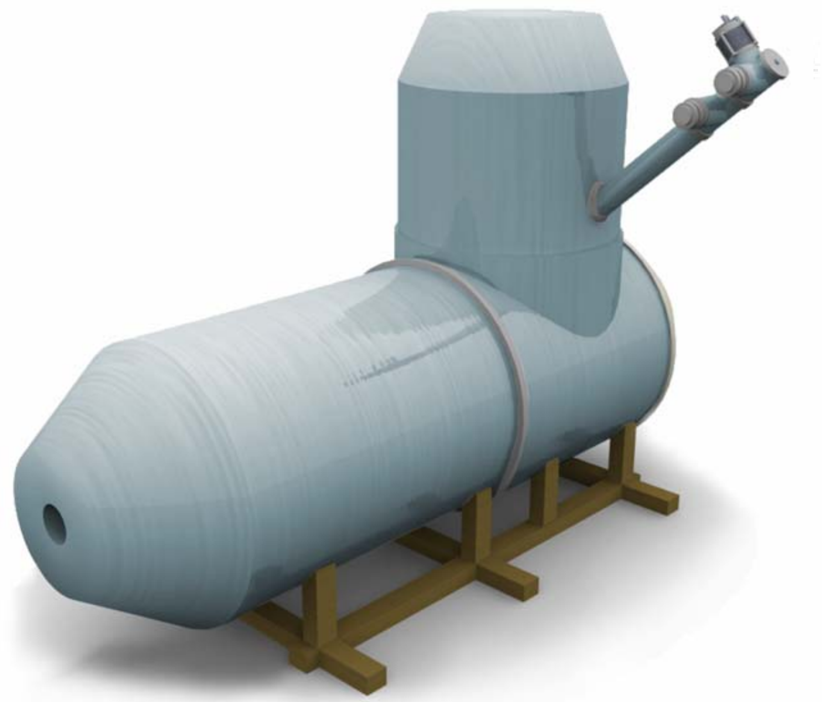
Search for a Neutron Electric Dipole Moment at the SNS



Chris Gould

North Carolina State University ,
Triangle Universities Nuclear Laboratory and
the nEDM project collaboration

NC STATE UNIVERSITY

OAK RIDGE NATIONAL LABORATORY

Executive Summary

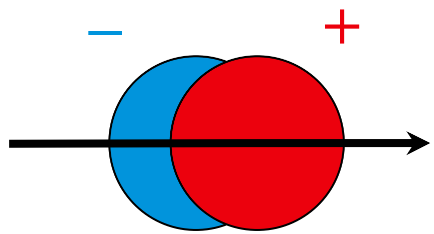
- *Goal*: To develop a new experimental technique to search for the neutron electric dipole moment (EDM) that offers a factor of at least 100 increase in sensitivity over existing measurements.
- *Motivation*: The search for this moment has the potential to reveal new sources of time reversal (*T*) and charge conjugation and parity (*CP*) violation and to challenge calculations that propose extensions to the Standard Model.

Collaborating Institutions (nEDM)

Definition of an EDM

- A permanent neutron EDM d: a separation of the charged constituents of the neutron along the direction of the spin.

$\vec{d}\cdot\vec{E}$



$\vec{s} = 1/2$

$\vec{d} = 2d_n\,\vec{\mathbf{s}}$

- An edm for a non-degenerate system is evidence of P and T symmetry breaking (W.E theorem **d ~ s,** but **d** is T-even, whereas **s** is T-odd; v.v for parity)

How large might an edm be?

- $d_n \sim e \times$ nucleon size $\times$ weak interaction $\times$ CP violation

  10^{-13} 10^{-7} 10^{-3}

  $\sim 10^{-23}$ e-cm

- The current experimental limit is a factor of hundred smaller: $d_n < 3 \times 10^{-26}$ e•cm (Institut Laue Langevin).

- Standard model prediction $\sim 10^{-32}$ e-cm, but extensions predict effects at 10^{-28} e•cm level.

Mission Impossible 4?

- We hope to obtain $d_n < 10^{-28}$ e•cm at the SNS

- Like looking for a 0.01 micron bump at the North Pole.

- What's new? Use ultracold neutrons stored in liquid helium, with polarized 3-He as a co-magnetometer (Golub and Lamoreaux- Phys. Reports)

CP-Violation in the Standard Model

- Occurs in two places:
  - As a complex phase in the CKM matrix
  - In the θ term in the QCD Lagrangian
- CP-violation observed in the kaon and B meson system is consistent with the presence of the phase
- Present bounds on the QCD-θ term from primarily EDM measurements give values for θ that are very small (10^{-9}). This small value has led to the search for axions.
- A new source of *CP*-violation is required to explain the observed matter-antimatter asymmetry in the Universe.

Uncertainty principle limit to edm measurement

Measure energies for ± spins in fields ±E for time T:

Uncertainty in each energy is $\delta W_{\pm} \sim \hbar / T$

Energy difference is $W_{+} - W_{-} = 4\, d_n\, E$

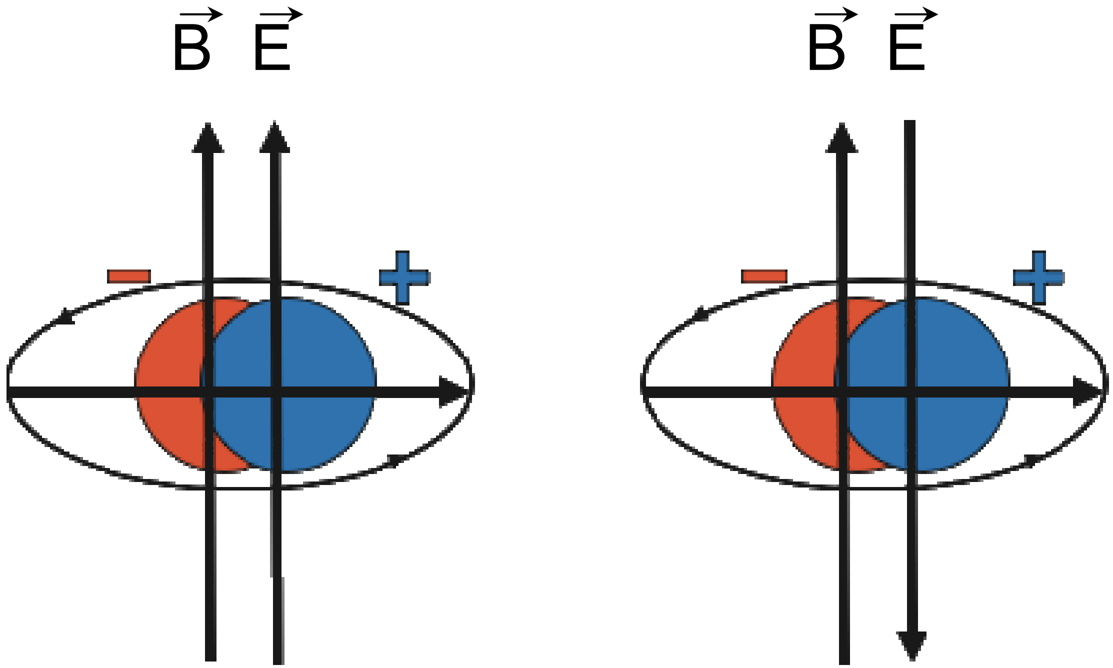
For N neutrons: $\delta d_n \sim \hbar / (2\, E\, T \sqrt{N})$

Need:

- large E ~ 10^6 V/m
- large N (~ 10^8 for ILL)
- long T (~ 100s for UCN's)

ILL experiment got within a factor of two!

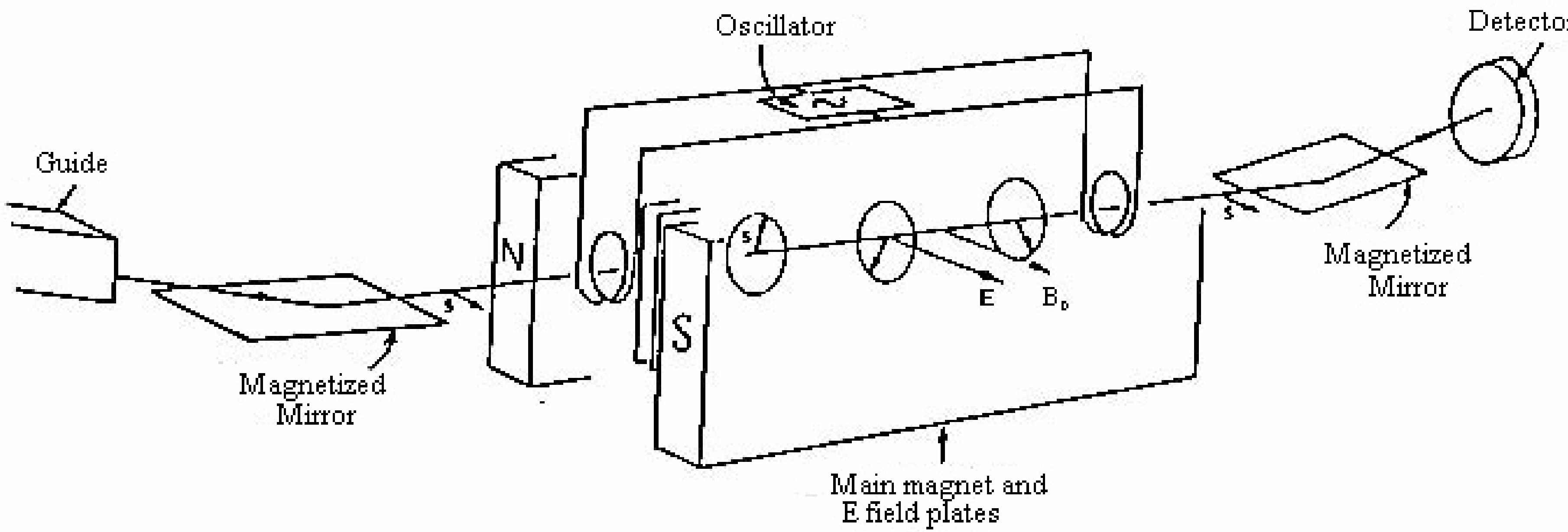
Basic Technique



Look for a precession frequency $\omega_n = 2\mu_n B \pm 2d_n E$

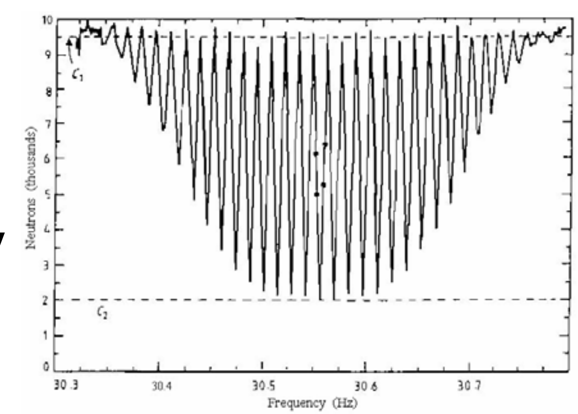
A moment of 10^{-25} e•cm in a 10 kV/cm electric field corresponds to a shift in frequency of 0.5 μHz!

Ramsey two coil method



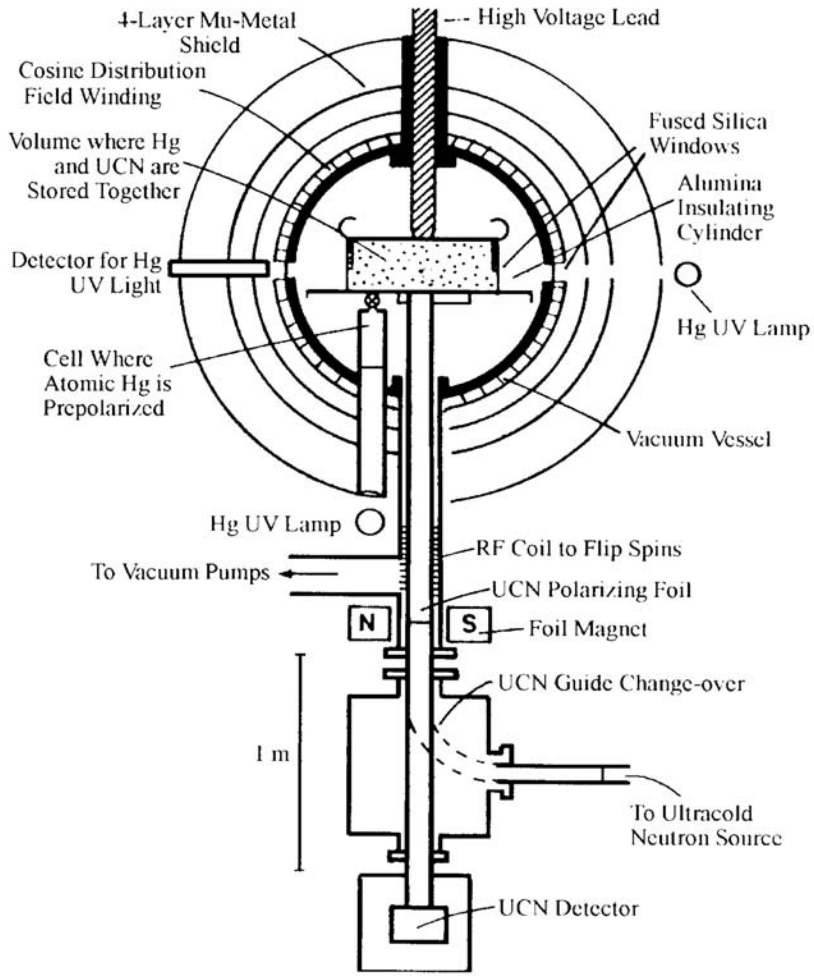
- Phase angle $\Phi = (\omega_B + \omega_E - \omega_{rf})\,T$
- Intensity at detector ~ $\sin^2(\Phi/2)$
- Look for change in neutron intensity when E is reversed

ILL 1990 data



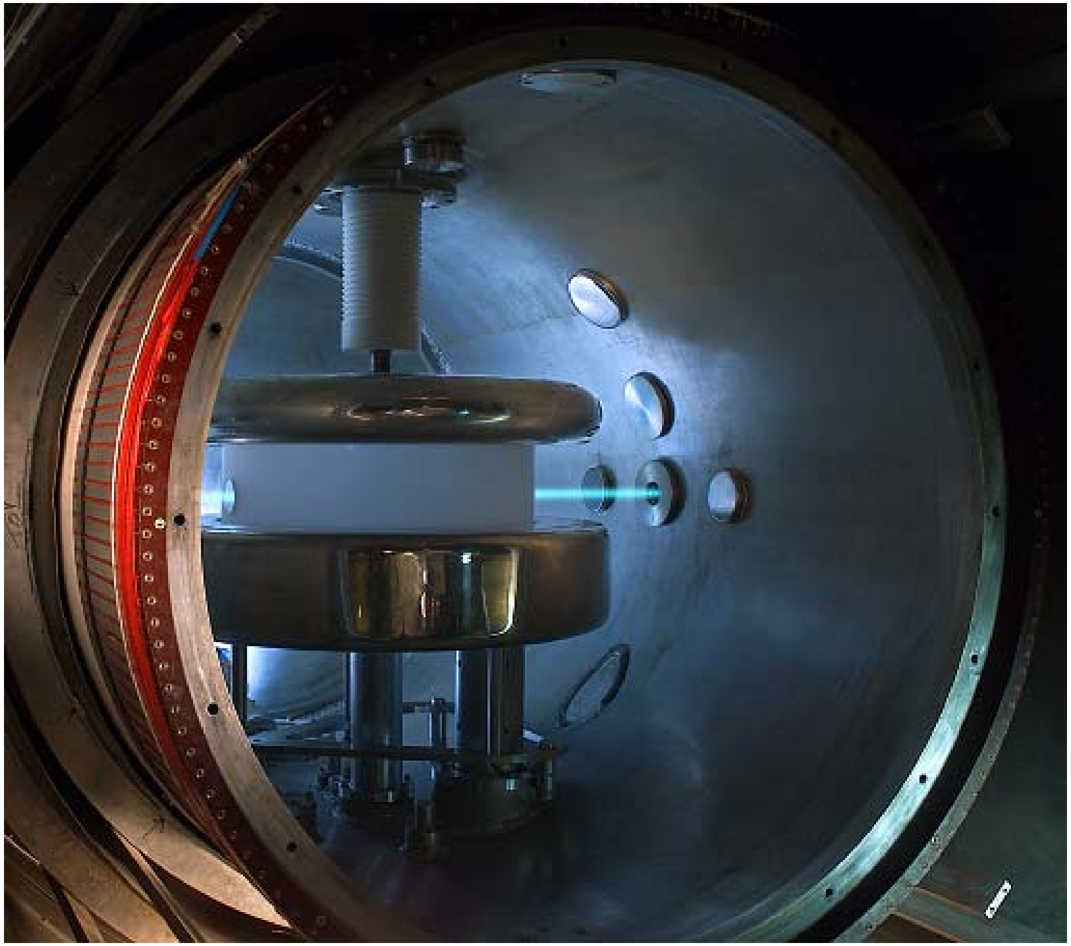
ILL Neutron EDM Experiment

- Provides the current best limit: $d_n < 3 \times 10^{-26}$ e•cm
- Employs a ^{199}Hg Co-magnetometer
- Characteristics:
  - 1 UCN/cc
  - 10 kV/cm
  - 100 s neutron storage time
- A new systematic
- “geometric phase” effect was found in this work (controllable to the $< 10^{-28}$ e•cm level for our experiment).



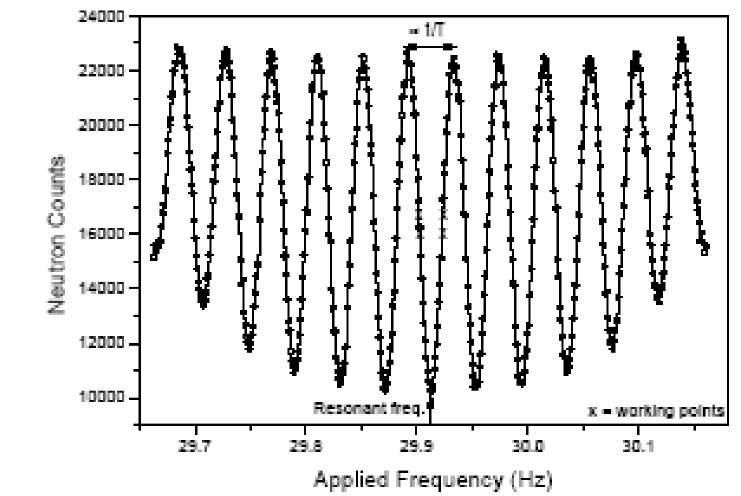
Schematic of the ILL UCN EDM experiment incorporating a ^{199}Hg comagnetometer

ILL EDM Experiment

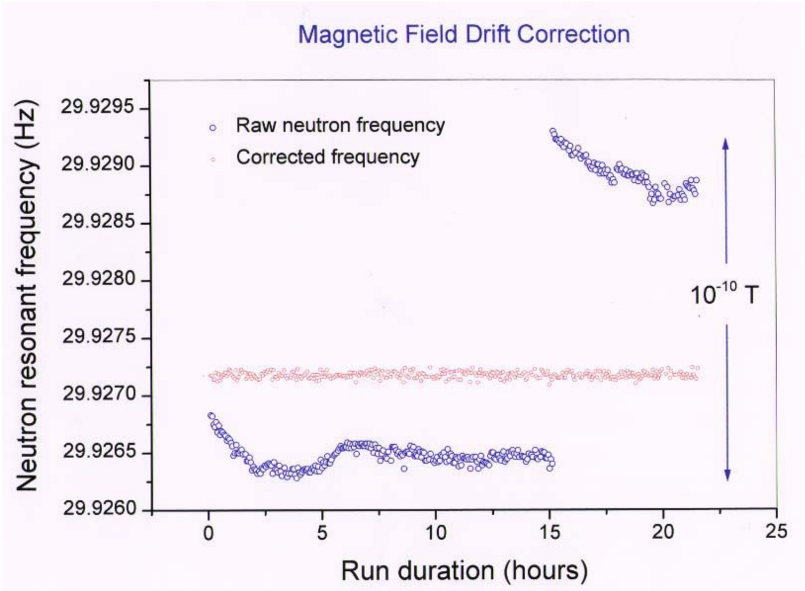


Importance of a co-magnetometer

- ILL experiment (Baker et al PRL 2006) uses a Hg vapor co-magnetometer– removes B field jump ~ 10^{-10} T



- Conclusion: need to monitor B where the neutrons are!
- Do better with ^{3}He?



Evolution of Neutron EDM Experiments

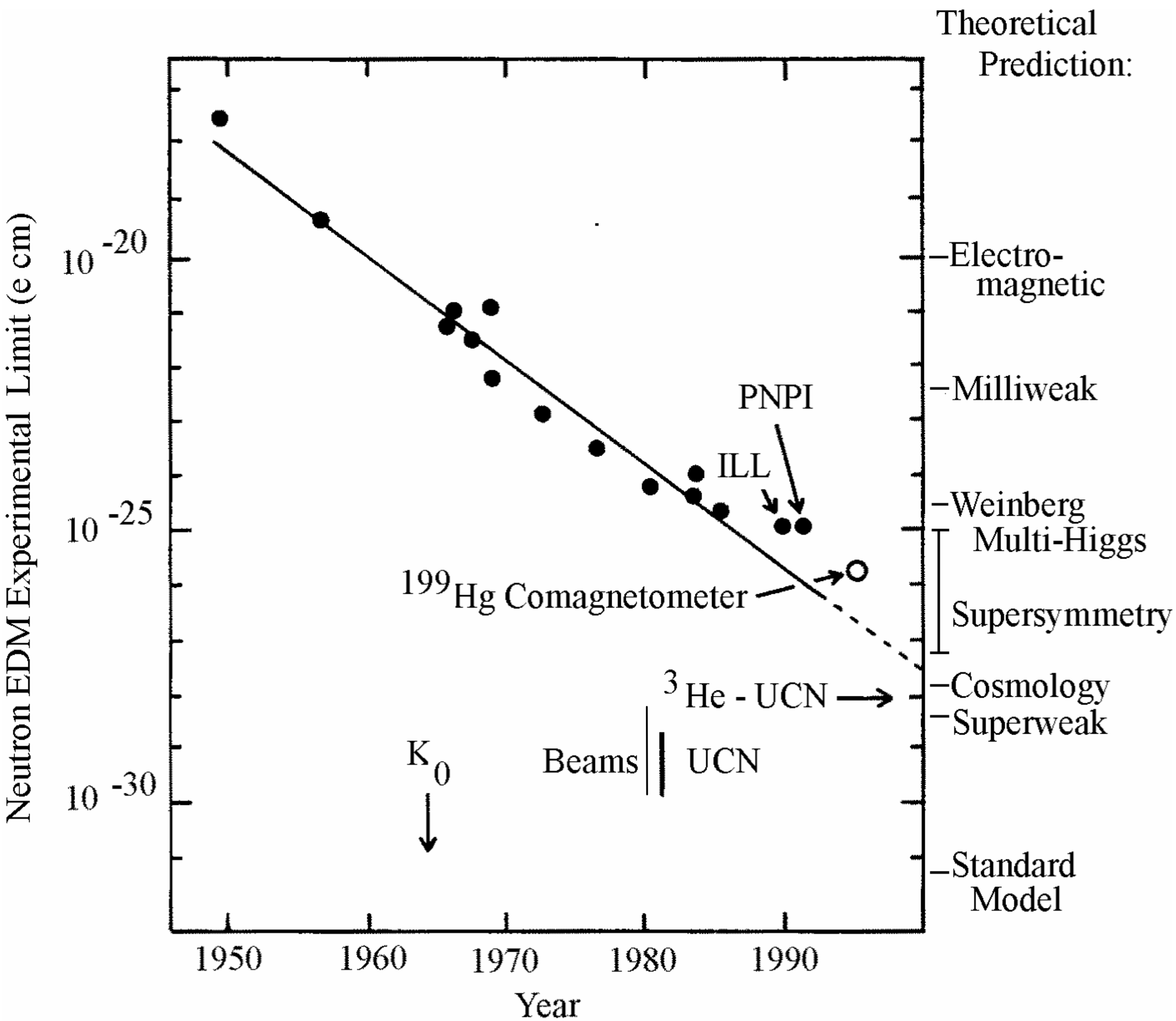


Figure of Merit for EDM Experiments

$$E\,\tau\,\sqrt{N}$$

By performing the experiment directly in superfluid helium-4 (dielectric properties + superthermal neutron production) that is doped with polarized helium-3 that serves as a co-magnetometer and spin precession analyzer:

$\tau \rightarrow 5\,\tau$
$N \rightarrow 100\,N$
$E \rightarrow 5E$

potentially × 250 when operated at the SNS

Lifetime τ in a Storage ($\tau \rightarrow 5\ \tau$)

- Goal: 500 seconds storage time
- Production rate at SNS implies P = 0.3-1 /(cc sec) production

$$\rho = P\,\tau$$

$$\frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_w} + \frac{1}{\tau_3} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{hole}}$$

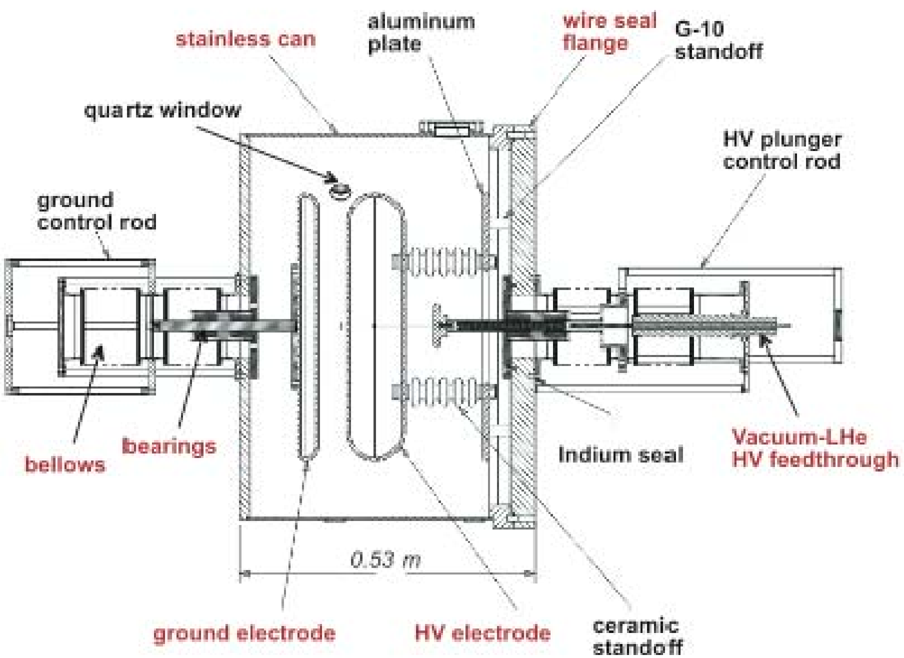
where τ_n is the neutron lifetime,
τ_w is the wall lifetime,
τ_3 is the absorption lifetime,
τ_{up} is the upscattering lifetime,
τ_{hole} is lifetime due to loss through holes.

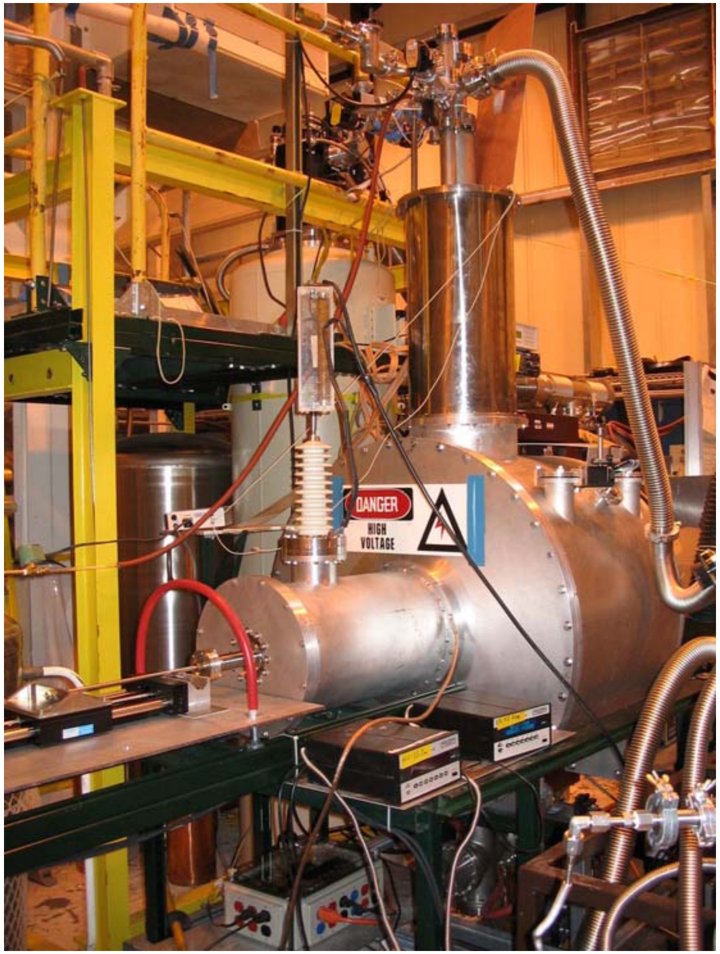
High Voltage Capacitor System (E → 5 E)

- Employs a capacitive amplification technique

d = 0.5	5	cm
HV = 50	500	kV

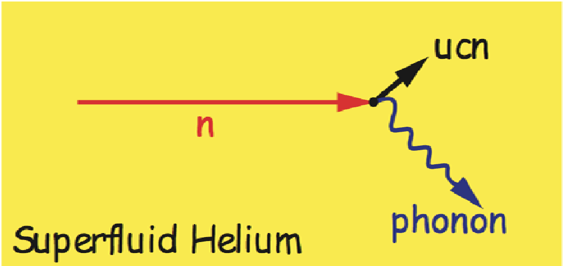
q=CV



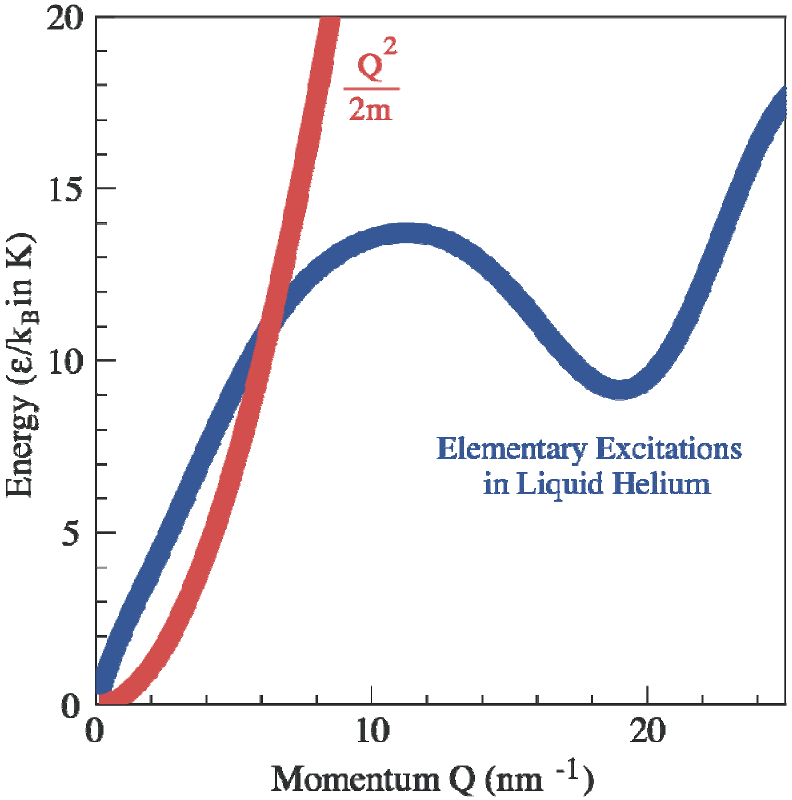


Superthermal Production of UCN (N → 100 N)

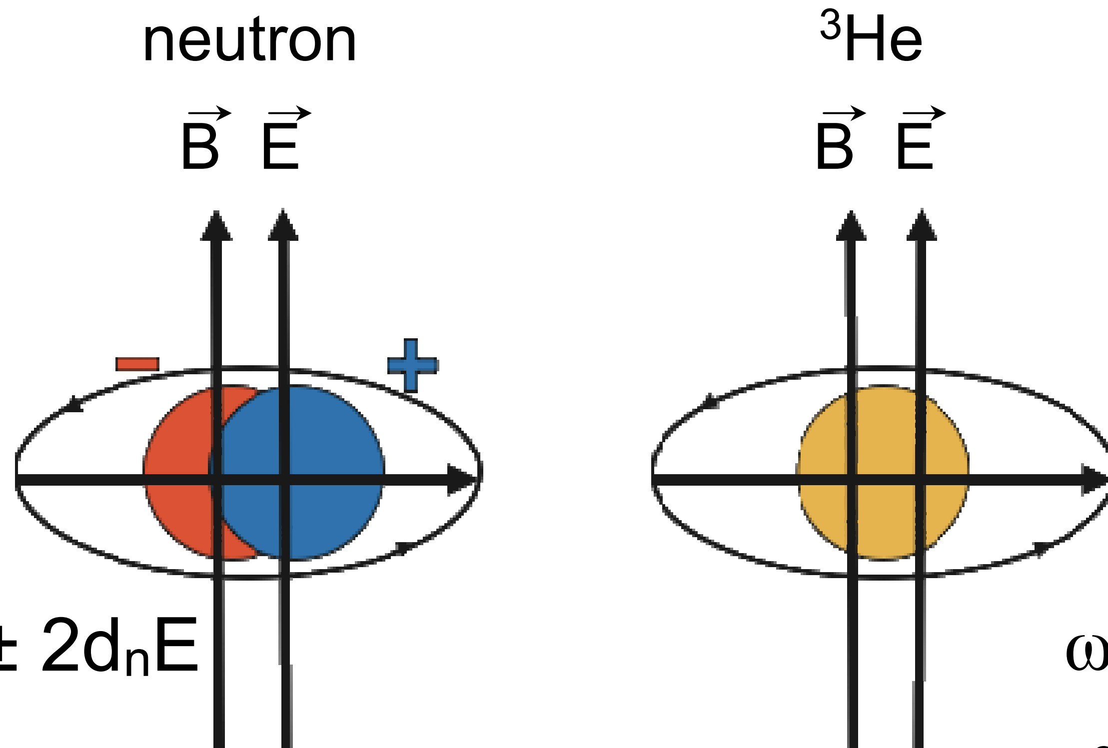
- 8.9 Å (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.



- Upscattering (by 12 K phonon absorption)
- ~ Population of 12 K phonons ~ $e^{-12\ K/T_{bath}}$



^{3}He Co-Magnetometer



$$\omega_n = 2\mu_n B \pm 2d_n E$$

$$\omega_3 = 2\mu_3 B$$

$$\mu_3 = 1.1\ \mu_n$$

- Look for a difference in precession frequency

  $$\omega_n - \omega_3 = 2(\mu_n - \mu_3)B \pm 2d_n E$$

^{3}He Co-Magnetometer

$$^3\mathrm{He} + n \rightarrow t + p$$

σ(parallel) < 10^2 b

σ(opposite) ~ 10^4 b

- $1 - \vec{p}_3 \cdot \vec{p}_n = 1 - p_3 p_n \cos[2(\mu_n - \mu_3)B_0 + 2dE]\, t$
- Detect ^{3}He precession rate with SQUIDS.
- $|\mu_n - \mu_3| = |\mu_3|/10$ – Sensitivity to magnetic fields is reduced by an order of magnitude!
- ^{3}He concentration must be adjusted to keep the lifetime τ reasonable for a given value of the ^{3}He polarization.
- The proper value for the fractional concentration $x = {}^3\mathrm{He}/{}^4\mathrm{He} \sim 10^{-10}$.

Dressed Spin

$$\gamma_3 = 1.1\gamma_n$$

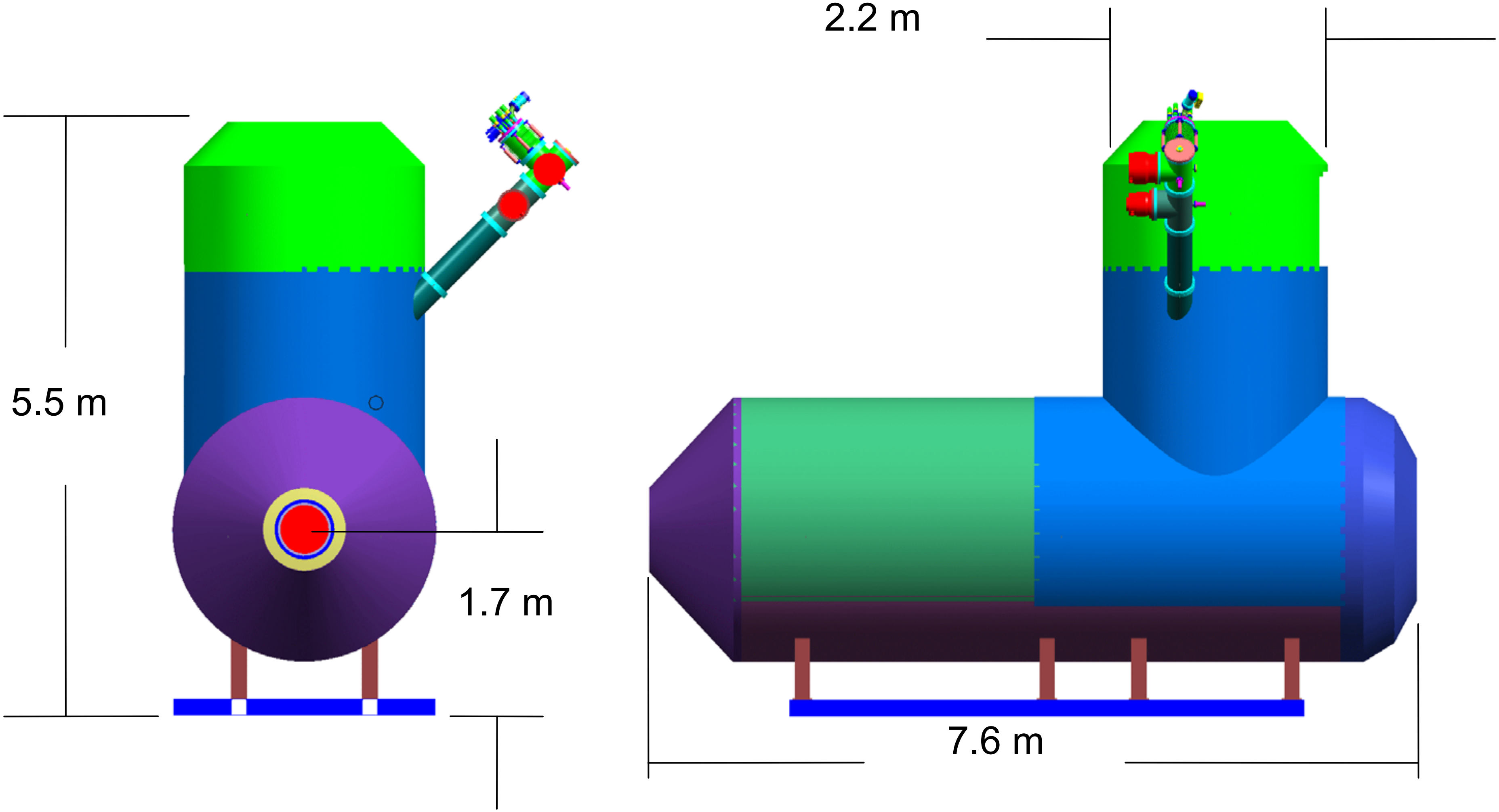
$$\gamma' = \gamma J_o(\gamma B_{rf}/\omega_{rf})$$

$$\gamma_n' = \gamma_3' \quad \text{when} \quad \gamma_n B_{rf}/\omega_{rf} \approx 1.1$$

- $B_{rf} >> B_0$ (1-10 mG) so B_{rf} ~ 1 G, $\omega_{rf}/2\pi$ ~ 3 kHz.
- RF field must be homogeneous at the 0.1–1% level.
- Heating and gradients due to eddy currents present design challenges.
- Eliminates need for SQUID magnetometers and may increase the sensitivity of the experiment.

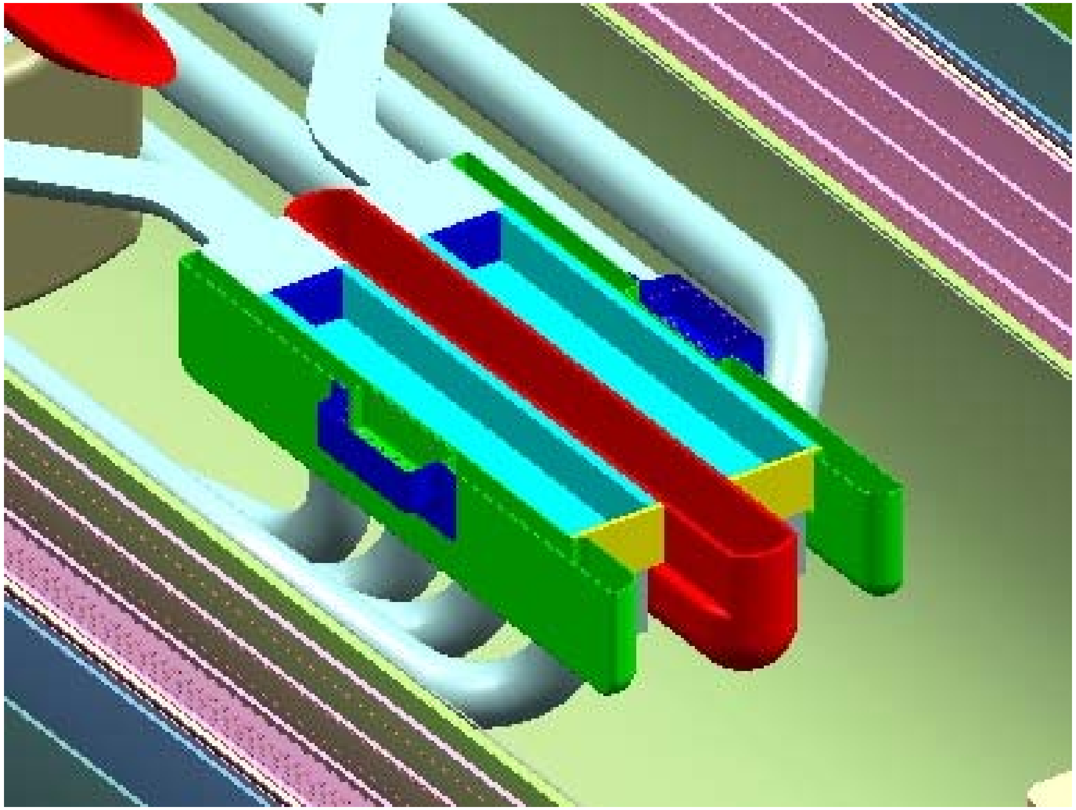
The Experimental Apparatus

Overall Size



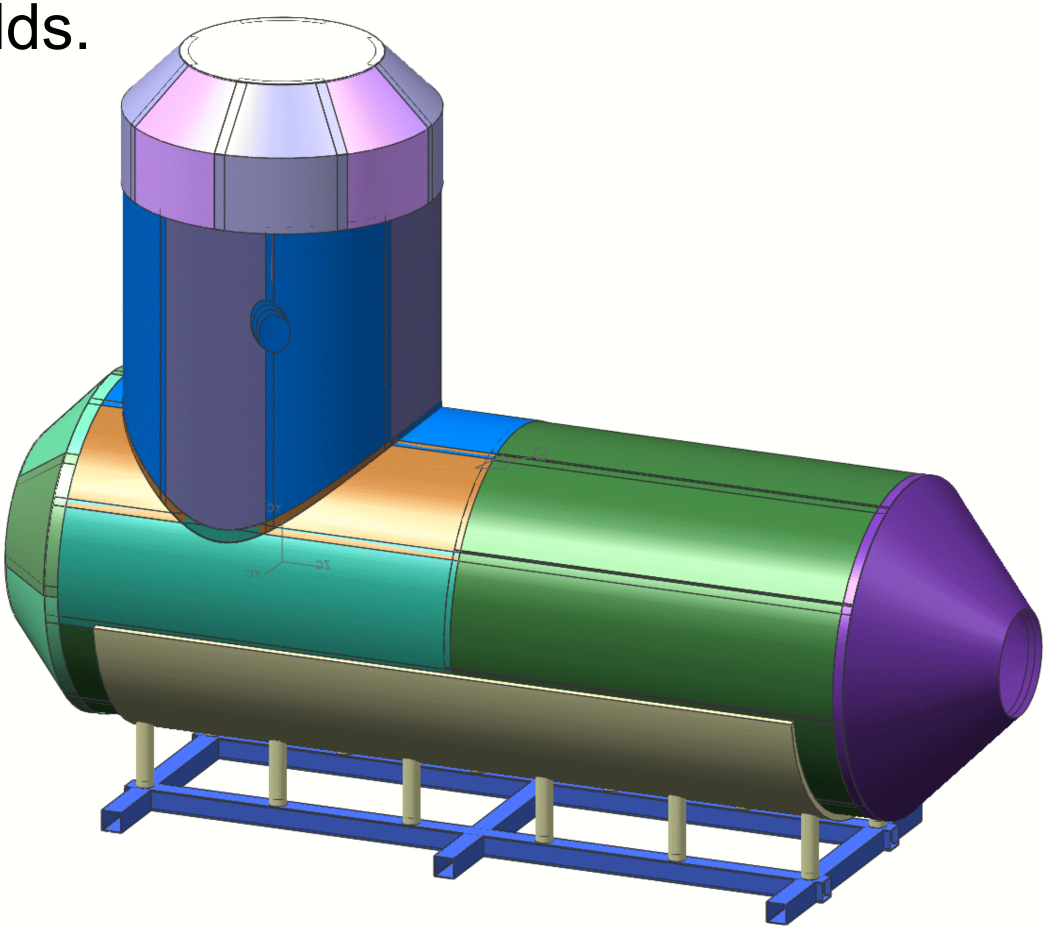
Measurement Cells

- 2 acrylic cells with inner dimensions of 7.62 cm (width) × 10.16 cm (height) × 50 cm (length)

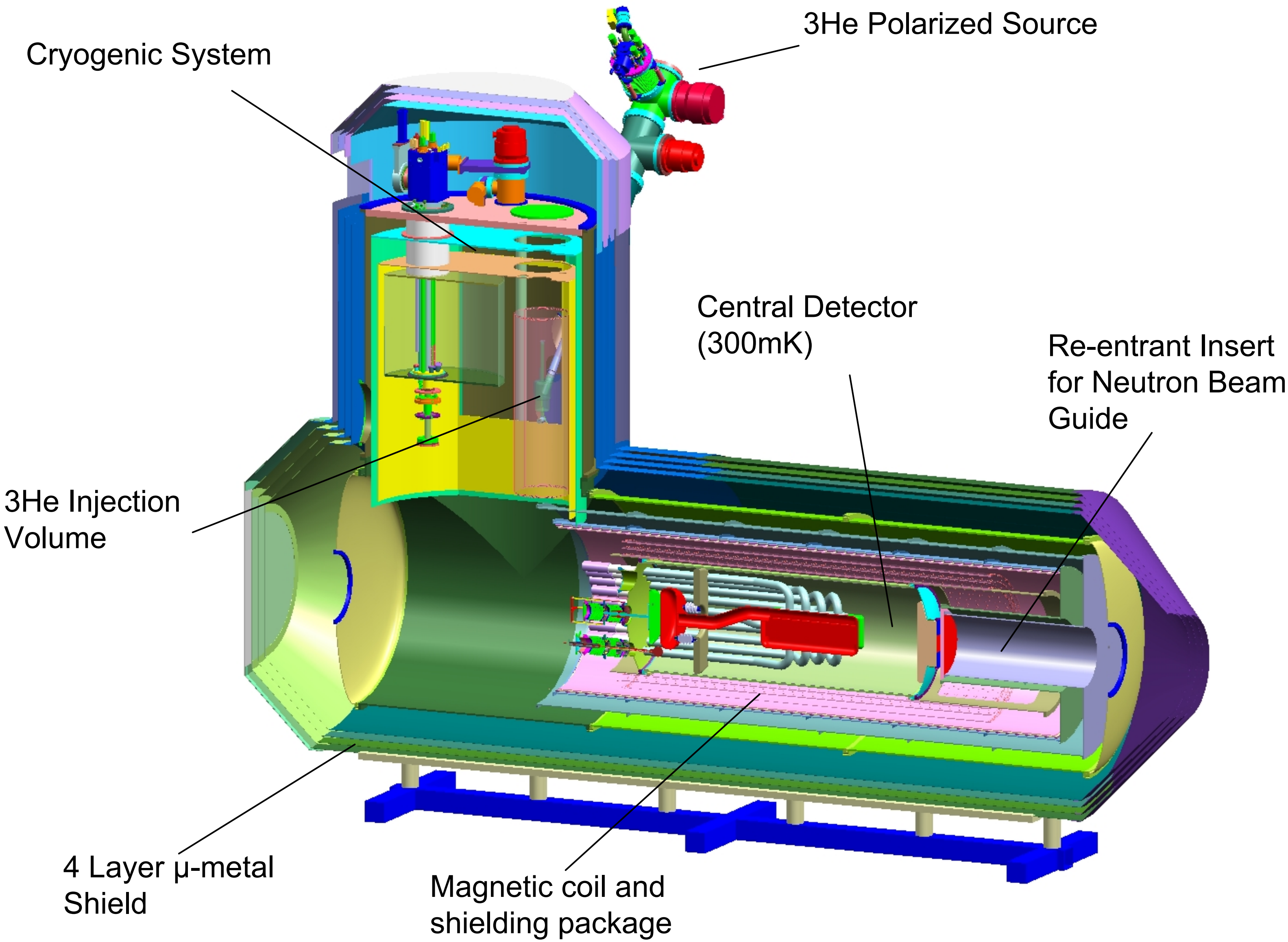


Four-Layer Conventional Magnetic Shield

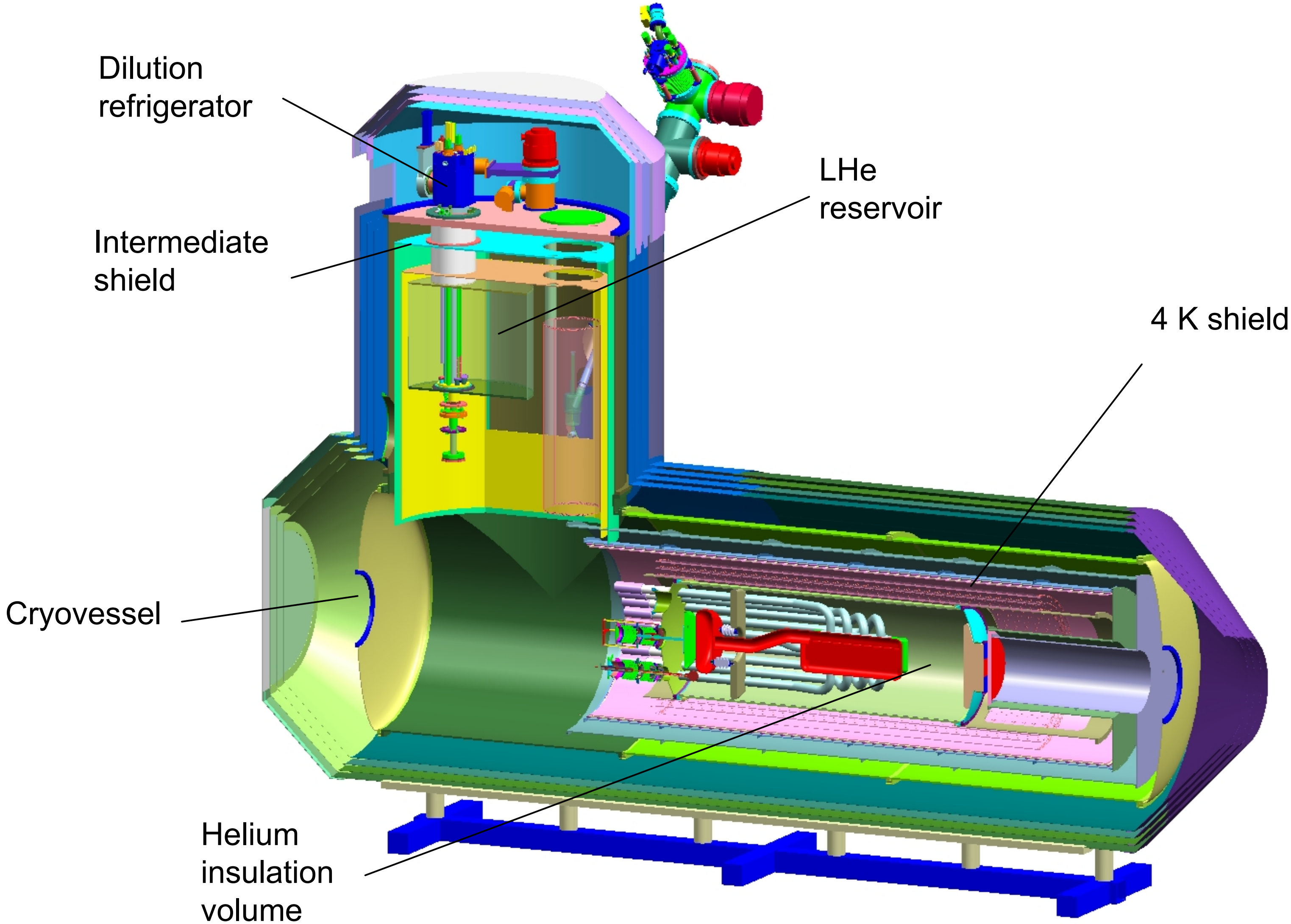
- Entire experimental apparatus enclosed within 4-layer conventional magnetic shield (μ-metal) designed to shield experiment from Earth's magnetic field and other ambient background fields.



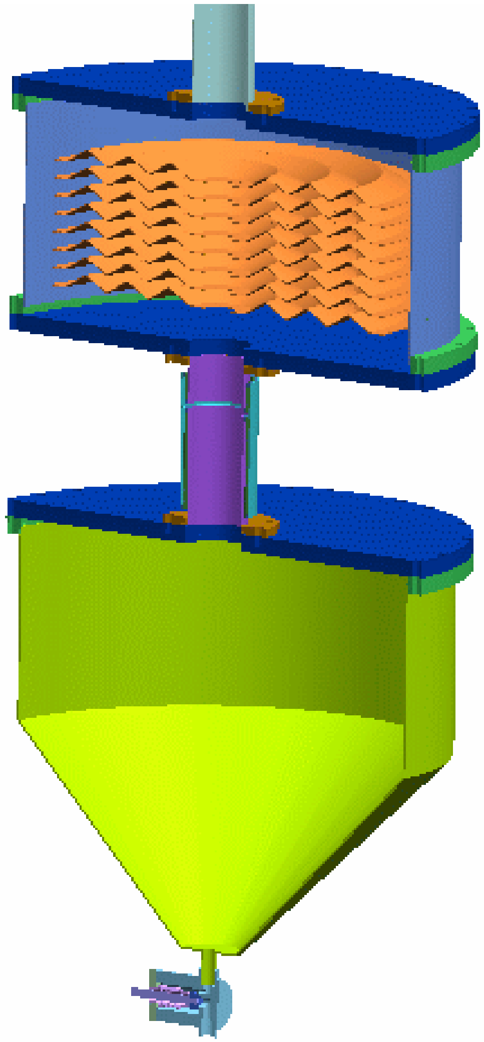
Major Internal Components



Internal Cryogenic System

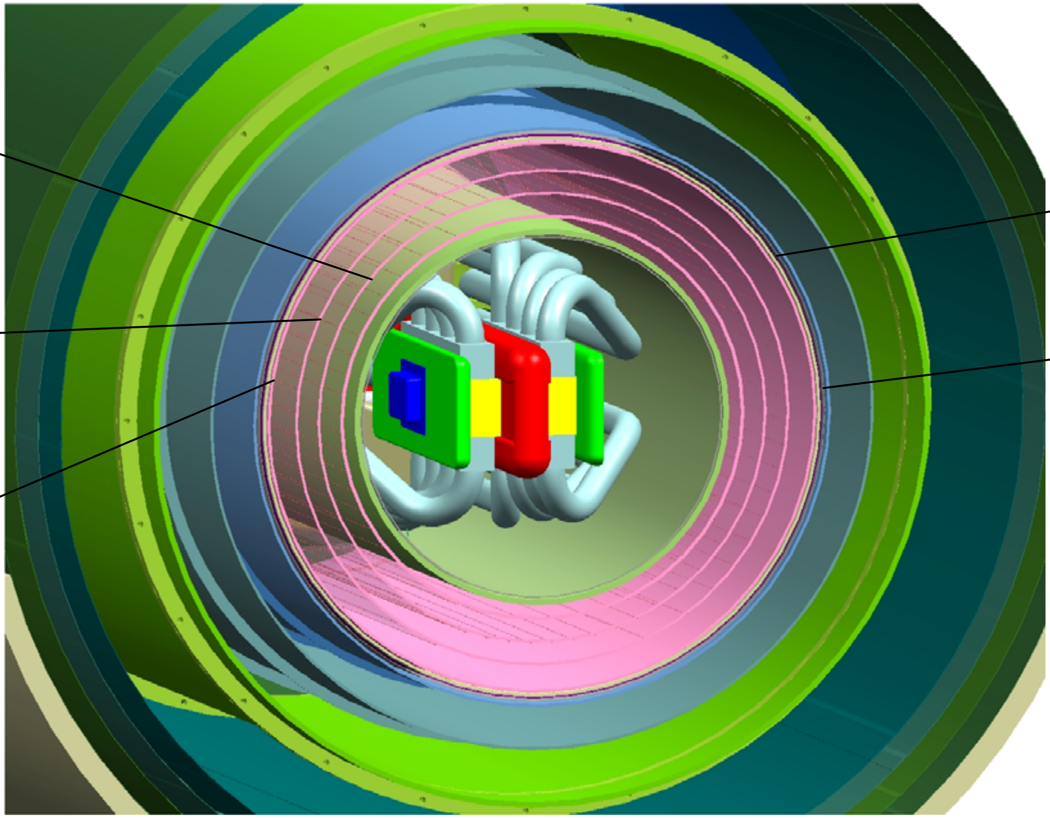


Processes sensitive to operating temperature



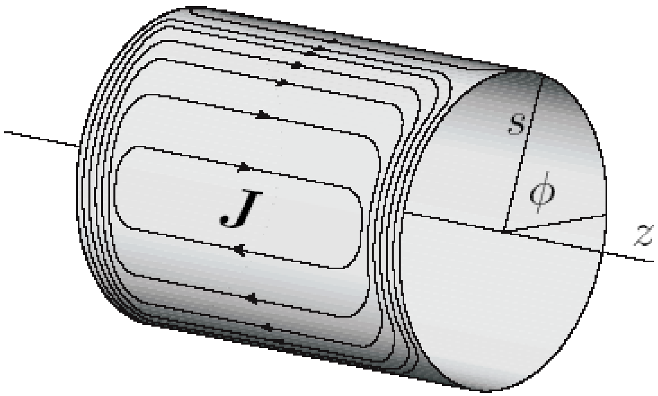
- ^{3}He transport by diffusion, T < 310 mK
- ^{3}He evaporation 370 mK < T < 420 mK
- Geometric phase T > 370 mK, $\partial B_z / \partial z < 10^{-7}$ gauss/cm
-
- ^{3}He depolarization (T2) T < 420 mK, $\partial B_z / \partial y < 10^{-7}$ gauss/cm

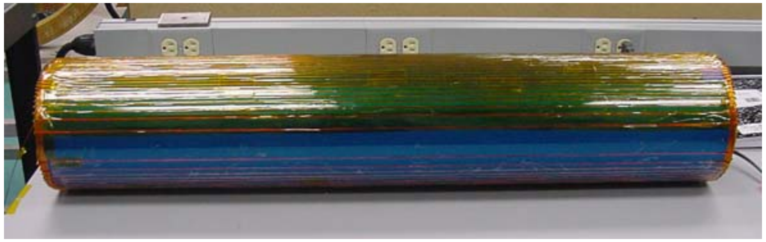
Magnets and Cryogenic Magnetic Shields



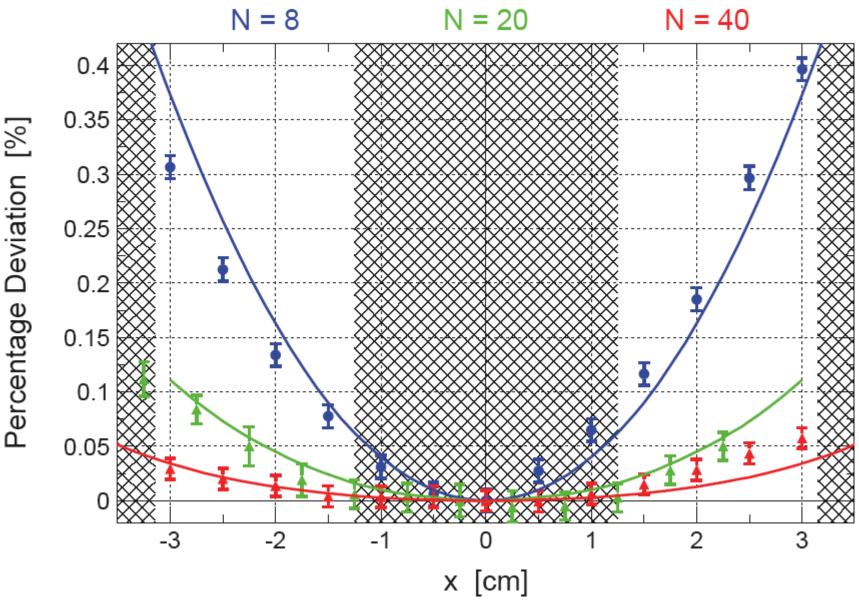
Main Static Field Prototype Coil

- open-ended “saddle-shaped” cos θ coil
- Field strength of B_0 = 10 mGauss
- temporal stability of 10^{-7}
- Uniformity of 5 x 10^{-4}
- $<\partial B_x/\partial x>$ of 0.01 μGauss/cm



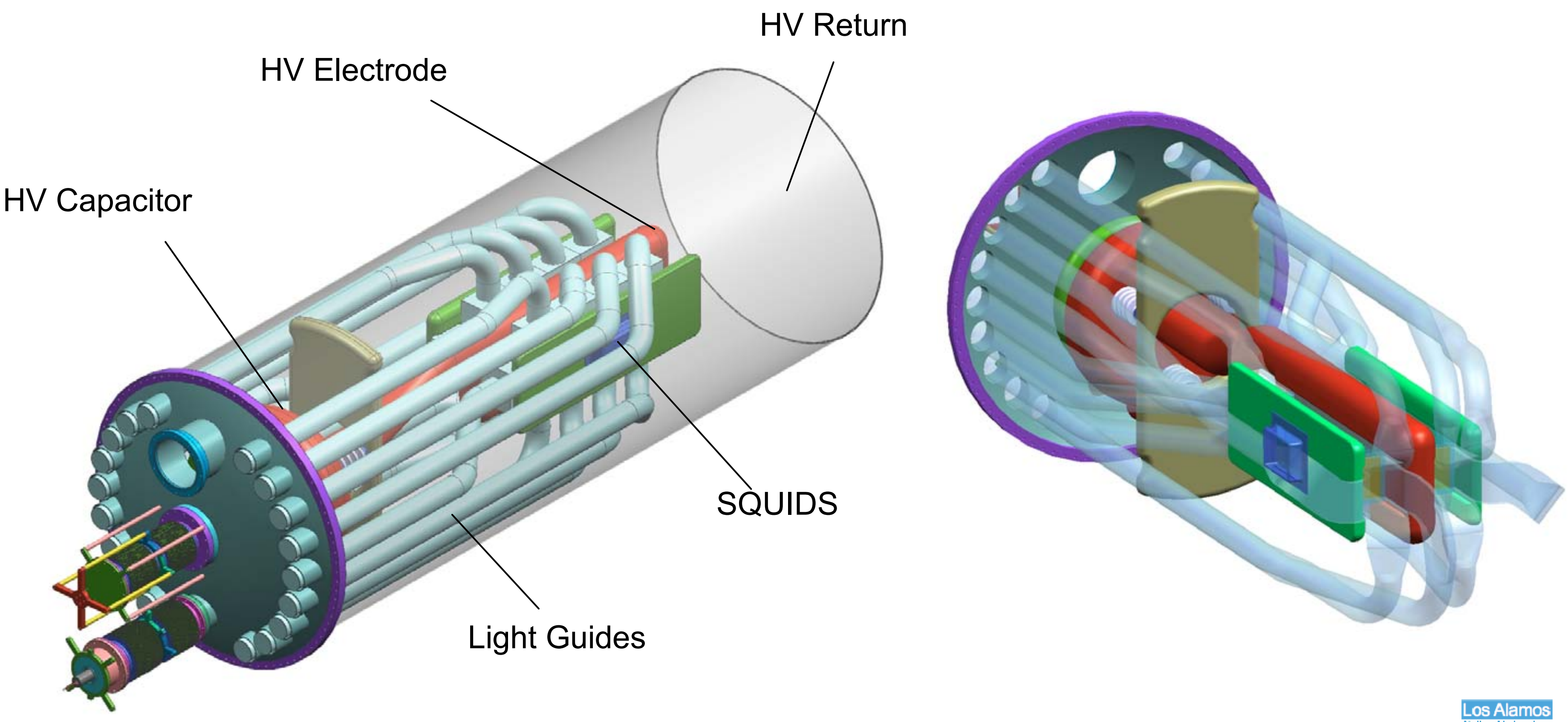


prototype N=40
cos θ coil

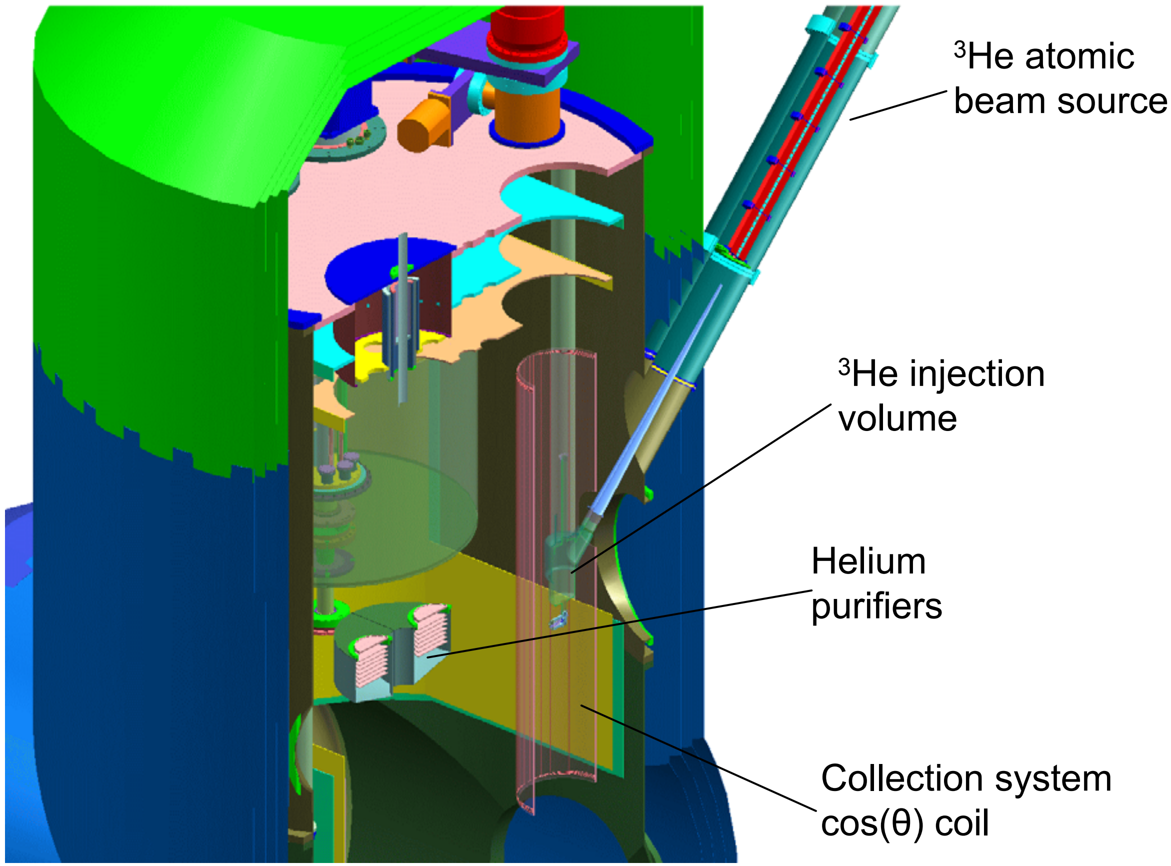


Central Detector and High Voltage System

•Contains the high-voltage capacitor and electrodes, the measurement cells and light collection system.

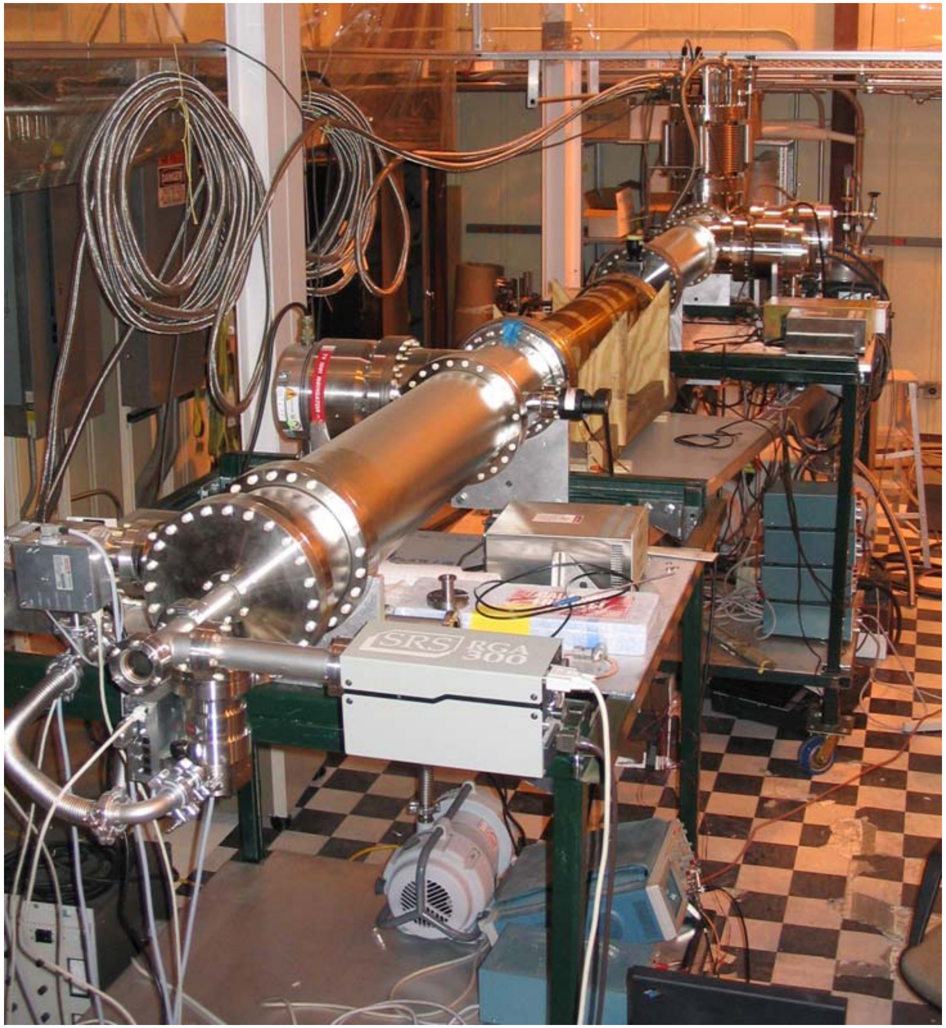


^{3}He System



^{3}He atomic beam source
^{3}He injection volume
Helium purifiers
Collection system cos(θ) coil

^{3}He Atomic Beam Polarizer



- Device commissioned
- Flux 1×10^{14} atoms/s with good emittance
- Average velocity ~150 m/s
- Polarization measurements (99.6 ± 0.25)%
- Loading time 300 s

Operation of the Experiment

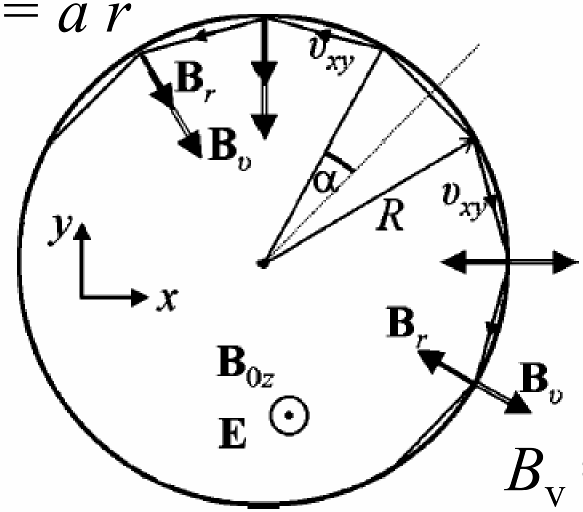
- Cell filled with superfluid helium, doped with polarized ^3He in a weak B field, strong E field.
- Accumulate UCN for about 1000 s (superthermal production).
- Flip neutron and ^3He spins 90° with respect to B_0 by RF pulses.
- Observe the scintillation and SQUID signals as a function of time for 1000 s.
- Drain cell of spent/unpolarized ^3He.
- Repeat after reversing E.

R & D Program

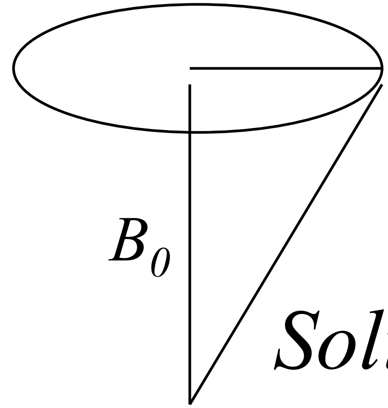
- A vigorous research and development program is underway.
- The program is spread across multiple institutions, with the intent of addressing high-risk areas in the proposed experiment.
- A conceptual model has been developed.
- Programs include:
  - Studies of systematic effects
  - Light detection and background suppression
  - High voltage tests
  - Magnetic shielding and magnetic coils
  - SQUIDS
  - 3He injection, storage, and removal

Geometric Phase Effect (Berry phase)

$B_r = a\,r$



$B_v = \pm(v/c)\cdot E$



$B_r \pm B_v$

Solid angle $\Omega = \pi\,(B_r \pm B_v)^2/B_0^{\,2}$

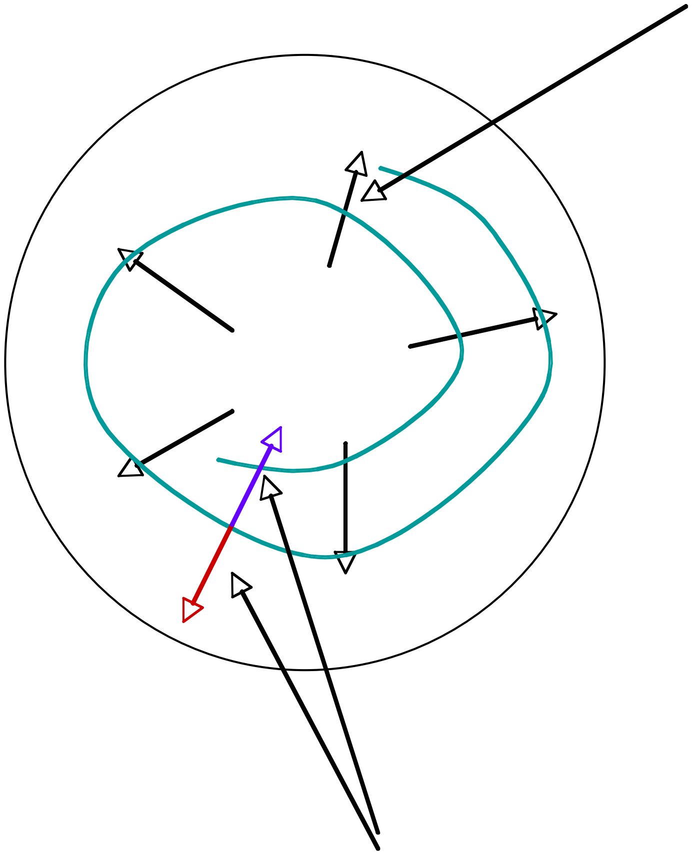
Berry phase (1984) $\Phi = m\,\Omega$

Net phase $\sim\frac{1}{2}(\Phi_c - \Phi_{cc}) \sim B_r B_v/B_0^{\,2} \sim E$ *!!*

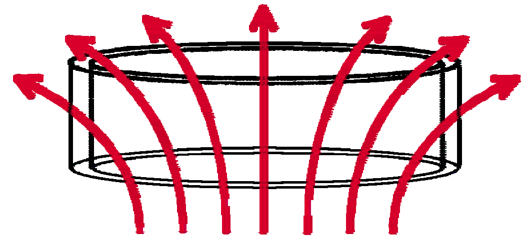
RBS shift for circular orbits r=R

B_0 and E up

$B_r = a\,r$



$B_v = \pm(v/c)\cdot E$



More generally, with $\omega_0 = \gamma B_0$ and $\omega_r = v/R$:

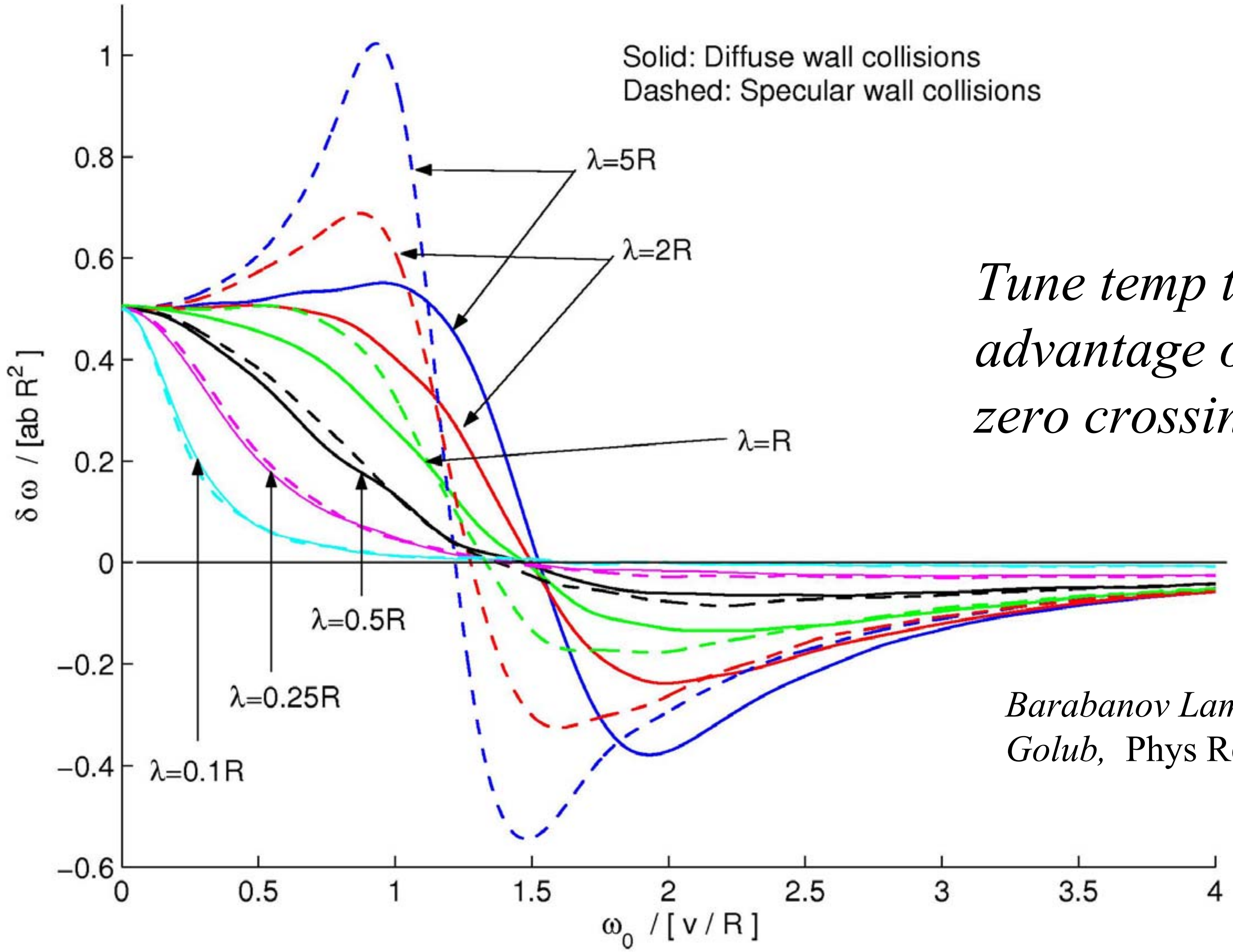
UCN's: $\omega_0 >> \omega_r$

$\Delta\omega = a\,v^2 E/cB_0^{\ 2}$

3He: $\omega_0 << \omega_r$

$\Delta\omega = \gamma^2 a\,R^2 E/c$

Monte Carlo Simulation of the Effect



Tune temp to take advantage of the zero crossing?

Barabanov Lamoreaux and Golub, Phys Rev A (2007)

"Stop the World" - false ILL edm due to Ω_{earth} ?

- Earth rotates $\Omega/2\pi = 11.6\ \mu Hz$
- $\omega_n = \gamma_n B_0 - \Omega \sin\theta_L$
- $\omega_{Hg} = \gamma_{Hg} B_0 - \Omega \sin\theta_L$
- False edm $d_{earth} \sim k\, \Omega \sin\theta_L / (\gamma' B_0) \sim 3 \times 10^{-26}$ e•cm
- k is slope of d_{meas} vs $R_a = (\omega_n / \gamma_n) / (\omega_{Hg} / \gamma_{Hg})$, with $(\gamma')^{-1} = |\gamma_n|^{-1} + |\gamma_{Hg}|^{-1}$
- See PRL 98 (2007) comment (SL and RG) and response (Baker et al)

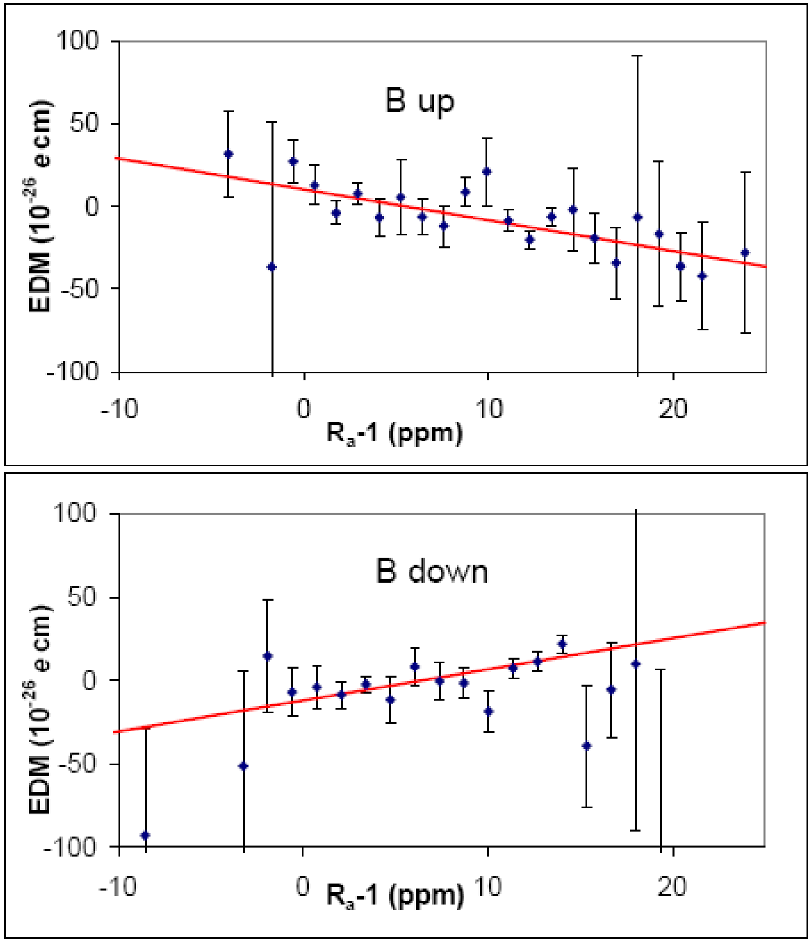
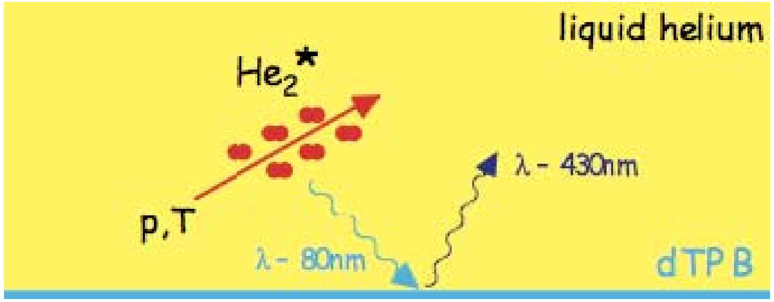


FIG. 2: (Color online) Measured EDM as a function of the relative frequency shift of neutrons and mercury. For clarity, data are binned.

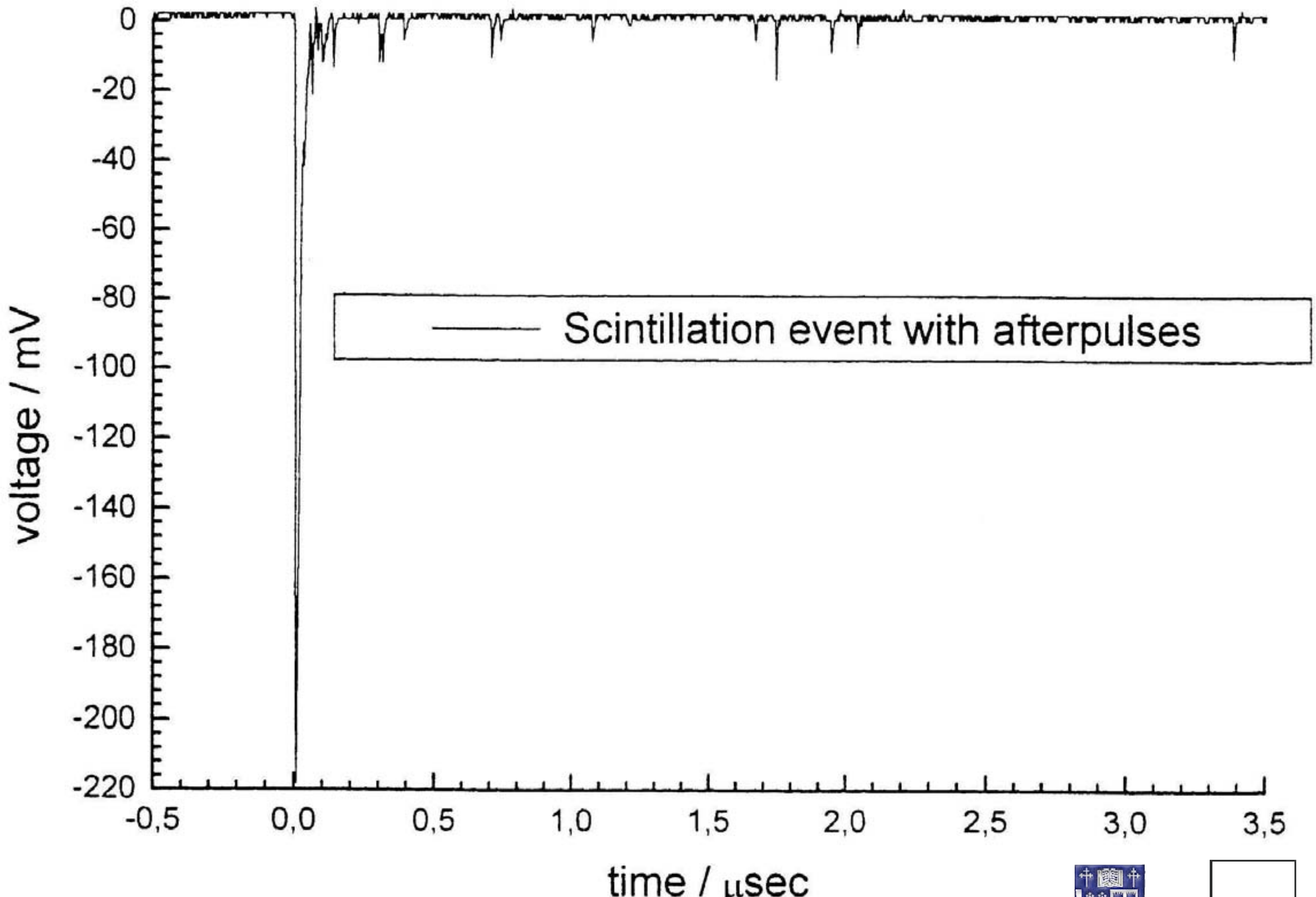
Background Discrimination

- Recoiling charged particle creates an ionization track in the helium.
- Helium ions form excited He_2^* molecules(ns time scale) in both singlet and triplet states.
- He_2^* singlet molecules decay, producing a large prompt
- (< 20 ns) emission of extreme ultraviolet (EUV) light.
- EUV light (80 nm) converted to blue using the deuterated organic fluor dTPB (tetraphenyl butadiene).

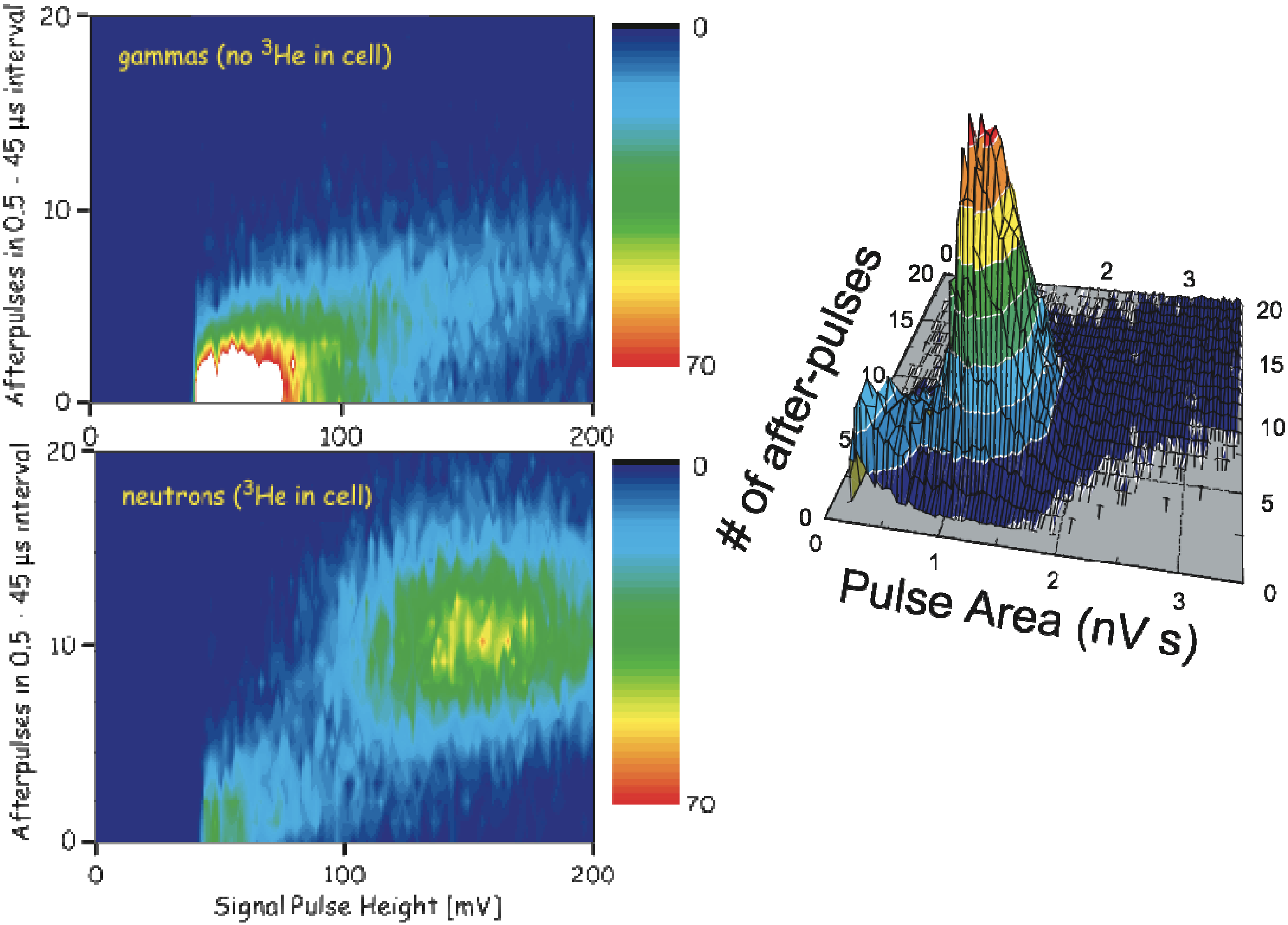
$$n + {}^3He \rightarrow p + T$$



Sample Event

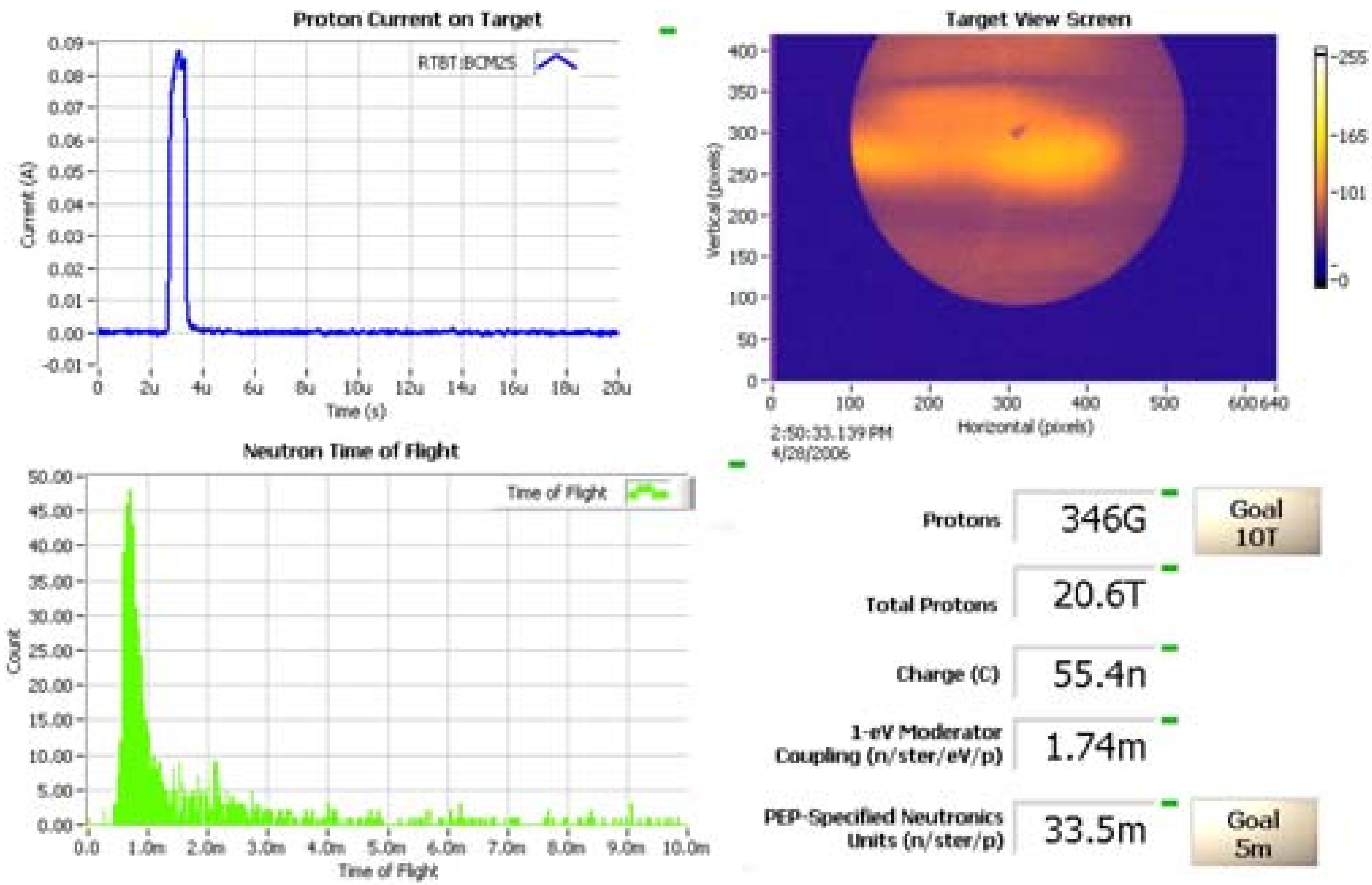


Background Discrimination

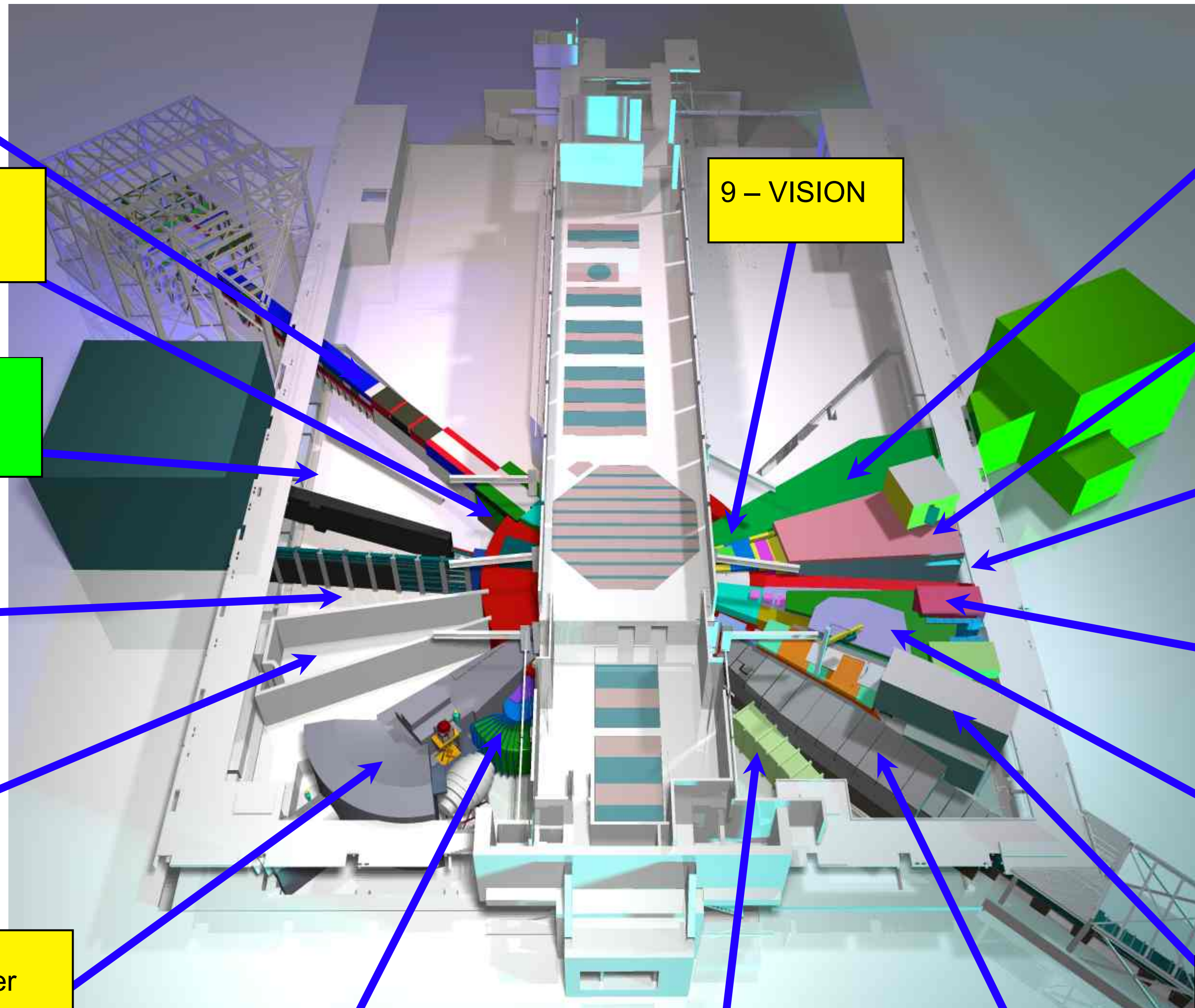


Spallation Neutron Source

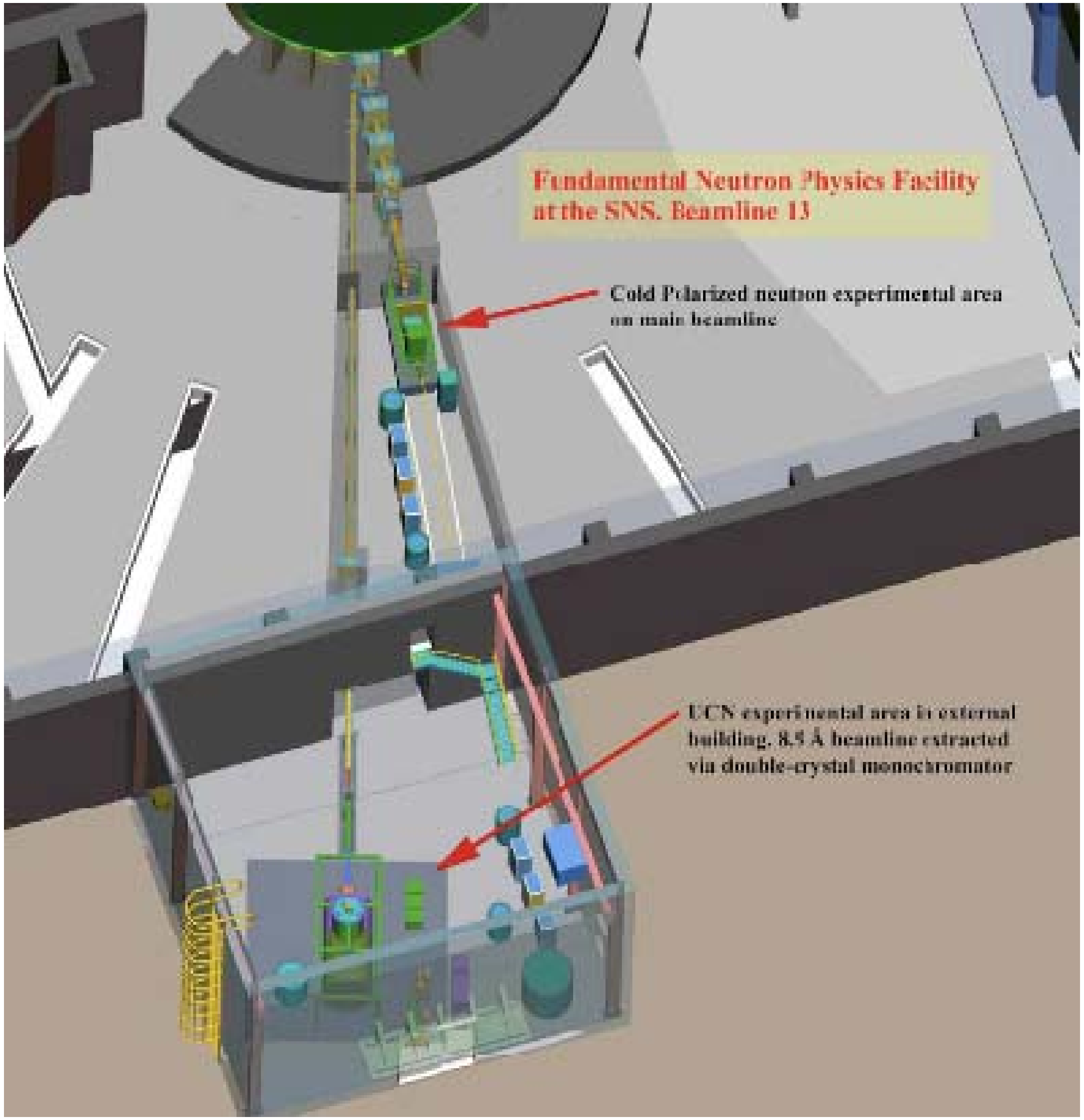
First SNS Beam on Target—April 28, 2006



Beamline 13 Allocated for Nuclear Physics



Fundamental Neutron Physics Beamline



Organizational Chart

National Science Foundation
Bradley Keister
Richard Boyd

Project Executive Committee
Doug Beck
Brad Filippone
Haiyan Gao
Bob Golub
Paul Huffman
Vince Cianciolo

Martin Cooper
(Project Manager, Co-spokesperson)
Steve Lamoreaux
(Co-spokesperson)
Jan Boissevain
(Chief Engineer)
Kim Selvage
(Project Controls Analyst)
Paul Huffman
(Technical Coordinator)
Vince Cianciolo
(ORNL Operations Manager/ES&H)
TBD
(Business Manager)

Physics Division
Jack Shlachter

NP Program
William Louis

Project Management Advisors
John Tapia, PMP
Doug Sankey

1.1 Research & Development
Martin Cooper (LANL)

1.2 Polarized Neutron Beam Line & Shielding
Wolfgang Korsch (Kentucky)

1.3 Cryostats, Refrigerators and Related Equipment
David Haase (NCSU)

1.4 3He Systems
Steve Williamson (Illinois)

1.5 Magnets and Magnetic Shielding
Brad Filippone (Cal Tech)

1.6 Central Detector Systems
Takeyasu Ito (LANL)

1.7 Electronics, Computers, Simulations, Data Analysis
(Chris Gould (NCSU))
Jim Miller (BU)

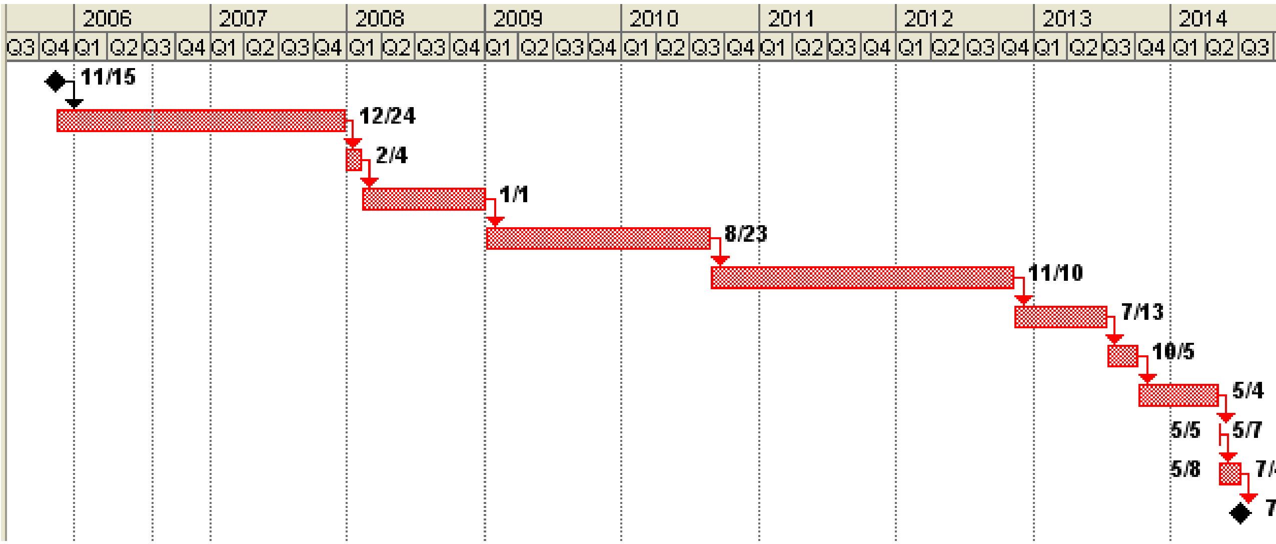
1.8 Infrastructure
Walt Sondheim (LANL)

1.9 Assembly & Commissioning
Paul Huffman (NCSU)

1.10 Project Management
Martin Cooper (LANL)

Project Timeline

WBS	Activity Name	Duration
1.12	CD-0	0 days
1.1	R&D	770 days
1.12	CD-2 Review Preparations	42 days
1.11	Budget Authority	332 days
1.3	Cryogeneic Subsystem	599 days
1.9	Assembly at NCSU	810 days
1.9	Assembly at ORNL	245 days
1.9	Commissioning	84 days
1.12	Schedule Float	211 days
1.12	CD-4 Review	3 days
1.12	CD-4 Approval	58 days
1.0	End of Project	0 days



- CD-0 – (mission need) issued fall 2005
- CD-1 – spring 2007
- CD-4 – project ends mid 2014 ($21M @40% contingency)
- 2014 - 20?? – EDM data collection

EDM Experiments in Other Systems

- CP violating EDM's are studied in particles, nuclei, atoms and molecules. Shielding comparison $R = E_{eff} / E_{applied}$
- Free neutrons $R=1$
- Diamagnetic atoms (^{199}Hg) $R \sim 10\ Z^2\ (r_{nuc}/r_{atom})^2 \sim 10^{-3}$
  Schiff shielding
- Paramagnetic atoms (Tl) $R \sim Z\ (Z\alpha)^2 \sim 600$
- Polar molecules (YbF, PbO) $R \sim 10^7$

EDM's elsewhere (BF, INT workshop spring 07)

particle	Present Limit (90% CL) (e-cm)	Laboratory	Possible Sensitivity (e-cm)	Standard Model (e–cm)
e^- (Tl) e^- (PbO) e^- (YbF) e^- (GGG)	1.6×10^{-27}	Berkeley Yale Sussex LANL/Indiana	 10^{-29} 10^{-29} 10^{-30}	$<10^{-40}$
μ μ	9.3×10^{-19}	CERN BNL	 $<10^{-24}$	$<10^{-36}$
n n n n	3×10^{-26}	ILL ILL PSI SNS	2×10^{-28} 5×10^{-28} 2×10^{-28}	$\sim 10^{-32}$
^{199}Hg ^{129}Xe ^{225}Ra ^{223}Rn d	1.9×10^{-27}	Seattle Princeton Argonne TRIUMF COSY/JPARC?	2×10^{-28} 10^{-31} 10^{-28} 1×10^{-28} $<10^{-28}$	$\sim 10^{-33}$ $\sim 10^{-34}$

Conclusions

- We are constructing apparatus to measure the neutron EDM at the SNS using UCN's and polarized 3He atoms in a superfluid 4He bath.
- The construction project has obtained CD1 approval from DOE and is moving towards finalizing a design for CD2 approval.
- We expect to begin taking data in ~2014.
- Our goal is to measure the magnitude of the neutron EDM, or to lower the current experimental limit by two orders of magnitude.