Neutron Electric Dipole Moment Search Experiments in the US

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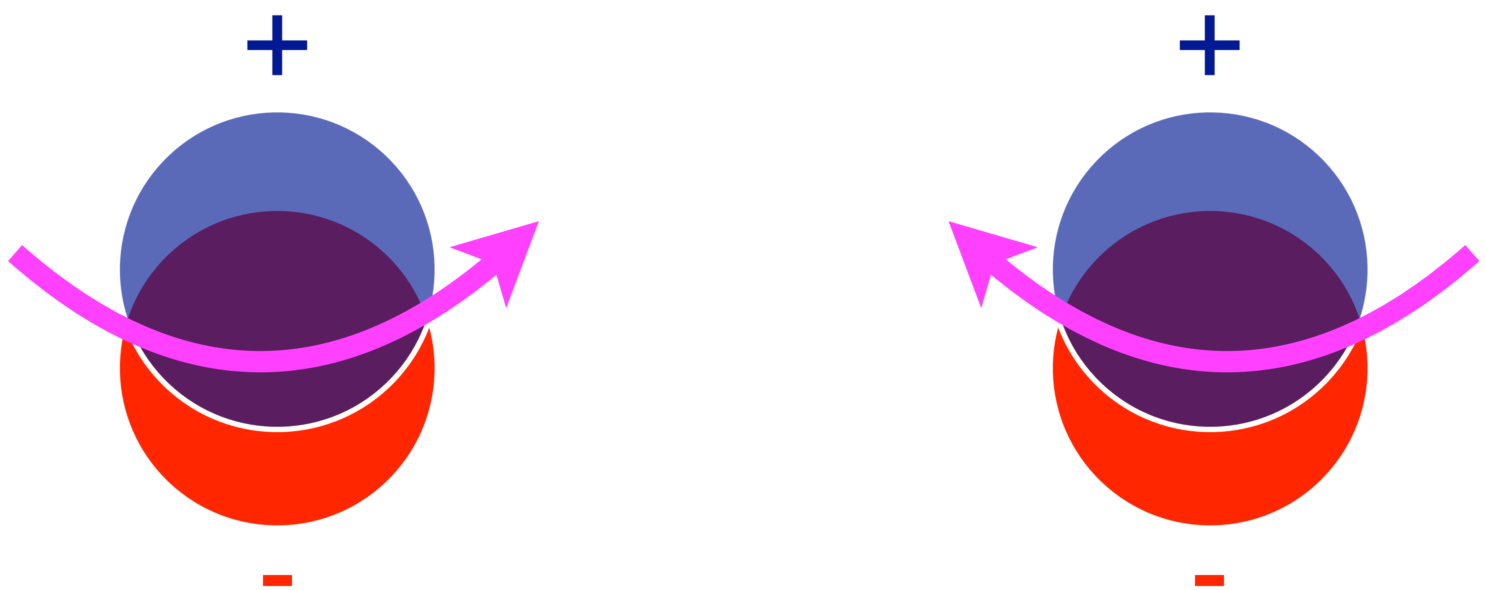
Atomic nuclei as laboratories for BSM physics

April 16, 2019

Neutron electric dipole moment



P or T reversed state

- Nonzero EDM violates both P and T (therefore CP) reversal symmetries.
- Standard model value (CKM): $d_n \sim 10^{-32}$ - 10^{-31} $e\cdot$cm

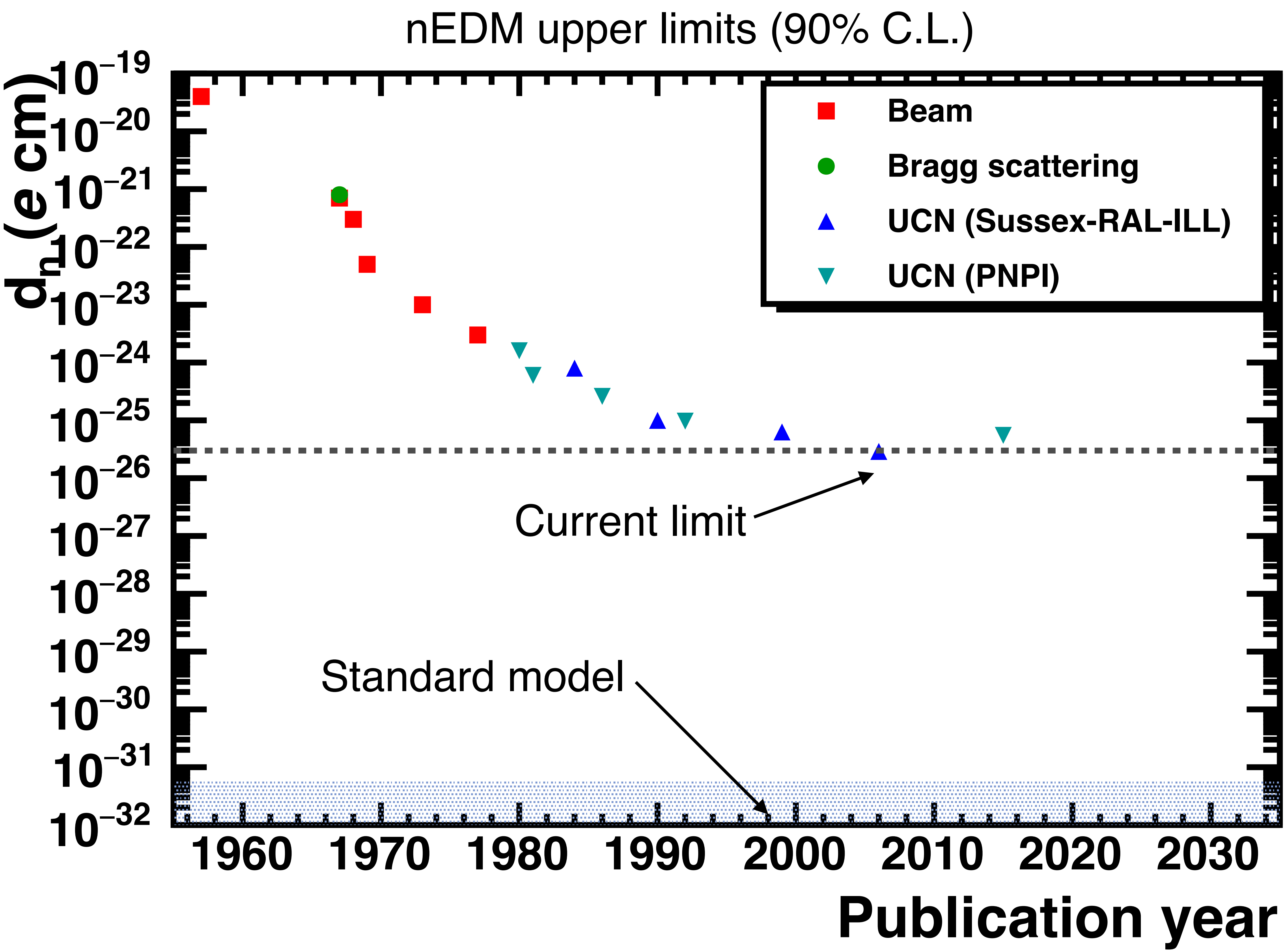
  ➡ Small!! Ideal probe for new physics

- Present limit: $d_n < 2.9\times10^{-26}$ $e\cdot$cm (90% C.L.) (PRL 97, 131801 (2006))

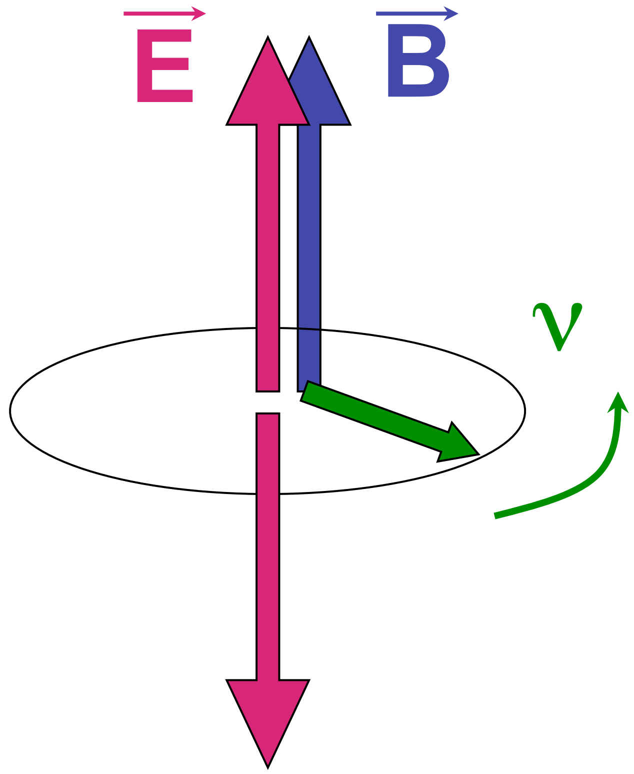
Motivations for nEDM search

- nEDM is a sensitive probe of new sources of CP violation
    - EDM due to the SM (CKM) is small because in the SM, CP violation only occurs in quark flavor changing processes to the lowest order
    - Many extensions of the SM naturally produce larger EDMs because of additional CP violating phases associated with additional particles introduced in the model
- Strong CP problem
    - The limit on the CP violating term in QCD Lagrangian (from nEDM) is very small
    - One proposed remedy, Peccei-Quinn symmetry, predicts axions. However, axions have not been observed.
- Baryon Asymmetry of the Universe provides additional motivation.
    - Baryogenesis requires new sources of CP violation

Evolution of nEDM experimental limits



nEDM measurement principle



$$\nu = \left(2\mu_n B \pm 2d_n E\right)/h$$

$$\Delta\nu = 4d_n E/h$$

$$\delta d_n = h\frac{\delta\Delta\nu}{4E}$$

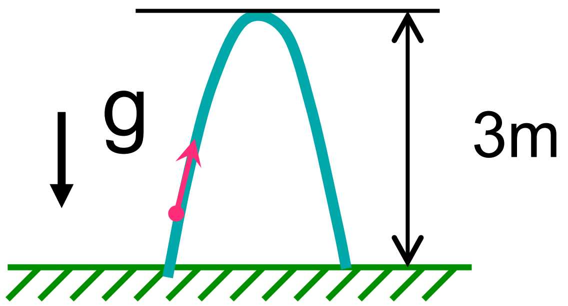
For B ~ 10 mG, ν = 30 Hz.
For E = 10 kV/cm and $d_n = 3\times10^{-27}$ e-cm, Δν=0.03 μHz.

For each measurement, the statistical sensitivity goes as

$$\delta d_n \propto \frac{1}{ET\sqrt{N}}$$

Ultracold neutrons

- Very slow neutrons (v<8 m/s)
- Totally reflected by some materials
- Hence, they can be totally confined within a bottle for periods in excess of 100 s.
- Typically:
  - Velocity < 8 m/s
  - Kinetic energy < 300 neV
  - Wavelength > 500 A
  - Temperature < 4 mK
- Gravity: 100 neV/meter
- Magnetic field (**μ**·**B**): 60 neV/T



$$V = \frac{2\pi\hbar^2}{m} Na$$

Mat.	V (neV)
^{58}Ni	346
SS	188
DLC	282
dPS	165

Sussex-ILL experiment

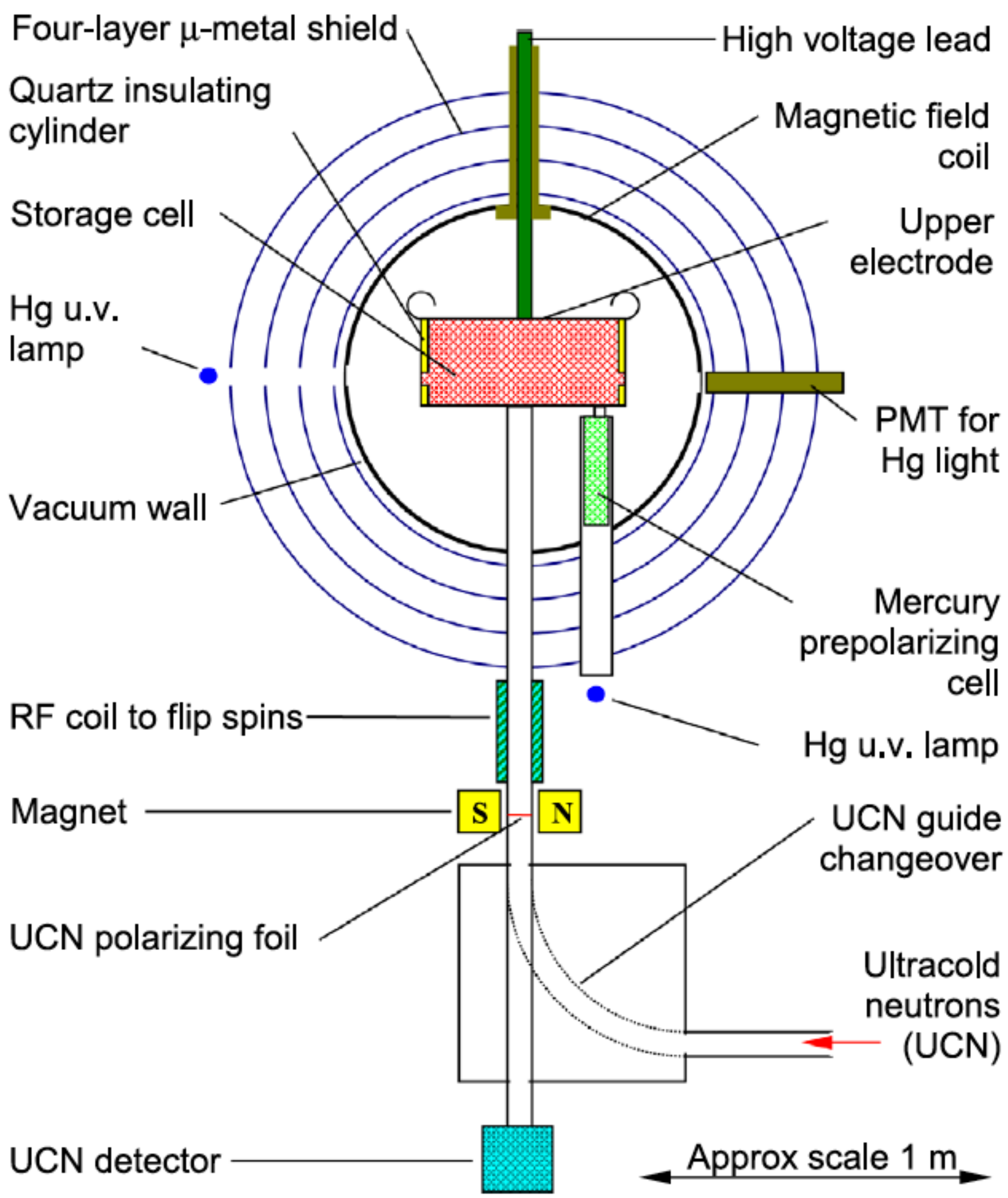
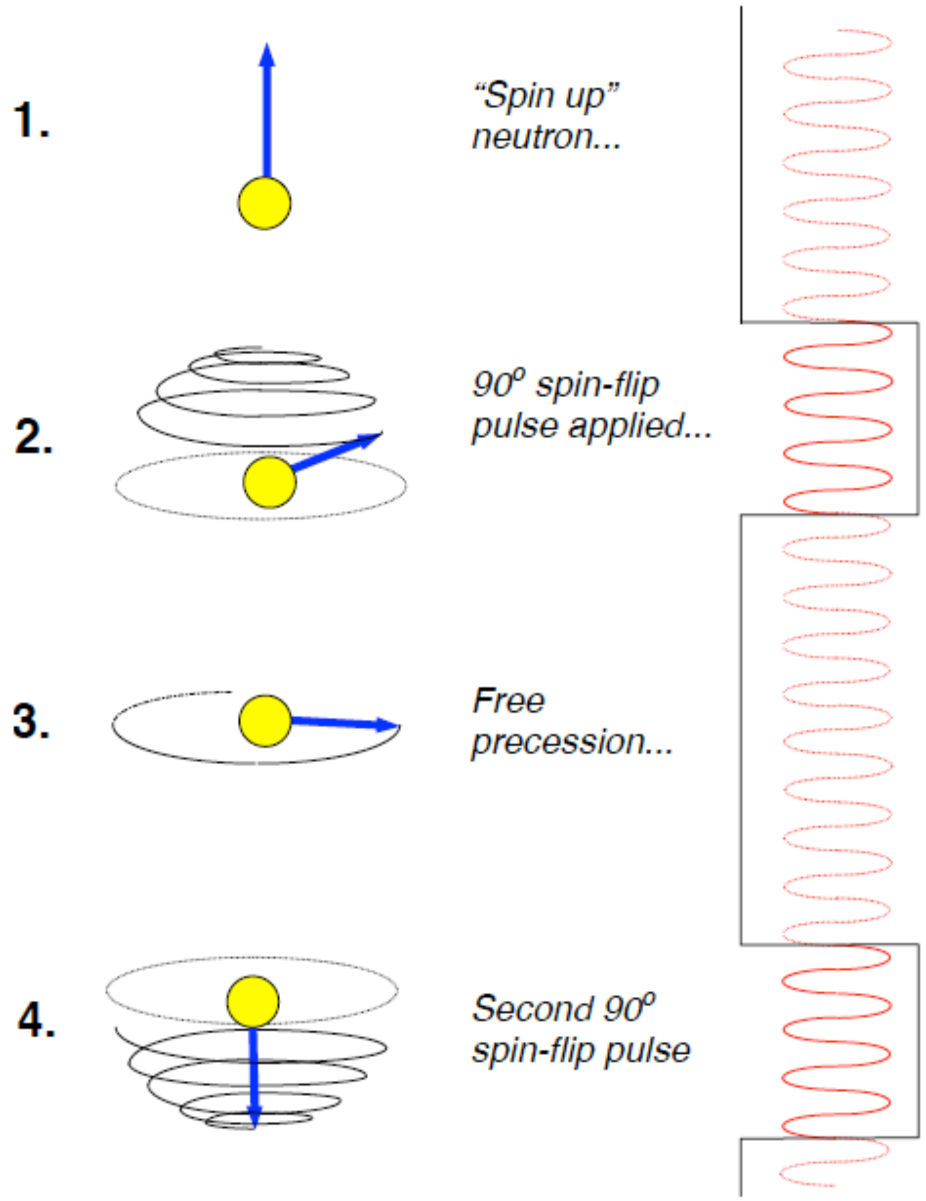
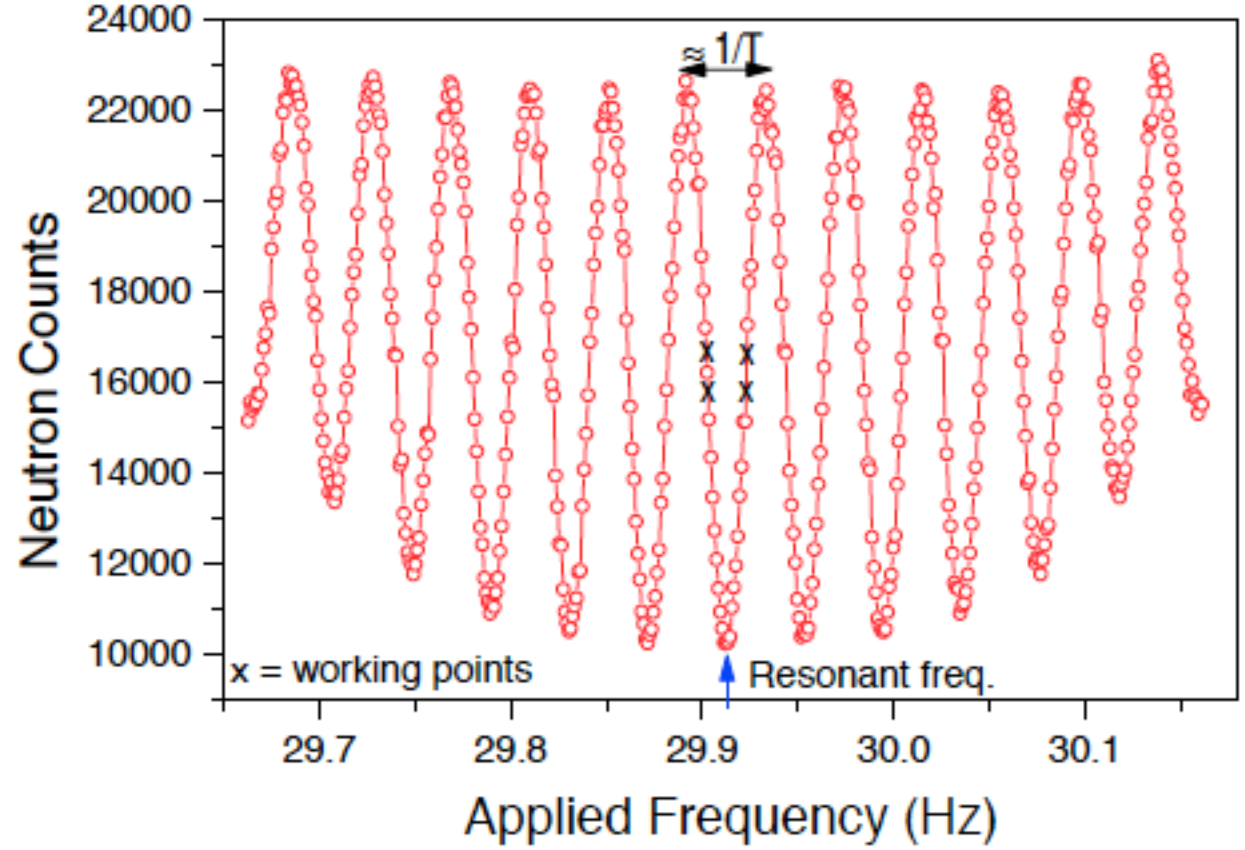


Fig. 6. The neutron EDM experimental apparatus.

- Precession measurement
  - Ramsey's separated oscillatory field magnetic resonance method
- Magnetometry
  - 199Hg comagnetometer
- Selected parameters
  - E ~ 10 kV/cm
  - N ~ 14,000
  - T ~ 130 s
- Results
  - $d_n < 2.9 \times 10^{-26}$ e-cm (90% C.L.)

Ramsey method of separated oscillatory fields

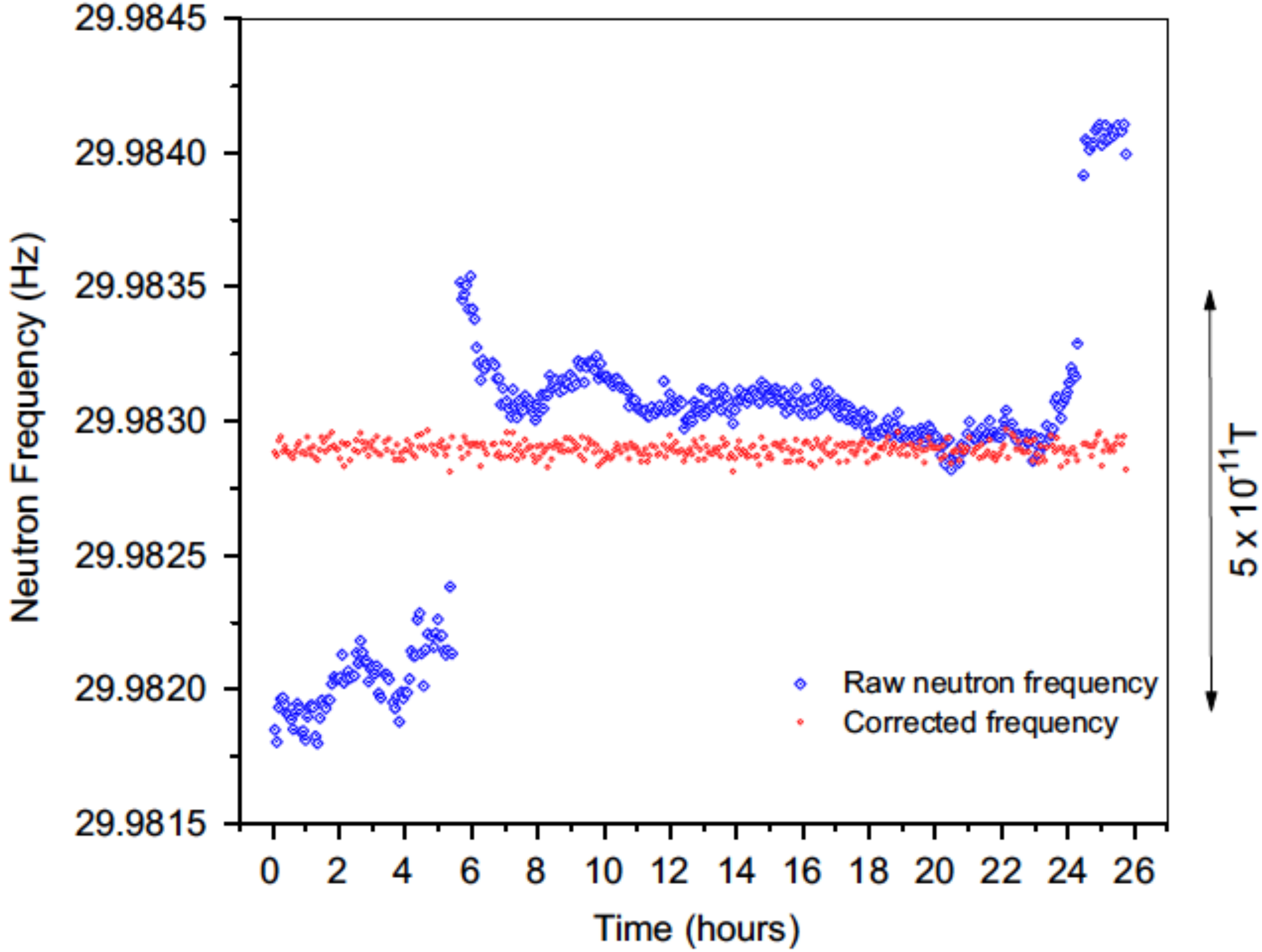




Baker et al, NIMA 736, 184 (2014) (arXiv:1305.7336)

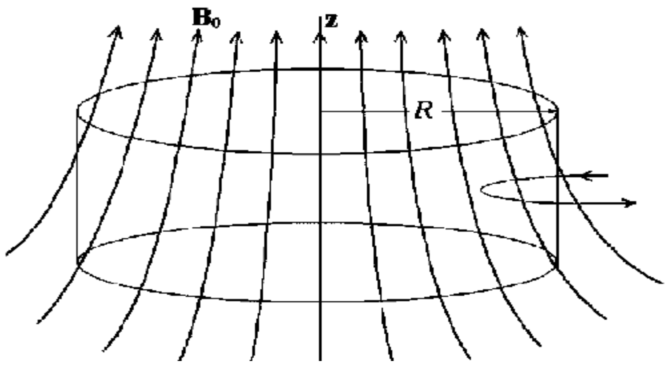
^{199}Hg co-magnetometer

Co-magnetometer: Magnetometer that occupies the same volume over the same precession time interval as the species on which an EDM is sought



Geometric phase effect

- Effect resulting from the interaction between the B field gradient and the E×v field

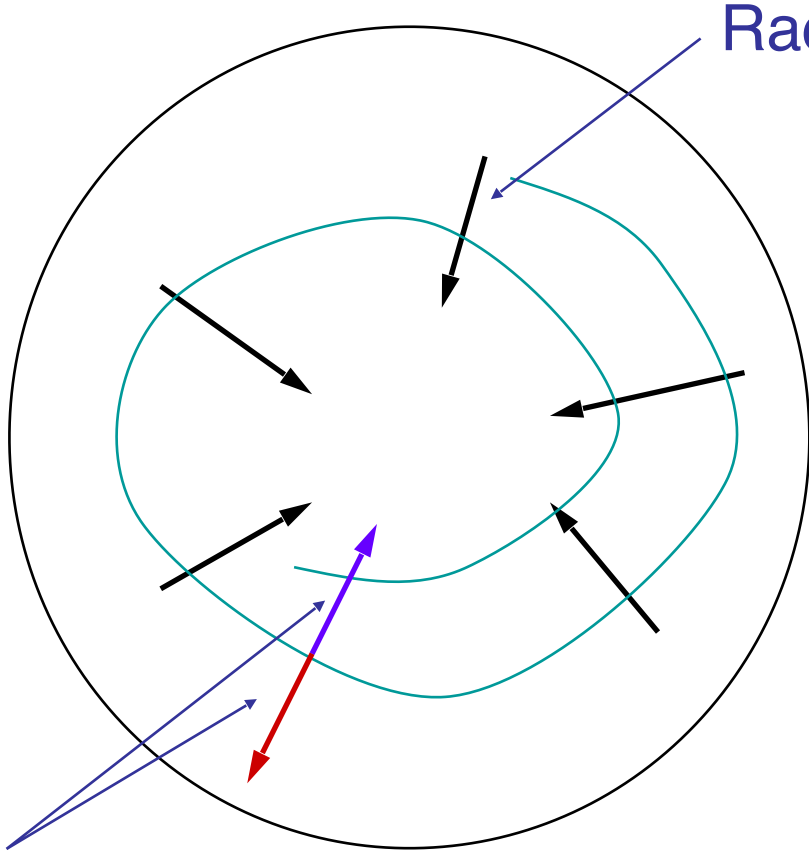


$$B_r = \frac{\partial B_0}{\partial z}\frac{r}{2} = ar$$

Consider particles in circular orbits with orbital frequency ω_r

Radial field from gradient

$$B_r = ar$$



E×v field changes sign with direction

Radial field (rotating at ω_r as seen by the particles)

$$B_R = B_r \pm B_E = aR \pm \frac{\omega_r R E}{c}$$

Block-Siegert shift (shift in precession frequency)

$$\delta\omega = \frac{(\gamma B_R)^2}{2(\omega_0 - \omega_r)}$$

Averaging over the rotation direction

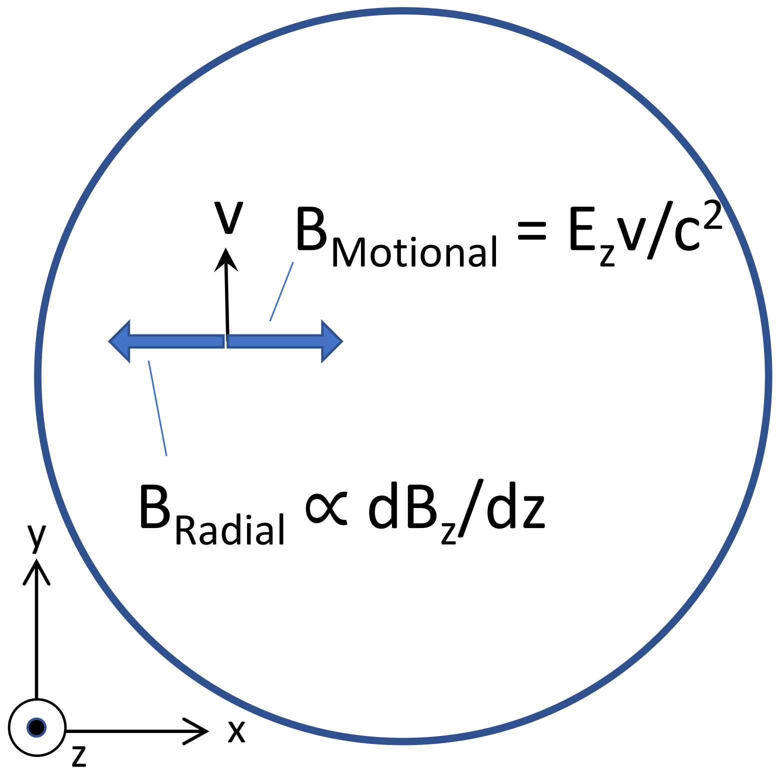
$$\delta\omega = \gamma\delta B = -\frac{\gamma^2 a v^2 E}{c(\omega_0{}^2 - \omega_r{}^2)}$$

Effect linear in E!

Pendlebury et al. PRA **70**,032102 (2004)
Lamoreux and Golub, PRA **71**, 032104 (2005)

Geometric phase effect — cont'd

E & B are in the z direction

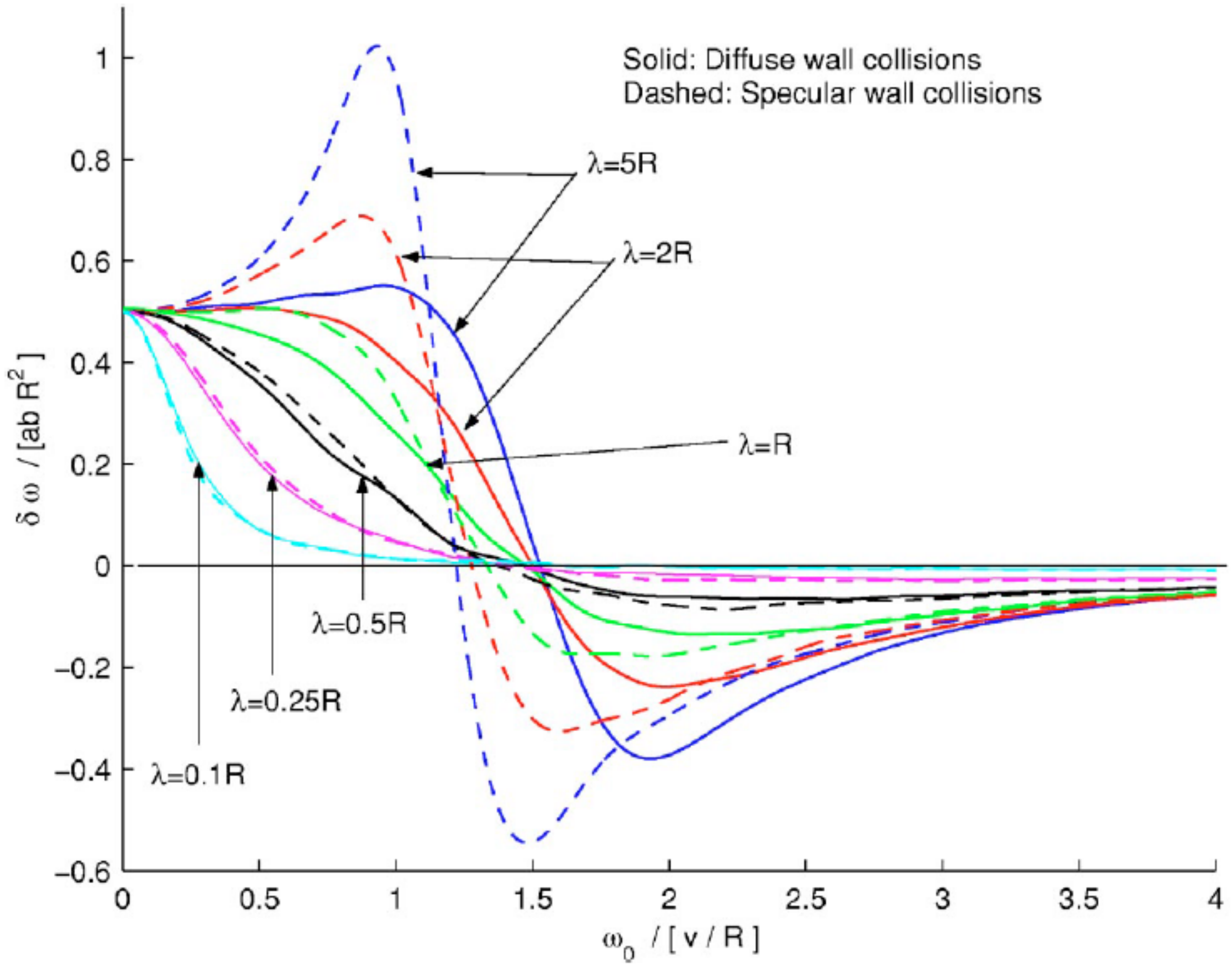


$$B_x = b_x - \frac{E}{c^2} v_y$$

$$B_y = b_y + \frac{E}{c^2} v_x$$

Successive application of rotations around x axis and y axis causes frequency shift.

$$[L_x, L_y] = iL_z$$



Lamoreaux & Golub, PRA 71, 032104 (2005)

How can we do better?

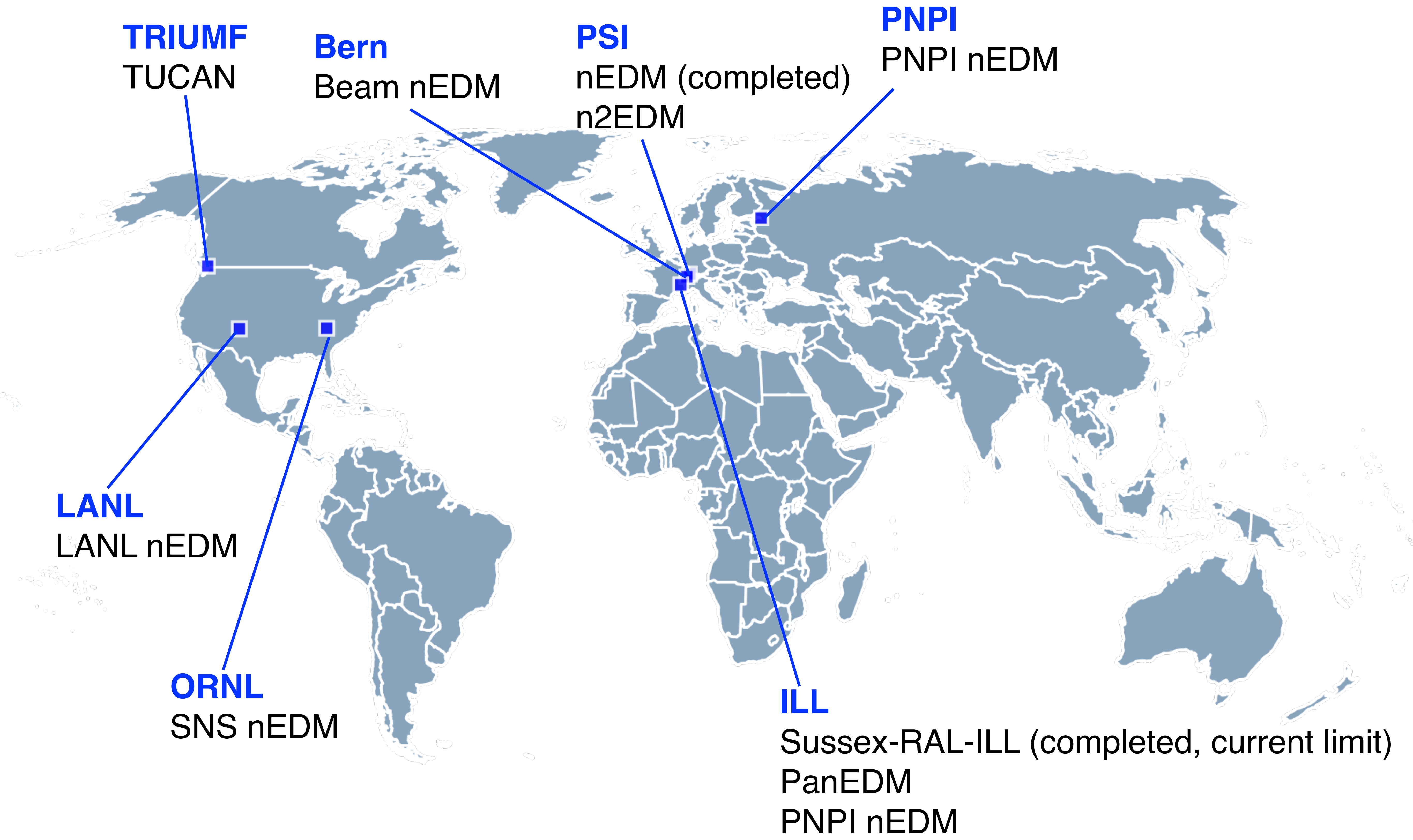
- Statistical sensitivity:

$$\delta d_n \propto \frac{1}{ET\sqrt{N}}$$

- Therefore we need:
  - Higher *E*
  - Longer *T*
  - Larger *N*

- Systematics
  - vxE (motional magnetic field) effect
  - Leakage currents
  - Non-uniformity and instability of magnetic field
  - Geometric phase effect

Worldwide nEDM efforts



nEDM efforts in the US

Experiment	UCN source	Method	Goal sensitivity
nEDM@SNS	In-situ producing in superfluid LHe	Golub-Lamoreaux method in cryogenic apparatus	10^{-28} e-cm
LANL nEDM	SD2 converter coupled to a pulsed spallation source	Ramsey method at room temperature with ^{199}Hg comagnetometer	10^{-27} e-cm

LANL nEDM Collaboration

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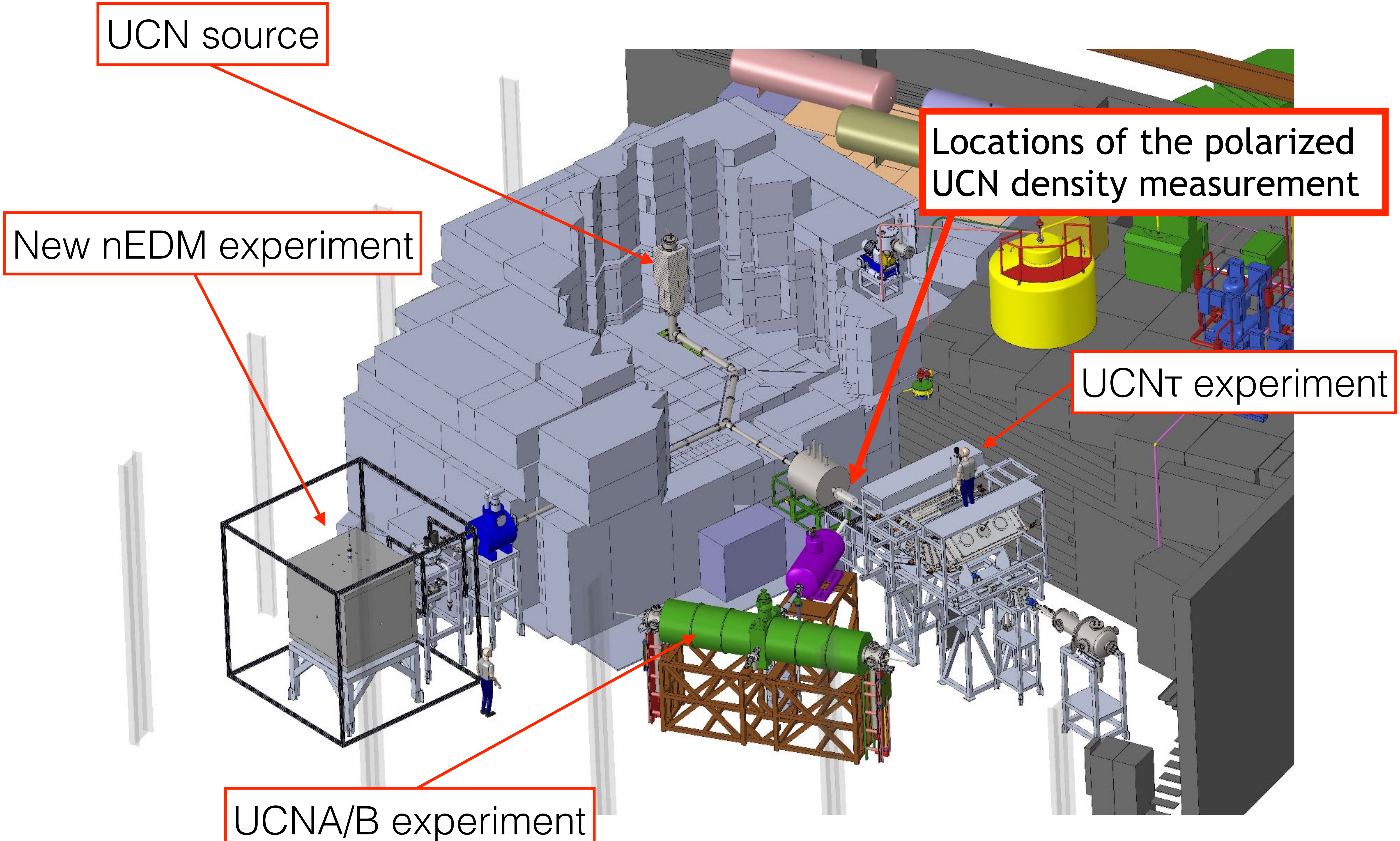
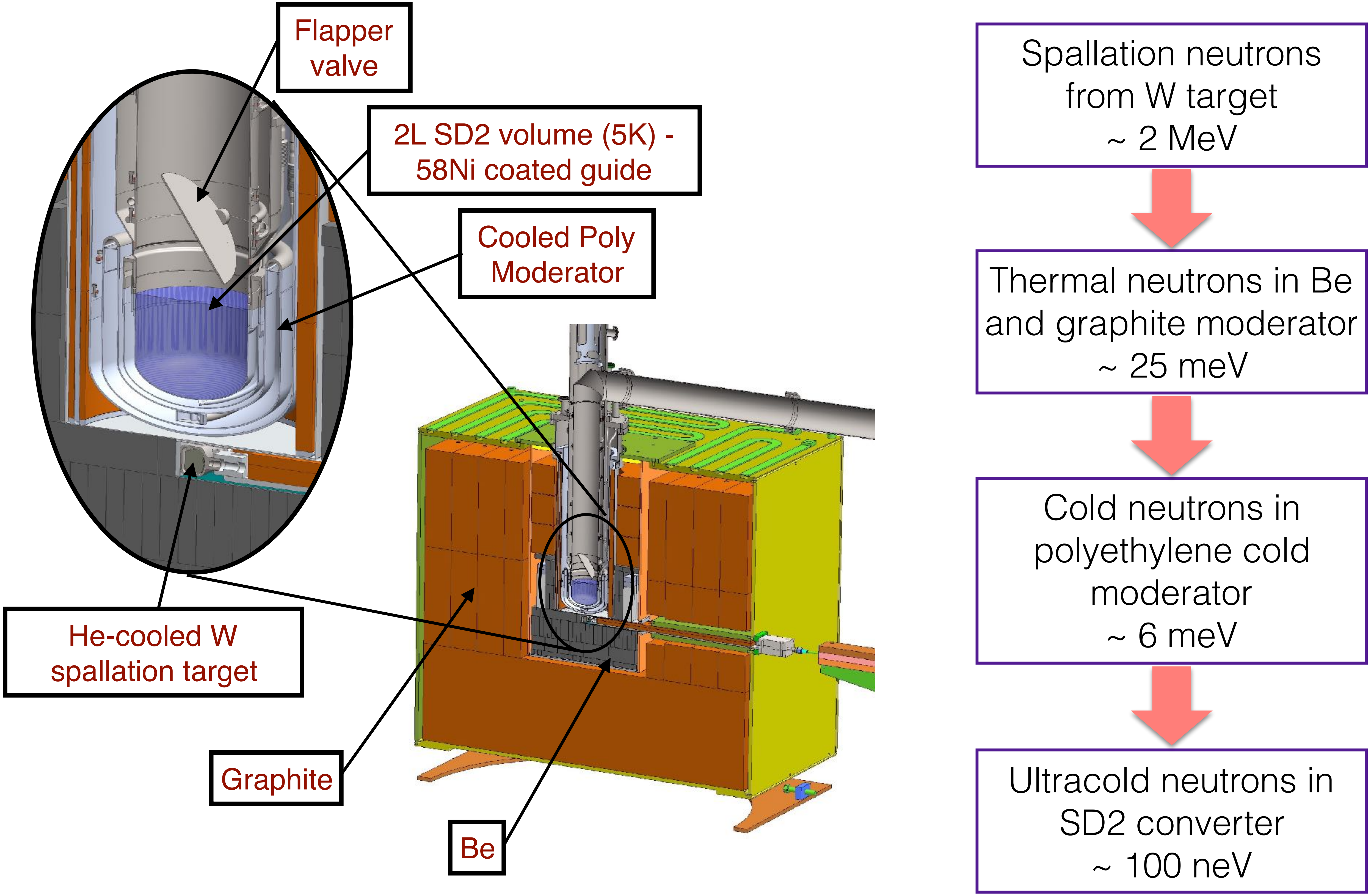
Concept for nEDM experiment at LANL

- A neutron EDM experiment with a sensitivity of $\delta d_n \sim O(10^{-27})$ e-cm based on already proven room temperature Ramsey's separated oscillatory field method could take advantage of the existing LANL SD_2 UCN source
  - nEDM measurement technology for $\delta d_n \sim O(10^{-27})$ e-cm exists. What is holding up the progress is the lack of UCN density.
  - The successfully upgraded LANL UCN source has shown to provide the UCN density required for an nEDM experiment with $\delta d_n \sim O(10^{-27})$ e-cm
- Such an experiment could provide a venue for the US nEDM community to obtain physics results, albeit less sensitive, in a shorter time scale with much less cost while development for the SNS nEDM experiment continues.

LANL UCN Facility

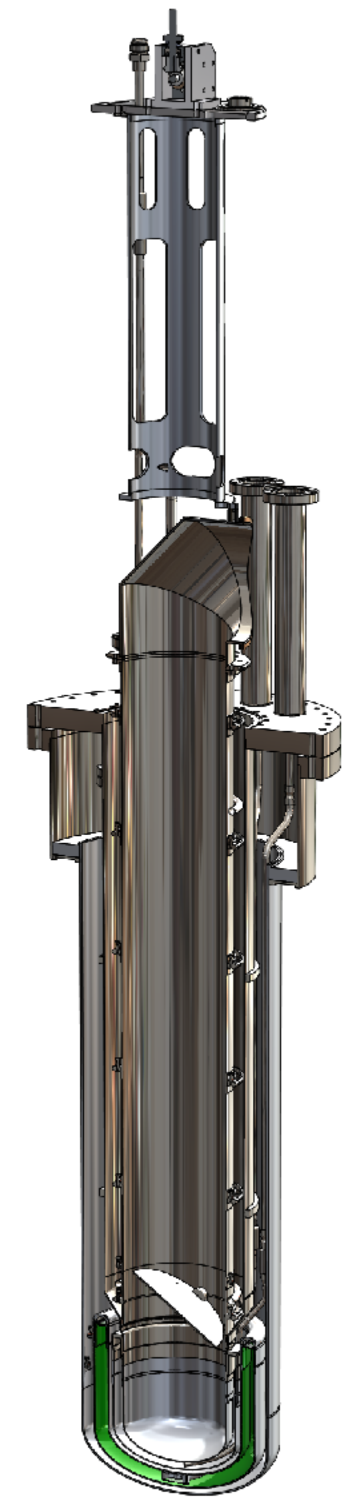


LANL UCN Source

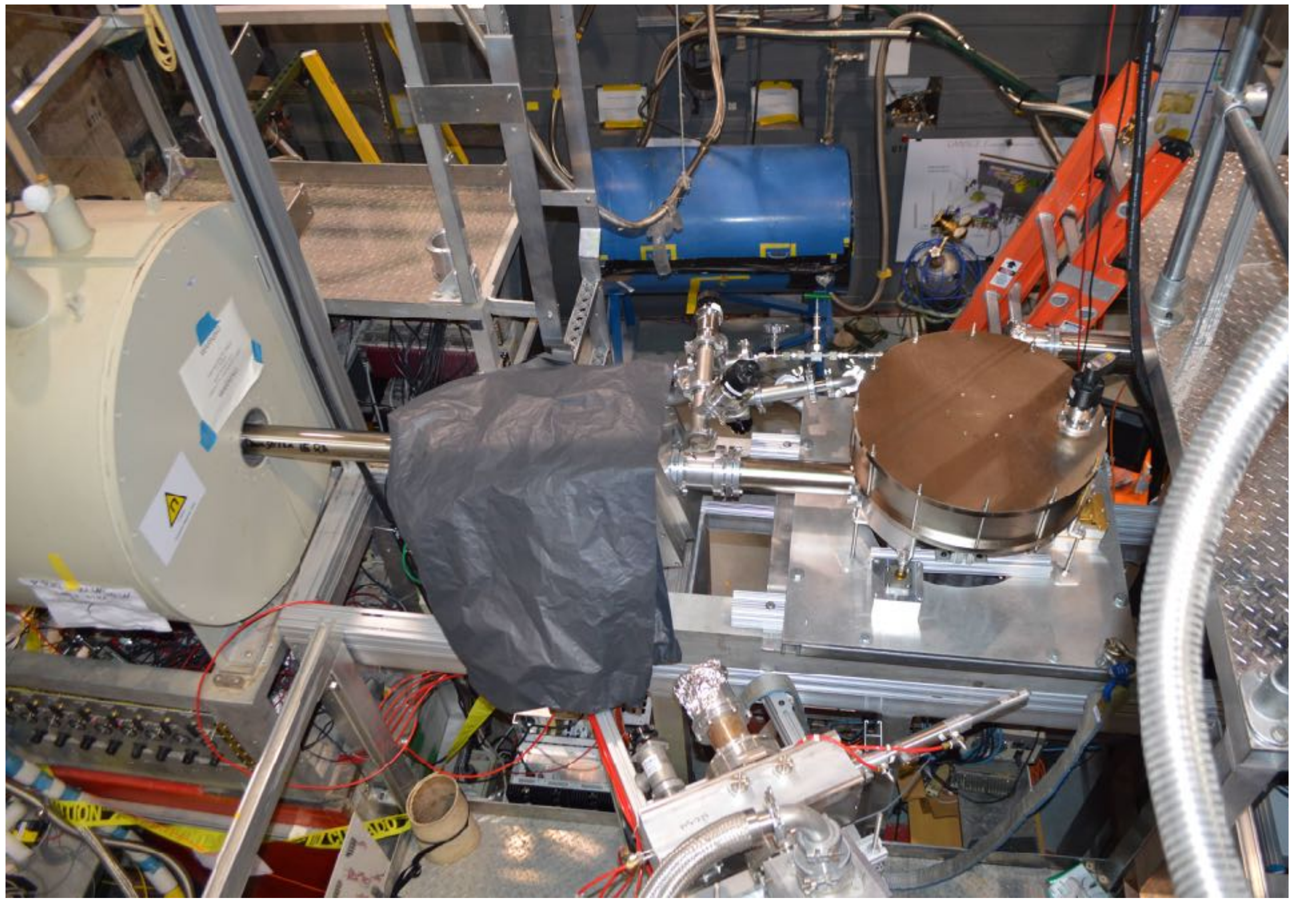


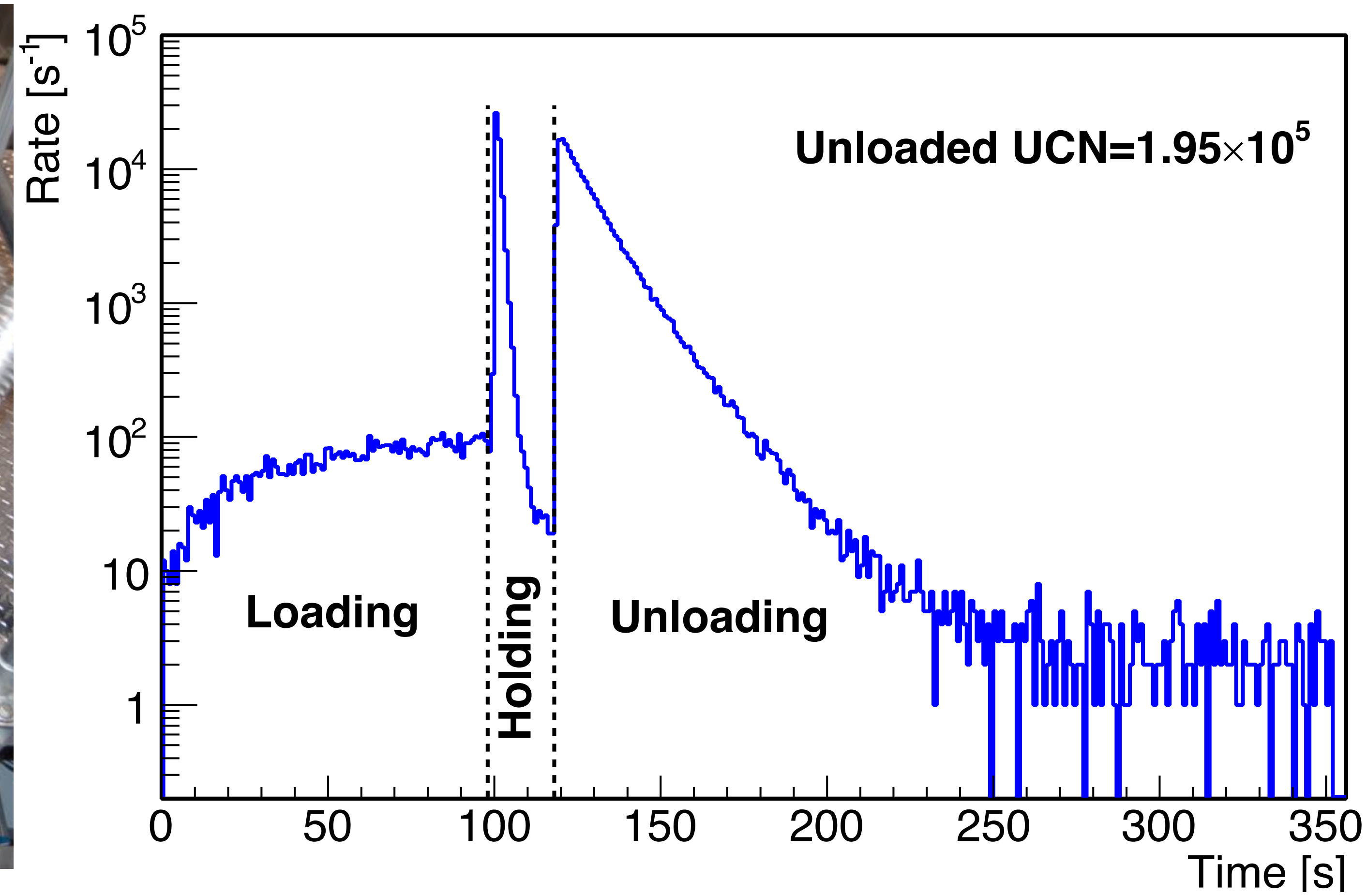
UCN source upgrade

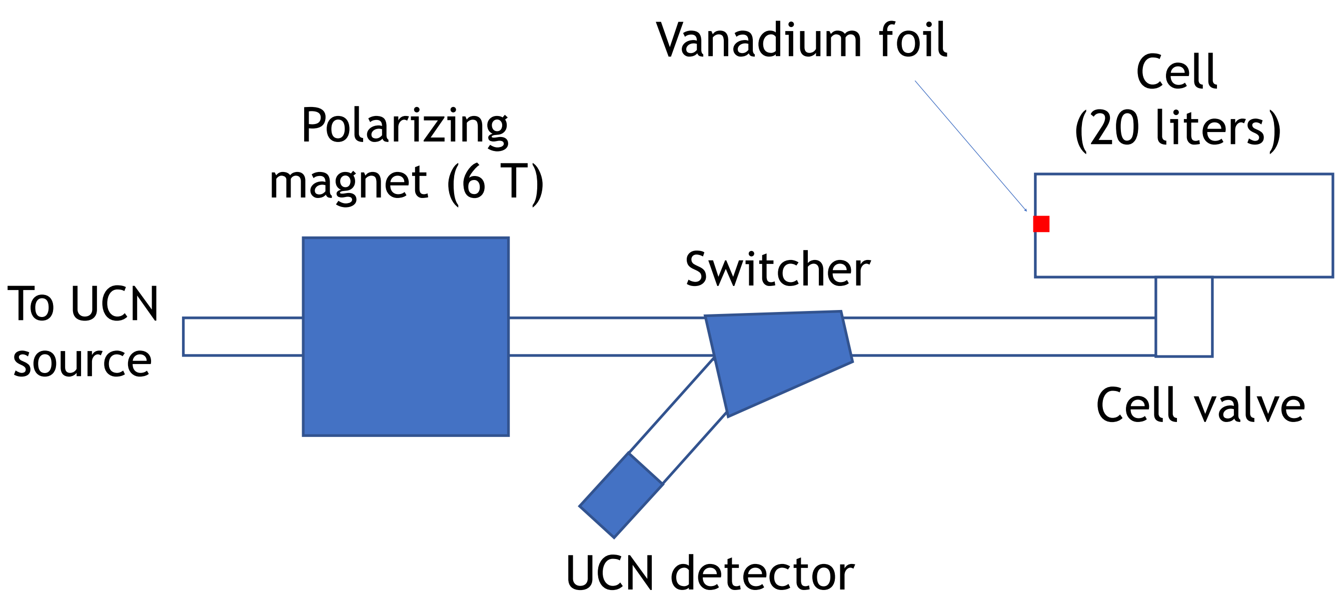
- New source cryostat
  - New design based on previous UCN source cryostat, which had been successfully operating since 2004
  - Dramatic, yet adiabatic changes
  - Optimize source cryostat and moderator geometry to improve UCN output (based on simulation that is benchmarked against the current source)
  - Replaceable moderator
- New flapper valve design based on current successful model
  - Most recent model has surpassed 1M cycles cold with UCN friendly materials
  - Tightly integrated with source cryostat design
  - Flapper drive components moved outside the UCN volume
  - Modify UCN tee geometry for improved UCN flow and reduced loss



Polarized UCN density in a dummy nEDM cell





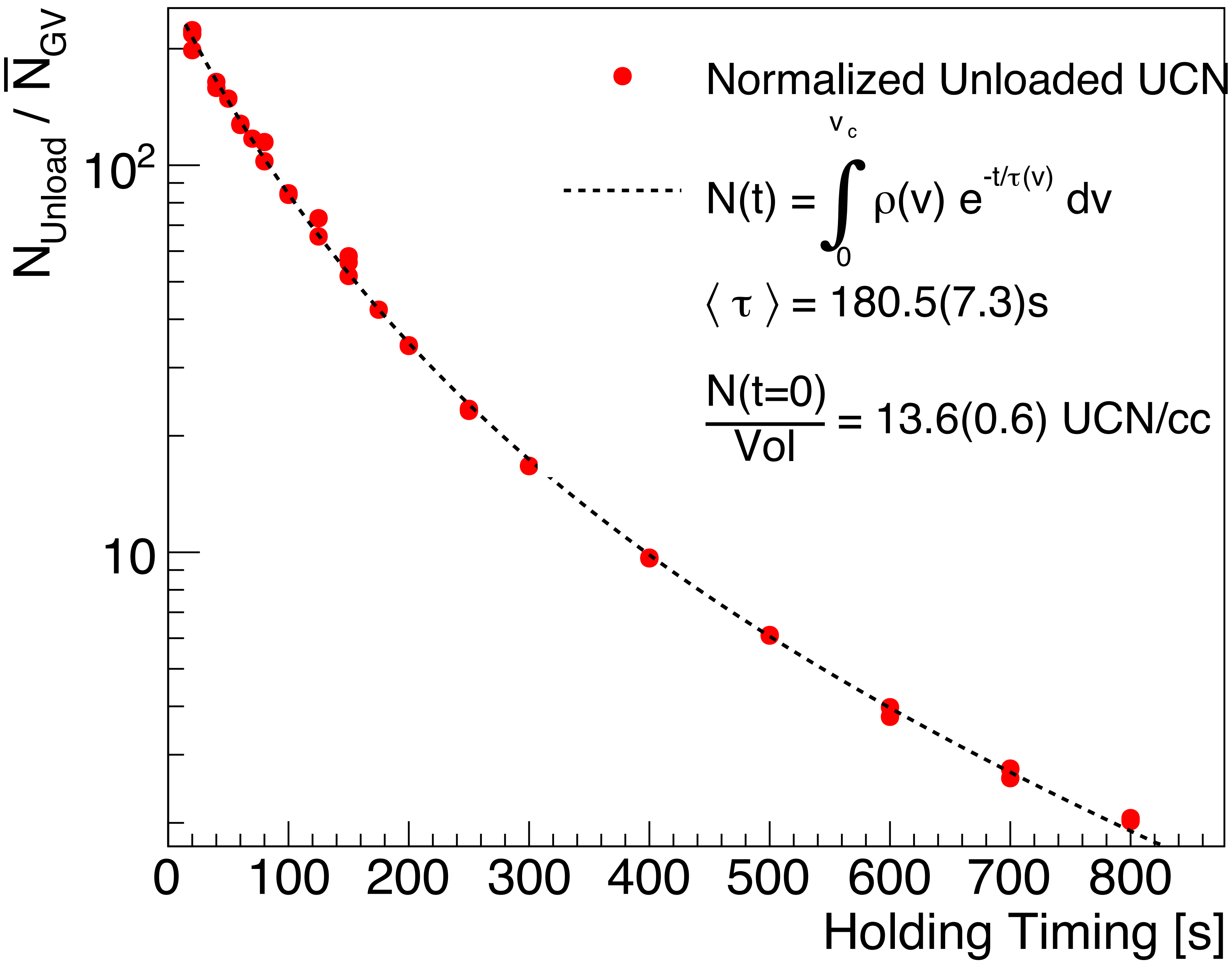


Polarized UCN density (E < 170 neV) at t=0

- 13.6(6) UCN/cc from the fill and dump measurement (was 2.5 UCN/cc before the source upgrade)
- 39(7) UCN/cc from vanadium foil activation measurement

The difference can be attributed to loss in the switcher (~0.5) and the finite detection efficiency (~0.7).

Storage time curve



Holding time	# of counted UCN
20	~200,000
150	~45,000

Estimated statistical sensitivity of an nEDM experiment

$$\delta d_n = \frac{\hbar}{2\alpha T E\sqrt{N}}$$

Parameters	Values
E(kV/cm)	12.0
N(per cell)	39,100
T_{free} (s)	180
T_{duty} (s)	300
α	0.8
σ/day/cell (10^{-26} e-cm)	5.7
σ/day (10^{-26} e-cm) (for double cell)	4.0
σ/year (10^{-27} e-cm) (for double cell)	2.1
90% C.L./year (10^{-27} e-cm) (for double cell)	3.4

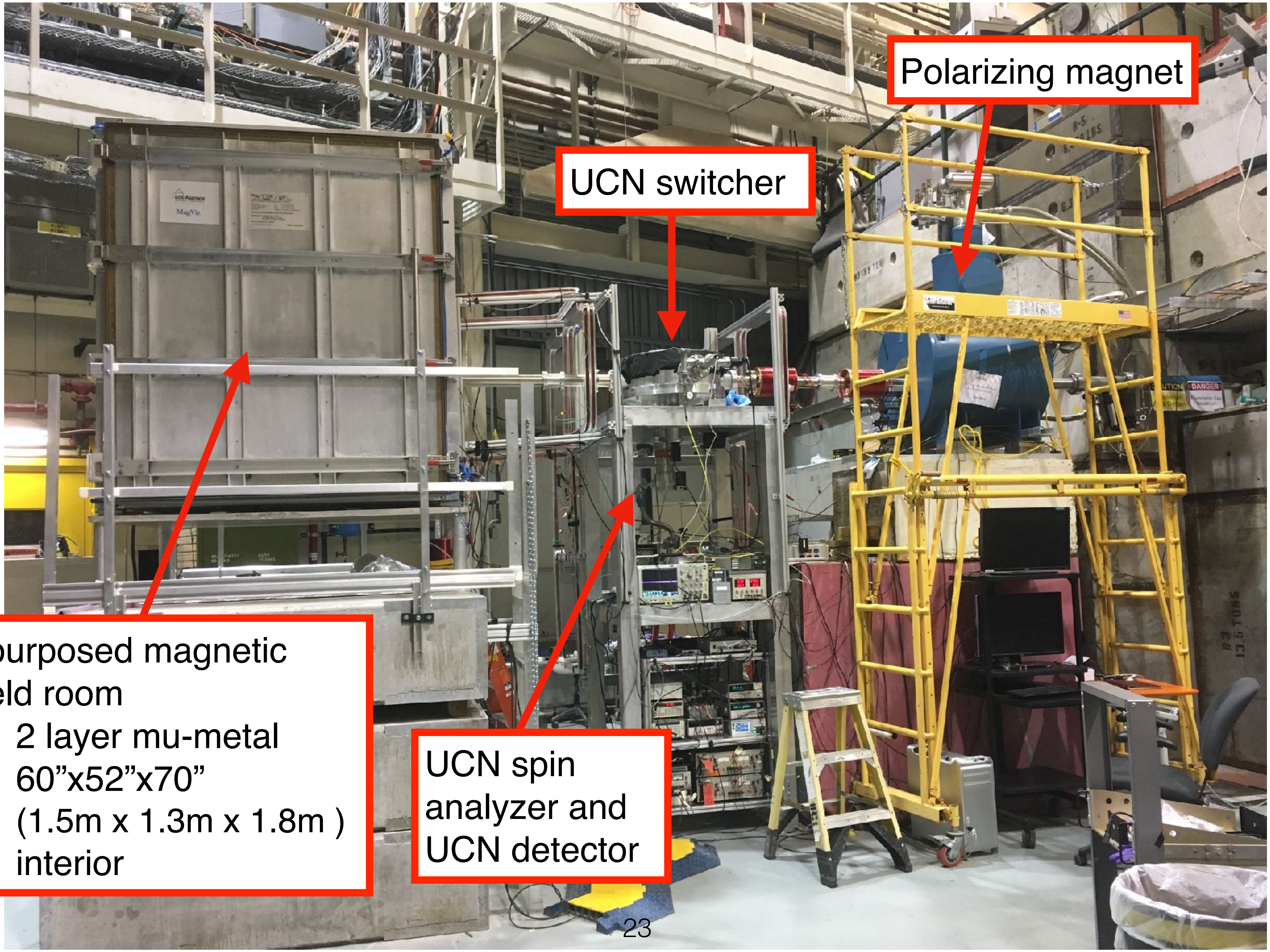
This estimate is based on the following:

- 50 cm diameter cell
- The estimate for E, T_{free}, T_{duty}, and α is based on what has been achieved by other experiments.
- The estimate for N is based on the actual detected number of UCN from our fill and dump measurement at a holding time of 180 s. Further improvements are expected (new switcher and new detector).

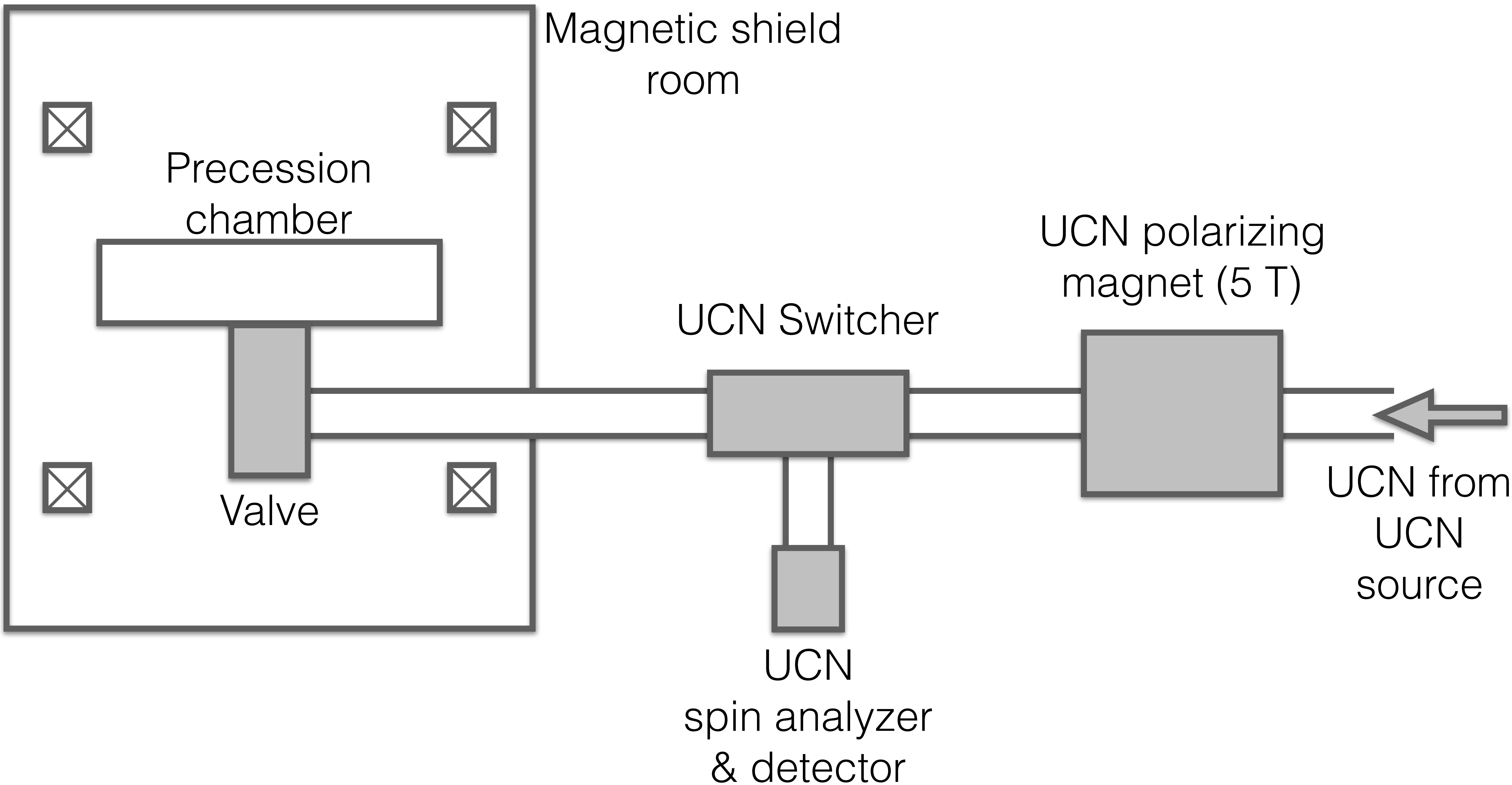
*** "year" = 365 live days. In practice, it will take 5 calendar years to achieve this with 50% data taking efficiency and nominal LANSCE accelerator operation schedule**

Ramsey demonstration apparatus

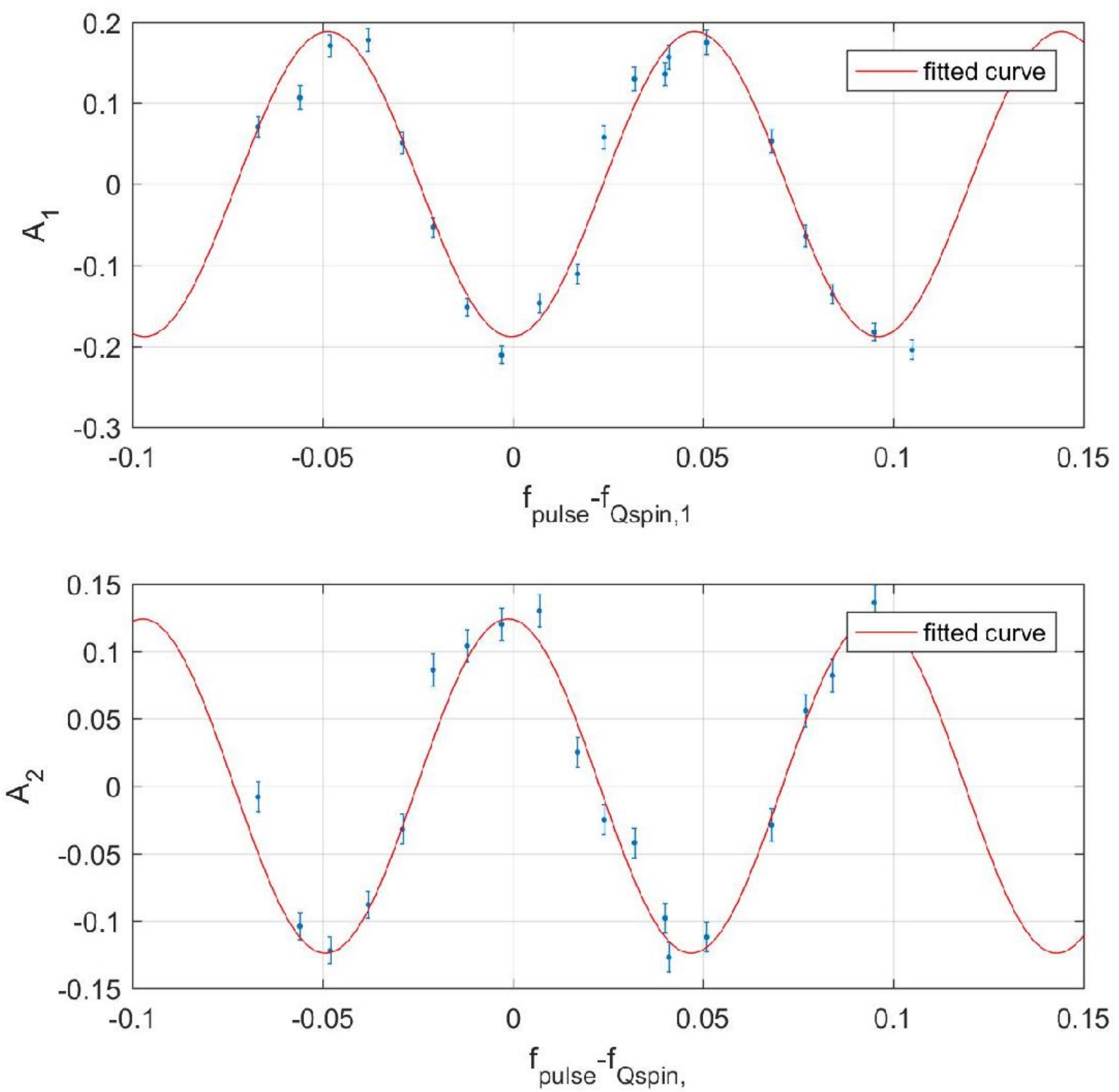
First step towards building an nEDM experiment



Schematic diagram of Ramsey demonstration apparatus

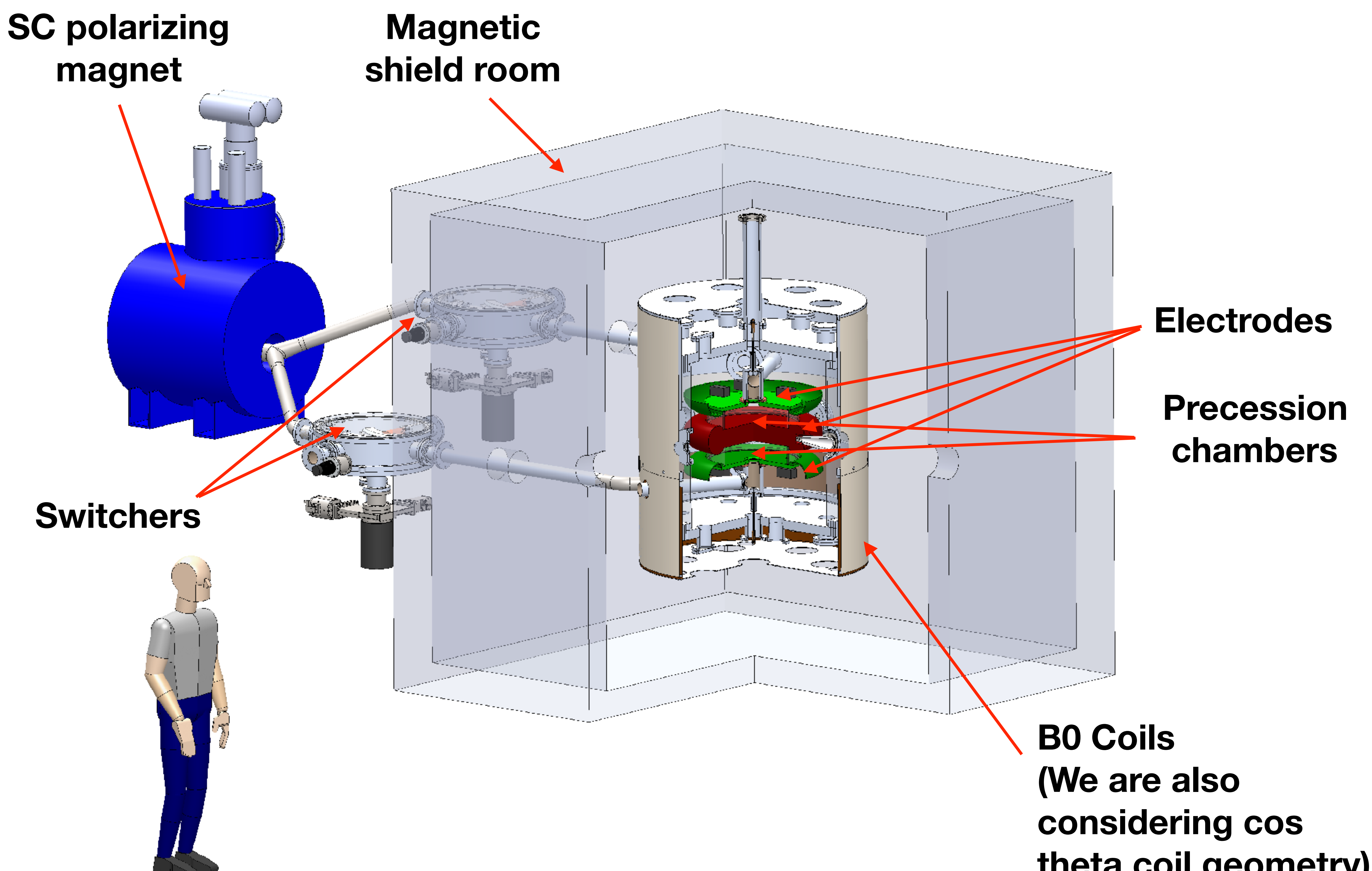


Ramsey curve with a 10 s free precession time



T2 ~ 20 s

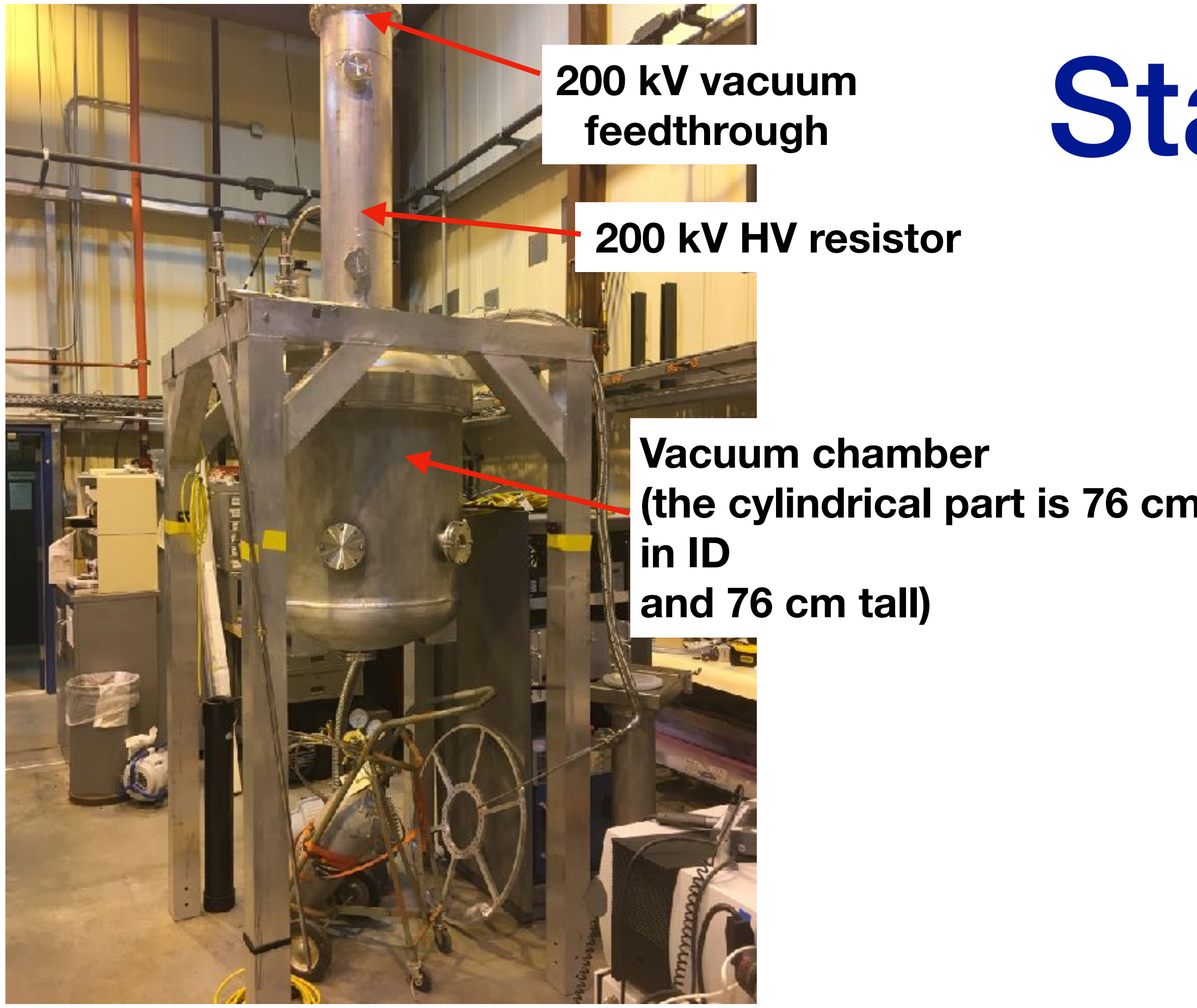
Proposed LANL nEDM experiment (conceptual)

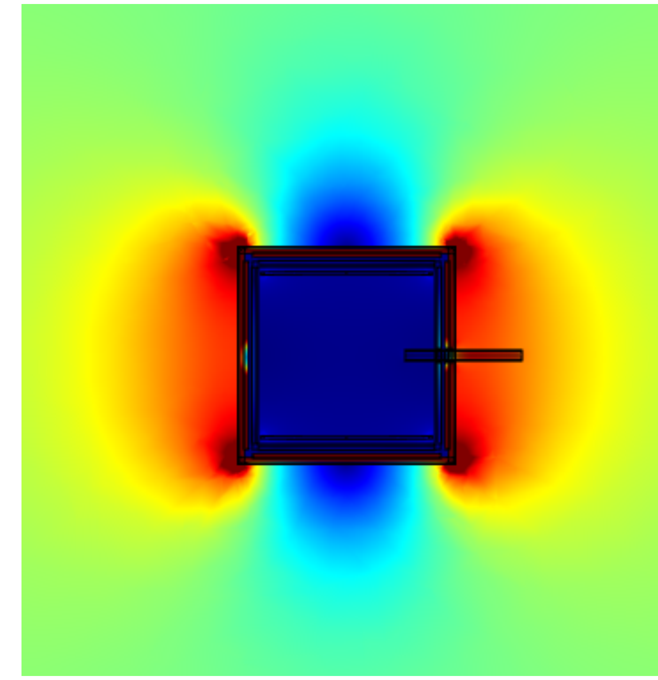


Status

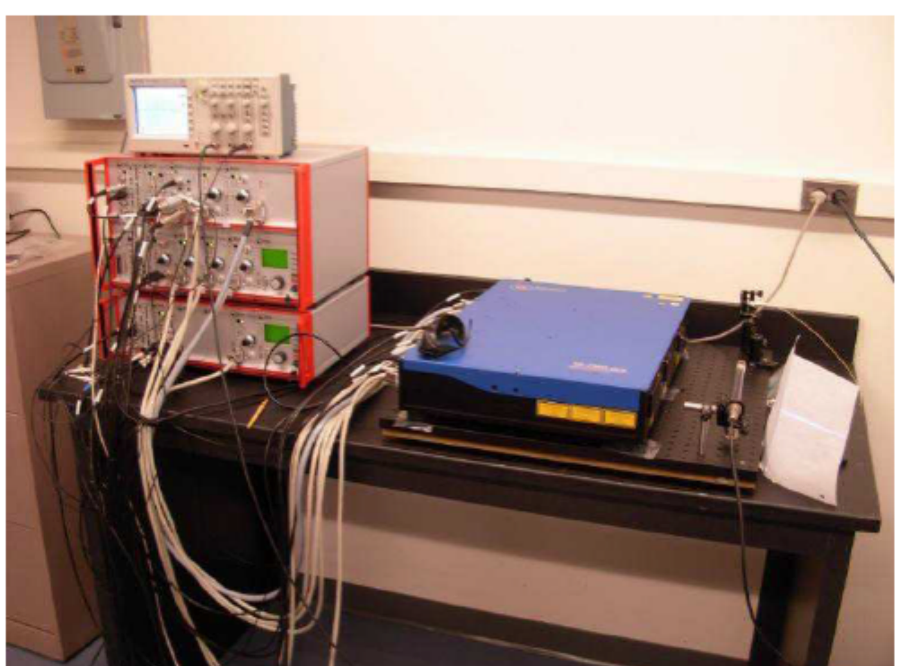
- Continued R&D using the prototype apparatus
  - Test bed for: spin transport, magnetic field, material selection, DAQ system, etc.
- The experimental apparatus being designed
  - Current focus is on the design of the MSR, longest lead-time component

Status

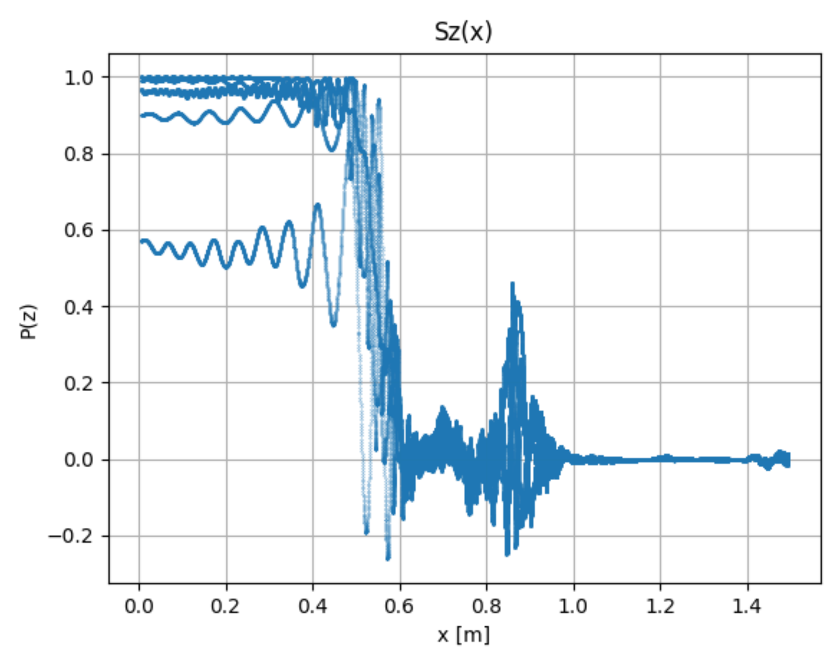




MSR simulation using COMSOL (Helmholz coil in mumetal box)



Topica quadrupled system



Spin transport simulation

nEDM@SNS

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SNS nEDM experiment key features

Golub and Lamoreaux, Phys. Rep. 237, 1 (1994)

- Experiment performed in superfluid LHe
- In situ production of UCN from 8.9 Å cold neutron beam via superthermal process
- Higher electric field expected to be achievable in LHe
- Longer UCN storage time expected at cryogenic temperatures
- ^{3}He as comagnetometer and spin analyzer for UCN
- Two complementary approaches to look for the nEDM signal ($\boldsymbol{d} \cdot \boldsymbol{E}$)
  - Free precession method
  - Dressed spin method

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- Higher electric field expected to be achievable in LHe
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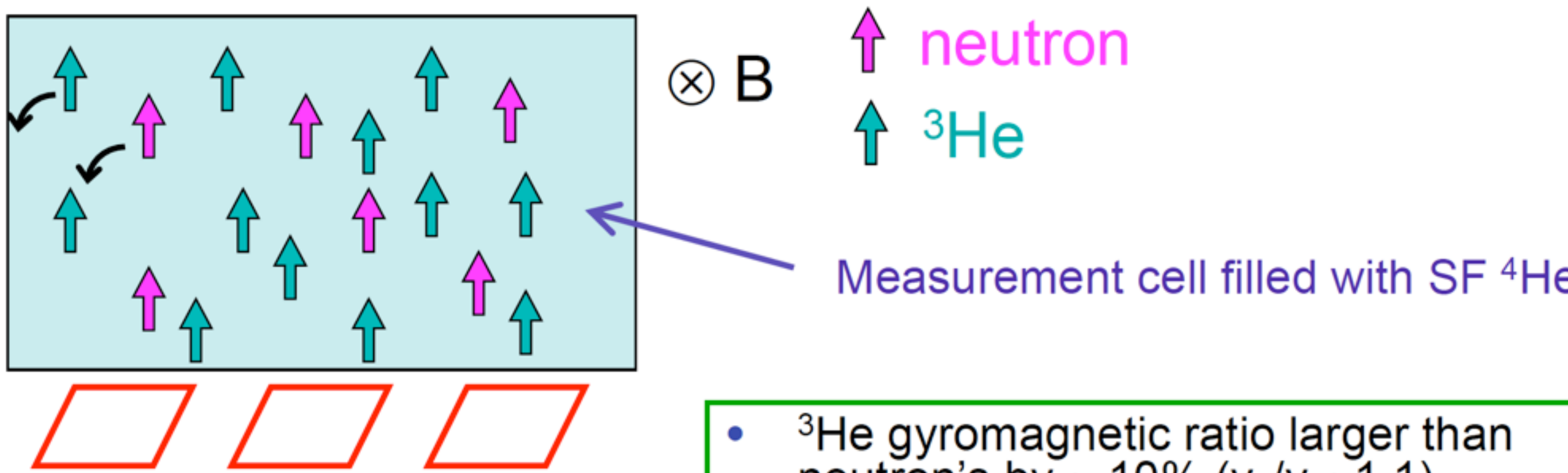
Statistical sensitivity increase due to the use of LHe

- ^{3}He as comagnetometer and spin analyzer for UCN
- Two complementary approaches to look for the nEDM signal ($\boldsymbol{d} \cdot \boldsymbol{E}$)
  - Free precession method
  - Dressed spin method

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

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)



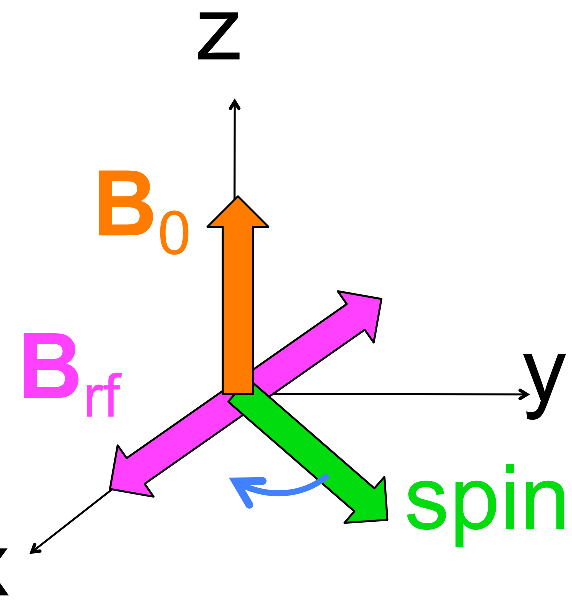
Change in magnetic field due to the rotating magnetization of ^{3}He detected by SQUID magnetometers

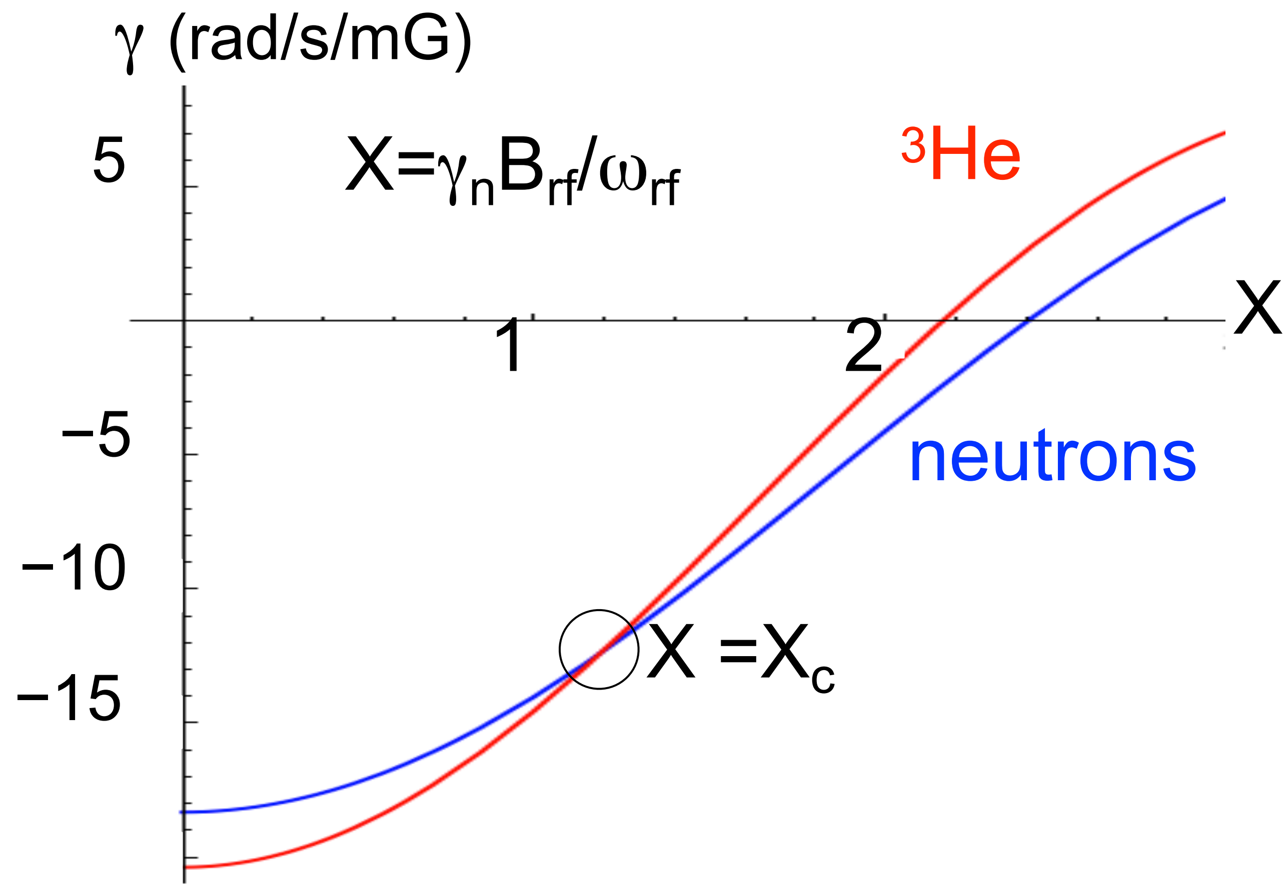
- ^{3}He gyromagnetic ratio larger than neutron's by ~ 10% (γ_3/γ_n~1.1)
- Neutron absorption on ^{3}He highly spin dependent ($\sigma_{\uparrow\downarrow} \gg \sigma_{\uparrow\uparrow}$)
- Reaction product of n+^{3}He→p+t generates UV (~80 nm) scintillation light in SF ^{4}He

Scintillation light from n-^{3}He capture reaction provides a measurement of ω_3-ω_n

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

Dressed spin method





A strong non-resonant RF field

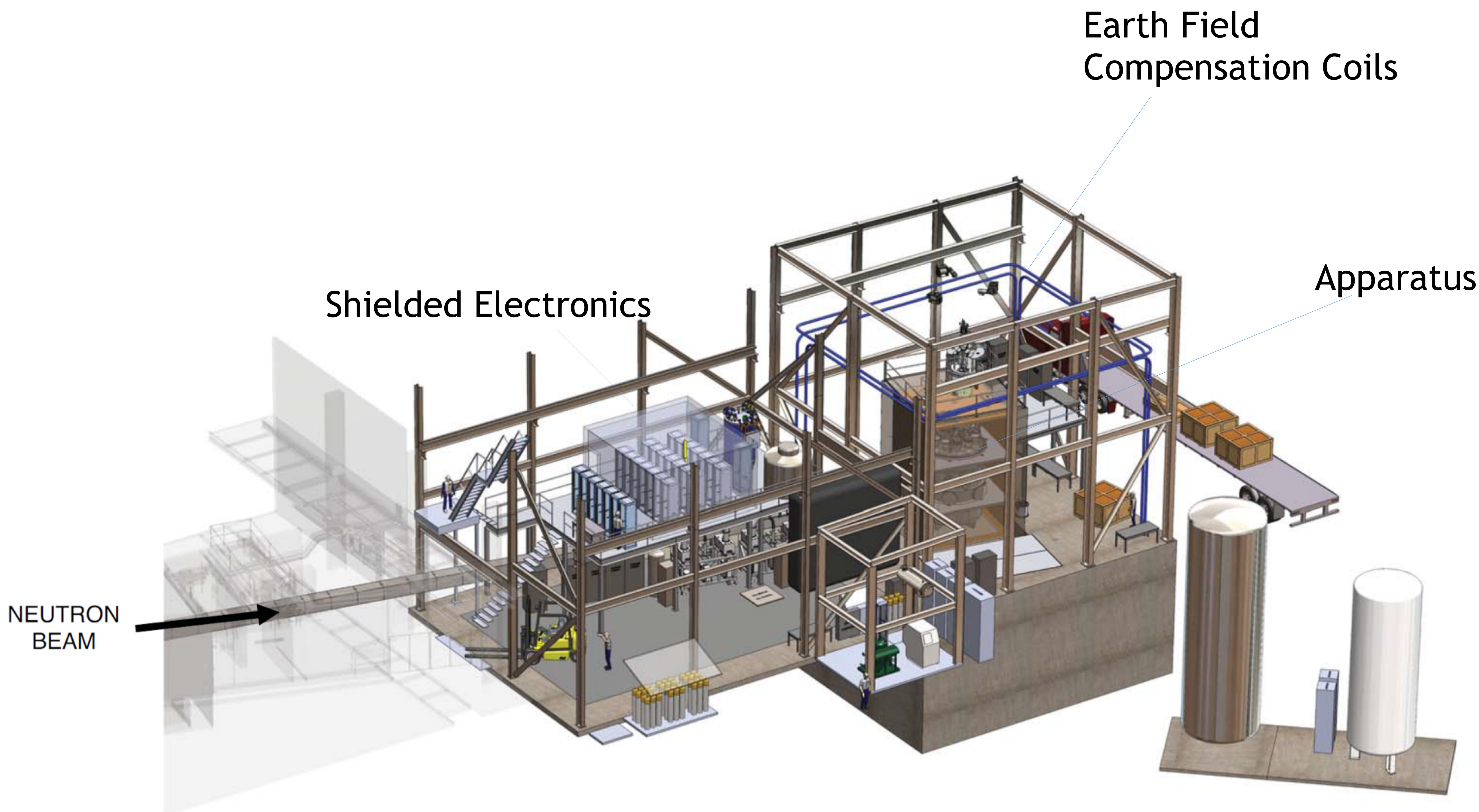
$\mathbf{B_{rf}} \perp \mathbf{B_0}$, $B_{rf} >> B_0$, $\omega_{rf} >> \omega_0$

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

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

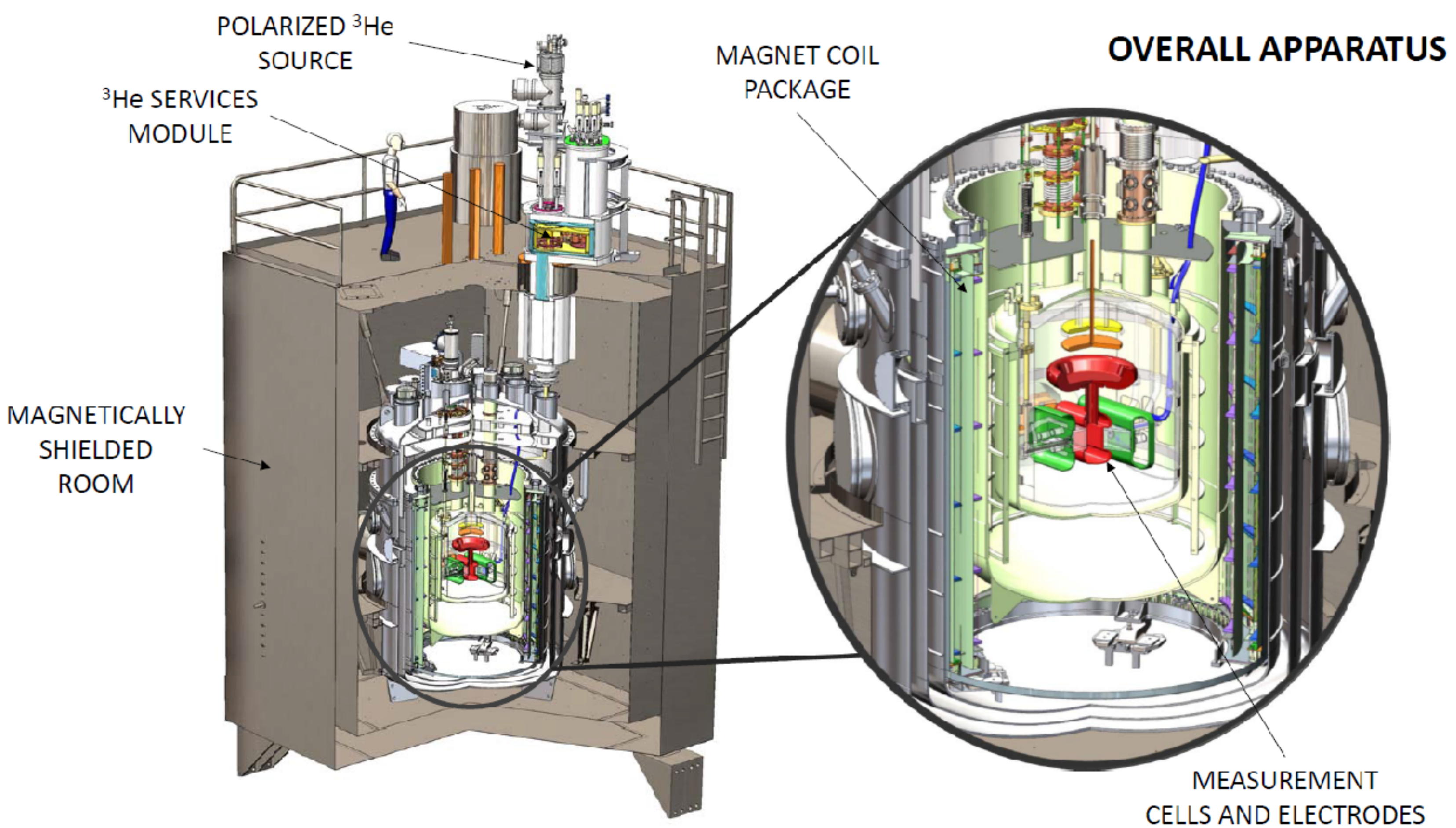
- Can tune the dressing parameter ($X = \gamma_n B_{rf}/\omega_{rf}$) until the relative precession between 3He and neutrons is zero ($X = X_c$).
- Look for X_c dependence on E field
- Provides access to EDM that is independent of variations of the ambient B-field

SNS Facility Floor plan

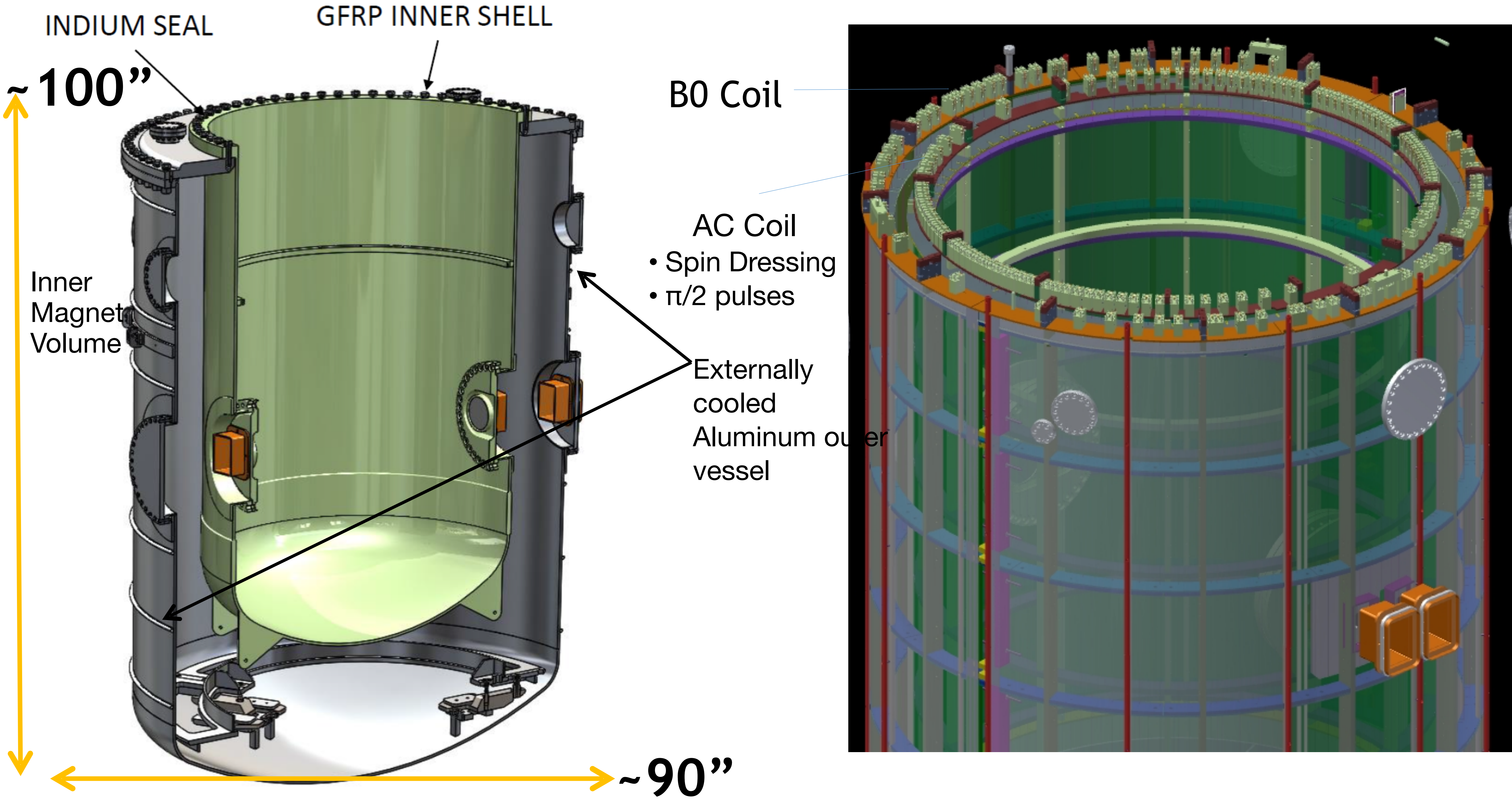


Apparatus Overview

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



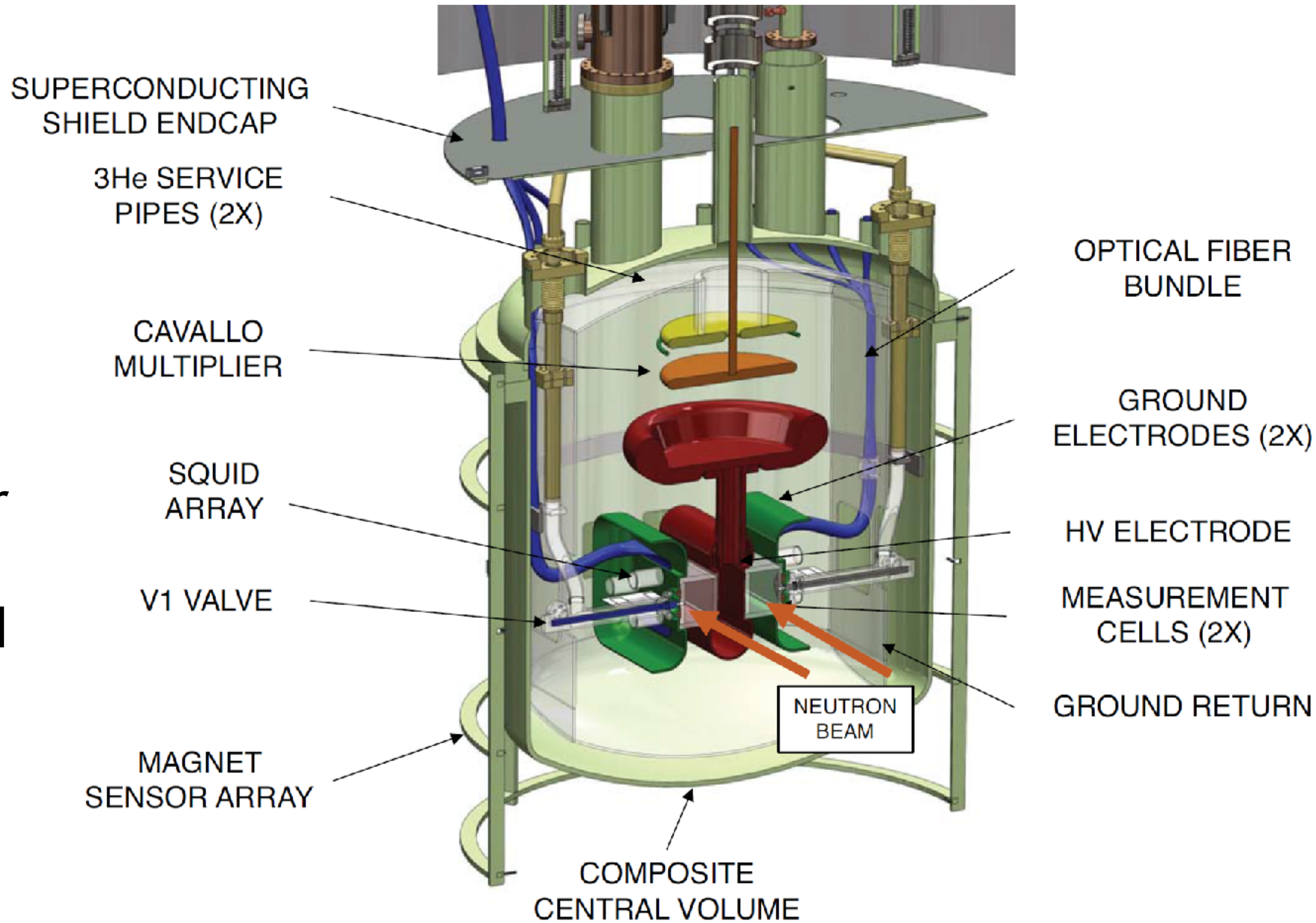
Magnetic Fields



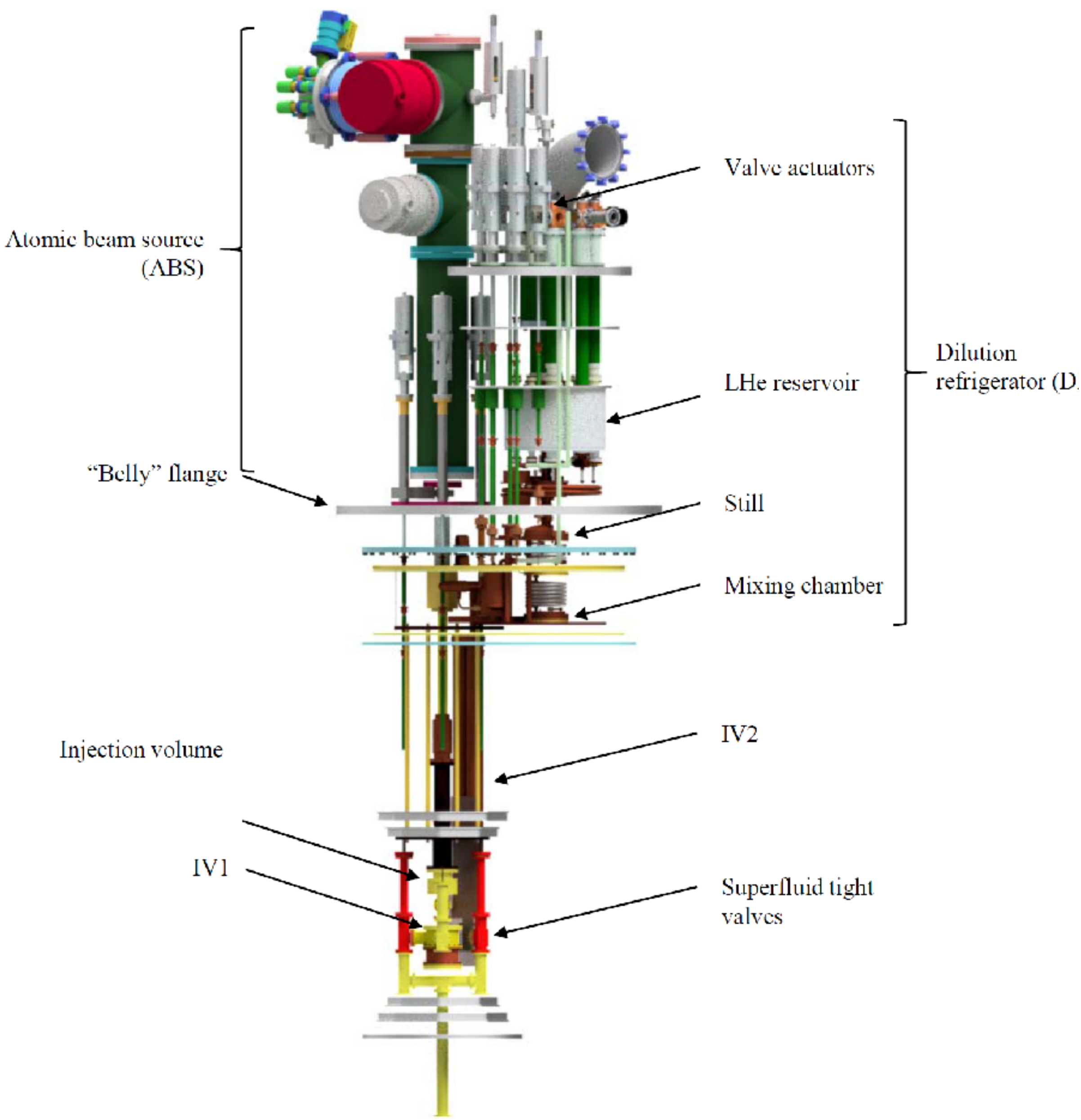
Central Detection System

Main components

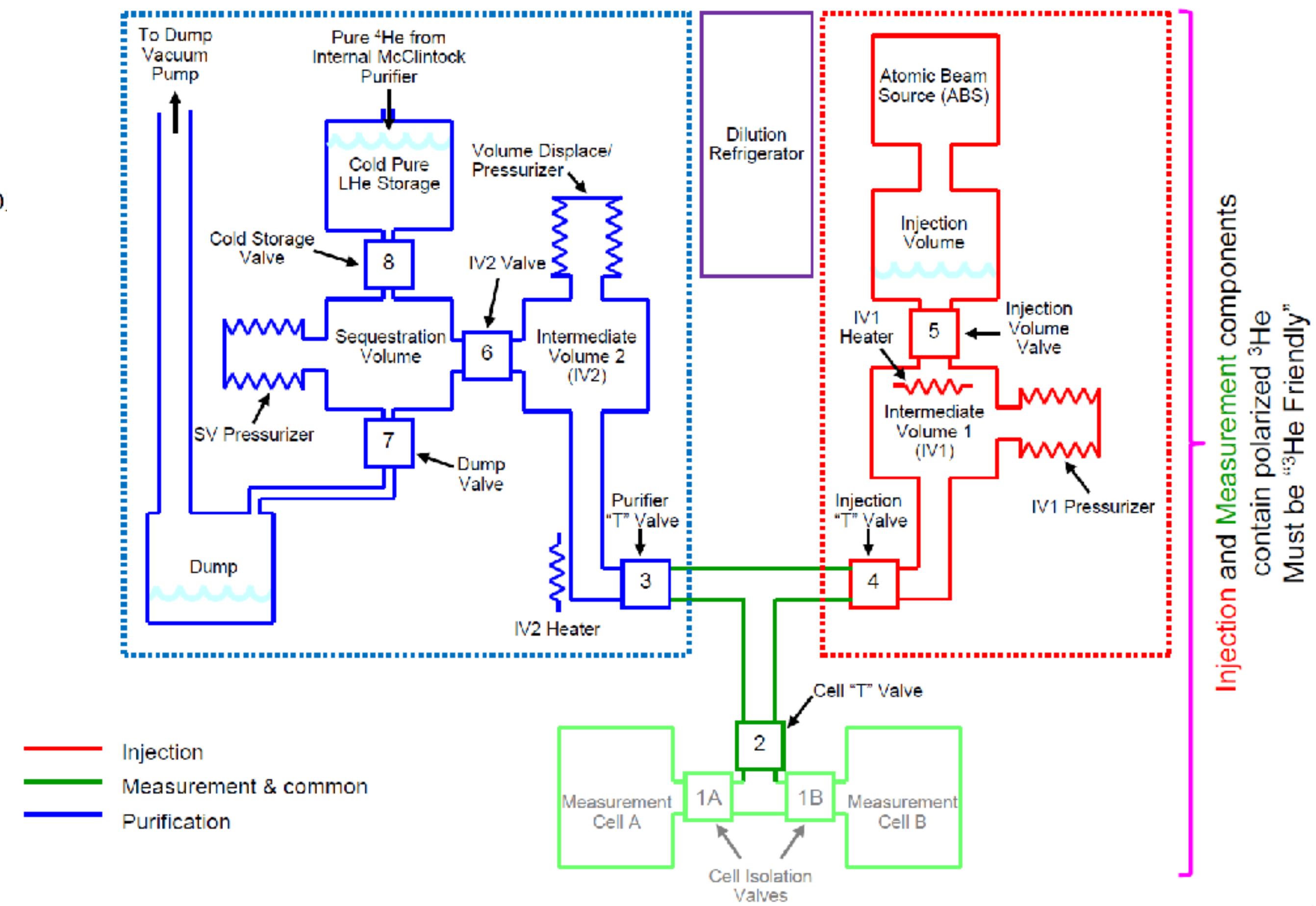
- Measurement cells with 75 kV/cm electric field inside
- Cavallo's Multiplier
- Squid Magnetometer
- 1600 L of super fluid helium
- Light collection



^{3}He Services



3He system block diagram

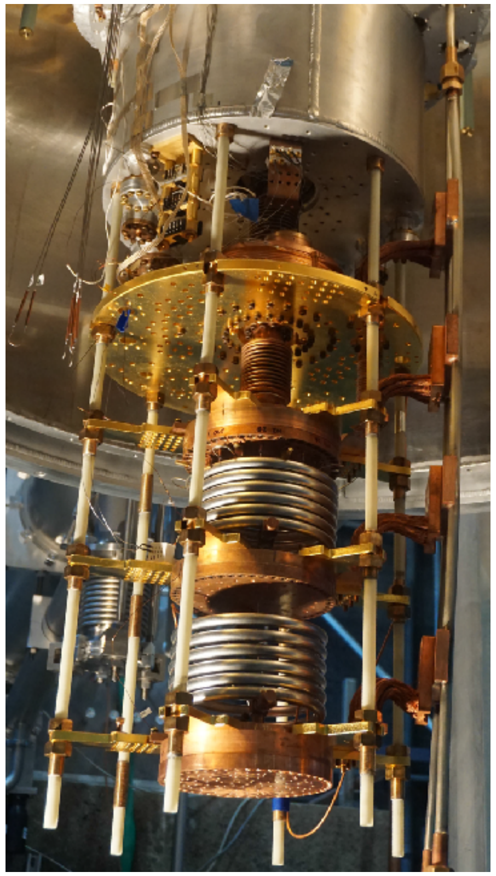


- Heat flush and diffusion methods is used to move ^{3}He
- ^{3}He flow is controlled by heaters, valves, and pressurizers.

Status

	Status
Magnetic field subsystem	• Full scale lower cryostat being commissioned • Full scale coil package under construction • Magnetic shield room being designed
Central detector system	• Half scale HV test apparatus under construction • Cryogenic Cavallo multiplier prototype being designed • Tests of UCN storage under way using UCN from LANL UCN source • Advanced prototype of SQUID being tested • Non-magnetic, high-power dilution refrigerator being constructed • Final prototype of the light collection readout electronics being fabricated
3He services	• Non-magnetic, high-power dilution refrigerator being commissioned • Atomic beam source being re-commissioned • Helium purification system components under construction
Systematic study apparatus	• Cryostat and various components under construction

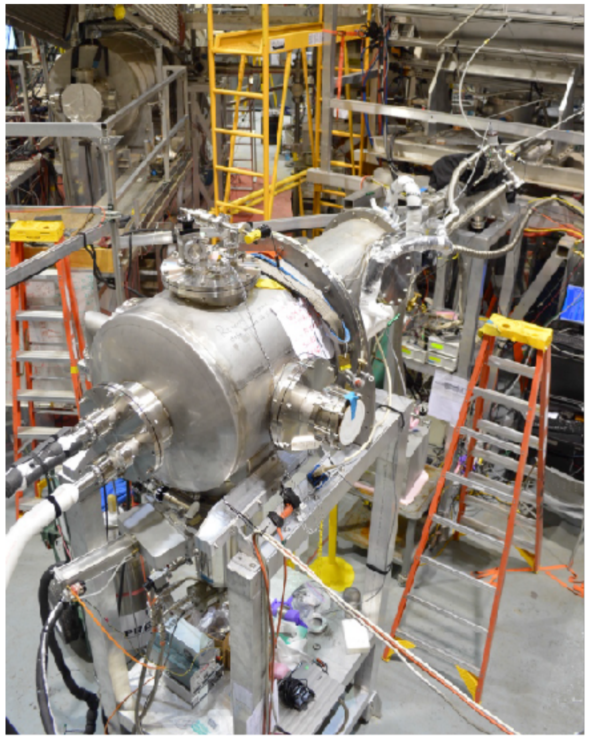
Status



Dilution refrigerator

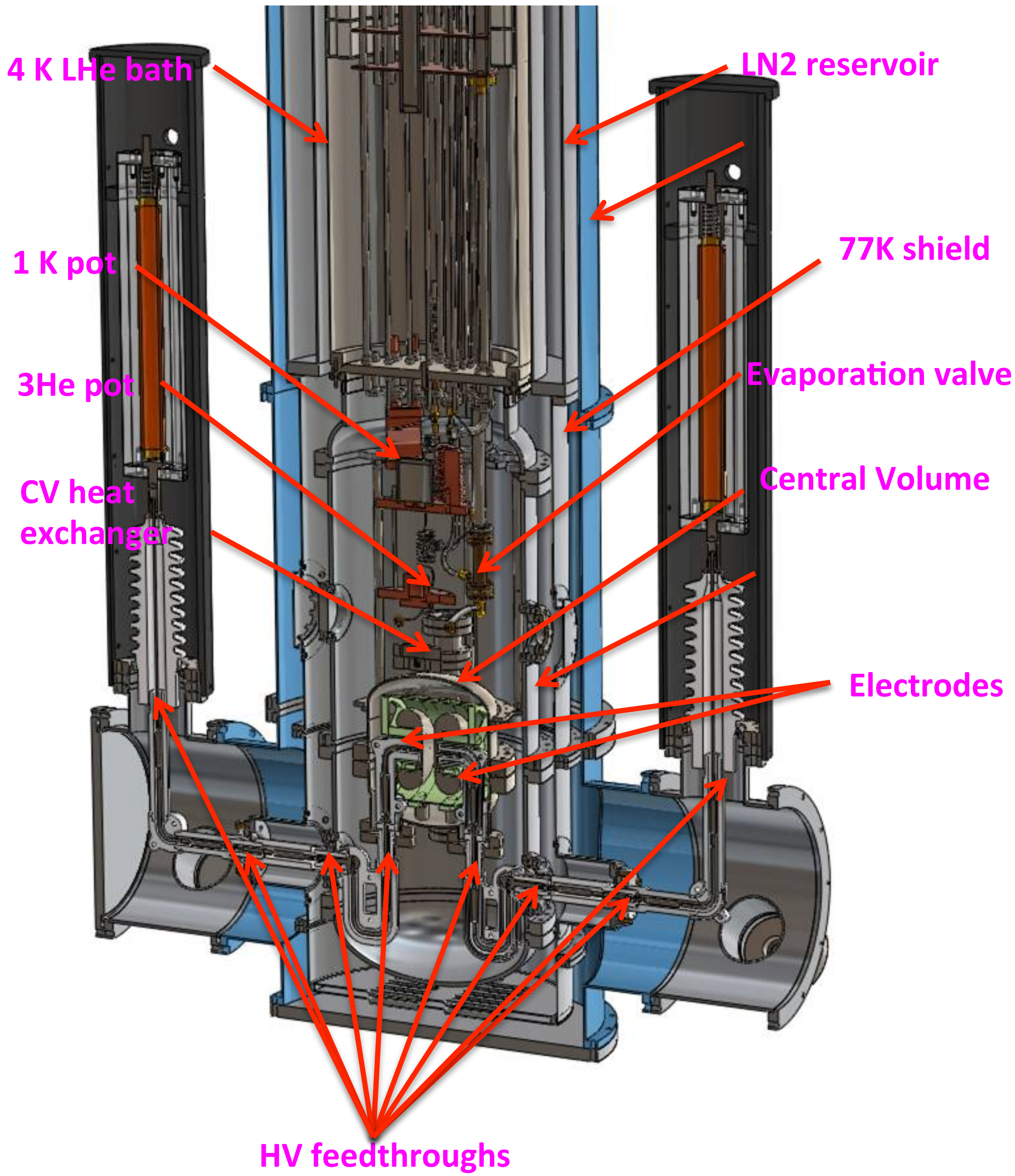
Half scale HV test apparatus

Cryovessel



UCN storage test

HV E-field R&D using Medium Scale HV Test System at LANL

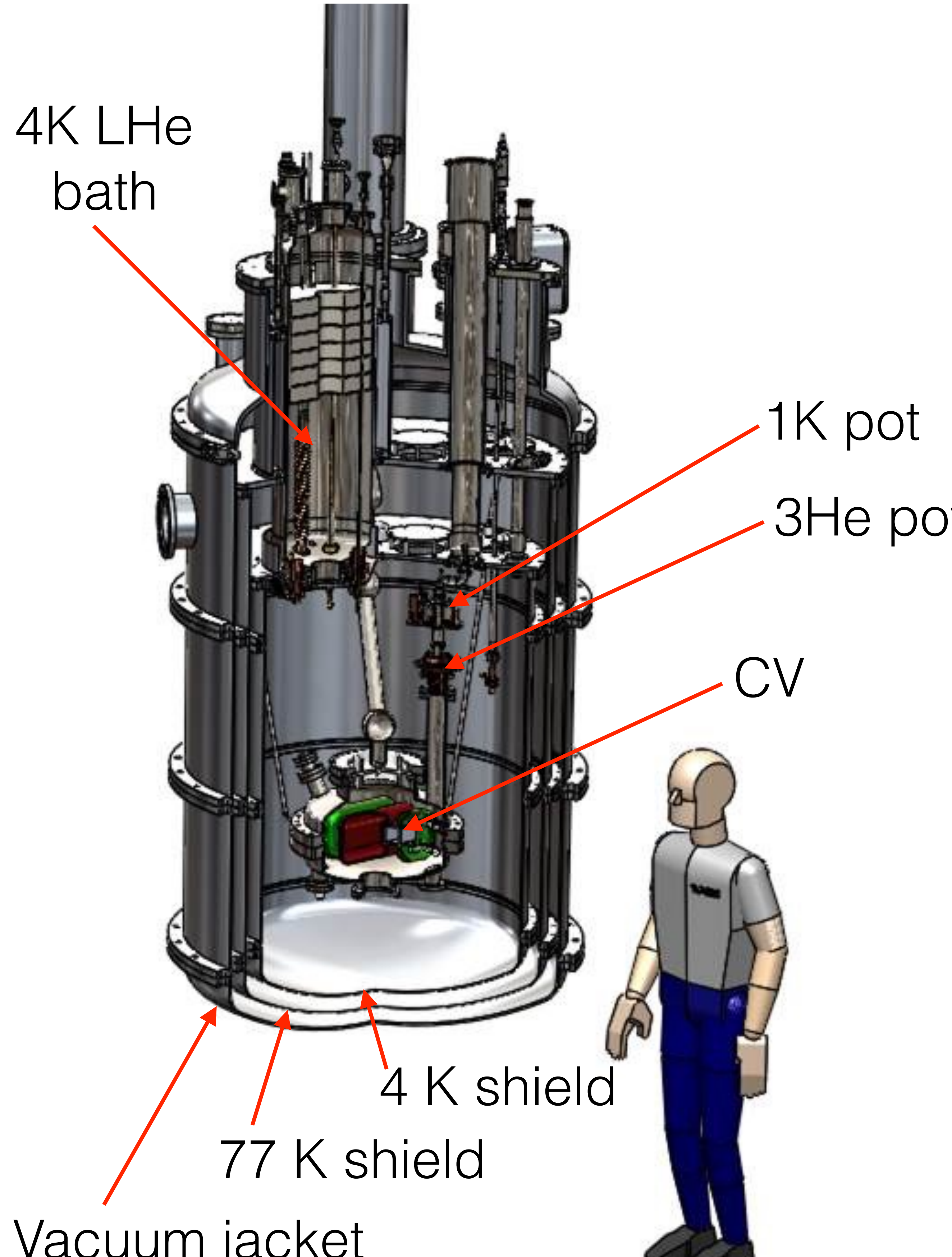


- MSHV main features:
  - 6 liter LHe volume cooled by a 3He fridge
  - Electrode size ~ 12 cm in diameter (~1/5 scale)
  - Electric field: up to 100 kV/cm in 1 cm gap
  - Lowest temperature ~ 0.4 K
  - Pressure: variable between SVP and 1 atm
- Main findings:
  - Stable electric field ≳ 75 kV/cm at 0.4 K for a wide range of pressures with and without PMMA cell inserted between electrodes.
  - Leakage current ≲ 1 pA at 40 kV voltage difference with and without PMMA cell inserted between electrodes.

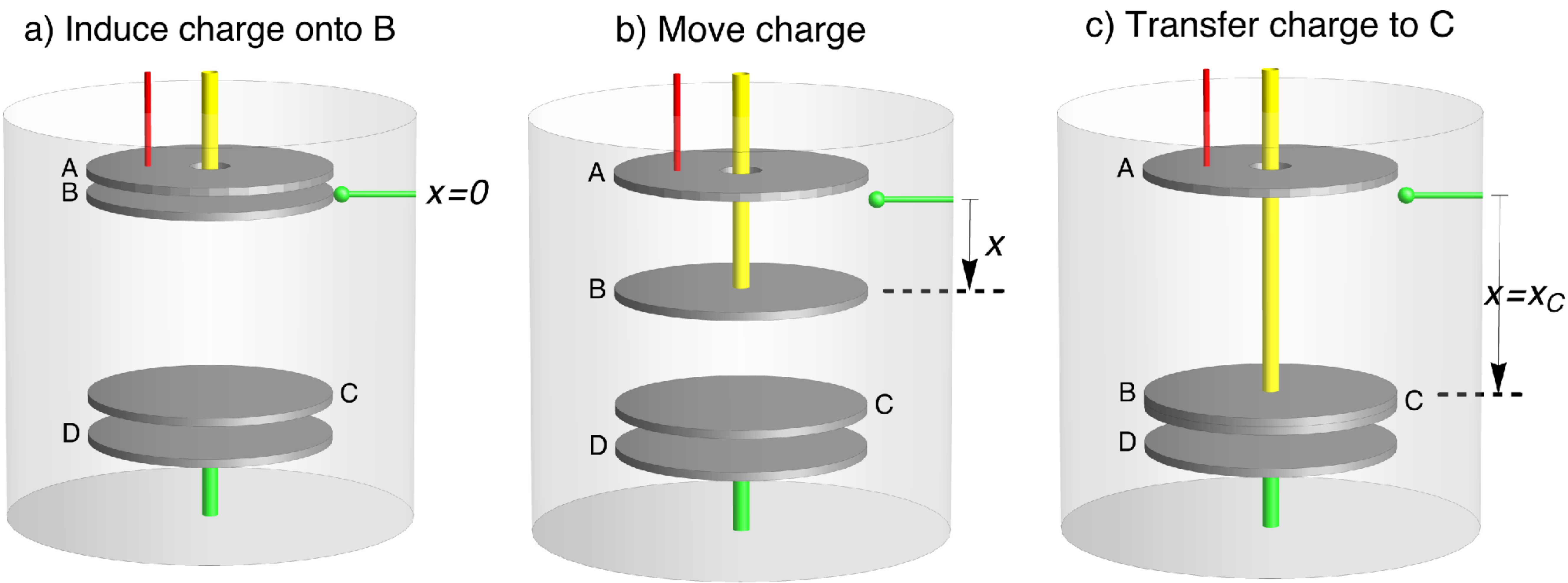
Ito et al., Rev. Sci. Instrum. 87, 045113 (2016).

Half scale HV test apparatus at LANL

A half-scale electrode system is immersed in 40 liter LHe volume cooled to 0.4 K. HV performance test will be performed with 200 kV direct HV feed. The cryostat is currently being commissioned.



Cavallo's Multiplier for SNS nEDM



This 1795 technology will be used to generate > 700 kV inside the SNS nEDM Central Volume from 50 kV, eliminating the need for a 700-kV, superfluid-tight, low-leakage-current HV feedthrough and simplifying the design of the experiment.

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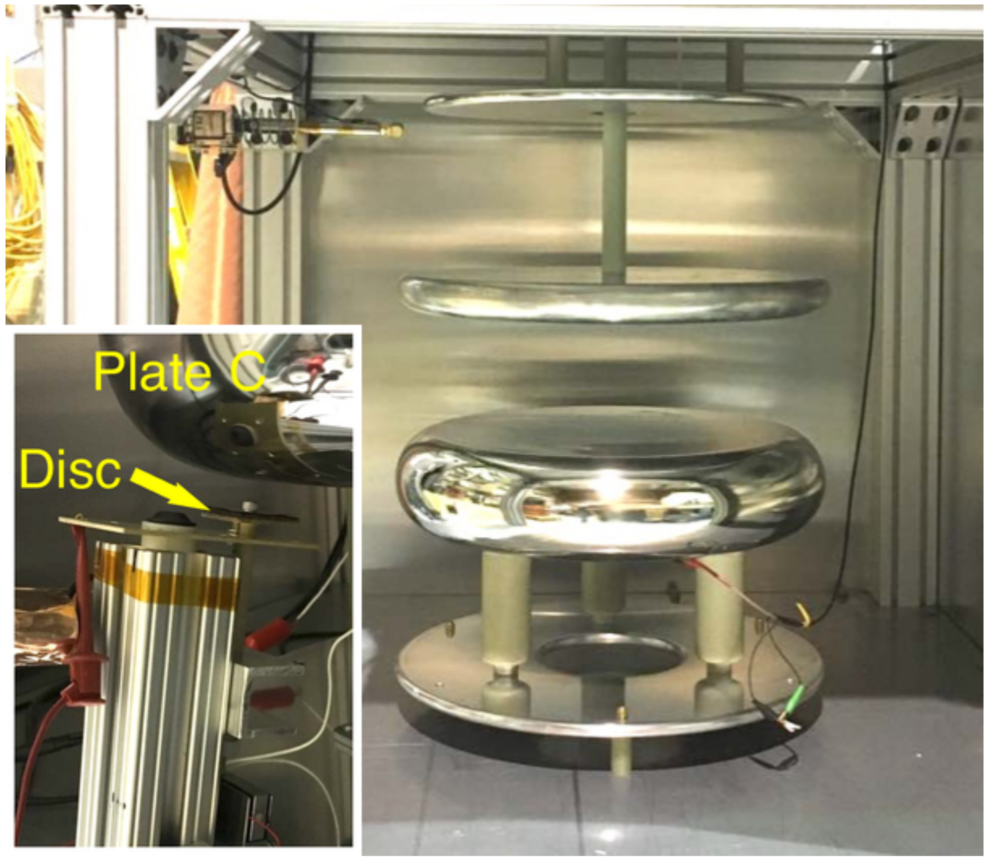
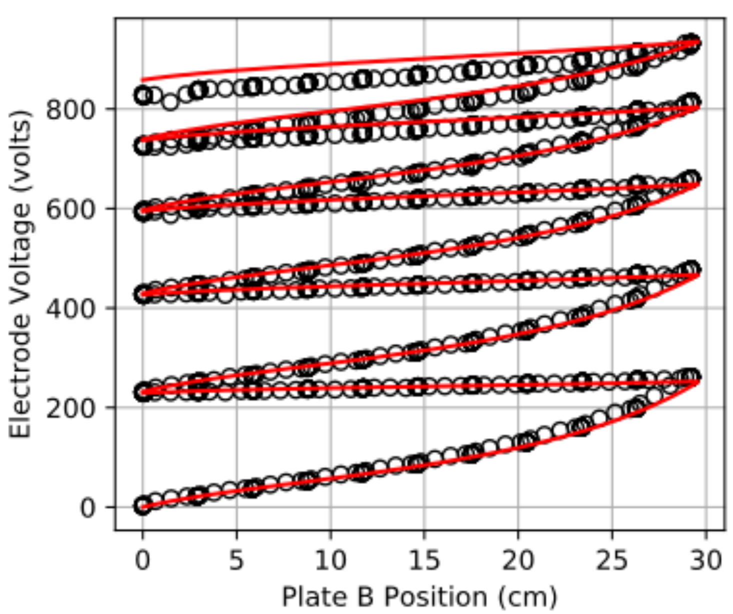
Cavallo HV multiplier development at LANL

Room temperature demonstration





Measured Voltage
Prediction based on measured C_{ij}

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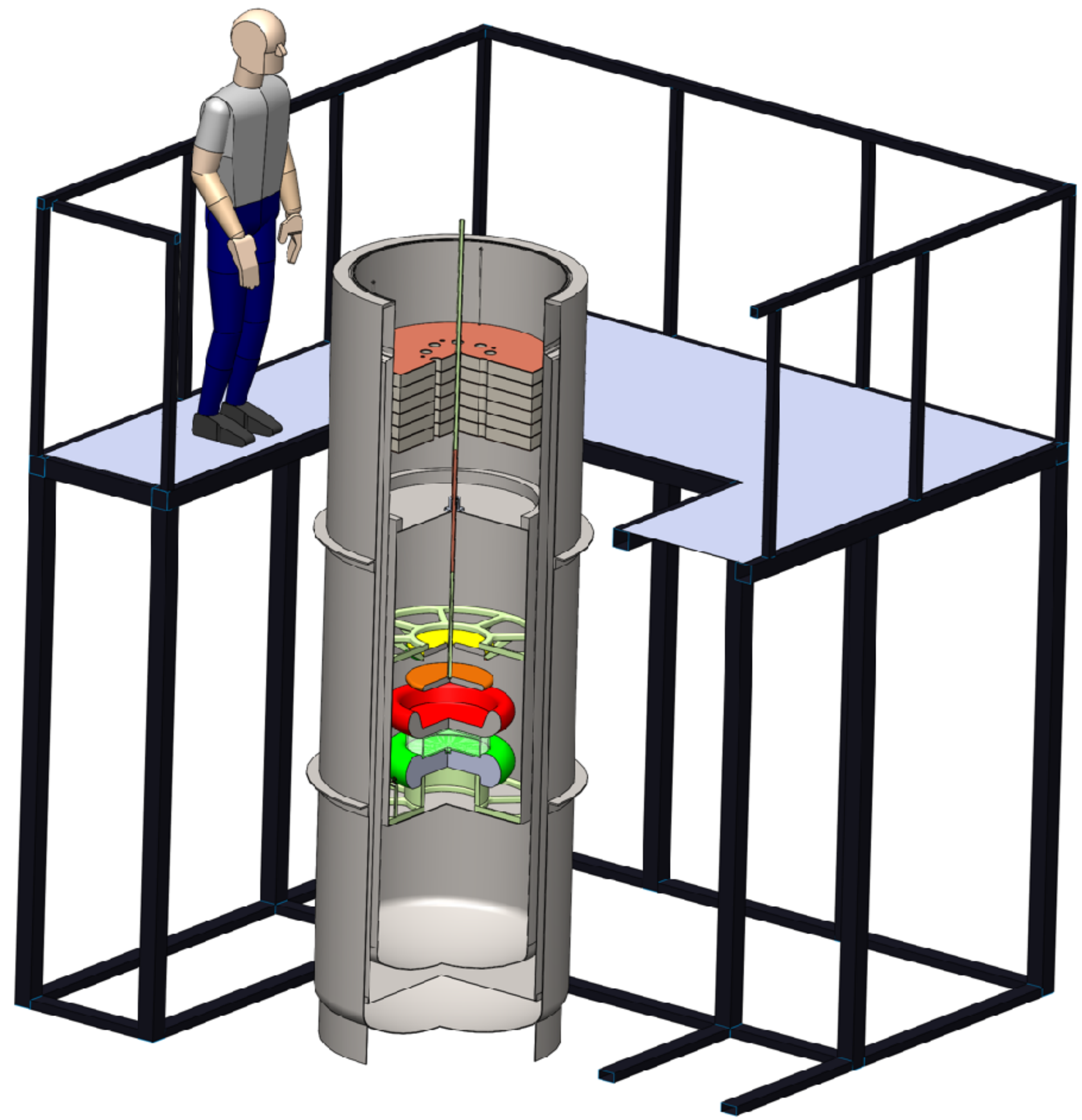
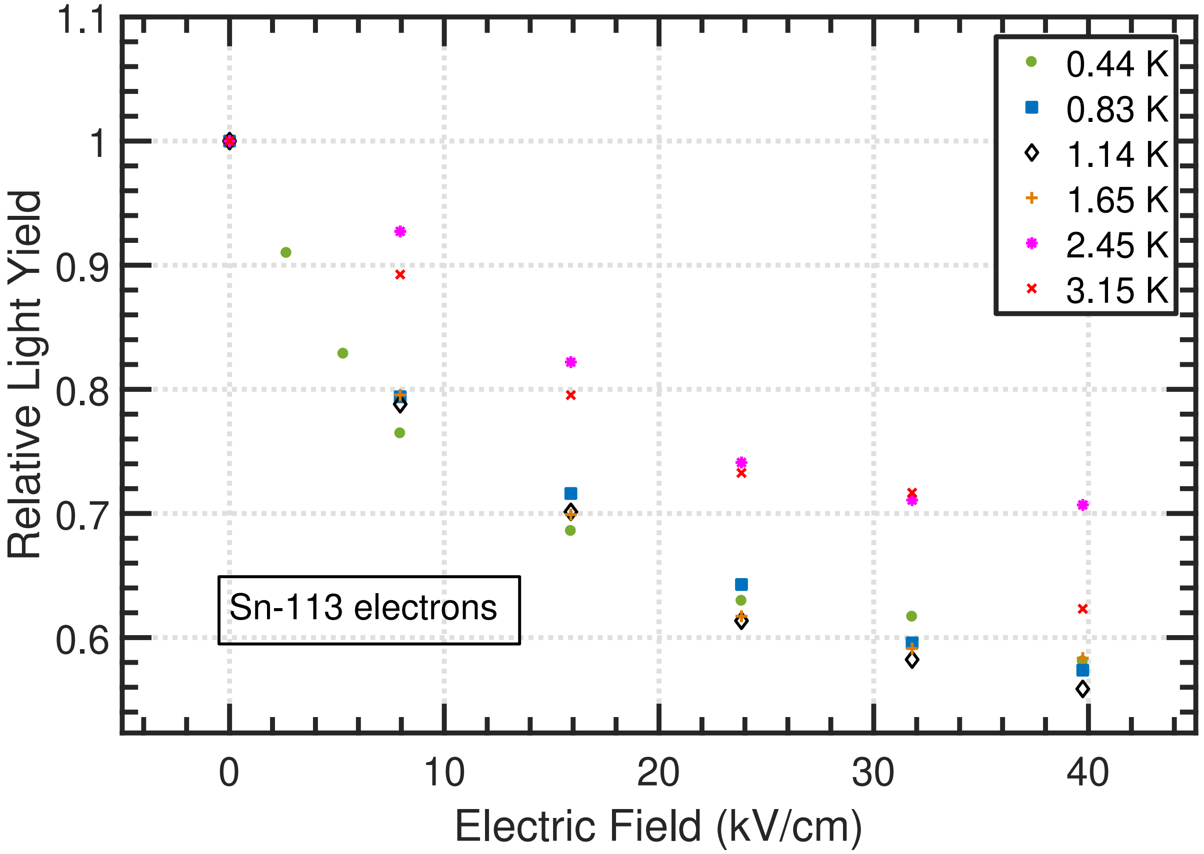
Cryogenic prototype



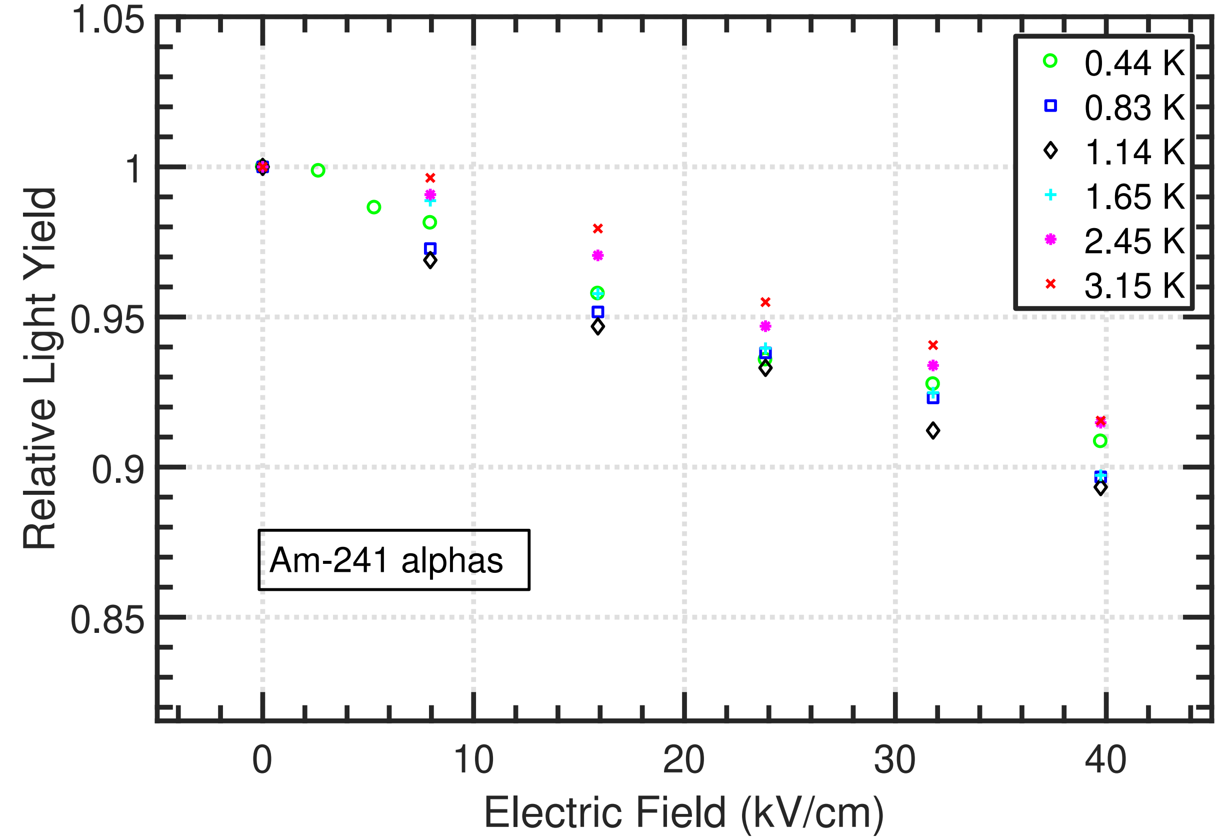
Study of the effect of an E field on LHe scintillation at LANL

LHe scintillation produced by electrons



Reduction in scintillation yield due to E field different between T > T_λ and T < T_λ.

LHe scintillation produced by α particles



The α particle measurement were performed as calibration. The results were consistent with our earlier measurement (Ito et al. PRA 2012)

We are currently preparing an experiment to measure the E field effect on LHe produced by n(^{3}He,^{3}H)p.

Summary

- nEDM is a sensitive probe of BSM physics.
- In the US, there are two complementary efforts:
  - LANL nEDM, a RT experiment based on well established Ramsey method with a goal sensitivity of 3×10^{-27} e-cm.
  - SNS nEDM, an ambitious cryogenic experiment with a goal sensitivity of 3×10^{-28} e-cm.