# Atomic Magnetometers for the TUCAN EDM Experiment

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February 13, 2025

# Neutron Electric Dipole Moment (nEDM)



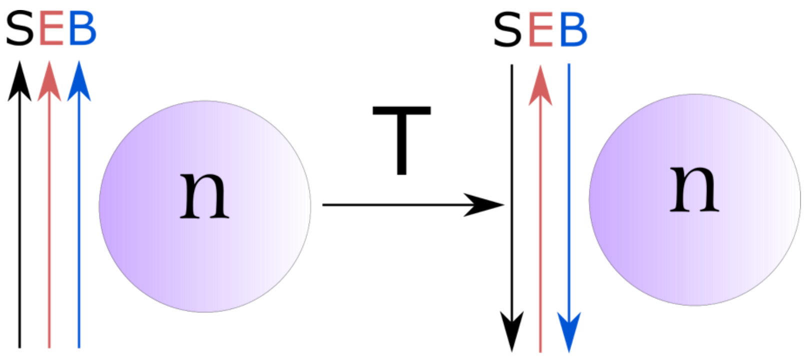
## ❖ nEDM

| | |
|---|---|
| Standard Model (CKM) | $10^{-32}$ *e*cm |
| BSM Predictions (SUSY) | $10^{-28}$ - $10^{-26}$ *e*cm |
| Current Limit (90% CL) | <1.8 x $10^{-26}$ *e*cm |

TUCAN EDM Goal ⟹ $10^{-27}$ e·cm

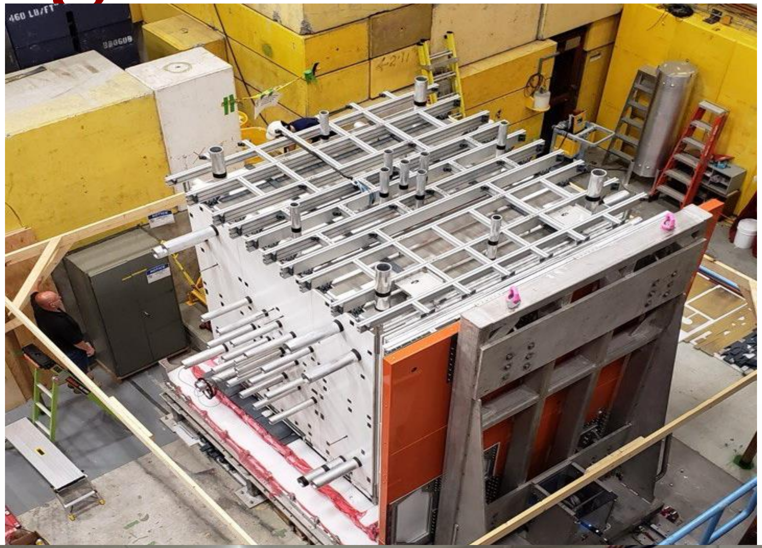
## ❖ CP or T violation

S: Spin
E: Electric field
B: Magnetic field




$$H = -\mu_n \boldsymbol{B} \cdot \frac{\boldsymbol{S}}{S} - d_n \boldsymbol{E} \cdot \frac{\boldsymbol{S}}{S} \xrightarrow{t \to -t} H = -\mu_n \boldsymbol{B} \cdot \frac{\boldsymbol{S}}{S} + d_n \boldsymbol{E} \cdot \frac{\boldsymbol{S}}{S}$$

# TUCAN EDM Experiment Magnetic Goals



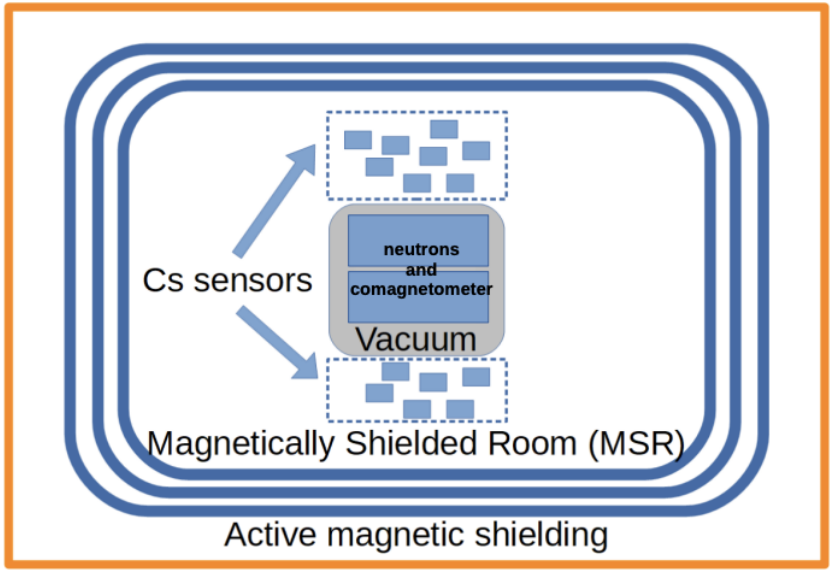
- Measuring $\hbar\omega_{n,\pm} = 2|\mu B \pm dE|$ requires measuring B = 1 μT to a precision of 10 fT within 100 s.

- Create a homogeneous magnetic field inside the MSR by adjusting shim coils.
  - Reduce neutron dephasing (increases $T_2$) to improve statistical error on EDM
    - ✓ Reduce $\Delta B_z$ = 3 nT in 1m$^3$ region to $\sigma(B_z)$ < 40 pT in cell(s)
  - Control/measure false EDM of Hg atoms, which arises due to magnetic gradients. Time-varying gradients are bad.

# nEDM Optical Magnetometers

## Cs Magnetometers

- ✓ Cs measures the field at multiple points surrounding the precession chamber
- ✓ Suite of 20 sensors can map gradients
- ✓ Stability: **90 fT over 150 seconds** meets 1 pT requirement for $10^{-27}$ e·cm nEDM measurement
- ✓ Sensitivity: 3.9 pT per measurement



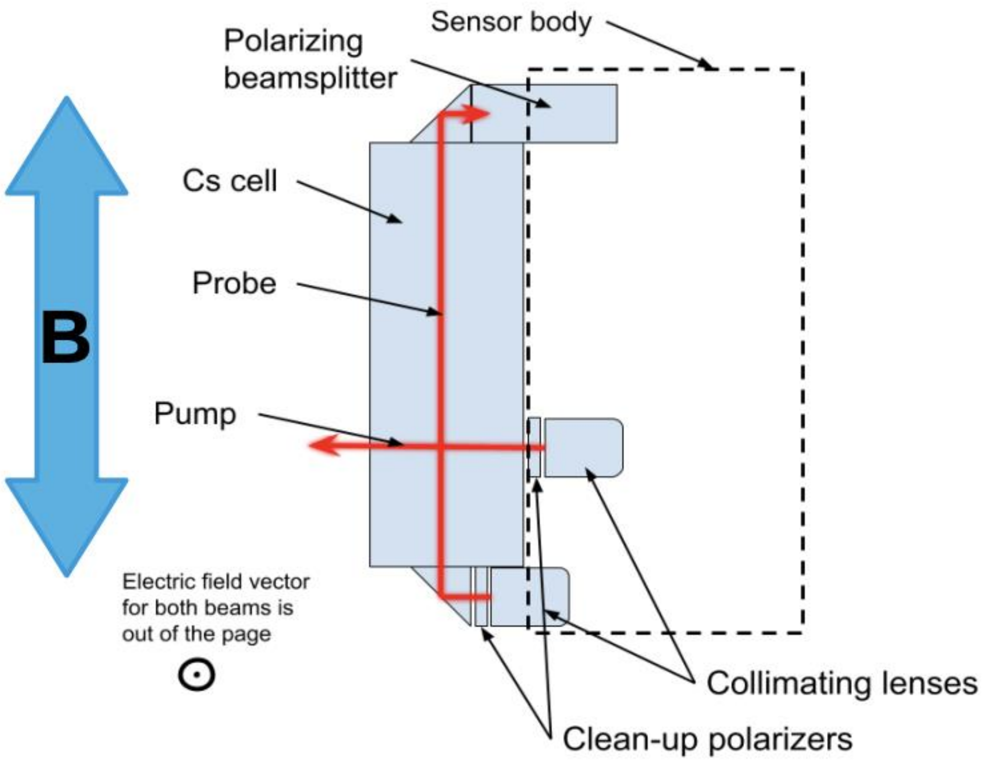

completely magnetically silent

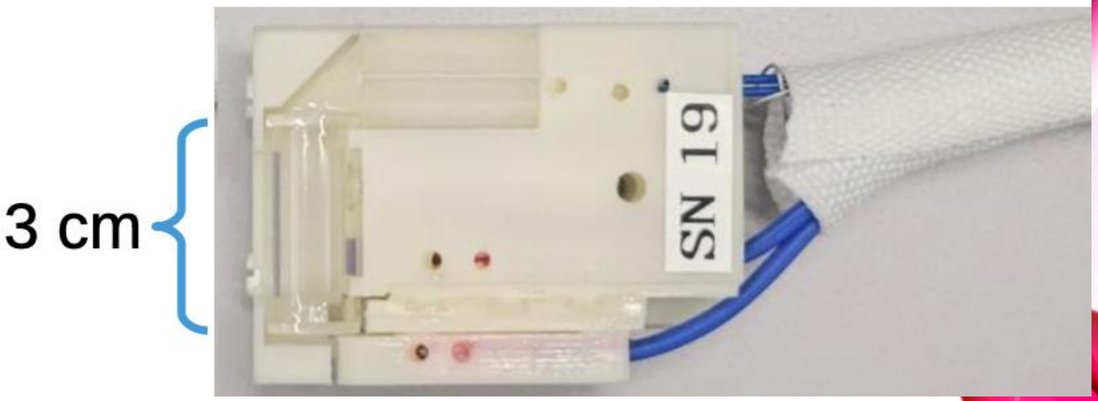
## Hg Comagnetometer

- ✓ Comagnetometer measures field in the precession chamber
- ✓ Measures (approx.) the same volume as the neutrons
- ✓ 10 fT per 100 seconds

# Cs Magnetometers

- **Pump**: light interacts with alkali atoms and polarizes them into an aligned state.
- **Precess**: Atoms interact with the magnetic field and rotate at their Larmor frequency.
- **Probe**: atoms periodically modulate the polarization angle of the beam at their Larmor frequency, by interacting preferentially with one polarization axis.

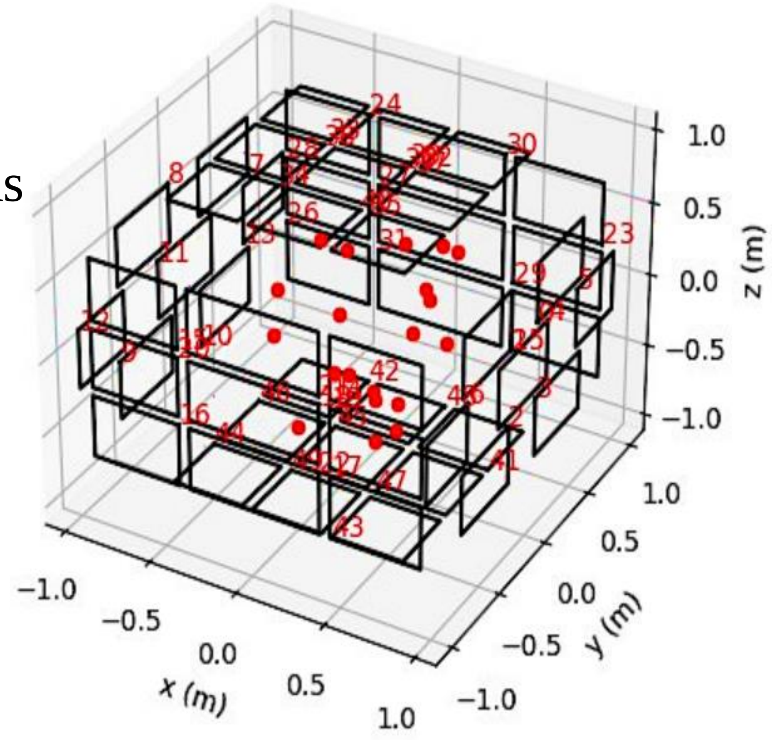


# 20 Vector Cs Magnetometers 20 Scalar Cs Magnetometers

❑ We can make the Cs magnetometers into vector magnetometers using an ancillary measurement where we purposely apply horizontal fields ("the variometer technique").

- Dim[B]=60 axis
- Dim[I]=54 coils
- Enough information to set coils




❑ We can also try using only the scalar information from the Cs magnetometers (magnitude of B)

- Dim[B]=20 axis
- Dim[I]=54 coils
- Not enough information to set coils
  - ✓ Tikhonov's matrix regularization

# 20 scalar Cs magnetometers

## Tikhonov's matrix regularization Method

- The matrix M can be calculated by setting each coil current I and measuring B at each sensor position.

$B = MI \rightarrow I = M^{-1}B$ **Not possible for an underdetermined problem!**

$$B_j = \sum_{i=1}^{c} M_{ij} I_i$$

$B_j$ : the magnetic field measured by each of the sensors,
$M_{ji}$: matrix of the number of sensors and the number of coils,
$I_i$: the current of each coil

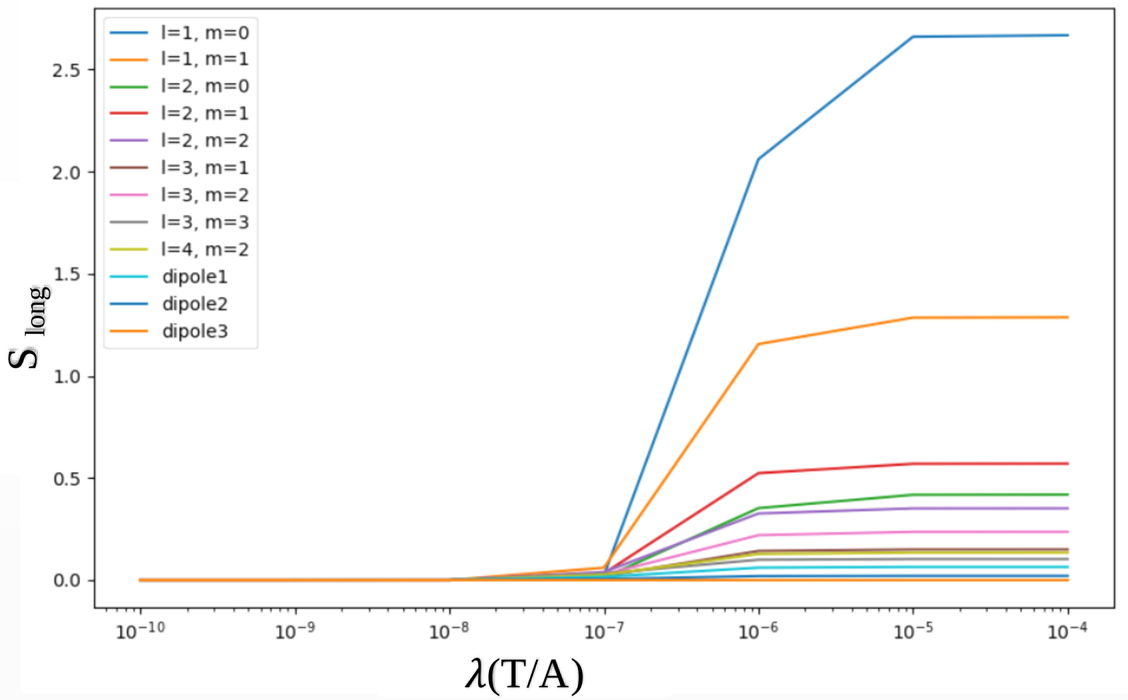
$$\underbrace{\sum_{j=1}^{s}(B_j - \sum_{i=1}^{c} M_{ij} I_j)^2}_{S_{Long}} + \lambda^2 \underbrace{\sum_{i=1}^{c} I_i^2}_{S_{Reg}} = 0 \rightarrow \frac{\partial}{\partial I_k}[\sum_{j=1}^{s}(B_j - \sum_{i=1}^{c} M_{ij} I_j)^2 + \lambda^2 \sum_{i=1}^{c} I_i^2] = 0$$

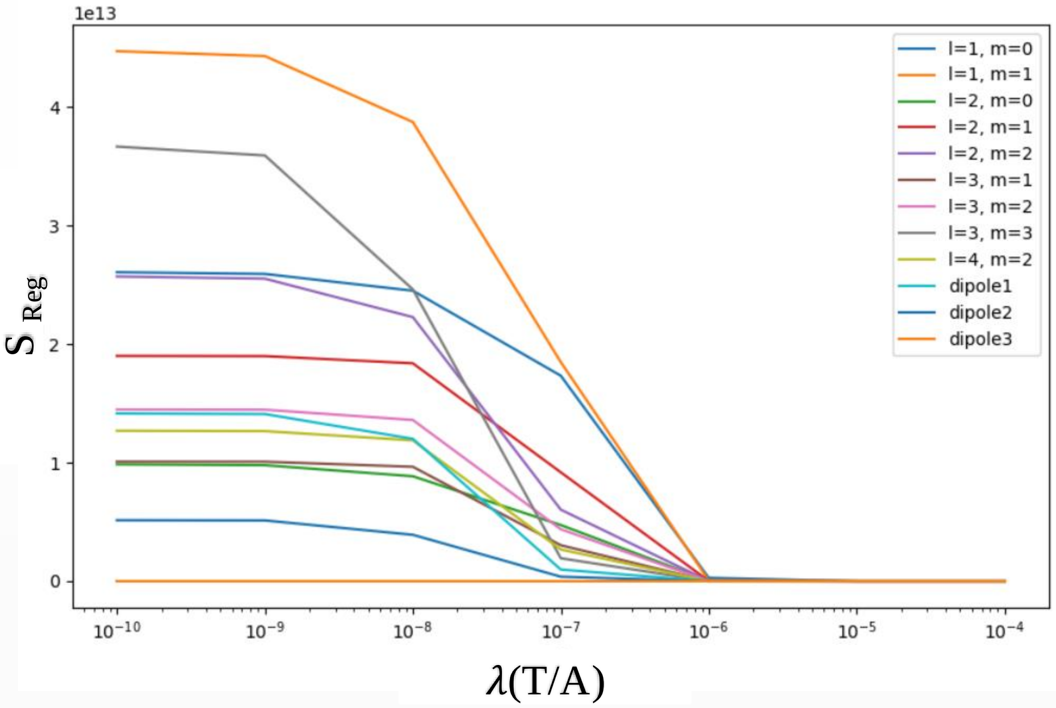
$$I = \underbrace{(M^T M + \lambda^2 I')^{-1} M^T}_{M^{-1}} B \rightarrow I = M^{-1} B$$

- ❑ We need to introduce a " regularization parameter" (λ)

Small λ → More important to solve B=MI
Large λ → More important to solve I=0 (keep currents small)

# The behaviors of $S_{Long}$ and $S_{reg}$ evaluated at different λ for different l ,m, and dipole




$$s_{long} = \sum_{j=1}^{s} (B_j - \sum_{i=1}^{c} M_{ij} I_j)^2$$

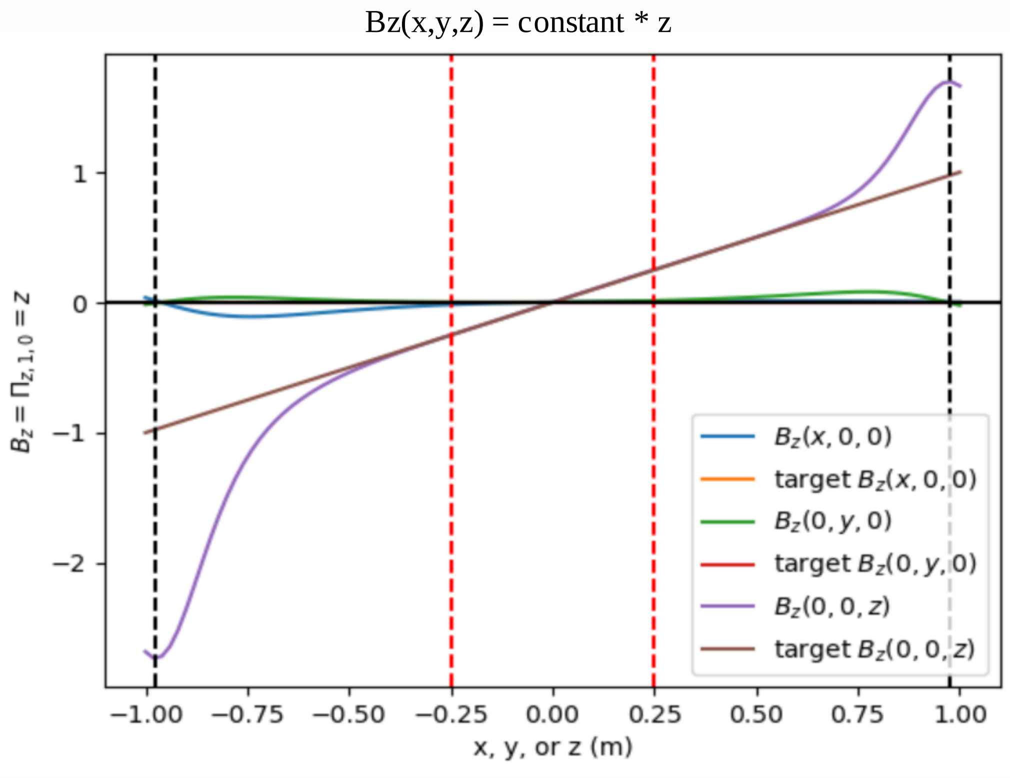
$$s_{Reg} = \sum_{i=1}^{c} I_i^2$$

$$\lambda \to \infty, I \to 0$$

# Results for λ(=$10^{-8}$ T/A)Using 20 Scalar Magnetometers

- Imagine Bz(x,y,z) = constant * z. We determine the currents needed to generate this field and then turn on the shim coils with the opposite of these currents to make the field very homogeneous. The graph shows how well the currents we determine mimic the target field.

**Conclusion: The method works! We can set 54 coil currents using only 20 scalar magnetic field measurements.**



# Future Plans

**Feb 2025:**

- Use shim coils to generate specific magnetic profiles inside the MSR.

**Mar 2025:**

- Use the Cs scalar magnetometers in conjunction with the regularization method.

**Nov 2025:**

- Using the Cs magnetometer in conjunction with neutron measurements.

# Thank you for your attention!

# BACK UP SLIDE

# FUNDAMENTAL SYMMETRIES

A physical law possesses symmetry under a specified transformation if it is unchanged by that transformation.

A. **Charge conjugation** (C): particles and anti-particles are swapped

$$(X, \bar{X}) \to (\bar{X}, X)$$

B. **Parity** (P): spatial coordinates are inverted

$$(x, y, z) \to (-x, -y, -z)$$

C. **Time reversal** (T): time is reversed

$$t \to -t$$

Particles can be either left- or right-handed.

Different physical laws are symmetric under different combinations of these transformations. All physics is assumed to have CPT-symmetry (derived for any local quantum field theory with Lorentz invariance)

# SAKHAROV'S CONDITIONS

Andrei Sakharov proposed a set of conditions that must hold in order to have baryogenesis:

1. Baryon number must be violated

1. Two symmetries must be violated:
   A. Charge conjugation (C): if C symmetry holds, then our process will be balanced by one that creates an equal number of antibaryons
   B. Charge-parity (CP): if CP symmetry holds, then our process will be balanced by one that creates an equal number of right-handed antibaryons as we create left-handed baryons (and vice versa)

2. The process must happen out of thermal equilibrium

# Why nEDM?

- At the nuclear energy scale, a measurement of nEDM is sensitive only to the nEDM itself, with some contribution from nucleon-pion couplings.

- The neutron's neutrality has made it substantially easier to study, it has only a minimal response to an electric field (in the form of relativistic effects).

# Why UCN?

- Ultracold neutrons can be confined by materials, gravity (in the vertical direction), and magnetic fields (if the UCNs are polarized).
- Their interaction with magnetic fields makes it possible to produce a fully polarized population by applying a sufficiently strong magnetic field, enabling spin-dependent measurements.
- Fully polarized population of UCNs can be stored for a relatively long time.

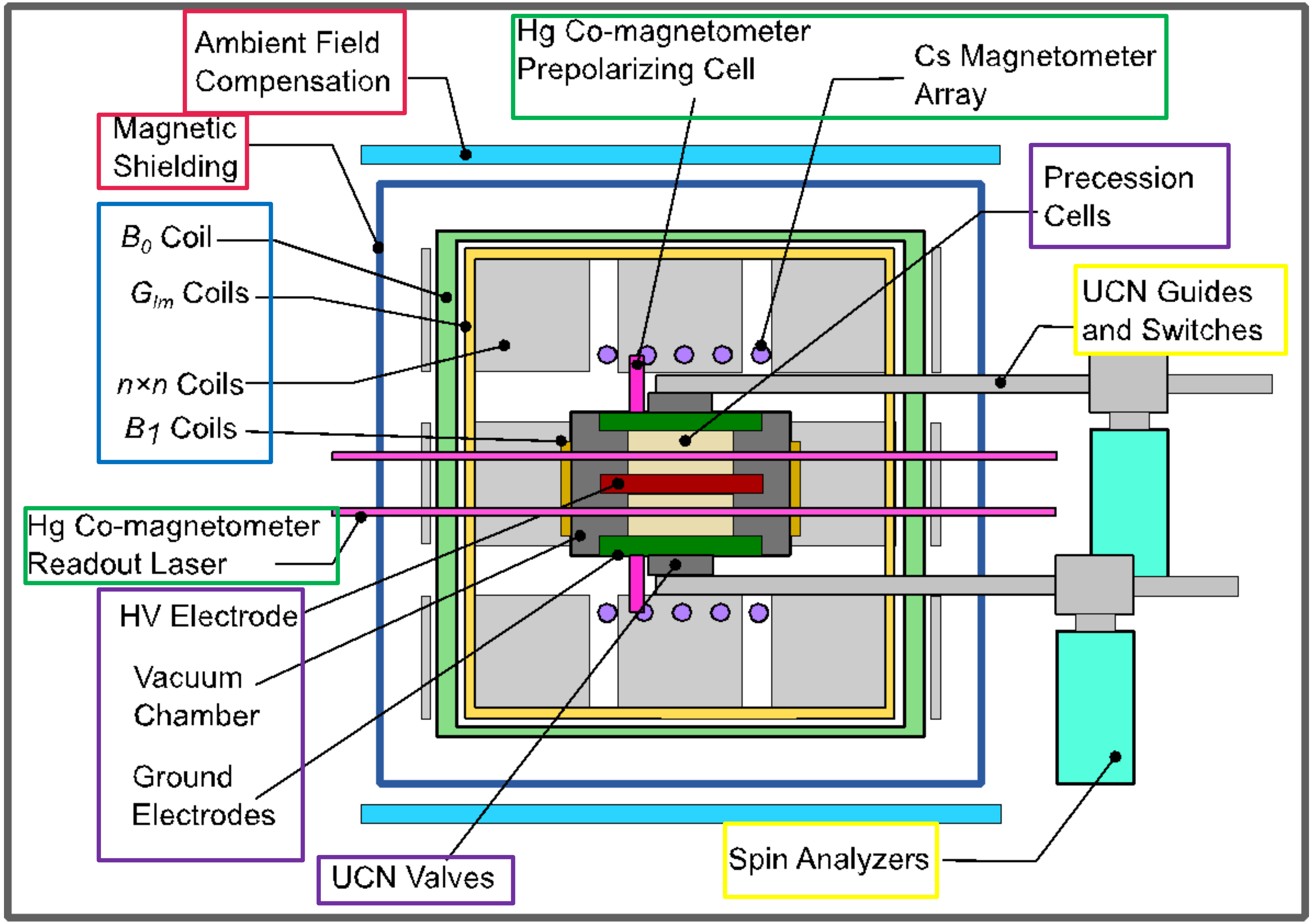
| System | Group | Technique | Status | Ref |
|---|---|---|---|---|
| **Paramagnetic Atoms** | | | | |
| $Xe^m$ | | Warm beam | $d_e < 3.1 \times 10^{-22}$ ecm (95% UL) | [226] |
| Cs | Amherst | Vapour cell | $d_e < 1.2 \times 10^{-25}$ ecm (95% UL) | [206] |
| Cs | Penn. State | Optical trap | Development | [277] |
| Tl | Berkeley | Warm beam | $d_e < 1.9 \times 10^{-27}$ ecm (95% UL) | [236] |
| YbF | Imperial College | Warm beam | $d_e < 1.2 \times 10^{-27}$ ecm (95% UL) | [143] |
| ThO | ACME | Cold beam | $d_e < 1.1 \times 10^{-29}$ ecm (90% UL) | [40] |
| $HfF^+$ | JILA/NIST/UC | Ion trap | $d_e < 2.1 \times 10^{-29}$ ecm (90% UL) | [238] |
| BaF | NL-eEDM | Cold beam | Development | [22] |
| BaF | $EDM^3$ | 4K Ar Matrix | Development | [289] |
| Fr | CYRIC/RIKEN | Atom trap | Development | [148, 244] |
| Fr | TRIUMF | Atomic fountain | Development | [204] |
| **Solid State Systems** | | | | |
| $Gd_3Ga_5O_{12}$ | | Induced magnetization | $d_e = (-5.57 \pm 7.98 \pm 0.12) \times 10^{-25}$ | [166] |
| $Eu_{0.5}Ba_{0.5}TiO_3$ | Yale | Induced magnetization | $d_e < 6.05 \times 10^{-25}$ (90% UL) | [103] |
| $Gd_3Fe_5O_{12}$ | Amherst | Induced polarization | $d_e < 5 \times 10^{-24}$ (90% UL) | [140] |
| **Others** | | | | |
| $\mu$ | BNL $g-2$ | Storage ring | $d_\mu < 1.8 \times 10^{-19}$ ecm (95% UL) | [112] |
| $\mu$ | PSI | Storage solenoid | Development | [242] |
| $\mu$ | J-PARC | Storage solenoid | Development | [245] |
| $\tau$ | Belle | $e^+e^- \to \tau^+\tau^-$ | $d_\tau = (1.15 \pm 1.70) \times 10^{-17}$ | [86] |

Table 1.1: A summary of current measured EDM limits and experiments under development in the leptonic sector.

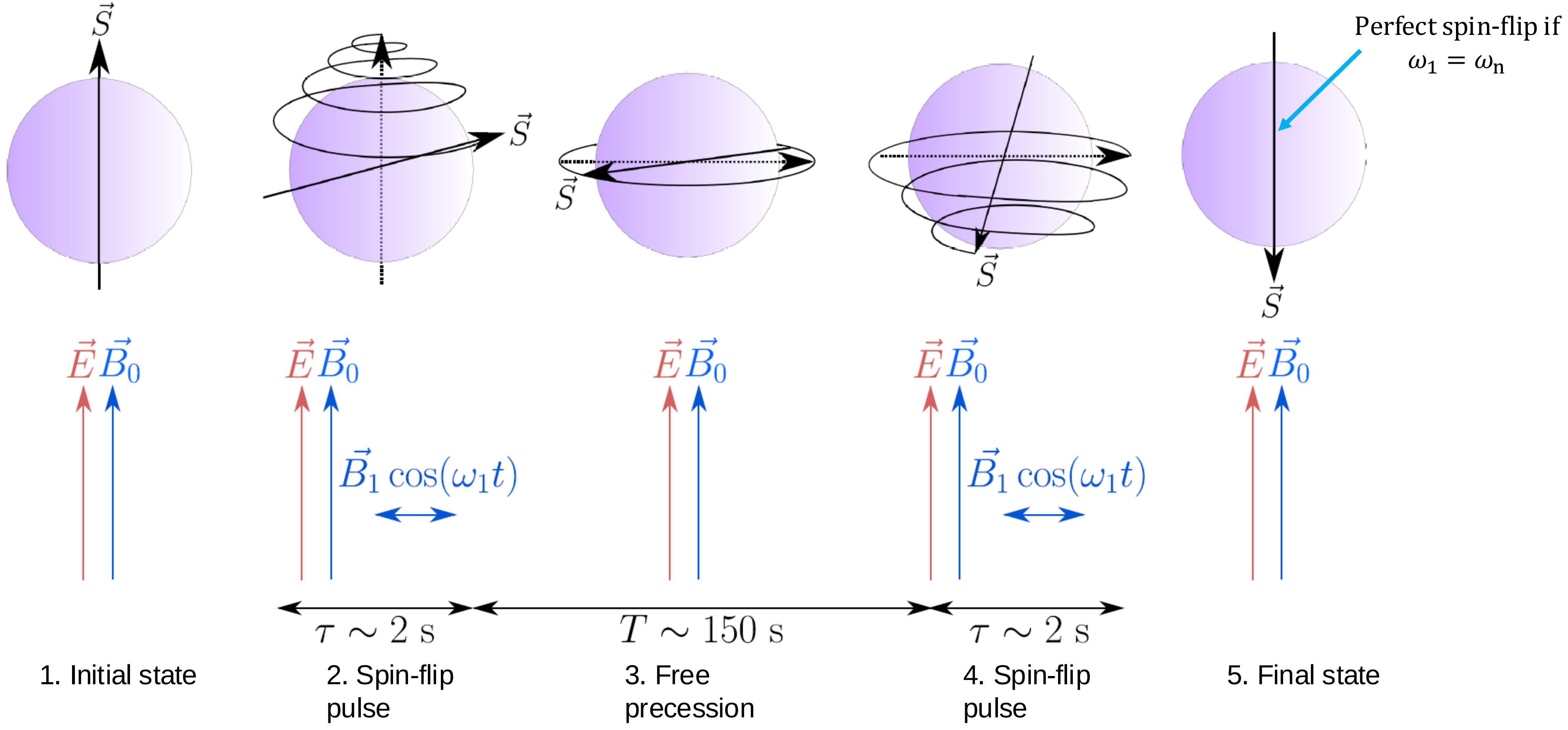
| System | Group | Technique | Status | Ref |
|---|---|---|---|---|
| | | **Diamagnetic Atoms** | | |
| $^{199}$Hg | Washington | Vapour Cell | $d_{Hg} < 7.4 \times 10^{-30}$ $e$cm (95% UL) | [125] |
| $^{199}$Hg | quMercury | Optical trap | Development | [183] |
| $^{129}$Xe | Mainz | Vapour cell | $d_{Xe} < 1.5 \times 10^{-27}$ $e$cm (95% UL) | [31] |
| $^{129}$Xe | PTB/UM/TMU/MSU | Vapour cell | $d_{Xe} < 1.4 \times 10^{-27}$ $e$cm (95% UL) | [239] |
| $^{129}$Xe | RIKEN | Vapour cell | Development | [246] |
| $^{225}$Ra | ANL | Optical trap | $d_{Ra} < 1.4 \times 10^{-23}$ $e$cm (95% UL) | [56] |
| $^{205}$TlF | Yale | Cold beam | $d_{Tl} < 6.5 \times 10^{-23}$ $e$cm (95% UL) | [77] |
| $^{205}$TlF | CeNTREX | Cold beam | Development | [126] |
| $^{171}$Yb | USTC/MSU | Optical trap | $d_{Yb} < 1.5 \times 10^{-26}$ $e$cm (95% UL) | [303] |
| | | **Others** | | |
| $d$ | JEDI | Storage ring | Analyzing | [186, 266] |
| $p$ | CPEDM | Storage ring | Development | [73] |
| $\Lambda$ | Fermilab | Beam | $d_{\Lambda} = (-3.0 \pm 7.4) \times 10^{-17}$ | [227] |

Table 1.2: A summary of the current measured EDM limits and experiments-in-development for hadronic systems, not including neutrons.

- Background magnetic field compensation and shielding
- Homogeneous and stable magnetic field generation
- Magnetic field measurement
- Polarized UCN transport and spin-sensitive detection
- UCN storage and high voltage application



# Measuring the nEDM: Ramsey's Method of Separated Oscillating Magnetic Fields

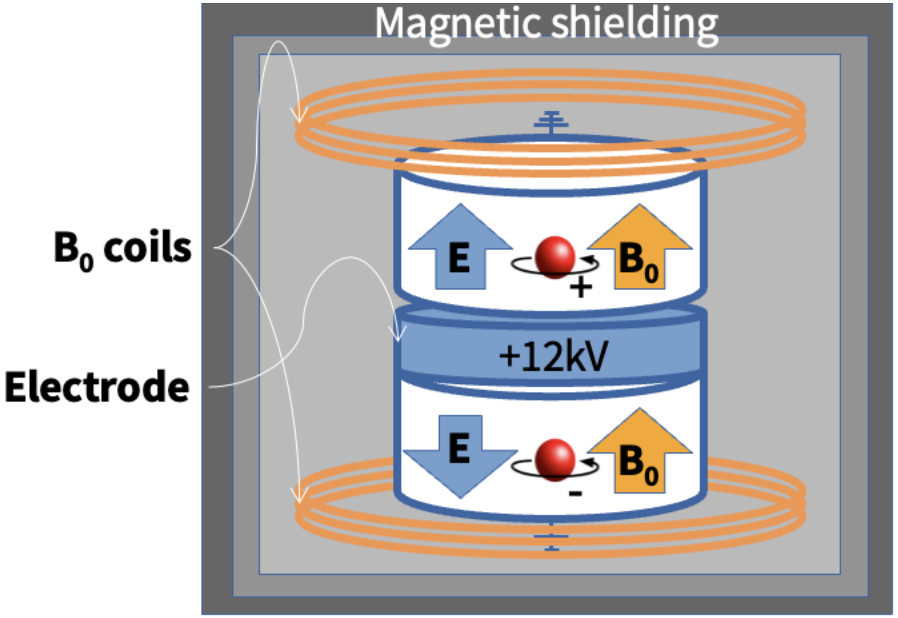


# False nEDM

- Magnetic field inhomogeneities can mimic an EDM signal by causing systematic shifts in the neutron's precession frequency.

- Comagnetometer atoms may experience a different average field than the neutrons, leading to incorrect field corrections, introducing a false EDM signal.

$$d_{\text{false}} = -\frac{\hbar\gamma^2}{2c^2}\langle xB_x + yB_y \rangle$$




✓ **Cs-based optical magnetometers play a key role in mapping and correcting magnetic field inhomogeneities in the experiment.**