Neutron EDM
Mercury co-magnetometry

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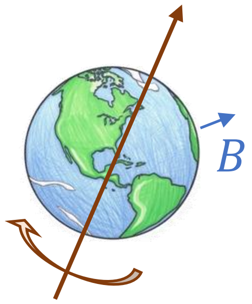
Les Houches, 2-7 March 2026

Outline

I – Context: why a mercury co-magnetometer?

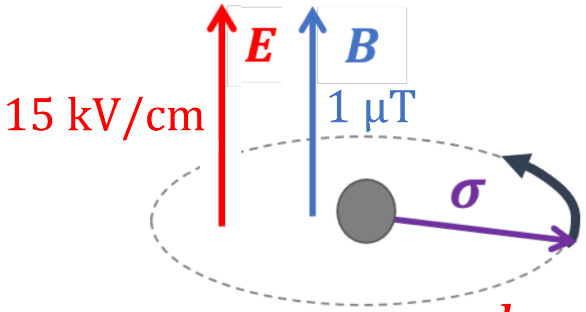
II- Measuring the mercury precession frequency

III – Results: The earth rotates!



I - Context

Measuring the neutron EDM



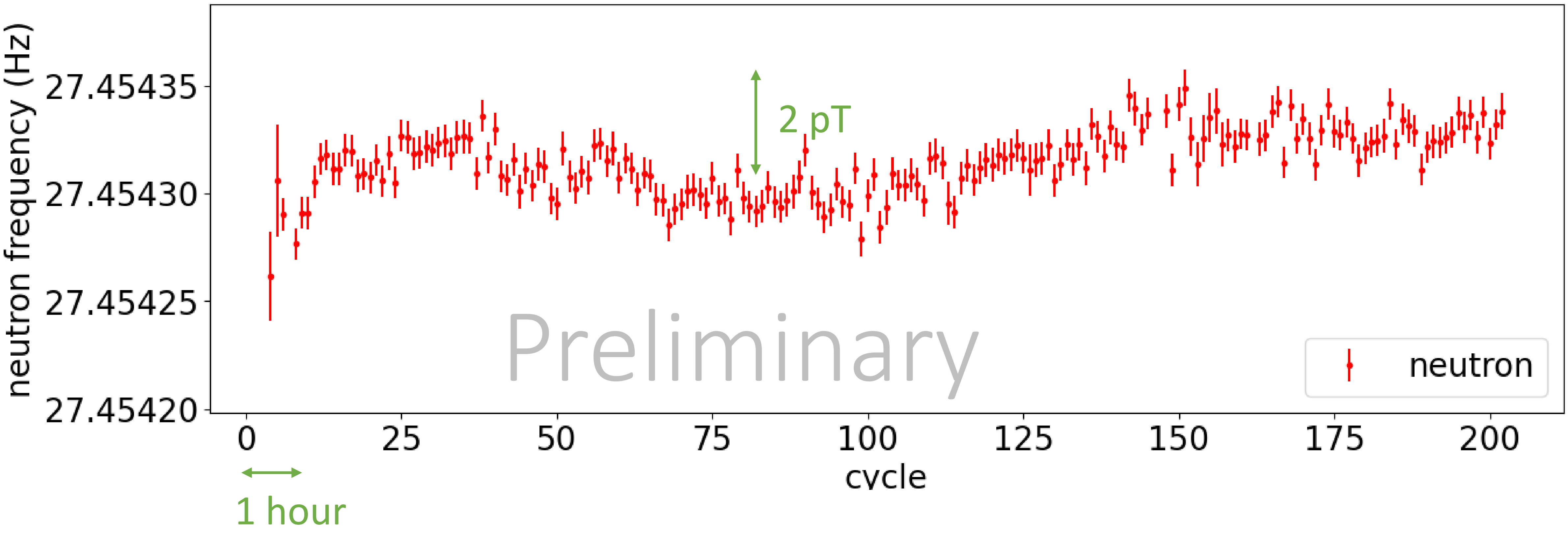
$$f_n = \frac{\mu_n}{\pi\hbar} B + \frac{d_n}{\pi\hbar} E$$

f_n measured many times, with $+E$ or $-E$.

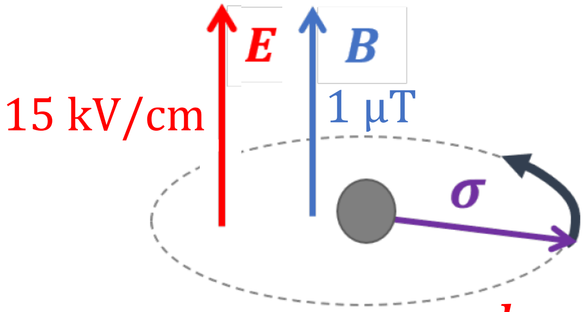
$$\sigma(f_n) = \frac{1}{2\pi\alpha T\sqrt{N}}, \qquad T = 3 \text{ minutes}$$

Neutron frequency is affected by magnetic field drifts!

Run 7982, 09-10 Dec 2025, TOP chamber



Measuring the neutron EDM



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

$$f_{\mathrm{Hg}} = \frac{\mu_{\mathrm{Hg}}}{\pi\hbar} B + 0$$

$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = R_0\left(1 + \delta + \frac{d_{\mathrm{n}}}{R_0 \pi\hbar} \frac{E}{f_{\mathrm{Hg}}}\right)$$

magnetic field **gradients** affect R because the **centers of mass** of **n** and **Hg** differ by 2 mm.

f_n measured many times, with $+E$ or $-E$.

$$\sigma(f_n) = \frac{1}{2\pi\alpha T\sqrt{N}}, \qquad T = 3 \text{ minutes}$$

In n2EDM, electric/magnetic term $\approx 10^{-9}$
→ any magnetic drift is prohibitive!

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

Monitoring of B:

- negligible EDM,
- nuclear spin,
- optical transition

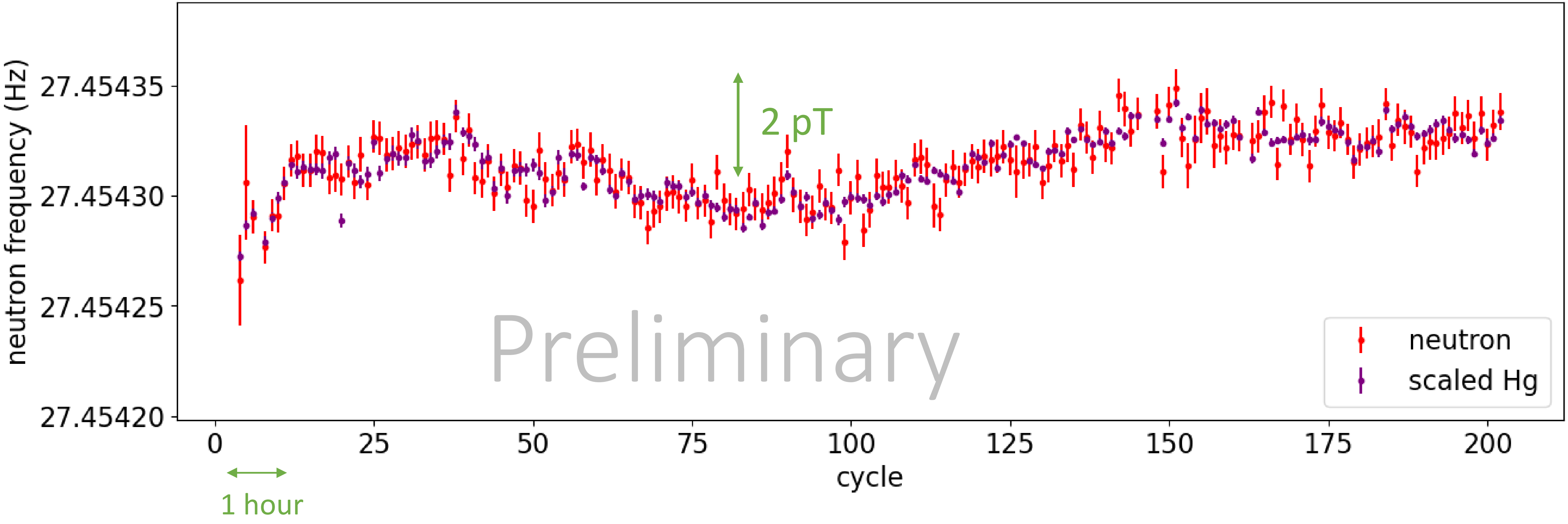
HG CO-MAGNETOMETRY

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

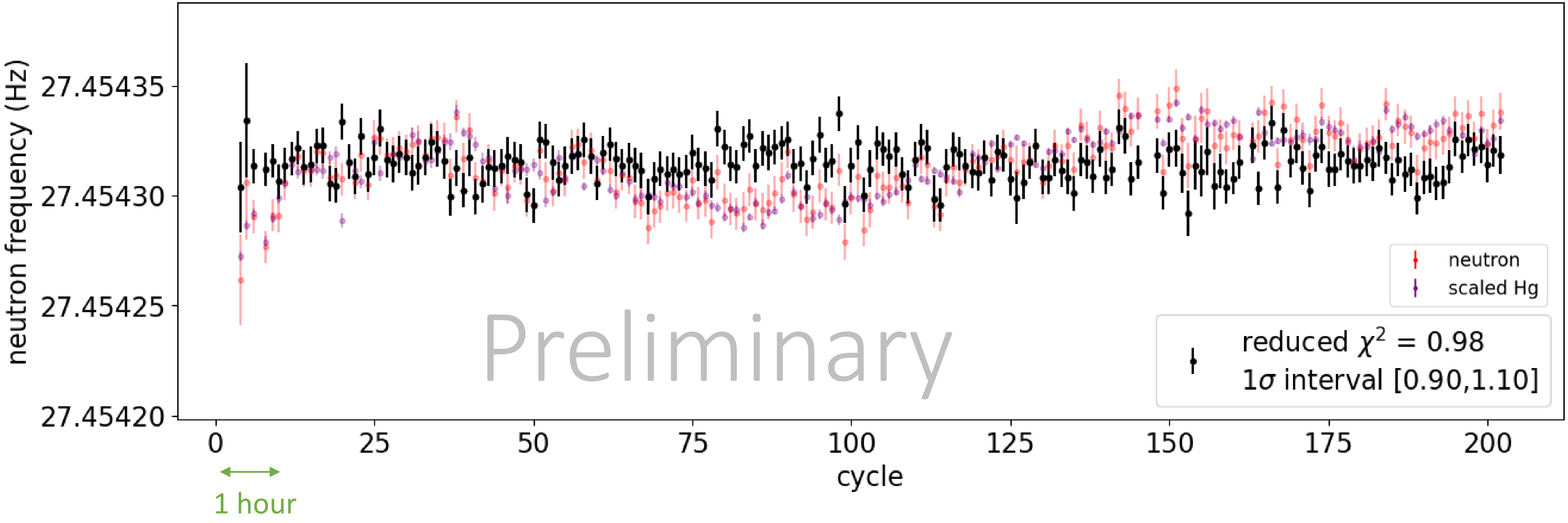
Magnetic field drifts

Run 7982, 09-10 Dec 2025, TOP chamber



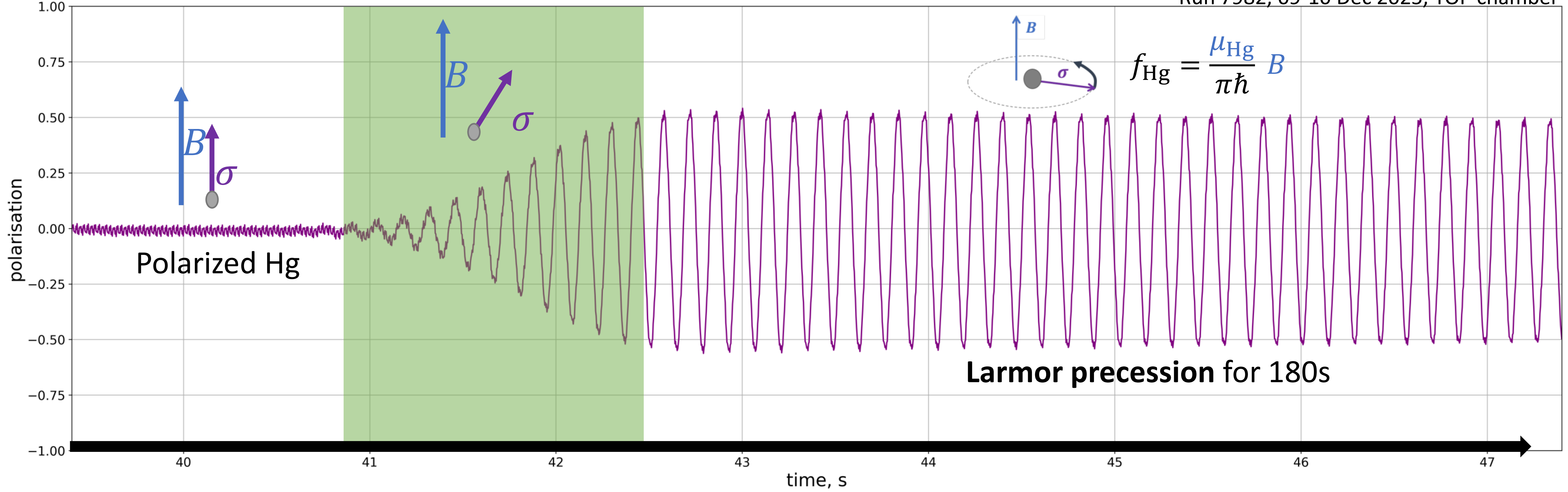
Mercury co-magnetometry: statistical fluctuation of the R ratio

Run 7982, 09-10 Dec 2025, TOP chamber



How do we measure B with Hg vapour? a continuous optical readout

Run 7982, 09-10 Dec 2025, TOP chamber



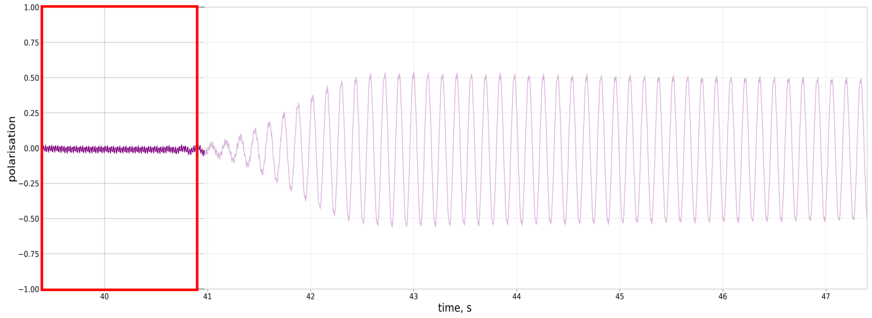
① Optical pumping ② Spin flip ③ Optical readout

1. Optical pumping

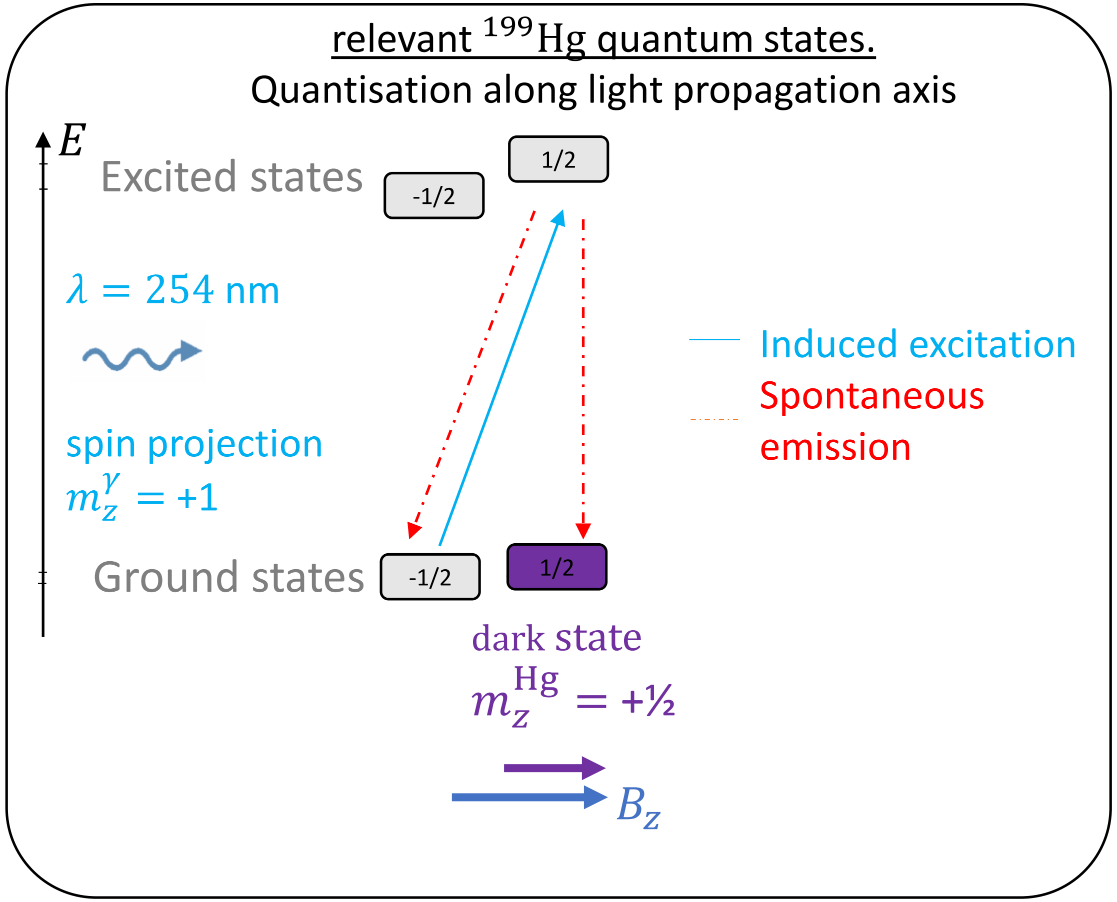
- Isotopically enriched $^{199}\mathrm{Hg}$
- Circularly polarised light
  - Right handed (RH): spin projection +1
  - *Select* some transitions of the hyperfine structure

“Trap” all atoms in the **dark state.**

Polarisation = population asymmetry of the two ground states.



Optical pumping



3. Free precession

- Vapour polarisation **perpendicular** to B_z
  - **Larmor precession**
- Circularly polarised light RH
  - *Selects* one transition

Max cross section when $p_x = -1$

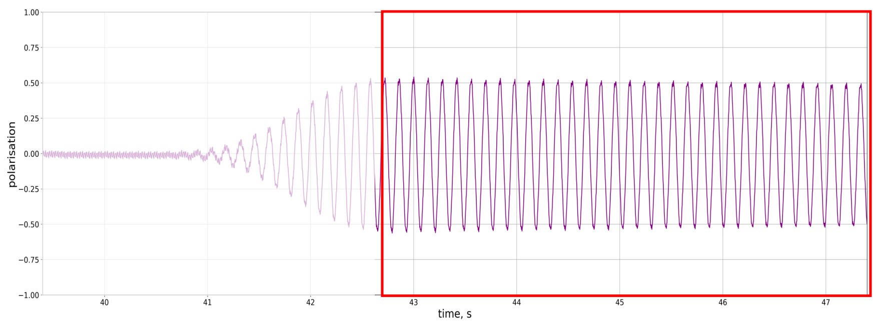
Zero cross section when $p_x = +1$

Intermediate cross section when $p_x = 0$

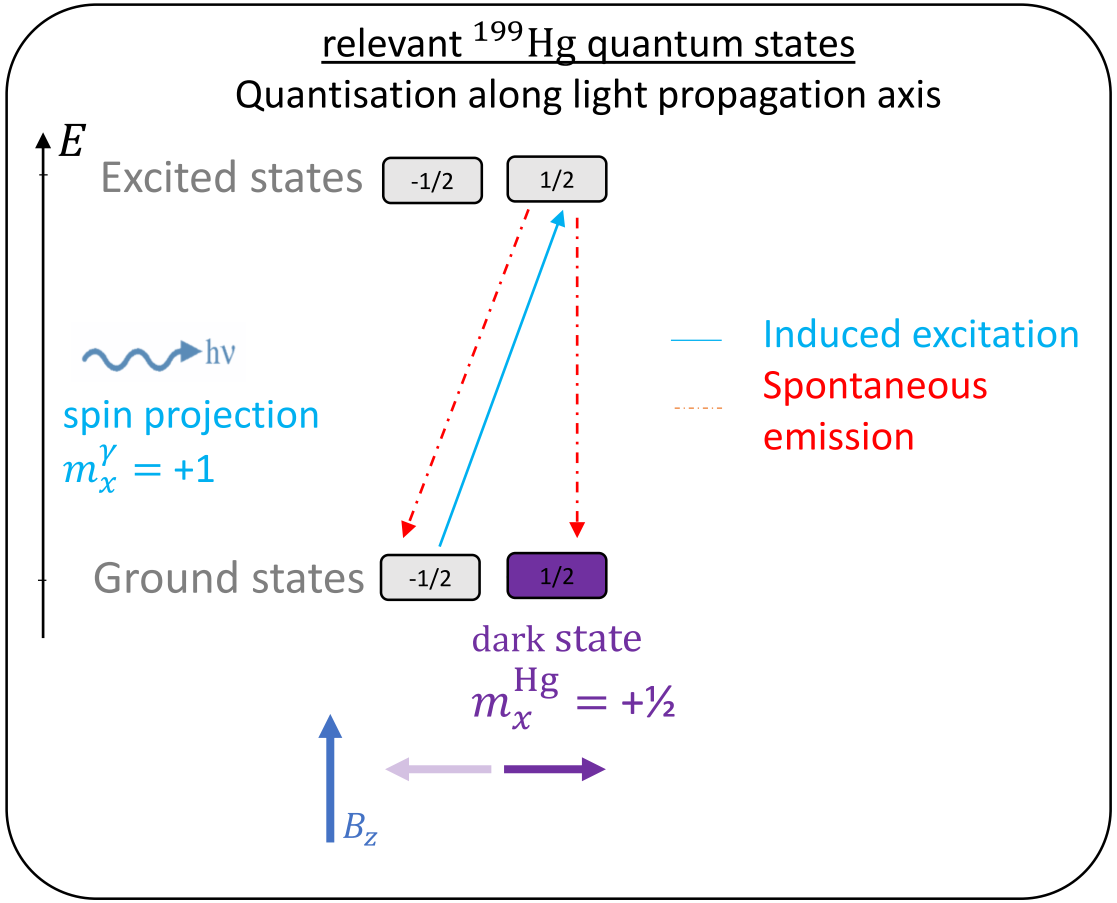
$$\boldsymbol{\sigma_{RH} = \sigma_u(1 - p_x)}$$

Modulation of transmitted power

-> Optical readout

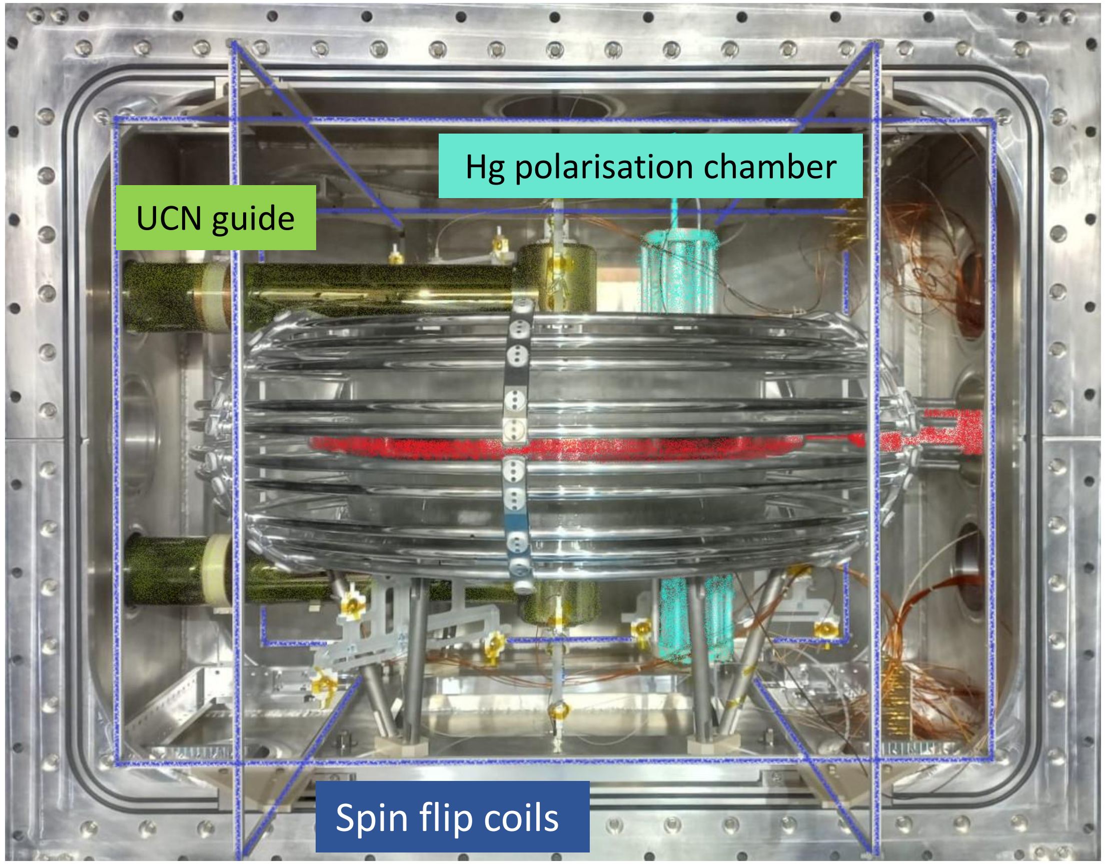


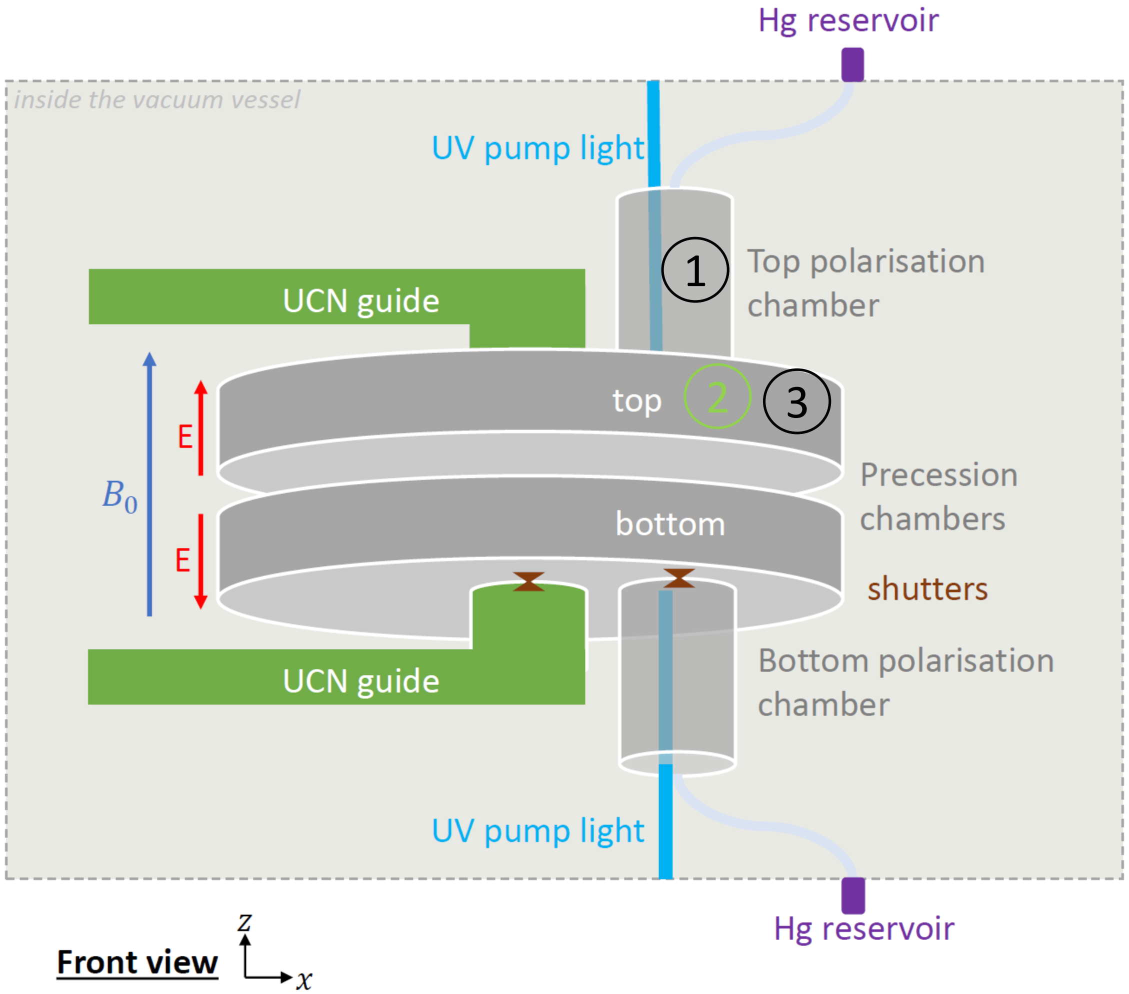
Optical readout



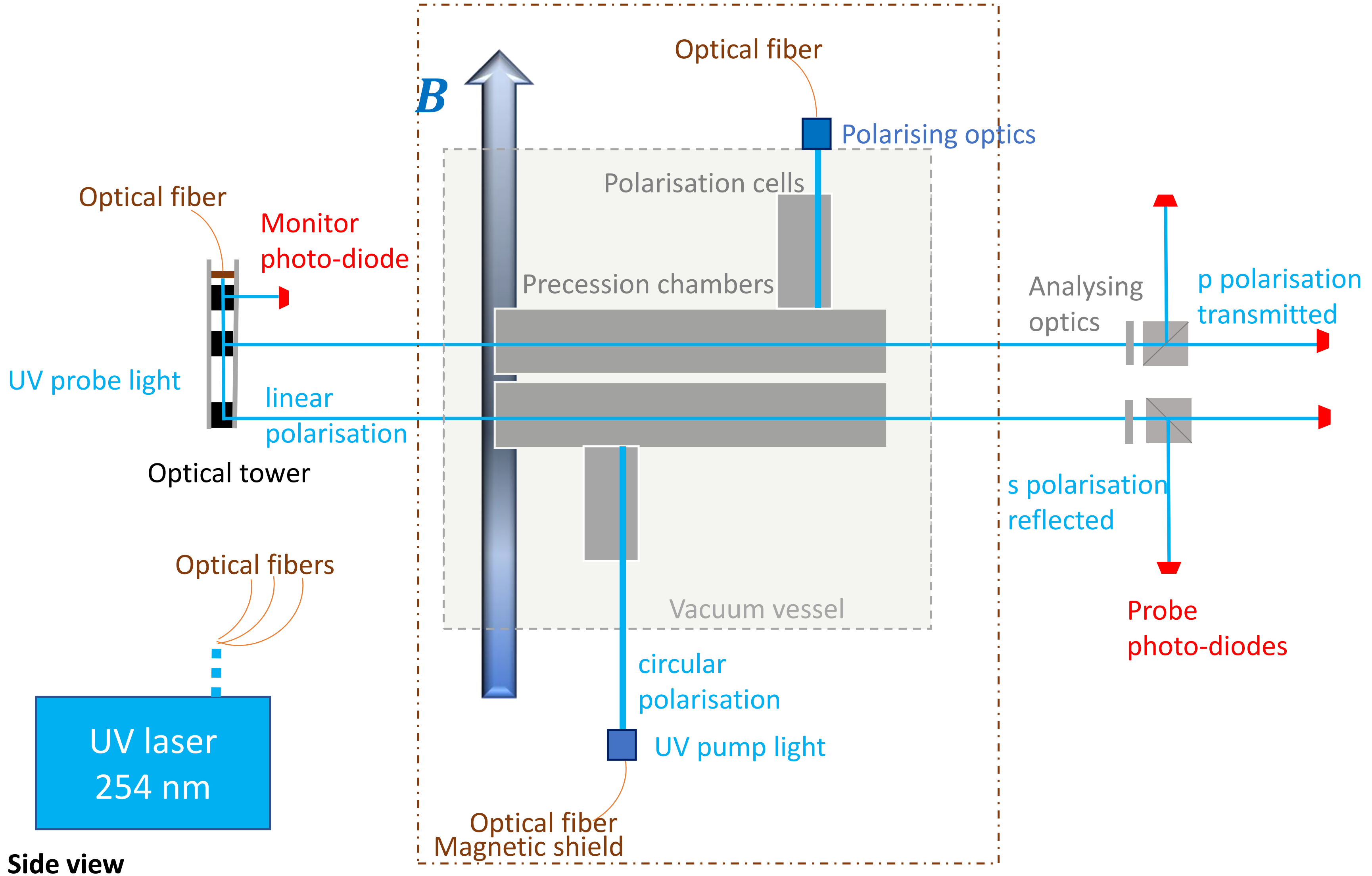
II- Measuring the mercury precession frequency

n2EDM experiment: overview





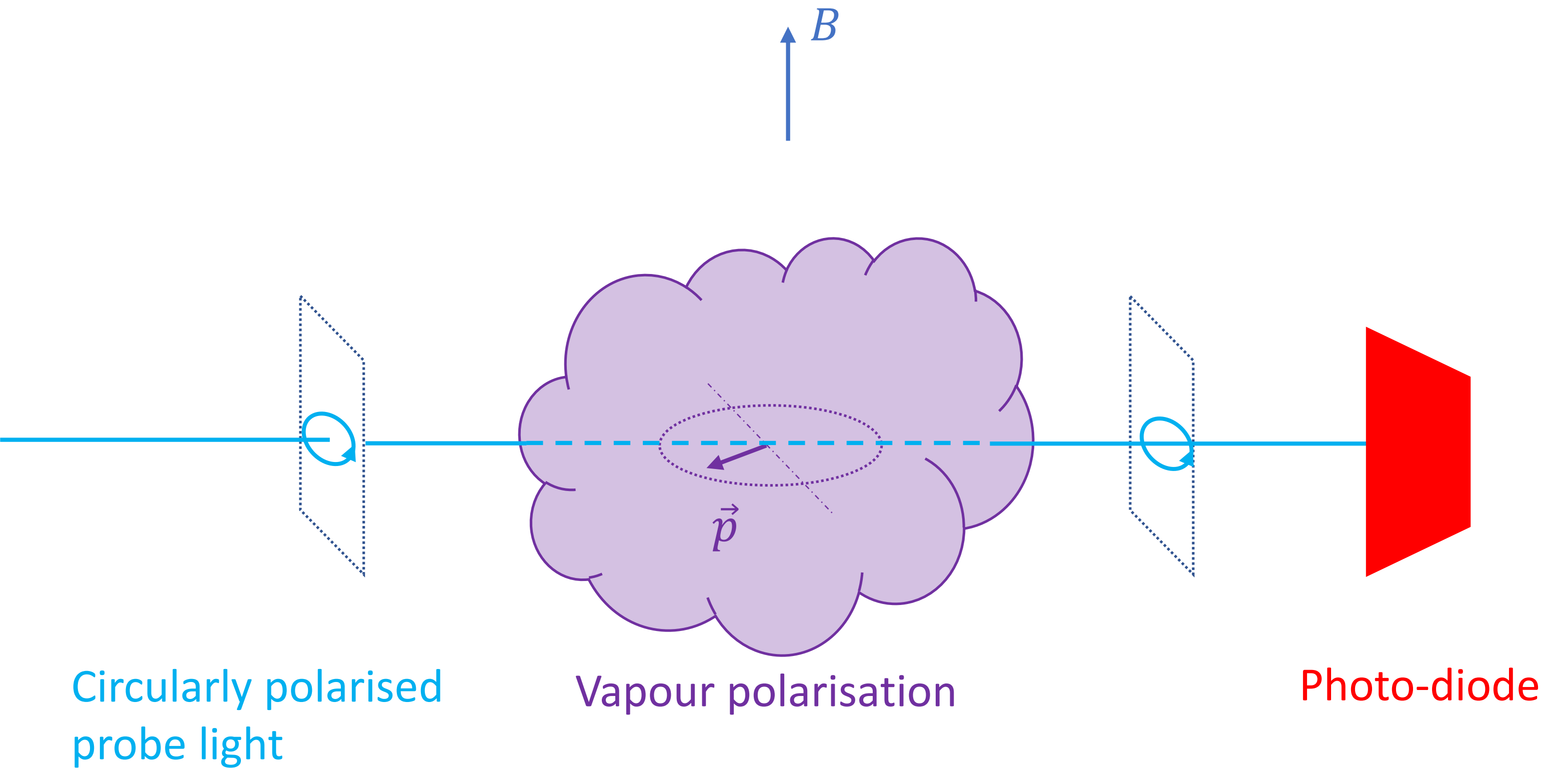
Hg-comagnetometer: overview



Side view

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

Circularly polarised probe light



Circularly polarised probe light: Modulation of the polarisation leads to **modulation** of the transmitted **power**.

Cross section

$$\sigma_{RH} = \sigma_u(1 - p_x)$$

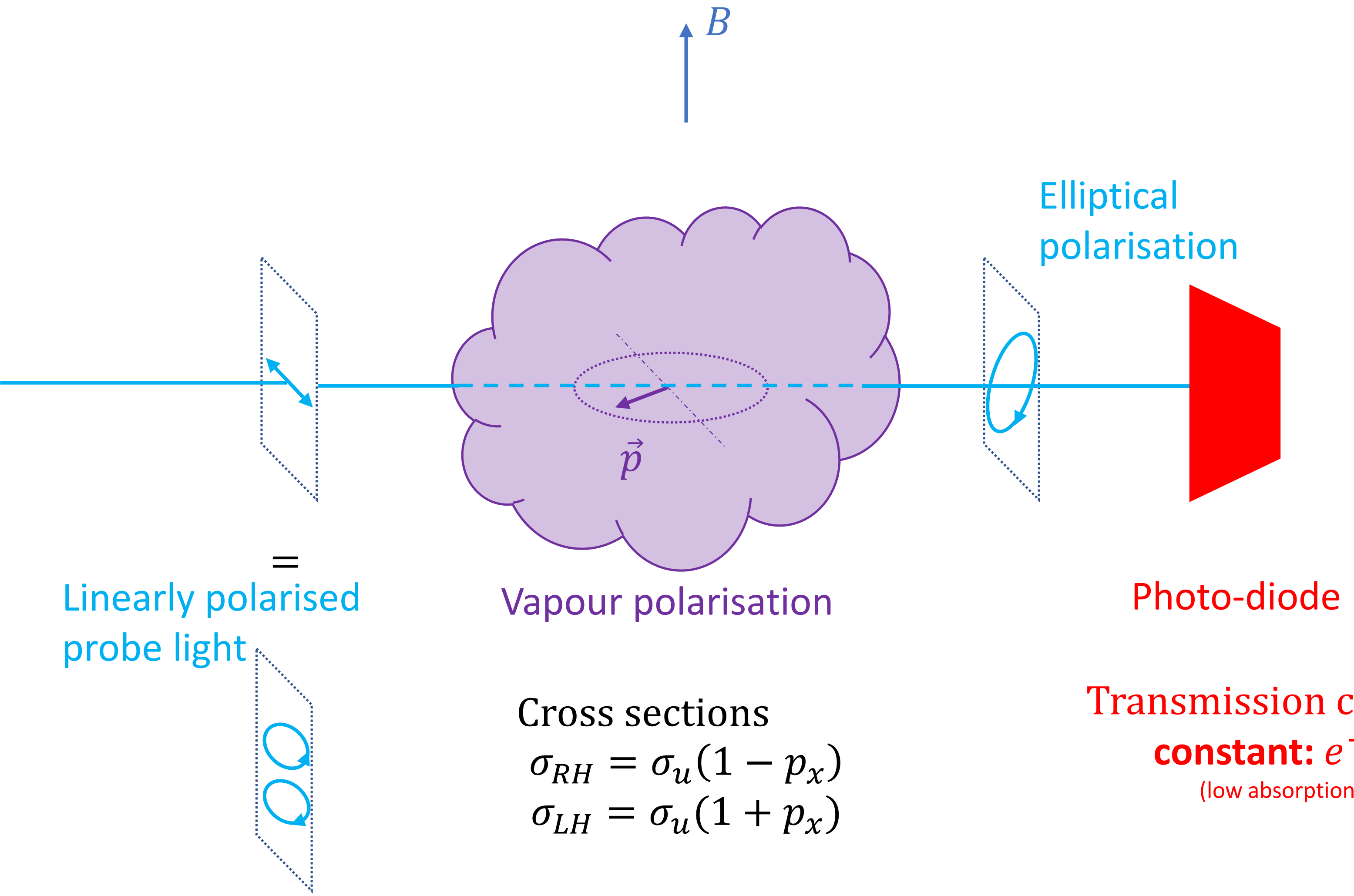
σ_u unpolarised cross section
p_x vapour polarisation

Transmission coefficient

$$e^{-\sigma_u(1-p_x)\, n\, L}$$

n vapour density
L length of the cell

Linearly polarised probe light



Linearly polarised probe light: Modulation of the polarisation leads to **modulation** of the transmitted **polarisation**.

Cross sections

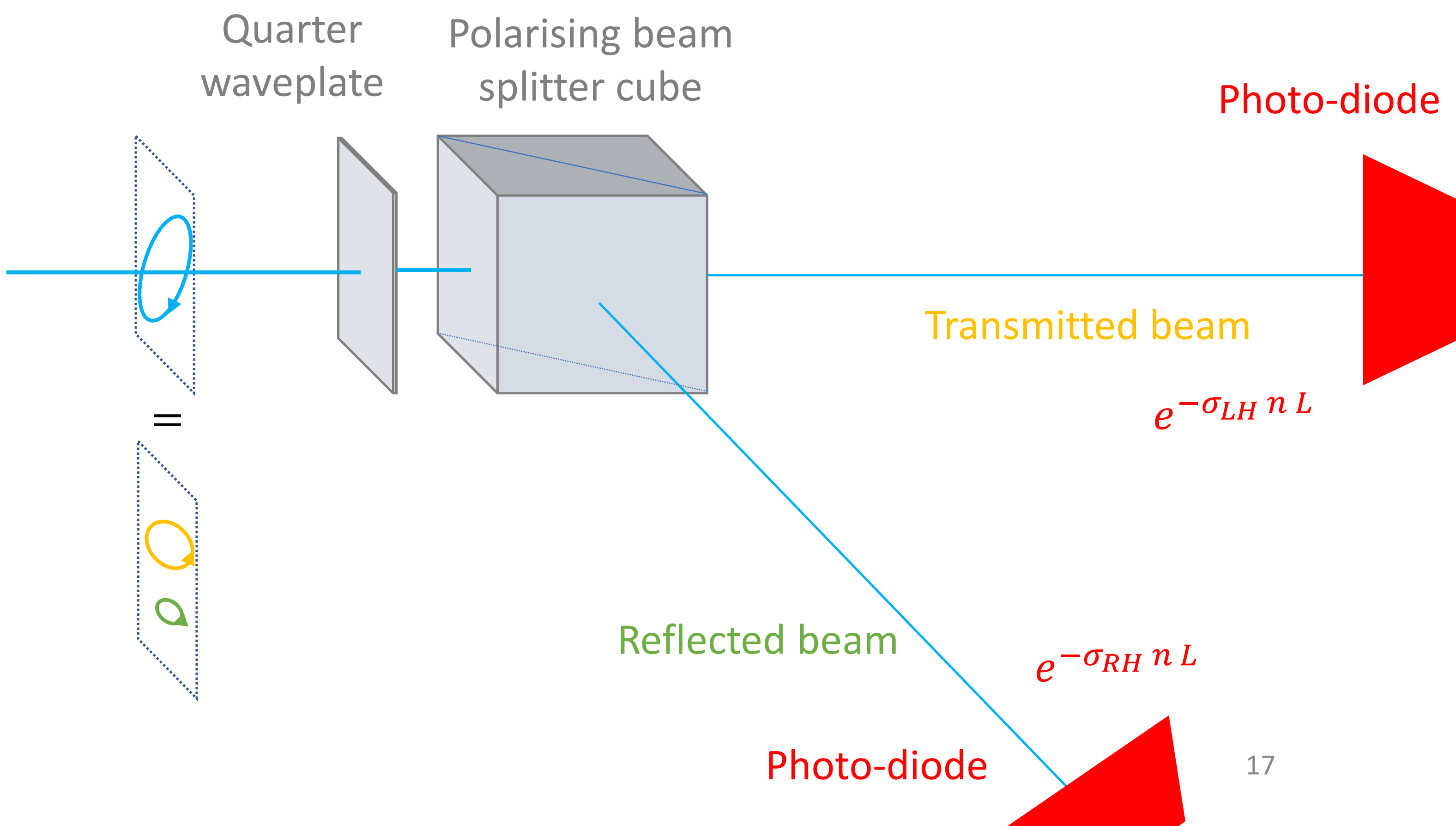
$$\sigma_{RH} = \sigma_u(1 - p_x)$$
$$\sigma_{LH} = \sigma_u(1 + p_x)$$

Transmission coefficient **constant:** $e^{-\sigma_u \, n \, L}$

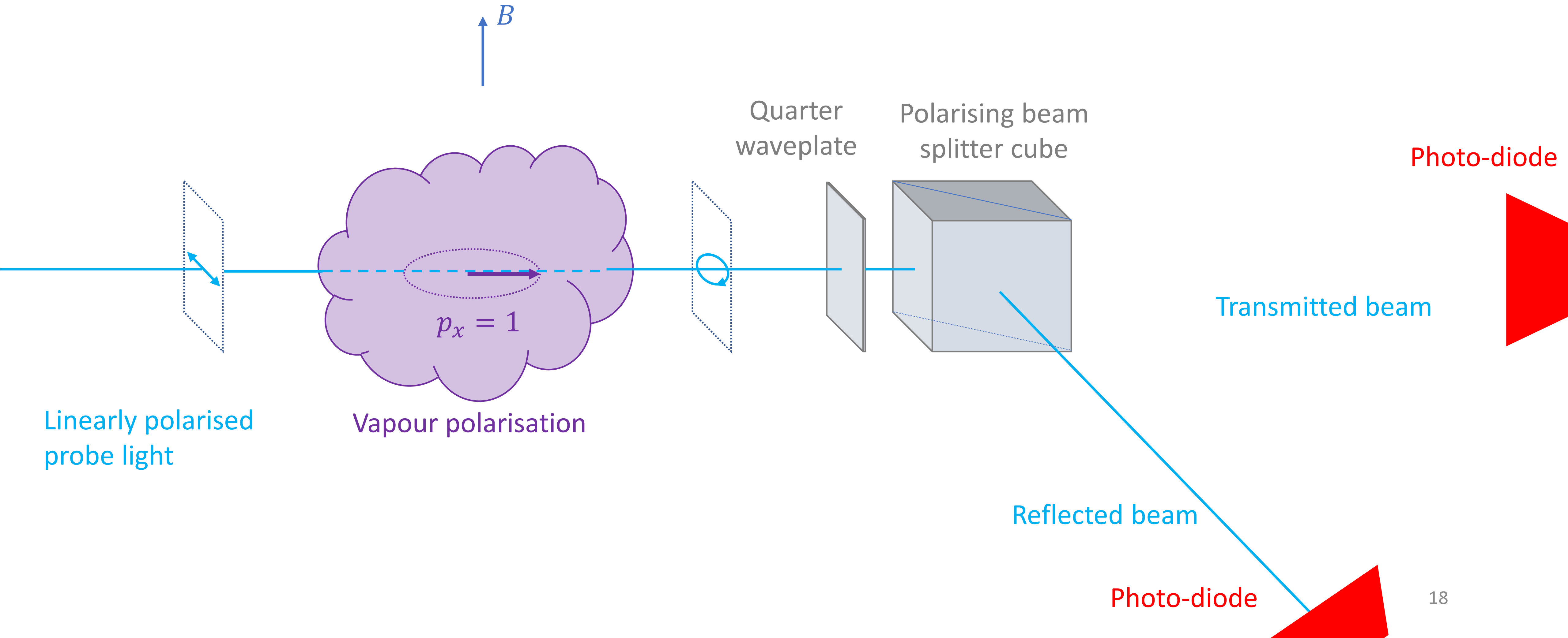
(low absorption limit)

Analysing optics

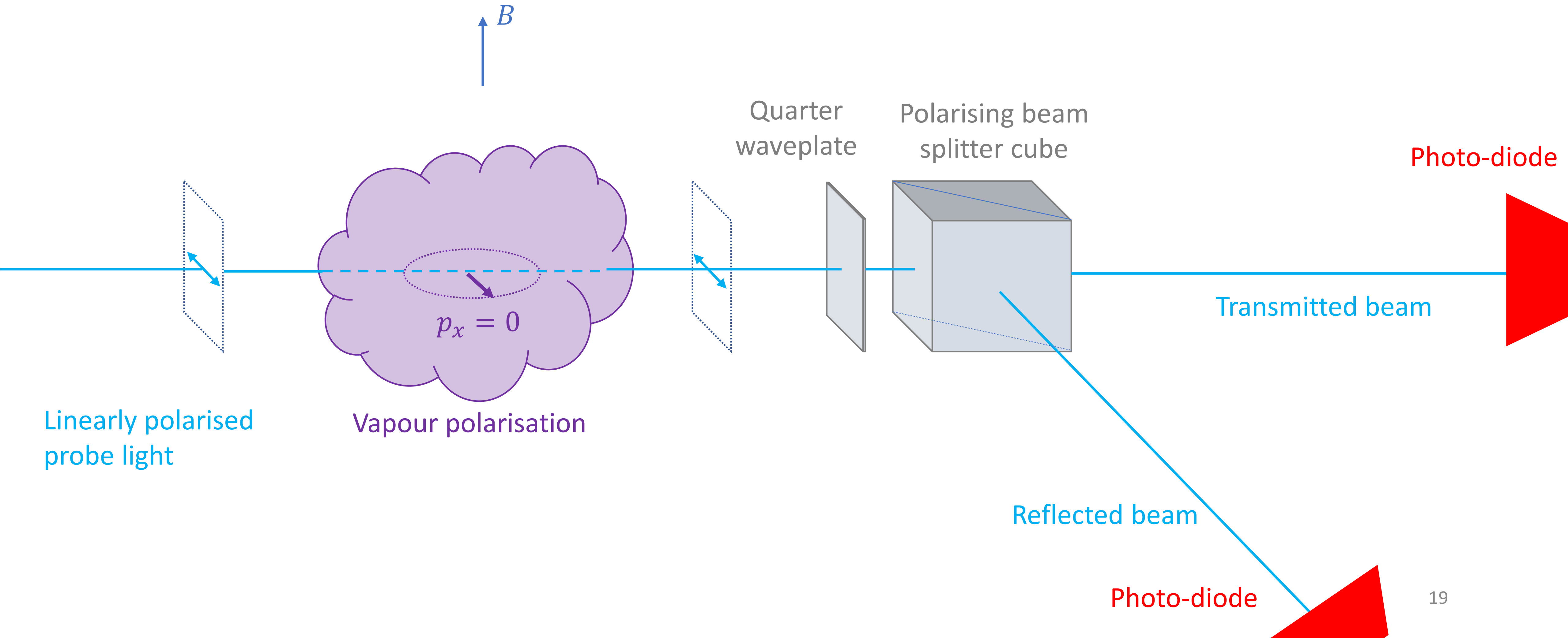
Analysing optics translate the **polarisation modulation** into **two power modulations** (out of phase).



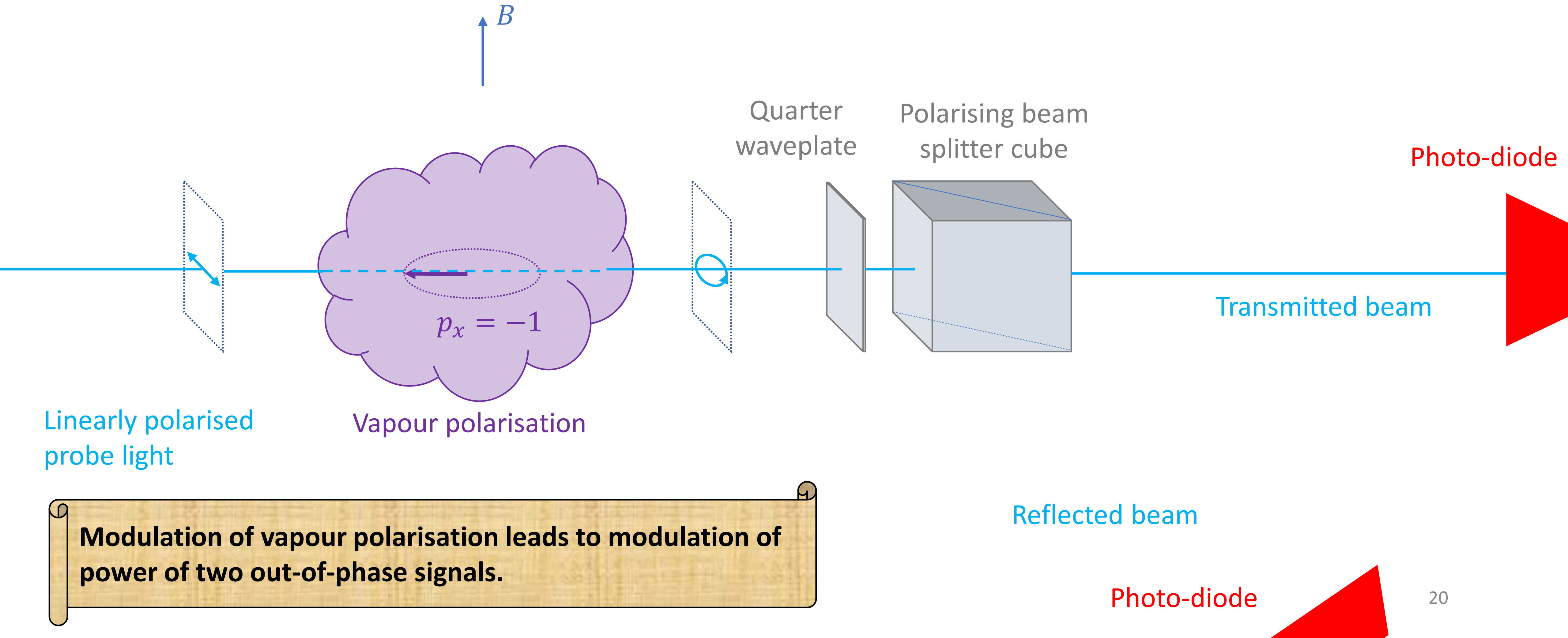
Linearly polarised probe light



Linearly polarised probe light



Linearly polarised probe light

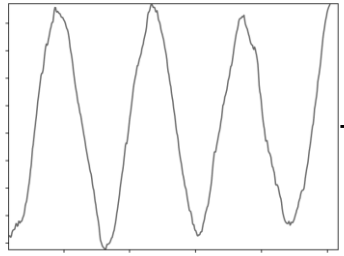


Modulation of vapour polarisation leads to modulation of power of two out-of-phase signals.

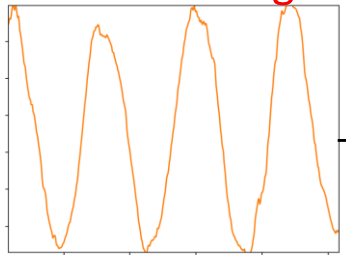
The great combination

$P_r = P_0 e^{-\sigma_u n L (1-p)}$

Reflected signal



Transmitted signal



$P_t = P_0 e^{-\sigma_u n L (1+p)}$

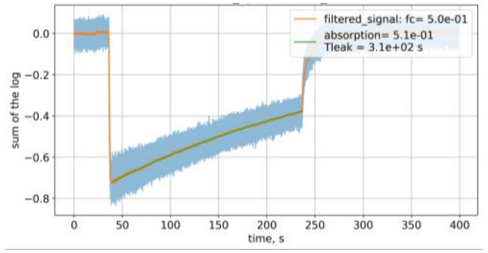
log

log

+

–

Unpolarised absorption

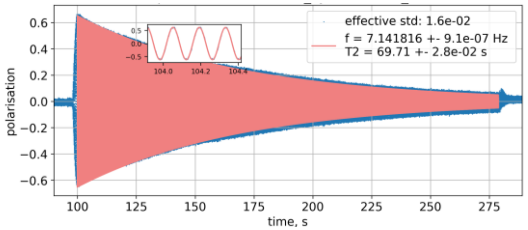


$\sigma n L$

- Absorption
- Leakage time

/

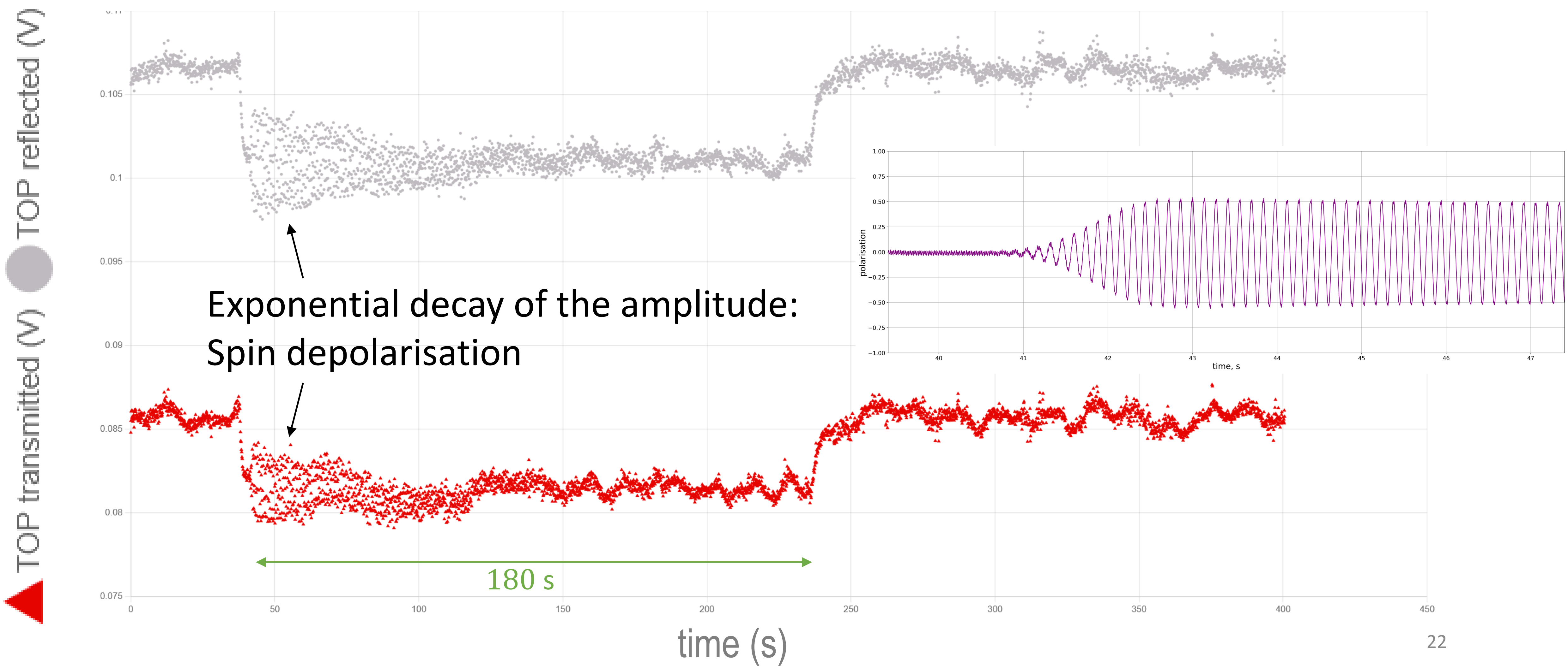
Precession signal



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

- Depolarisation time
- Initial polarisation
- Precession frequency

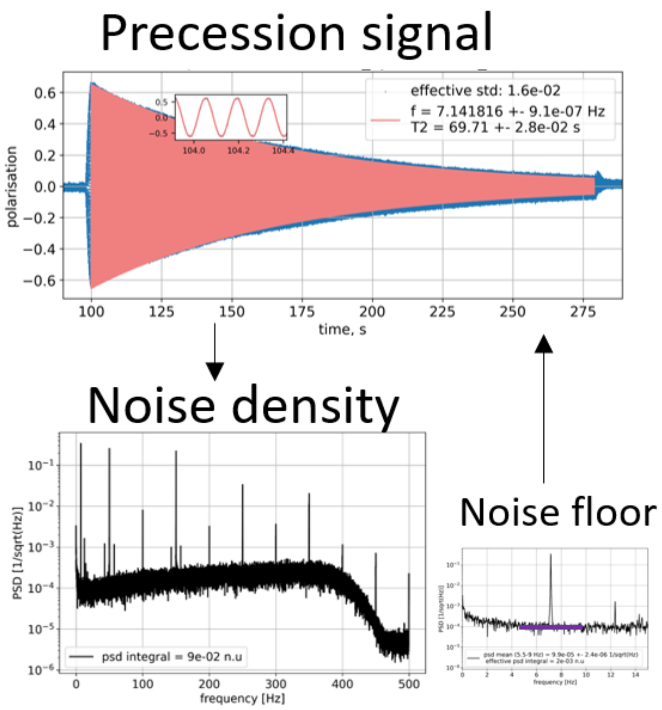
Raw data: TOP chamber. Great combination



A word on the uncertainty derivation

Philosophy: filtering without filtering (no biais!)

→ Only the noise at the frequency of the signal affects our estimator f_{Hg}



Equivalent white noise as input of the χ^2 minimisation fit.
→ diagonal elements of the covariant matrix give the uncertainties.

Verified with simulated data. ✓
$f_{\mathrm{Hg}}^{TOP} - f_{\mathrm{Hg}}^{BOT}$ fluctuations are statistical. ✓

A word on the accuracy: biaises

- Any feature not included in the model could lead to a **frequency biais**.

Know features in n2EDM:

- **Magnetic field drifts**. Frequency drifts within one cycle. Understood, can be corrected for.
- **Light shift:**
  - Probe polarisation ensures minimal light shift.
  - Has been measured.
- …

We *believe* that the frequency estimator is unbiaised.

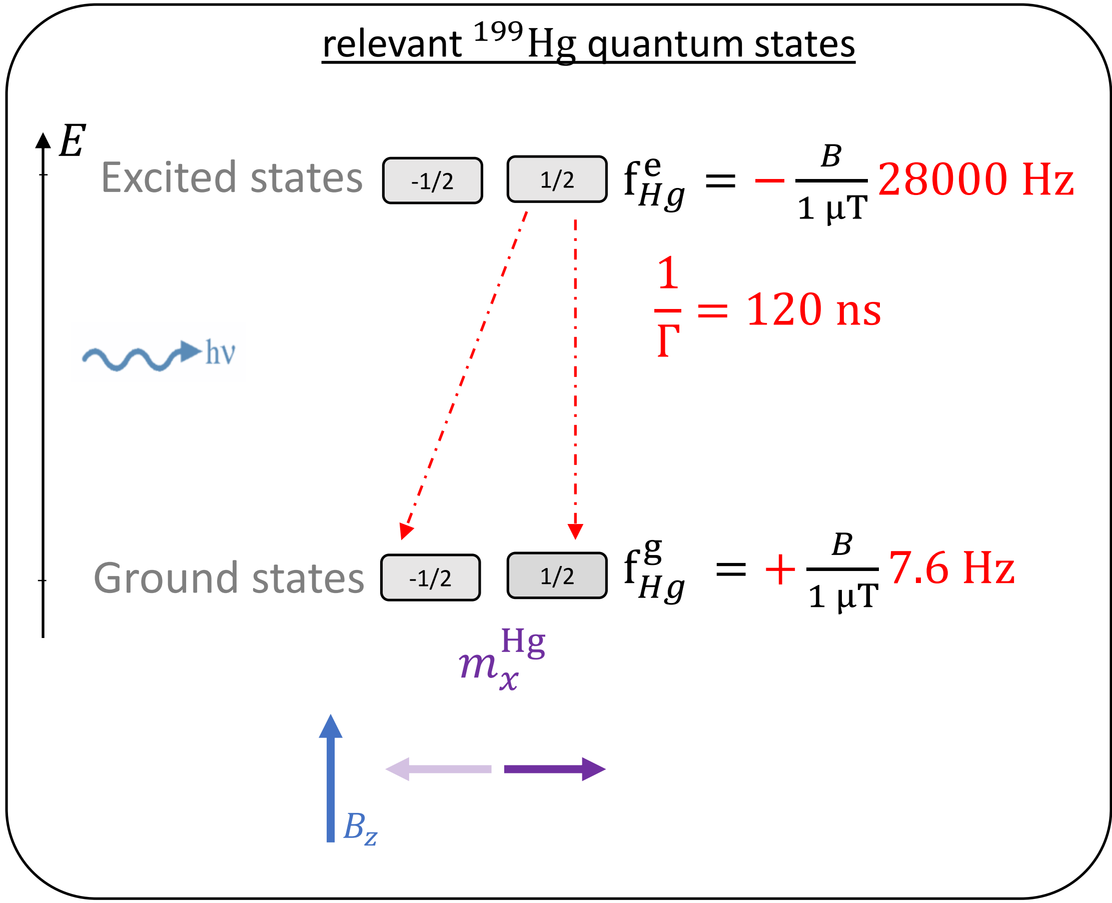
Light shift in n2EDM

- Two sources of light shift: real and virtual.
- We consider the virtual light shift to be negligible. (frequency locking, $B \perp k$)
- The real light shift depends on light

polarisation: $\delta f = \frac{\Gamma'}{12\pi} \frac{\Gamma\Omega}{\Gamma^2+\Omega^2} \left\|\overrightarrow{e_{||}}\right\|^2$

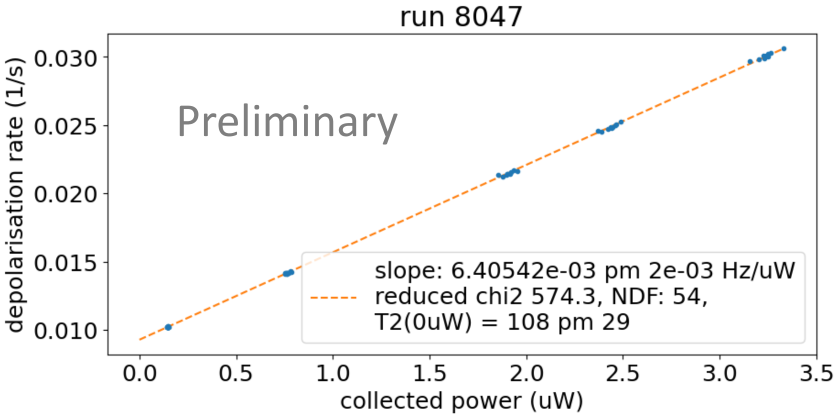
In n2EDM, for $A = 0.1$,

$$\delta f^{max} = -\frac{P}{1\ \mu\text{W}} \times 360\ \text{nHz}$$



Light shift measurements

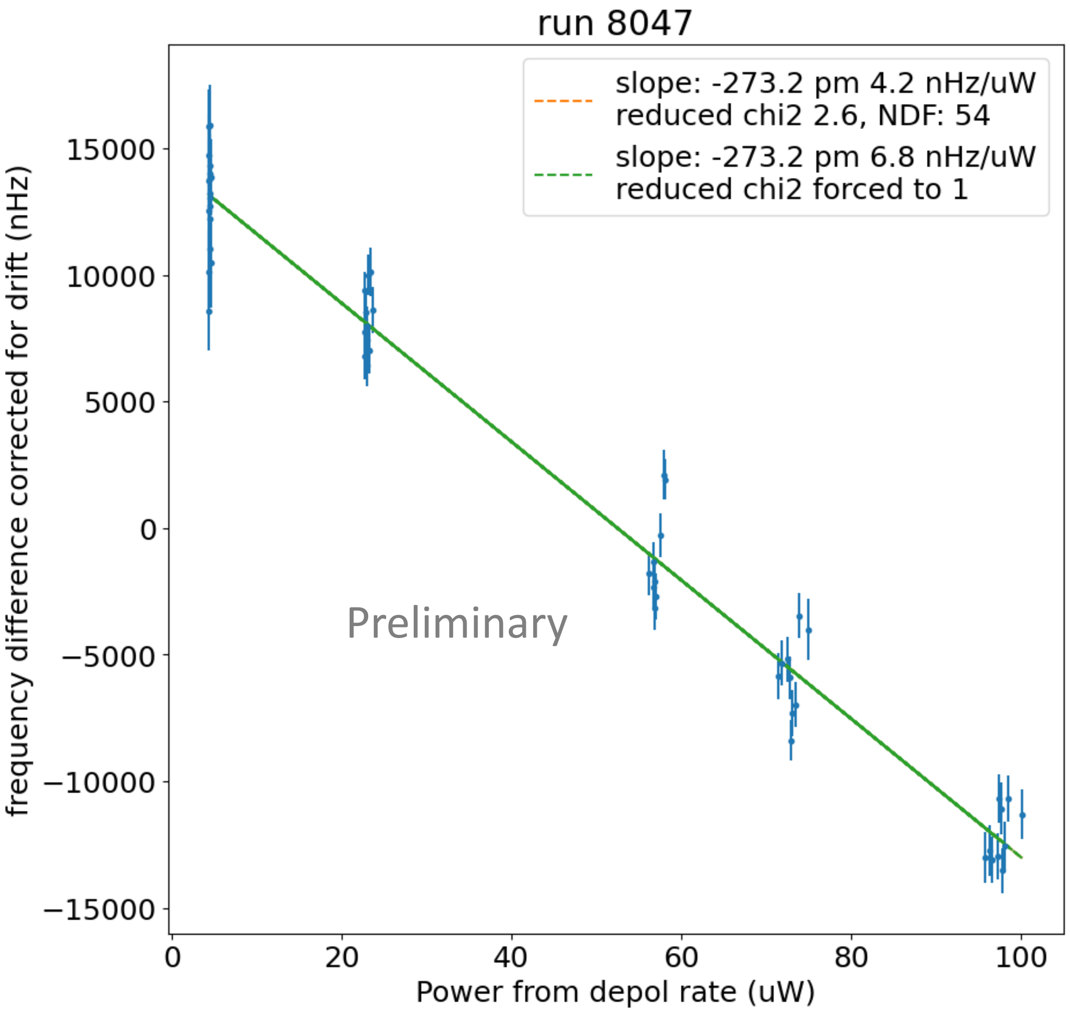
- Determine the power: use depolarisation vs light power!



- Determine the light shift.

Preliminary	δf^{max} for 1 μW	δf^{min} for 1 μW
TOP chamber	$-(273 \pm 7)$nHz	$+(19 \pm 4)$ nHz
BOT chamber	$-(250 \pm 7)$nHz	$-(5 \pm 5)$ nHz

Light shift for a 1μW probe light in n2EDM, as measured in January 2026.



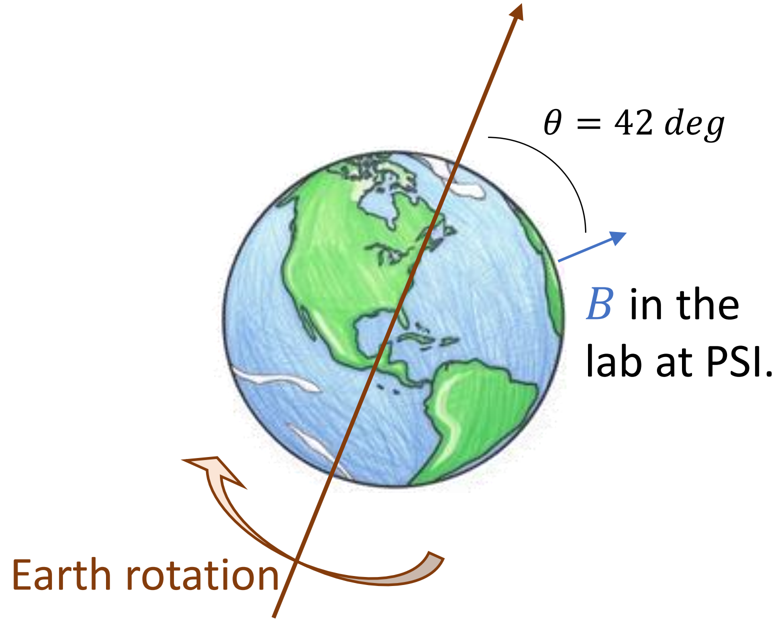
III - Some cool physical results!

- Measuring the earth rotation

The earth rotates!

- Laboratory referential is rotating (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.

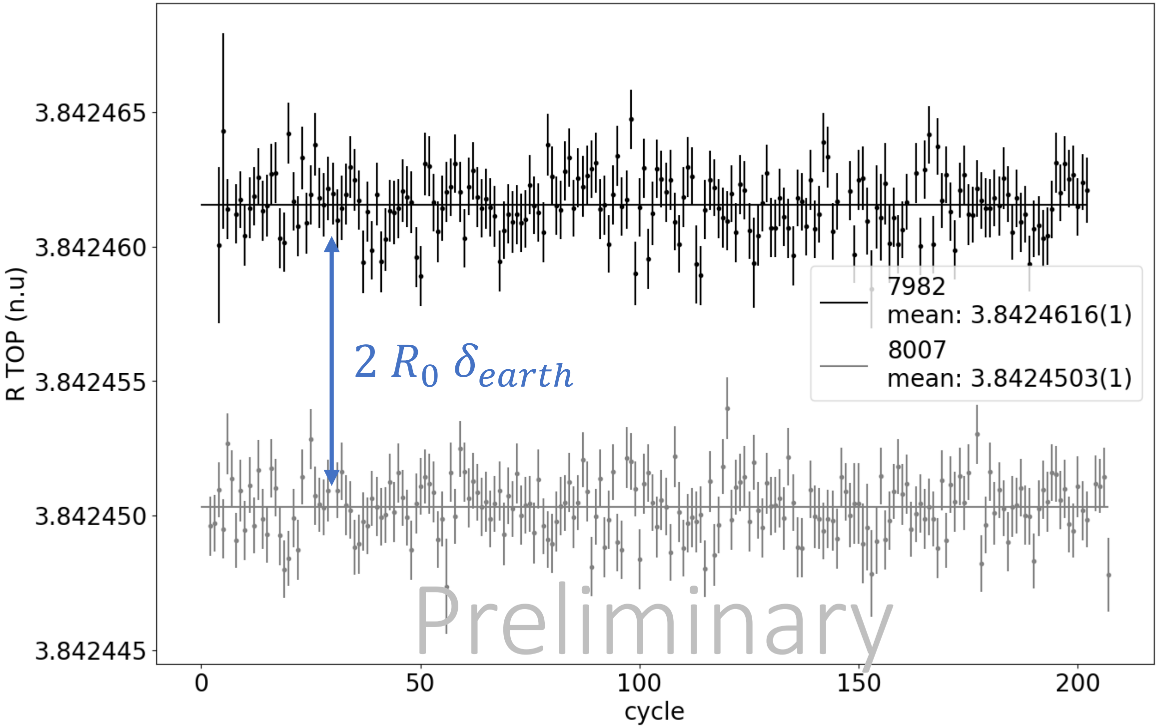
$$R = \frac{f_n}{f_{Hg}} = |\frac{\mu_n}{\mu_{Hg}}|(1 \pm \delta_{earth})$$



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

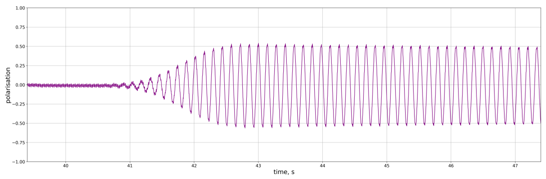
Magnetic field down

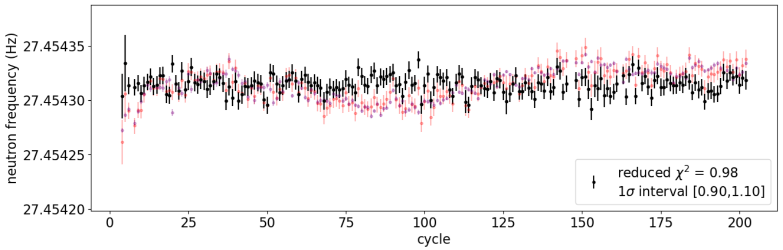
Magnetic field up



Preliminary result:
Rotation period
$24{,}8(3)_{stat}$ hour

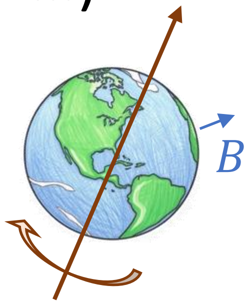
https://ch.geoview.info/villigen_psi_west,10385716



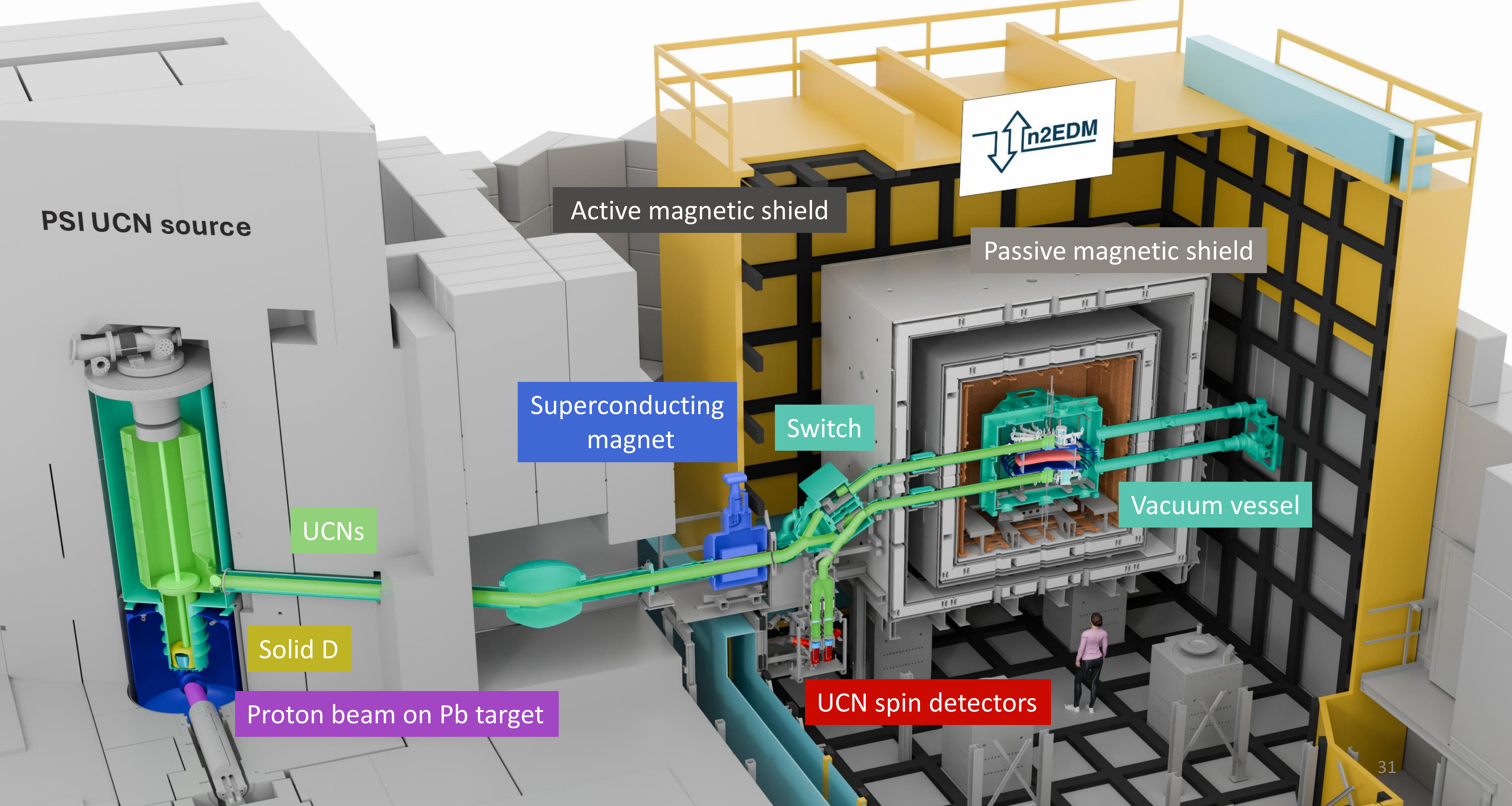


Conclusion

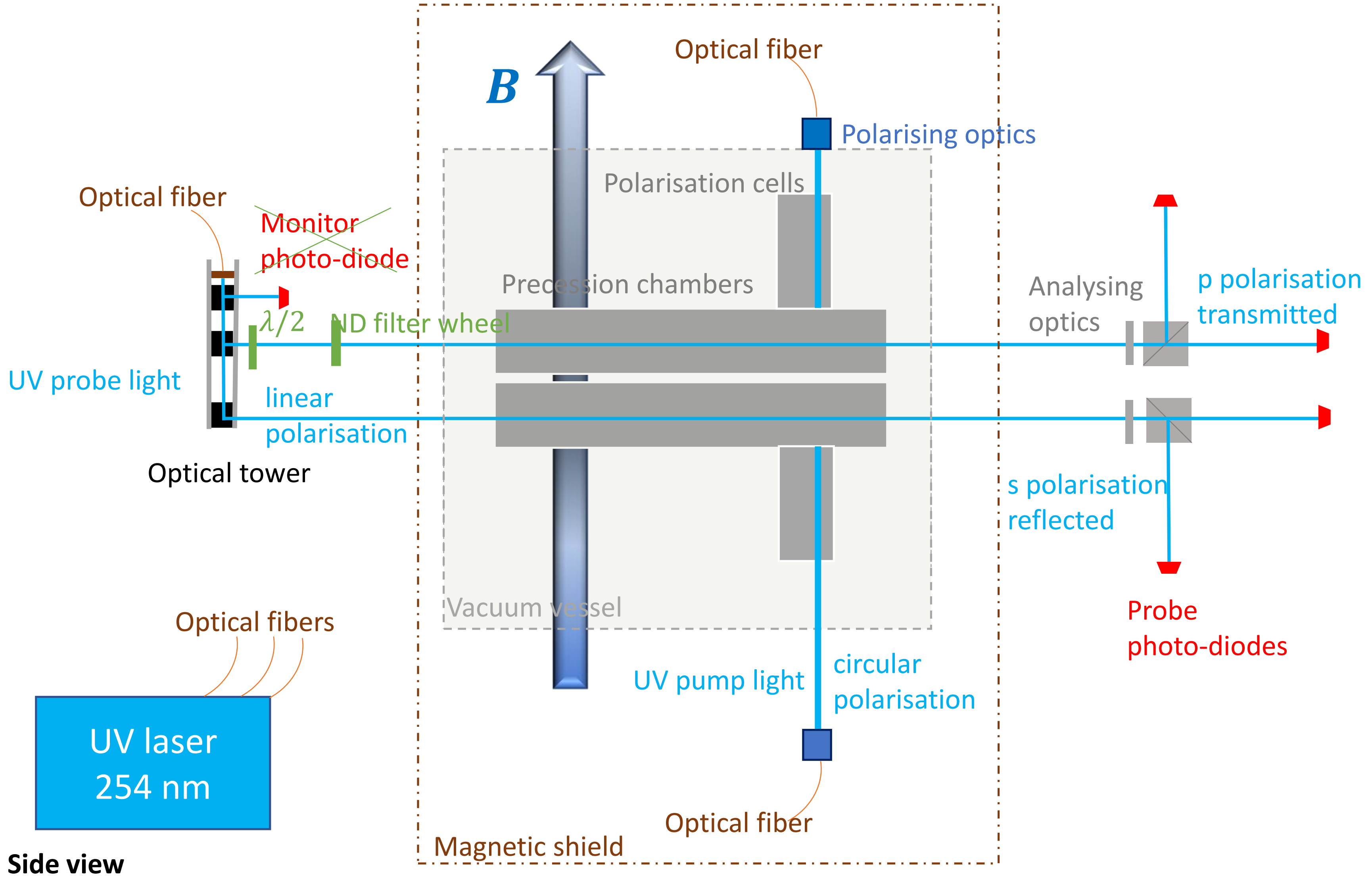
- Mercury vapour enables an **accurate** measurement of the magnetic field with a **precision** of $30\ \mathrm{fT}$ (200 nHz on precession frequency). Satisfy requirements for EDM measurement.
- Still room for improvement! (Technical noise, Hg density, depolarisation …)
- Opens the door to measurements of systematic effects!



Additional slides

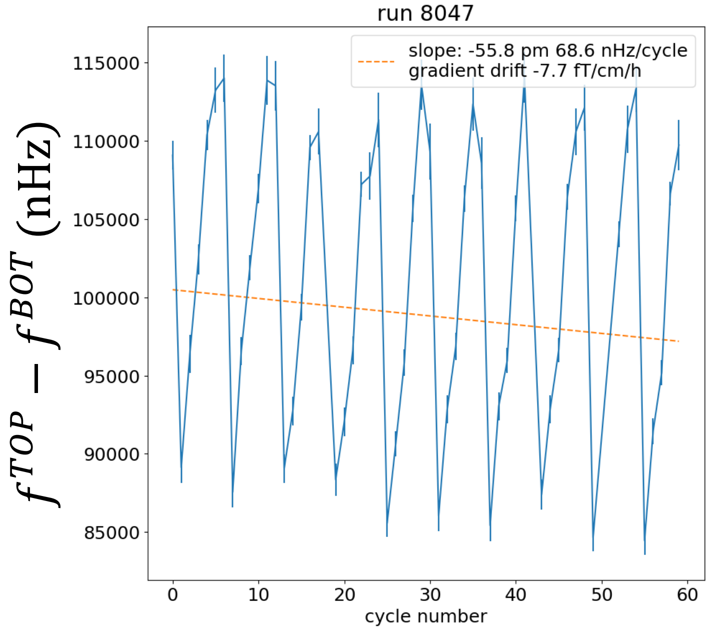

PSI UCN source
n2EDM
Active magnetic shield
Passive magnetic shield
Superconducting magnet
Switch
Vacuum vessel
UCNs
Solid D
Proton beam on Pb target
UCN spin detectors

Light shift measurement



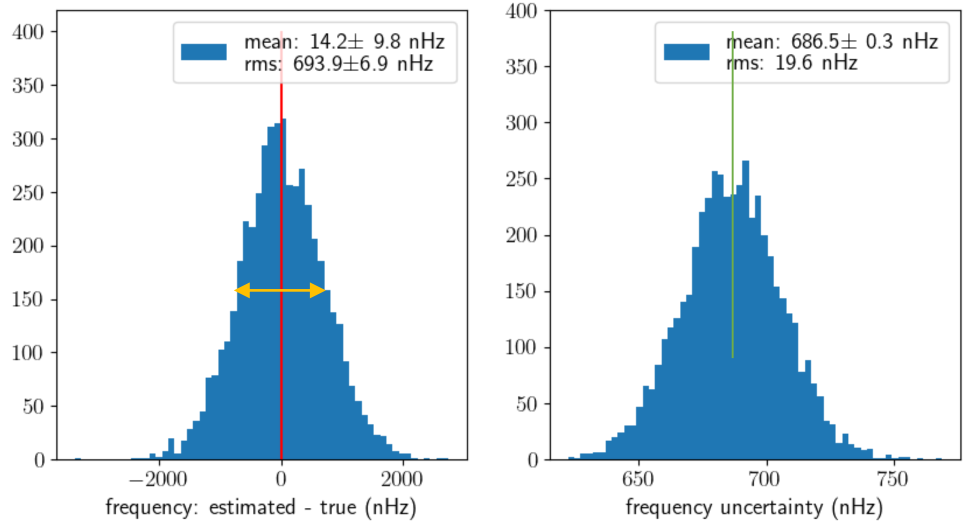
Side view

Measure light shift in one chamber (motorized ND filter to vary power). Second chamber for co-magnetometry.



Frequency derivation: with simulated data

5000 simulated cycles with known
noise density, $f_{Hg}, T_2\ , p_0\ , \phi$
Provides 5000 estimators.



Frequency error $$< \tilde{f} - f_{true} > \pm \frac{\sqrt{< (\tilde{f} - f_{true})^2 >}}{\sqrt{N}}$$ $14 \pm 10\ nHz$

$1,4\ \sigma$ tension to 0
→ no biais

Spread of the estimated freq error $$\sqrt{< (\tilde{f} - f_{true})^2 >} \pm \frac{\sqrt{< (\tilde{f} - f_{true})^2 >}}{\sqrt{2N}} ★$$ $694 \pm 7\ nHz$

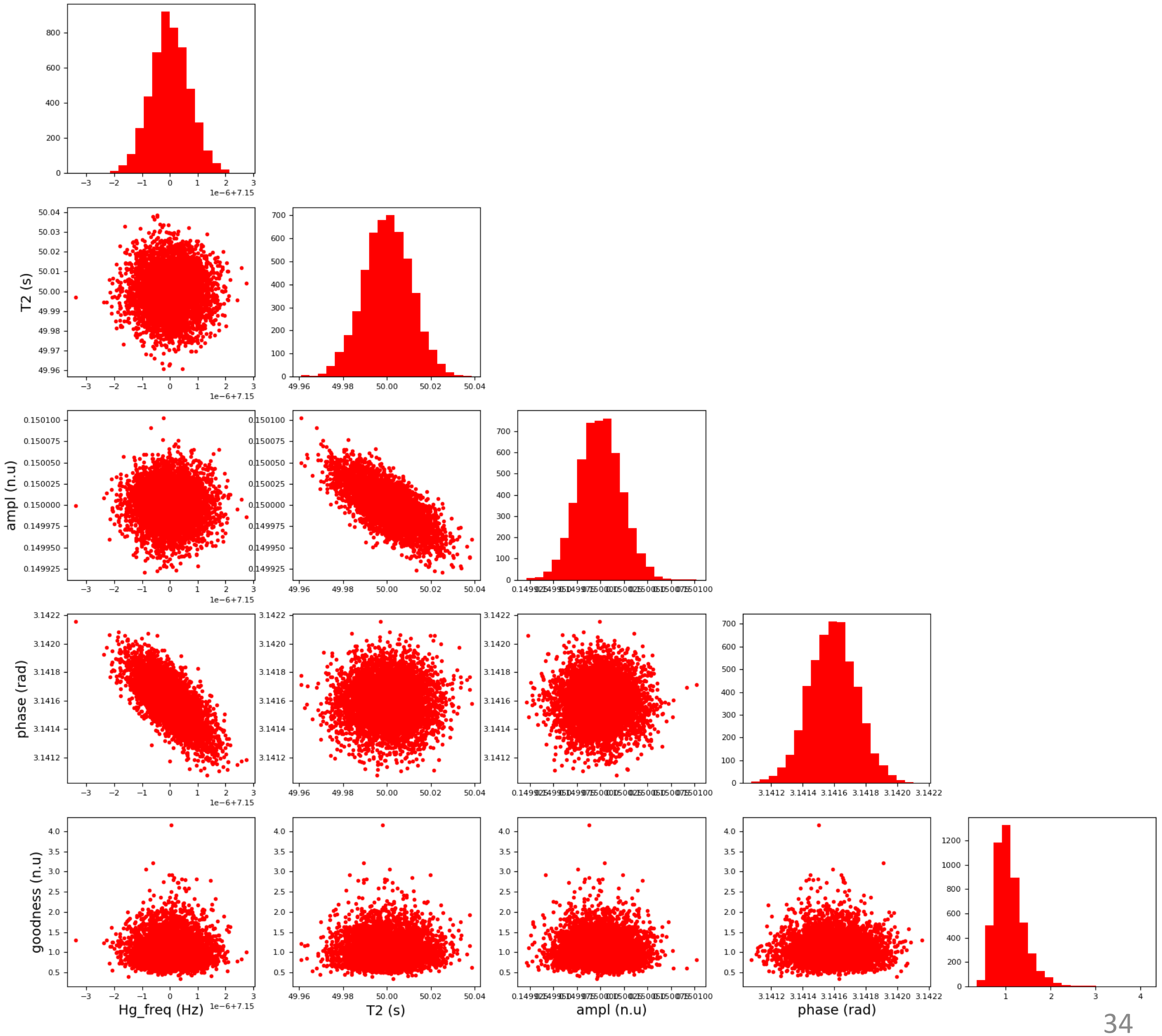
1 σ tension to each other
→ good uncertainty derivation

Mean estimated freq uncertainty $$< \widetilde{\sigma_f} > \pm \frac{\sqrt{< \widetilde{\sigma_f}^2 >}}{\sqrt{N}}$$ $687 \pm 0.3\ nHz$

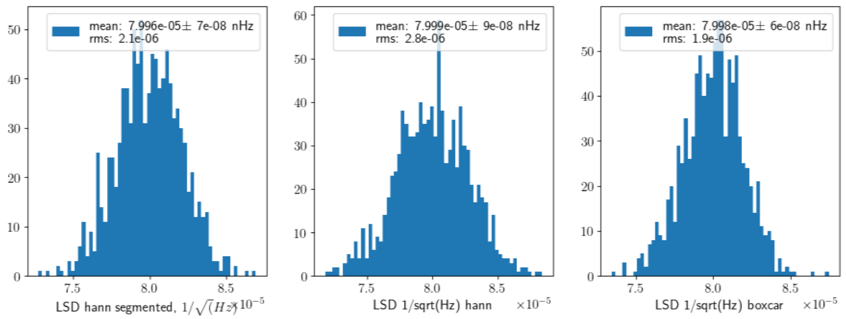
★ Variance of the empirical variance estimator:
$$\sigma^2_{\widetilde{\sigma^2}} = \frac{2\sigma^4}{N-1}$$

Correlations (simulated data)

- The amplitude p_0 and depolarisation time T_2 are anti-correlated.
- The frequency f_{Hg} and the phase ϕ are anti-correlated



Noise density derivation



- Power spectral density from scipy.optimize.welch method
- Possibility to analyse a windowed signal (Hann window)
- Welch method generally divides the time interval into a given number of segments. Derives the PSD of each of them. Takes the mean.
- Conclusions: less points in the PSD, but less dispersion also.
- **Here we show that the noise density estimator is unbiaised** (true PSD of 8e-5)
- Hann segmented and Boxcar perform the same, but the signal peak is not enlarged by the sharp window in the first method.
- We prefer the first method.

Magnetic field drifts

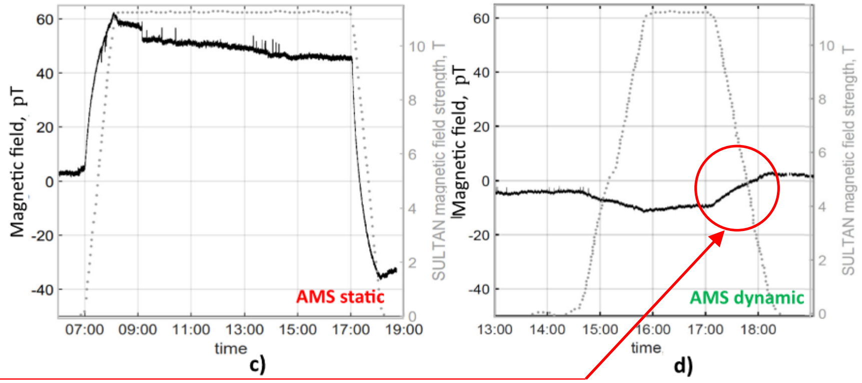
- SULTAN STC ramp up (AMS on)

D = 10 pT/hour

In units of mercury precession frequency,

$\frac{\gamma D}{2\pi} = 20$ nHz/s.

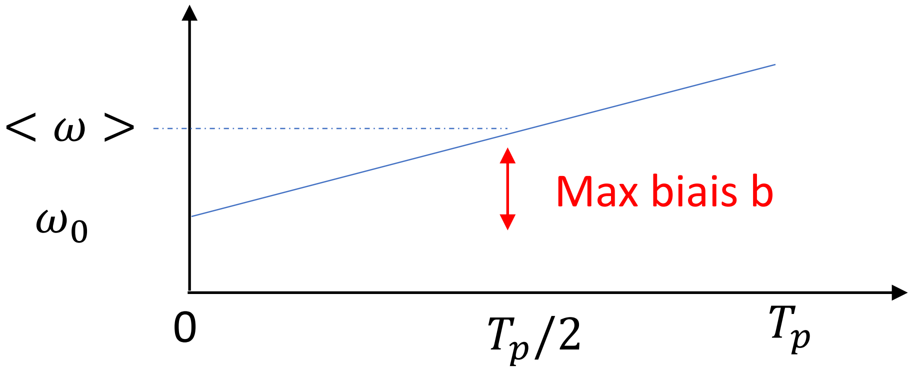
$$B = B_0 + Dt$$
$$\omega := \gamma B = \omega_0 + \gamma D t$$
$$\omega := \frac{d\phi}{dt}$$
$$\phi = \omega_0 t + \frac{1}{2}\gamma D t^2 + \phi_0$$



'ig. 18 The AMS suppression of magnetic fields from SULTAN: a, b ıagnetic fields measured by the feedback fluxgates outside the MSR uring two different SULTAN ramps with the AMS system in static (a) nd dynamic (b) modes; c, d the magnetic fields of the SULTAN magnet for the two ramps (dotted grey line, right scale) along with the corresponding magnetic field measured by an optically-pumped (QuSpin) magnetometer [31] inside the MSR (black line, left scale)

A large 'Active Magnetic Shield' for a high-precision experiment

n2EDM collaboration, 2023



Simulated data: $y_i = \sin\left(\omega_0 t + \frac{1}{2}\gamma D t^2\right) e^{-\Gamma t}$

Biais proportional to the magnetic drift

Analytical result:

$$b = -\left(F(\Gamma T_p) + 1 \right) \gamma D \frac{T_p}{2}$$

Weighted mean:

$$b = -f \, \gamma D \frac{T_p}{2}$$

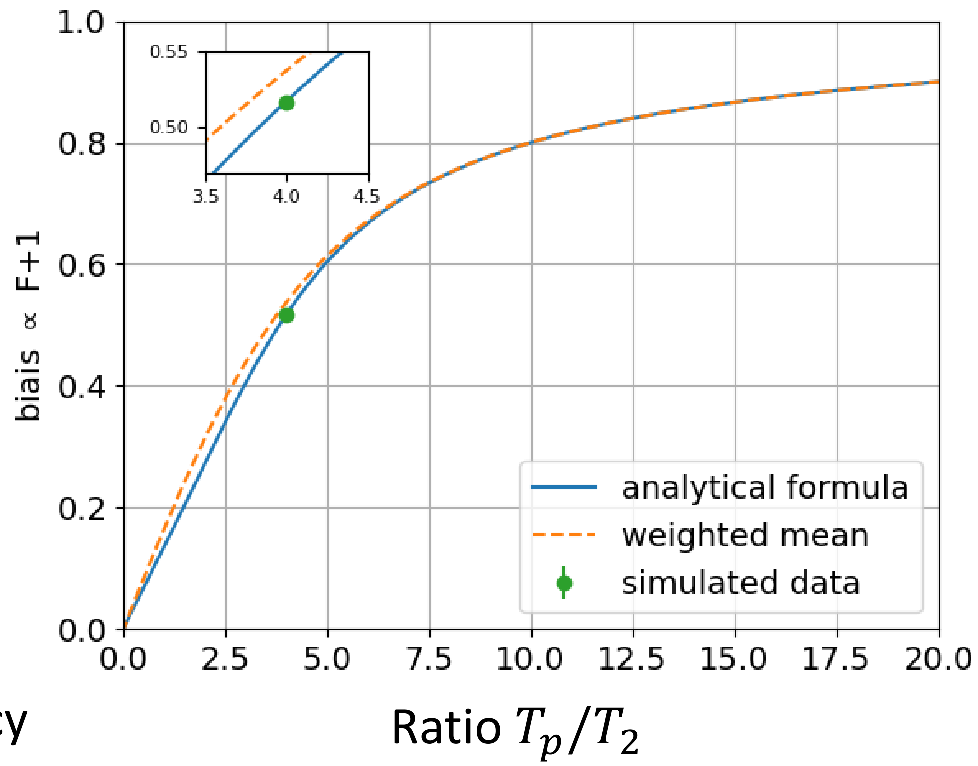
Simulated data:

- For $T_p = 200s$ and $T_2 = 50s$, $\frac{T_p}{T_2} = 4$

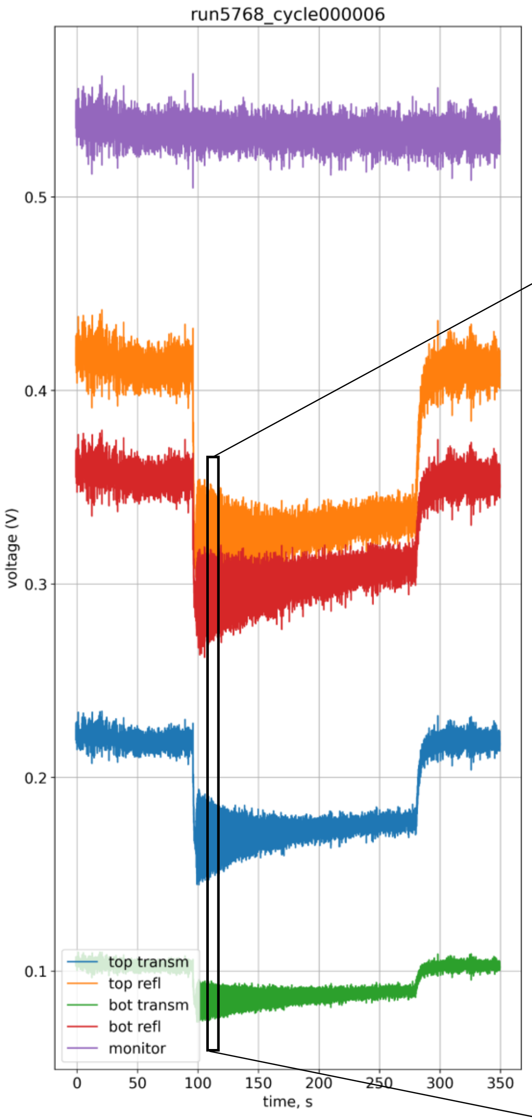
T_p precession duration

γD magnetic field drift in unit of precession angular frequency

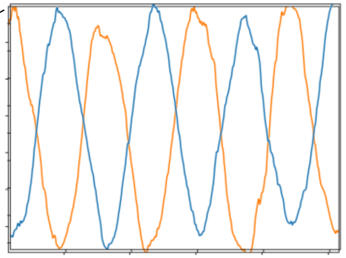
b frequency biais.



Optical reading of Hg precession

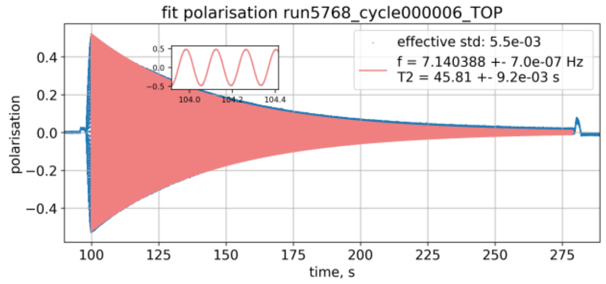


TOP chamber

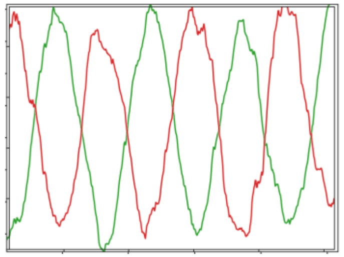


reflected

transmitted

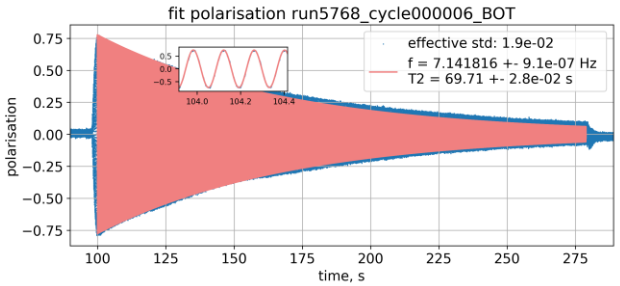


BOT chamber



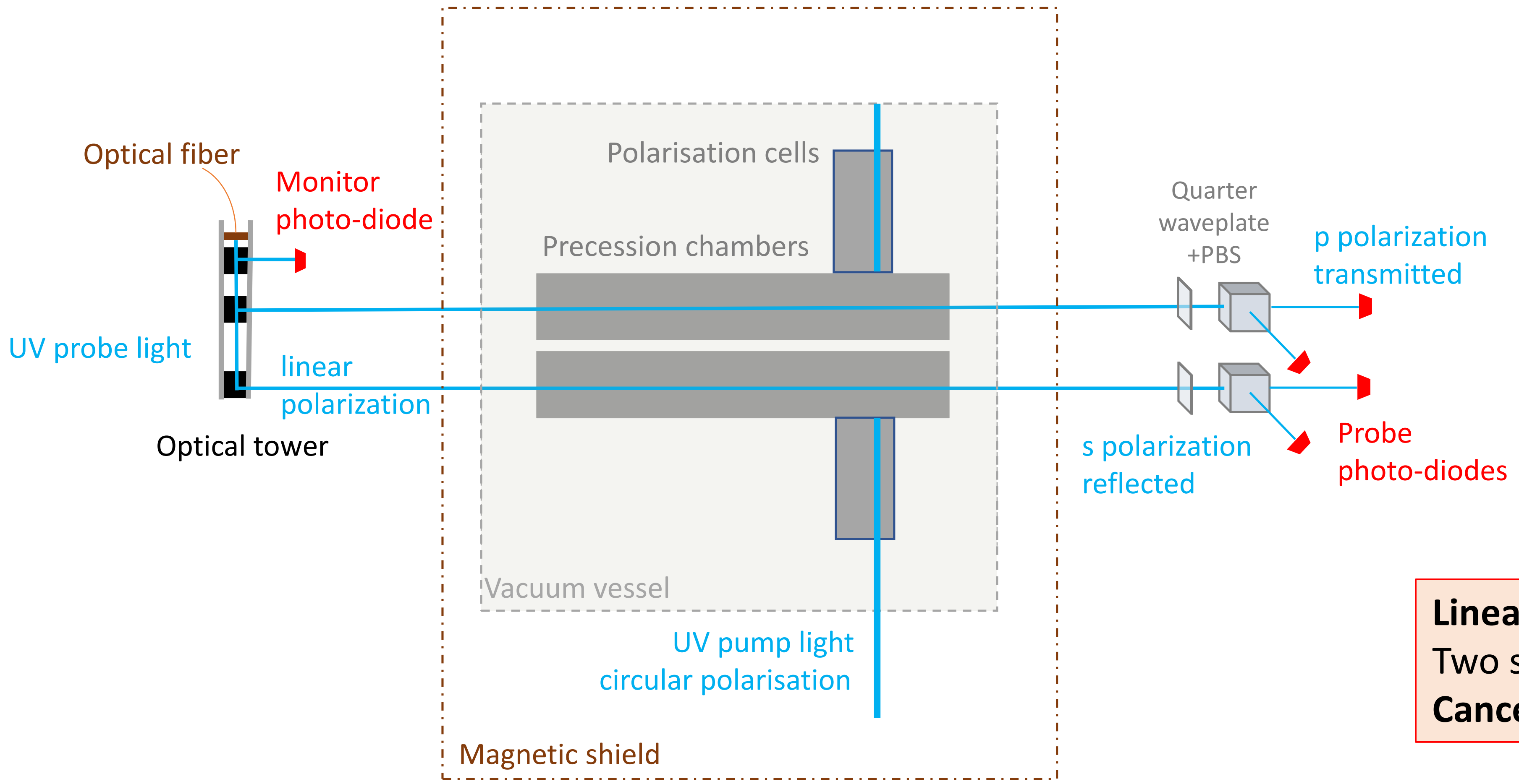
reflected

transmitted



Linearly polarised probe lowered the uncertainty by a factor 3.

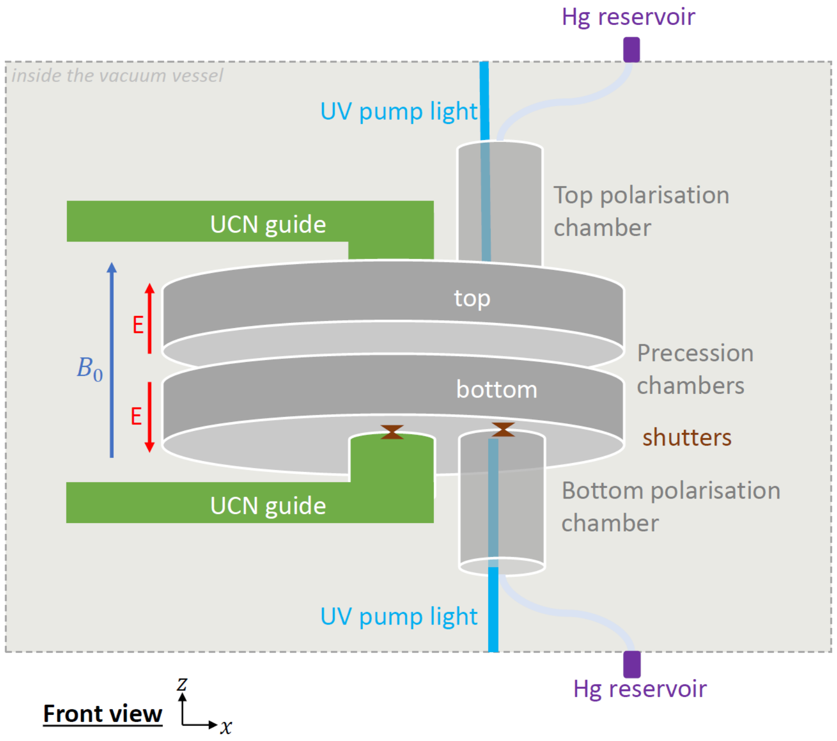
Optical reading of Hg precession

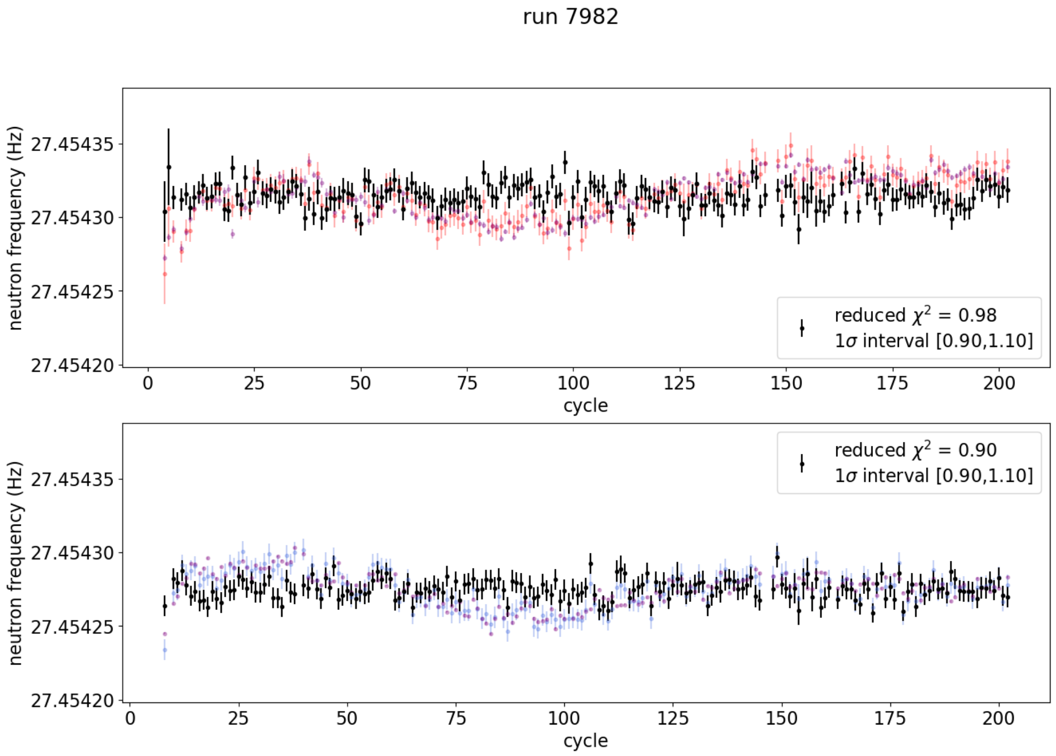


Linearly polarised probe light.
Two signals for each chamber.
Cancellation of common noise.

Mercury co-magnetometry

- In n2EDM, simultaneous measurement in the TOP and BOTTOM chambers. But we also want to **combine different runs**.





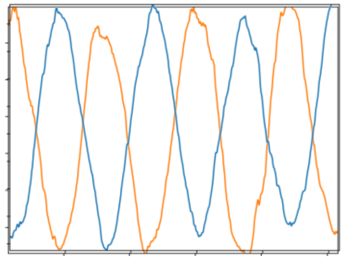
The great combination with linearly polarised light

Transmitted power

$$P_t = P_0 e^{-\sigma_u n L(1+p)}$$

Reflected power

$$P_r = P_0 e^{-\sigma_u n L(1-p)}$$



reflected
transmitted

σ_u unpolarised cross section
n mercury density
L length of the cell
p vapour polarisation along light propagation axis

(1) $$\ln(P_t) + \ln(P_r) = 2\ln(P_0) - 2\sigma_u n L$$

Derive $\sigma_u n L$
with $n = n_0\, e^{-t/T_{leak}}$

(2) $$\ln(P_t) - \ln(P_r) = -2\sigma_u n L\, p$$

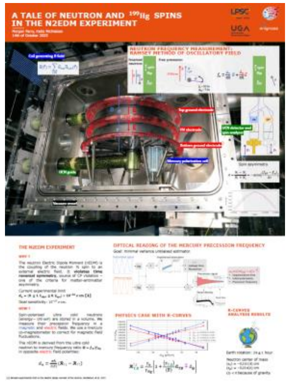
Derive p
knowing $\sigma_u n L$

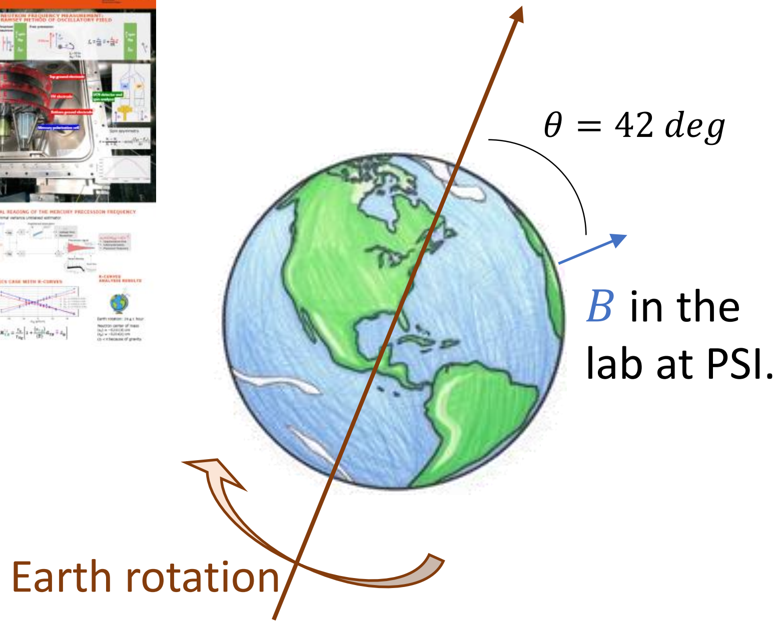
$$p(t) = p_0 \cos(2\pi f_{\mathrm{Hg}} t + \phi)\, e^{-\frac{t}{T2}}$$

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

(2) 2nd fit provides
- Polarisation of vapour p_0
- Depolarisation time T_2
- Phase ϕ
- Noise spectrum
- Precession frequency f_{Hg}

The earth rotates!





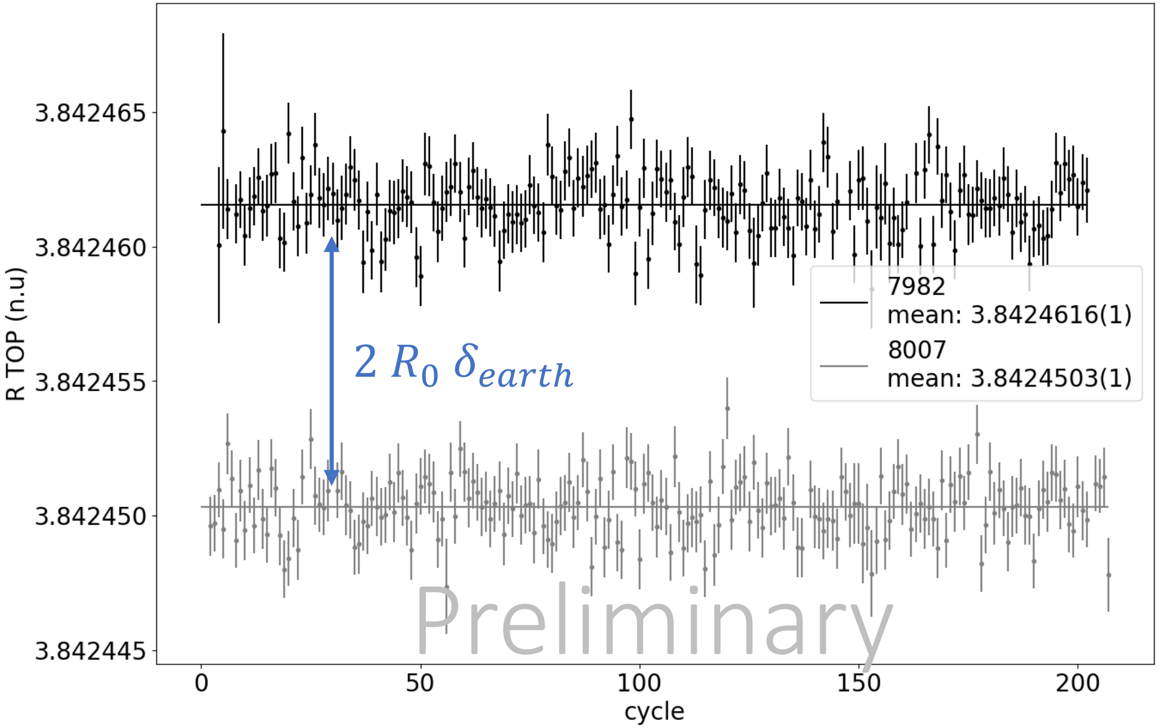
- Laboratory referential is rotating (earth rotation)
- Magnetic momentum of neutron and mercury have opposite sign ($\mu_n < 0$). Depending on B one frequency is enhanced, the other is diminished.

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

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

Magnetic field down

Magnetic field up



Preliminary result:
Rotation period
$24{,}8(3)_{stat}$ hour

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