

The Neutron Electric Dipole Moment (nEDM) Experiment at the Spallation Neutron Source

Zhaowen Tang
for SNS nEDM Collaboration



CP violation

- Sakharov conditions for baryogenesis in the early universe:
 - Baryon number violation
 - C and CP symmetry violation
 - Interactions out of thermal equilibrium
- Experimental evidence of Standard Model CP violation comes from K/B meson decay.
- However, it is not enough to explain the baryon asymmetry that we see today.

$$\frac{n_B - n_{\overline{B}}}{n_\gamma}$$

SM expected: $\sim 10^{-18}$ Observed: $\sim 10^{-10}$

- Motivation for search of Beyond the Standard Model mechanisms for CP violation.

nEDM experiments

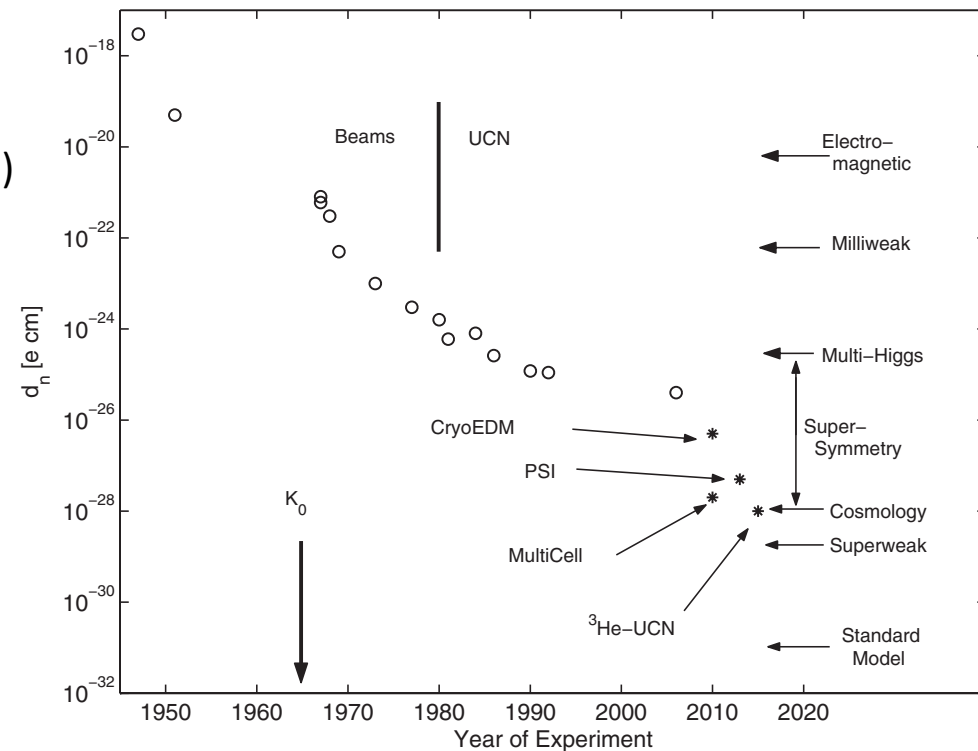
- Electric dipole moment violates both P and T symmetries
- Great platform for BSM physics
 - SM contribution (CKM δ) to EDM is small. ($d_n \sim 10^{-32} \text{ e} \cdot \text{cm}$)

- neutron electric dipole moment

$$\hbar\omega = 2\mu_n B \pm 2d_n E$$

- Beam experiments (systematics from $\mathbf{v} \times \mathbf{E}$)
- Ultracold Neutron (UCN) experiments
 - $V_n < 8 \text{ m/s}$
 - Stored in bottles ($\langle \mathbf{v} \rangle = 0$)
 - Room Temperature
 - Cryogenic experiment

$$-\delta d_n \sim \frac{1}{|\vec{E}| T \sqrt{m N_{ucn}}}$$



SNS nEDM Experiment

- Goal:
 - $\delta d_n \sim 2-3 \times 10^{-28} \text{ e} \cdot \text{cm}$
- Key features:
 - Experiment performed in He II
 - Superthermal production of UCN in situ
 - Higher electric field is achievable in LHe
 - Longer UCN storage time at cryogenic temperatures
 - ^3He co-magnetometer
 - ^3He as neutron spin analyzer
 - Use of LHe scintillation as method for detection
 - Two methods of measurement:
 - Free precession
 - Spin dressing

Golub & Lamoreaux, Phys. Rep. 237, 1 (94)

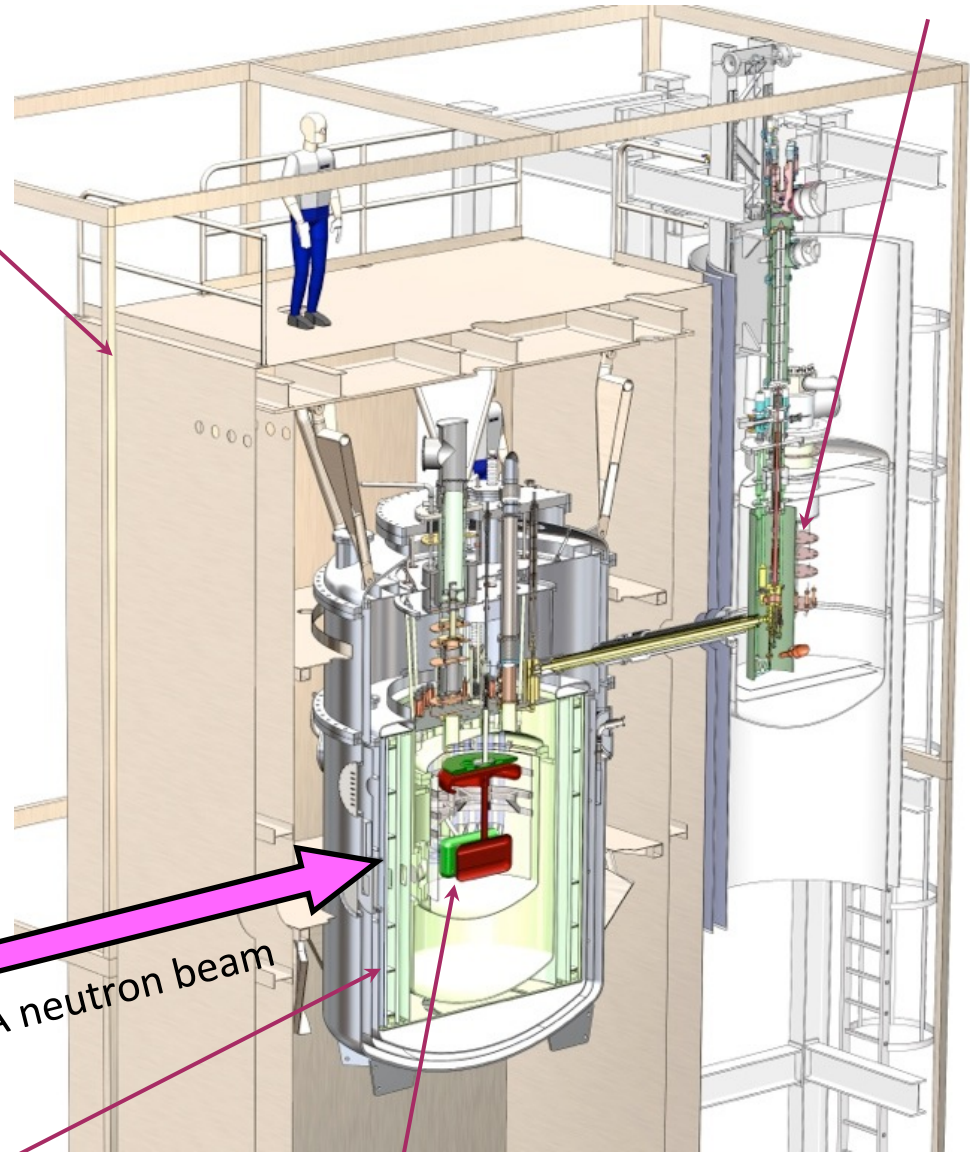
Magnetically shielded house

^3He services

8.9 Å neutron beam

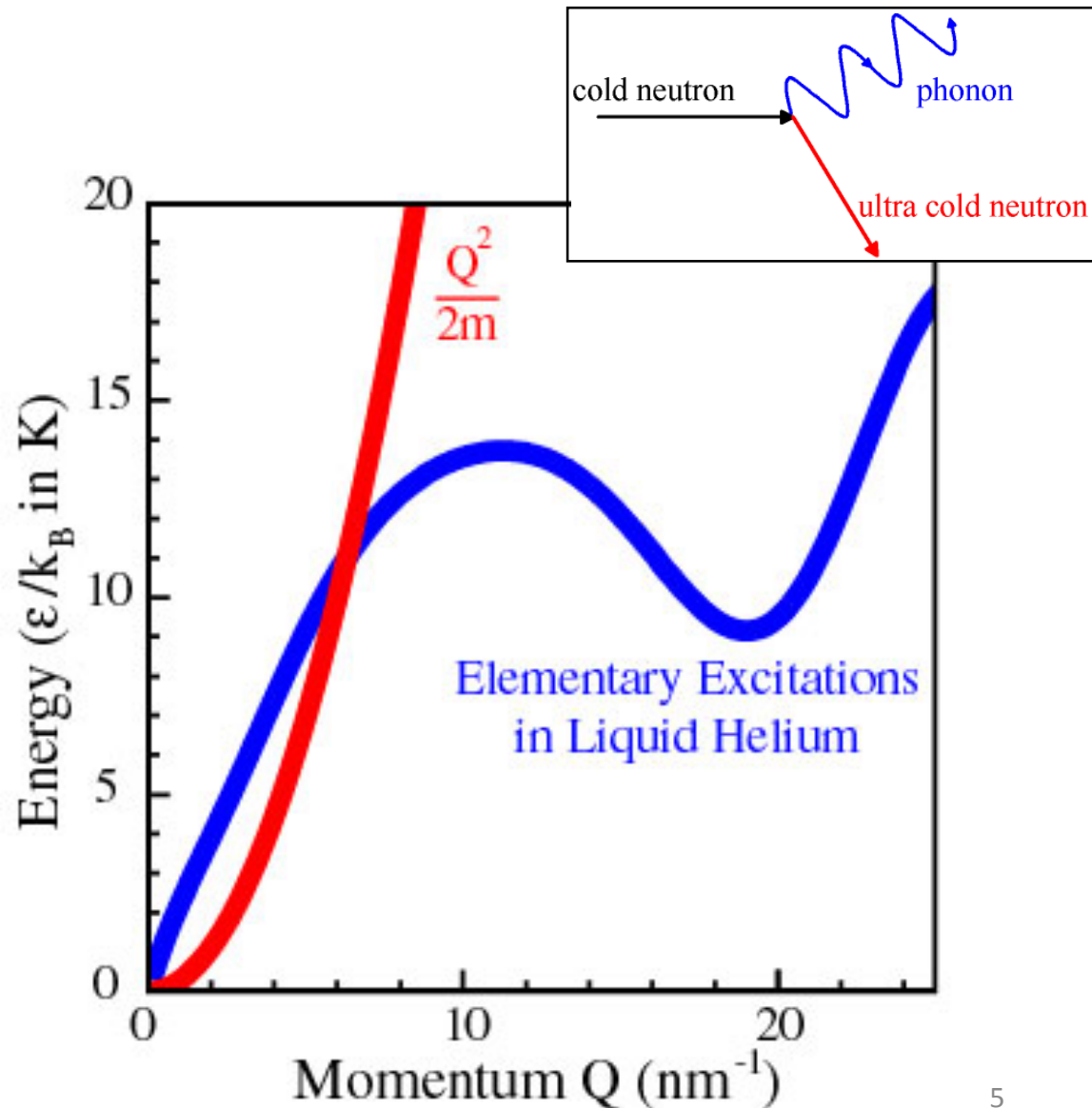
Magnet and shielding package

Central LHe volume (400 mK, 1500 liters)



Superthermal production of UCN

- Downscattering of 8.9 Å neutrons in superfluid ^4He .
- Upscattering process is suppressed at 0.4 K.
- Achievable density at SNS FNPB => ~150 UCN/c.c.



^3He co-magnetometer and spin-analyzer

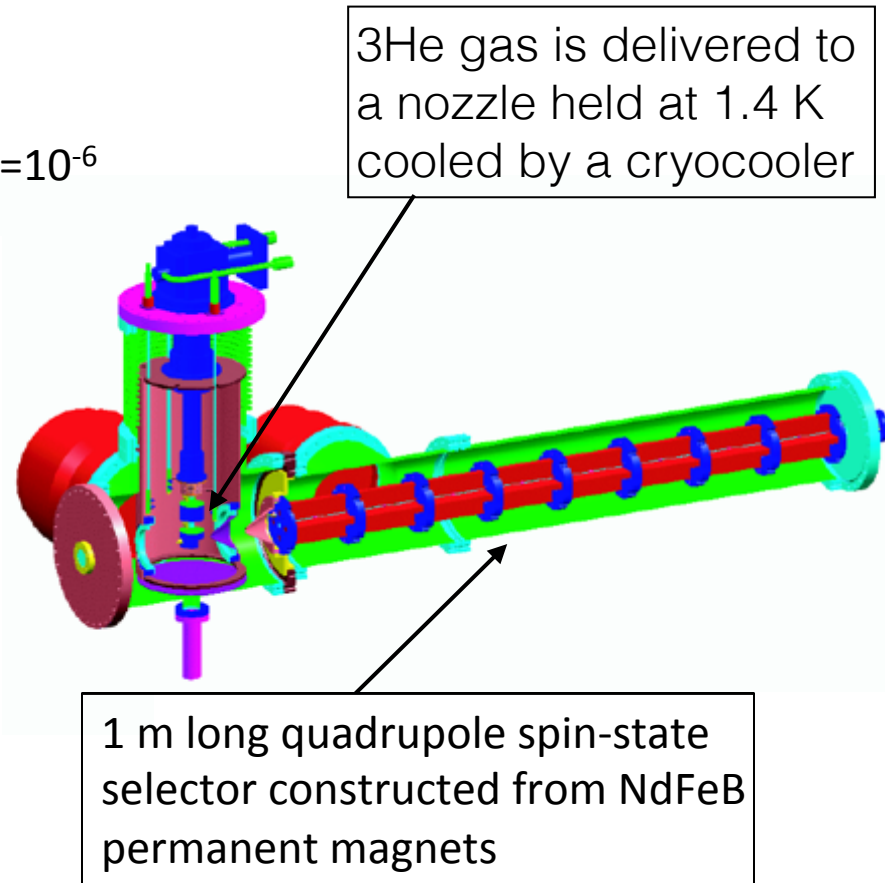
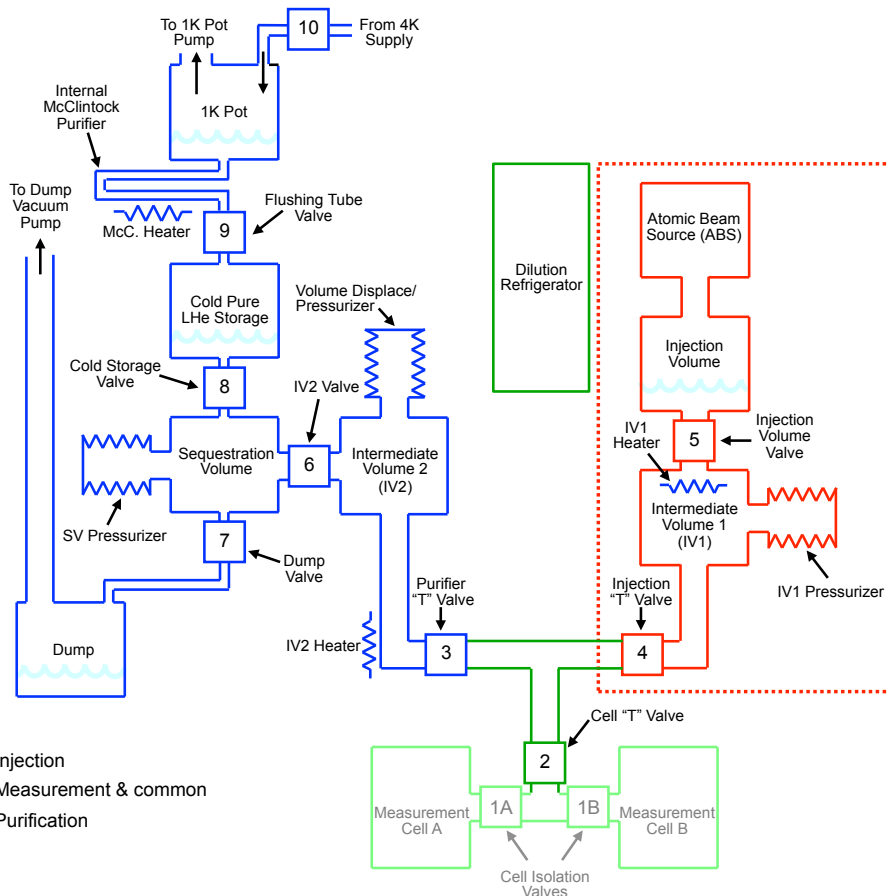
- ^3He has small EDM $\sim 10^{-32} \text{ e}^*\text{cm}$.
- Only co-magnetometer that will work at 0.4 K
- Long spin relaxation time.
- Large contrast of spin dependent neutron capture cross section for ^3He .

$$\sigma_{\uparrow\uparrow} \sim 10000 \text{ barns} \quad \sigma_{\uparrow\downarrow} < 100 \text{ barns} \quad (\text{KE}_n = 25.3 \text{ meV})$$

- Gyromagnetic ratios $\gamma_{^3\text{He}}/\gamma_n = 1.1$
- Varying ^3He velocity gives handle on systematic errors from geometric phase effect. (K. K. Leung Talk at 11:30)

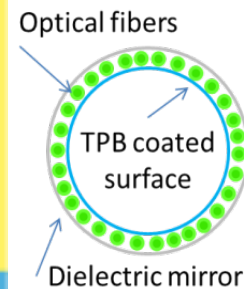
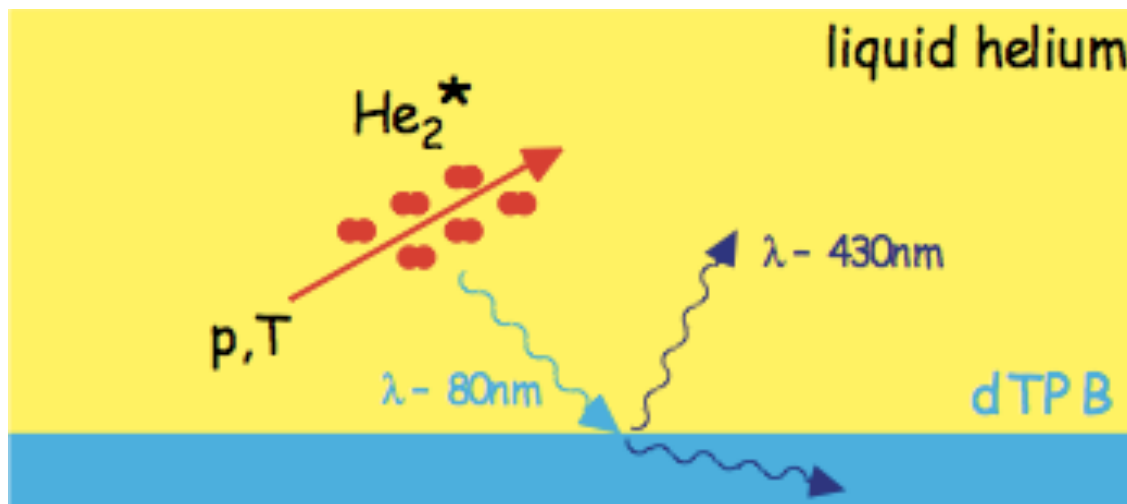
^3He services

- ^3He atomic beam source ($P = 99.6 \pm 0.25\%$, flux = 10^{14} atoms)
- Heat flush method to control flow of ^3He
- Recently observed heat flush signal with $x(^3\text{He}) = 10^{-6}$



Detection Method

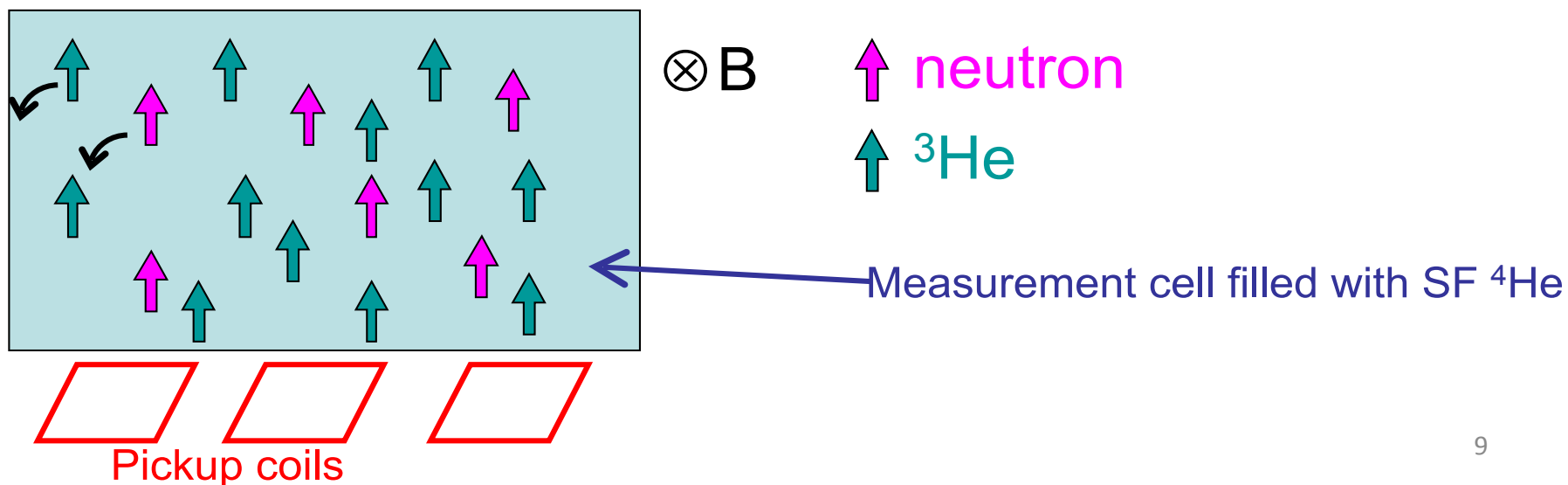
- $(n, {}^3\text{He})_{\uparrow\downarrow} \rightarrow p + T$ generates 80 nm UV scintillation light in LHe.
- UV light is then downconverted by dTPB wavelength shifter.
- Blue light is then further converted to green light using wavelength shifting fiber.
- Green light is then detected using SiPM.
- Recent test with eTPB coating has measured 38 PE using alpha source => >13 PE projected yield



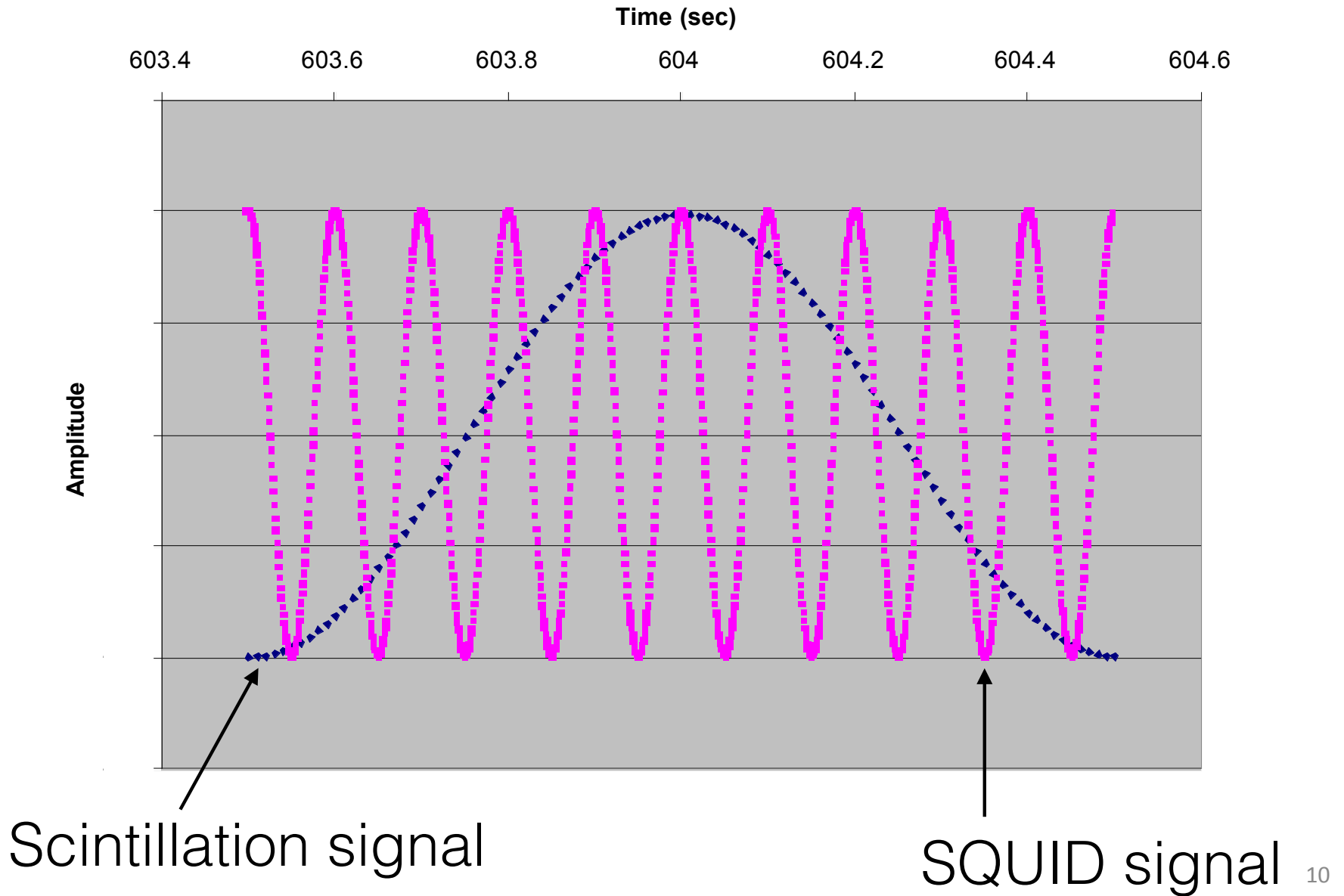
Measurement Methods: Free Precession

- $\pi/2$ rotation to start free precession of neutron and ^3He .
- SQUID magnetometers are used to read out the precession frequency of ^3He .
- Current SQUID sensitivity at 1 fT.
- Signature of EDM appears as a shift in $\omega_3 - \omega_n$ corresponding to the reversal of E with respect to B .

$$d_n = \frac{\hbar}{2E} [(\omega_s^\uparrow - \omega_s^\downarrow) - \frac{(\gamma_3 - \gamma_n)}{\gamma_3} (\omega_3^\uparrow - \omega_3^\downarrow)]$$



Free Precession Signal



Spin Dressing

- Apply non-resonant RF field in x direction

$$B_x(t) = B_{\text{rf}} \cos(\omega_{\text{rf}} t)$$

- Precession frequency in y-z plane is:

$$\omega(t) = \dot{\theta}(t) = \gamma B_x(t)$$

- The angle θ with respect to z axis is:

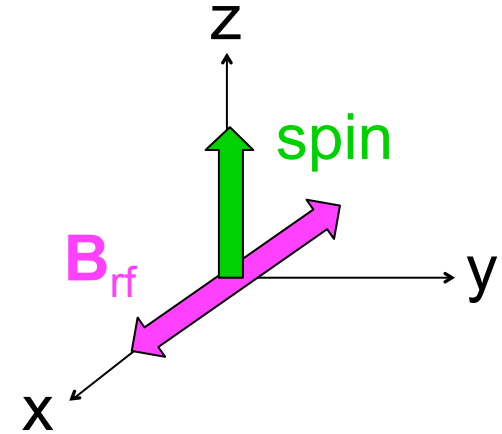
$$\theta(t) = -\gamma(B_{\text{rf}}/\omega_{\text{rf}}) \sin(\omega_{\text{rf}} t)$$

- The time averaged z component of spin is:

$$\langle \cos \theta(t) \rangle_T = \frac{1}{T} \int dt \cos[-\gamma(B_{\text{rf}}/\omega_{\text{rf}}) \sin(\omega_{\text{rf}} t)] = J_0(x) \quad x = \gamma(B_{\text{rf}}/\omega_{\text{rf}})$$

- The effective gyromagnetic ratio becomes:

$$\gamma_{\text{eff}} = \gamma_0 J_0(x)$$



Critical spin dressing

- Relative precession

$$\omega_{rel} = (\gamma_n^{eff} - \gamma_3^{eff}) B_0; \quad \gamma_i^{eff} = J_0(x_i) \gamma_i;$$

$$x_i = \gamma_i B_{rf} / \omega_{rf}; \quad i = \text{UCN}, {}^3\text{He}$$

- The effect of B field can be eliminated if

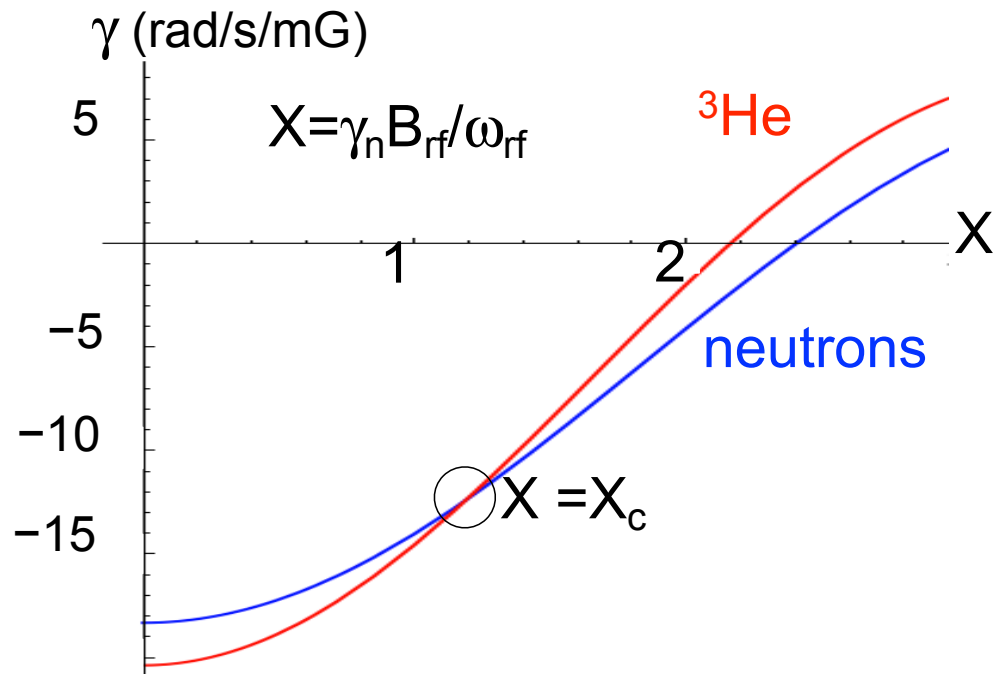
$$\gamma_n J_0(x_n) - \gamma_3 J_0(x_3) = 0$$

- This means

$$\alpha J_0(\alpha x_c) = J_0(x_c); \quad \alpha = \gamma_3 / \gamma_n = x_3 / x_n$$

- Solution: “critical dressing”

$$x_c \approx 1.19, \quad J_0(x_c) = 0.65$$



Detection of nEDM with dressed spin method

- In the presence of nEDM:

$$\omega_{rel} = (\gamma_n^{eff} - \gamma_3^{eff})B_0 + 2ed_nEJ_0(x)/\hbar$$

- At critical dressing:

$$\omega_{rel} = 2ed_nEJ_0(x_c)/\hbar$$

$$\theta_{n3} = \omega_{rel}t = 2ed_nEJ_0(x_c)t/\hbar$$

- Modulate the dressing field around x_c

$$x(t) = x_c + \epsilon \cos \omega_m t + kd_nE$$

$$\delta\theta \sim (\epsilon/\omega_m) \sin \omega_m t + kd_nEt = \delta\theta_0 + kd_nEt$$

- Scintillation rate

- Without nEDM: $S \propto (\delta\theta_0)^2$

- With nEDM: $S \propto (\delta\theta_0)^2 + 2\delta\theta_0kd_nEt$

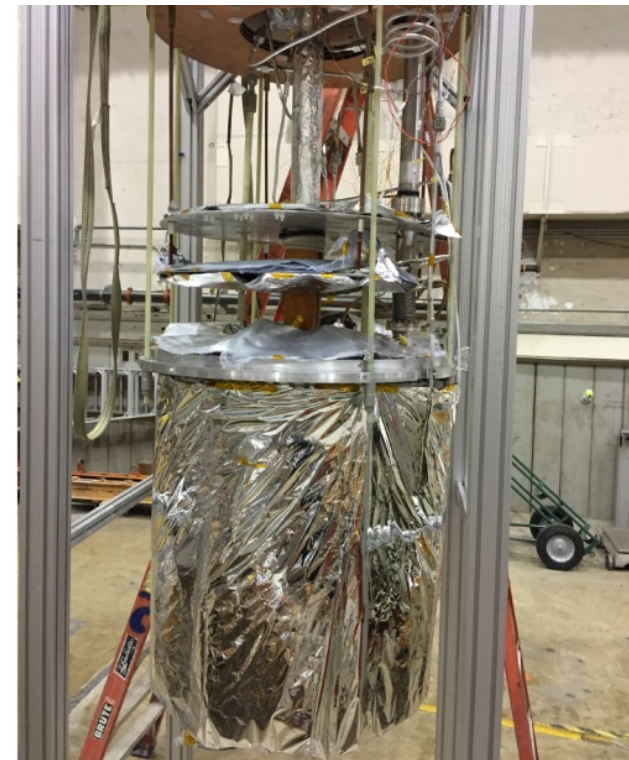
Increasing with t



- Apply feedback to dressing parameter to zero first harmonic; then this feedback vs. E-field direction is the EDM signal.

Magnetic shielding

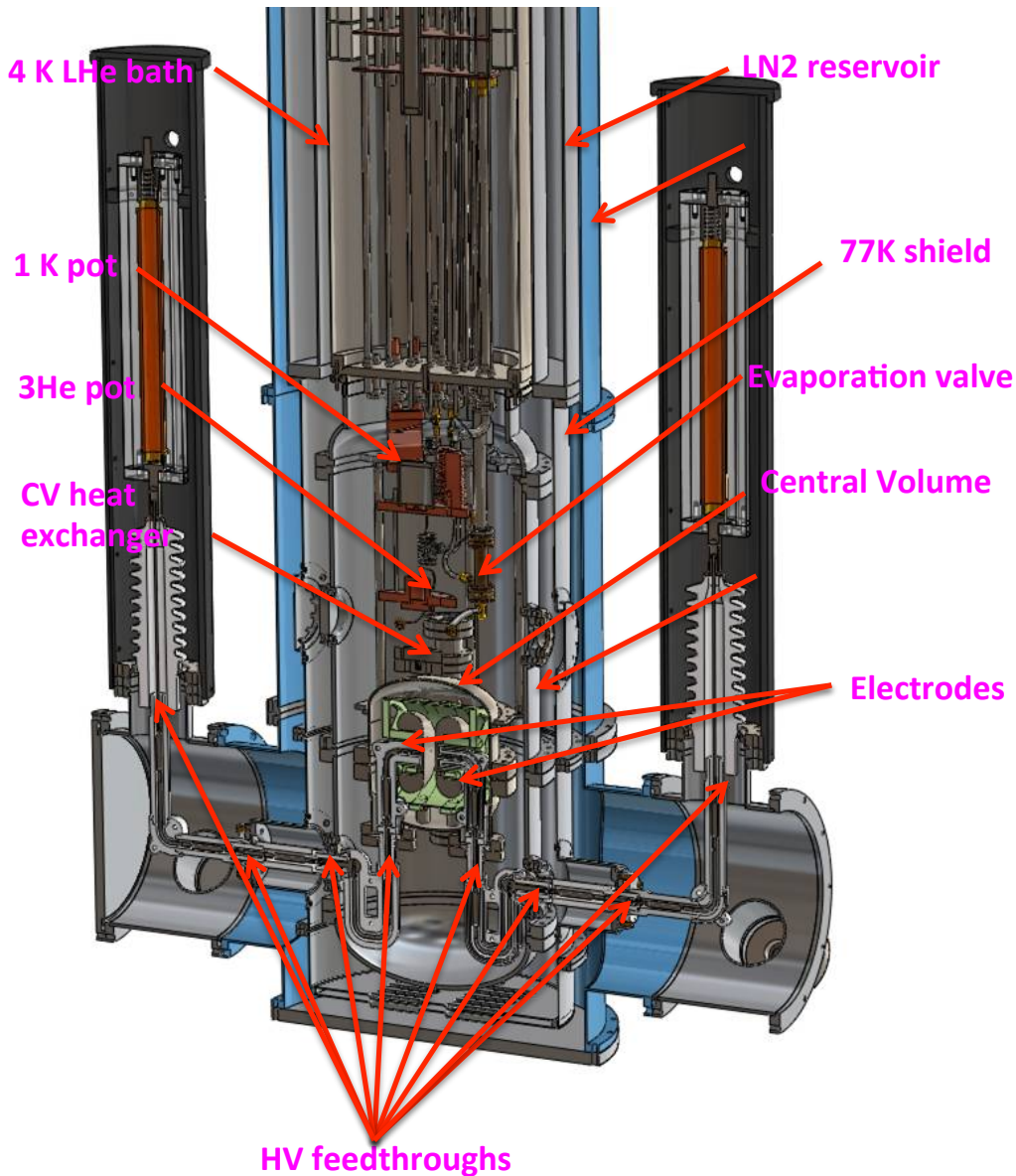
- Shield house requirements:
 - Gradients: $< 10^{-7}$ G/cm over 1m central volume
 - Shielding Factors: > 150 @ 1 Hz, > 10000 @ 10-10000 Hz
- Cryogenic magnet package:
 - Superconducting B_0 coil
 - Metglas (ferromagnetic) B_0 flux return
 - Superconducting shield/field shaper
 - Dressed spin coil
- Current 1/3 scale prototype is operational
- Procuring full scale magnet package.



High Voltage System

- Design goal 70 kV/cm => 600 kV between electrodes
- Minimum leakage current between the electrodes
- Electrodes made of PMMA coated with conductive material
- Resistant to thermal cycling and sparking
- Minimal activation due to exposure to neutron beam
- Non-magnetic
- Fabrication technique scalable to large (10x40x80 cm³) complicated 3D shape
- Current efforts:
 - R&D with Medium Scale High Voltage System
 - Design of Half Scale High Voltage System

MSHV



Purpose

- To study breakdown field dependence on
 - Temperature
 - Pressure
 - Gap size
 - Electrode material
 - Presence of dielectric object

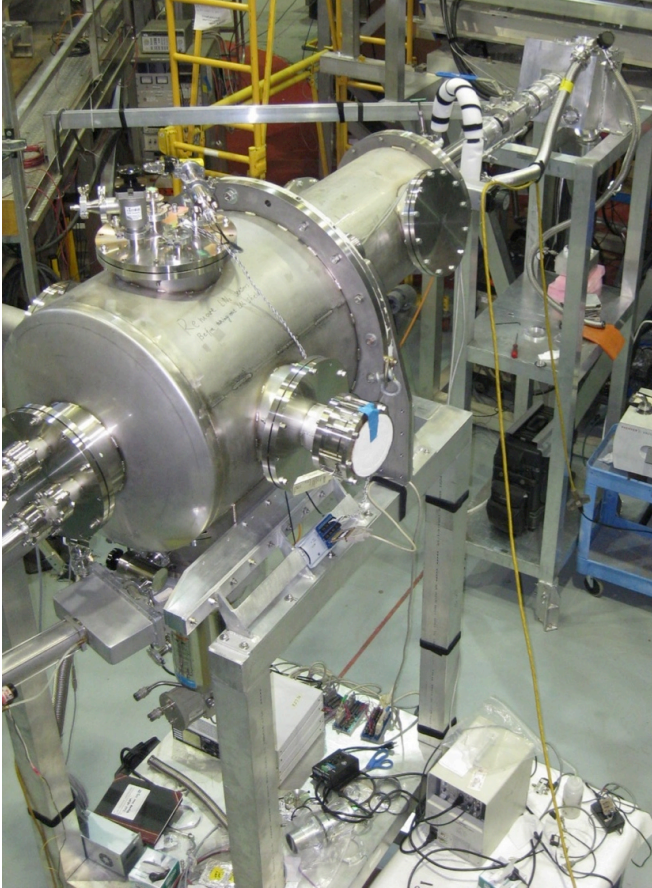
Features

- 6 L LHe volume cooled by a ^3He fridge
- Electrode size ~ 12 cm in diameter
- Electric field: up to 100 kV/cm in 1 cm gap
- Gap size: adjustable
- Lowest temperature ~ 0.4 K
- Pressure: variable between SVP and 1 atm
- Turn around time ~ 2 weeks

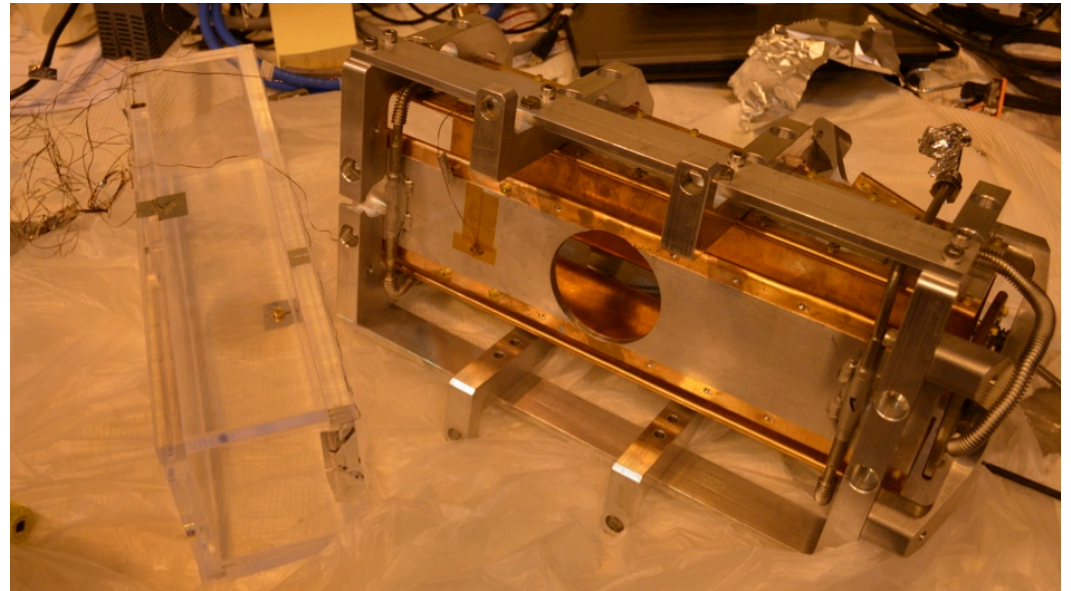
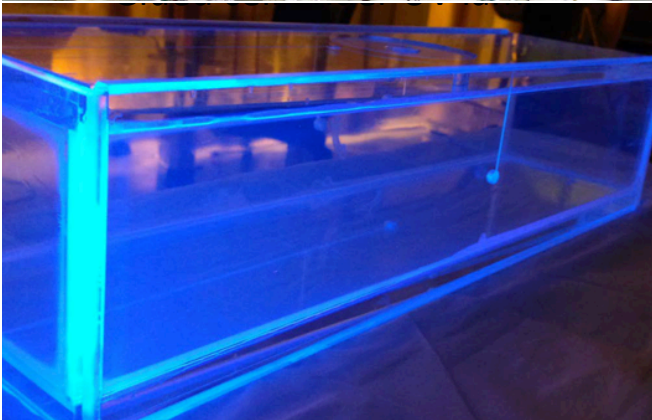
Key Results

- $E_{\text{BD}} > 105$ kV/cm in 1 cm gap for EP SS electrodes
- $E_{\text{BD}} > 85$ kV/cm in 1 cm gap for Cu implanted PMMA electrodes
- $E_{\text{BD}} > 80$ kV/cm in 1 cm gap for EP SS electrodes with PMMA insert
- Leakage current ≤ 2 pA at 40 kV with PMMA insert

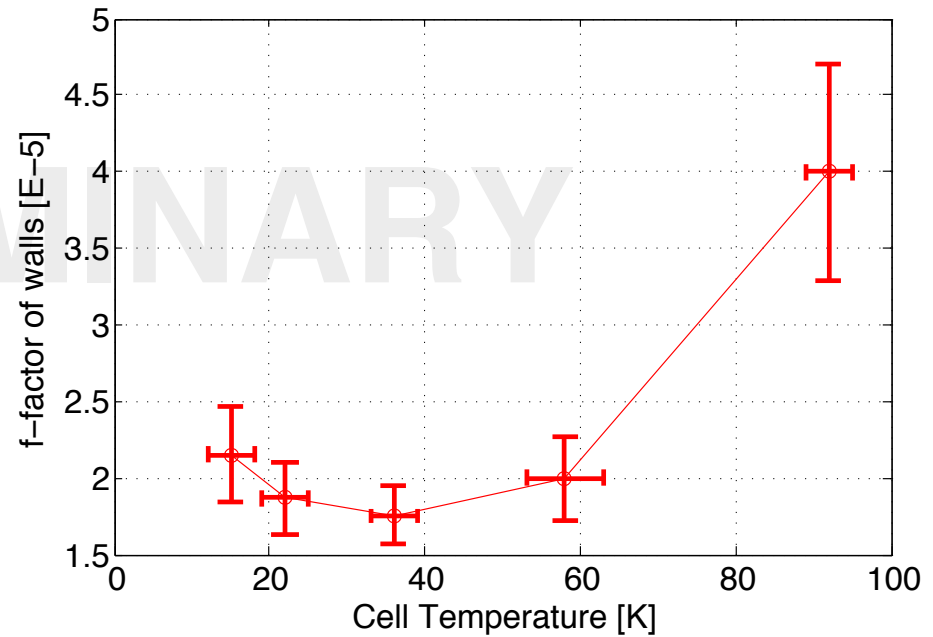
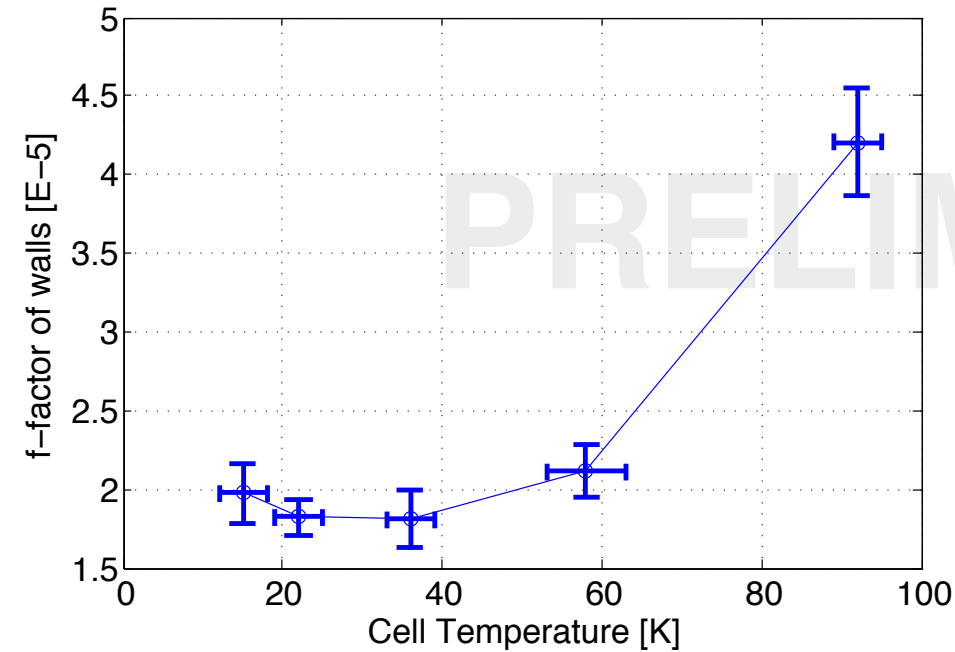
UCN Storage measurements



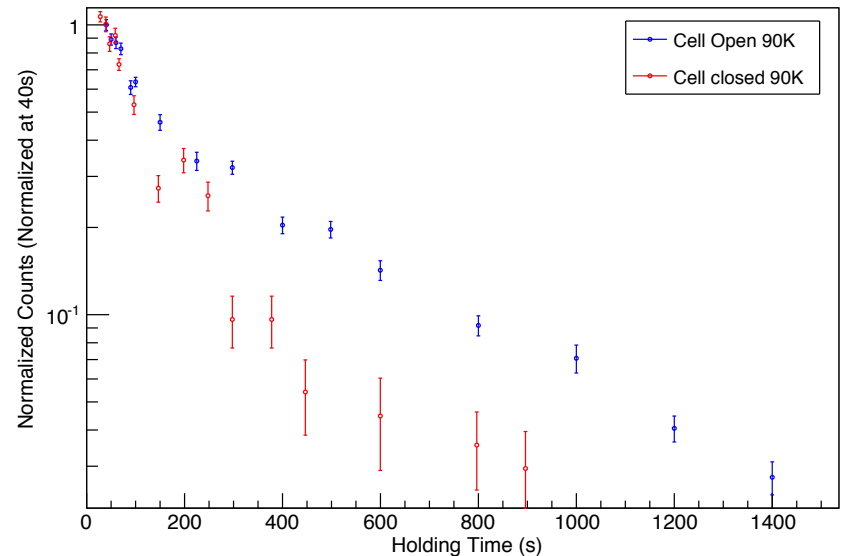
- Goal is to use existing LANL UCN source to test prototype cells.
- Measured UCN storage time of a new prototype measurement cell at different temperatures.
- Temperature dependence allows extrapolation down to 0.4 K.
- Also measured the storage curve with contamination frozen on cell wall during cooling.



Results



- $\sim 2\text{E-}5$ for loss factor, goal for the final experiment is $0.8\text{E-}5$
- Contamination run shows that cell must be actively pumped during cool down.



Summary

Significant progress in

- ^3He heat flush studies
- Light collection of 80 nm light
- Cryogenic magnet package design and operation
- Tests of high voltage electrodes
- UCN storage time of prototype measurement cells

What is next?

- Collaboration is moving toward a large scale integration phase.
- Scheduled for commissioning data at end of 2021.

Leakage current requirements

| Effects | Limit | Comments |
|--|--------|---|
| Magnetic field generated by leakage currents | 1 nA | 50 pA without comagnetometer |
| Heating due to leakage current affecting ^3He distribution, coupled with B-field gradient | 1 pA | In order for this effect to mimic EDM signal, leakage current location need to be dependent on the E field direction, and the leakage current to be flowing on the inner wall |
| Voltage reduction due to leakage current | 100 pA | 100 pA current in each cell changes the HV by 10% over 6 hours |