Ultra Cold Neutrons and mercury spins in magnetic fields.
n2EDM experiment

Morgan Ferry, Katia Michielsen
LPSC (Grenoble)

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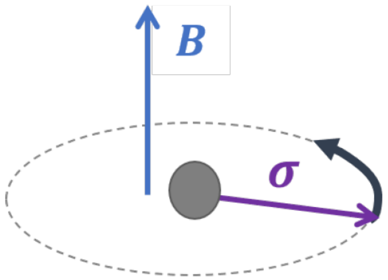
I - Context

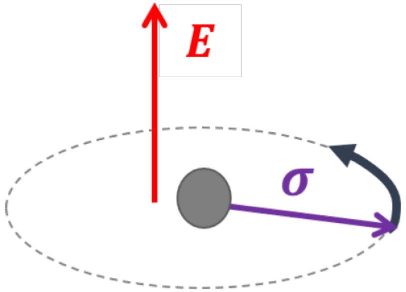
What is an EDM ?

Coupling of the spin to the magnetic field



Observable = magnetic moment μ

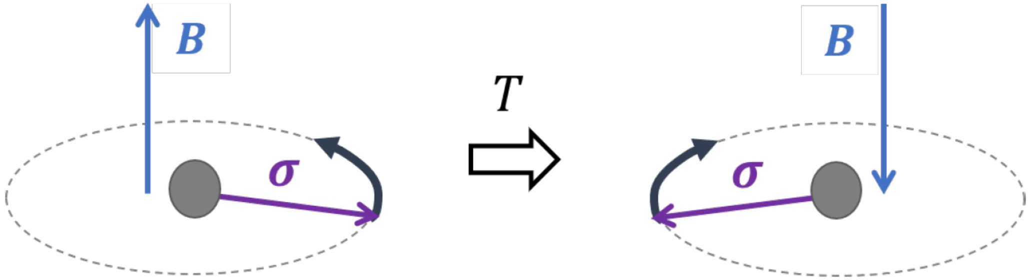
Coupling of the spin to the electric field



Observable = electric dipole moment (EDM) d

An EDM violates Charge Parity symmetry.

Coupling of the spin to the magnetic field



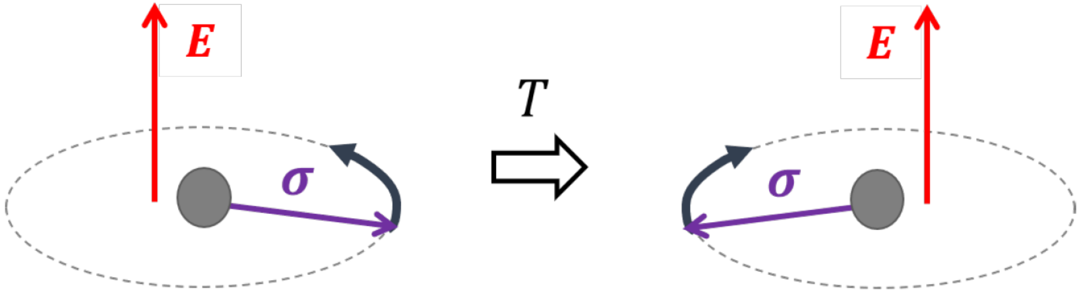
Observable = magnetic moment μ

$\mu > 0$

$\mu > 0$

T-invariant

Coupling of the spin to the electric field



Observable = electric dipole moment (EDM) d

$d > 0$

$d < 0$

not T-invariant

T violation ↔ CP violation

CP violation is one of the Sakharov criteria for matter anti-matter asymmetry during baryogenesis.

What do we know about the nEDM?

Theory: $$d_n = \underbrace{10^{-32} e\,\mathrm{cm}}_{\text{weak interaction}} + \underbrace{\bar{\theta} \cdot 10^{-16}\, e\,\mathrm{cm}}_{\text{strong interaction}} + \underbrace{\quad}_{\text{new physics?}}$$

Current limit [1] : $d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst})\mathbf{10^{-26}} e\,\mathrm{cm}$

n2EDM sensitivity goal : $\mathbf{10^{-27}} e\,\mathrm{cm}$

- CP violation probe in
  - **strong sector** : $\bar{\theta} < 10^{-10}$ "strong CP problem"—> introduction of **axion**
  - **new physics** with mass scale of > 1 PeV (EFT)
- Generic probe

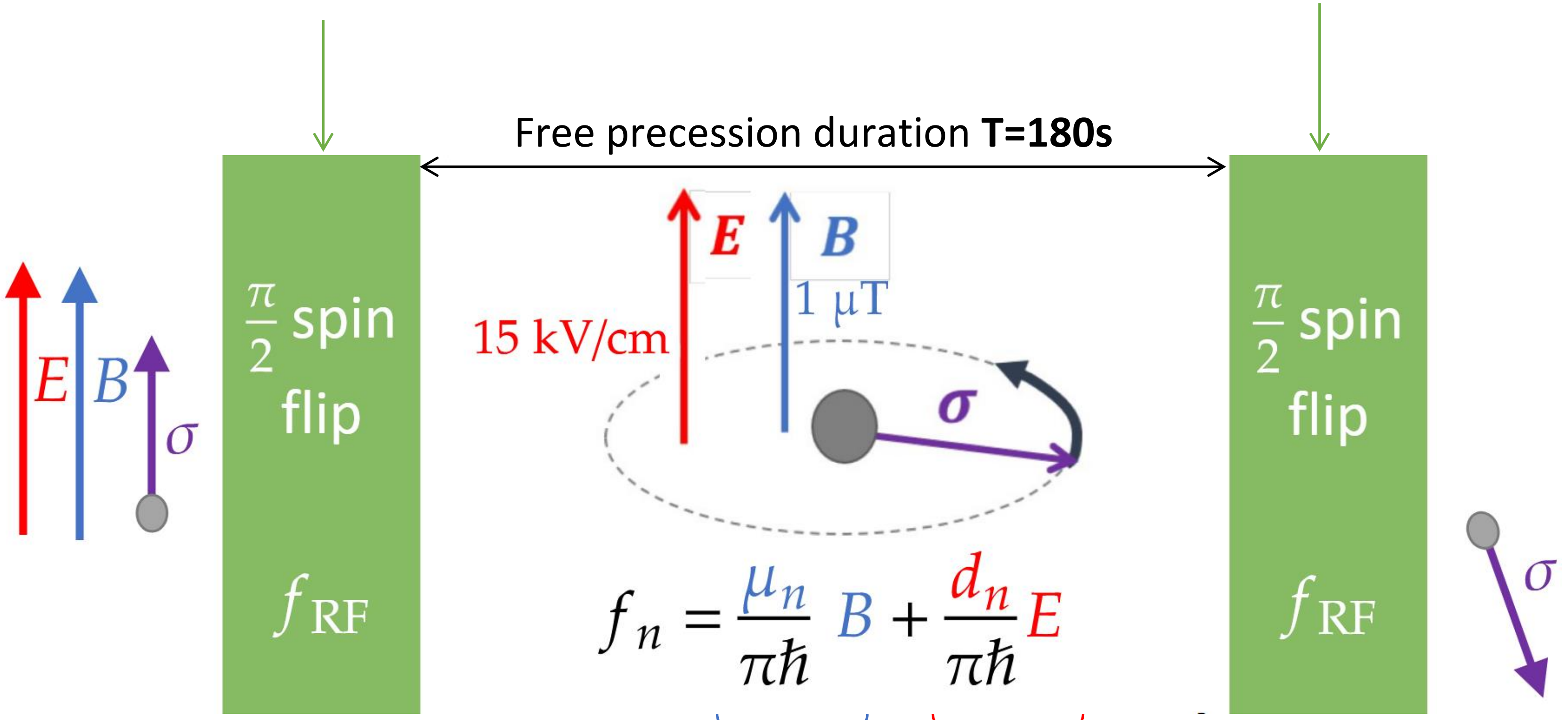
—> Complementary EDM measurements required : proton, electron, muon EDM

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

II – n2EDM overview

Larmor precession frequency f_n measurement

Ramsey method of oscillatory fields : 2 spin flips



Free precession duration **T=180s**

$$f_n = \underbrace{\frac{\mu_n}{\pi\hbar} B}_{\sim 30\text{Hz}} + \underbrace{\frac{d_n}{\pi\hbar} E}_{\substack{< 10^{-7}\text{ Hz} \\ \sim 0.5\text{yr}^{-1}}}$$

Spin Asymmetry :

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

Number of neutrons spin aligned/anti-aligned with B

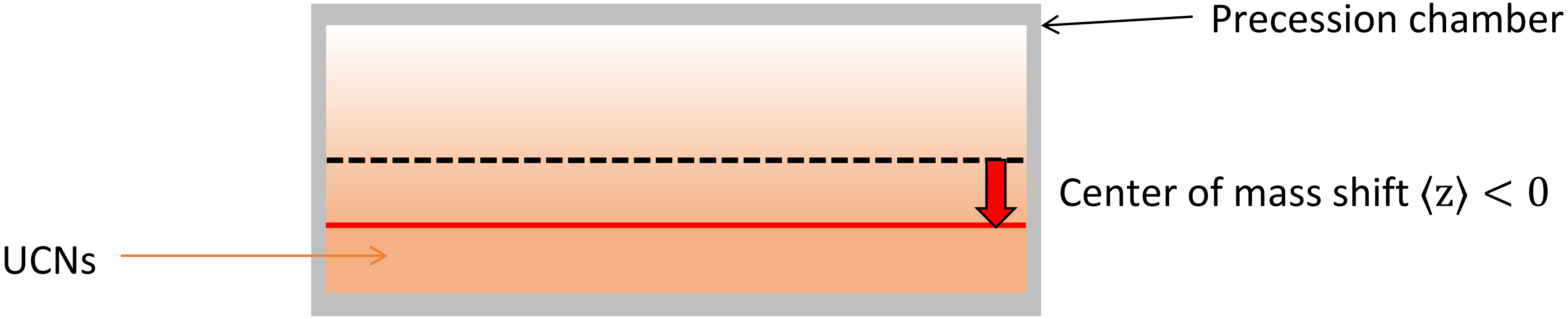
$$\sigma(f_n) = \frac{1}{2\pi\alpha T\sqrt{N}} \sim 10^{-6}\text{ Hz}$$

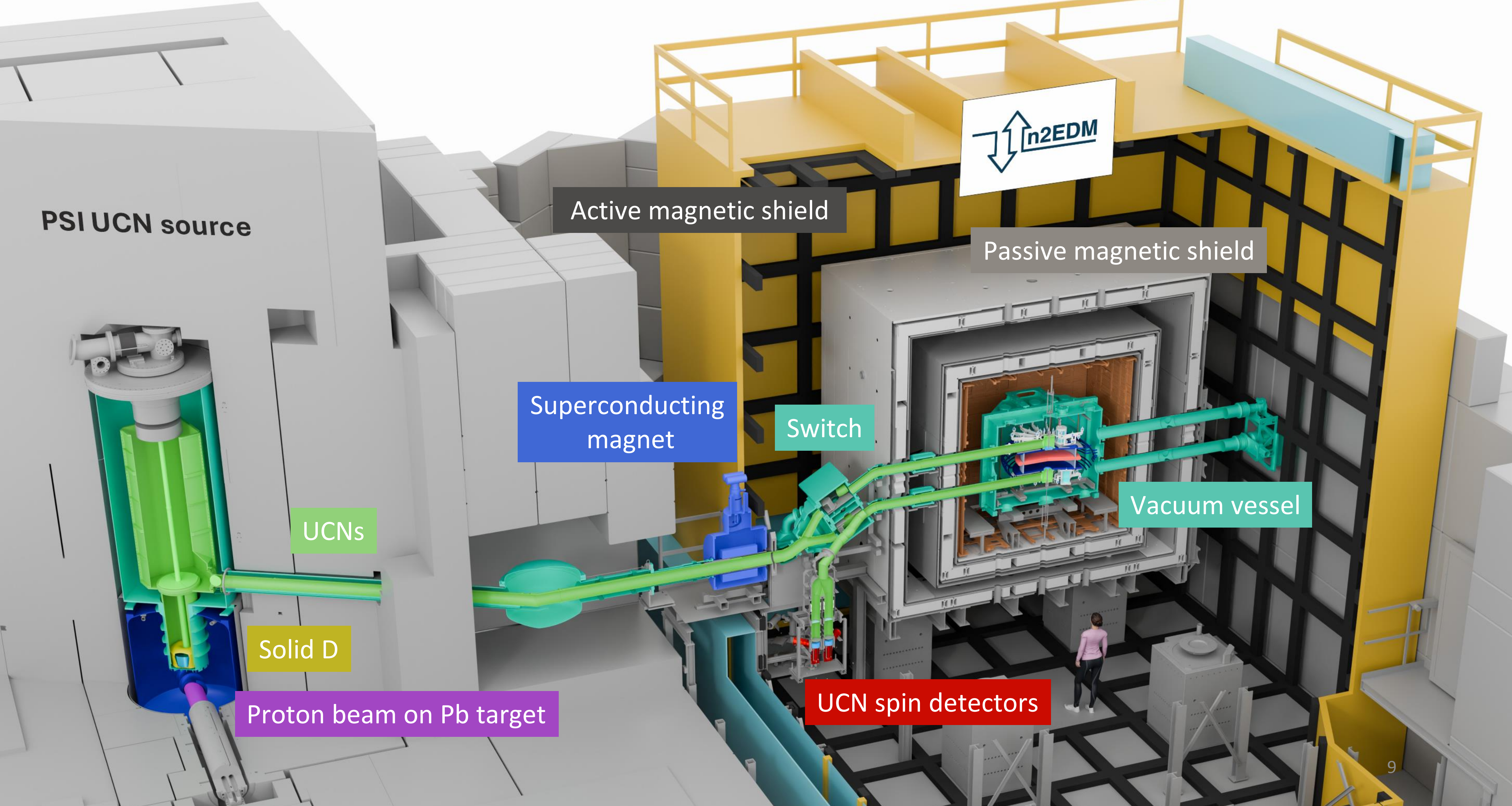
Measure f_n in a known magnetic field and strong electric field.

The use of Ultra Cold Neutrons (UCN)

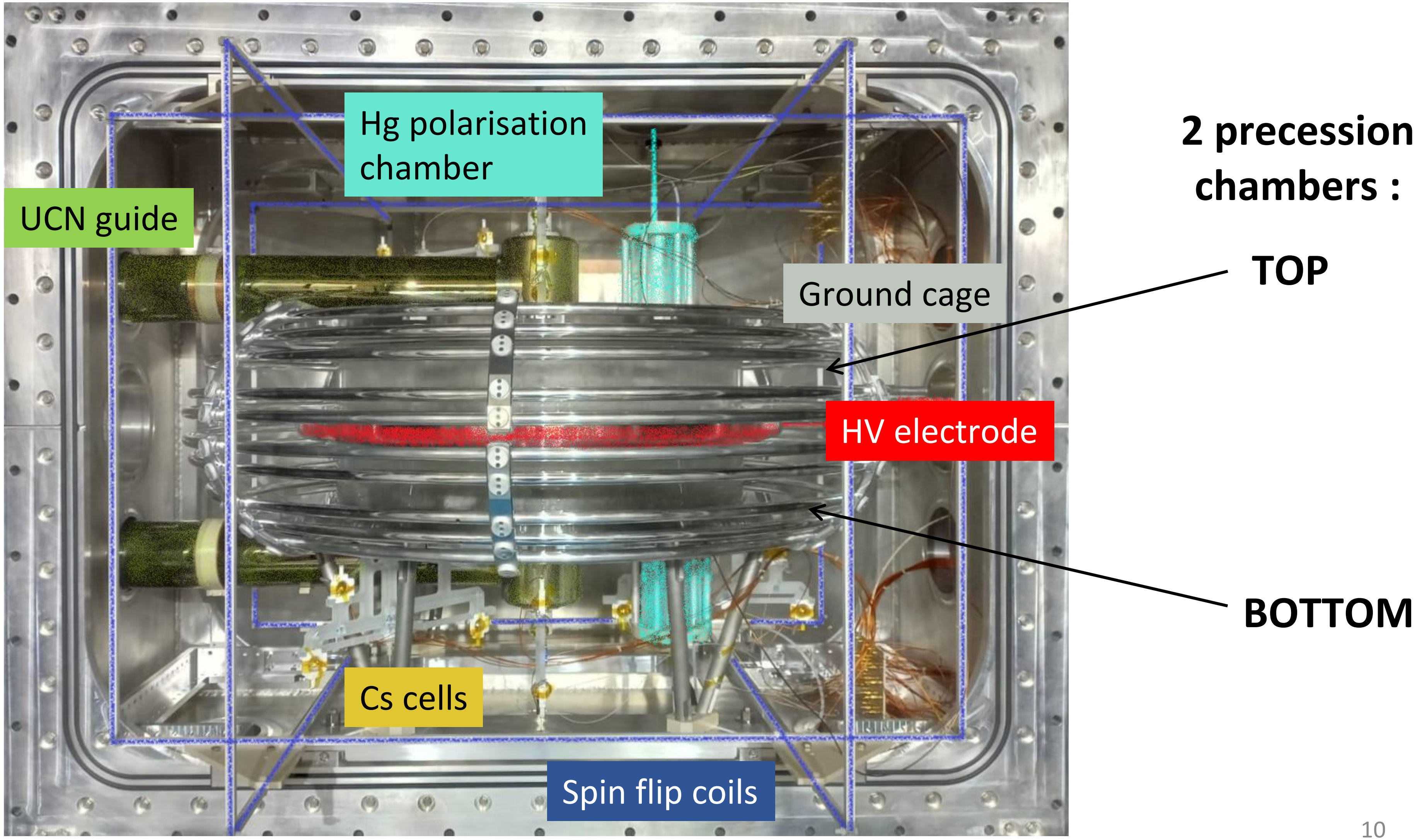
- Challenge : **trap** the neutrons while measuring their precession. No charge…
- UCN = Kinetic energy $< 100\ \mathrm{neV}$ → **bounce** off the walls
- Gravitational potential energy $\sim 100\ \mathrm{neV}$!!

→ **Sag in the gravitational potential** (unlike gases, their center of mass is below the geometric center)




PSI UCN source
n2EDM
Active magnetic shield
Passive magnetic shield
Superconducting magnet
Switch
Vacuum vessel
UCNs
Solid D
Proton beam on Pb target
UCN spin detectors

Experiment overview



2 precession chambers :

III- The Hg co-magnetometer

Concept, setup and performances.

Why do we need a co-magnetometer?

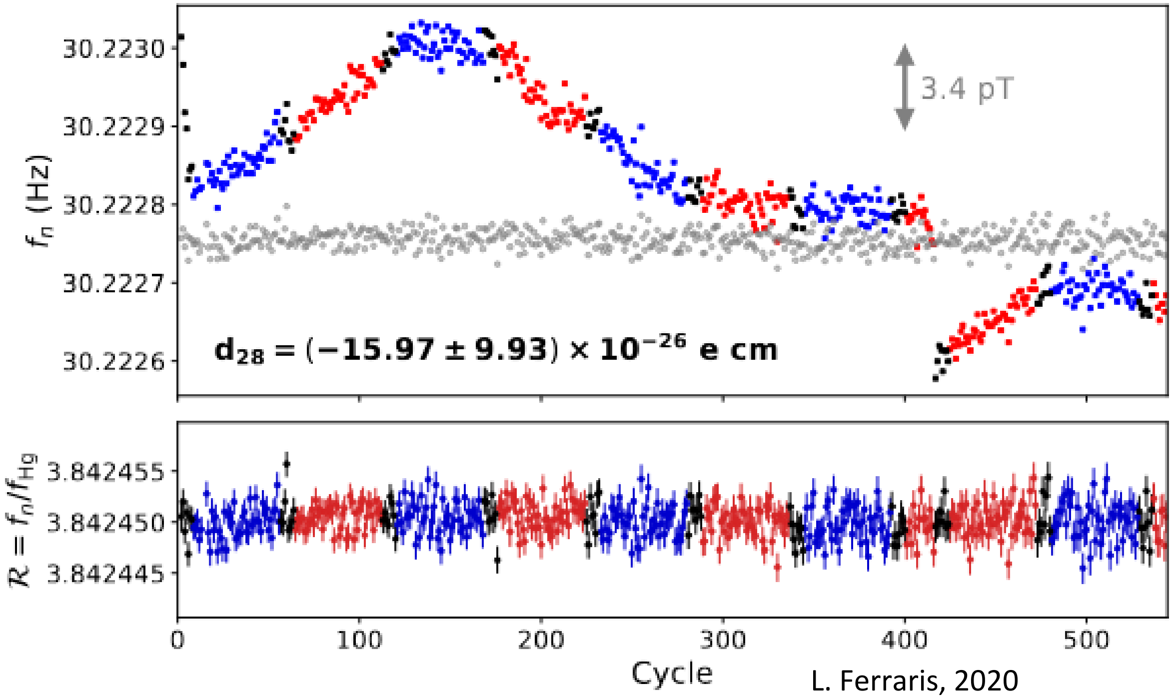
- Magnetic field drifts dominate f_{n} fluctuations

$$f_n = \underbrace{\frac{\mu_n}{\pi\hbar} B}_{\sim 30\mathrm{Hz}} + \underbrace{\frac{d_n}{\pi\hbar} E}_{< 10^{-7}\ \mathrm{Hz}}$$

- Atom with nuclear spin and a negligible EDM [2]

-> Mercury vapour (same volume, same time as n): $f_{\mathrm{Hg}} = \frac{\mu_{\mathrm{Hg}}}{\pi\hbar} B$

- We define $\mathcal{R} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}}$



L. Ferraris, 2020

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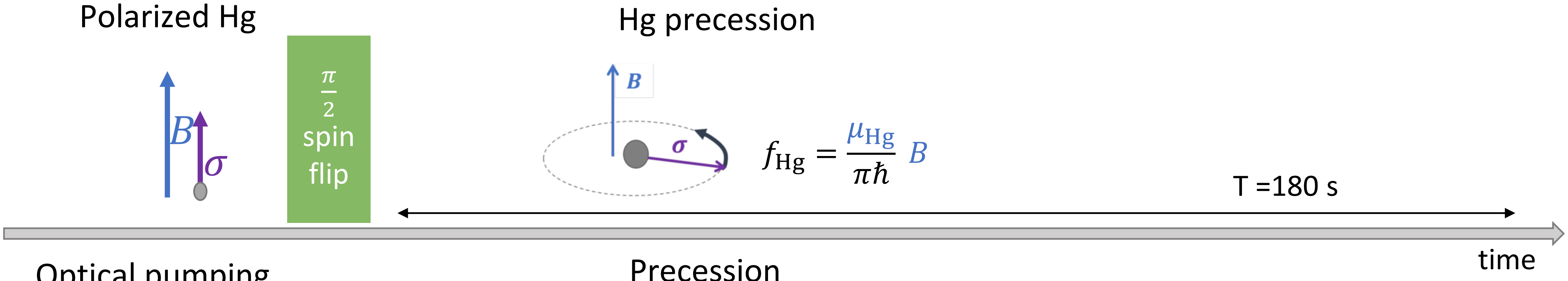
[2] *Reduced limit on the permanent electric dipole moment of Hg 199. Graner, Brent, et al. PRL (2016)* :Hg EDM $|d_{Hg}| < 7{,}4\ \ 10^{-30}\ e\ \mathrm{cm}$

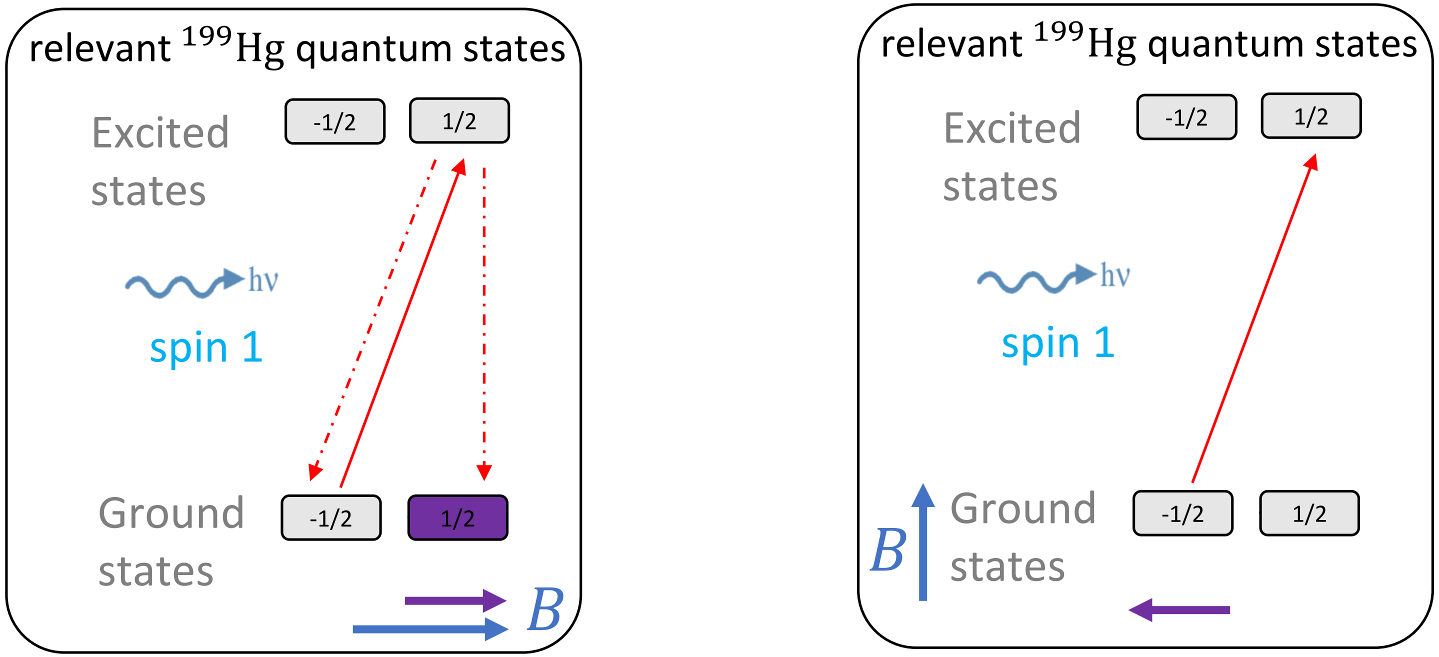
Hg magnetometry concept in n2EDM



$$f_{\mathrm{Hg}} = \frac{\mu_{\mathrm{Hg}}}{\pi\hbar} B$$

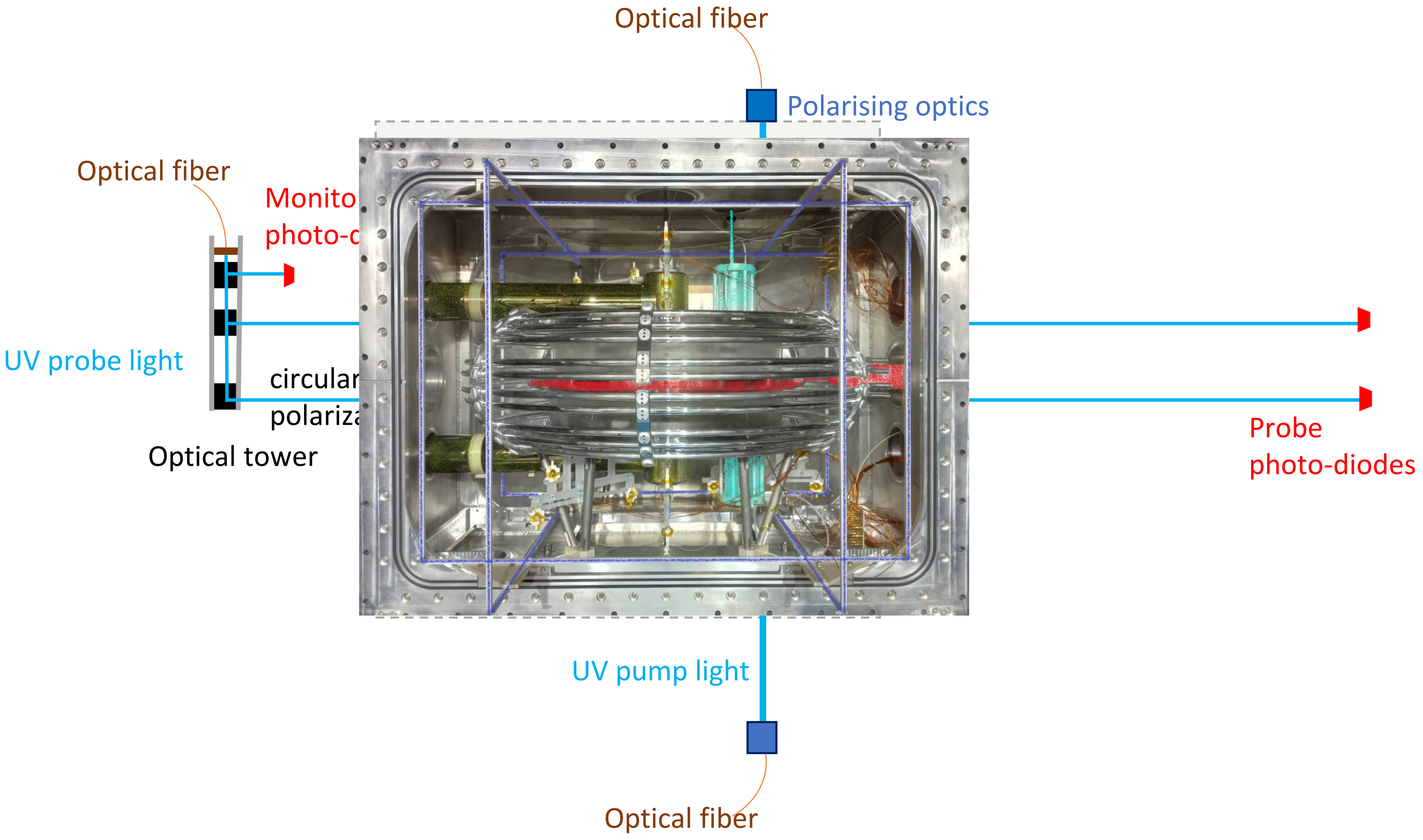
Optical pumping

Precession

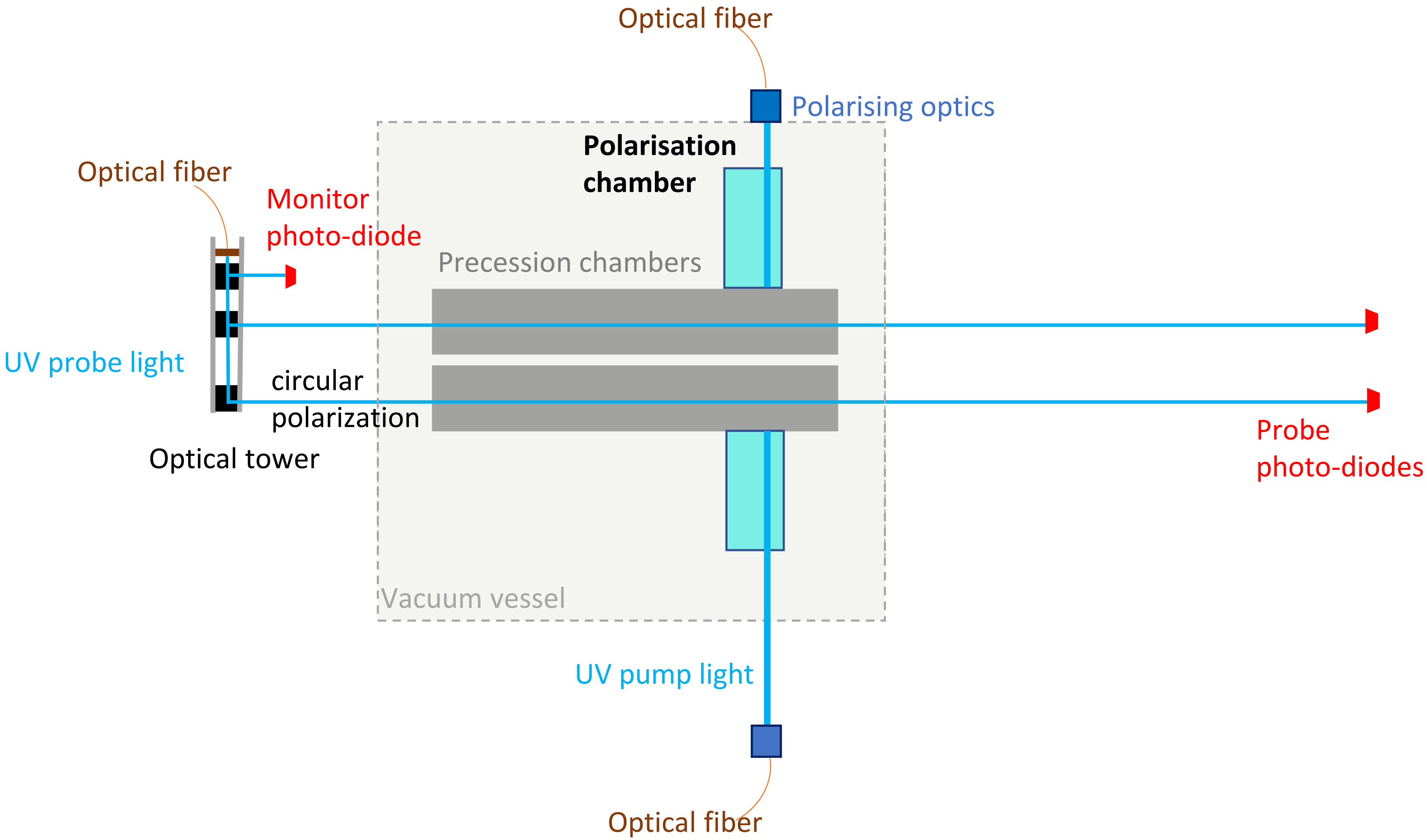


Absorption/transmission modulated at the precession frequency.

Hg magnetometry implementation in n2EDM

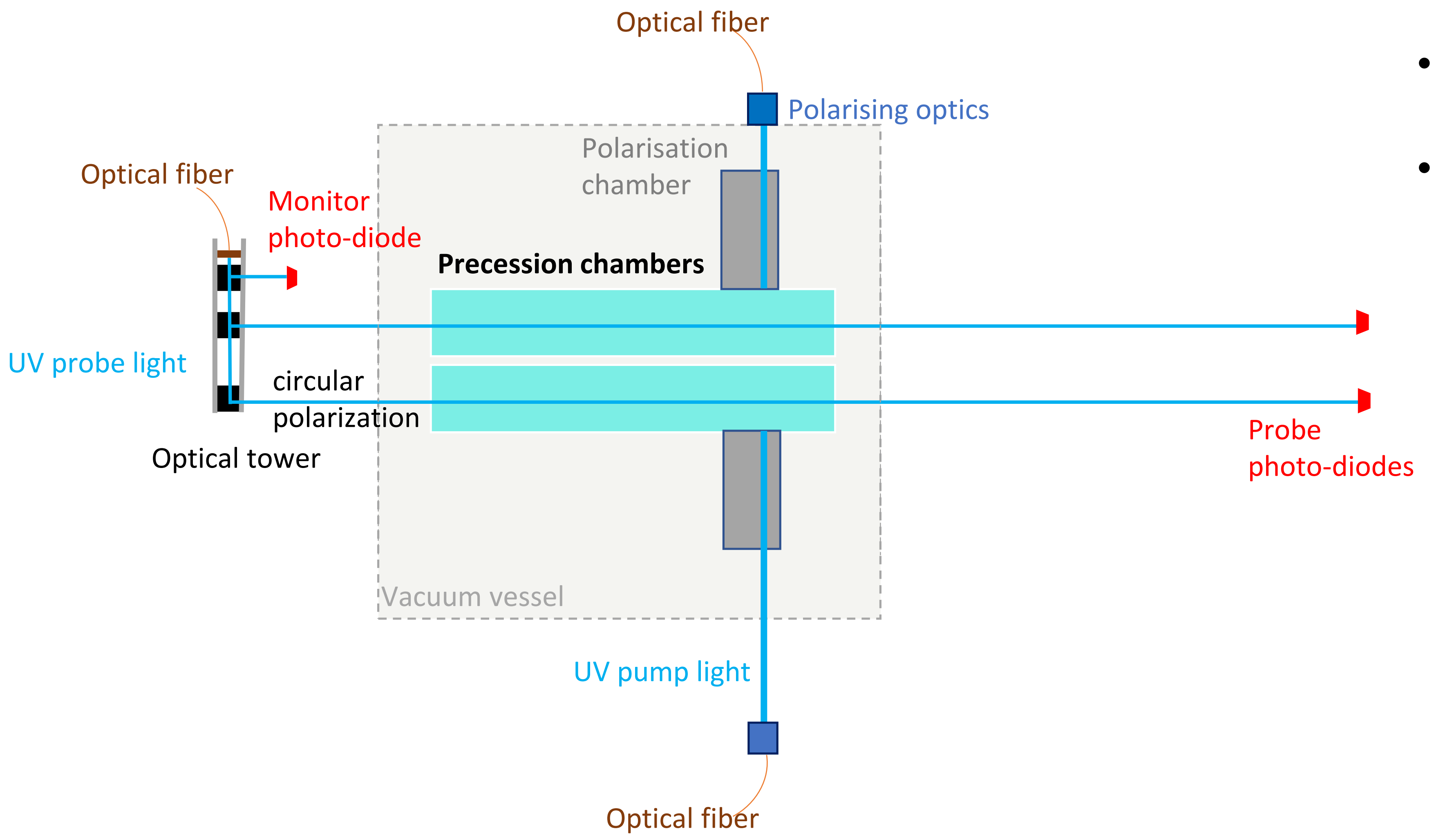


Hg magnetometry implementation in n2EDM



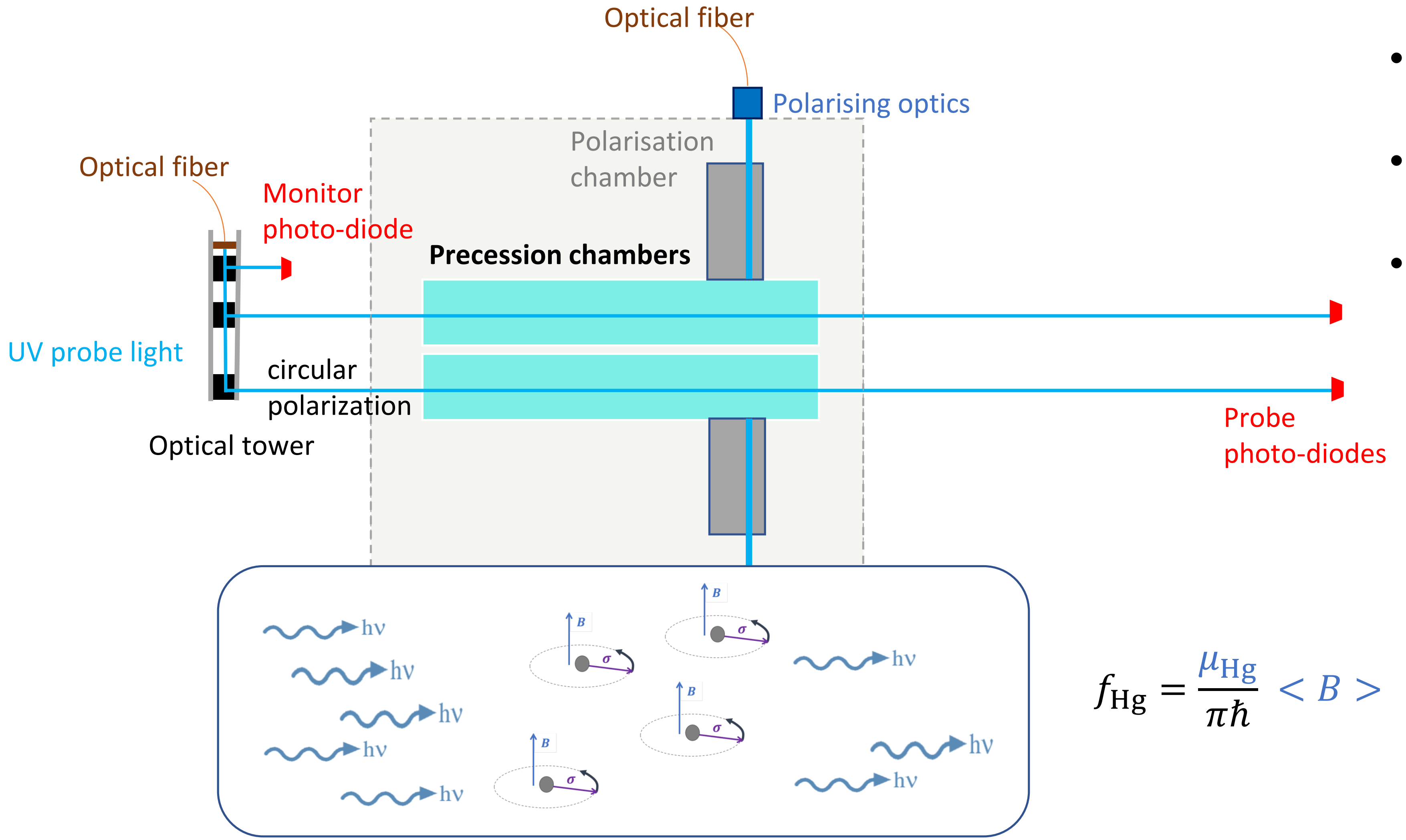
- **Hg vapour is polarised prior to injection**

Hg magnetometry implementation in n2EDM



- Hg vapour is polarised prior to injection
- **Hg and neutron precession occur simultaneously**

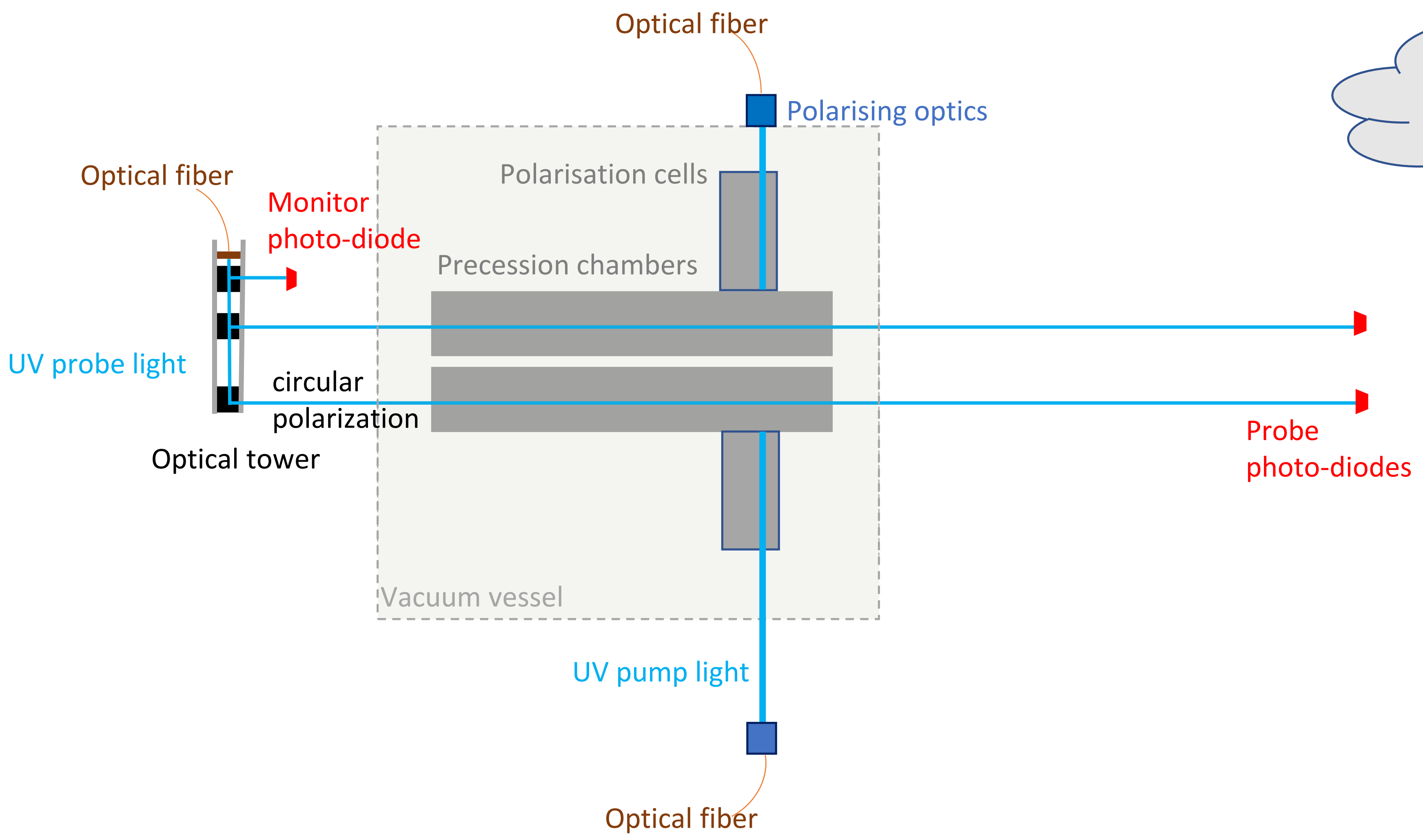
Hg magnetometry implementation in n2EDM



- Hg vapour is polarised prior to injection
- Hg and neutron precession occur simultaneously
- **Modulated transmitted light is continuously recorded.**

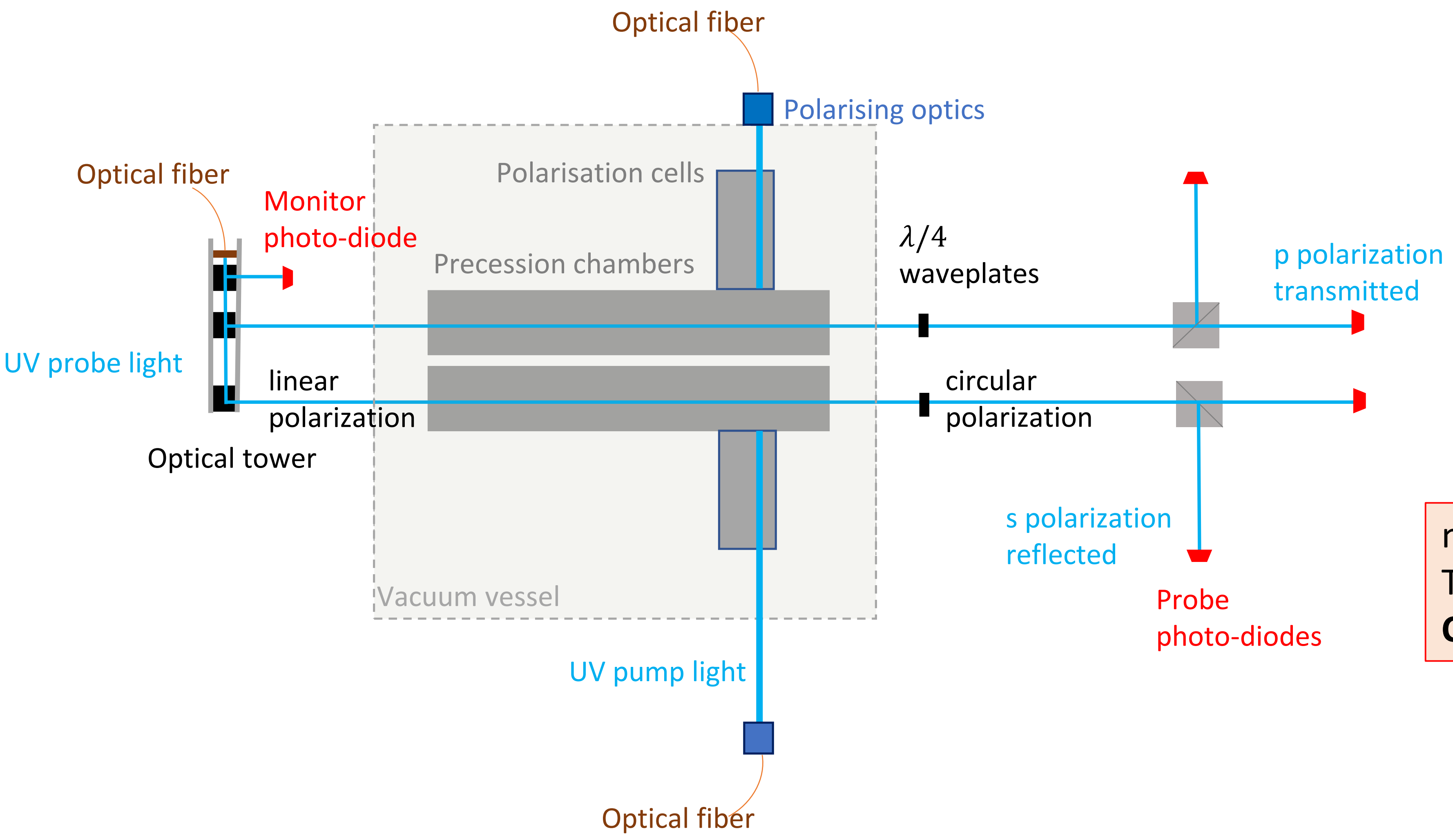
$$f_{\mathrm{Hg}} = \frac{\mu_{\mathrm{Hg}}}{\pi\hbar} < B >$$

Optical reading of Hg precession



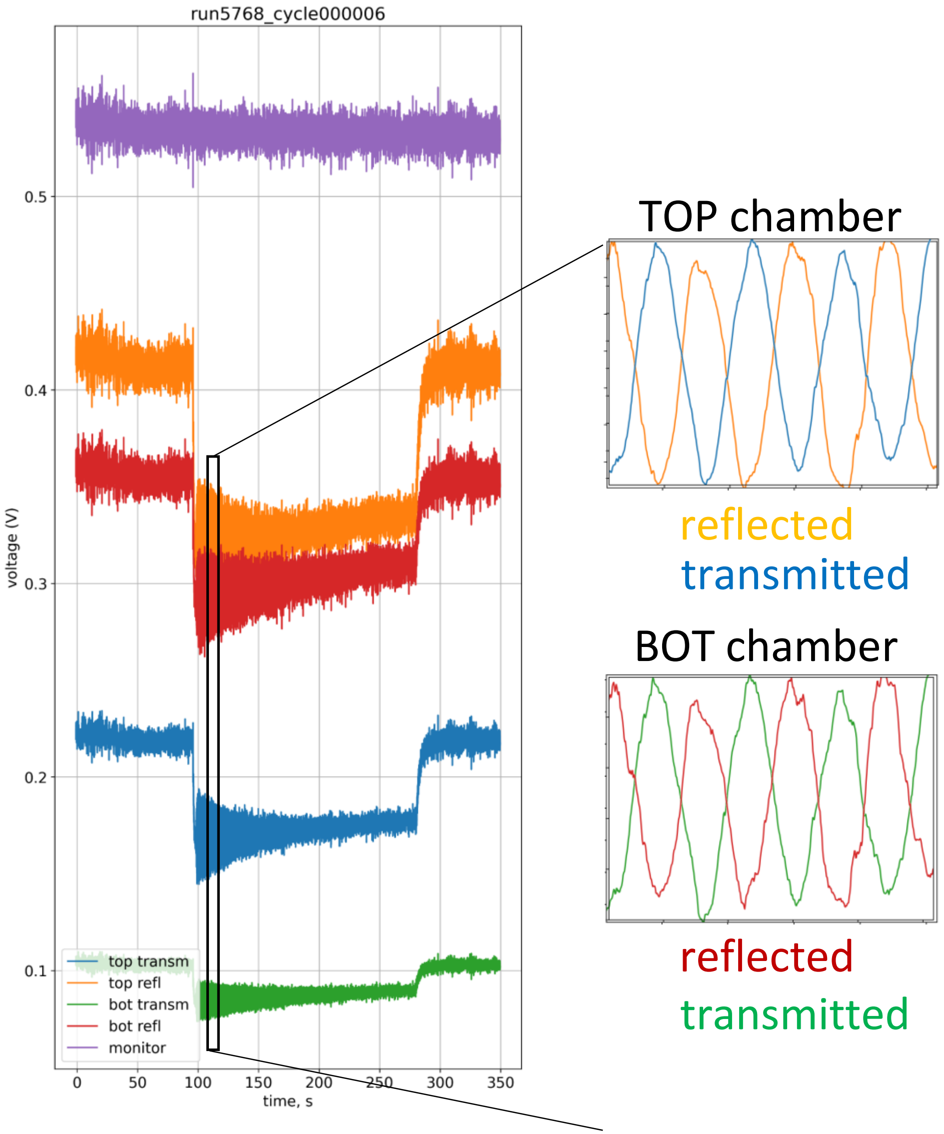
nEDM: Circularly polarised probe.
One signal per chamber.

Optical reading of Hg precession



n2EDM: linearly polarised probe.
Two signals for each chamber.
Cancellation of common noise.

Optical reading of Hg precession



TOP chamber

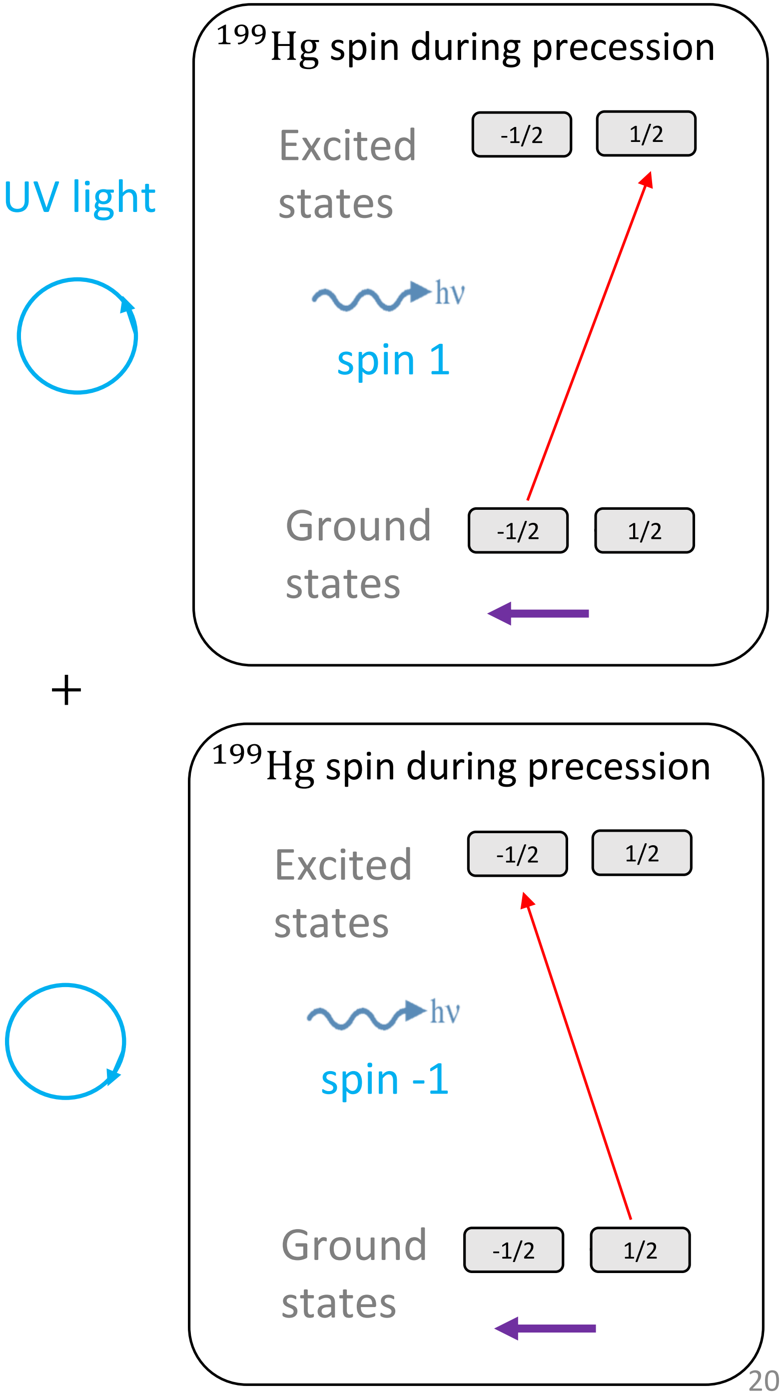
reflected

transmitted

BOT chamber

reflected

transmitted



UV light

^{199}Hg spin during precession

Excited states

spin 1

Ground states

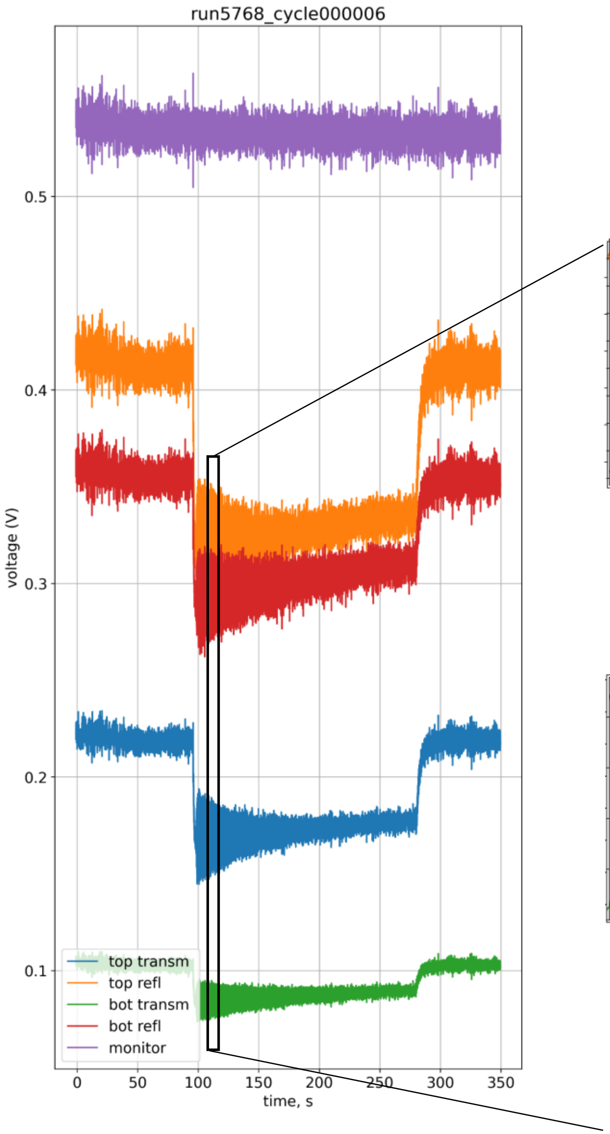
^{199}Hg spin during precession

Excited states

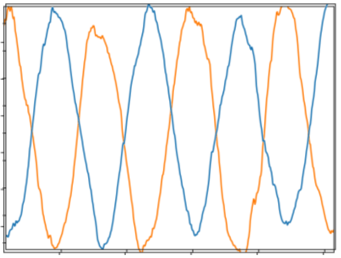
spin -1

Ground states

Optical reading of Hg precession

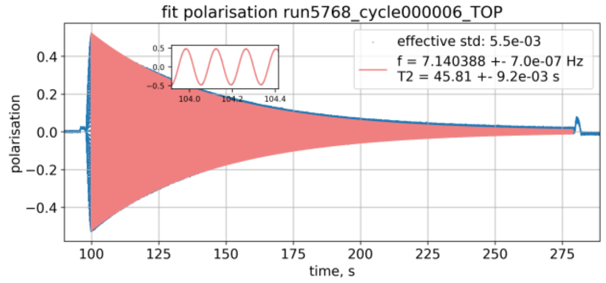


TOP chamber

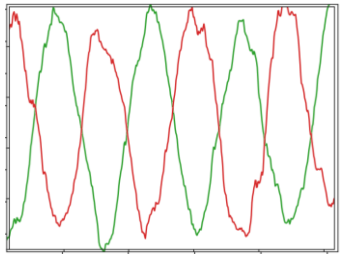


reflected

transmitted

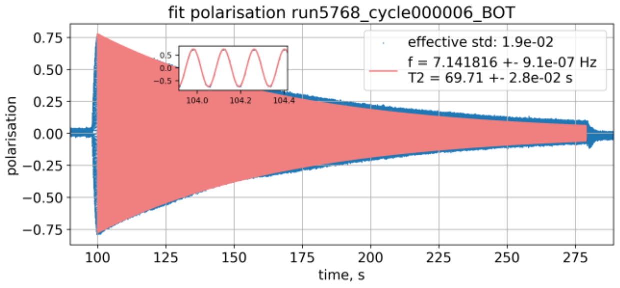


BOT chamber



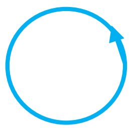
reflected

transmitted



Linearly polarised probe lowered the uncertainty by a factor 3.

UV light



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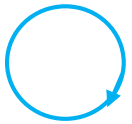
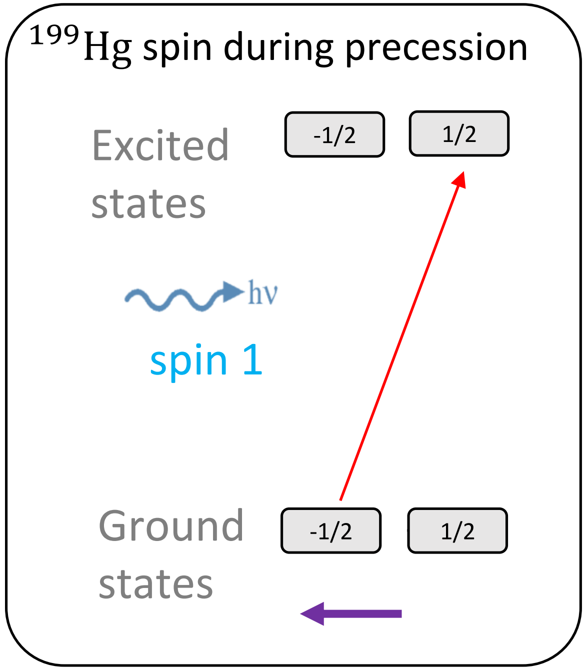




^{199}Hg spin during precession

Excited states

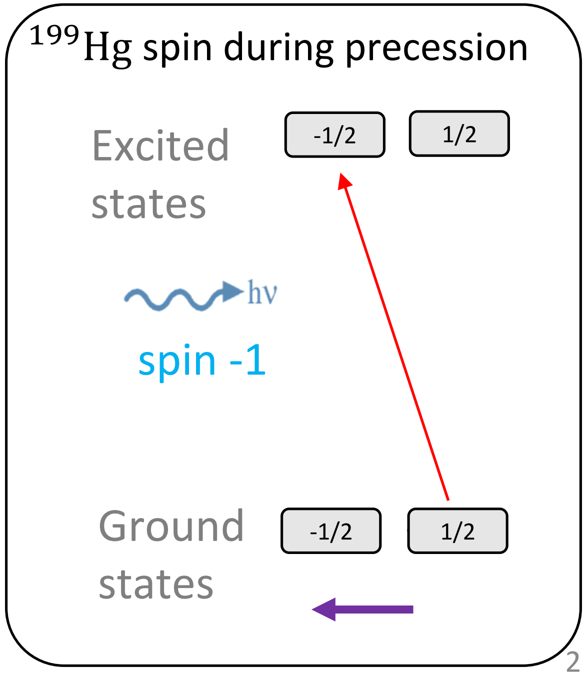
-1/2 1/2

hν

spin 1

Ground states

-1/2 1/2



^{199}Hg spin during precession

Excited states

-1/2 1/2

hν

spin -1

Ground states

-1/2 1/2

The great combination with linearly polarised light

Transmitted power

$$\Pi_t = a\,\Pi_0 e^{-\sigma n L(1+p)}$$

Reflected power

$$\Pi_r = (1-a)\Pi_0 e^{-\sigma n L(1-p)}$$

$$\Pi_r \Pi_t = a(1-a)e^{-2\sigma n L}$$

Derive $\sigma n_0 e^{-t/T_{leak}} L$

$$\frac{\Pi_r}{\Pi_t} = e^{-2\sigma n L p}$$

Derive p knowing $\sigma n L$

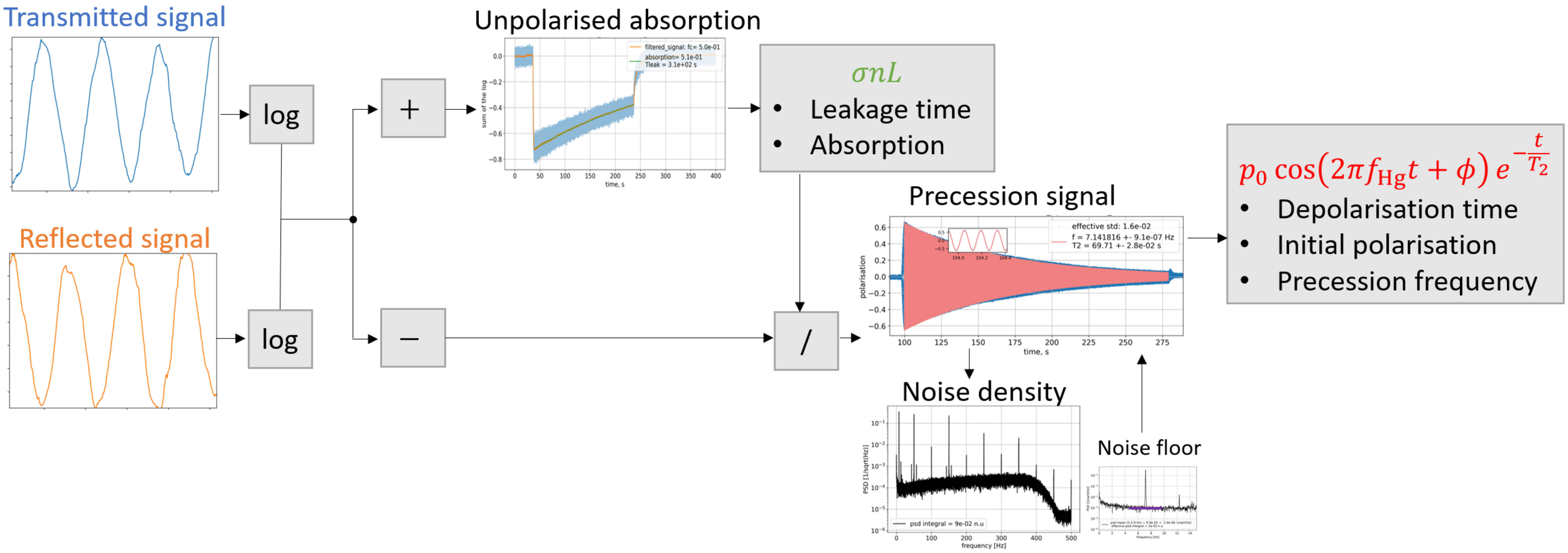
σ unpolarised cross section
n mercury density
L length of the precession volume
p polarisation of the mercury vapour
Transmission/reflection factors:
a and $1-a$

$$-\frac{1}{2\sigma n L}\ln\left(\frac{\Pi_r}{\Pi_t}\right) = p_0 \cos\left(2\pi f_{\mathrm{Hg}} t + \phi\right) e^{-\frac{t}{T2}}$$

1st fit provides
- Absorption
- Leakage time of precession chamber

2nd fit provides
- Polarisation of mercury vapour p_0
- Depolarisation time $T2$
- Noise spectrum
- Precession frequency f_{Hg}

Hg precession analysis: summary



$\sigma n L$

- Leakage time
- Absorption

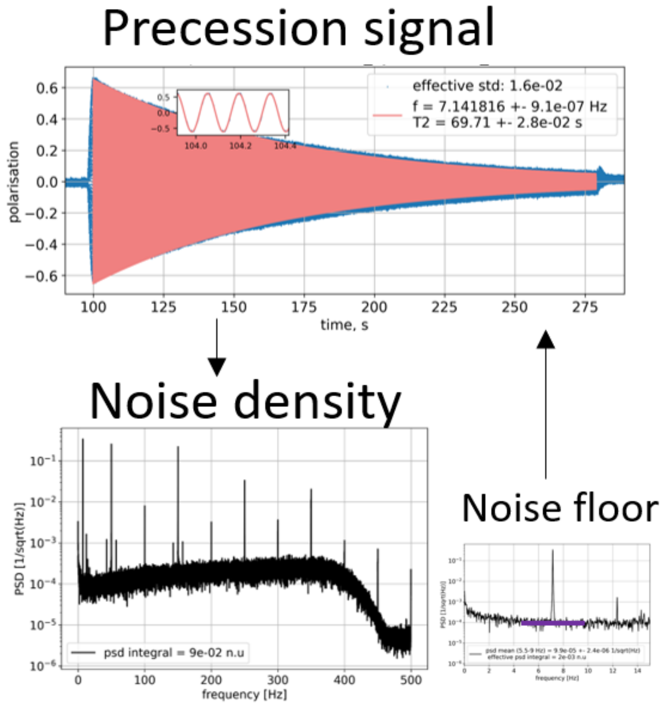
$$p_0 \cos(2\pi f_{\mathrm{Hg}} t + \phi)\, e^{-\frac{t}{T_2}}$$

- Depolarisation time
- Initial polarisation
- Precession frequency

Uncertainty derivation of precession frequency

Philosophy: filtering without filtering

→ Only the noise at the frequency of the signal affects our estimator



Equivalent white noise as input of the χ^2 minimisation fit.

→ diagonal elements of the covariant matrix give the uncertainties.

Verified with simulated data. ✓

Performance of the Hg magnetometer

- Precision:

TOP chamber $\frac{\sigma(f_{\mathrm{Hg}})}{f_{\mathrm{Hg}}} = 7 \times 10^{-8}$ $\frac{\sigma(f_{\mathrm{n}})}{f_{\mathrm{n}}} = 2 \times 10^{-7}$

BOT chamber $\frac{\sigma(f_{\mathrm{Hg}})}{f_{\mathrm{Hg}}} = 4 \times 10^{-8}$ $\frac{\sigma(f_{\mathrm{n}})}{f_{\mathrm{n}}} = 2 \times 10^{-7}$

- Accuracy: unbiaised estimator?
  - effect of non-white noise,
  - magnetic field drifts within one cycle

status
✓
ongoing

Magnetic field measured with a precision of 70 fT !

Also vertical gradient G_{TB} is measured.

→ Study systematic effects affecting $\mathcal{R} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}}$

IV – Physics cases

Expression of $\mathcal{R} = f_n/f_{Hg}$

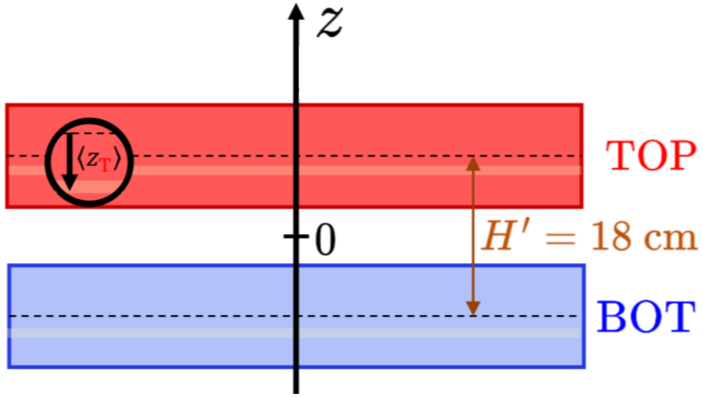
$$\mathcal{R}^{\uparrow,\downarrow}_{T,B} = \frac{\gamma_n}{\gamma_{Hg}}\left[1 + \underbrace{\frac{\langle z_{T,B}\rangle}{B} G_{TB}}_{\sim 10^{-7}} \mp \underbrace{\delta_\oplus}_{\sim 10^{-6}}\right]$$

- At first order, $\mathcal{R} \sim \frac{\gamma_n}{\gamma_{Hg}}$ neutron & Hg gyromagnetic ratios

...but there are some minor corrections that depend on :

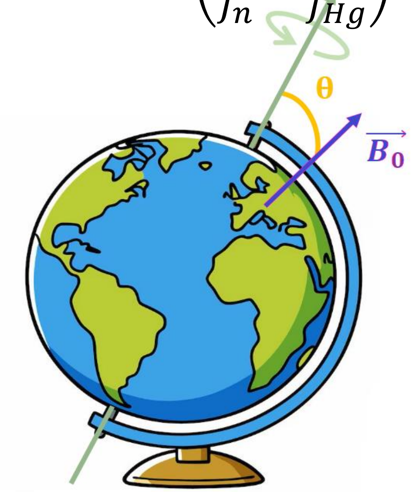
  - G_{TB} : vertical magnetic gradient
  - Chamber TOP, BOT
  - B orientation ↑, ↓

Gravitational shift effect :



Earth rotation effect :

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



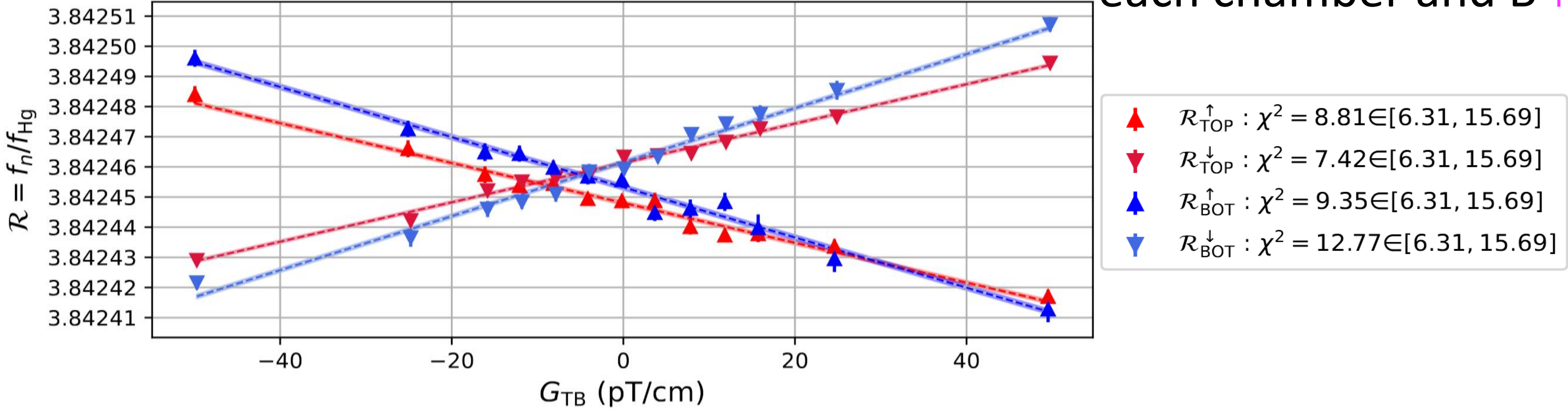
$\mathcal{R}$ –Curves for the probe of physics cases

- $\underline{\mathcal{R} - \text{Curves}}$: $\mathcal{R}_{T,B}^{\uparrow,\downarrow} = \underbrace{\frac{\gamma_n}{\gamma_{Hg}} \frac{\langle z_{T,B} \rangle}{B}} \boldsymbol{G_{TB}} + \underbrace{\frac{\gamma_n}{\gamma_{Hg}} (1 \mp \delta_\oplus)}$

$$= \quad a_{T,B} \quad \boldsymbol{G_{TB}} + \quad b^{\uparrow,\downarrow}$$

→ 4 affine functions $\mathcal{R}_{TOP}^{\uparrow}, \mathcal{R}_{TOP}^{\downarrow}, \mathcal{R}_{BOT}^{\uparrow}, \mathcal{R}_{BOT}^{\downarrow}$ VS G_{TB}

- Measure $\mathcal{R}_{T,B}^{\uparrow,\downarrow}$ for different values of G_{TB} (coils) for each chamber and B ↑,↓



γ_n / γ_{Hg}	$\langle z_{TOP} \rangle$ (cm)	$\langle z_{BOT} \rangle$ (cm)	$T_\oplus$ (h)
3.8424557(3)	−0.161(4)	−0.214(6)	24(1)

Compatible with [1]

Compatible with [2]

[1] : *A measurement of the neutron to 199Hg magnetic moment ratio, nEDM collaboration, 2014*

[2] : *Ultracold neutron energy spectrum and storage properties from magnetically induced spin depolarization*, n2EDM collaboration, 2025

Conclusion

- First data-set not limited by Hg uncertainty
- Gravitational shift and Earth rotation measurements
- Newer of more precise data —> access to new systematic effects
- nEDM data taking at the end of 2025

Thank you for your attention!

Questions?

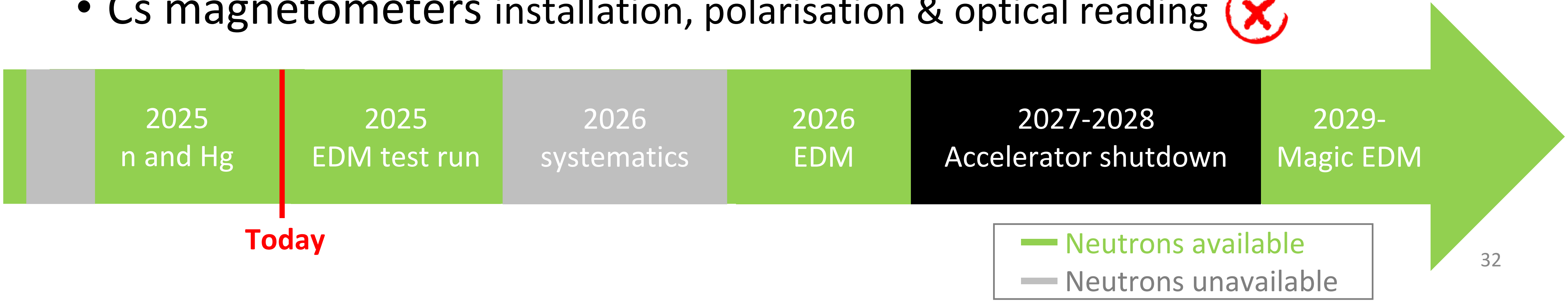
Additional slides

n2EDM status and outlook

- UCN production, detection, polarization, spin transport ✓
- Magnetic shielding and characterization ✓
- Magnetic field generation and characterization ✓
- Electric field ✗
- Hg co-magnetometer injection, polarization, optical reading ✓
- Cs magnetometers installation, polarisation & optical reading ✗

✓ Operational

✗ Not yet operational



2025
n and Hg

2025
EDM test run

2026
systematics

2026
EDM

2027-2028
Accelerator shutdown

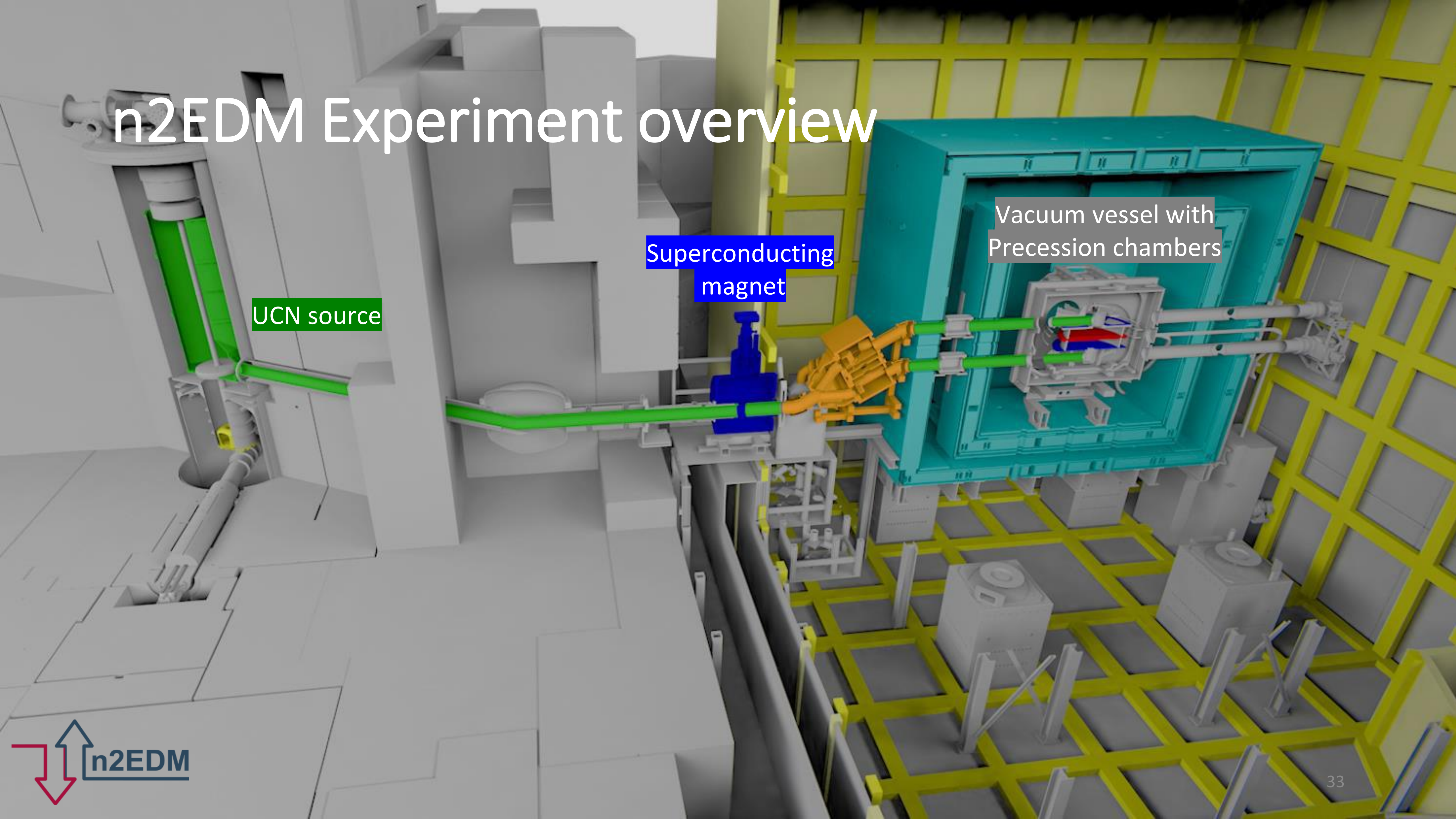
2029-
Magic EDM

Today

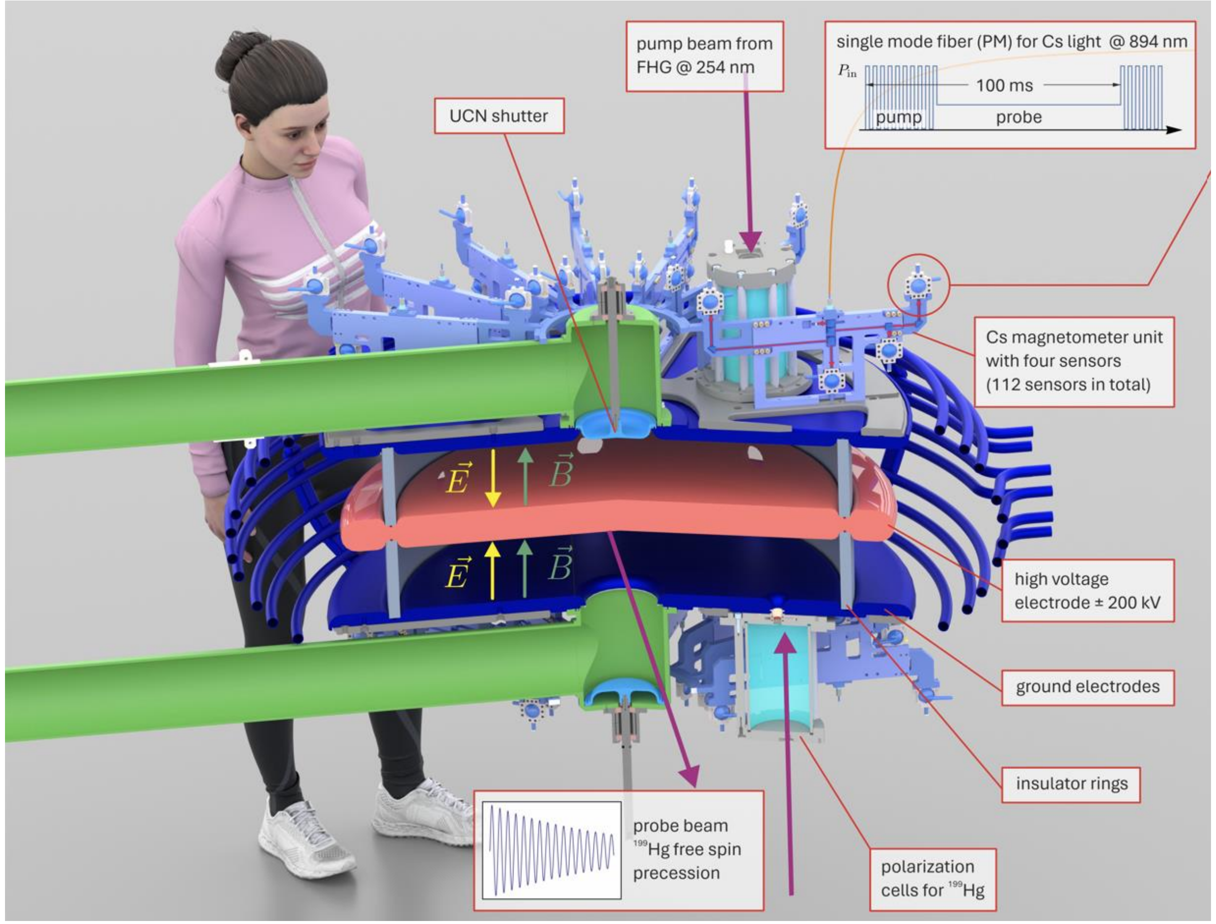
🟩 Neutrons available

⬜ Neutrons unavailable

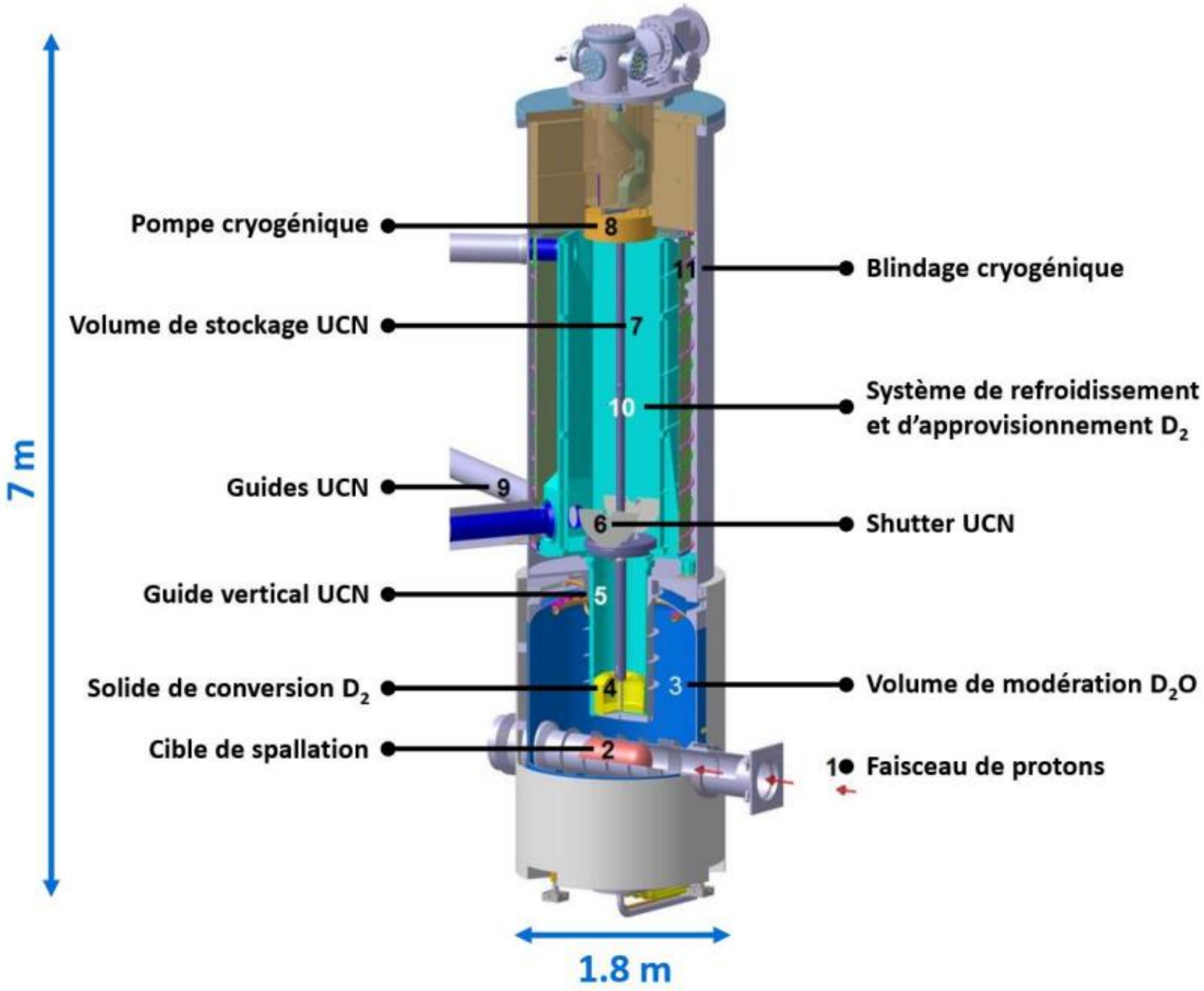
n2EDM Experiment overview



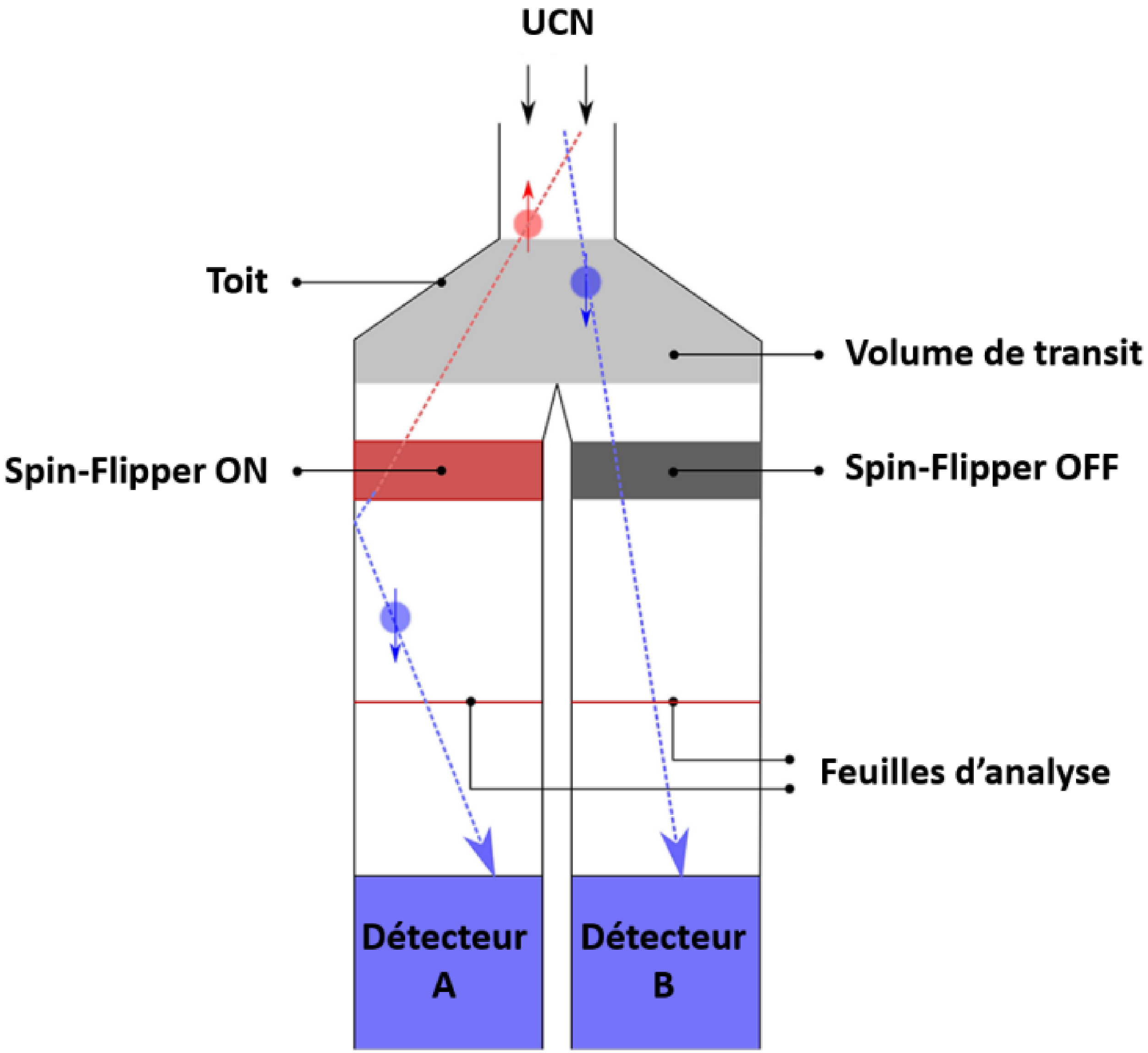
n2EDM Experiment overview



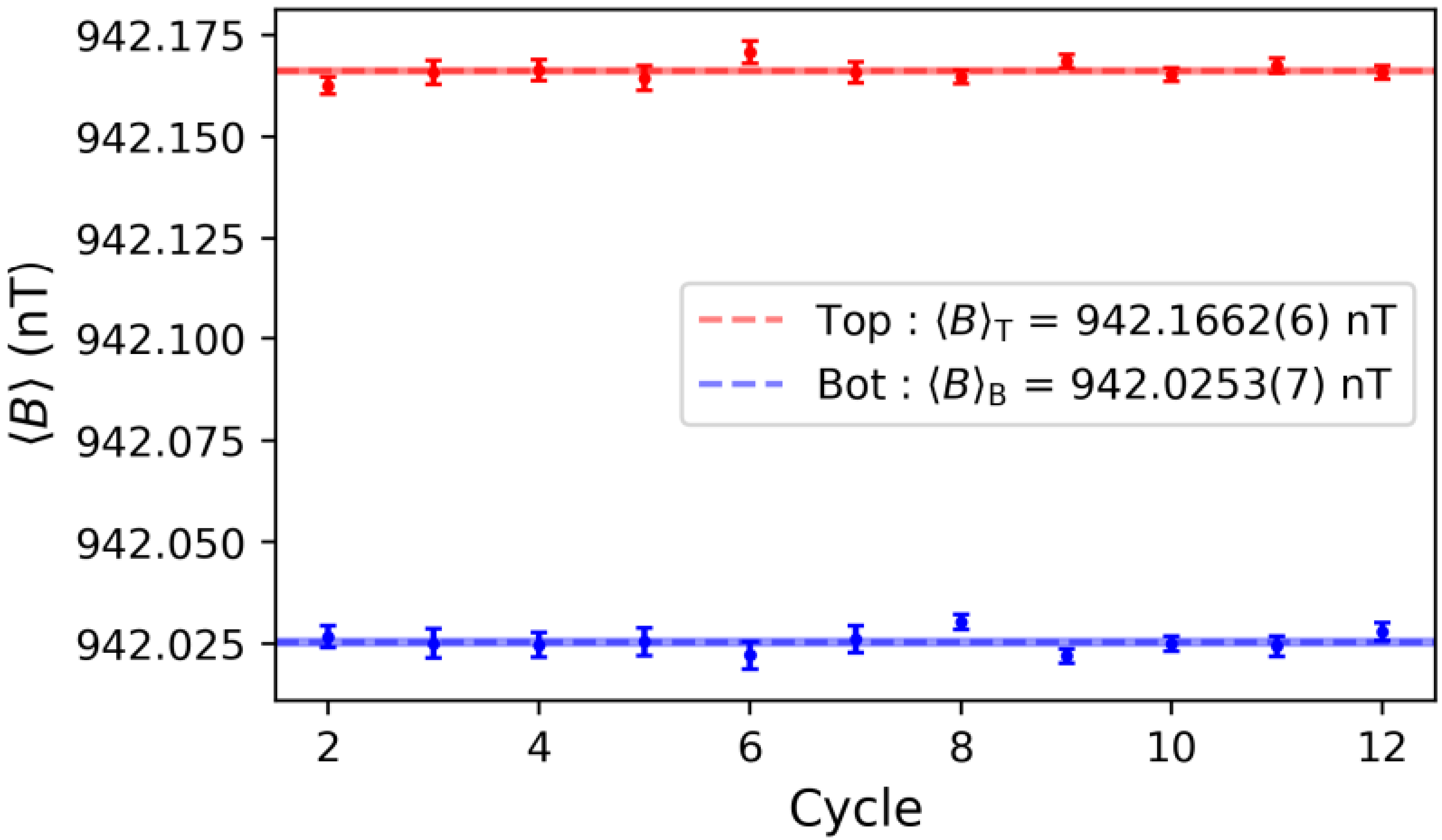
UCN production



UCN spin detectors



Magnetic field measurement in the presence of gradient



Spin asymmetry fit

$$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \alpha\cos[\frac{(f_{RF} - \boldsymbol{f}_n)}{\Delta\nu}]$$

$$f_n \sim \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} f_{\mathrm{Hg}}$$