neutron Electric Dipole Moment search for BSM violating CP

Katia Michielsen, PhD at LPSC, Grenoble

What is an Electric Dipole Moment?

- Spins couple to magnetic fields.
  Magnetic moment is the coupling μ

- Spins couple to electric fields.
  EDM is the coupling d

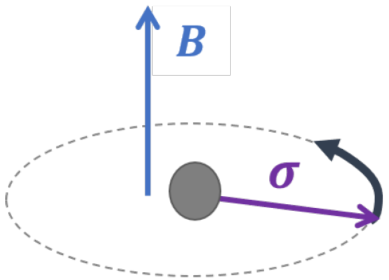
Non-relativistic limit of the fermion-photon interaction:

$$H = -\mu\,\sigma B \; - d\,\sigma E$$

$|\uparrow\rangle$

$\hbar\omega = 2\mu B$

$|\downarrow\rangle$

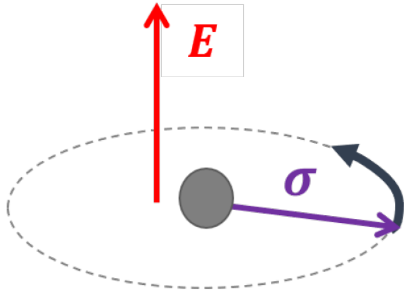


Larmor precession of a spin in a magnetic field at frequency $f = \frac{\mu B}{\pi\hbar}$

$|\uparrow\rangle$

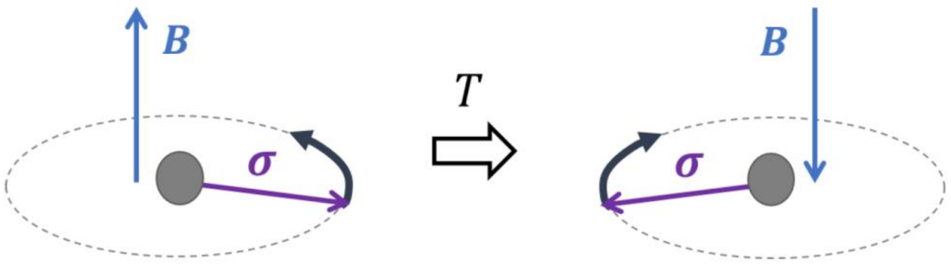
$\hbar\omega = 2dE$

$|\downarrow\rangle$



Larmor precession of a spin in an electric field at frequency $f = \frac{dE}{\pi\hbar}$

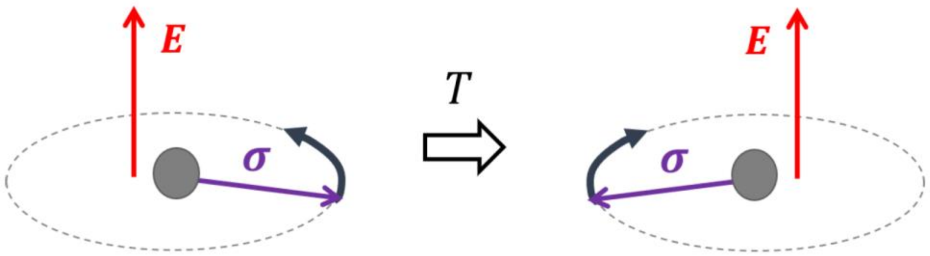
An EDM violates Time reversal (T) symmetry



Observable = magnetic moment μ

$\mu > 0$ $\mu > 0$

T-invariant



Observable = EDM d

$d > 0$ $d < 0$

not T-invariant

CPT symmetry ↔ Lorentz invariance & causality of the SM.
T violation ↔ **CP violation**

Why measure the neutron EDM?

From the Standard Model we expect $d_n = \underbrace{10^{-32} e\text{ cm}}_{\text{weak interaction}} + \underbrace{\bar{\theta} \cdot 10^{-16}\, e\text{ cm}}_{\text{strong interaction}} + \underbrace{\quad\quad}_{\text{new physics?}}$

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}}) \times \mathbf{10^{-26}} e\text{ cm}$$

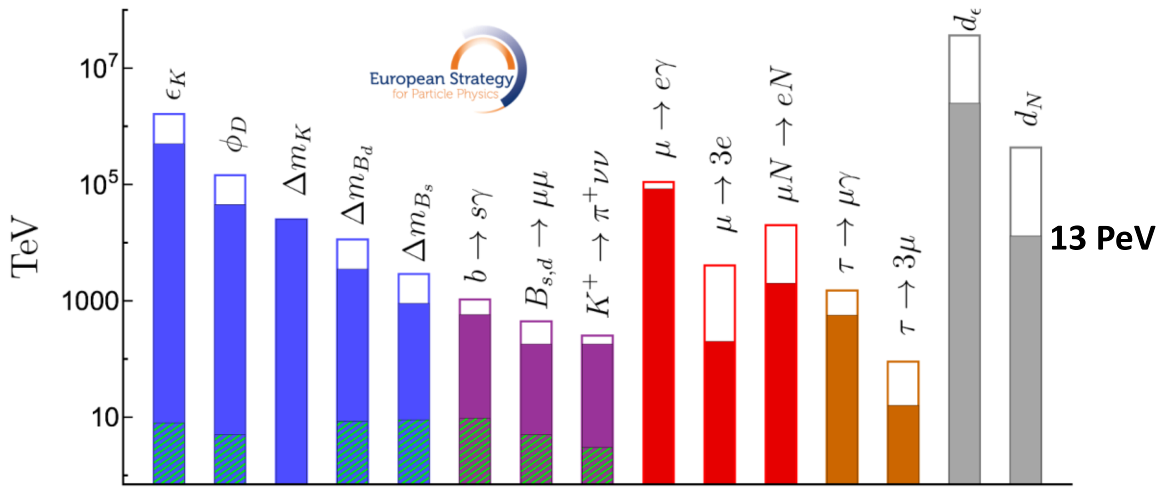
$|d_n| < 1,8 \times 10^{-26}\, e$ cm (90% CL) **[1]**

- Constrains the CP violation in the strong sector $\bar{\theta} < 10^{-10}$ "strong CP problem"

Peccei-Quinn, axion?, also a good candidate for dark matter.

- sensitive probe to **new physics**.

The better the sensitivity, the higher the mass scale (SMEFT). Probes mass scales of >13 PeV.

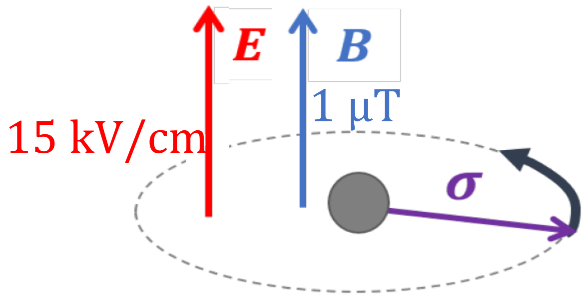


Physics Briefing Book: Input for the 2026 update of the European Strategy for Particle Physics

[1] Measurement of the Permanent Electric Dipole Moment of the Neutron, nEDM collaboration, 2020

II- **How** do we measure the nEDM at PSI

nEDM Figure of Merit



Larmor precession frequency of neutrons,

in a *controlled* magnetic field and *strong* electric field.

$$f_n = \frac{\mu_n}{\pi\hbar} B \pm \frac{d_n}{\pi\hbar} E$$

If $|d_n| = 2 \times 10^{-26}$ e cm , electric/magnetic term = 10^{-9}

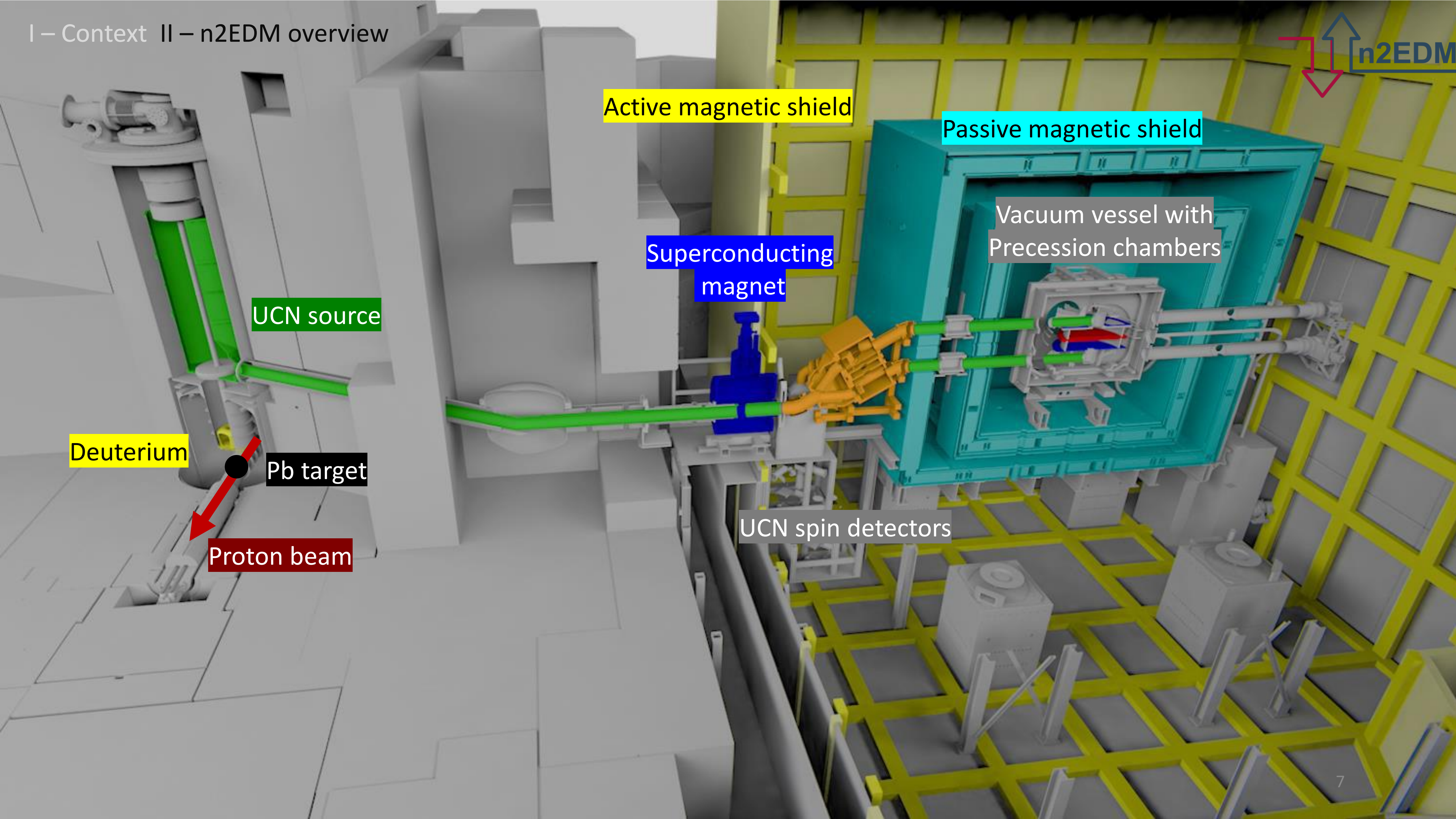
1. **Ramsey method of separated oscillatory fields (NMR method).**

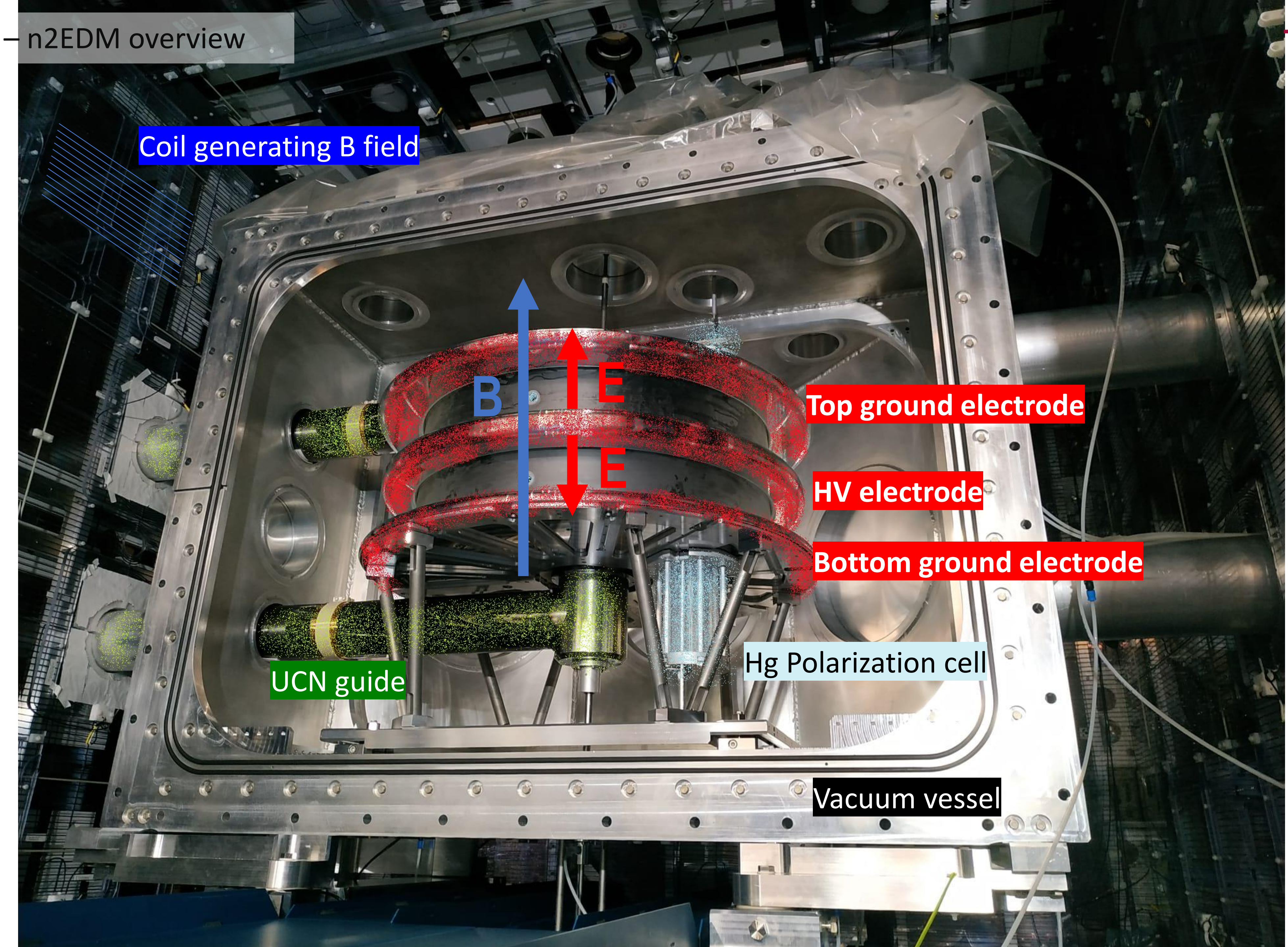
$\sigma(f_n) \propto \frac{1}{T\sqrt{N}}$, $T = 3$ minutes

Ultra Cold Neutrons (UCNs)

($\sim$100 neV, **storable**!)

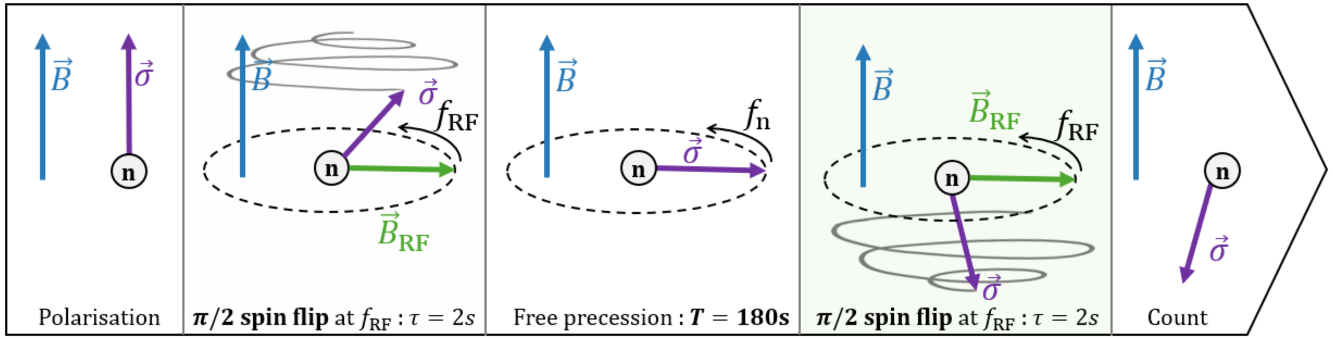
1. **Mercury co-magnetometry to monitor B.**


n2EDM
Active magnetic shield
Passive magnetic shield
Vacuum vessel with
Precession chambers
Superconducting
magnet
UCN source
Deuterium
Pb target
Proton beam
UCN spin detectors

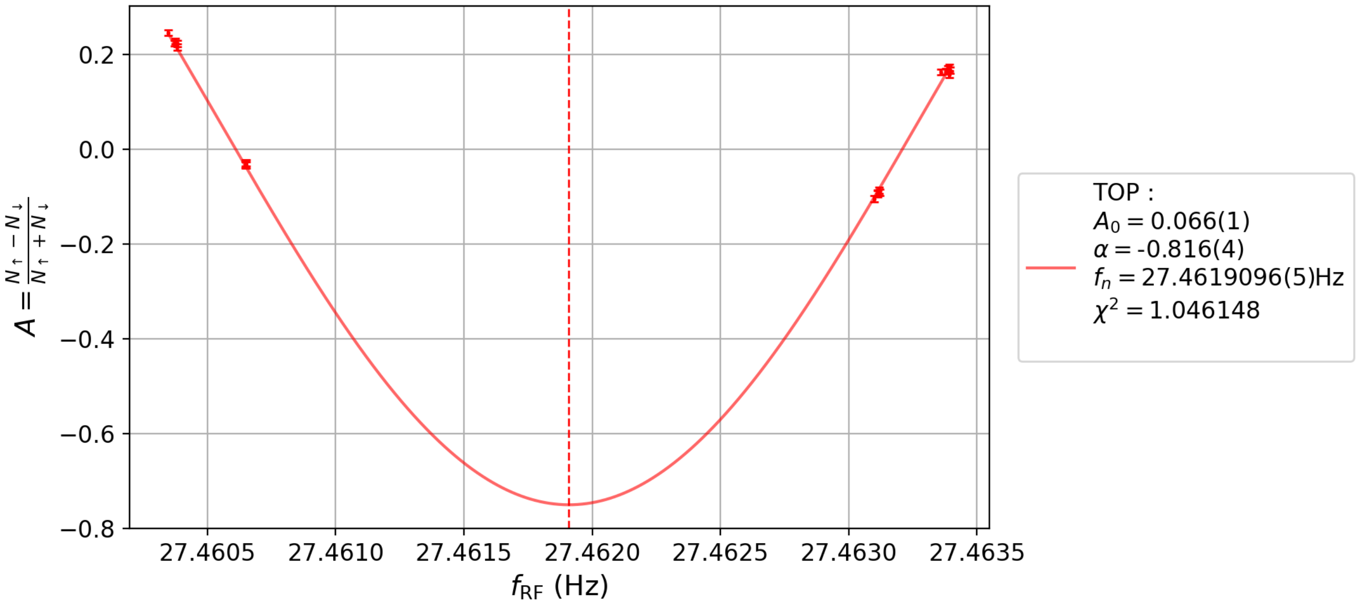


Coil generating B field
B
E
E
Top ground electrode
HV electrode
Bottom ground electrode
UCN guide
Hg Polarization cell
Vacuum vessel

1. Ramsey method to measure f_n (NMR technique)



Run 7446 : UCN Asymmetry VS f_{RF}



Neutron spin asymmetry:

$$\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = A_0 - \alpha \cos\left(\frac{\pi(f_{RF} - \boldsymbol{f_n})}{\Delta\nu}\right)$$

α visibility = total spin depolarization

$\Delta\nu = \left(2T + \frac{8\tau}{\pi}\right)$ fringe width, known

f_{RF} , τ parameters of the spin flip, known

$\boldsymbol{T = 180\ s}$ **precession time**

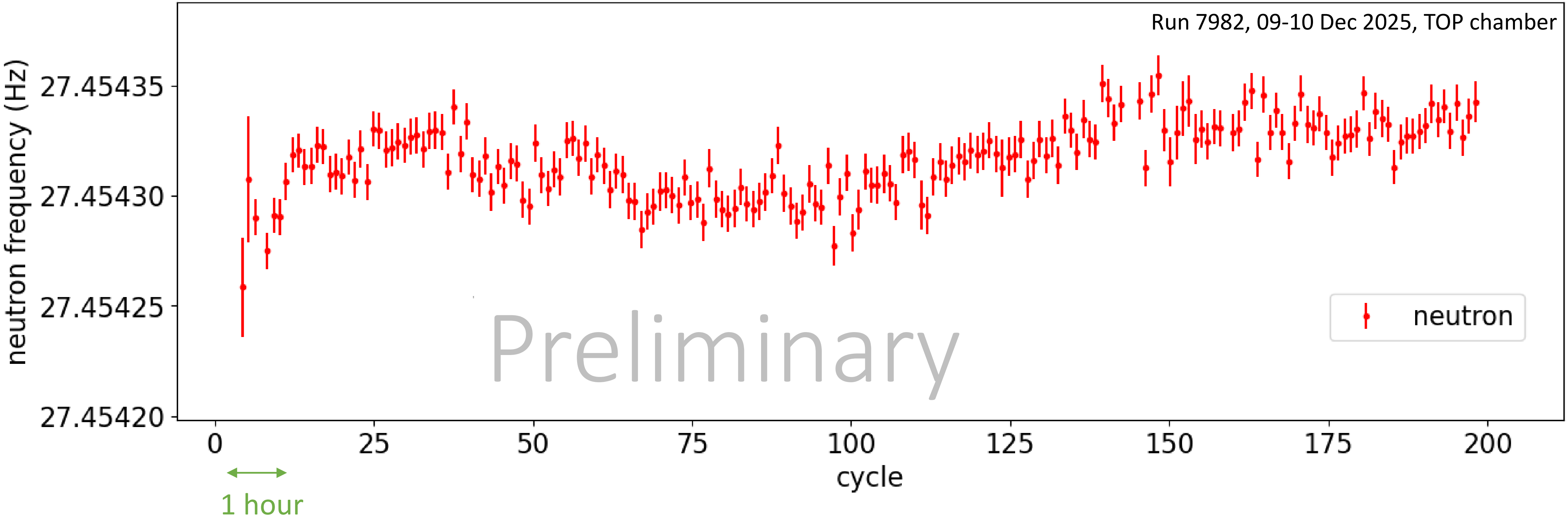
unknown parameters,

4 working points frequencies, repeated

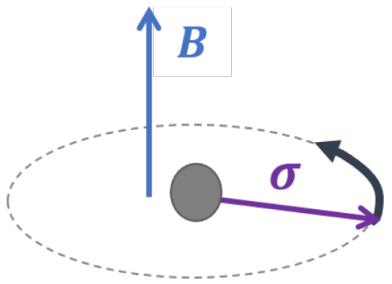
$$f_n \approx 30\ \mathrm{Hz}$$

$$\sigma(f_n) = \frac{1}{2\pi\alpha T\sqrt{N}} \approx 0.5\ \mu\mathrm{Hz}$$

1. Ramsey method to measure f_n (NMR technique)



2. Mercury co-magnetometer

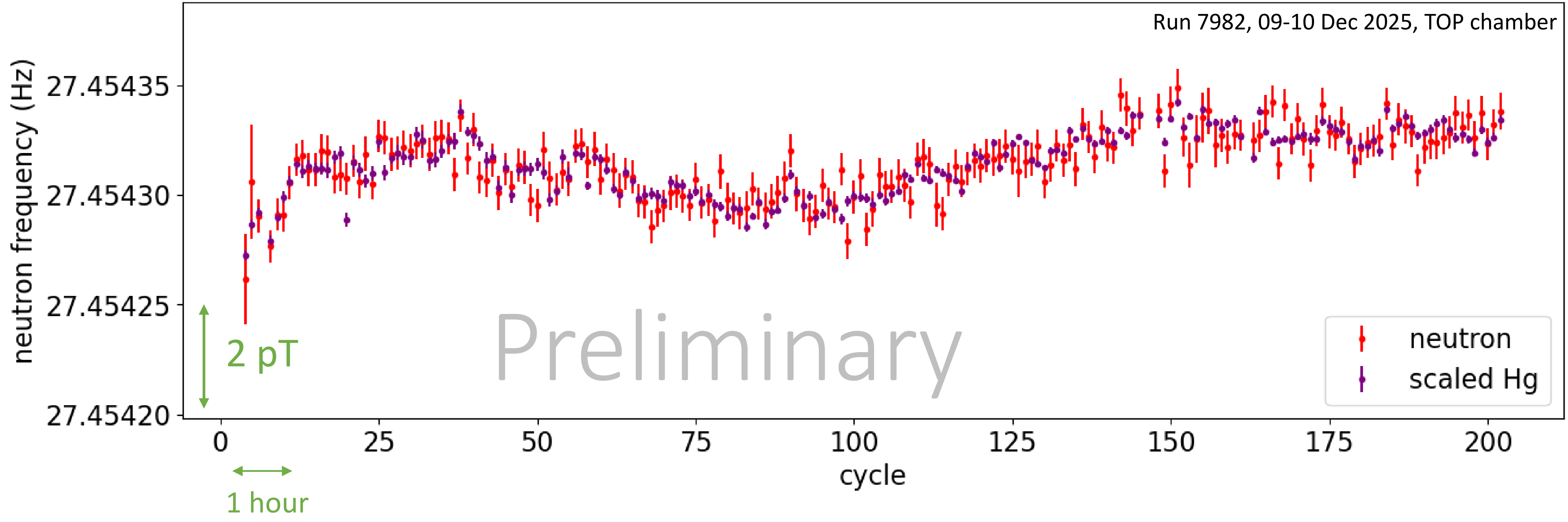


$$f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$$

$\approx$ 7 Hz in n2EDM

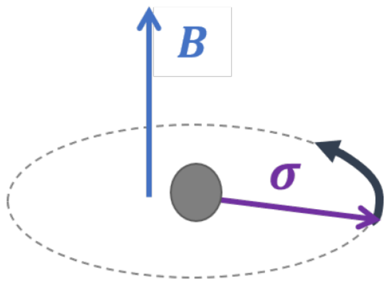
^{199}Hg : only diamagnetic (nuclear spin ½) atomic vapour with optical transition.

Precision: $\sigma\left(f_{\mathrm{Hg}}\right) < 200\ \mathrm{nHz} \quad \leftrightarrow \quad \sigma(B) < 30\ \mathrm{fT}$



Reduced limit on the permanent electric dipole moment of Hg 199. Graner, Brent, et al. PRL (2016) Hg EDM $|d_{Hg}| < 7{,}4\ \ 10^{-30}\ e$ cm

2. Mercury co-magnetometer



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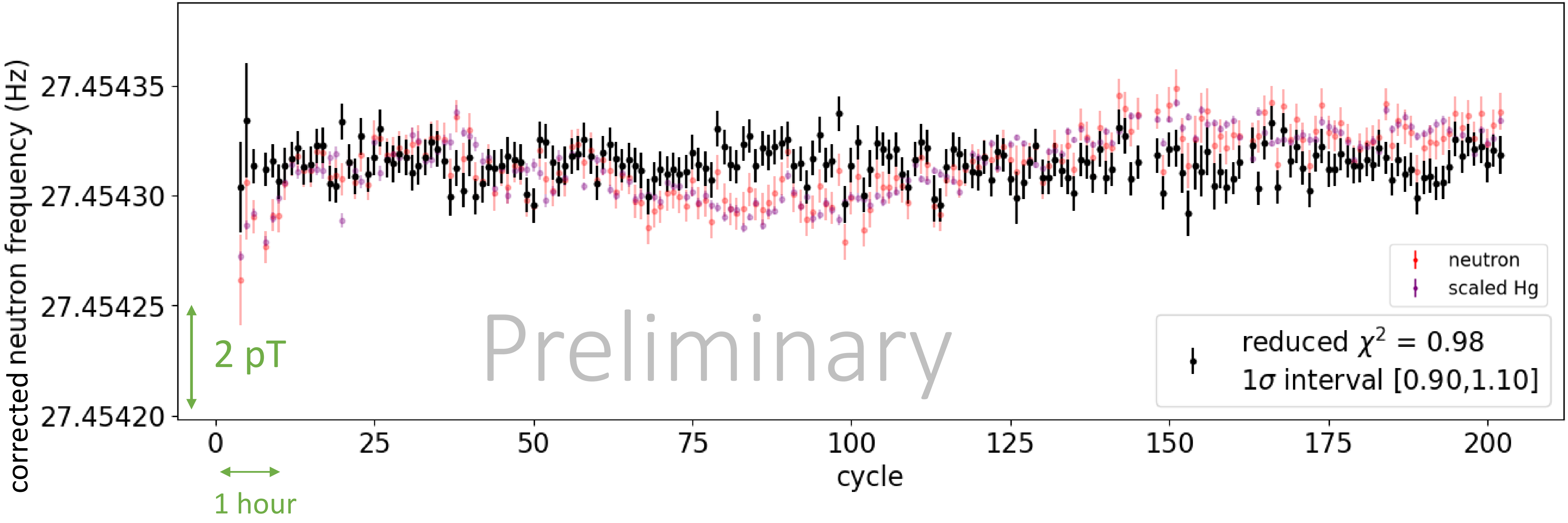
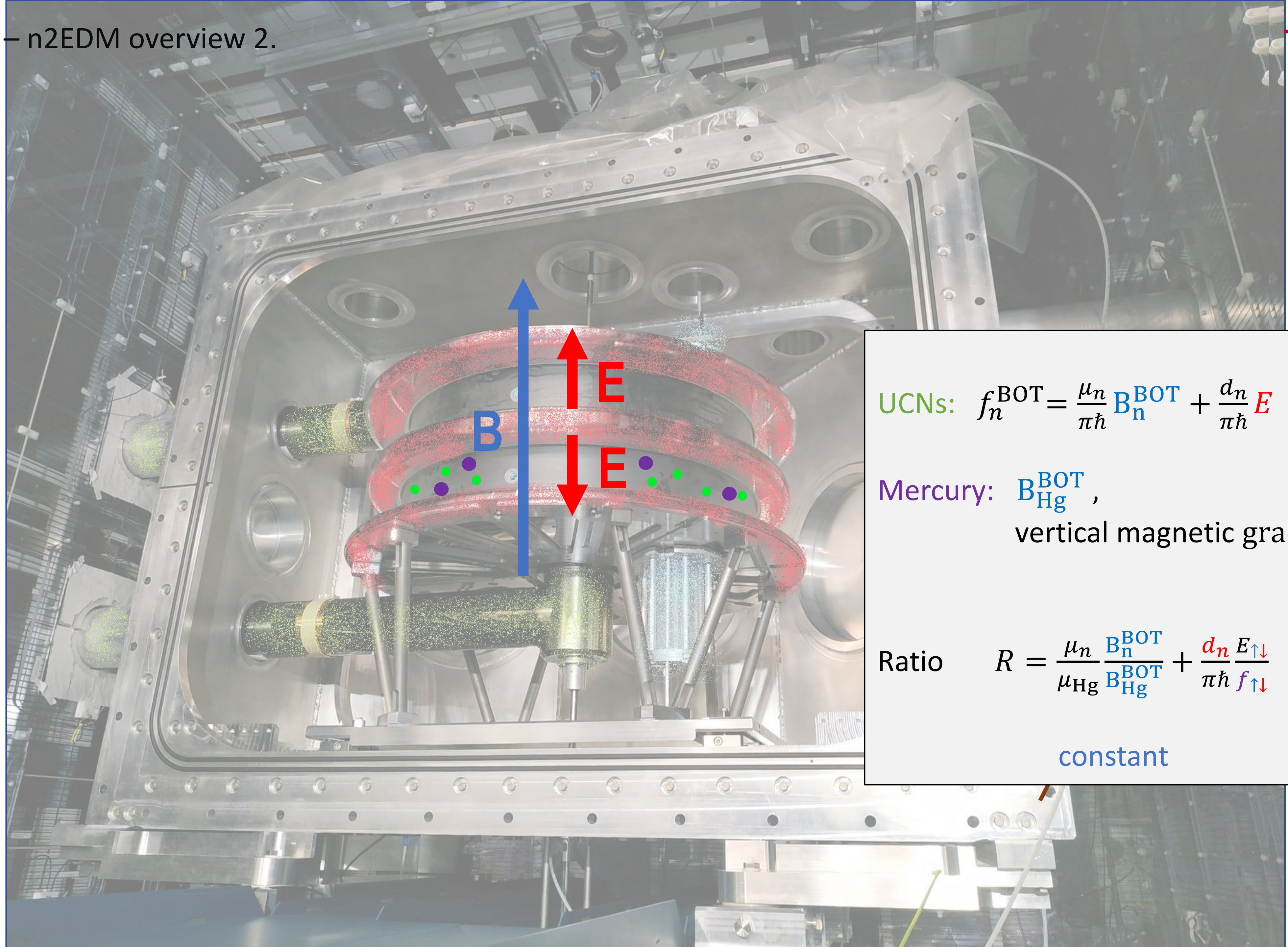
Run 7982, 09-10 Dec 2025, TOP chamber



Reduced limit on the permanent electric dipole moment of Hg 199. Graner, Brent, et al. PRL (2016) Hg EDM $|d_{Hg}| < 7{,}4\ \ 10^{-30}\ e$ cm n2EDM



UCNs: $f_n^{\mathrm{BOT}} = \frac{\mu_n}{\pi\hbar} \mathrm{B}_\mathrm{n}^{\mathrm{BOT}} + \frac{d_n}{\pi\hbar} E$

Mercury: $\mathrm{B}_{\mathrm{Hg}}^{\mathrm{BOT}}$,

vertical magnetic gradient G_{TB}.

Ratio $R = \frac{\mu_n}{\mu_{\mathrm{Hg}}} \frac{\mathrm{B}_\mathrm{n}^{\mathrm{BOT}}}{\mathrm{B}_{\mathrm{Hg}}^{\mathrm{BOT}}} + \frac{d_n}{\pi\hbar} \frac{E_{\uparrow\downarrow}}{f_{\uparrow\downarrow}}$

constant

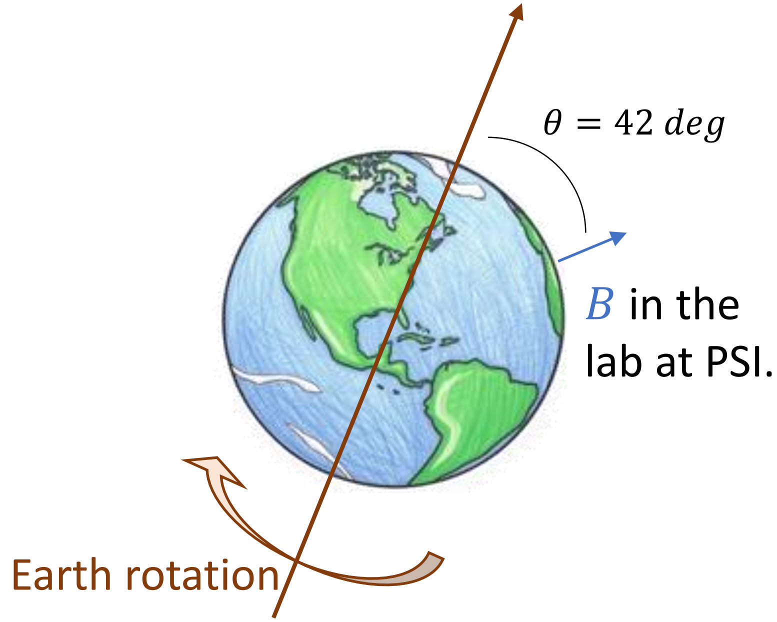
III- n2EDM early results

1. **The Earth rotates!!**
2. Ultracold neutrons are lazy…
3. **Status and outlook**

1. The earth rotates!

- Laboratory referential is not inertial : Earth rotation
- Magnetic momentum of neutron and mercury have opposite sign ($\mu_n < 0$). Depending on B one frequency is enhanced, the other is diminished.

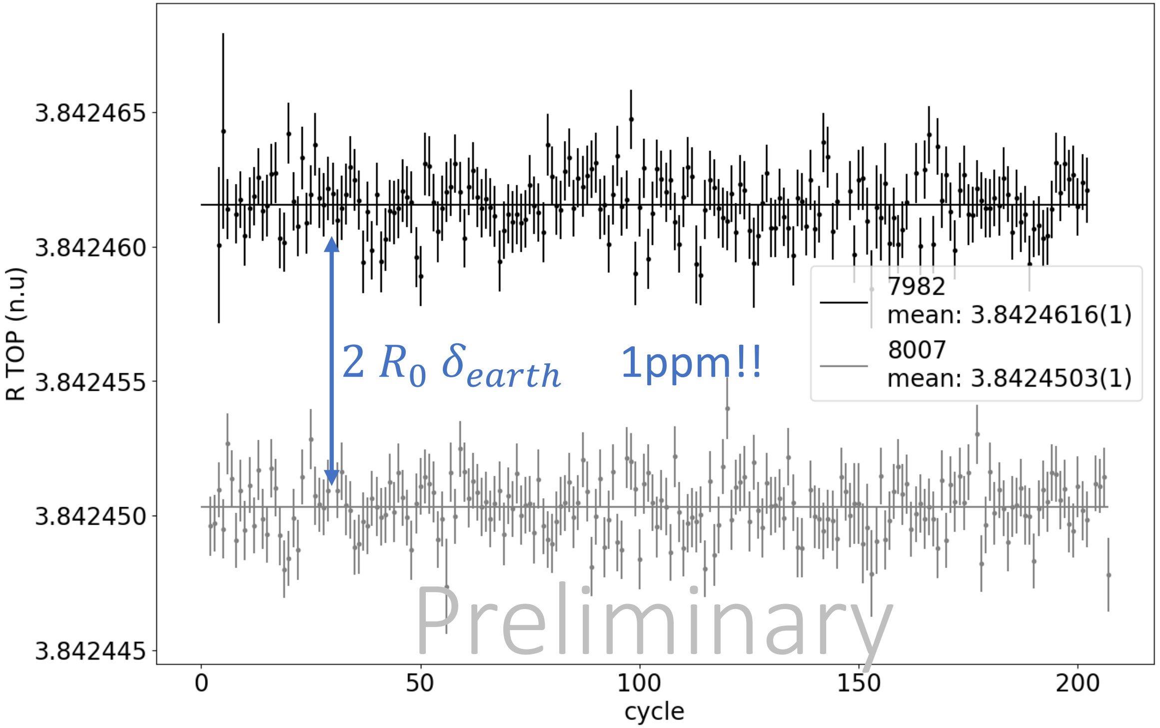
$$R = \frac{f_n}{f_{Hg}} = |\frac{\mu_n}{\mu_{Hg}}|(1 \pm \delta_{earth})$$



$$\delta_{earth} = -f_{earth} \cos\theta \left(\frac{1}{f_n} + \frac{1}{f_{Hg}}\right)$$

Magnetic field down

Magnetic field up

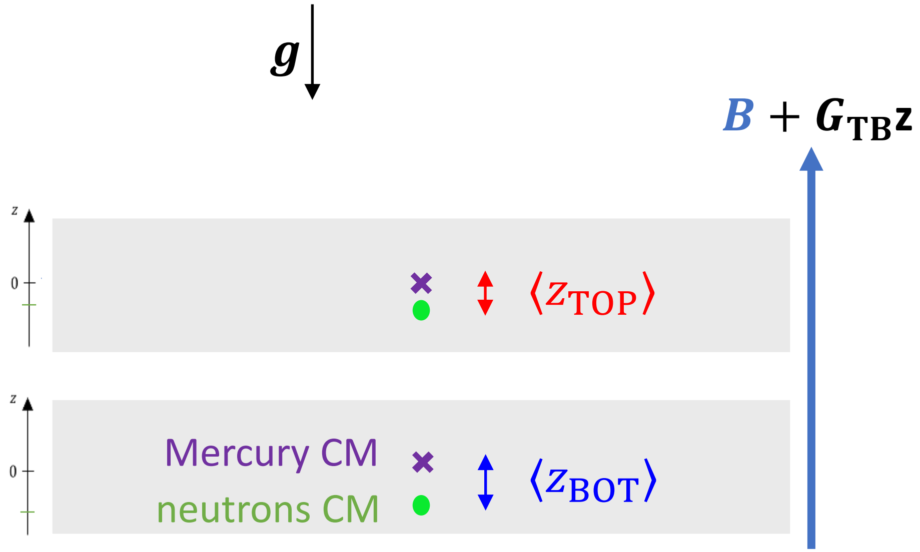


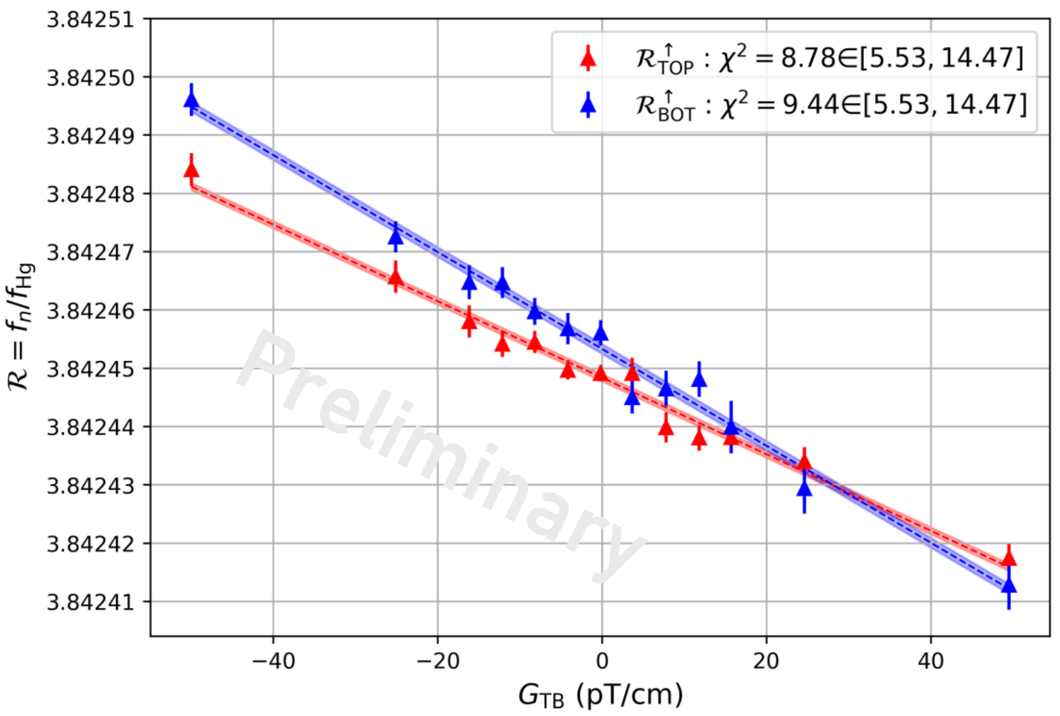
Preliminary result:
Rotation period
24h 09(12)$_{stat}$min

https://ch.geoview.info/villigen_psi_west,10385716

Ultracold neutrons are lazy…

- UCNs have a lower center of mass (CM) than Hg atoms (room temperature) because of gravity





Susceptibility to vertical gradient

$$\frac{dR^{TOP/BOT}}{dG_{TB}} = R_0 \frac{< z_{TOP,BOT} >}{< B >}$$

Result:

$$\langle z_{TOP} \rangle = -0.161(4)\ \mathrm{cm}$$
$$\langle z_{BOT} \rangle = -0.214(6)\ \mathrm{cm}$$

Provides information on the energy spectrum of neutrons!

Status and outlook

- EDM data-set December 2025:

$N_{\text{tot}} = 66000$ neutrons per cycle

$\sigma(f_{\text{Hg}}) \approx 300$ nHz per cycle

Electric field $|E| = 110\text{kV}/12\text{cm}$

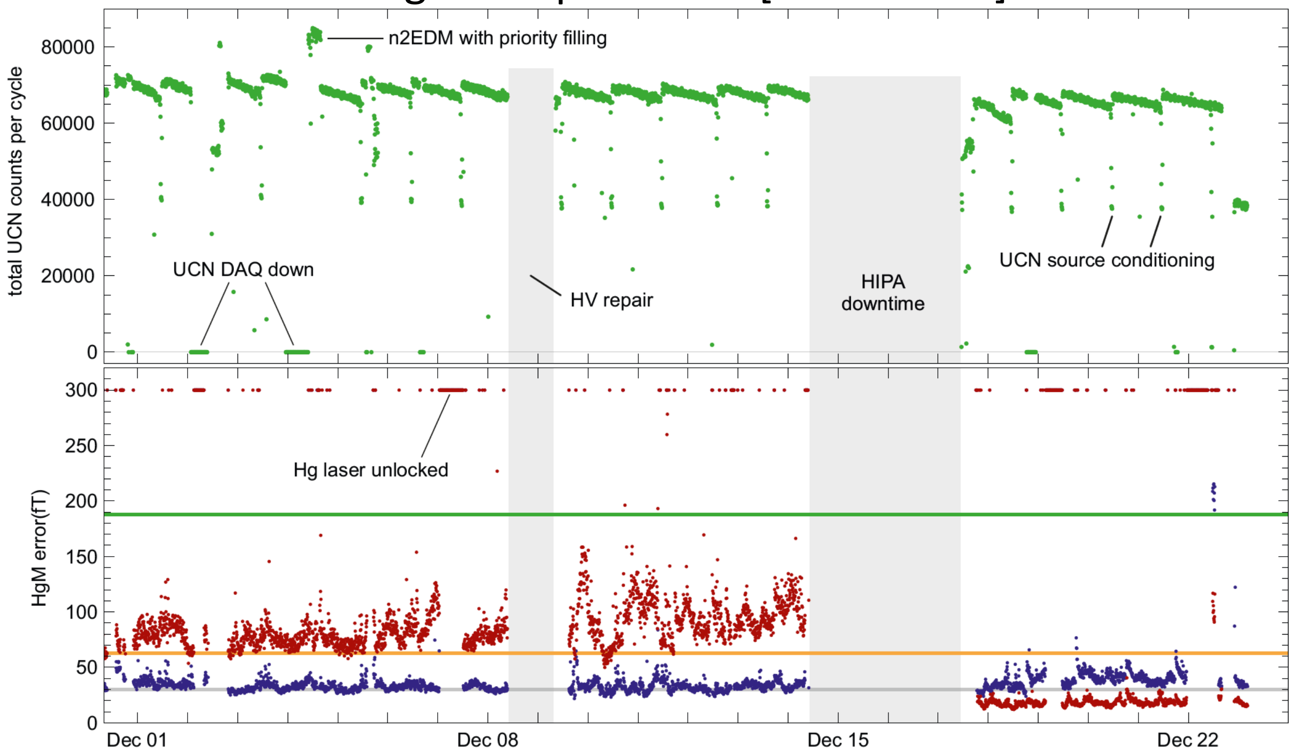
$\alpha^{\text{TOP}} = 0{,}83 \qquad \alpha^{\text{BOT}} = 0{,}89$

$T = 180\ s$

200 cycles/day

$$\sigma(d_n) = \frac{\hbar}{4\alpha\, E\, T\sqrt{N}}$$

n2EDM Progress report 2025 [internal PSI]



$$\sigma(d_n) = 90 \times 10^{-26}\ e\ \text{cm per cycle}$$
$$= \quad 6 \times 10^{-26}\ e\ \text{cm} \quad \text{per day}$$

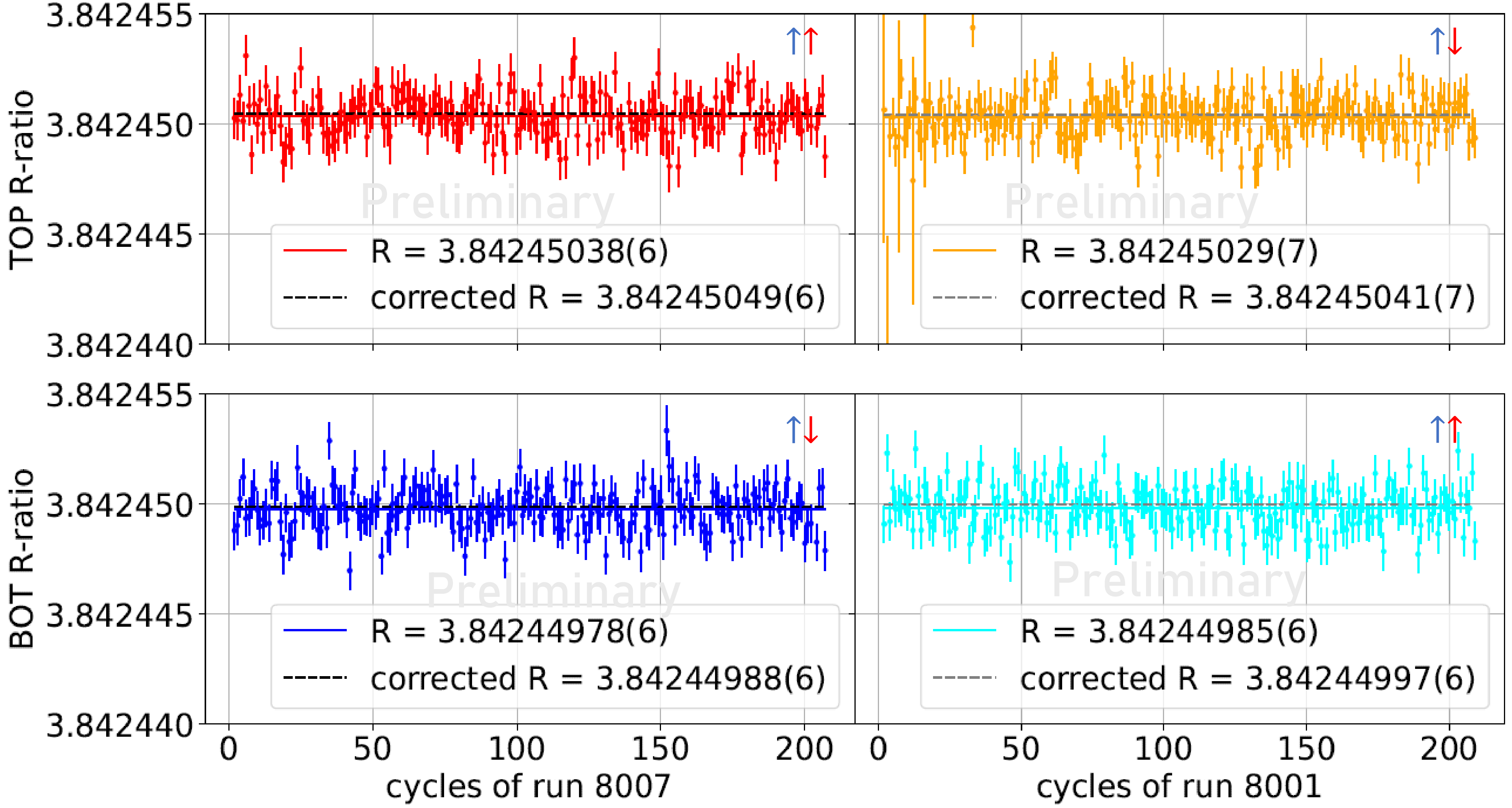
(2.3 times larger than design)

n2EDM data-taking (blinded) starts in 08/2026, until HIPA long shutdown 08/2027. Restart in 2030-2033.

Thank you for your attention!
Questions?

Additional slides

Example: how to determine the nEDM



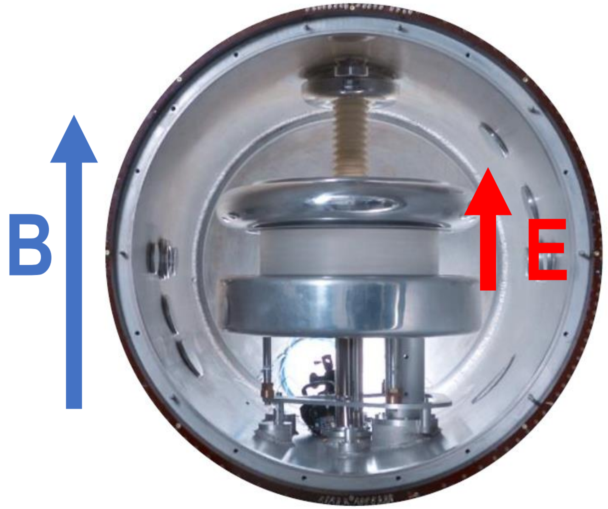
Current most sensitive measurement: nEDM at PSI

Measurement of the Permanent Electric Dipole Moment of the Neutron, nEDM collaboration, 2020

$$d_n = \left(0.0 \pm 1.1_{stat} \pm 0.2_{syst}\right) \times 10^{-26}\ e\ cm$$

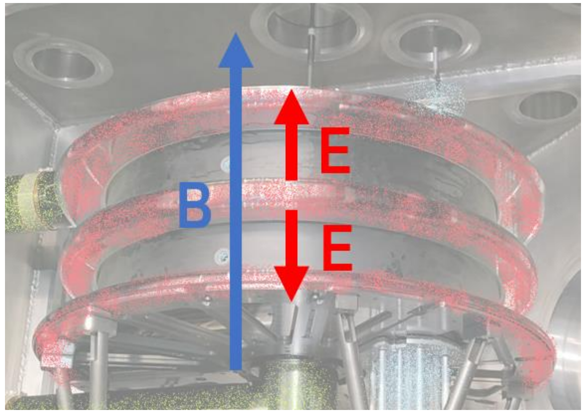
Number of neutrons

Homogeneity of B

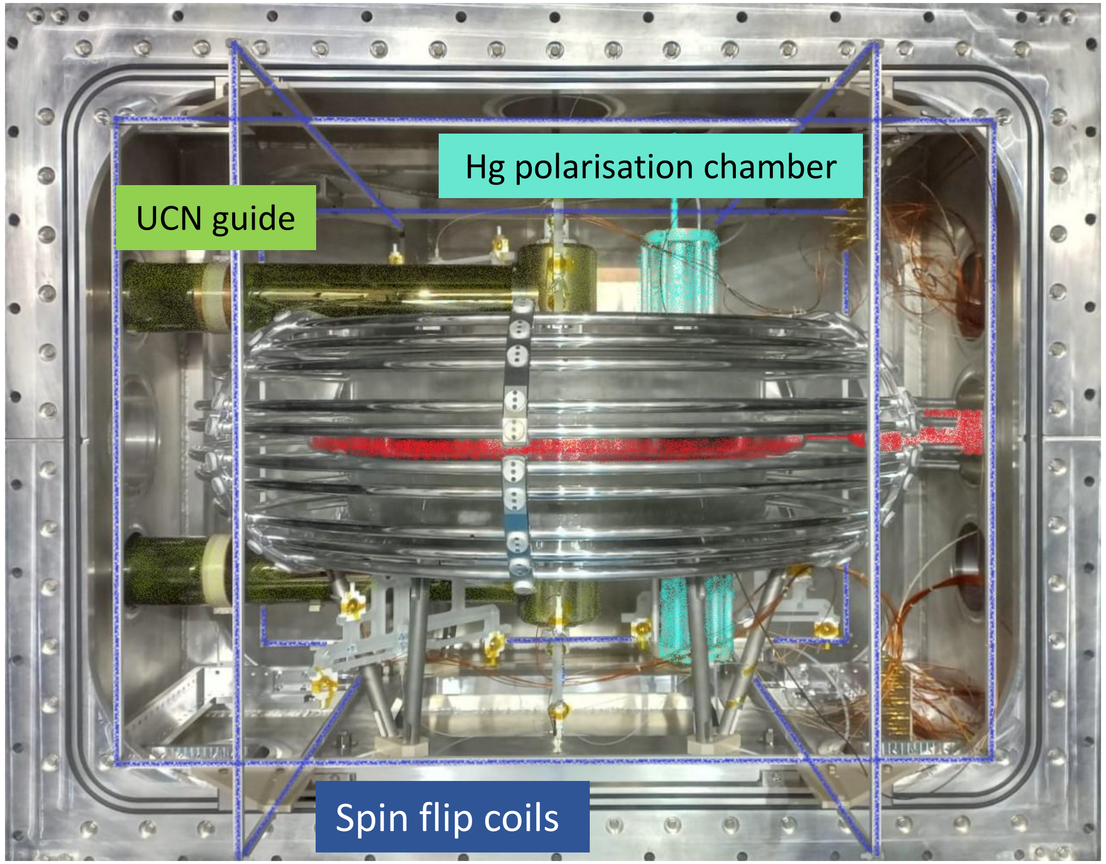


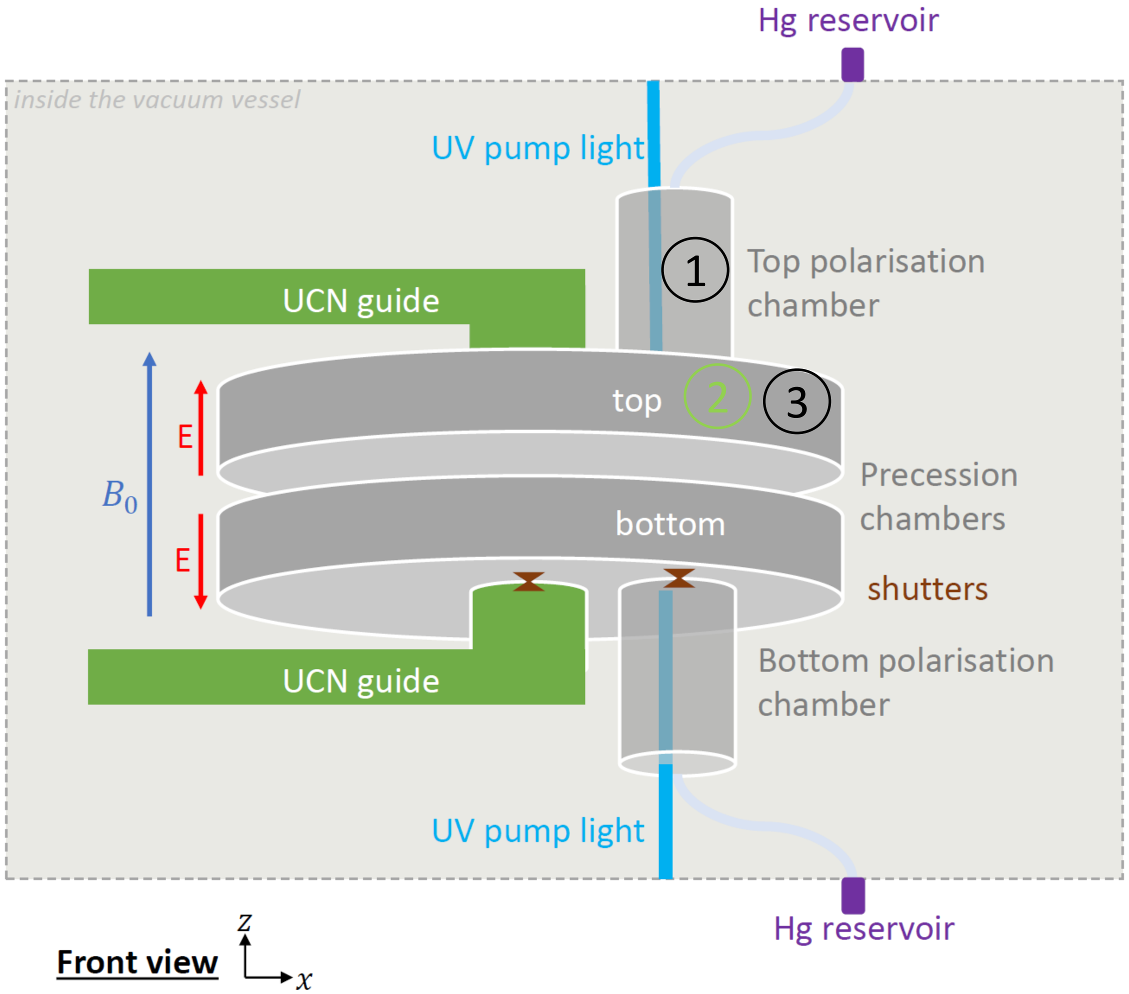
In n2EDM:

- Increase statistics in larger volume with a better controlled magnetic field: **simultaneous measure is two chambers** for both electric polarities.
- Same principle of co-magnetometry: Hg and Cs.

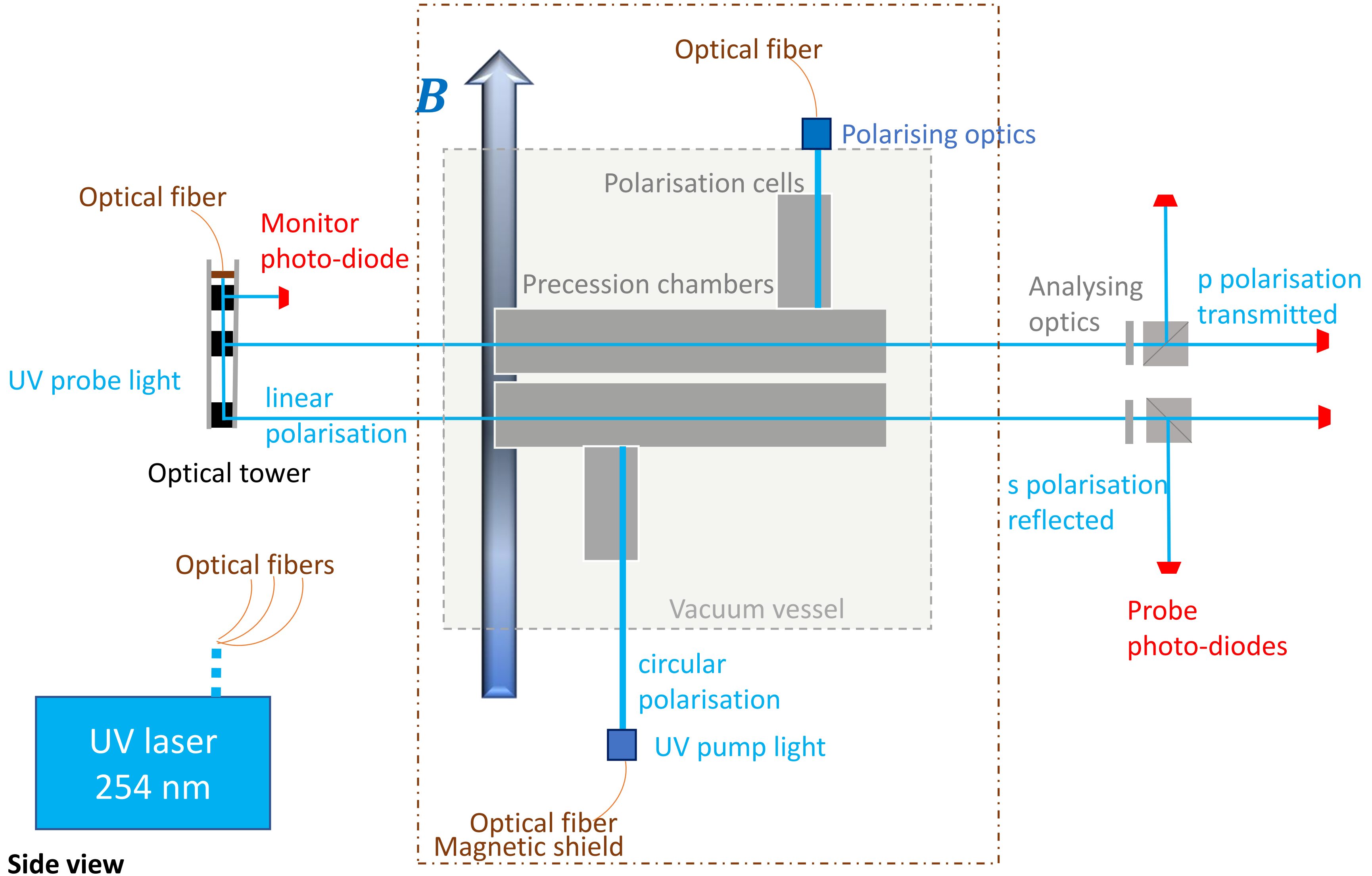


n2EDM experiment: overview





Hg-comagnetometer: overview



Linearly polarised probe.
Two signals per chamber.
Cancels common noise.

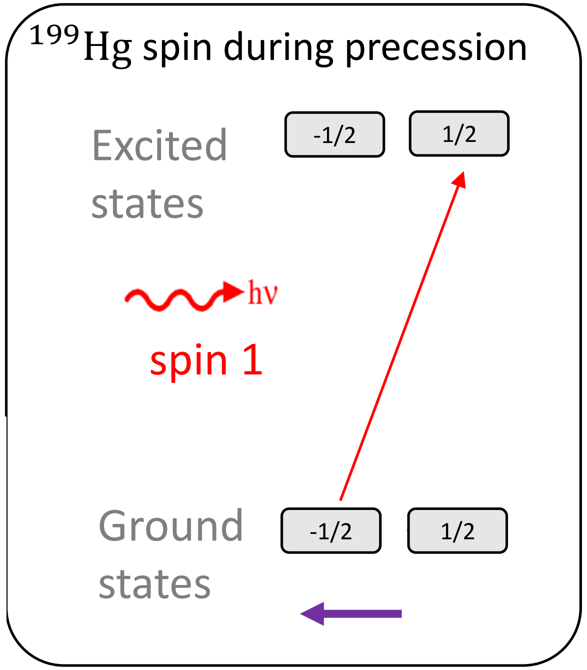
Side view

Hg Precession :

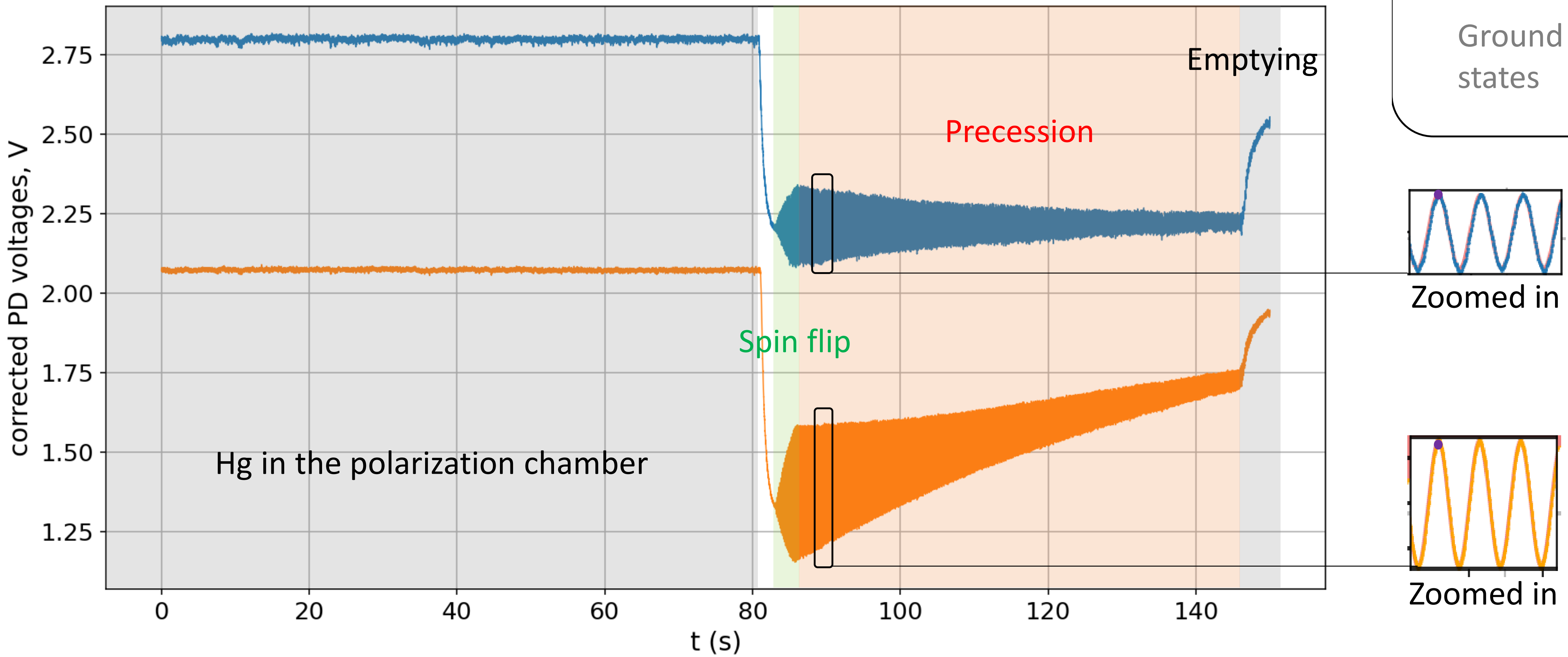
$$s_0 e^{-\sigma L n(t)(1-p(t))}$$

Hg density

Vapour spin polarisation along light propagation axis



p oscillates at Larmor frequency, so does the transmitted power.



n2EDM Magnetic field specifications

- Expansion in harmonic modes :

$$B(x,y,z) = \sum_{l,m} \underbrace{G_{lm}}_{\text{Gradient terms}} \underbrace{\Pi_{l,m}(x,y,z)}_{\text{Legendre polynomials}}$$

  - G_{00} : Uniform vertical magnetic field
  - G_{10} : vertical gradient
  - G_{lm} $l \geq 2$: non uniformities

- Non uniformities (modes $l \geq 1$) affect the frequency ratio R.
- **Odd-modes** result in an EDM-like signal

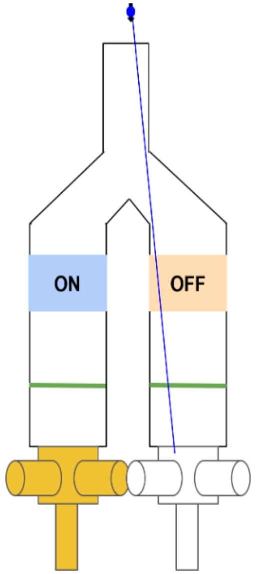
Specifications	fT/cm	Measured by…
Mode 1 of the magnetic field	$\delta G_1 < 25$	Hg, online
Mode 3 of the magnetic field	$\delta G_3 < 20$	Cs, online
Mode 5 of the magnetic field	$\delta G_5 < 20$	Mapper, offline

The design of the n2EDM experiment. nEDM Collaboration, EPJ C, 2021

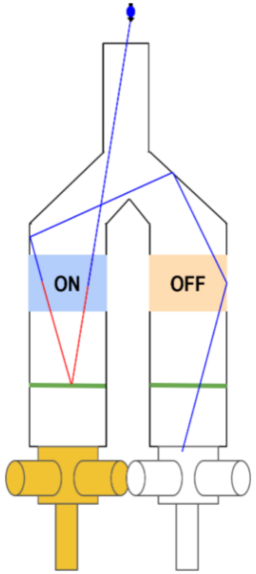
1. Neutron Spin Analyzer: measure $\frac{N_{up} - N_{down}}{N_{up} + N_{down}}$

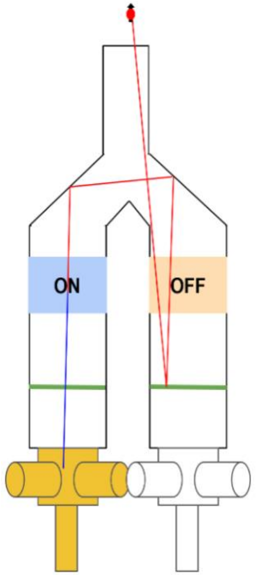
Simultaneous detection of both spin components in gaseous detector:

- **Analyzing foil**: spin down transmitted (spin up reflected).
- Two arms: - one with a **spin flipper**: detects spin up neutrons
  - one without: detects spin down neutrons

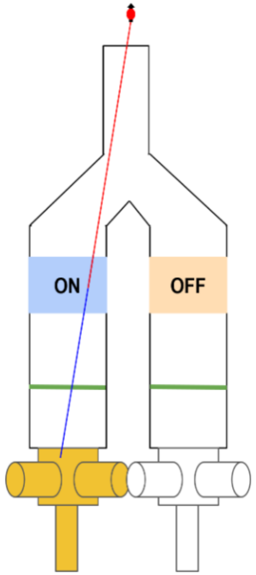


spin ↓
detection





spin ↑
detection



Why measure the neutron EDM?

Matter predominance is observed by cosmological probes:

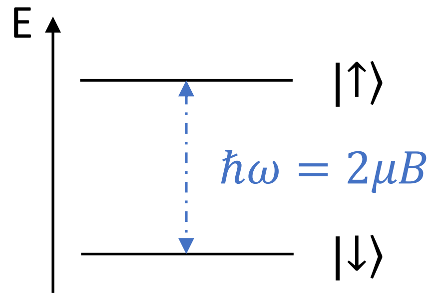
Baryon asymmetry $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6{,}1 \pm 0{,}2) \times 10^{-10}$ (BBN, Planck)

Charge Parity (CP) violation is one of the Sakharov condition for baryogenesis.

1. All EDMs violate CP,
2. Electron EDM and neutron EDM probe **BSM physics** at scales $> 10\ \mathrm{PeV}$.
3. nEDM is defining the **strong CP problem** $|\bar{\theta}| < 10^{-10}$

What is the magnetic moment?

- Spins couple to magnetic fields. Magnetic moment is the coupling strength μ

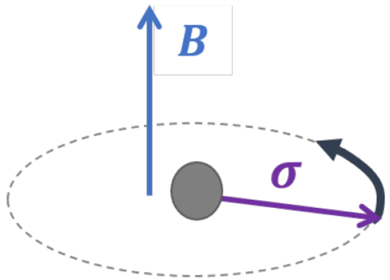


Non-relativistic limit of the fermion-photon interaction:

$$H = -\mu\, \sigma B$$

“torque” on the spin, resulting in **Larmor precession**

$$\frac{d\vec{s}}{dt} = \gamma \vec{s} \times \vec{B}$$



Larmor precession of a spin in a magnetic field at frequency $f = \frac{\mu B}{\pi\hbar}$