A laser based mercury magnetometer for the n2EDM experiment at PSI

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on behalf of the nEDM collaboration

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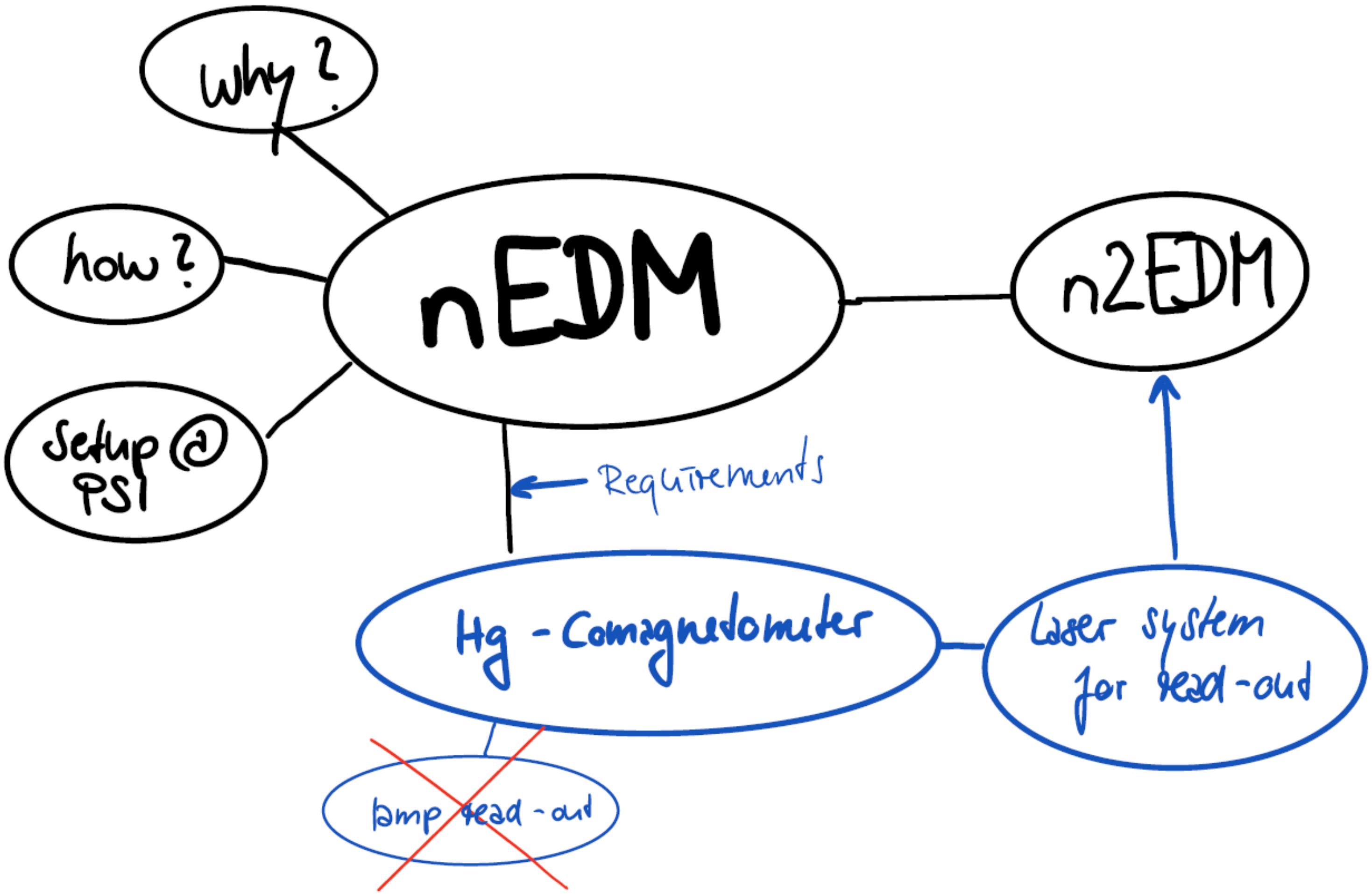
Overview



why ?
how ?
Setup @ PSI
nEDM
n2EDM
Requirements
Hg - Comagnetometer
Laser system for read-out
lamp read-out

Why search for a nEDM?

Obvious but unexplained baryon asymmetry in the Universe:
Where has all the anti-matter gone?

Observed:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$$

Sakharov 1967:
- B-violation
- C & CP-violation
- thermal non-equilibrium
(JETP Lett. 5 (1967) 24)

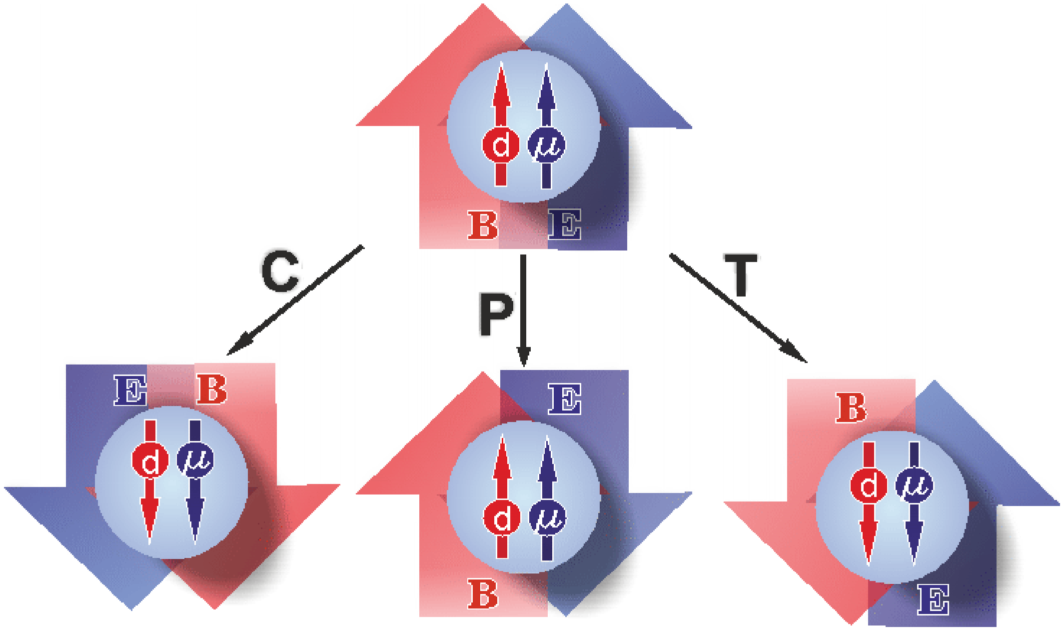
SM expectation:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$$

The discovery of a nEDM would indicate a yet unobserved source of CP violation.

CP violation and nEDM

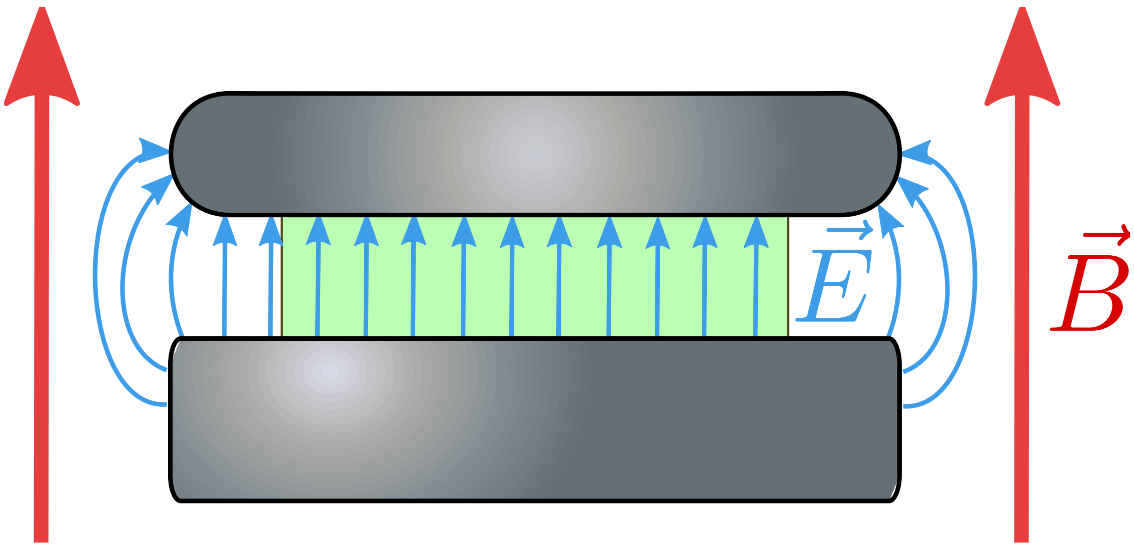
$$\mathcal{H} = -d\frac{\vec{s}}{|\vec{s}|}\vec{E} - \mu\frac{\vec{s}}{|\vec{s}|}\vec{B}$$



A non-zero particle EDM violates *P*, *T* and, assuming *CPT* conservation, also *CP*.

Search for the electric dipolemoment of the neutron

$$f_n = \frac{2}{h}\left(\vec{\mu}_n \cdot \vec{B} + \vec{d}_n \cdot \vec{E}\right)$$



$\vec{B} \uparrow\downarrow \vec{E}$

$\vec{B} \uparrow\uparrow \vec{E}$

Search for the electric dipolemoment of the neutron

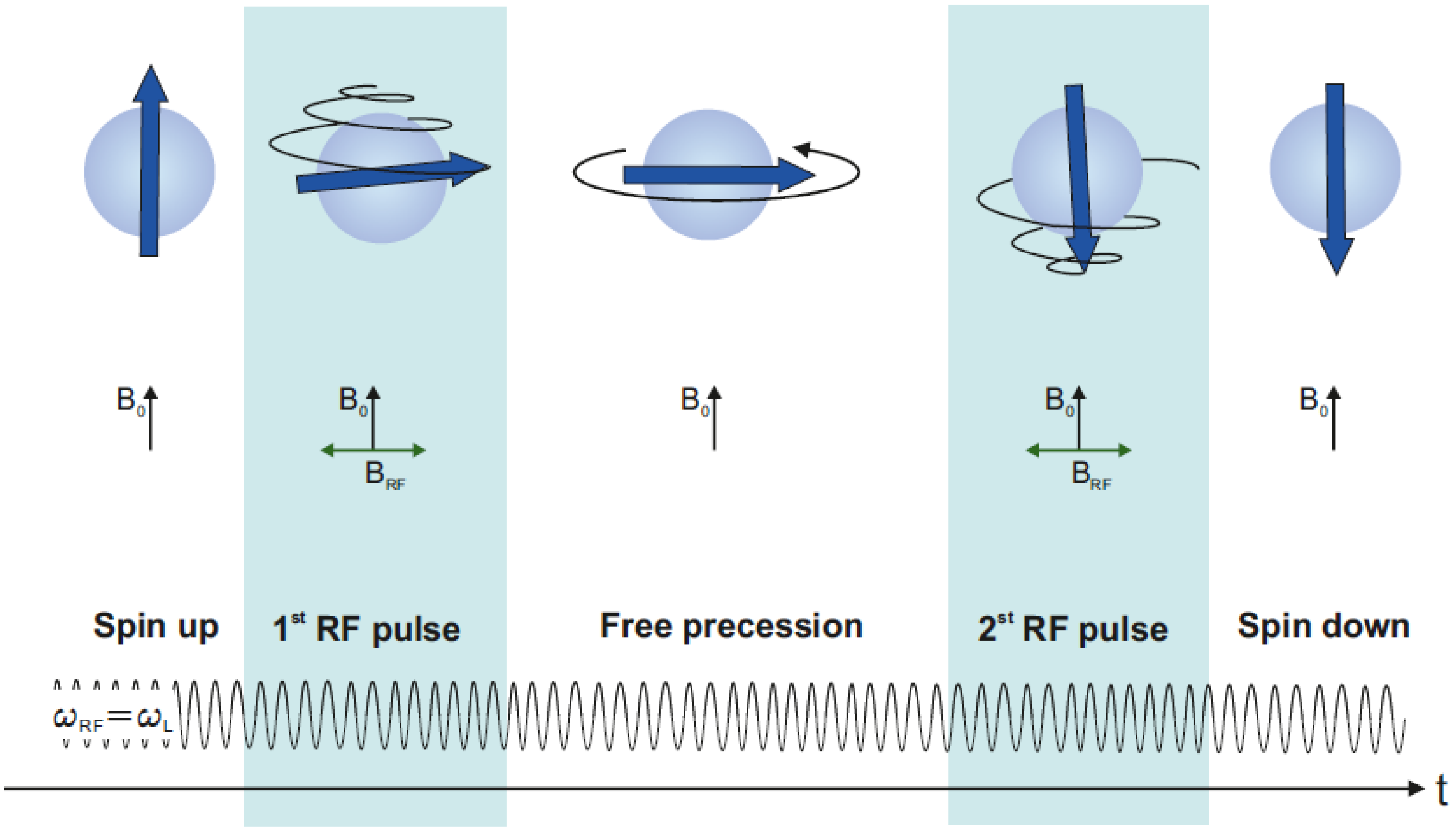
$$d_n = \frac{1}{2E}\left(h\left(f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow}\right) + \mu_n\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)\right)$$

$$d_n = \frac{1}{2E}\left(h\Delta f_n + \mu_n \Delta B\right)$$

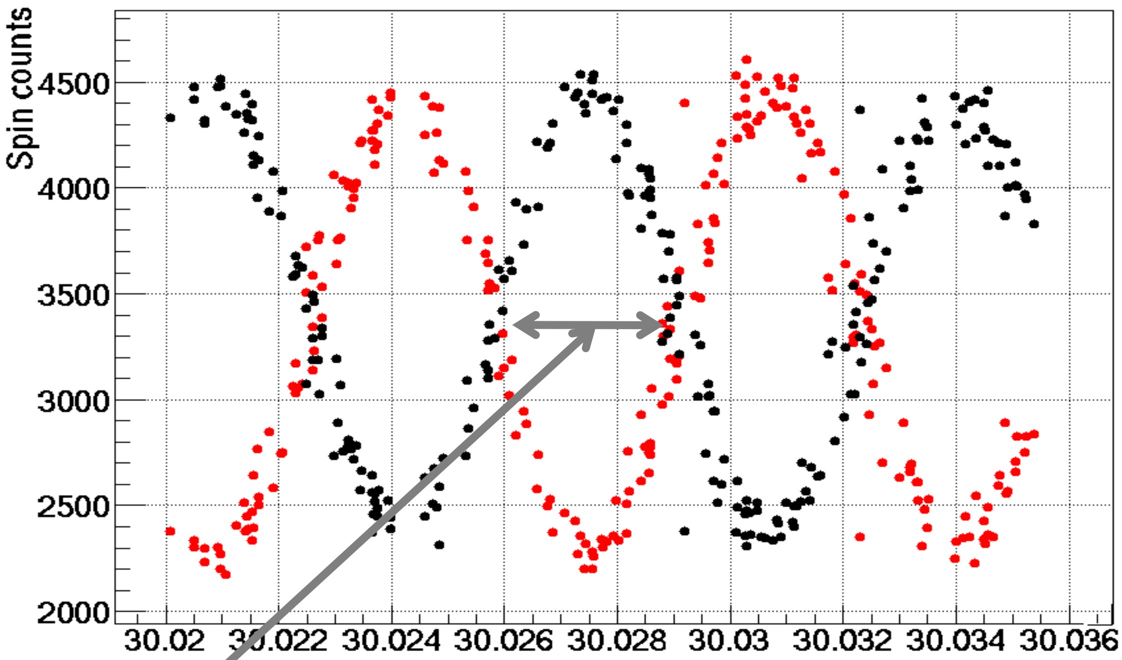
Major source for systematic effects

How to measure the spin precession frequency of the neutrons?

Ramsey's method of separated oscillatory fields



Ramsey's Method



$\Delta\nu$

f_{rf}

$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

Sensitivity

→ Predicted value by the Standard Model:

Khriplovich et al, Physics Letters B 109 (1982)

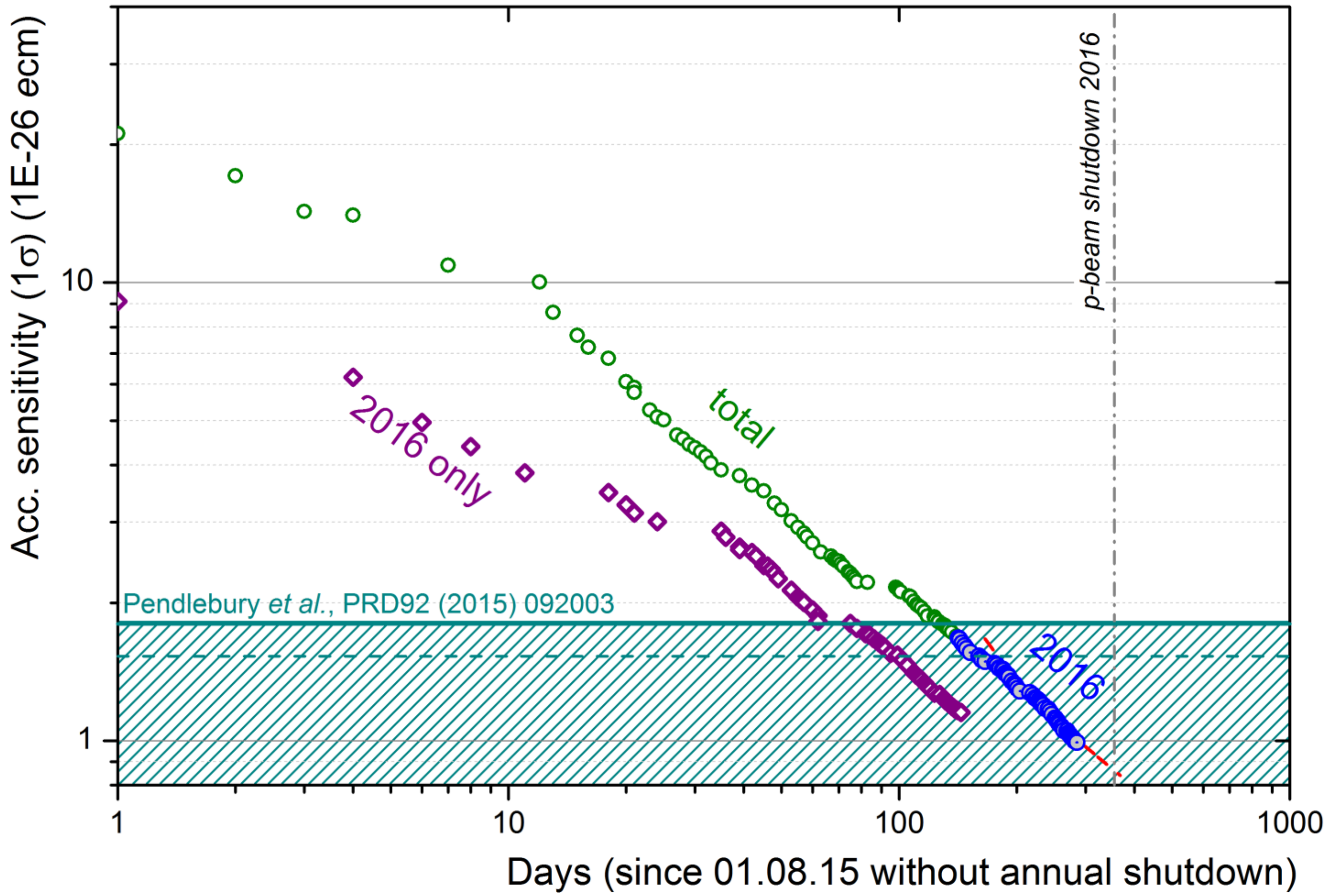
$$d_\mathrm{n} \approx 2 \cdot 10^{-32}\, \mathrm{e{\cdot}cm}$$

→ Current limit:

Pendelbury et al, Phys. Rev. D 92 (2015)

$$d_\mathrm{n} < 3.0 \cdot 10^{-26}\, \mathrm{e{\cdot}cm} (90\% \mathrm{C.L.})$$

Current sensitivity of nEDM@PSI



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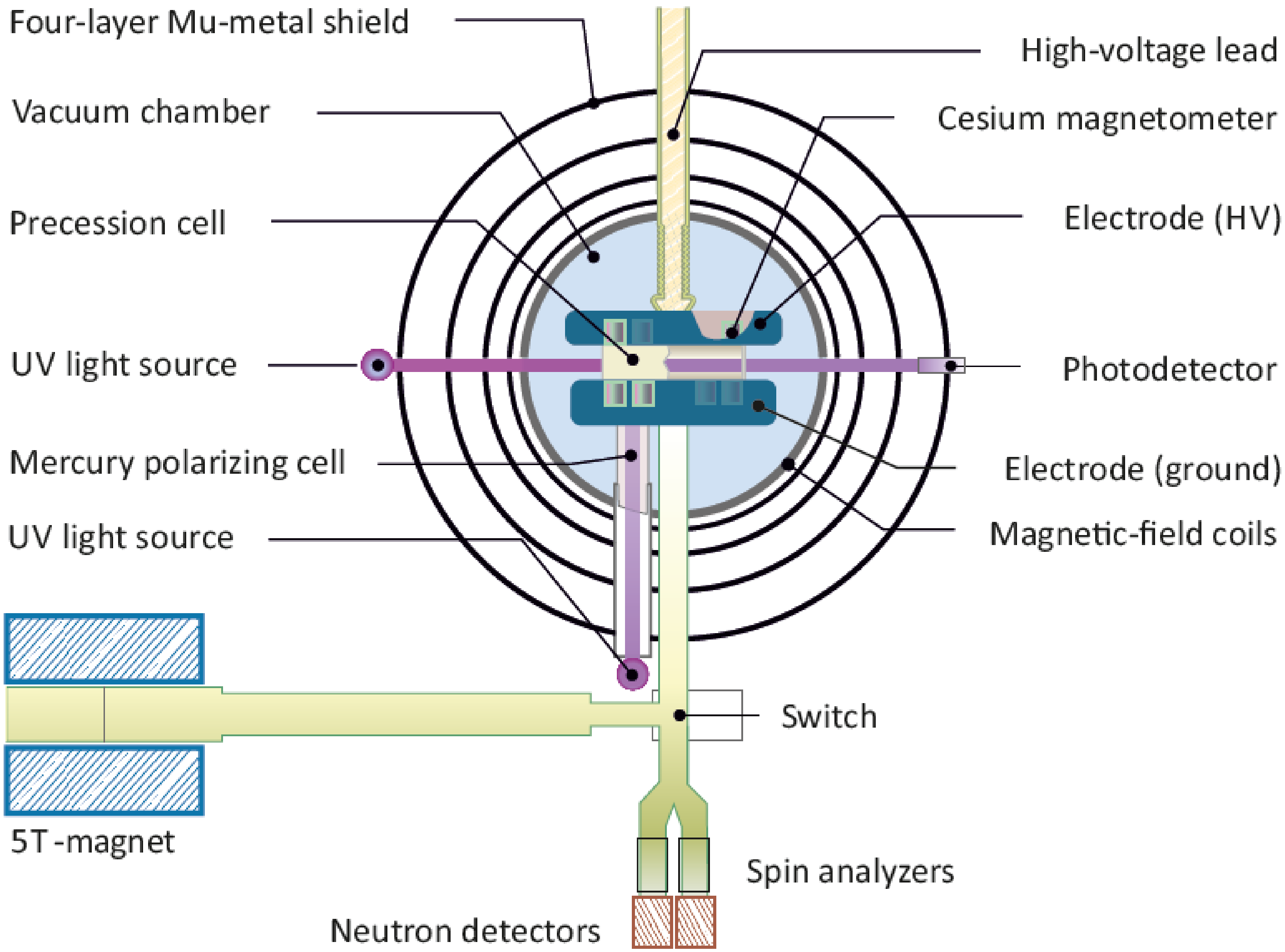
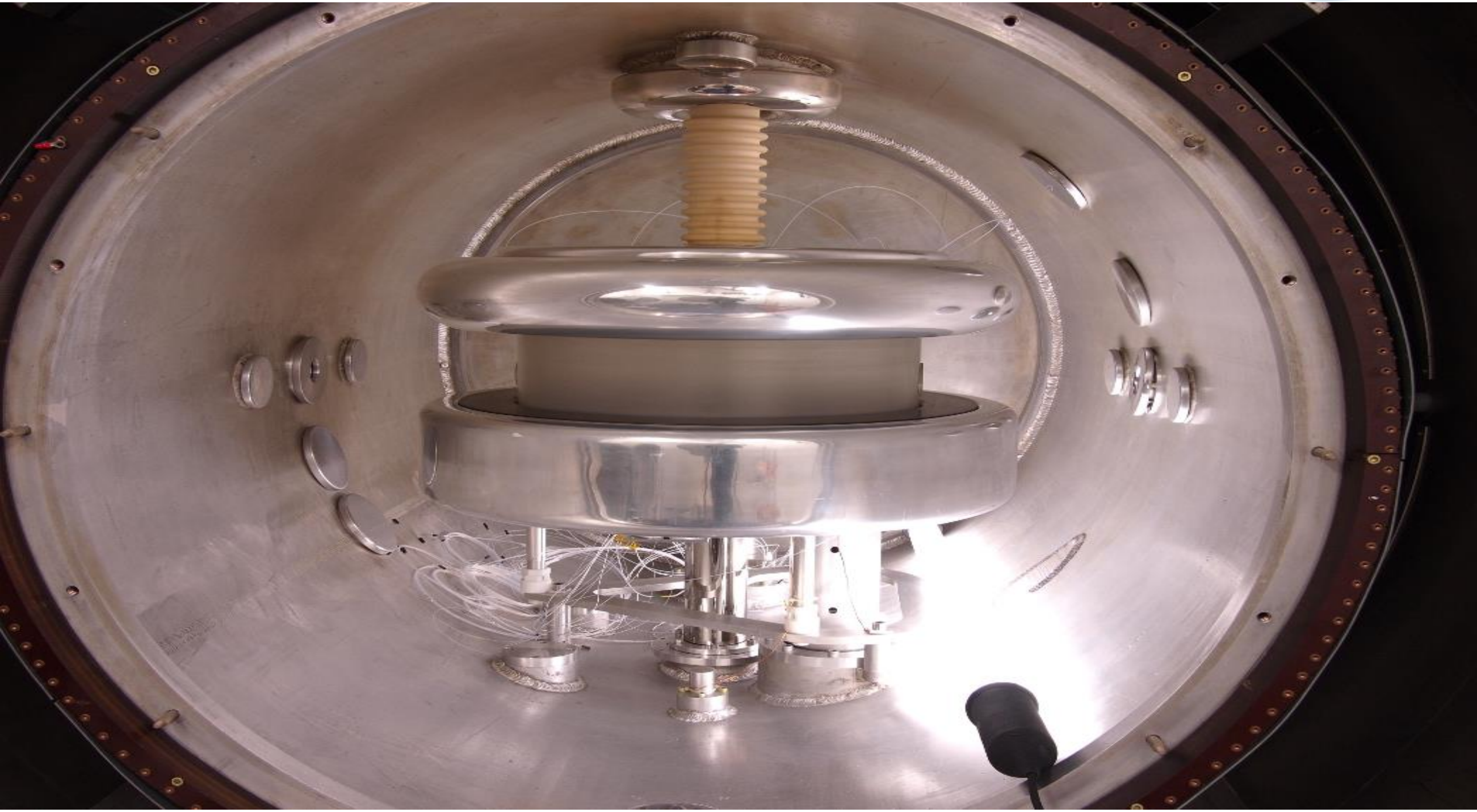
The nEDM apparatus



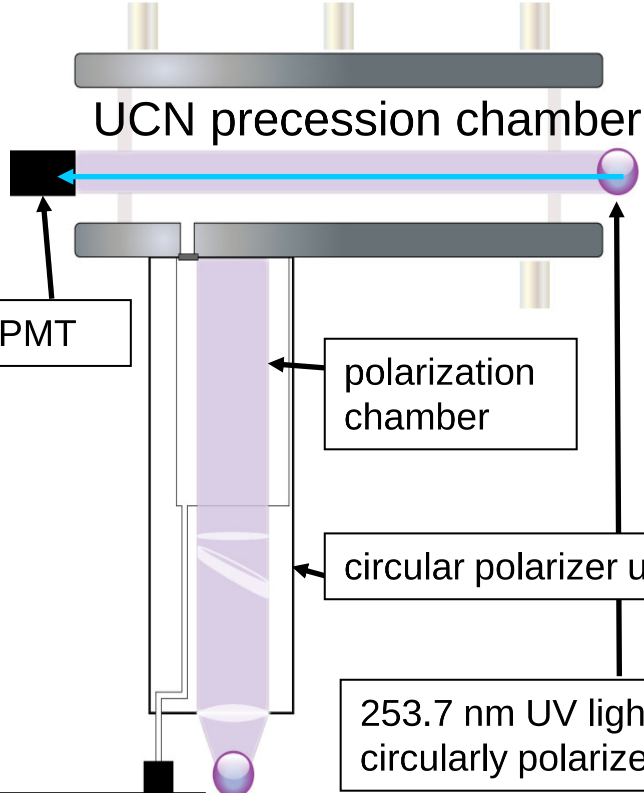
surrounding field compensation

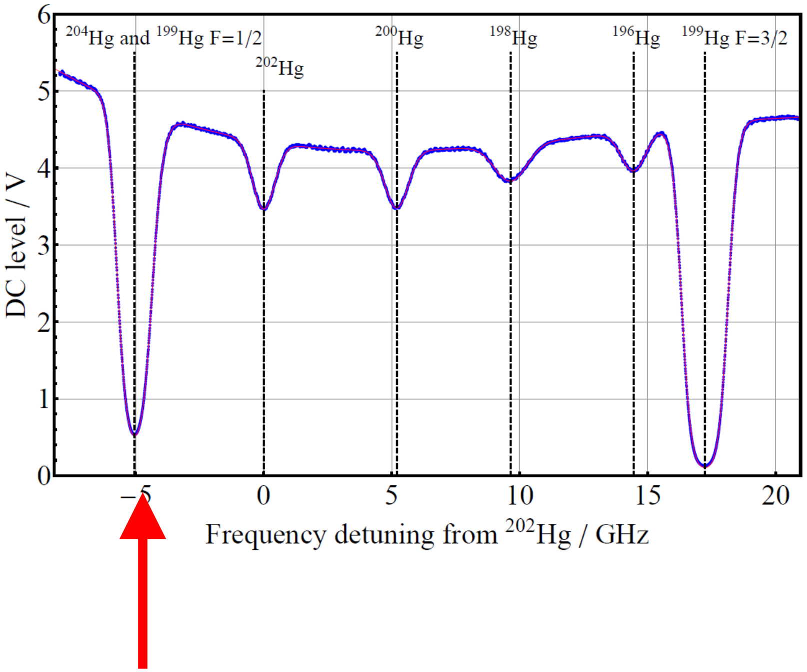
The nEDM apparatus



Hg-Comagnetometer

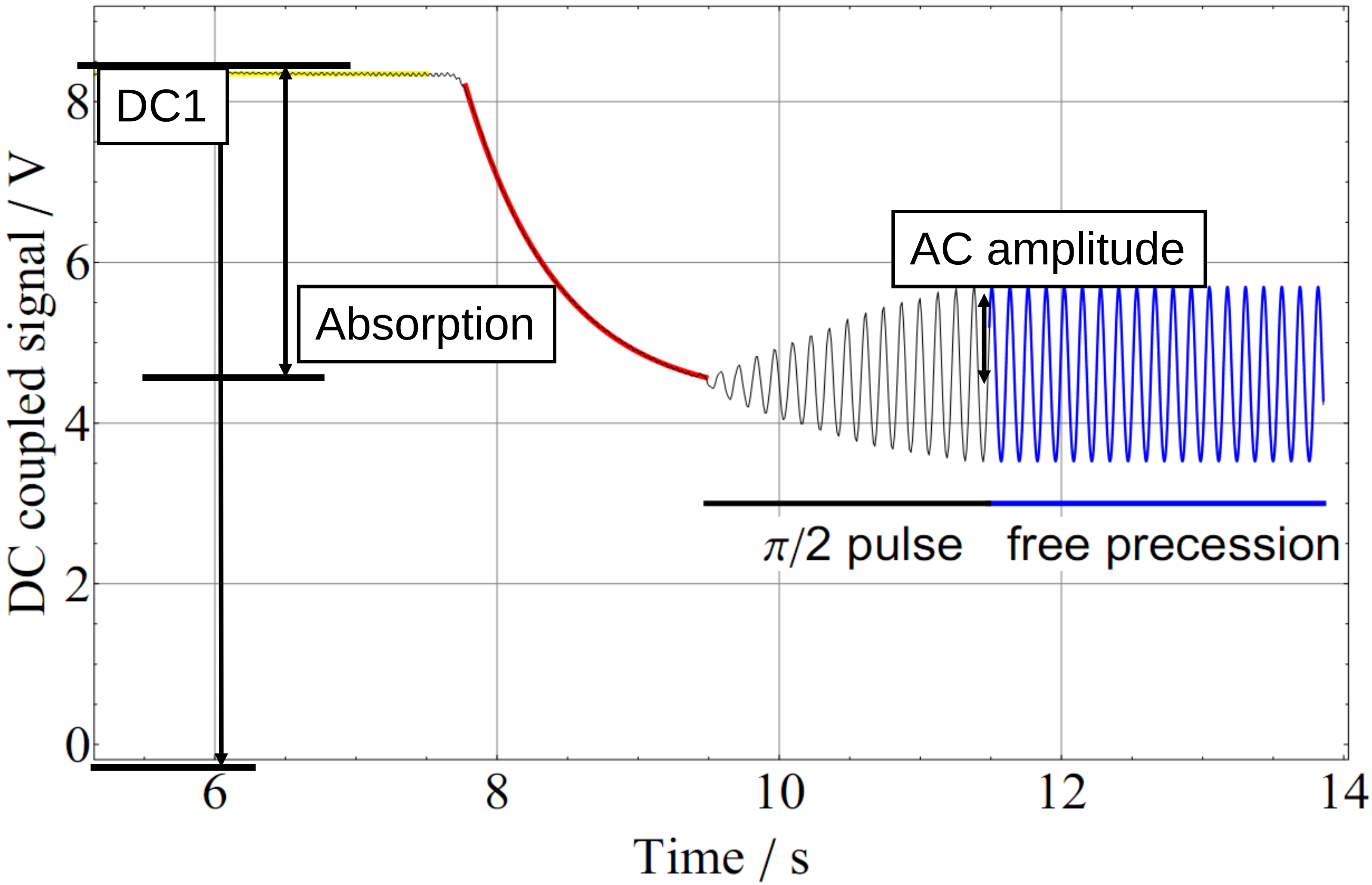
→ Measure residual magnetic field drifts with **optically detected nuclear magnetic resonance (ODMR)**



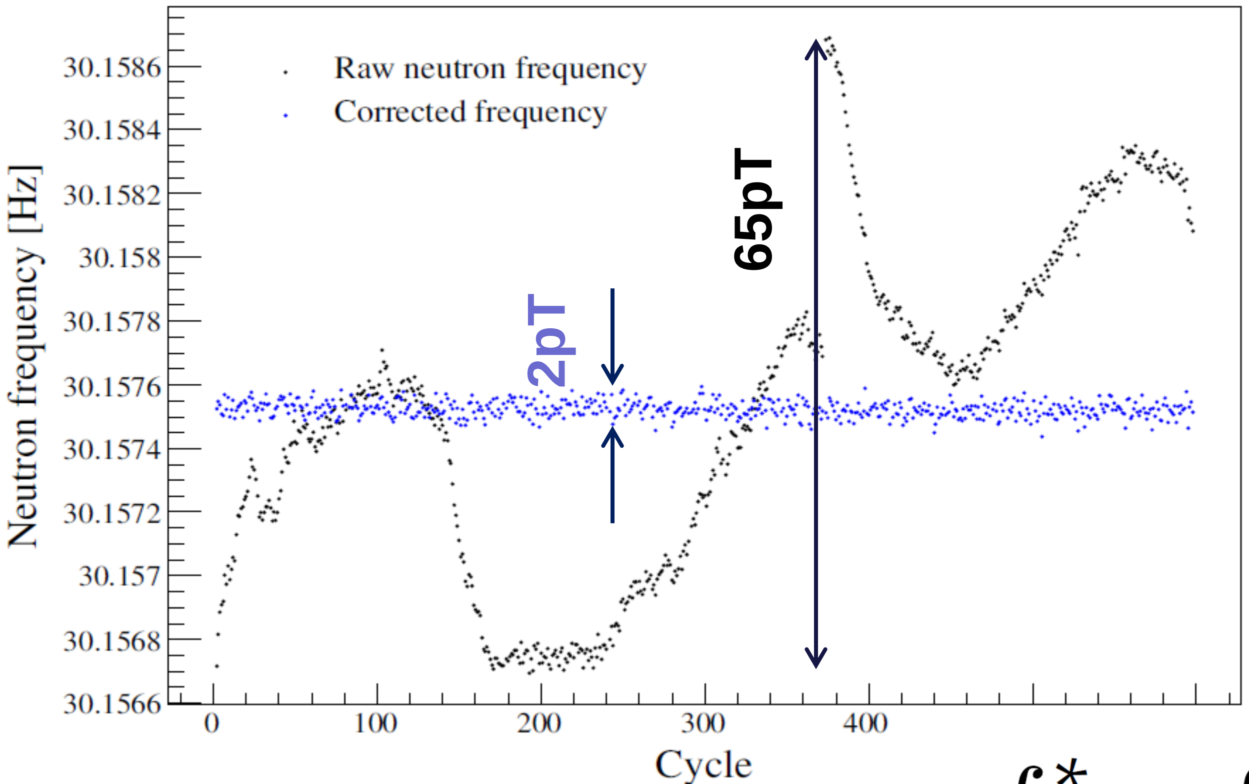


^{199}Hg 6 $^1S_0$ → 6 $^3P_1$ F=1/2 transition @ 253.7nm

Hg-Comagnetometer



Performance of the Hg-Comagnetometer



$$f_n^* = f_n - \frac{\gamma_n}{\gamma_{Hg}} f_{Hg}$$

corrected raw
UCN frequency

gyromagnetic ratios

Sensitivity requirements

Correction:

$$f_{\mathrm{n}}^{*} = f_{\mathrm{n}} - \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} f_{\mathrm{Hg}}$$

Error propagation:

$$\Delta f_{\mathrm{n}}^{*} = \sqrt{\Delta f_{\mathrm{n}}^{2} + \left(\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \Delta f_{\mathrm{Hg}}\right)^{2}}$$

$$= \Delta f_{\mathrm{n}} \sqrt{1 + \left(\frac{\Delta f_{\mathrm{Hg}}/f_{\mathrm{Hg}}}{\Delta f_{\mathrm{n}}/f_{\mathrm{n}}}\right)^{2}}$$

Increased error not more than 5%:

$$\frac{\Delta f_{\mathrm{Hg}}}{f_{\mathrm{Hg}}} = \frac{\Delta B}{|\vec{B}|} < \frac{1}{3.1} \frac{\Delta f_{\mathrm{n}}}{f_{\mathrm{n}}}$$

Sensitivity requirements

$$\frac{\Delta f_{\mathrm{Hg}}}{f_{\mathrm{Hg}}} = \frac{\Delta B}{|\vec{B}|} < \frac{1}{3.1}\frac{\Delta f_{\mathrm{n}}}{f_{\mathrm{n}}}$$

Current running nEDM: $\frac{\Delta f_{\mathrm{n}}}{f_{\mathrm{n}}} = 0.25\,\mathrm{ppm}$ $\longrightarrow$ $\frac{\Delta f_{\mathrm{Hg}}}{f_{\mathrm{Hg}}} < 0.08\,\mathrm{ppm}$

Magnetometric resolution

$$\Delta B < 80\,\mathrm{fT}$$

Next generation n2EDM:
8 times improved sensitivity

$$\Delta B < 10\,\mathrm{fT}$$

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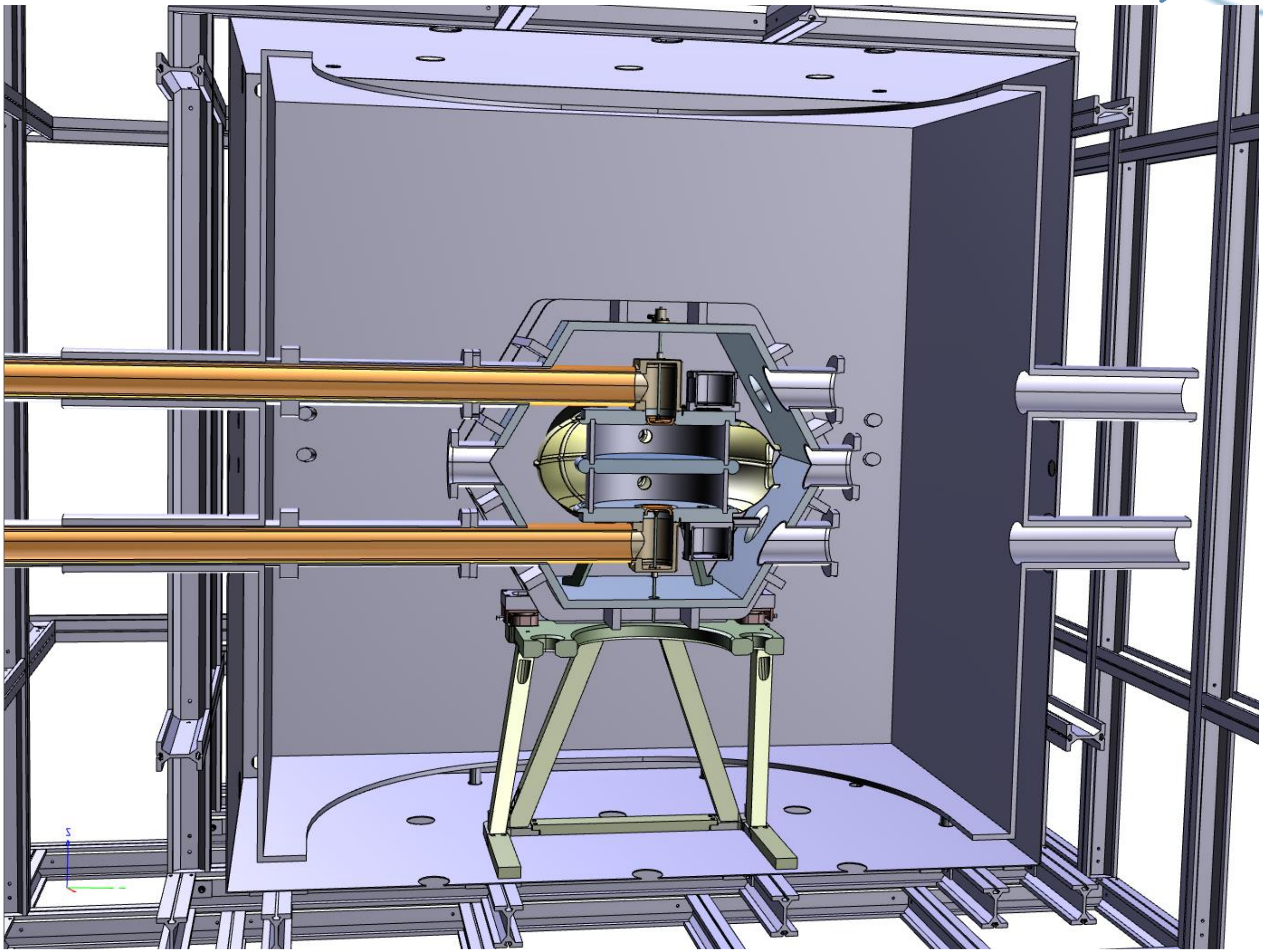
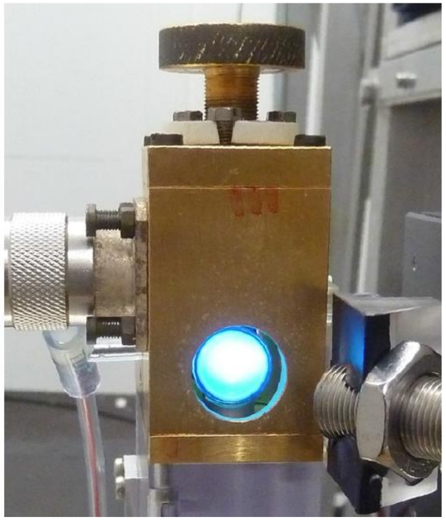
Preview: n2EDM setup



Exchanging the light source

current light sources: ^{204}Hg discharge bulbs
→ Large uncertainty on the output frequency spectrum

- self absorption
- Temperature changes
- Light cannot be focused / collimated
- Emission lines are Doppler-broadend
- …..

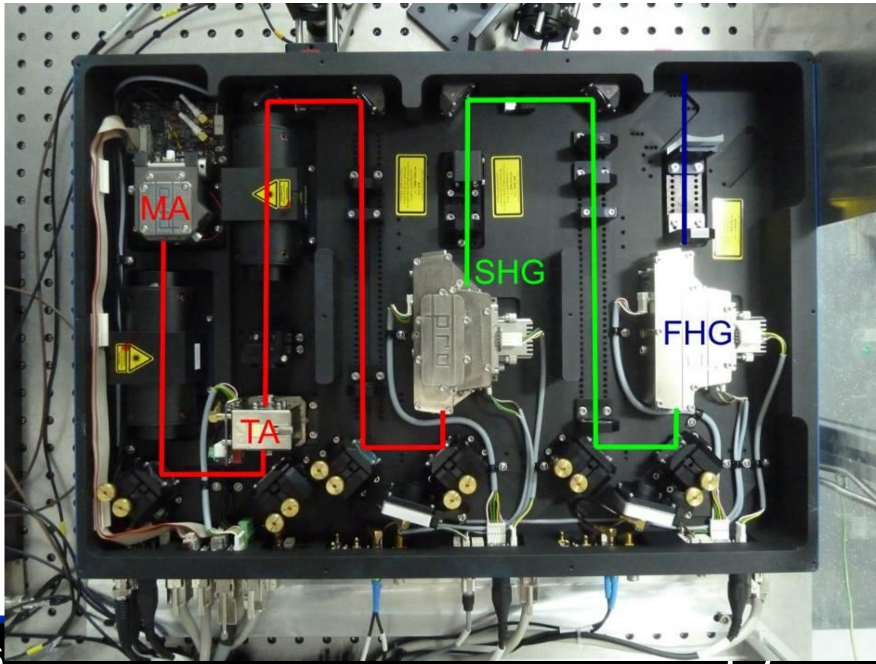


New light source: UV laser system

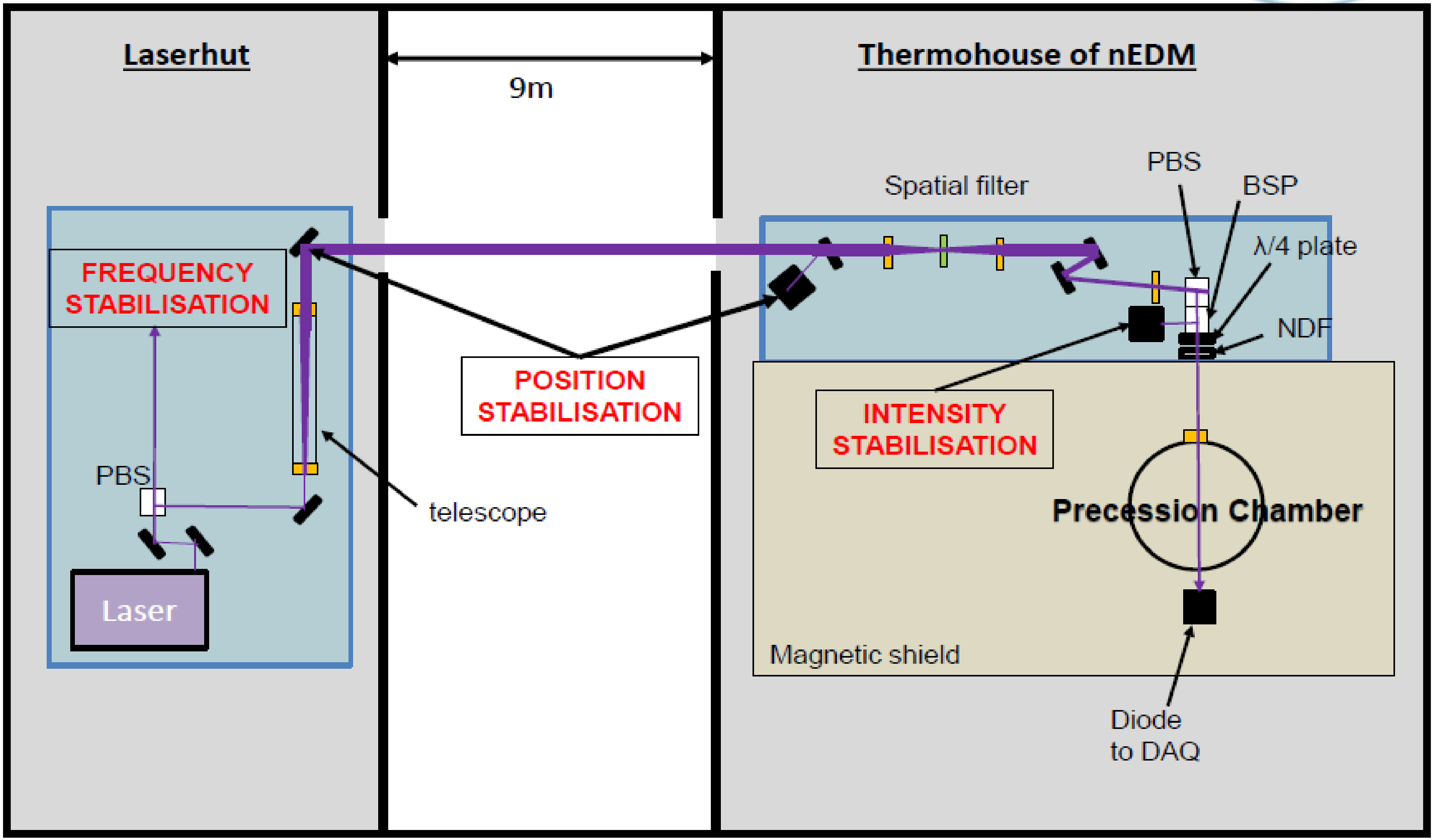
FHG (fourth harmonic generator):

IR → Vis → UV

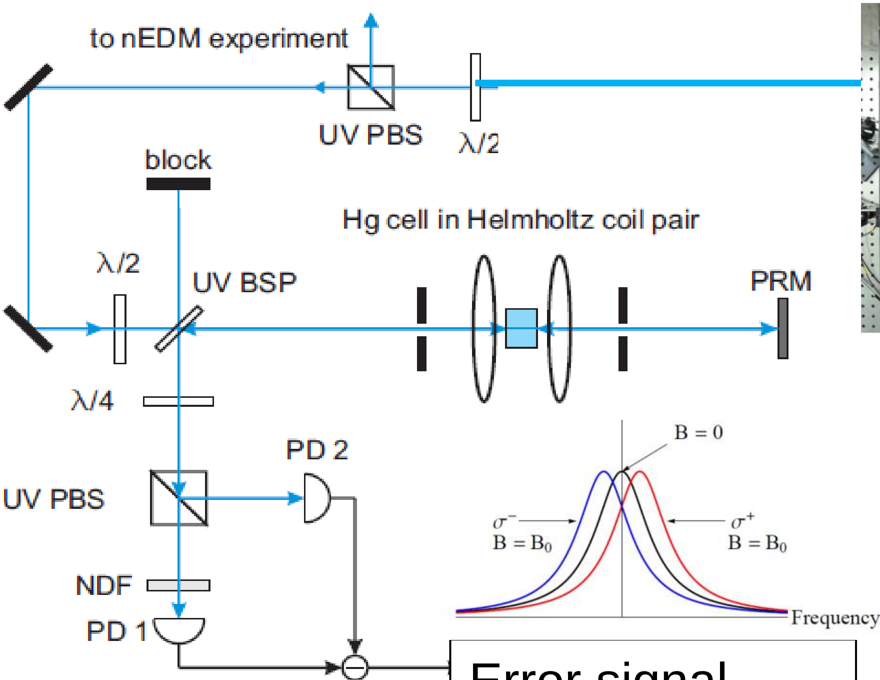
- Higher intensity
- Much lower frequency range of the light

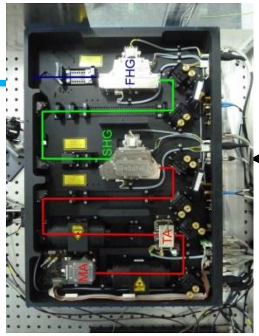


The laser system



Frequency stabilisation

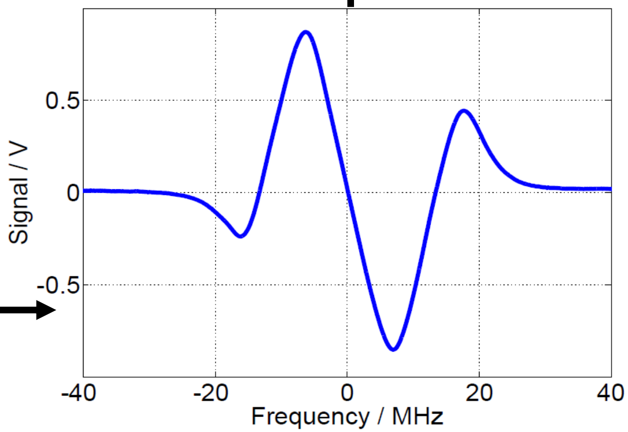




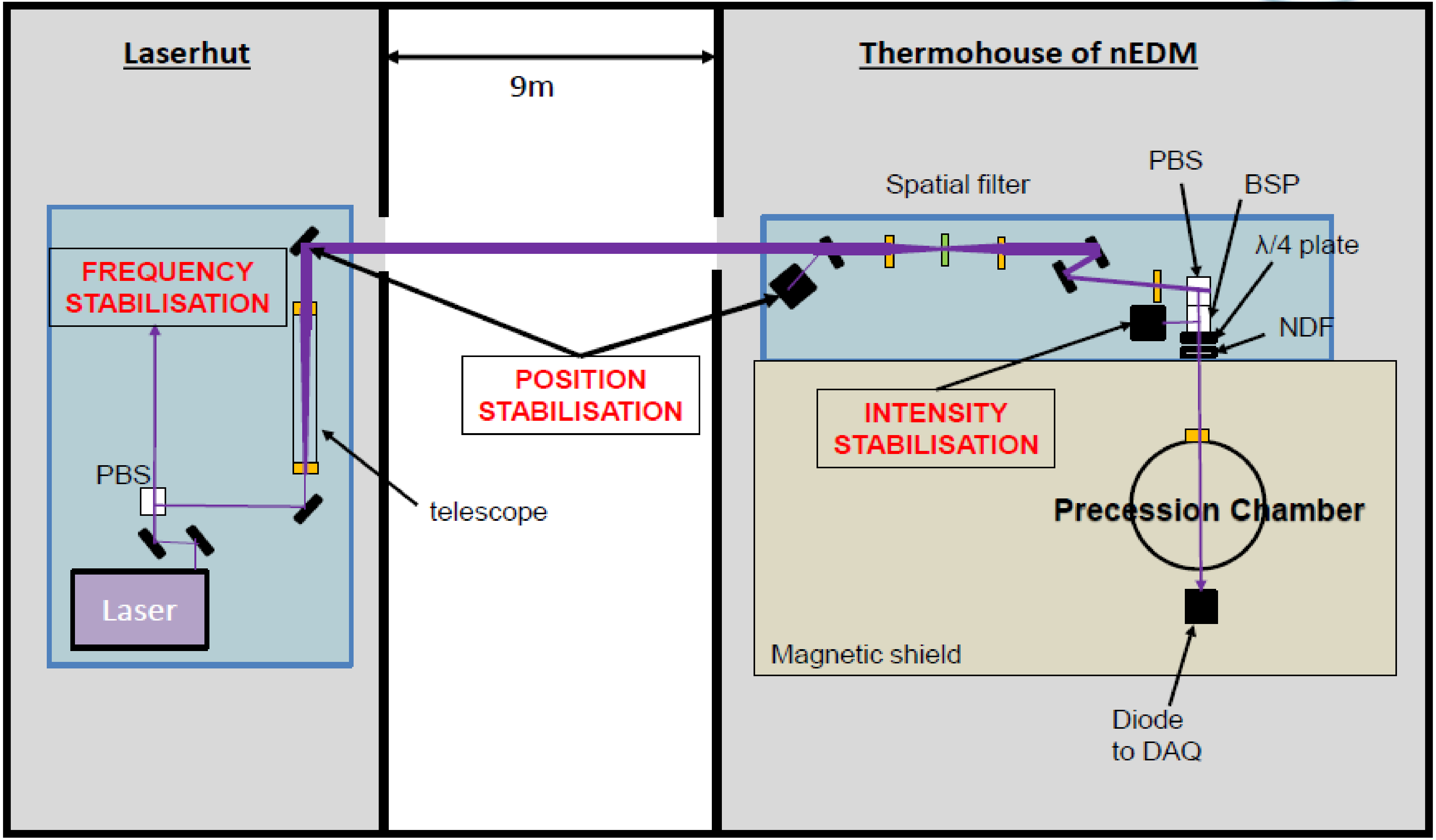
to feedback-loop

Error signal

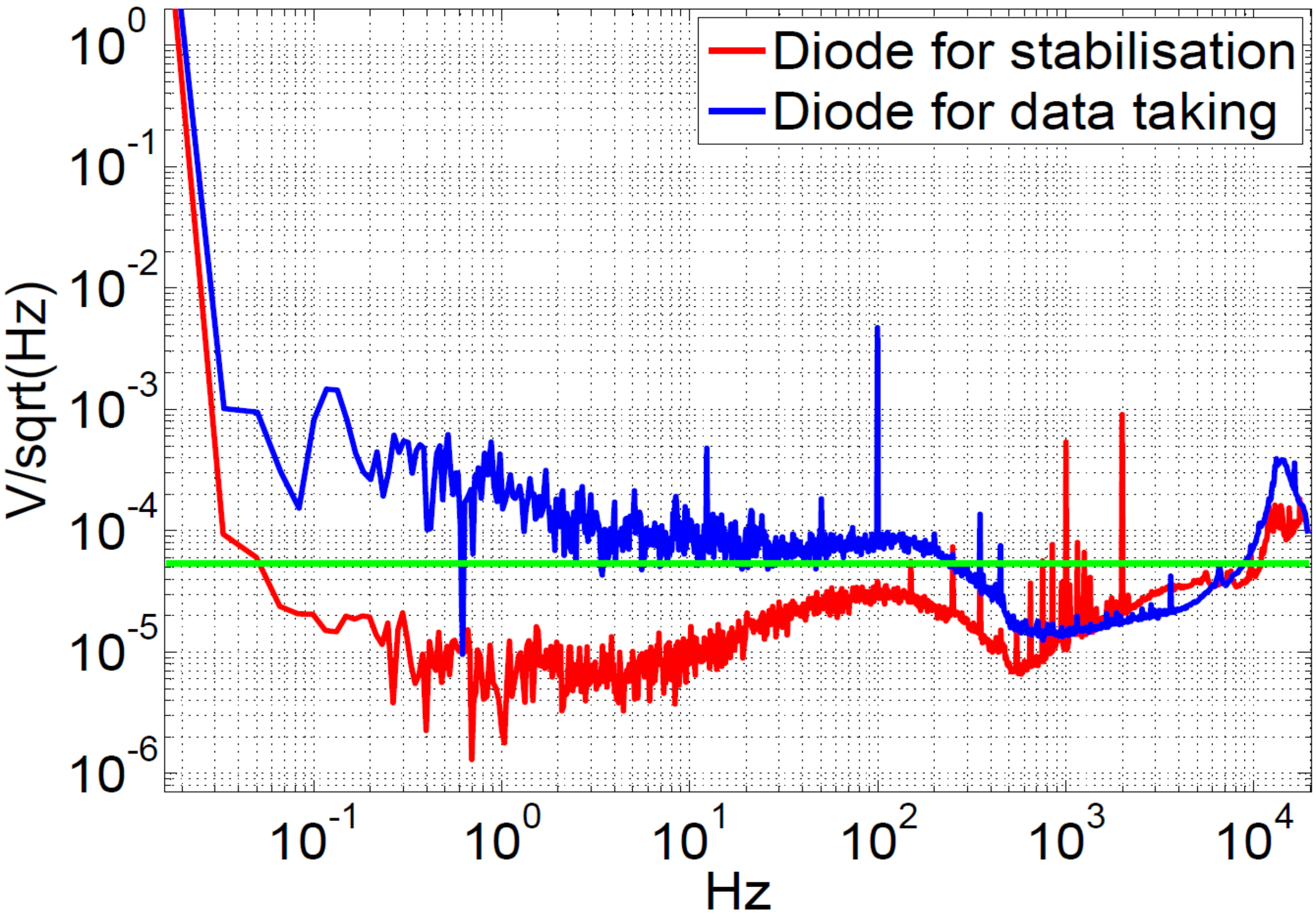
Second derivative with Lock-In amplifier



The laser system



Intensity stabilisation



Characterization of the performance

Cramer-Rao lower bound: $r = \tau / T$

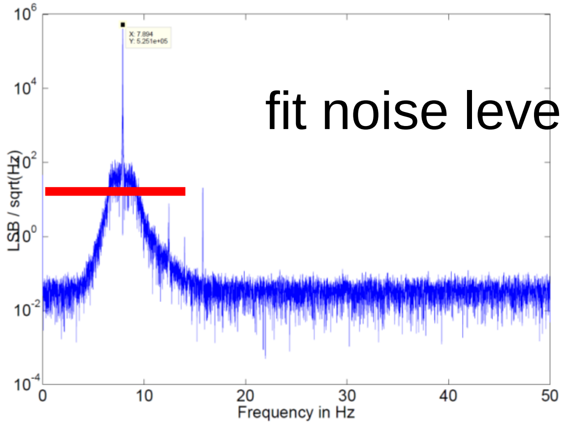
$$\delta \mathrm{B} \geq \frac{\sqrt{12}}{\gamma_{\mathrm{Hg}} \frac{a_s}{\rho} T^{3/2}} \underbrace{\sqrt{\frac{e^{2/r} - 1}{3r^3 \left(\cosh\left(2/r\right) - 1\right) - 6r}}}_{C(r)}$$

for typical values of T=180s and tau=100s

$$\left(\frac{a_s}{\rho}\right)_{\mathrm{n2EDM}} \geq 7700 \, \frac{\mathrm{V}}{\mathrm{V}/\sqrt{\mathrm{Hz}}}$$

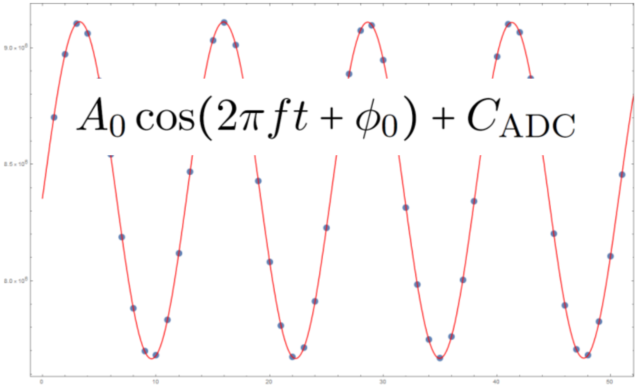
SNDR

FFT (Hanning windowed) of the 8Hz bandpass filtered signal



fit noise level: 45 $\frac{LSB}{Sqrt(Hz)}$

Fit signal amplitude of precession:



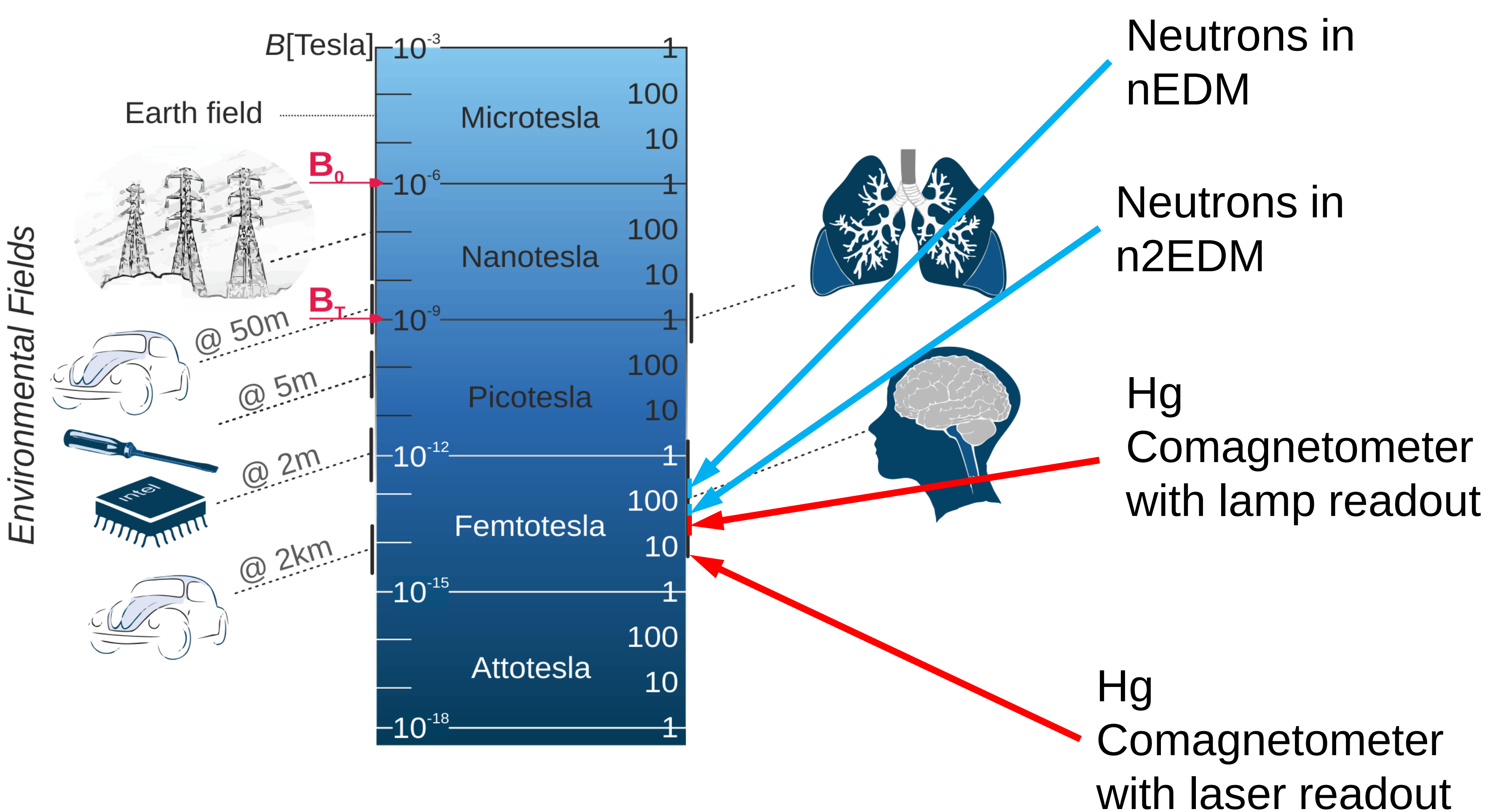
$$A_0 \cos(2\pi f t + \phi_0) + C_{\mathrm{ADC}}$$

SNDR :

$$10406\ \frac{LSB}{LSB/Sqrt(Hz)}$$

Calculated sensitivity with Cramer-Rao Lower Bond:

δB=7.5fT


B[Tesla]
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
Earth field
B_0
B_T
Microtesla
Nanotesla
Picotesla
Femtotesla
Attotesla
1
100
10
Environmental Fields
@ 50m
@ 5m
@ 2m
@ 2km
Neutrons in nEDM
Neutrons in n2EDM
Hg Comagnetometer with lamp readout
Hg Comagnetometer with laser readout

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