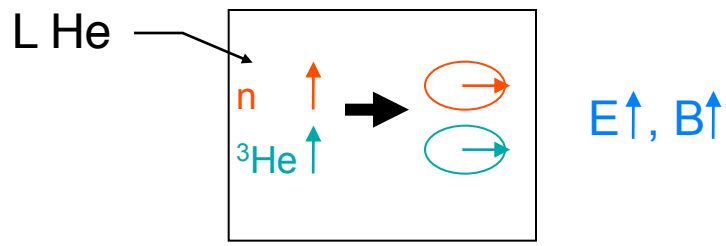
- Can tune the dressing parameter ($X = \gamma_n B_{rf}/\omega_{rf}$) until the relative precession between 3He and neutrons is zero ($X = X_c$).
- Look for X_c dependence on E field
- Provides access to EDM that is independent of variations of the ambient B-field

Experiment Cycle

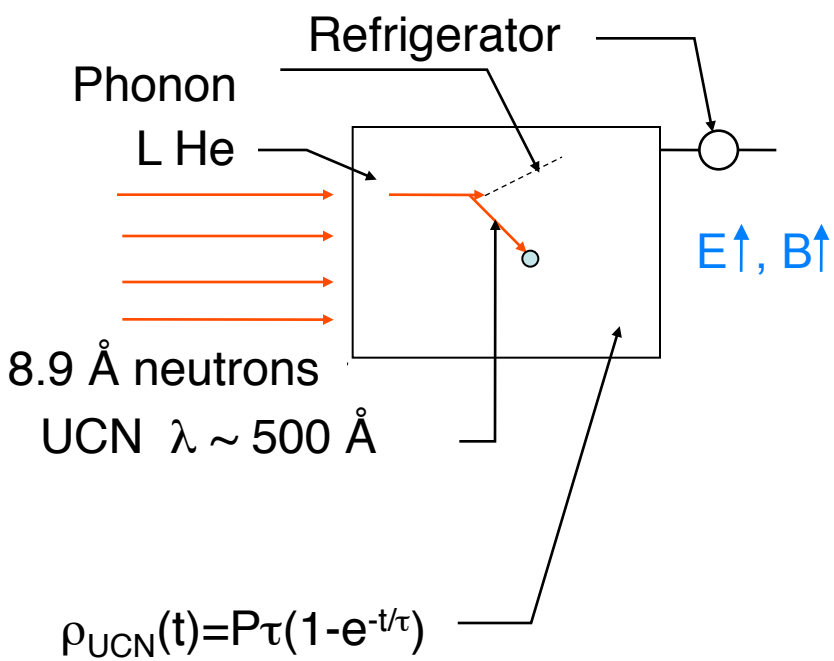
T = 0 - 40 s Fill ^{4}He with $\vec{^3He}$



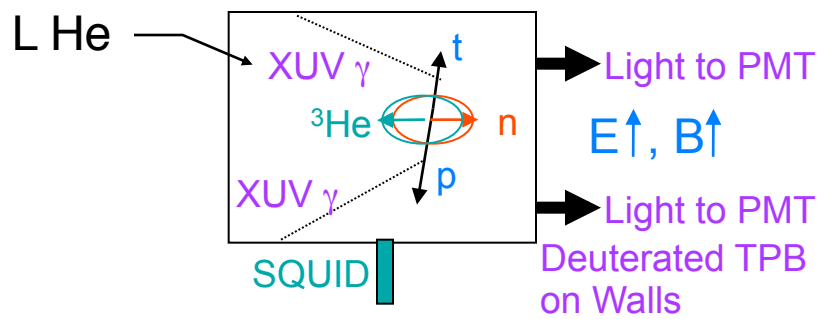
T = 1040 - 1041 s π/2 pulse



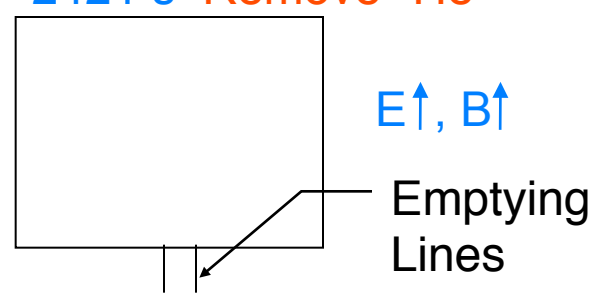
T = 40 - 1040 s $\vec{UCN}$ from Cold n



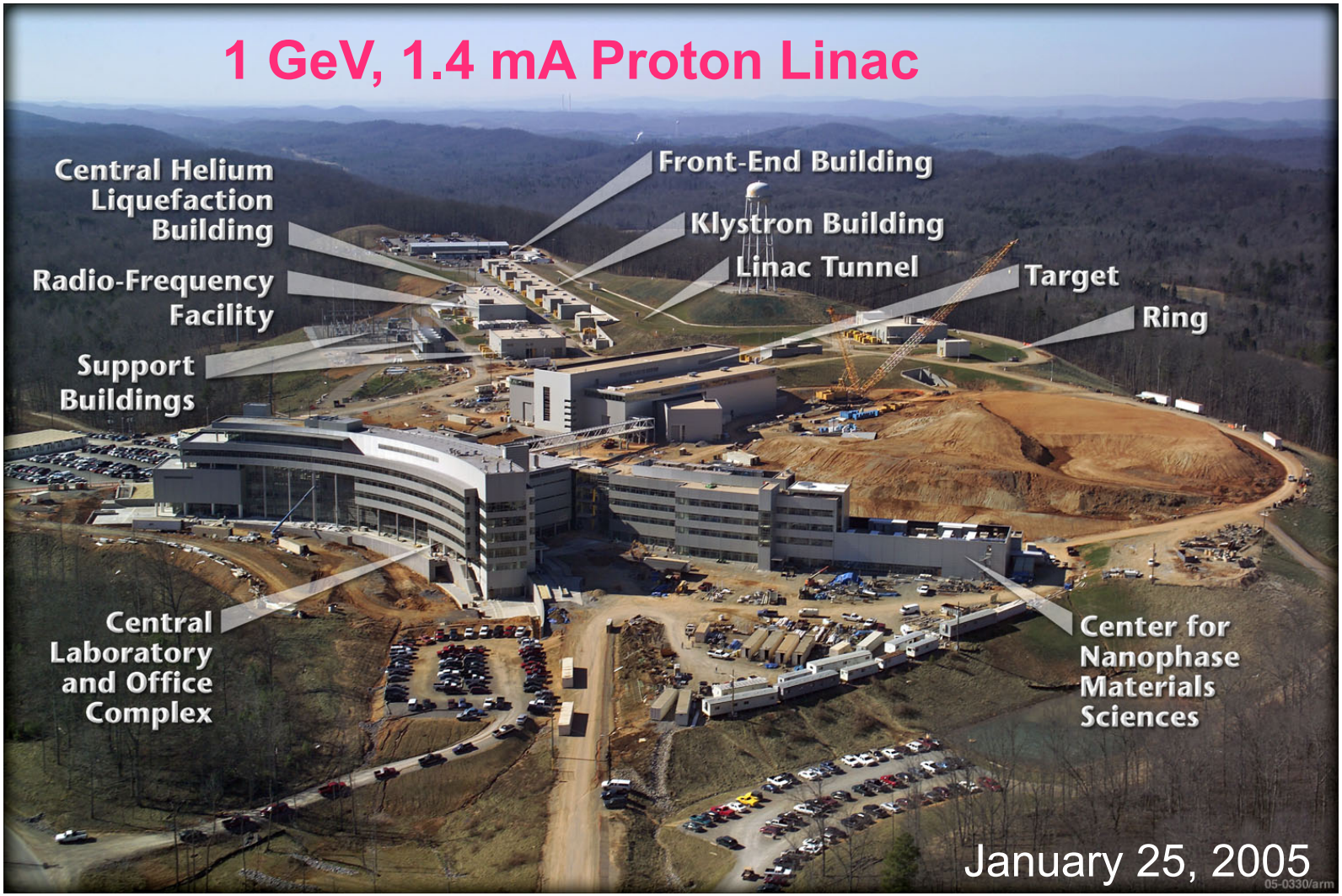
T = 1041 - 2041 s Precession about $\vec{E}$ & $\vec{B}$



T = 2041 - 2421 s Remove ^{3}He

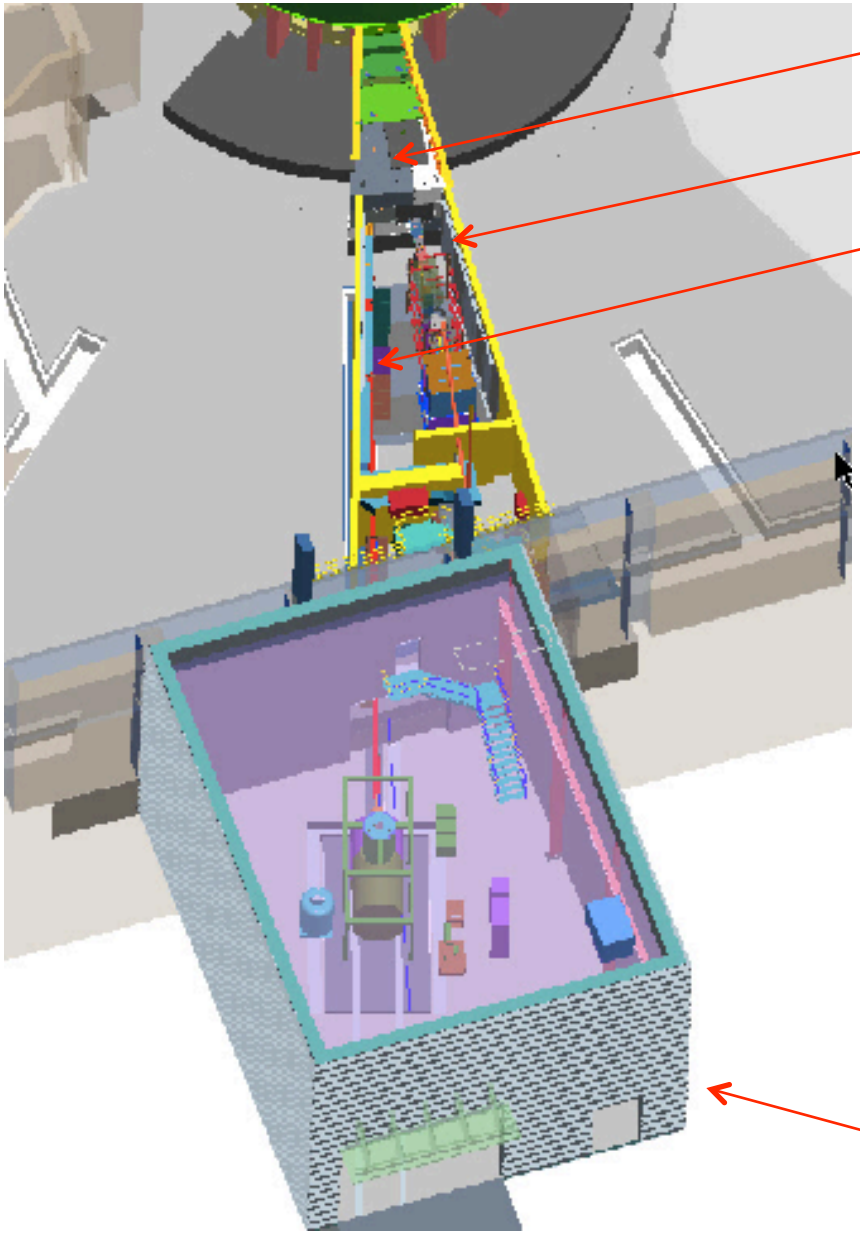


Spallation Neutron Source (SNS) at ORNL



- SNS construction completed: 2006

Fundamental Neutron Physics Beamline (FNPB)



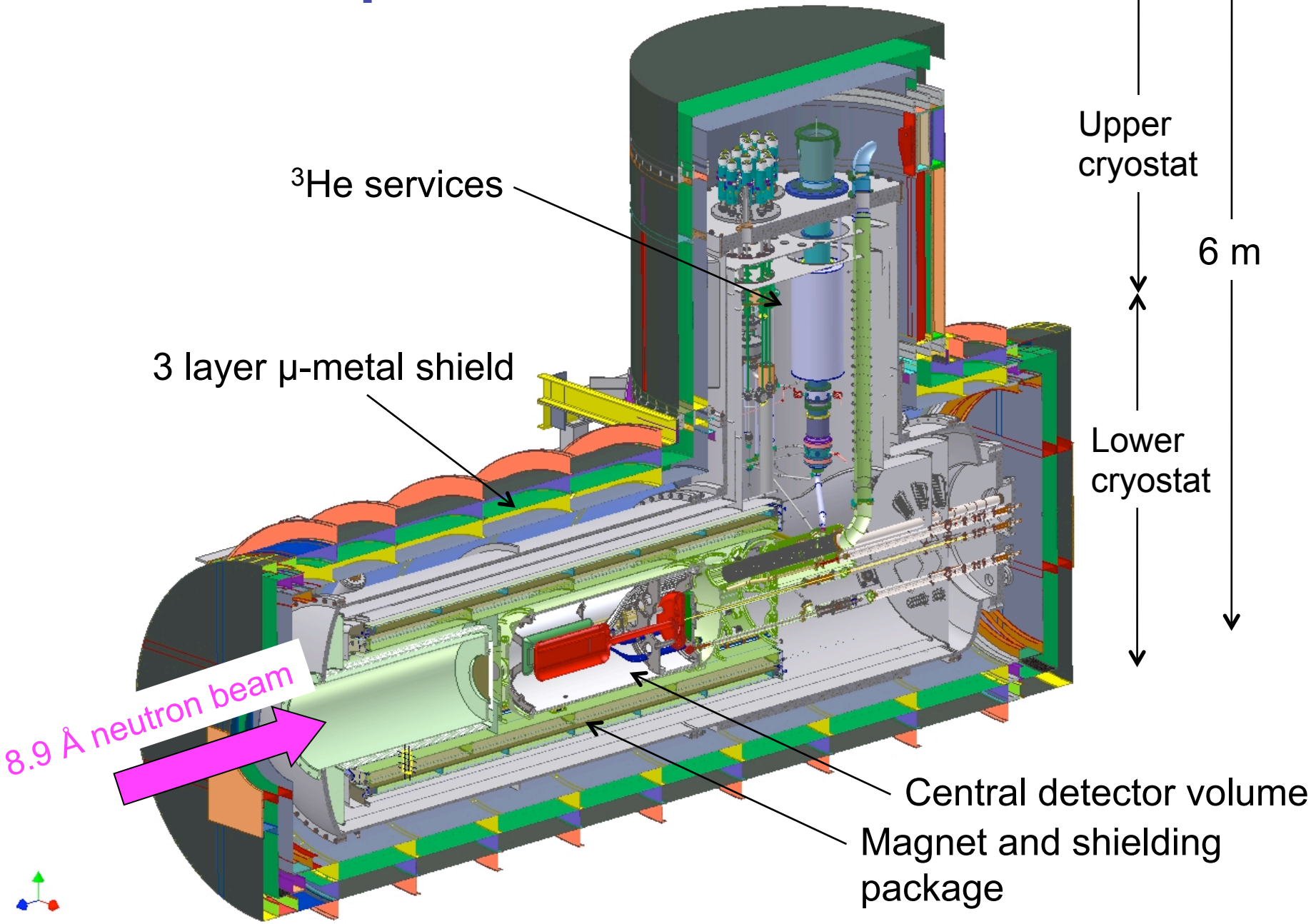
8.9 Å monochrometer

Cold beam line

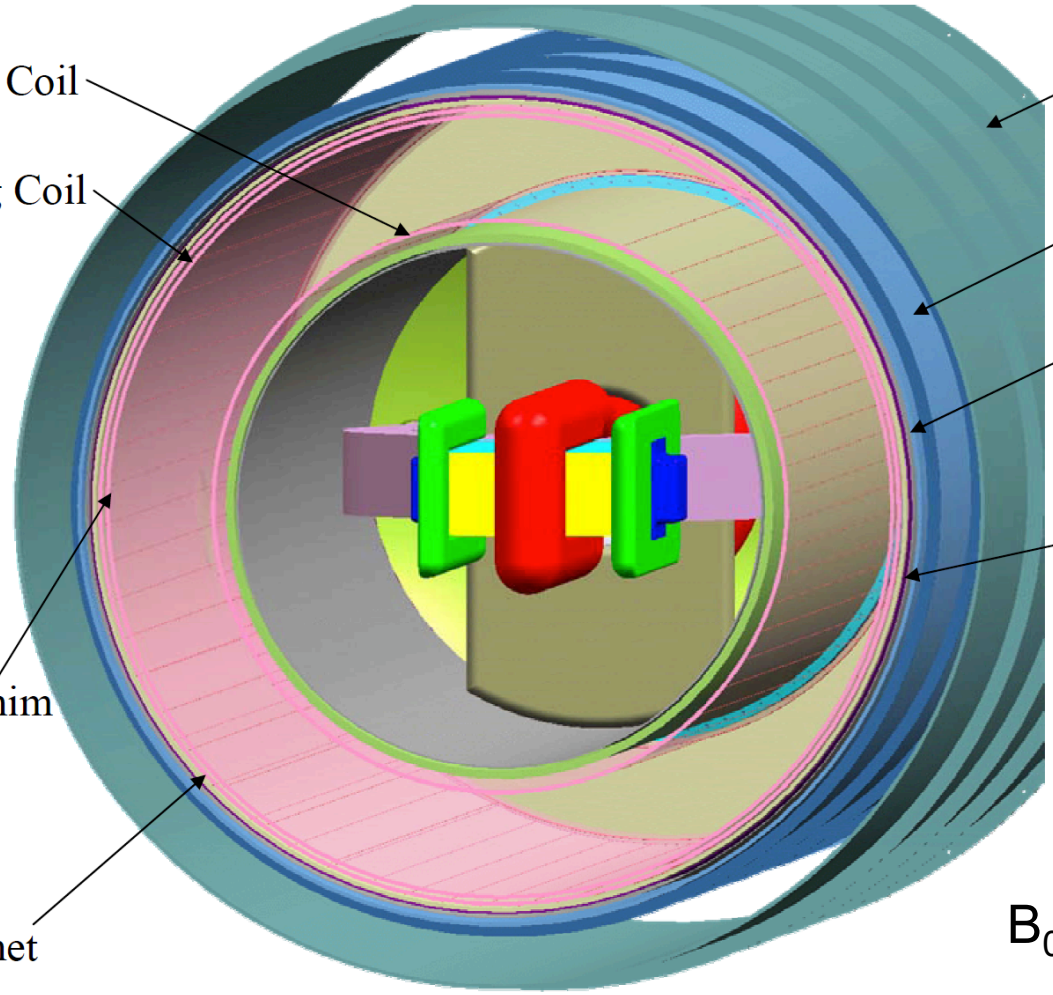
8.9 Å beam line

External nEDM building
(completed Nov 2009)

nEDM Experiment Schematic



Magnet System



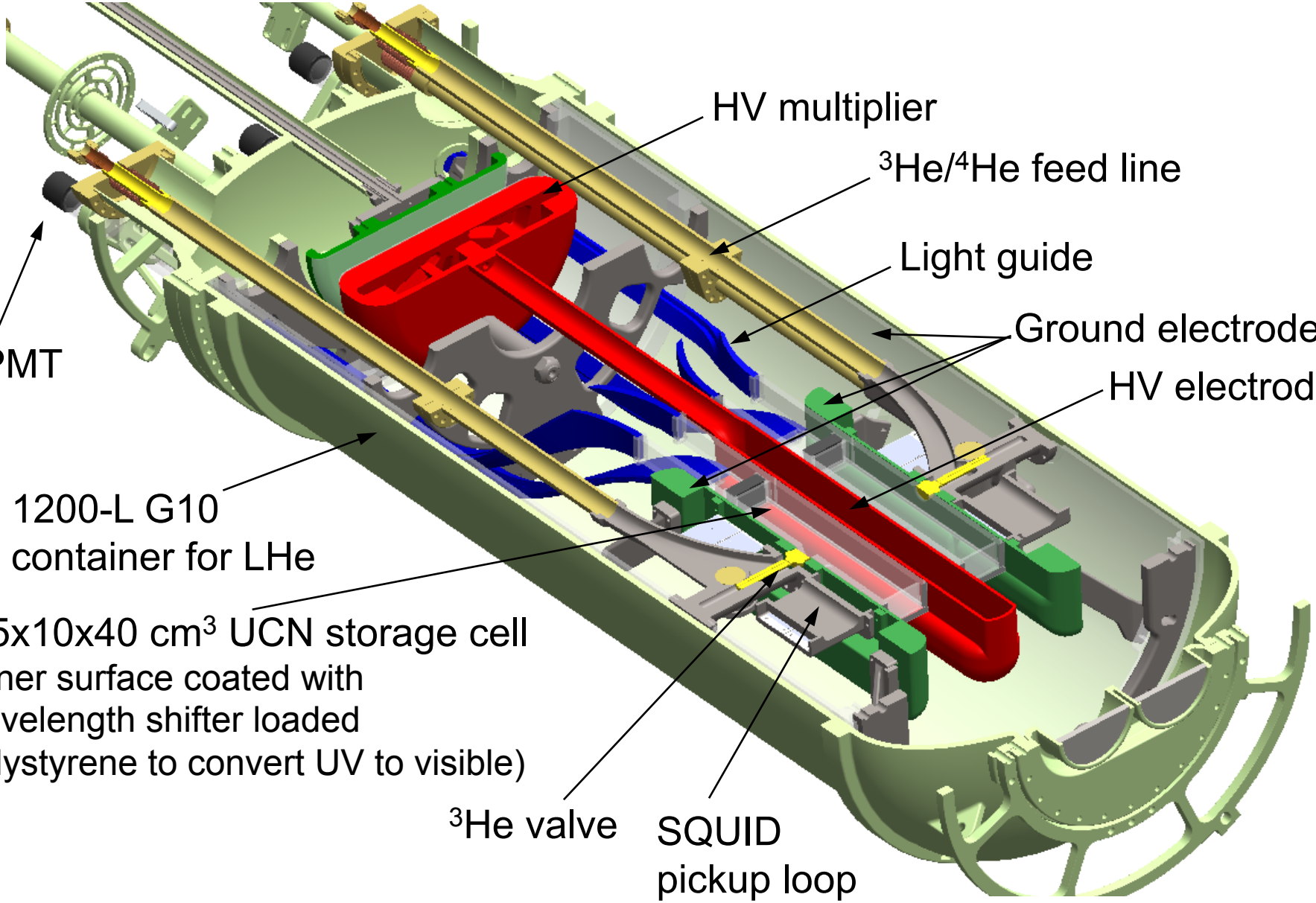
B_0 = 10 - 50 mG

Uniformity requirements:

- Uniformity of 5×10^{-4} from relaxation times for the polarized neutrons and ^{3}He
- $< \partial B_x/\partial x >$ < 0.05 μgauss/cm, $< \partial B_z/\partial z >$ < 0.1 μgauss/cm, $< \partial B_y/\partial y >$ < 0.1 μgauss/cm from geometric phase effects.

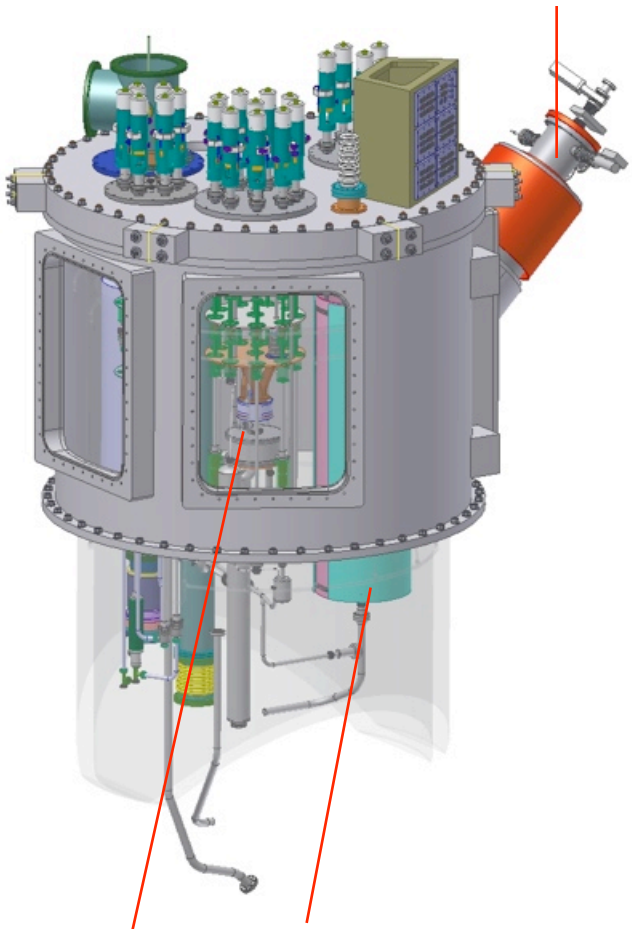
See R. Picker's talk

Central Detector System



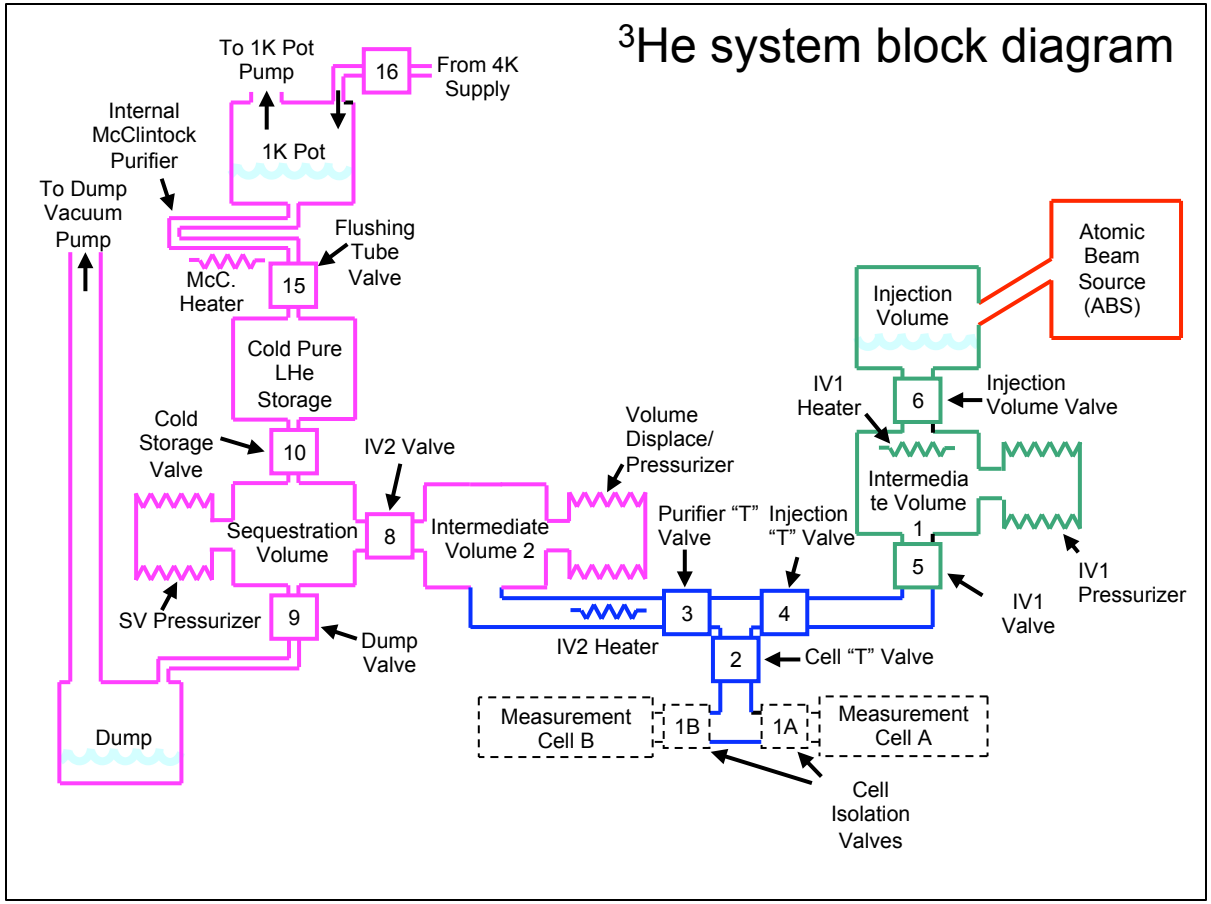
^{3}He Services

Atomic Beam Source



Injection System

Purification System



- Heat flush and diffusion methods is used to move ^{3}He
- ^{3}He flow is controlled by heaters, valves, and pressurizers.

See S. Williamson's talk

R&D

Need R&D in all areas:

- Electric field generation
- Magnetic shielding and magnetic field generation
- 3He injection, transport, and removal
- Signal generation and detection (scintillation & SQUIDs)
- UCN production and storage
- Systematics control and mitigation

Challenges

- Central detector module @ 0.3 –0.45K
- Magnet module @ 4K
- Eddy currents in conductors due to dressing field RF
- Stringent B-field uniformity requirements
- SQUIDs operation near HV
- Materials of cell and ^{3}He transport must maintain neutron & ^{3}He polarization

Selected R&D studies
(Organized according to the related function)

Color coding: BLACK = complete; RED = ongoing

Electric field generation	• HV amplifier and initial HV test • New HV test apparatus • Electrode material selection
Magnetic shielding and magnetic field generation	• 1/7 scale prototype • ½ scale prototype
3He injection and removal	• 3He diffusion coefficient measurement • Development of 3He atomic beam source • 3He wall relaxation time • SF tight 3He valves • Superfluid film burner
Signal generation and detection	• Room temperature light collection test • LHe scintillation in a high electric field • Full scale cryogenic light collection system prototype • Initial SQUID noise test • SQUID gradiometer development and test • MC simulation of scintillation signal
UCN production and storage	• FNPB simulation • UCN storage time measurements
Systematics control and mitigation	• Correlation function measurement • Pulstar Systematics study apparatus

Focused R&D

- HV & electrode material
- Magnetic field uniformity & superconducting magnetic shielding studies
- Light collection from LHe scintillation
- Development of facility at PULSTAR for polarized UCN & ^{3}He test
- ^{3}He transport studies
- Other issues
  - SQUID development and UCN storage studies

HV/Electrode R&D

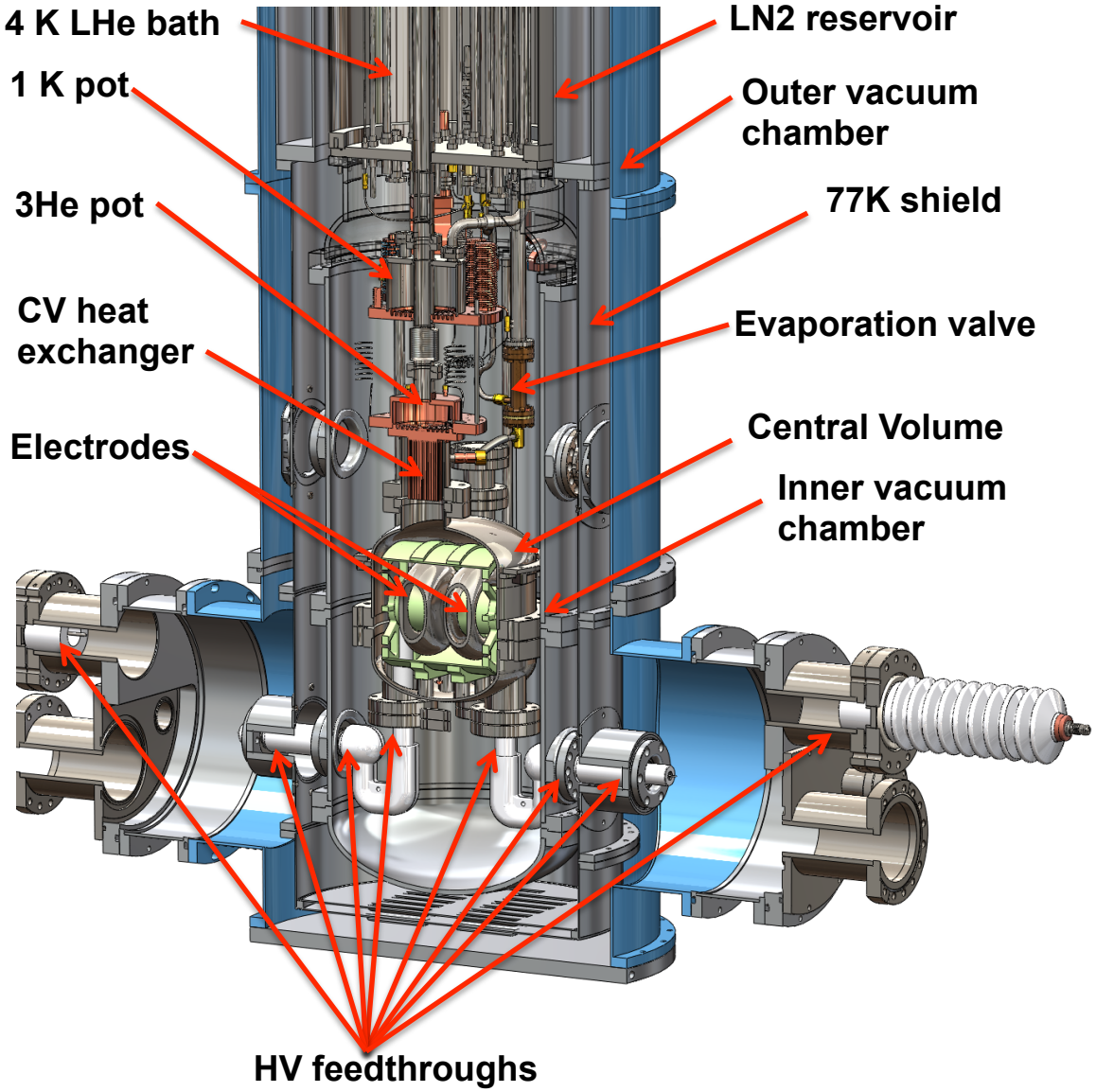
Goal

Demonstrate that a sufficiently high electric field can be established in a region inside an acrylic cell sandwiched between two electrodes in a condition approximating the nEDM operating condition.

Electrode material requirements

- Electrode made of PMMA coated with conductive material
- Electrical resistivity: $10^2\ \Omega/\square < R_S < 10^8\ \Omega/\square$
- Robust to thermal cycling and sparks
- Minimal activation due to exposure to neutron beam.
- Non-magnetic
- Fabrication techniques scalable to large (10x40x80 cm^3) complicated 3D shape

New HV test apparatus @ LANL



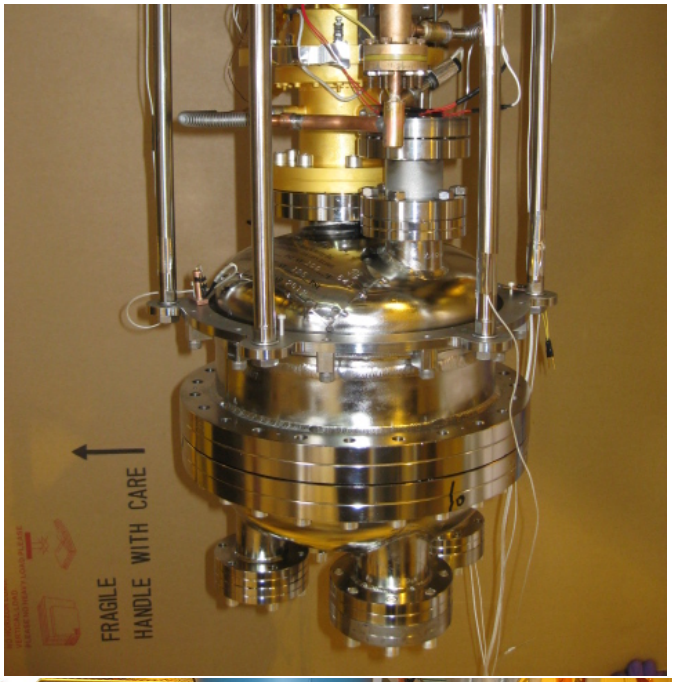
Features

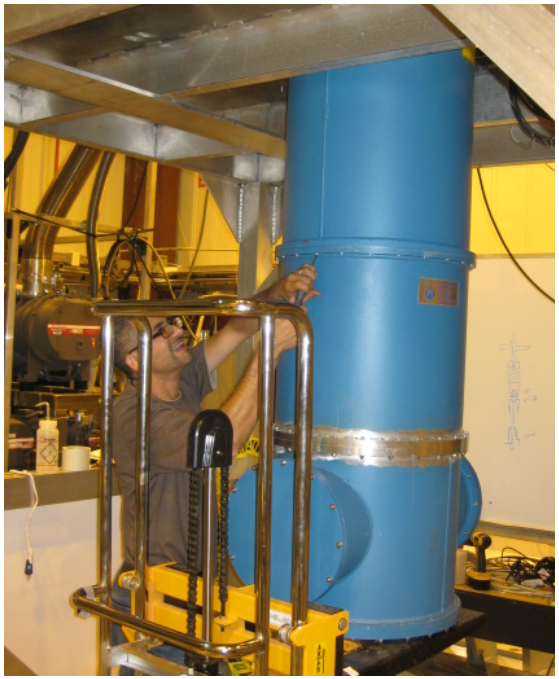
- 6 liter LHe volume is cooled by a 3He fridge
- Electrodes size: ~ 12 cm in diameter
- Electric field: up to 75 kV/cm in 2 cm gap
- Gap size adjustable between 0.5 cm and 2.0 cm
- Lowest temperature: < 0.5 K
- Pressure: variable between SVP and 1 atm
- Turn around time: 2 weeks

Purpose

- To study breakdown field dependence on
  - Temperature
  - Pressure
  - Gap size
  - Electrode material

New HV test apparatus @ LANL





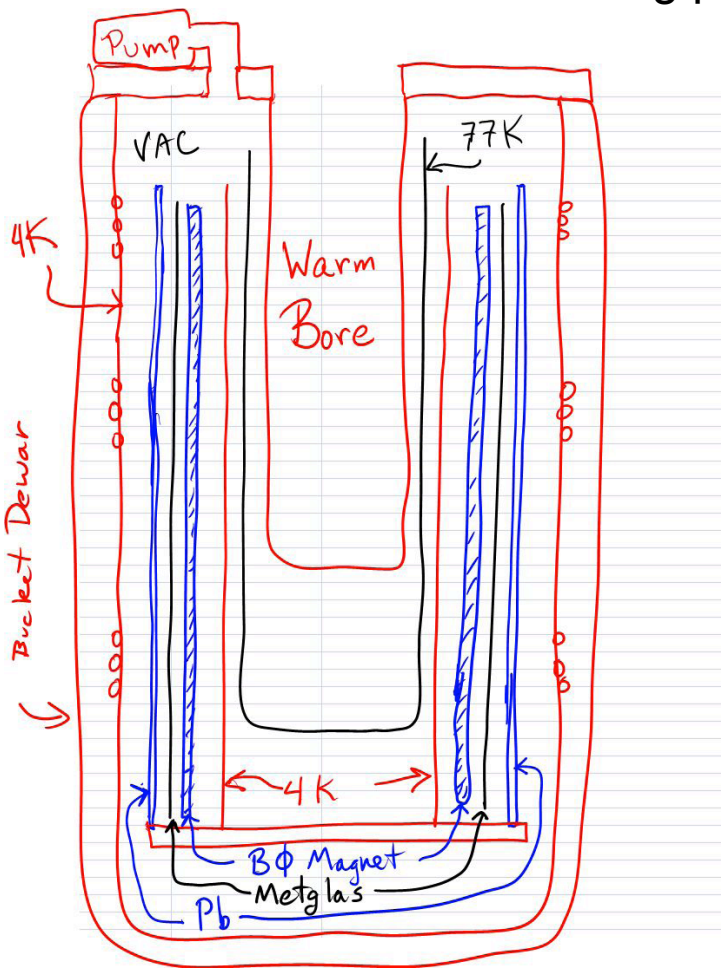
- The first full system cooldown (without HV components) was performed in August 2012.
- The CV was filled with LHe and cooled to 0.42 K.
- The CV LHe pressure was varied between SVP and 1 atm.
- The next cooldown (with the HV components and first electrodes installed) is planned for early November.

See J. Long's talk

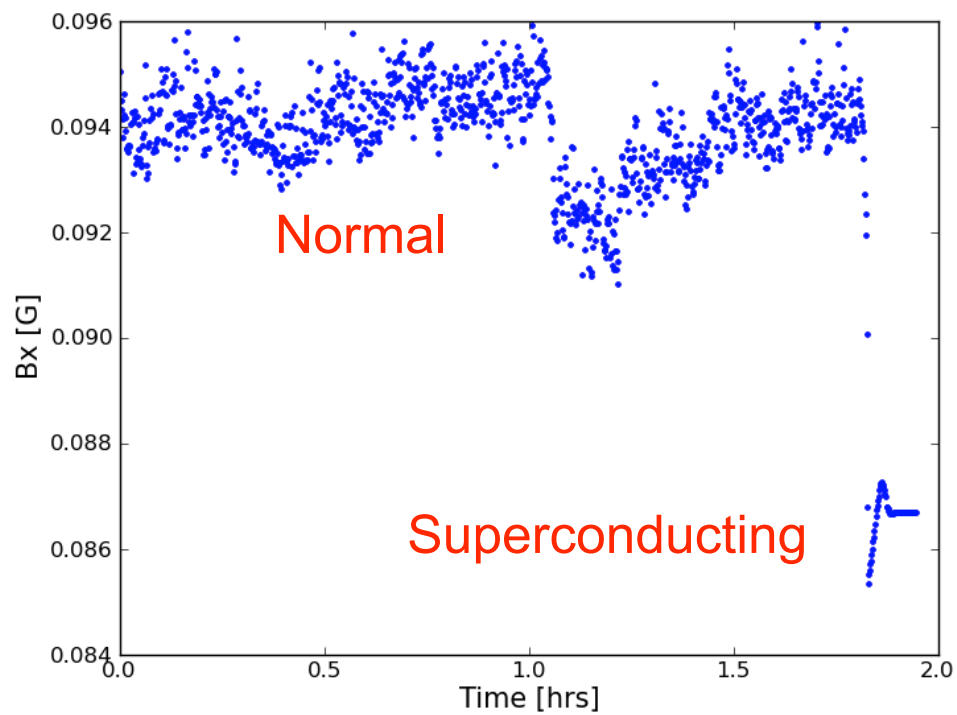
½ B0 magnet and SC shield test @ Caltech

Goals:

- Verity that the required field uniformity can be achieved at the operating field
- Characterize the shielding performance and stability of the SC shield

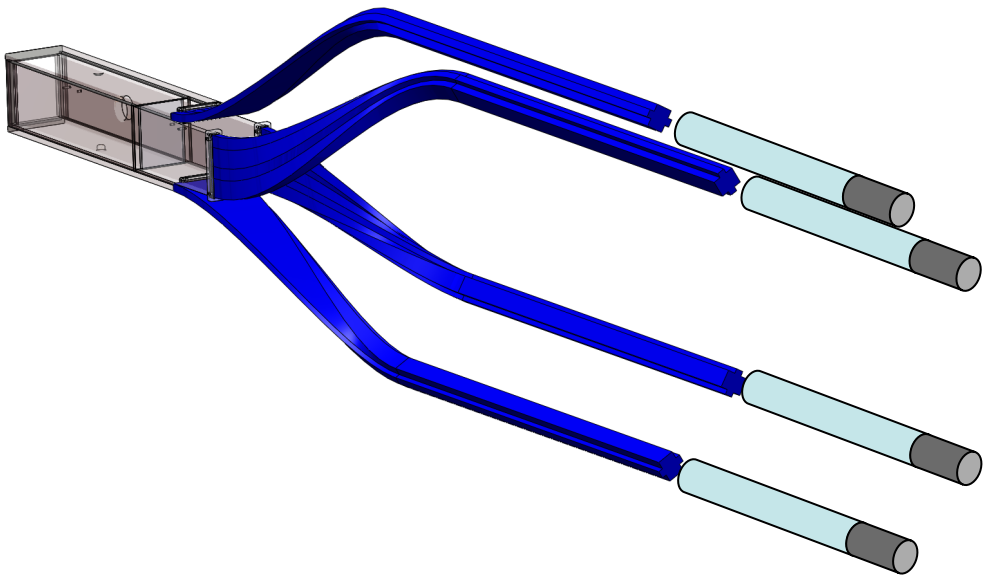


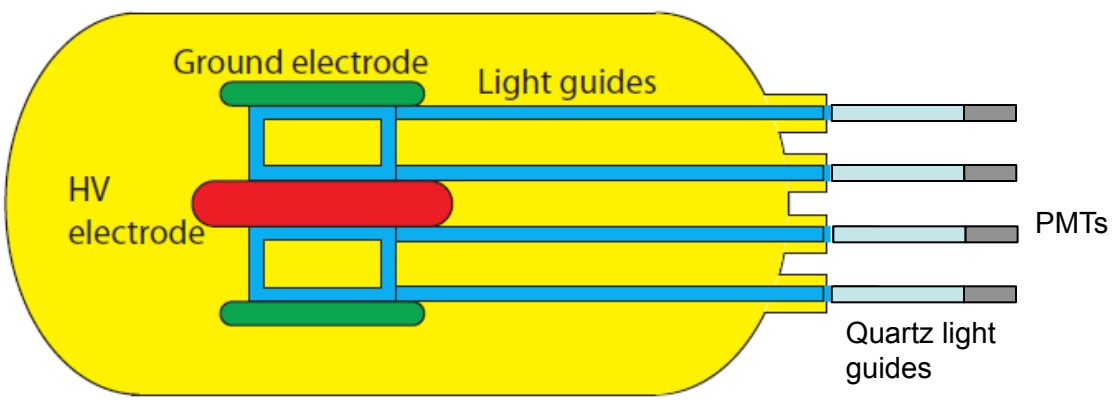
Recent results



See R. Picker's talk

Full scale cryogenic light collection test @ ORNL





Current estimate of the #PE

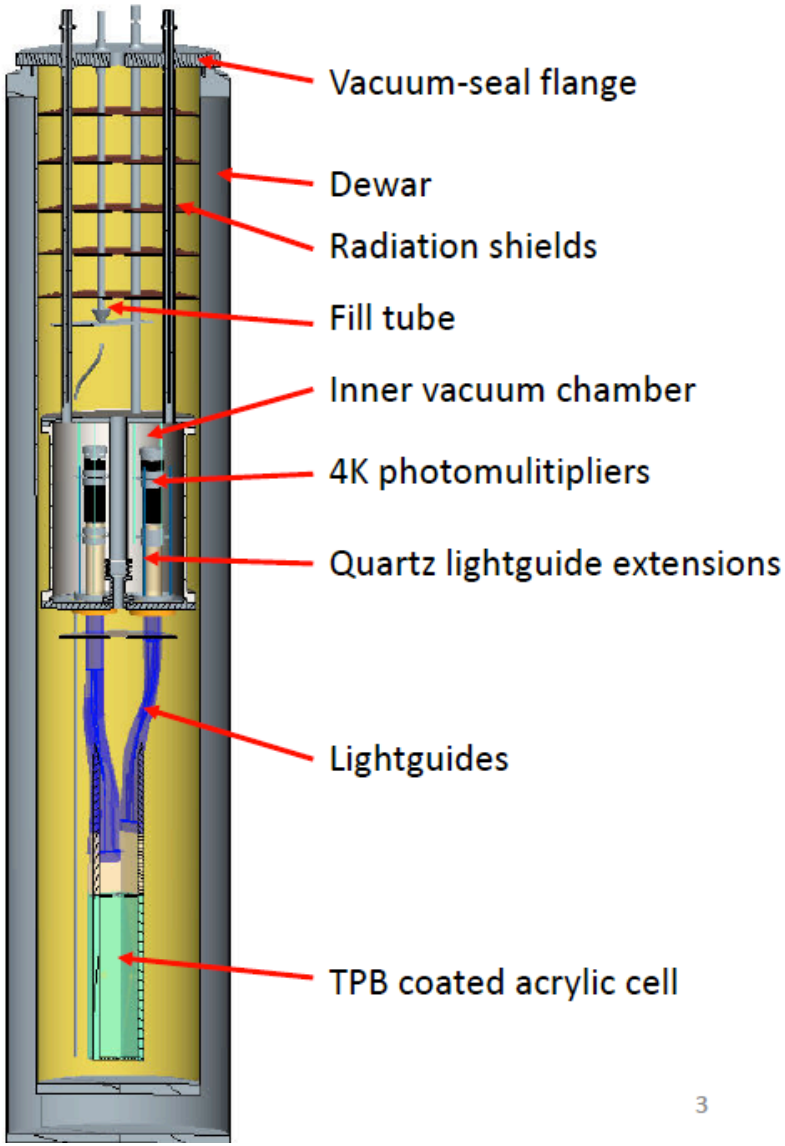
- Based on calculations and measurements of individual loss factors

	Factor	Value	% Error
✓	N_{XUV}	4800	15
✓	ε_{HV}	0.76	5
	$\Omega_{TPB}/4\pi$	0.90	1
✓	ε_{conv}	0.33	19
✓	$\varepsilon_{collect}$	0.21	5
✓	ε_{coated}	0.92	5
	$\varepsilon_{endcaps}$	0.87	1
	ε_{holes}	0.97	10
	ε_{gaps}	0.78	5
✓	g_{AR}	1.05	4
✓	$\varepsilon_{straight\text{-}guide}$	0.64	3
✓	ε_{bend}	0.88	10
✓	ε_{PMT}	0.18	10
	#PE	**14.8**	**32**

✓ Directly measured

✓ Indirectly measured

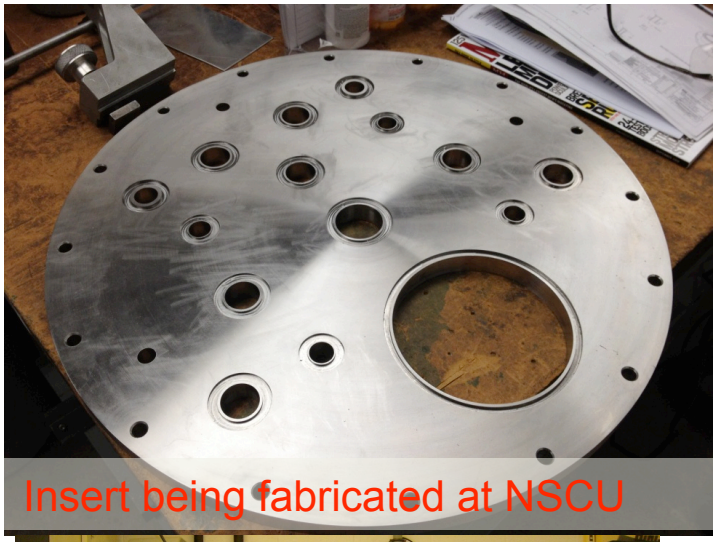
Full scale cryogenic light collection test @ ORNL



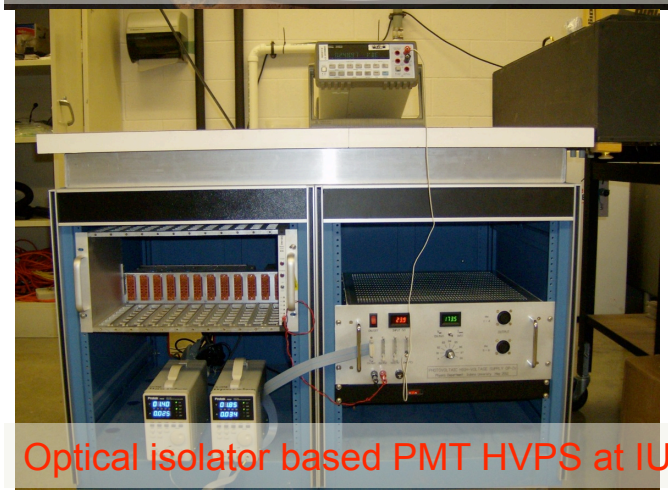
- Goal: demonstrate that there is a sufficiently high number of PE's for neutron capture events
  - Cross check the estimate made based on calculations and measurements of individual loss factors
- Hardware under construction
- First results anticipated near the end of this year.

Full scale cryogenic light collection test @ ORNL

Dewar @ ORNL passed leak test, measuring heatload.



Insert being fabricated at NSCU

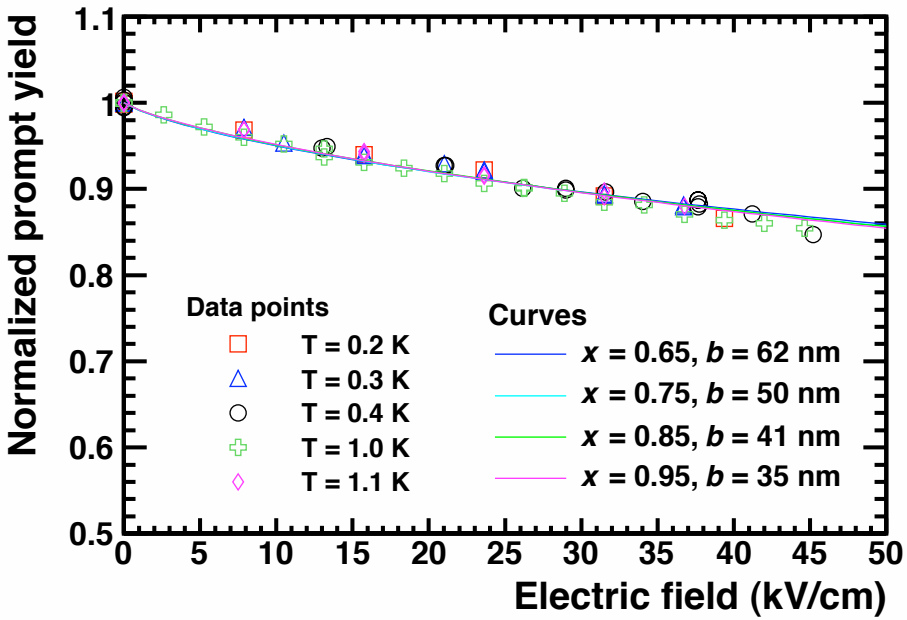


Optical isolator based PMT HVPS at IU

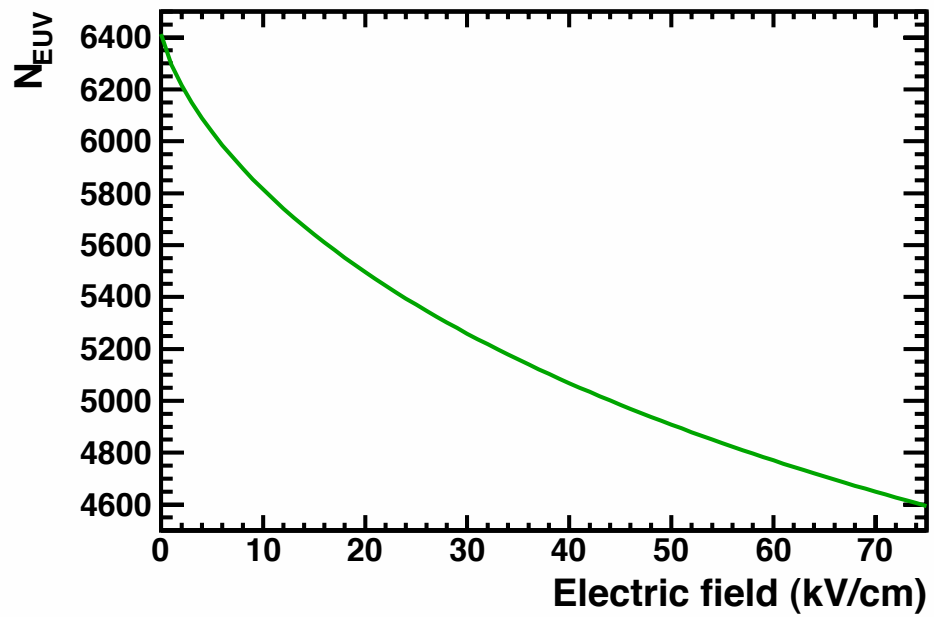
Liquid helium scintillation in an E field (LANL, IU, Brown)

T. M. Ito et al., Phys. Rev. A **85**, 042718 (2012)

Data taken with α particles



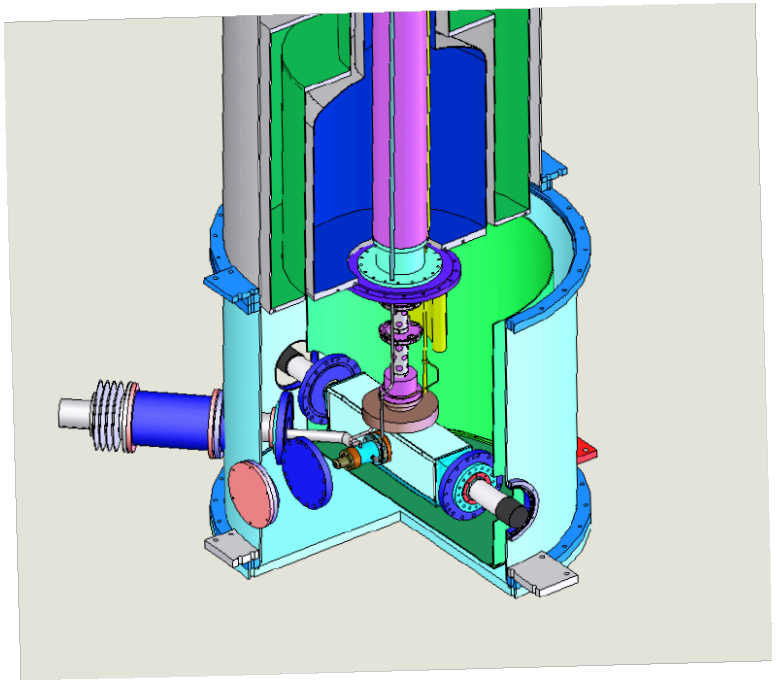
Model prediction for n capture



- The scintillation yield reduces by ~ 15% @ 50 kV/cm.
- The data can be well described by the Jaffe-Kramers columnar theory of recombination (G. Jaffe (1913), H. A. Kramers (1952)).
- The data were used to make a prediction on N_{Euv} for $^3He(n,p)^3H$.

Systematics study apparatus @ NSCU PULSTAR reactor

- A system that consists of a single full size measurement cell at the nEDM operating temperature.
- Long term goal: address key scientific issues
  - Critical dressing
  - Geometric phase studies
  - Spin manipulation studies
- Short term goal
  - UCN storage in the cell
  - Insert and removal of 3He

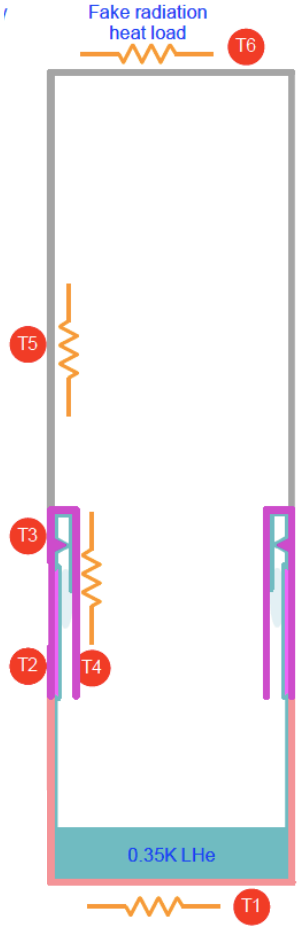


See C. Swank's talk

SF film control test @ Harvard

- SF film need to be controlled for efficient 3He injection into LHe
- Performance of film burner is difficult to model ➔ a test is needed to prove a given design
- First phase of the test complete

Phase 1 test assembly on DR before IVC installation



See S. Williamson's talk

SQUIDs for ^{3}He Co-magnetometer Readout

$$d_n = \frac{\hbar}{2E}\left[2\pi(f_s^{\uparrow} - f_s^{\downarrow}) - \frac{(\gamma_3 - \gamma_n)}{\gamma_3} 2\pi(f_3^{\uparrow} - f_3^{\downarrow})\right]$$

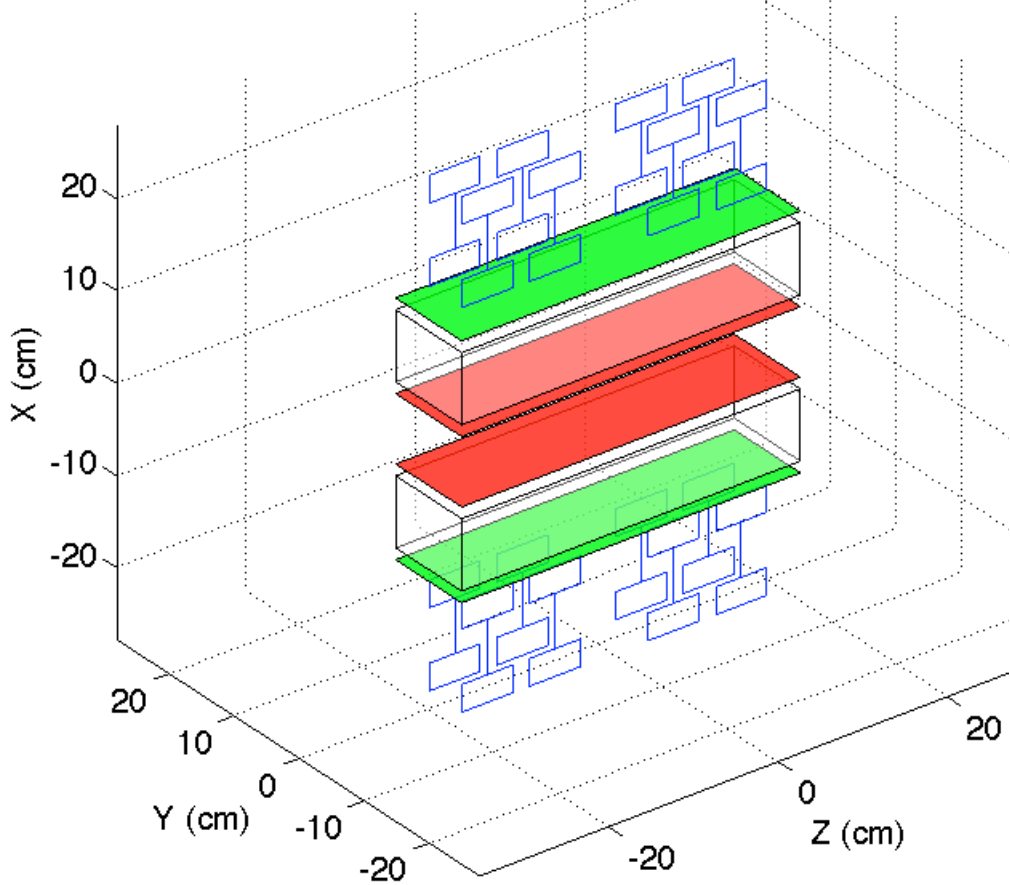
= 0.1

scintillation signals ~10 Hz

^{3}He precession readout ~100 Hz

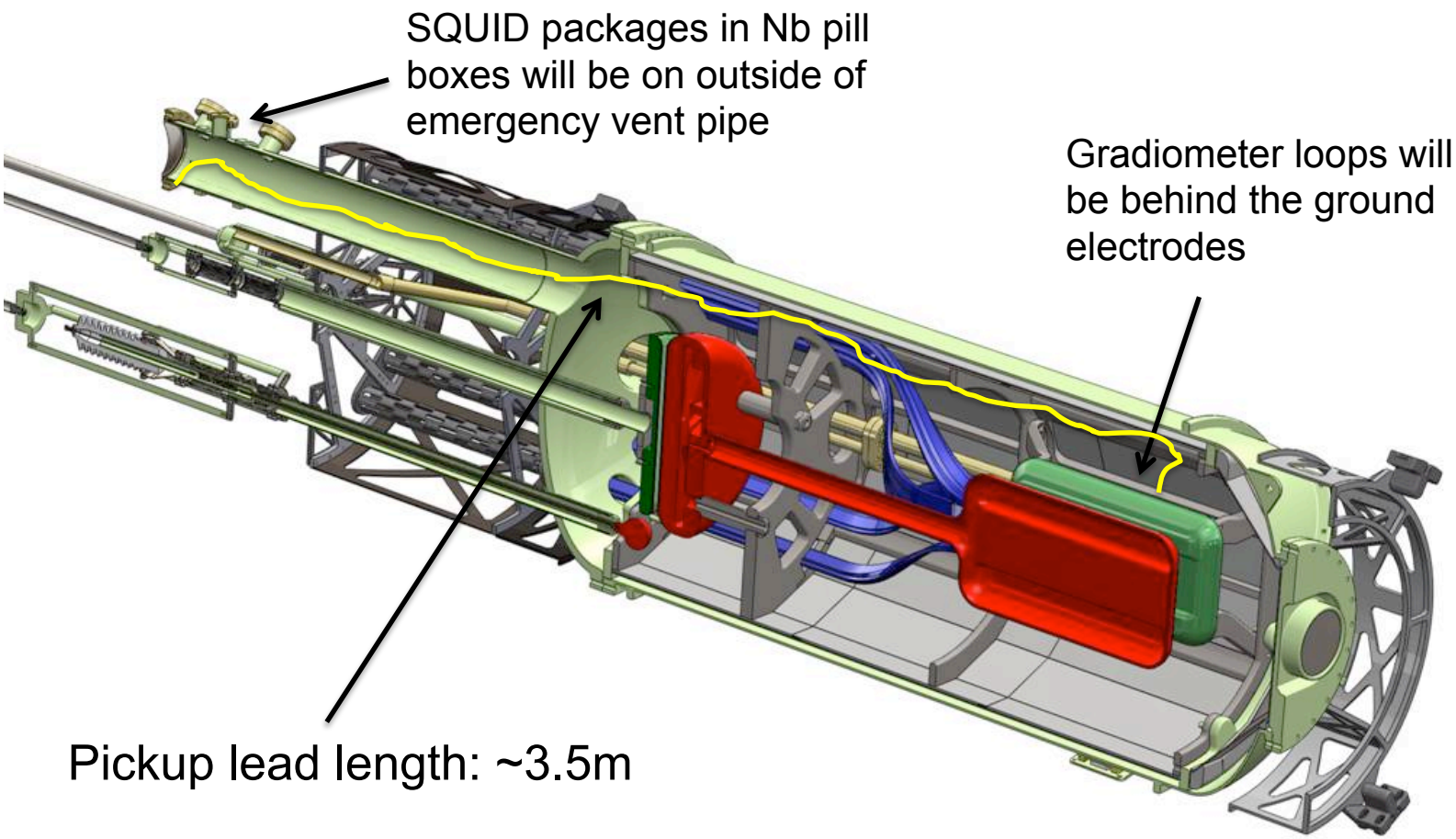
To match statist. error of scint. signal, we need $\delta f_3 \approx 26\mu\text{Hz}$ per 800 s measurement period. The goal is to be much more precise to not contribute significantly to the overall error.

- Required noise-to-signal ratio << 1/rtHz
- Expected avg signal over half gradiometer: 2.3 fT
- The goal is ≤ 1fT/rtHz noise (referred to half gradiometer)
- If the noise in each gradiometer is uncorrelated, we win a factor √8
- Must meet the requirements under constraints from other experimental components

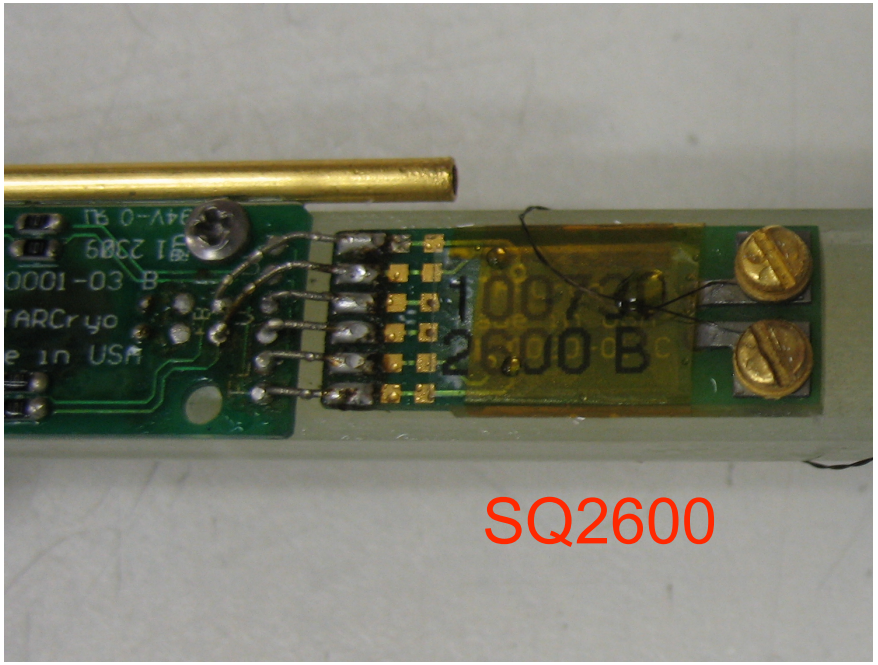


“Remote SQUID” Configuration

- SQUIDs mounted outside the central detector volume and connected to pickups with long (~3.5 m) twisted-pair leads



SQUIDs R&D @ LANL

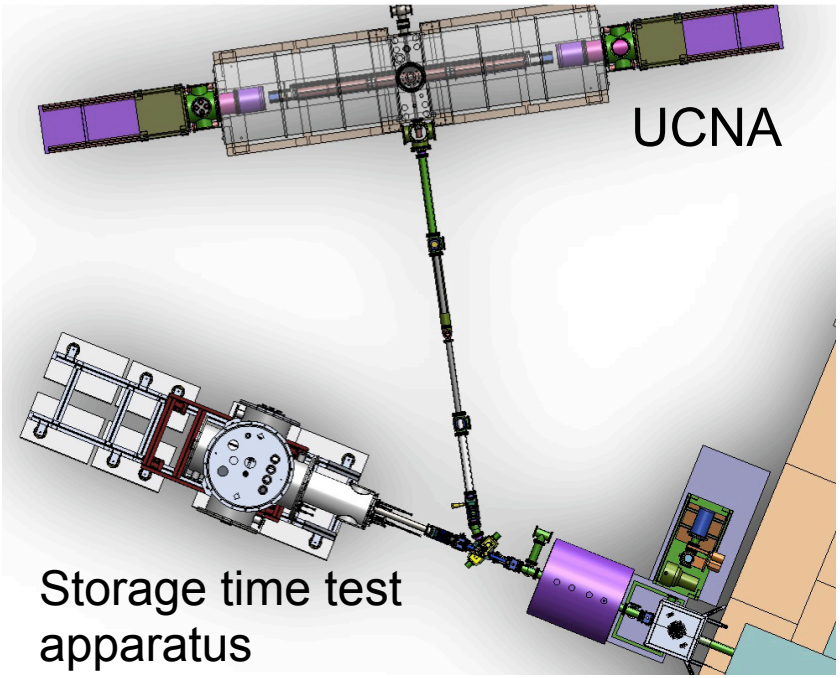


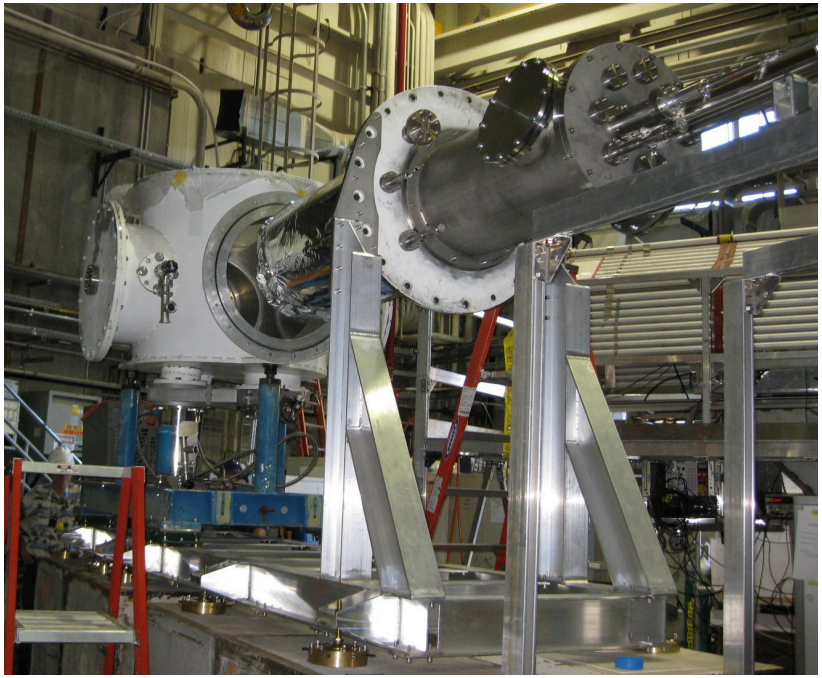
G10 dewar in 2-layer magnetically-shielded room

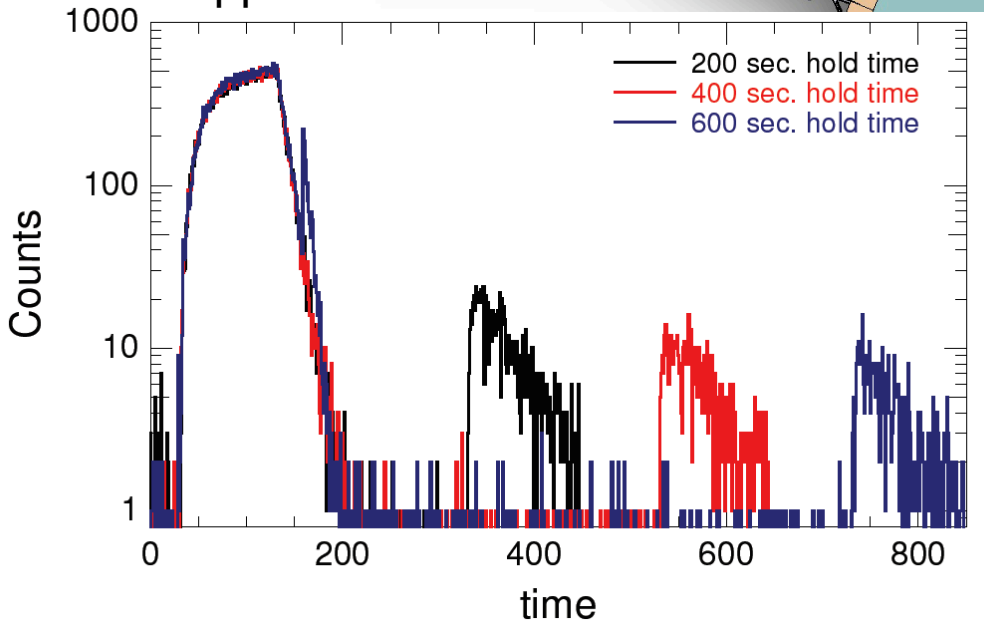
We are testing a candidate high-inductance SQUID: Star Cryoelectronics SQ2600.

- Based on intrinsic noise, it should work well.
- We plan to test performance with a pickup loop attached in a shielded room.
- Also, we will test for interference from e.g. PMTs.
- We are considering tests in the Caltech magnet/shielding prototype.
- Testing SQUIDs near HV is planned as future activity

Neutron storage tests @ LANL







- Utilizes currently operating LANSCE SD2 UCN source
- Test wall coatings and cell construction for UCN storage
- Cells developed at LANL and NSCU

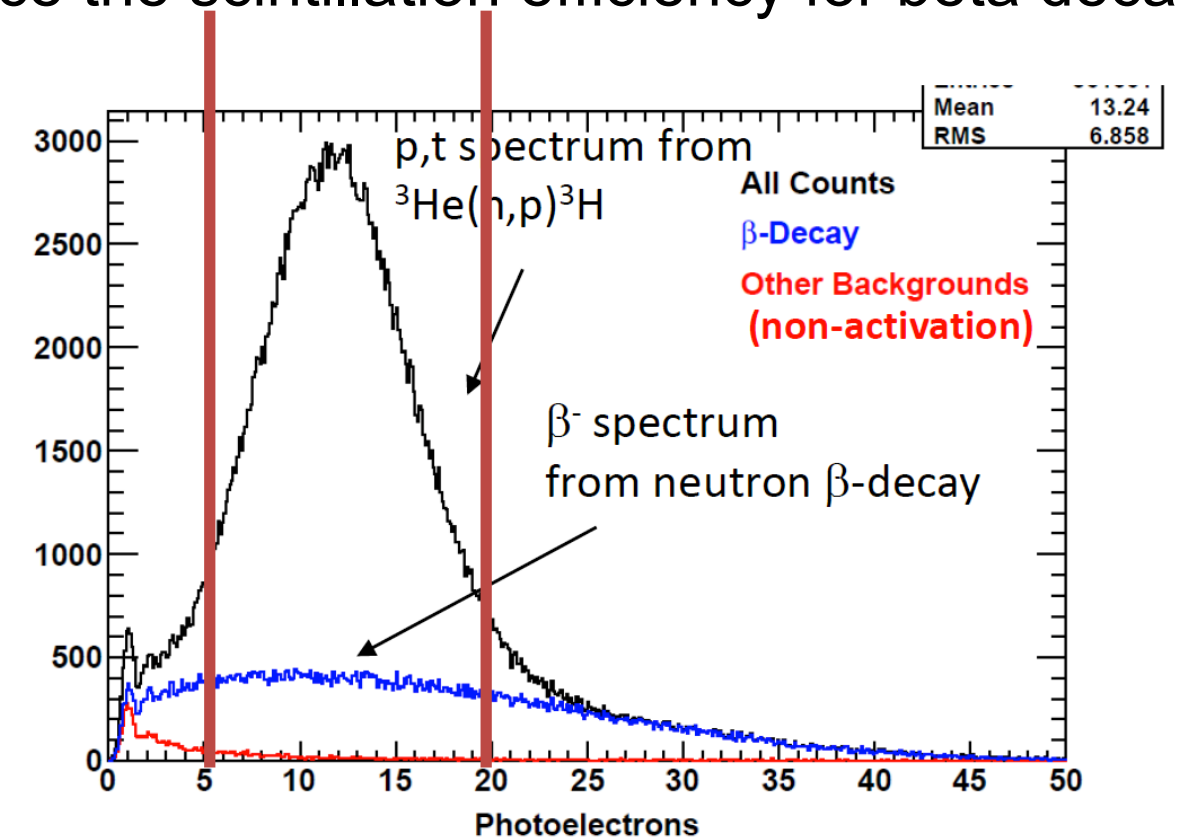
See M. Cooper's talk

Monte Carlo simulation studies by Kentucky, BU, UIUC, MS State, MIT, Caltech, NCSU, ORNL, LANL

- Cold neutron beam transport (GEANT4 and McStas)
  - Provided cold neutron beam flux at the cell ➔UCN production rate in the cell
- GEANT4 based cell simulation
  - n-^{3}He capture, neutron β decay, 2.2 MeV γ from UCN wall loss, cosmic ray background, ambient gammas
  - PMT output generated
  - Results used for sensitivity estimate and systematic studies
  - Also generated mock data
- Neutron activation simulation

Simulated PMT spectra

- Width of the neutron capture peak depends on the number of photoelectrons
- Scintillation efficiency for neutron capture events is ~ 1/3 of that for beta decay (electric field effect may reduce the scintillation efficiency for beta decay)



Main experimental parameters

Optimum parameters: collaboration goals based on reasonable projections

Quantity	Definition	Value
P_{UCN}	UCN production rate	0.26 UCN/cc/s
N	number of UCNs at t=0 in each 3000 cc cell	3.8×10^5
τ_β	β decay lifetime	885 s
τ_3	UCN-^{3}He absorption time	500 s
τ_{cell}	UCN-wall absorption time	2000 s
E	Electric Field	74 kV/cm
T_m	measurement time	1000 s
T_f	cold neutron fill time	1000 s
T_d	dead time between cycles	400 s
P_3	^{3}He initial polarization	0.98
P_n	UCN initial polarization	0.98
Γ_p	^{3}He and UCN depolarization rate	1/20,000s
ϵ_3	detection efficiency for UCN-^{3}He absorption	0.93
ϵ_β	detection efficiency for β decay	0.5
ϕ_B	other background (radioactivities, muons, etc.)	5 Hz

Controllable parameters: T_m, T_f, τ_3

$$\tau = 275 \text{ s}, \quad \tau_{fill} = 614 \text{ s}$$

Statistical sensitivity estimate Free precession case

- Uncertainty in EDM depends on the uncertainty in the neutron precession frequency determination

$$\sigma_d\left(90\%\ \mathrm{CL}\right) = h\frac{1.64\sigma_f}{4E}\sqrt{2}$$

- Extract scintillation frequency by fitting a decaying oscillatory function to the scintillation data. The uncertainty in the frequency extraction for a single measurement is given by

$$\sigma_\omega = 2\pi\sigma_f = \frac{1}{\alpha\tau\sqrt{\frac{N_0}{2}\left[2 - e^{-x}\left(x^2 + 2x + 2\right)\right]}}$$

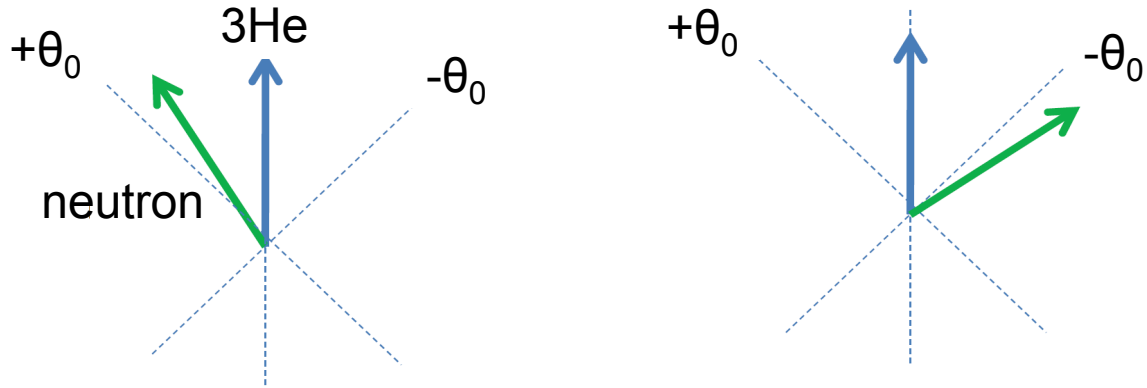
$$\alpha = \frac{\varepsilon_3\Gamma_3 P_3 P_n}{\varepsilon_3\Gamma_3 + \varepsilon_\beta\Gamma_\beta}\sqrt{\frac{\varepsilon_3\Gamma_3 + \varepsilon_\beta\Gamma_\beta}{\Gamma}}, \qquad x = \frac{T_m}{\tau}$$

- Optimize the sensitivity by adjusting T_m, T_f, and τ_3
- Results from analytical method and MC generated data agree

Statistical sensitivity estimate
Dressed spin case

- At critical dressing: $\theta(t) = \theta_0 \pm \frac{2J_0(x_c)d_n E}{\hbar} t$

$$\phi(t) = N_0 e^{-\Gamma t}\left[\varepsilon_\beta \Gamma_\beta + \varepsilon_3 \Gamma_3 (1 - P\cos\theta_0) \mp \varepsilon_3 \Gamma_3 P \frac{2J_0 d_n E}{\hbar} \sin\theta_0 t\right] + \phi_B$$



$$A_d(t_i) = \frac{N_- - N_+}{N_- + N_+} = \frac{N_0 \varepsilon_3 \Gamma_3 P \frac{2J_0 d_n E}{\hbar} \sin\theta_0 t_i e^{-\Gamma t_i}}{e^{-\Gamma t_i}\left[\varepsilon_\beta \Gamma_\beta + \varepsilon_3 \Gamma_3 (1 - P\cos\theta_0)\right] + \phi_B}$$

$$\sigma_A = \frac{1}{\sqrt{N_- - N_+}}$$

$$\sigma_d = \frac{\sigma_A}{A} d_n = \left(\frac{\sqrt{N_- + N_+}}{N_- - N_+}\right) d_n$$

- Optimize the sensitivity by adjusting T_m, T_f, τ_3 , and modulation parameters (waveform, maximum angle).

Projected sensitivity

- Projected statistical sensitivity (limited by the neutron density in the storage cells):

  90% CL $\sigma_d < (3\text{-}5) \times 10^{-28}$ e-cm in 300 live-days

  (using the cold beam line)

- Dressed spin method gives a slightly better sensitivity

Projected systematic uncertainties

Error Source	Projected systematic error (e-cm)	Comments
Geometric phase (linear E×v)	$< 2 \times 10^{-28}$	Uniformity of B_0
Quadratic E×v	$< 0.5 \times 10^{-28}$	E field reversal to 1%
Pseudomagnetic field effects	$< 1 \times 10^{-28}$	π/2 pulse, compare two cells
Uncompensated leakage current effects (gravitational offset)	$< 0.2 \times 10^{-28}$	Leakage current < 1 nA
E×v from rotational UCN flow	$< 1 \times 10^{-28}$	Uniformity of E, damping time of the rotational motion of UCN
Heat from leakage currents	$< 1.5 \times 10^{-28}$	Leakage current on the inner surface of the cell wall correlated with the E field direction
Miscellaneous	$< 1 \times 10^{-28}$	

See C. Swank's talk

Approaches to systematic effects

- Known effects
  - Study the properties and possible size of the effects carefully (theoretical studies as well as necessary measurements).
  - Incorporate features in the design of the experiment that eliminate or minimize such effects.
  - Incorporate features in the design of the experiment that allow us to vary the size of such effects so that we can study
  - When running the experiment, perform necessary measurements to characterize the effects (in situ or ex situ)
- Unknown effects
  - Build enough “handles” in the experiment that can be varied.
  - If unexpected effects are found, perform necessary measurements to characterize the effects (in situ and ex situ)

The significance of a non-zero result requires multiple approaches to unforeseen systematics.

Systematic controls

- Two cells with opposite E fields
- Free precession and dressed spin methods
- Study dependence on temperature, B-field, B-field gradient, and 3He concentration
- Ex-situ apparatus to study systematics

Schedule

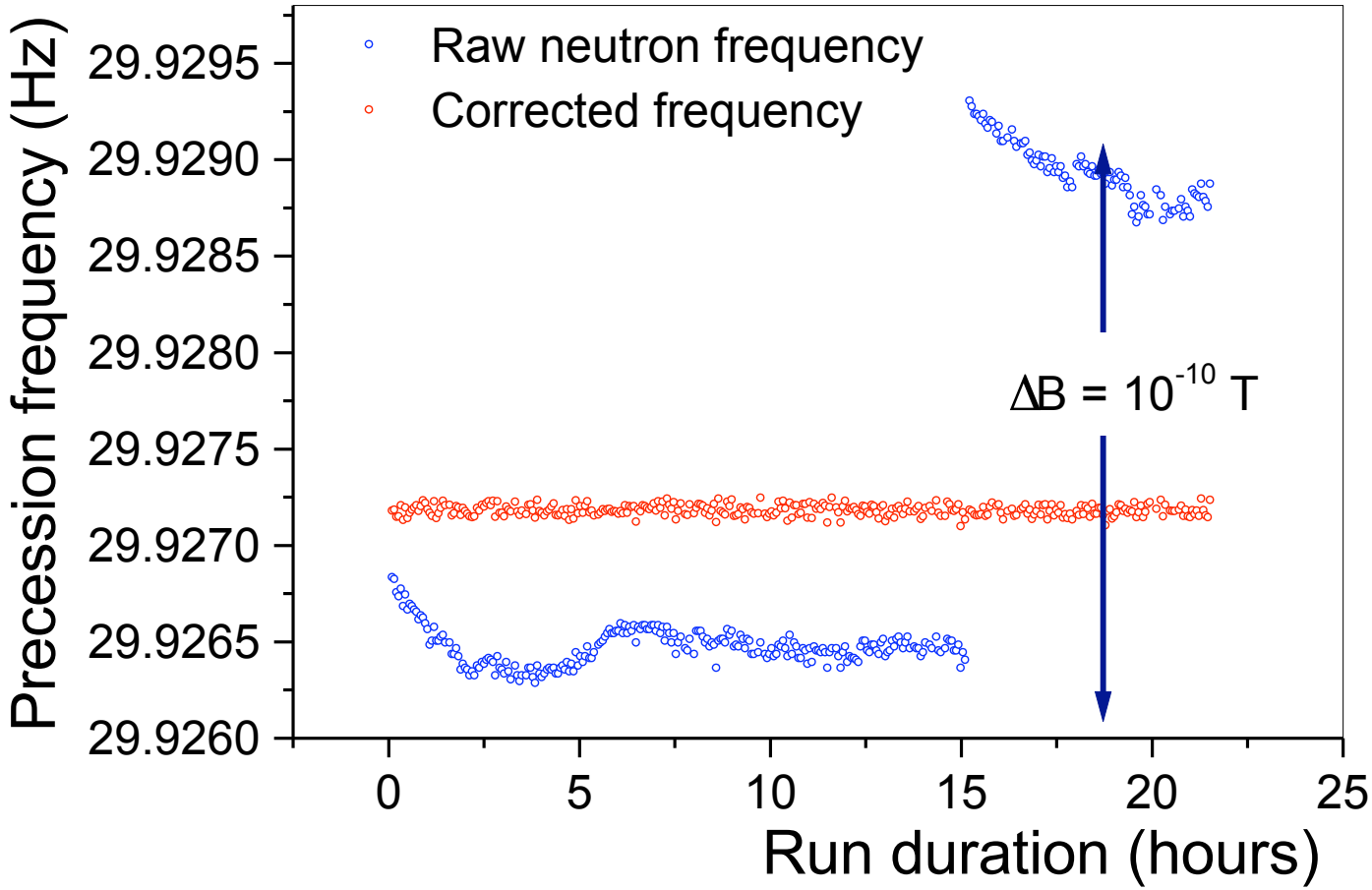
- 2012-2013: critical R&D program
- 2013-2018: final design & construction
- 2019 - : commissioning & operation

Summary

- A neutron EDM experiment at SNS is underway.
- The experiment at the SNS has unique and powerful capabilities for addressing some systematic effects.

Magnetic noise

From ILL neutron EDM experiment with ^{199}Hg co-magnetometer



Projected accuracy of each measurement cycle in nEDM @SNS ~ 2.0 μHz