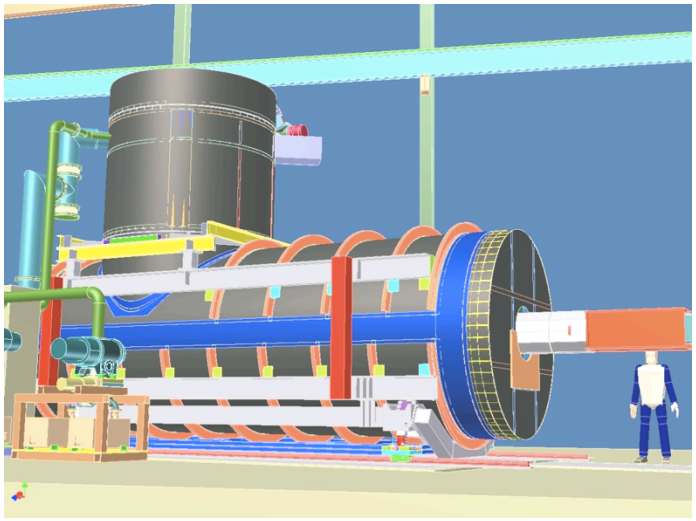
# nEDM @ SNS
## Status, Cost & International Context

- Brief overview of Experiment
  - Assumed that Science Case has been covered
- Summary of Status & Timeline
  - Active R&D program underway
- Estimate of Cost
- Role of nEDM@SNS in worldwide context



B. Filippone
FunSymNeut Workshop
8/11/12

# The nEDM Collaboration

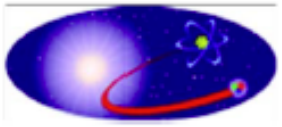
M. Ahmed[6], R. Alarcon[1], R. Allen[15], S. Baeßler[19], S. Balascuta[1,A], L. Bartoszek, D. Beck[9], J. Boissevain, D. Budker[4], M. Busch[6], R. Carr[5], P. Chu[6,C], V. Cianciolo[15], S. Clayton[11], M. Cooper[11,B], C. Crawford[10], C. Daurer, K. Dow[12], D. Dutta[13], M. Espy[11], B. Filippone[5,B], N. Fomin[11,C], H. Gao[6], G. Greene[17], C. Griffith[11,C], R. Golub[14,D], T. Gorringe[10], C. Gould[14], D. Haase[14], D. Hasell[12], A. Hawari[14], M. Hayden[16], E. Hazen[3], P. Huffman[14], E. Ihloff[12], T. Ito[11], M. Karcz[8,A], J. Kelsey[12], D. Kendellen[14,A], A. Kolarkar[3], E. Korobkina[14], W. Korsch[10], E. Leggett[13,A], C.-Y. Liu[8], I. Logashenko, J. Long[8], M. Makela[11], S. Malkowski[10,A], E. Martin[10,A], A. Matlashov[11], M. Mendenhall[5,A], H.O. Meyer[8], J. Miller[3], R. Milner[12], P. Mueller[15], E. Olivas[11], B.K. Park[4,A], C. Pena[5,A], J.-C. Peng[9], S. Penttila[15], A. Perez Galvan[5,C], G. Phelps[10,A], R. Picker[5,C], B. Plaster[10], S. Rahaman[11,C], J. Ramsey[11], R. Redwine[12], L. Roberts[3], R. Schmid[5,A], J. Seele[12,C], G. Seidel[2], I. Silvera[7], M. Snow[8], W. Sondheim[11], S. Stanislaus[18], C. Swank[14,A], G. Swift[6], E. Tsentalovich[12], C. Vidal[12], P. Volegov[11], D. Wagner[10,A], S. Williamson[9], W. Yao[15], Q. Ye[15,C], J. Yoder[11,C], A. Young[14], Y. Zhang[6,A], W.Z. Zheng[6,A]

**Manpower is significant and probably sufficient (NSAC subcommittee)**

1 Arizona State University
2 Brown University
3 Boston University
4 University of California, Berkeley
5 California Institute of Technology
6 Duke University
7 Harvard University
8 Indiana University
9 University of Illinois, Urbana-Champaign
10 University of Kentucky
11 Los Alamos National Laboratory
12 Massachusetts Institute of Technology
13 Mississippi State University
14 North Carolina State University
15 Oak Ridge National Laboratory
16 Simon Fraser University
17 University of Tennessee
18 Valparaiso University
19 University of Virginia

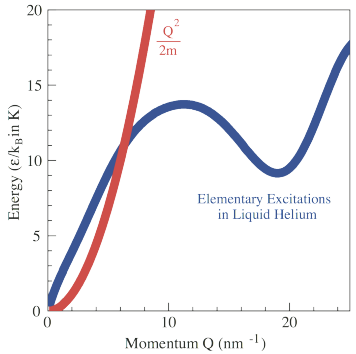
A Graduate Student
B Co-spokesperson
C Postdoc
D Chief Scientist

Office of Nuclear Physics



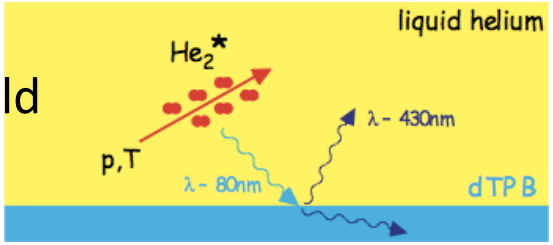
# Novel Experimental Techniques

**Based on: R. Golub & S. K. Lamoreaux, Phys. Rep. 237, 1 (1994)**




- 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*

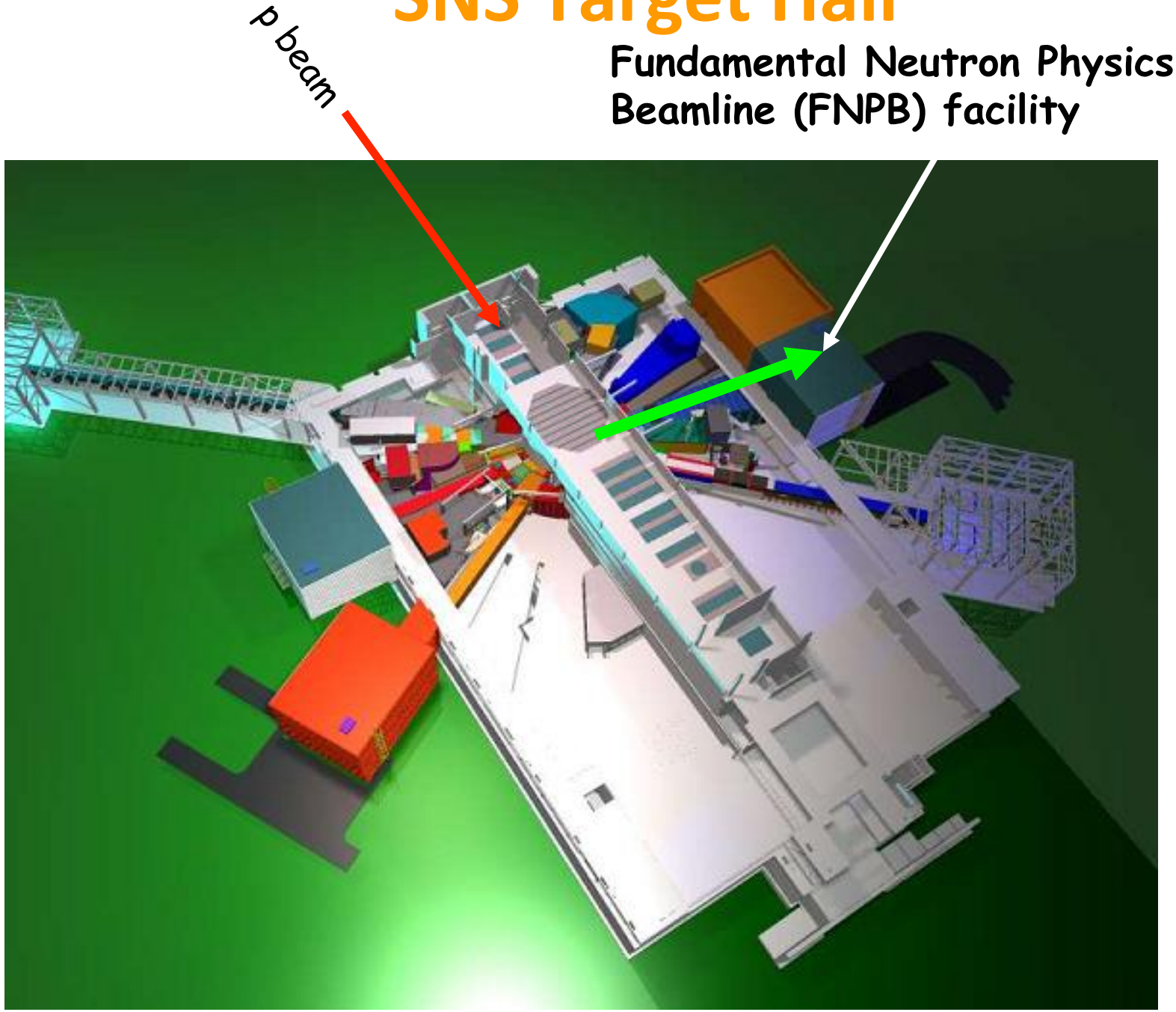



- Use of a $^3\vec{He}$ co-magnetometer and superconducting shield
  – *better control of magnetic field systematics*

- Use $\vec{n}$-$^3\vec{He}$ capture → light to measure neutron precession frequency
  – two different measurement techniques: *free precession and dressed spin techniques* ( spin-dependence of n+$^3$He→p+t+0.8MeV )

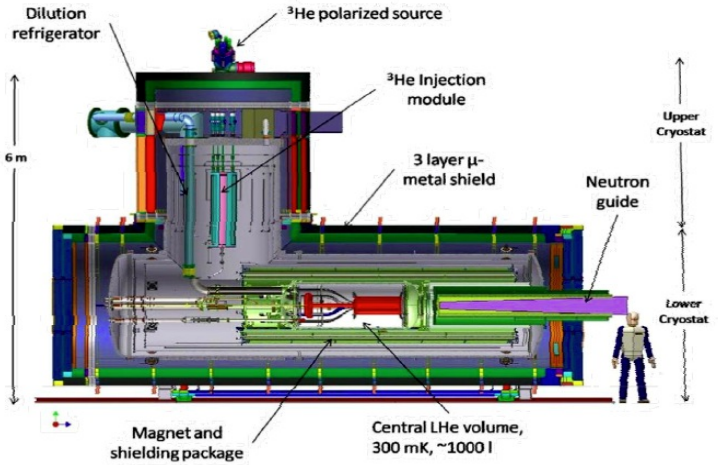
- Our goal is to obtain a sensitivity of $\boldsymbol{d_n < 4 \times 10^{-28}\ e\cdot cm}$ (90% CL)
  – *the current experimental limit is* $\boldsymbol{d_n < 300 \times 10^{-28}\ e\cdot cm}$
  *(Institut Laue Langevin).*

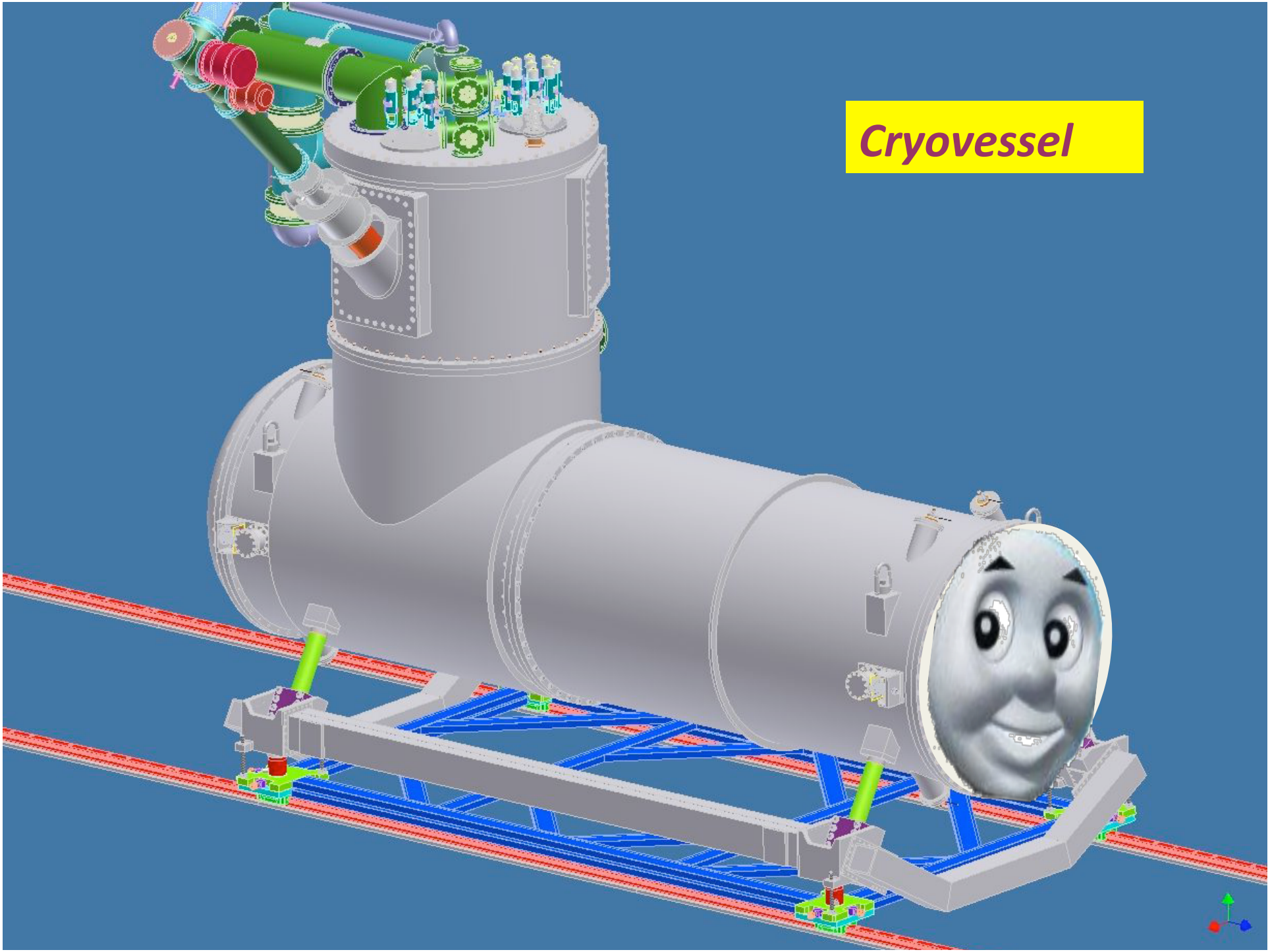
# SNS Target Hall



# Summary of Experimental Components

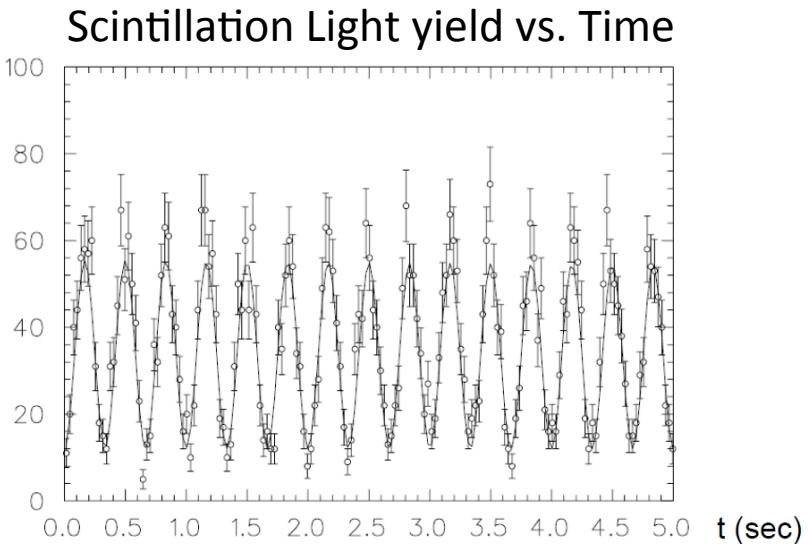
- Cold Neutron Beam
- Cryogenic system (77K, 4K, 300-450mK)
- Polarized 3He System
  - Must inject, transport and remove 3He
    - With minimal polarization loss & high efficiency
- Magnets and Magnetic Shielding
  - Including superconducting shielding
- Central Detector
  - HV
  - Light collection
  - SQUID monitors, …




Cryovessel

# Measurement of EDM

## Free Precession

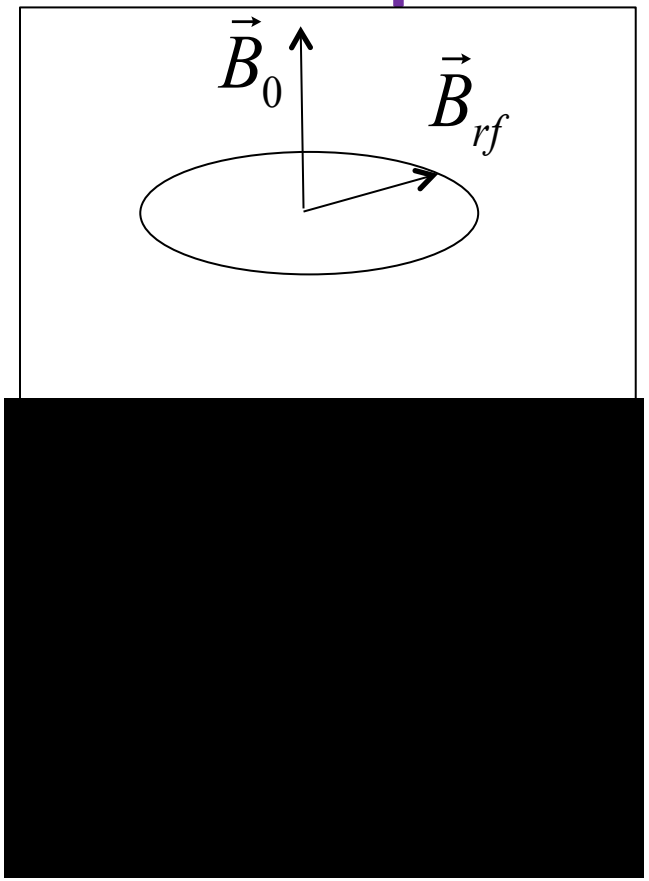



Measure difference in precession frequencies (beat frequency) of n & $^3$He

Detect precession of $^3$He magnetization via SQUIDS to correct for ambient B-field

**Two techniques provide critical cross-check of EDM result with different challenges and different systematics**

## Dressed Spin




Apply RF field to match the n & $^3$He precession frequencies (in absence of E-field) to minimize sensitivity to background fields (if $d_n \neq 0$, then E-field shifts neutron frequency)

# Systematic Effects in EDM

- Variation of B-field
  - Co-magnetometer cancels B-field variations
- Leakage currents from Electric Field
  - These may produce heating that changes with E-field (must be less than picoAmps)
- $\vec{v} \times \vec{E}$ effects are the largest sources of systematic error in previous ILL exp.
  - $\vec{B}_E = \vec{v} \times \vec{E} \rightarrow$ changes $\vec{\mu}$ precession frequency
    - Adds geometric phase when combined with B gradients

# Projected systematic errors

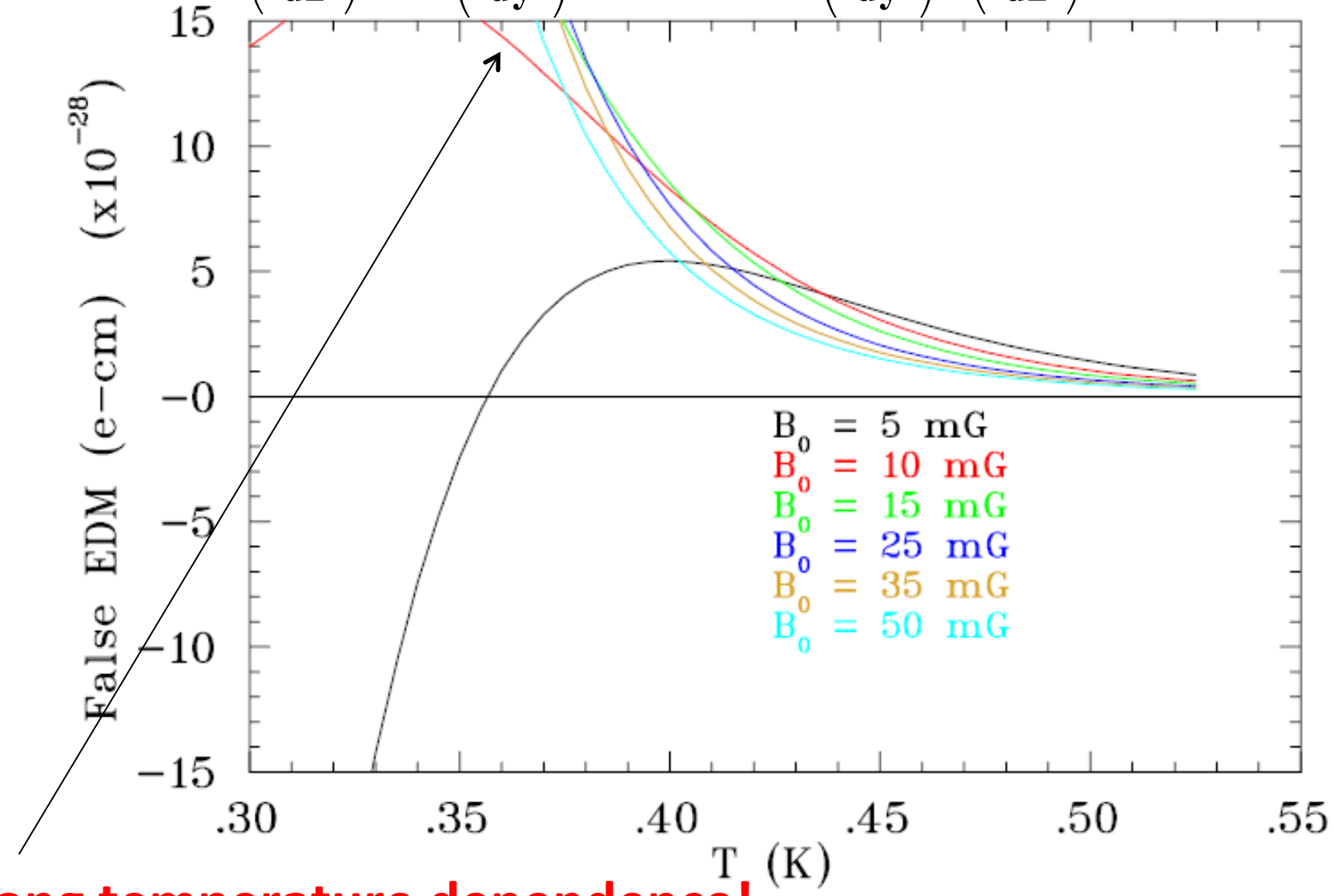
| Error Source | Systematic error (e-cm) | Comments |
|---|---|---|
| Linear vxE (geometric phase) | $< 2 \times 10^{-28}$ | Uniformity of $B_0$ field |
| Quadratic vxE | $< 0.5 \times 10^{-28}$ | E-field reversal to <1% |
| Pseudomagnetic Field Effects | $< 1 \times 10^{-28}$ | $\pi/2$ pulse, comparing 2 cells |
| Gravitational offset | $< 0.2 \times 10^{-28}$ | With E-field dependent gradients < 0.3nG/cm |
| Heat from leakage currents | $< 1.5 \times 10^{-28}$ | < 1 pA |
| vxE rotational n flow | $< 1 \times 10^{-28}$ | E-field uniformity < 0.5% |
| E-field stability | $< 1 \times 10^{-28}$ | $\Delta E/E < 0.1\%$ |
| Miscellaneous | $< 1 \times 10^{-28}$ | Other vxE, wall losses |

# Systematic Controls in nEDM@SNS experiment

- Highly uniform E and B fields
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Ability to vary influence of $B_0$ field
  - via "dressed spins"
- Can study dependence on $|B|$, $\vec{B}$, B-gradients & $^3He$ density
- Control of central temperature
  - Can vary $^3He$ diffusion which changes geometric phase effect on $^3He$

# e.g. - Geometric phase effect for $^3$He

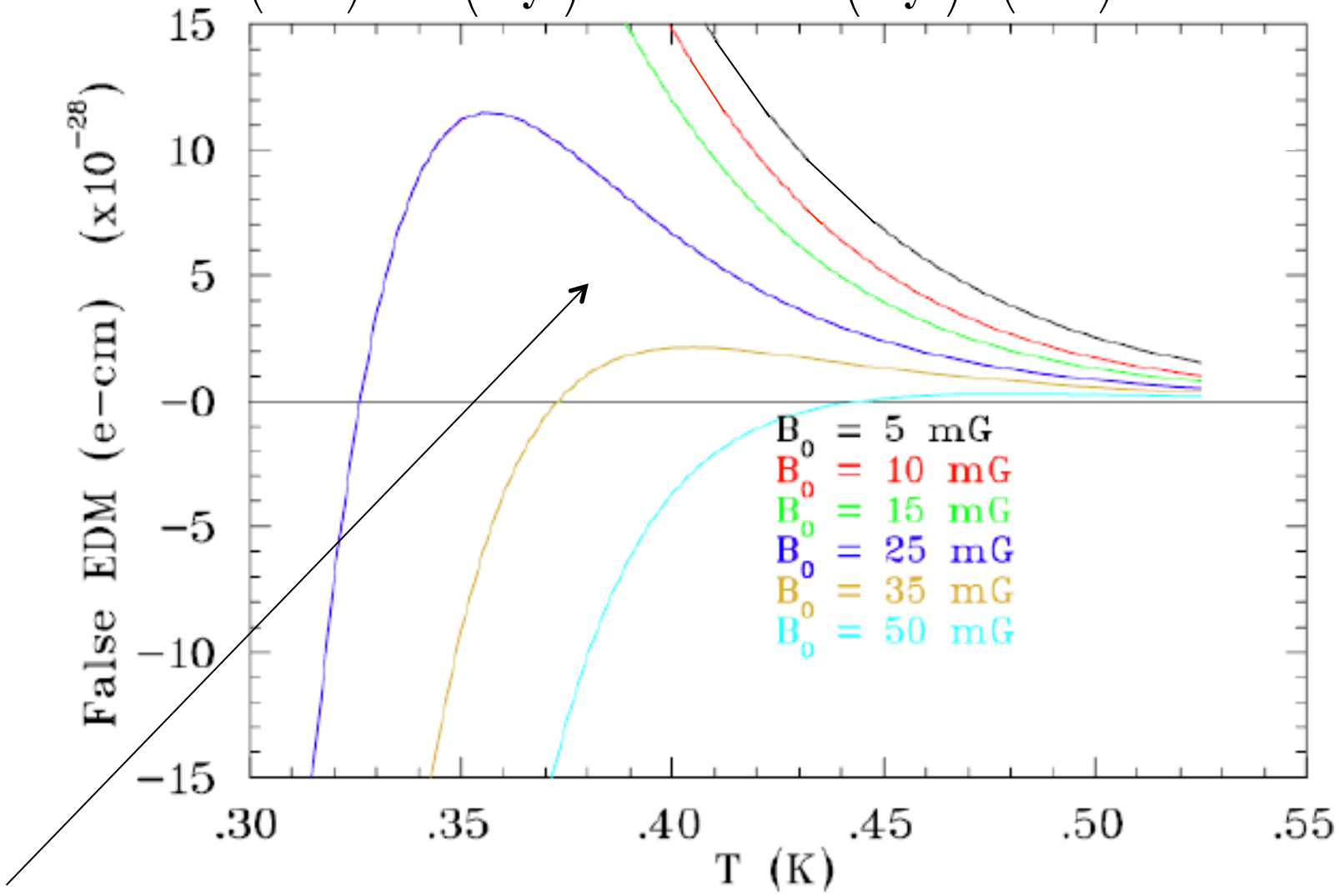
$$\left(\frac{\partial B_z}{dz}\right) = -\left(\frac{\partial B_y}{dy}\right) \; ; \; Assuming \; \left(\frac{\partial B_y}{dy}\right), \left(\frac{\partial B_z}{dz}\right) \propto B_0$$




**Strong temperature dependence!**

# e.g. - Geometric phase effect for $^3$He

$$\left(\frac{\partial B_z}{dz}\right) = +\left(\frac{\partial B_y}{dy}\right) \; ; \; Assuming \; \left(\frac{\partial B_y}{dy}\right), \left(\frac{\partial B_z}{dz}\right) \propto B_0$$




**Strong temperature dependence!**

# Status & Timeline

## Recent NSAC (Nuclear Science Advisory Committee) Subcommittee on Fundamental Nuclear Physics with Neutrons (report 11/11)

### Motivation remains Strong

The successful completion of an nEDM experiment, the initiative with the highest scientific priority in US neutron science, would represent an impressive scientific and technical achievement for all of nuclear physics, with ramifications that extend far beyond the field.

### Sensitivity Remains Compelling

- **nEDM conceptual design is novel**
  - *large active volume: gain statistical sensitivity to 1-10x10$^{-28}$ e-cm*
  - *several novel techniques to explore unknown new systematics*
  - *only concept aimed directly at exploring a new regime of sensitivity*
- **nEDM reach is nominally estimated at 4x10$^{-28}$ e-cm**
  - *such reach would have profound impact beyond subfield even if negative*

### But …

A 2-year window is proposed to allow collaboration to complete critical R&D prior to starting construction (main focus is HV studies)

### Construction can then begin (~ 4-5 years required)

# NSAC subcommittee Report 11/11

No Showstoppers

- **Significant further R&D is required**
  - *Fundamental physics concepts related to measurement techniques validated, but important details still being worked out*
  - *Several key aspects of the measurement technique remain unproven under true experimental conditions: HV breakdown limit, electric field monitoring, electrode coating, and total photoelectron yield per signal event*
- **The subcommittee feels that the collaboration needs:**
  - *A singular focus on outstanding R&D issues*

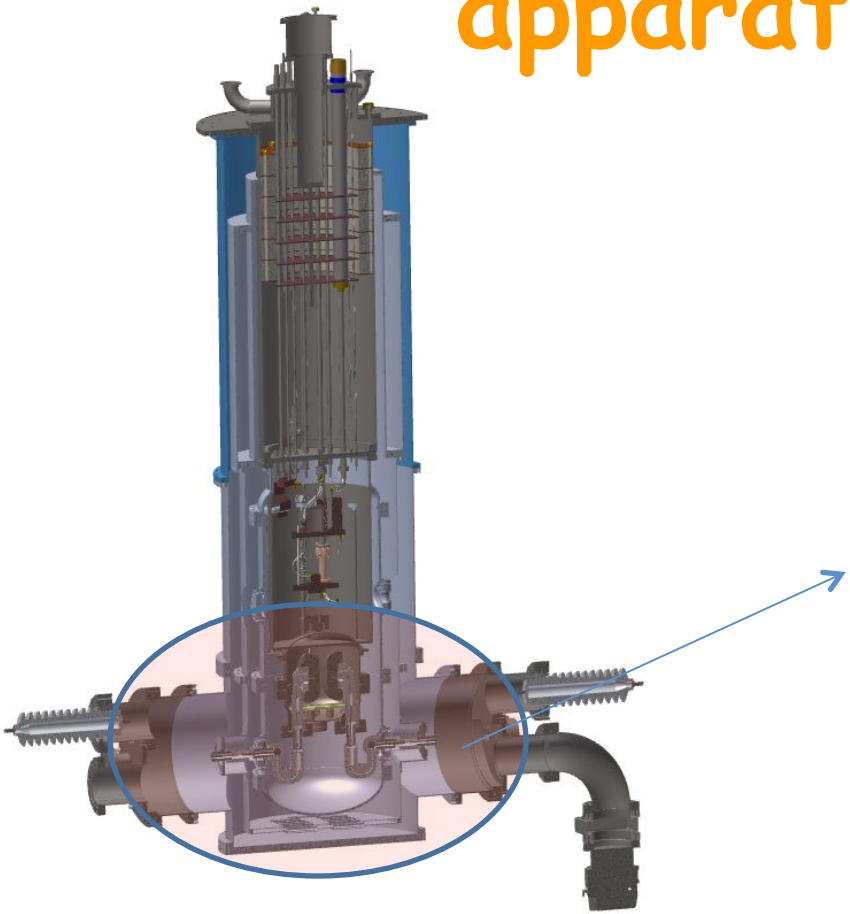
Less focus on advance to CD2 (a.k.a. project base-lining for construction project - challenging due to R&D nature of some aspects of the experiment)

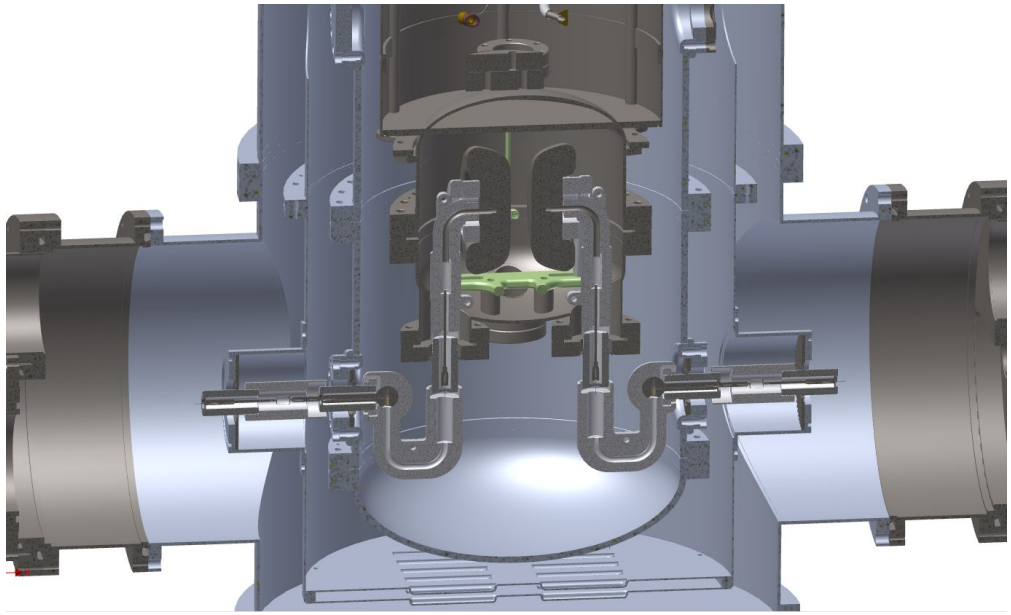
- **Impact of Review**
  - MIE project has been stopped
  - Active R&D is underway

# Singular focus on R&D

- HV strength & electrode material
- Magnetic field uniformity & Superconducting shielding studies
- Light collection from scintillation
- Development of polarized UCN & $^3$He test facility
- 3He transport studies
- Other issues
  - SQUID development & UCN storage studies

# New "Medium-Scale" HV apparatus @ LANL

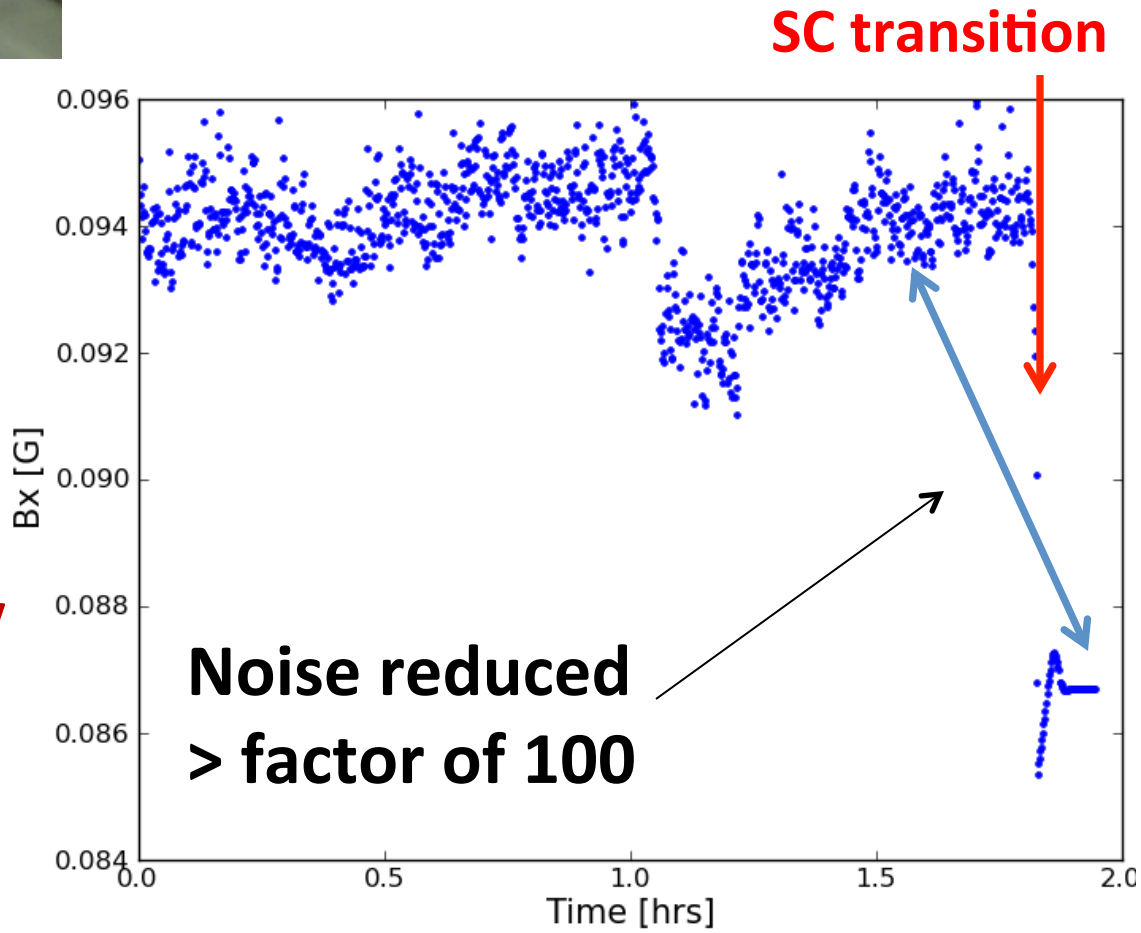




- New apparatus has faster turn-around and flexibility
- Detailed electrode materials studies underway
- V. Cianciolo (ORNL) → Electrode Materials Czar

# ½-scale Magnet & Super- conducting Shield Studies @ Caltech

- Characterize stability and shielding of superconducting shield
- Verify required uniformity at operating field

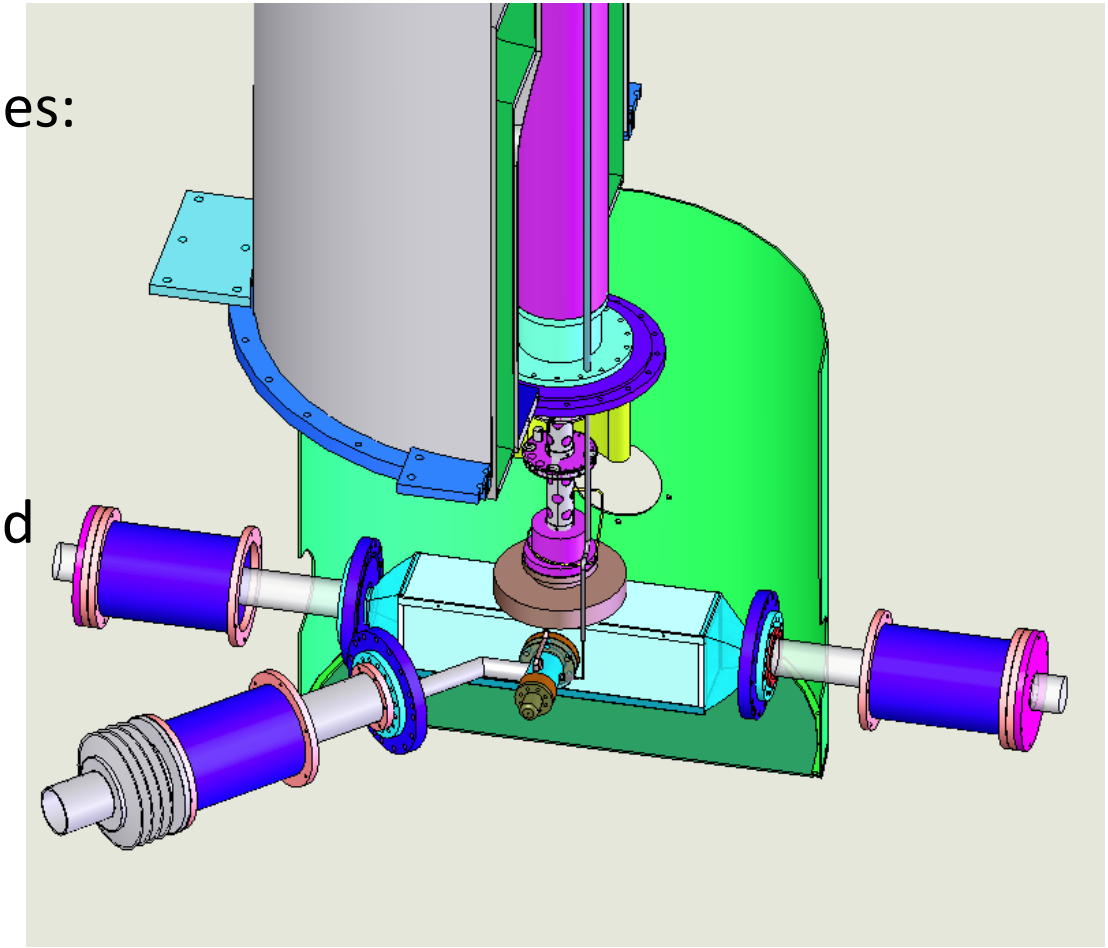


# Test Facility using PULSTAR reactor @ NCSU

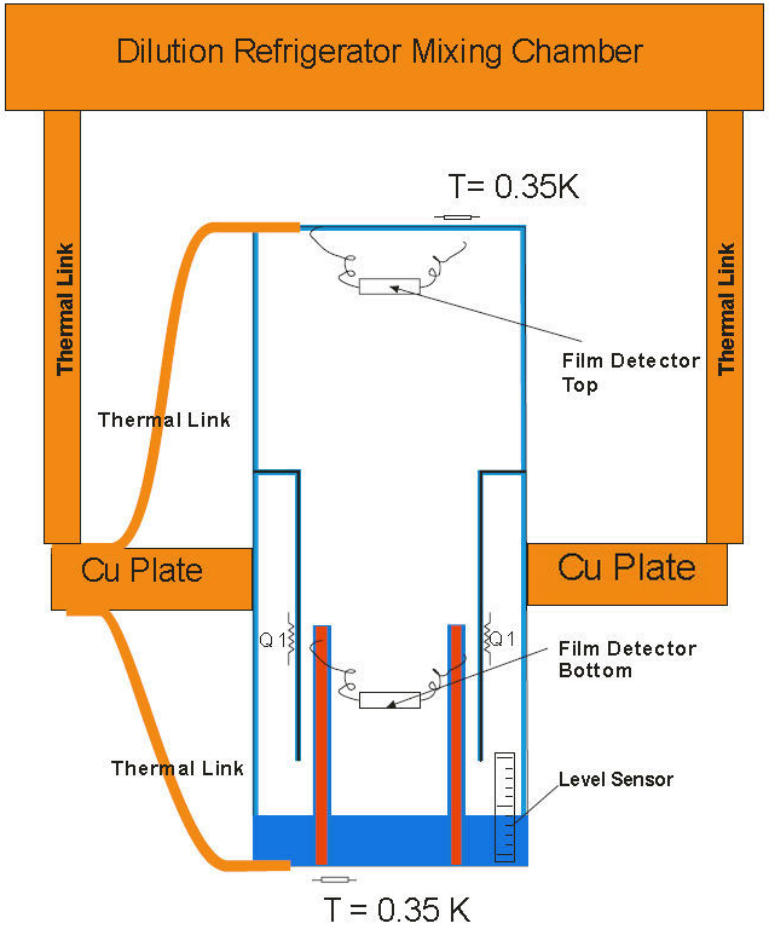
- Smaller, simpler apparatus allows fast turnaround

  (~ 2 weeks vs ~ 2 months)

- Addresses key scientific issues:
  - Critical Dressing
  - Geometric phase studies
  - Spin Manipulation Studies
- Expertise gained in these studies will result in reduced systematic uncertainties



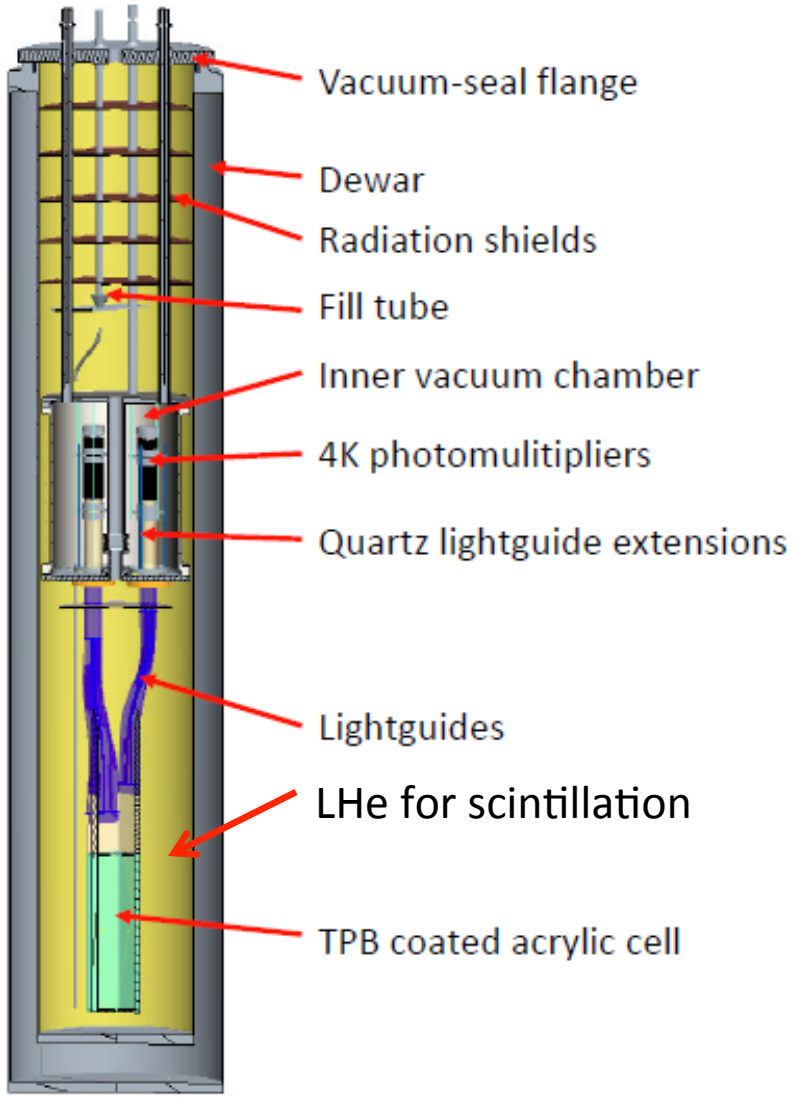
# Film Burner studies @ Harvard



**Need to suppress superfluid film flow at large scale for efficient $^3$He injection into LHe**

# Cryogenic Light Collection studies @ ORNL

- Cross check calculations of scintillation light production and transport
- Hardware under construction with tests planned for 2012



# Overall Cost Estimate

| nEDM Estimated Construction Profile ($M) | < FY14 | FY14 | FY15 | FY16 | FY17 | FY18 | FY19 | FY20 | FY21 | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Estimated Spending Profile (DOE +NSF) | 13.5 | 3.9 | 11.7 | 7.4 | 6.0 | 3.6 | 2.1 | 1.9 | 0.3 | 50.0 |
| Funding (Flat-flat at FY13 levels) | 13.5 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 23.5 |
| Difference | 0.0 | -2.6 | -10.4 | -6.1 | -4.7 | -2.3 | -0.8 | -0.6 | 1.0 | -26.5 |
| Cumulative Difference | 0.0 | -2.6 | -13.0 | -19.1 | -23.8 | -26.1 | -26.9 | -27.5 | -26.5 | |

- R&D funded for next 18 months via capital $$, program funds & carry-over
- Construction costs to complete hardware ~ 27M$

# Worldwide nEDM experiments

| Exp | UCN source | cell | Measurement techniques | $\sigma_d$ ($10^{-28}$ e-cm) |
|---|---|---|---|---|
| **ILL CryoEDM** | **Superfluid $^4$He** | **$^4$He** | Ramsey technique for $\omega$<br>External SQUID magnetometers | **Phase1 ~ 50**<br>**Phase 2 < 5** |
| **PNPI – ILL** | **ILL turbine**<br>**PNPI/Solid $D_2$** | **Vac.** | Ramsey technique for $\omega$<br>$\vec{E}$=0 cell for magnetometer | **Phase1<100**<br>**< 10** |
| **ILL Crystal** | **Cold n Beam** | **solid** | Crystal Diffraction | **< 100** |
| **PSI EDM** | **Solid $D_2$** | **Vac.** | Ramsey for $\omega$, external Cs & $^3\vec{He}$ magnetom.Possible Xe or Hg comagnetometer | **Phase1 ~ 50**<br>**Phase 2 < 5** |
| **Munich FRMII** | **Solid $D_2$** | **Vac.** | Under Construction (similar to PSI | **< 5** |
| **SNS EDM** | **Superfluid $^4$He** | **$^4$He** | $^3\vec{He}$ capture for $\omega$<br>$^3\vec{He}$ comagnetometer<br>SQUIDS & Dressed spins | **< 5** |
| **TRIUMF** | **Superfluid $^4$He** | **Vac.** | Phase I @ RCNP | **< 10** |
| **JPARC** | **Solid $D_2$** | **Vac.** | Under Development | **< 5** |
| **NIST** | **Crystal** | **Solid** | R & D | **~ 5 ?** |

# Why so many nEDM??

- Science remains compelling even with LHC data

"…it may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron electric dipole moment."

**S. Weinberg arXiv:hepph/9211298**

"The top priority projects (**ATLAS, CMS, nEDM) were confirmed in this status and were** graded alpha 5. "

**Particle Physics, Astronomy and Nuclear Panel - UK - 2008**

- Superthermal UCN sources promise higher densities
- Exciting opportunity for new & existing facilities
  - New = FRMII,JPARC,SNS
  - Existing = ILL,PSI,TRIUMF

# It's More than just Sensitivity & Timescale

- The "known" systematic effects are part of the experimental design
- Tackling the unknown effects requires unique handles in the experiment that can be varied
- The significance of a non-zero result requires multiple approaches to unforeseen systematics
- nEDM @ SNS is unique in its use of a polarized $^3$He co-magnetometer, characterization of geometric phase effects via temperature variation, as well as both SQUID & dressed-spin measurement capability

# Comparison of Capabilities

| | CRYOEDM1 | CRYOEDM2 | PSIEDM2 | PSIEDM3 | SNSEDM | |
|---|---|---|---|---|---|---|
| Δω via accumulated phase in n polarization | ■ | ■ | ■ | ■ | ■ | |
| Δω via light oscillation in $^3$He capture | ■ | ■ | ■ | ■ | ■ | |
| Co-magnetometer | ■ | ■ | ■ | ■ | ■ | ★ |
| Superconducting B-shield | ■ | ■ | ■ | ■ | ■ | ★ |
| Dressed Spin Technique | ■ | ■ | ■ | ■ | ■ | ★ |
| Horizontal B-field | ■ | ■ | ■ | ■ | ■ | |
| Multiple EDM cells | ■ | ■ | ■ | ■ | ■ | ★ |
| Temperature Dependence of Geo-phase effect | ■ | ■ | ■ | ■ | ■ | ★ |

■ = included ■ = not included ★ = systematics advantage

# Long term Prospects (>2020):

- Fermilab Project X may be an upgrade path for higher neutron density $\delta d_n \propto 1/\sqrt{N_n}$
  - $n - \bar{n}$ oscillation phase I beam may give ~ 25x more cold neutron flux = 25x more UCN for nEDM
- Once systematics have been studied at ORNL pushing statistics to $\delta d_n < 1 \cdot 10^{-28}$ e-cm may be reasonable

# Take Away Message …

- Importance of greatly improving neutron EDM sensitivity is recognized worldwide
- A number of exciting technologies are being developed to extend the nEDM sensitivity by at least two orders-of-magnitude
- nEDM@SNS is world-leading in sensitivity and systematic error control

**Advertisement:**
**International Workshop on Neutron EDM Experimental Techniques at ORNL 10/11-13/2012**

# Extra Slides…

# Examples of the Experimental Challenges

- UCN storage
  - Sufficient storage & polarization time
- Scintillation light production & transport
  - Getting EUV to wavelength shifter
  - Sufficient photoelectrons after conversion & transport
- SQUIDs
  - Sensitivity
  - Survival after HV sparks
  - Ability to measure B-field gradients

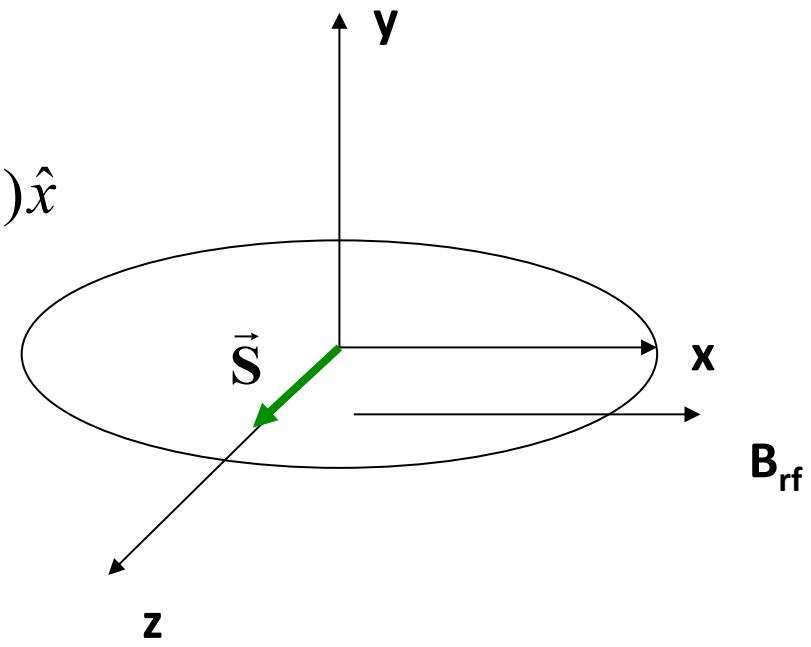
# Examples of the Experimental Challenges

- HV in superfluid He
  - > 70kV/cm at T < 0.5K
  - Non-metallic electrodes to minimize magnetic Johnson noise and eddy currents
  - Electrodes that minimize neutron activation
  - Robust system that can survive accidental sparking
- B-field
  - Superconducting shield (not used in previous EDM experiments)
  - Uniformity (gradients < 100nGauss/cm) and control (< 0.1ppm measurement of $B_1$ dressing field for E-field flip)
  - Eddy current heating during dressed spin
- $^3$He
  - Polarization, purity and transport
  - 3He injection in presence of superfluid film flow
  - Heat flush in large-scale system below 0.5K

# Classical spin in AC B-field

**Consider**

$$\vec{B} = B_{rf}\cos(\omega_{rf}t)\hat{x}$$




**Solution:**

Spin precesses with frequency: $\omega(t) = \dot{\theta}(t) = \gamma B = \gamma B_{rf}\cos(\omega_{rf}t)$

$$S_z = \cos(\theta) = \cos\left[\left(\frac{\gamma B_{rf}}{\omega_{rf}}\right)\sin(\omega_{rf}t)\right] \quad ; \ \& \text{ averaging over time:}$$

$$\langle S_z \rangle = \frac{\omega_{rf}}{\pi}\int_0^{T/2} S_z dt \equiv \frac{1}{\pi}\int_0^{\pi}\cos\left[\frac{\gamma B_{rf}}{\omega_{rf}}\sin(\theta)\right]d\theta \equiv J_0\left(\frac{\gamma B_{rf}}{\omega_{rf}}\right) = J_0(x)$$