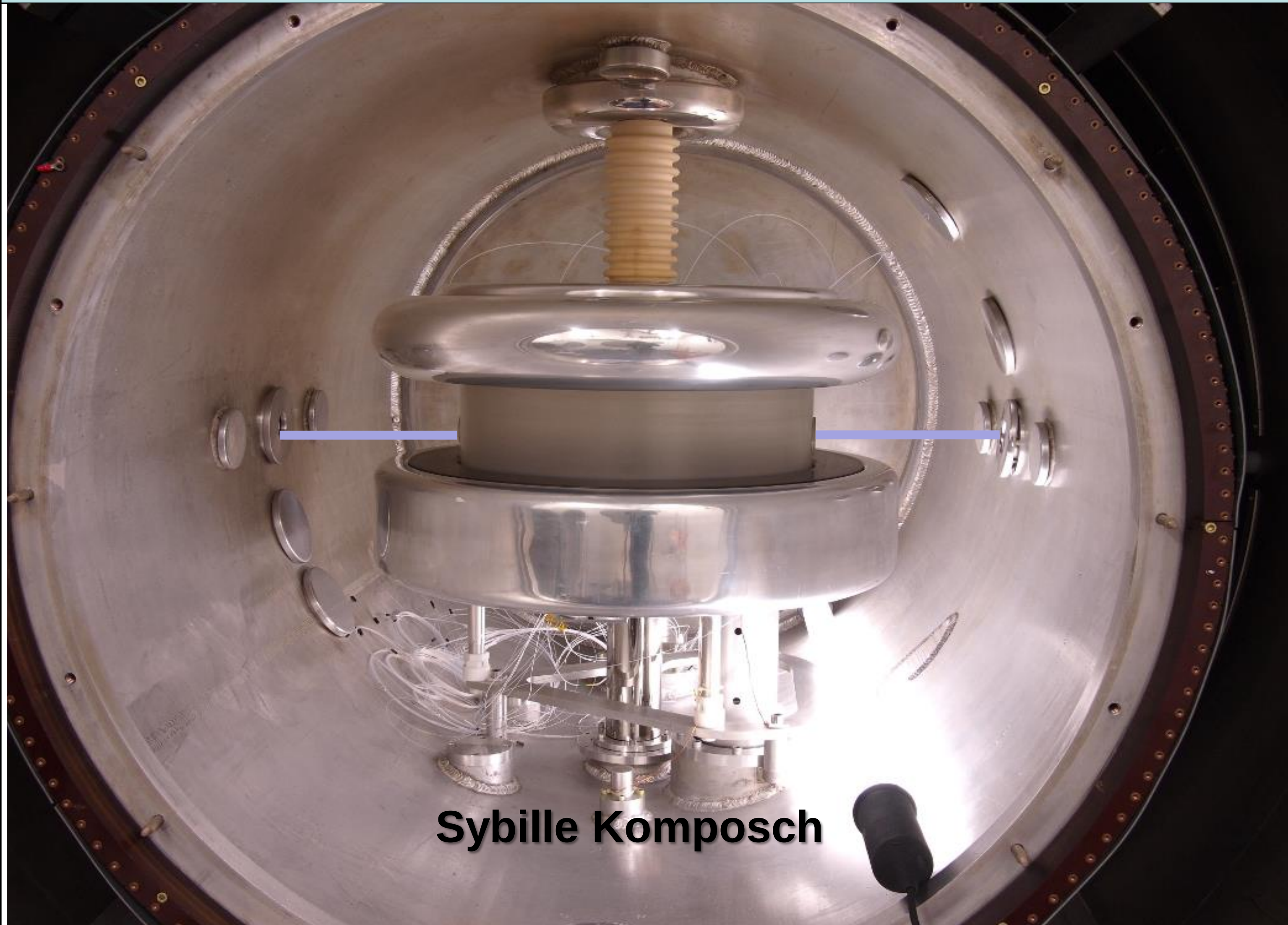
Realization of a high-performance laser-based mercury magnetometer for neutron EDM experiments

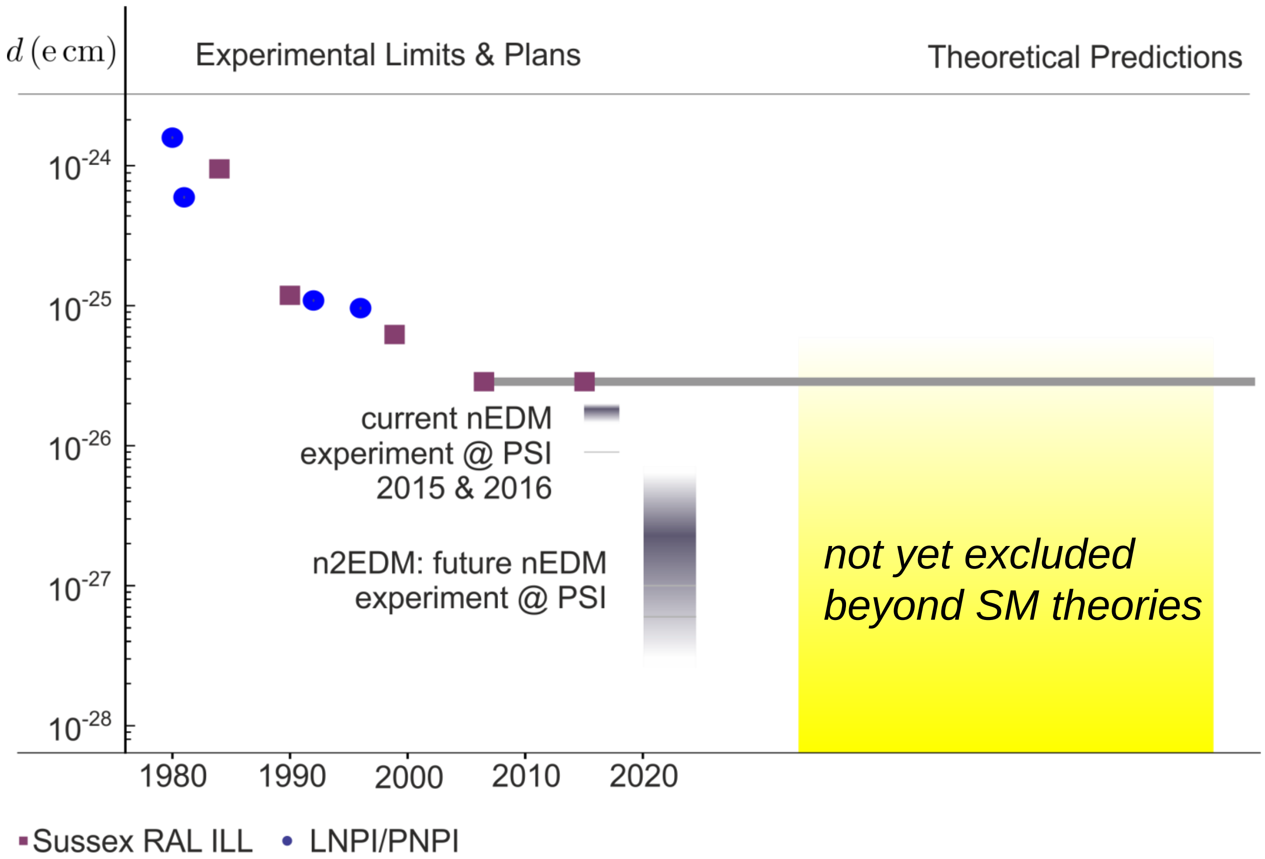


Sybille Komposch

PAUL SCHERRER INSTITUT

Why?

nEDM → new source of CP violation → important guide to explain the baryogenesis



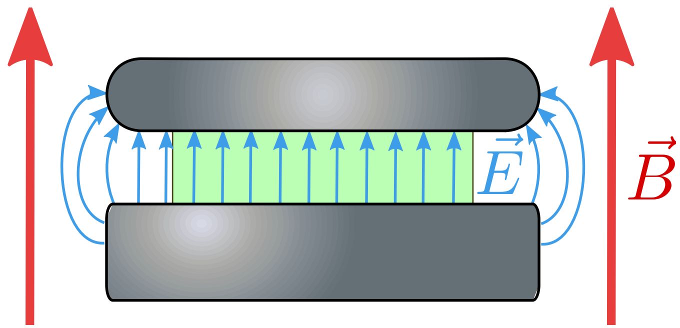
→ Predicted value by the Standard Model:

Khriplovich et al, Physics Letters B 109 (1982)

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

The measurement principle

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



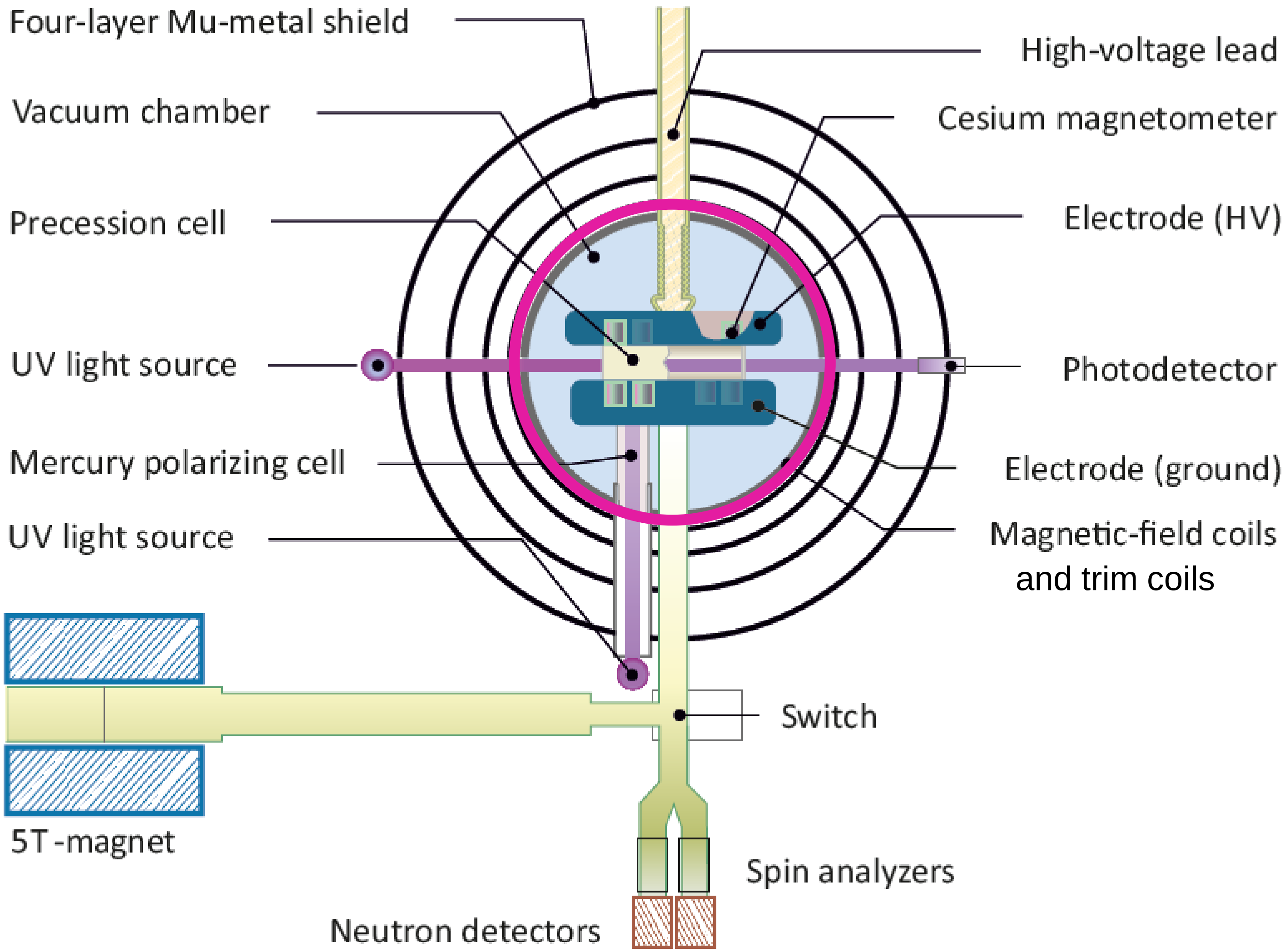
$\vec{B} \uparrow\downarrow \vec{E}$

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

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

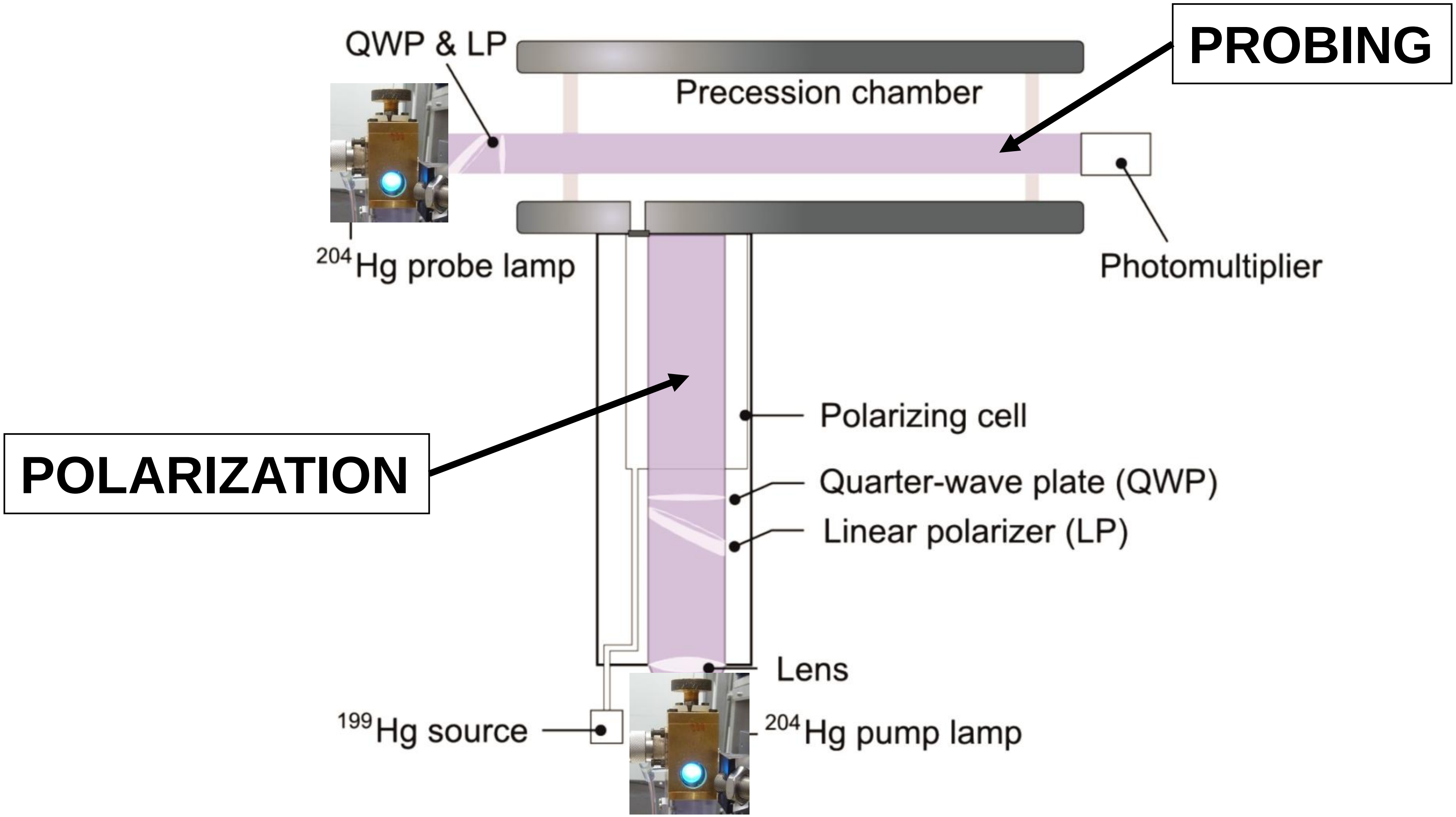
Correction of magnetic field drifts

The nEDM apparatus

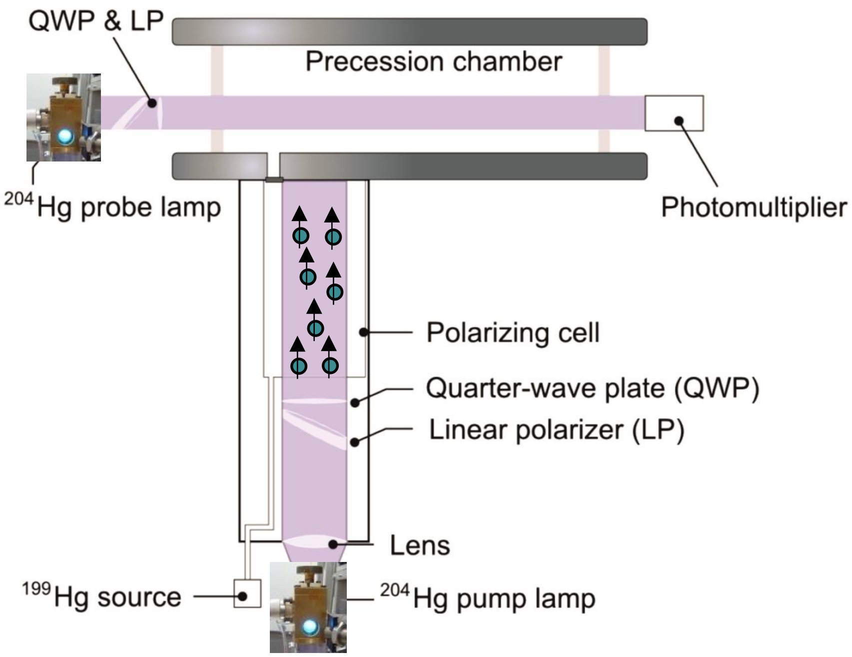


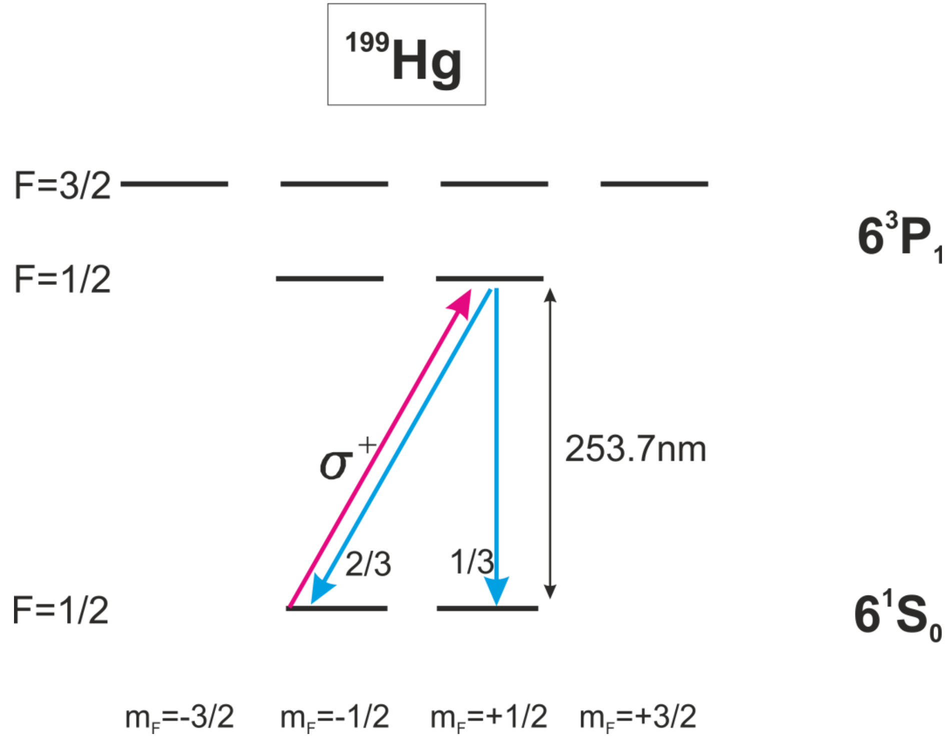
surrounding field compensation

Hg co-magnetometer



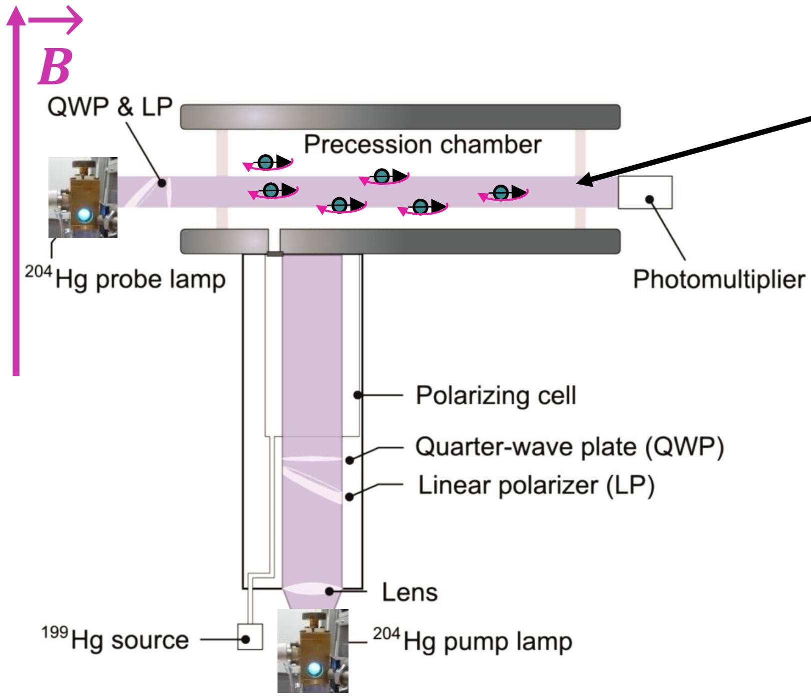
Optical Pumping

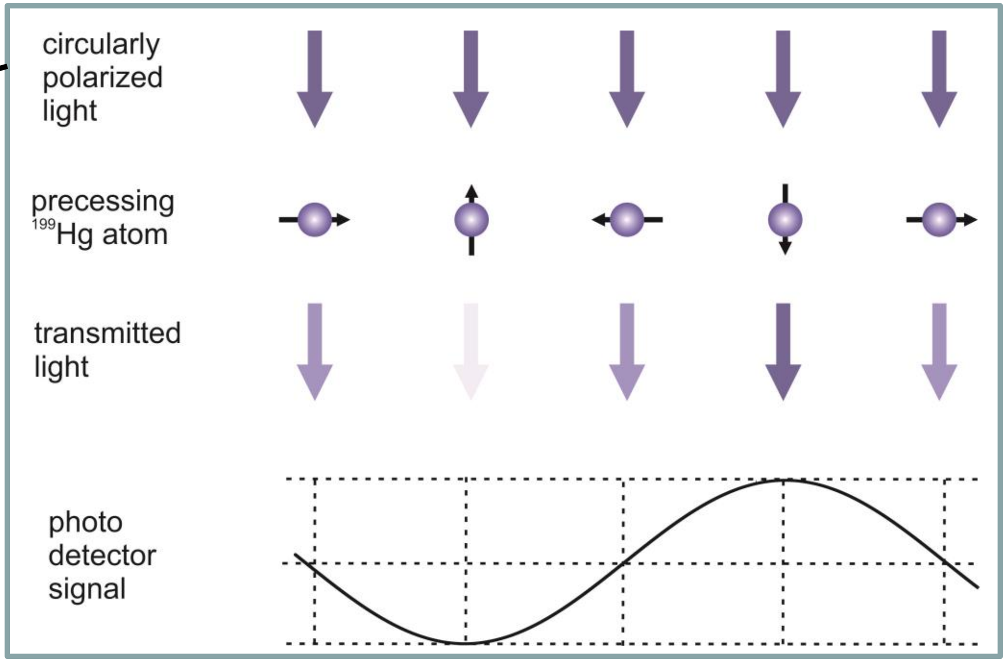




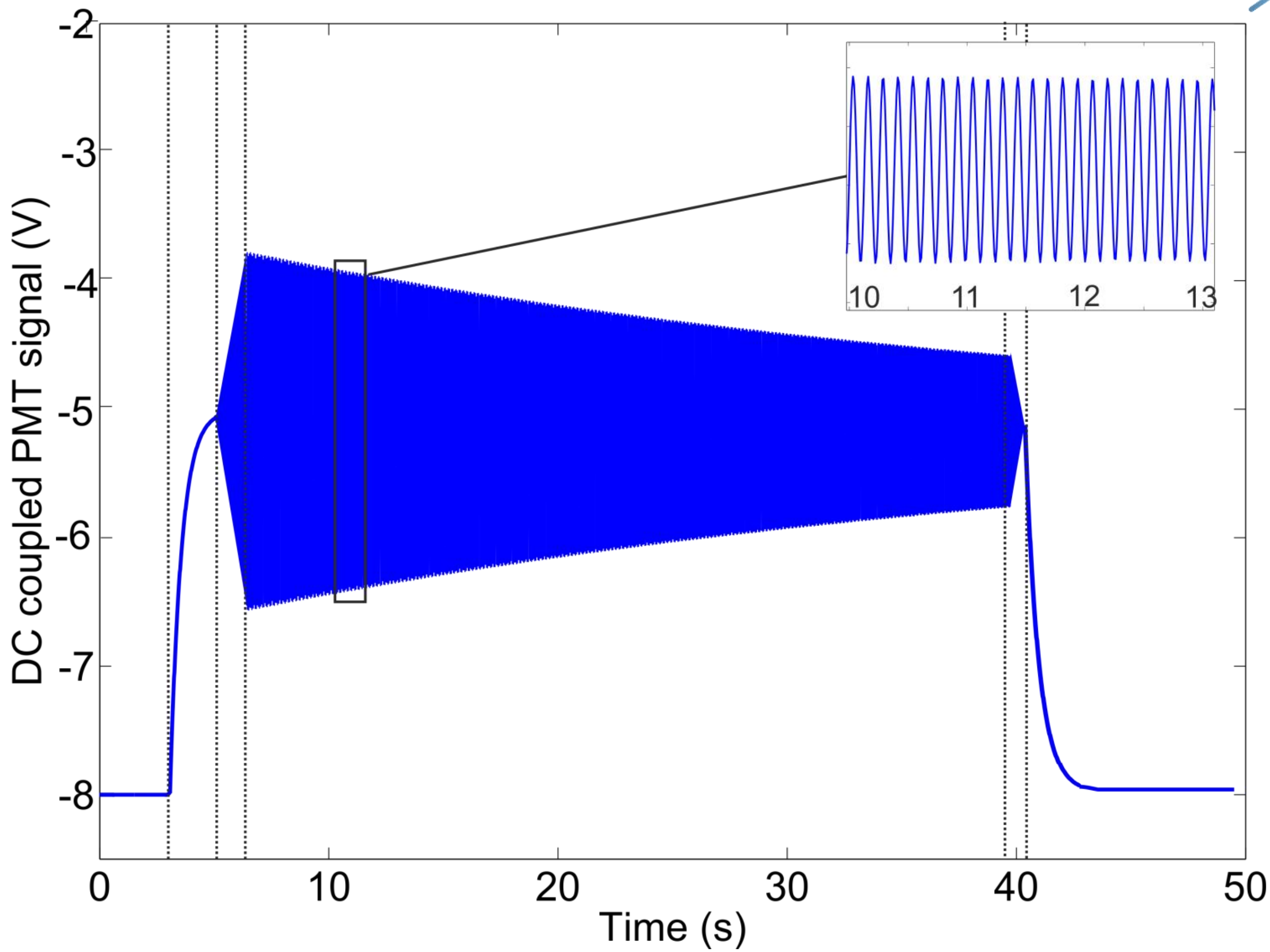
Probing

$$f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}} B}{2\pi} \approx 8\,\mathrm{Hz}\ @1\,\mu\mathrm{T}$$



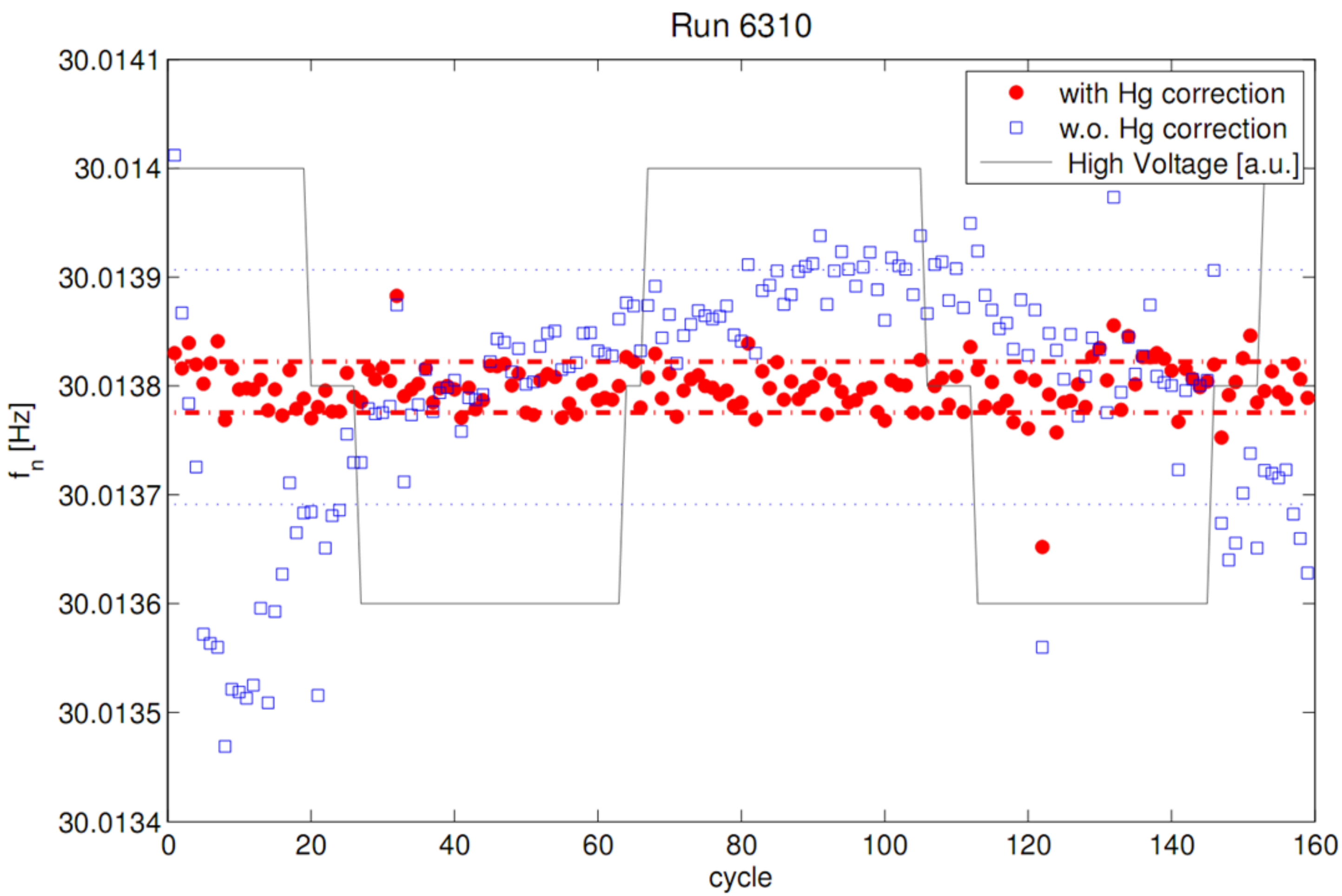


Hg Cycle



$$A(t) = a_s \, e^{-t/\tau} \sin\left(2\pi f t + \phi_0\right)$$

Magnetic field drift correction



Requirements

Correction:

$$\omega_n^* = \omega_n - \frac{\gamma_n}{\gamma_{Hg}}\omega_{Hg}$$

Error propagation:

$$\Delta\omega_n^* = \sqrt{\Delta\omega_n^2 + \left(\frac{\gamma_n}{\gamma_{Hg}}\Delta\omega_{Hg}\right)^2} = \Delta\omega_n K$$

Increase of the statistical error due to correction:

$$K = \sqrt{1 + \left(\frac{\Delta\omega_{Hg}/\omega_{Hg}}{\Delta\omega_n/\omega_n}\right)^2}$$

For nEDM: K < 1.05 →

$$\frac{\Delta\omega_{Hg}}{\omega_{Hg}} = \frac{\Delta B}{|B_0|} < \frac{1}{3.1}\frac{\Delta\omega_n}{\omega_n}$$

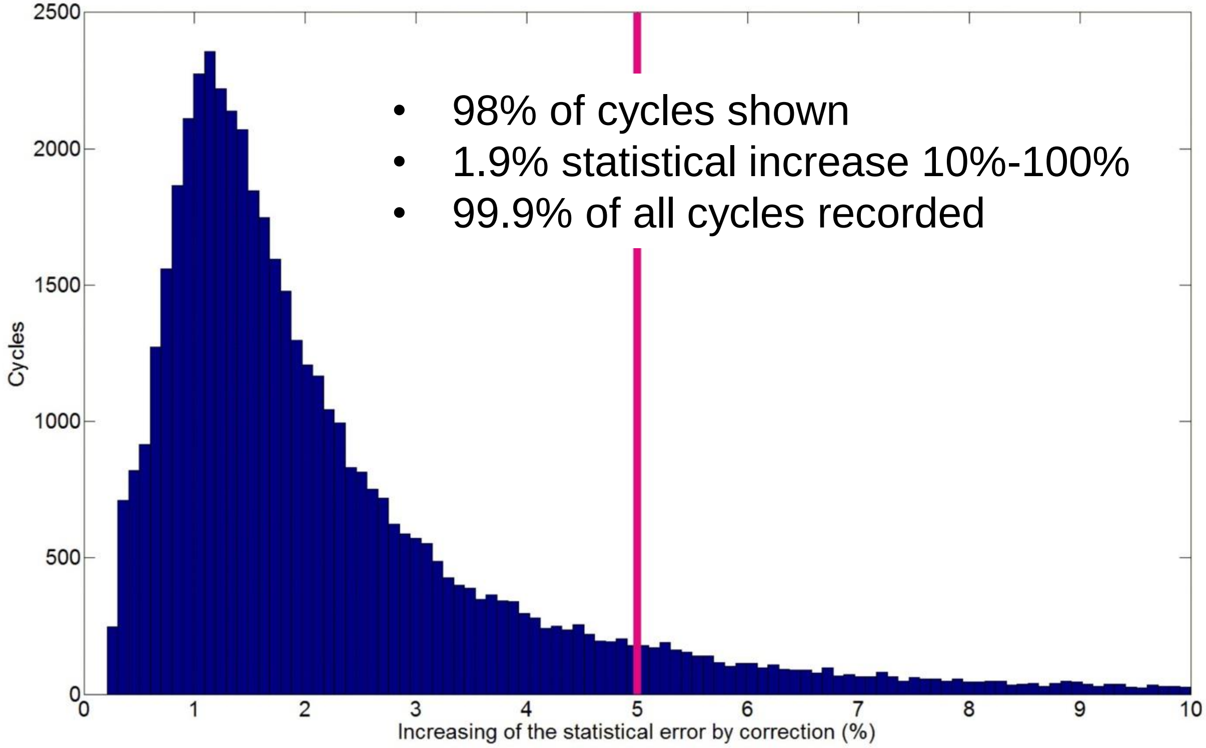
$$\Delta\omega_n/\omega_n = 0.25\,\mathrm{ppm} \quad \longrightarrow \quad \Delta\omega_{Hg}/\omega_{Hg} < 0.08\,\mathrm{ppm}$$

Magnetometric resolution:

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

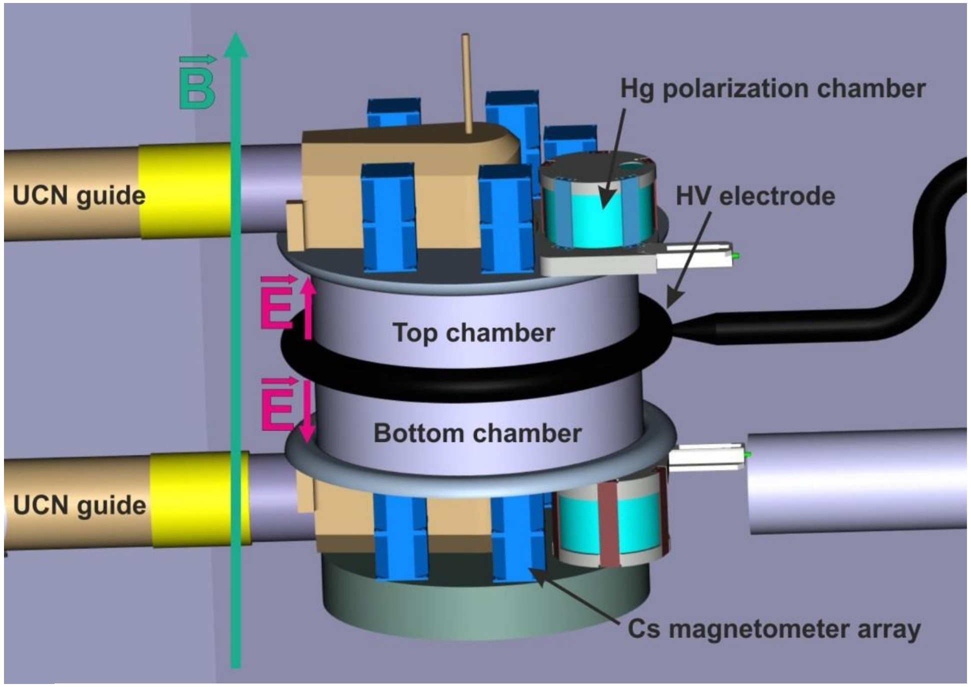
Performance Hg magnetometer in nEDM

Data taking 2015-2016: 56007 cycles in total



- 98% of cycles shown
- 1.9% statistical increase 10%-100%
- 99.9% of all cycles recorded

Preview: n2EDM setup



Magnetometric resolution per cycle:

$$\Delta B = 16\,\mathrm{fT}$$

	d chamber (cm)	Coating	α	E (kV/cm)	N UCN per cycle after 180 s	$\sigma(d_n)$ ($e\cdot$cm) per day	$\sigma(d_n)$ ($e\cdot$cm) 500 data days
nEDM	47	dPS, DLC	0.75	11	15000	11×10^{-26}	5.0×10^{-27}
n2EDM	47	dPE, DLC	0.8	15	100300	2.8×10^{-26}	1.3×10^{-27}
n2EDM	80	dPE, DLC	0.8	15	292000	1.7×10^{-26}	7.5×10^{-28}
n2EDM	100	dPE, DLC	0.8	15	400000	1.4×10^{-26}	6.4×10^{-28}

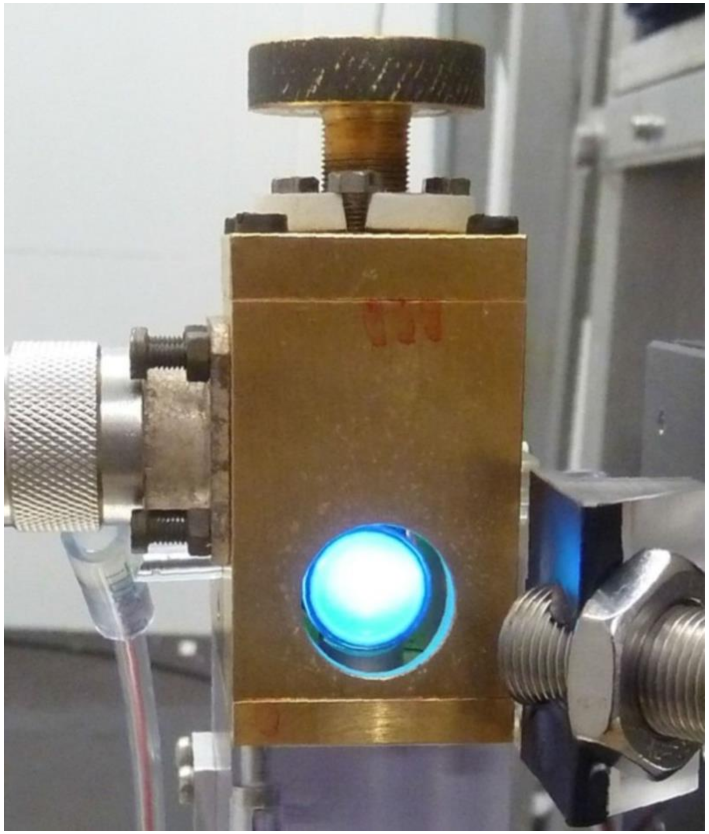
n2EDM - Design status report 2017

Sensitivity lamp-based magnetometer

<u>Sensitivity: > 35 fT</u>

Large uncertainty on the output frequency Spectrum:

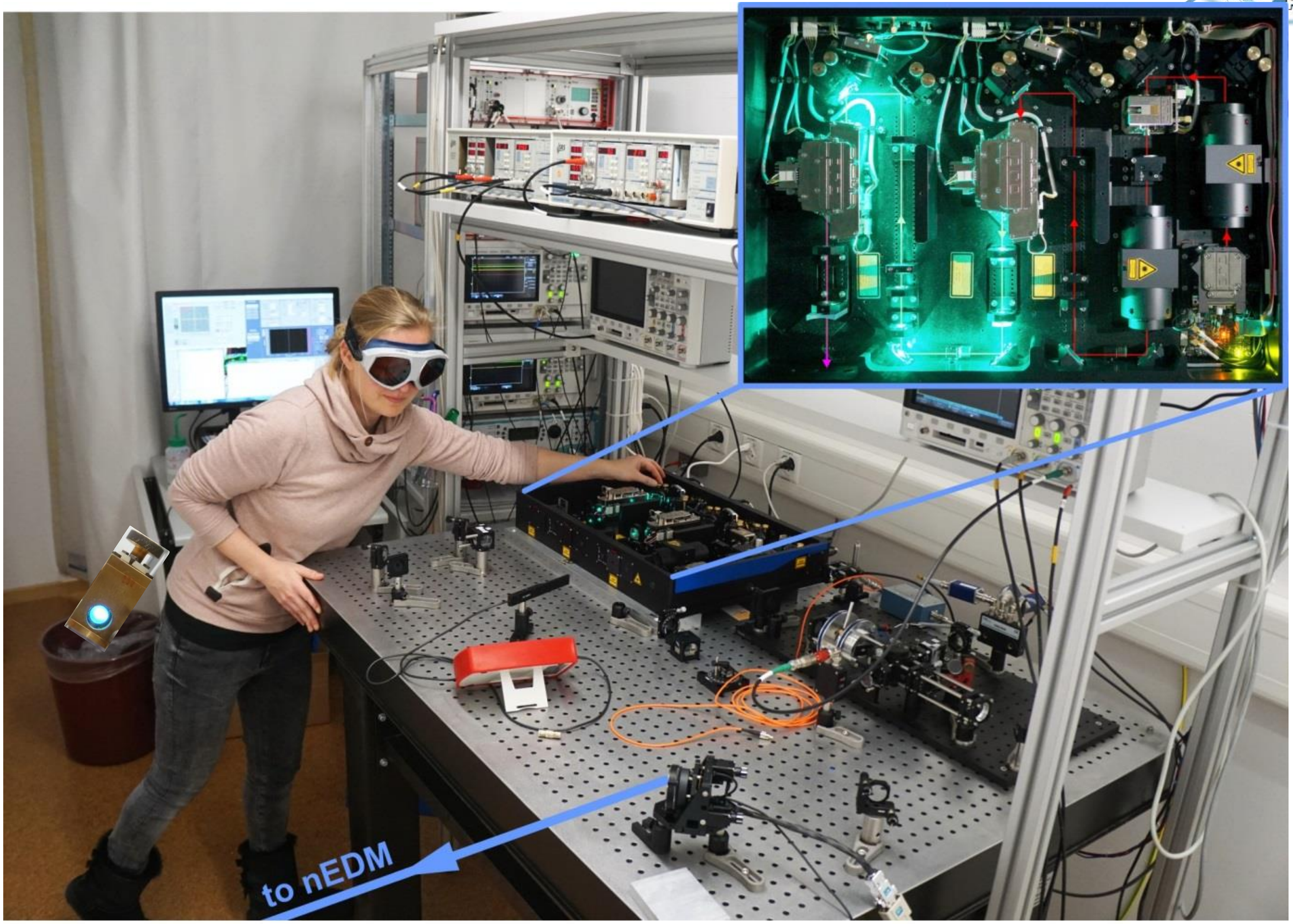
- **Emission light is Doppler-broadend**
- **Self absorption**
- **Light cannot be focused / collimated**
- **….**



→ Improve with UV-laser-system

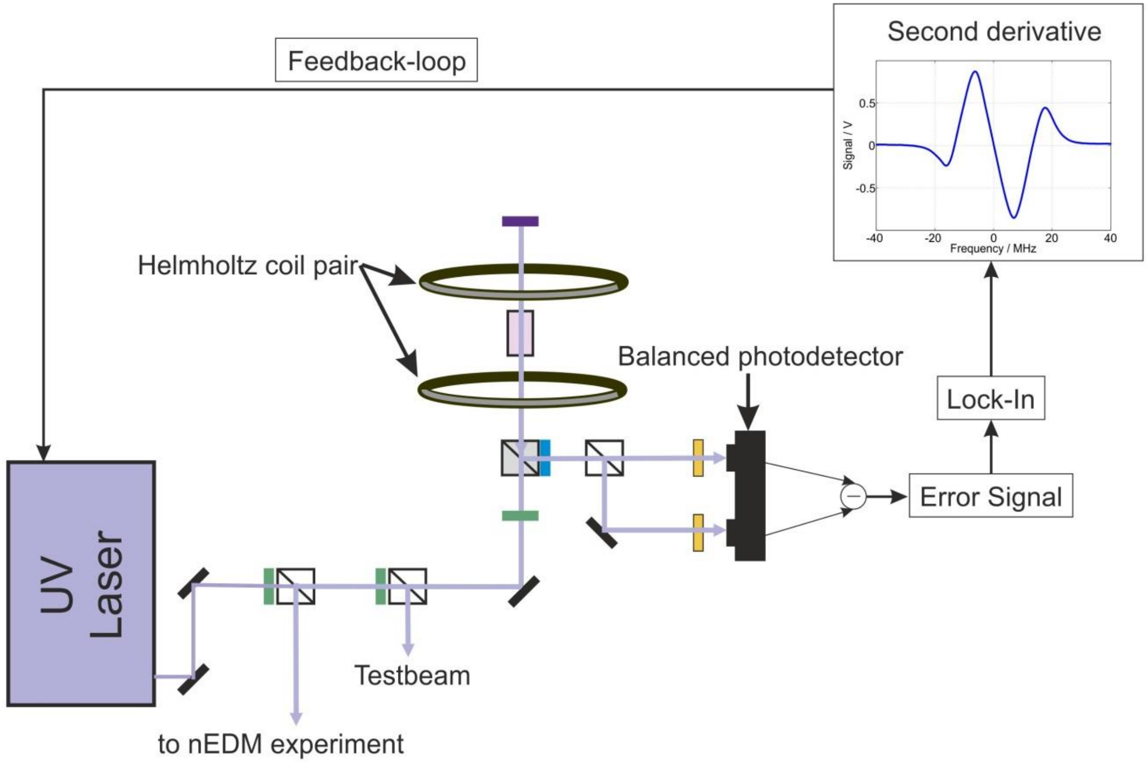
Proof of principle measurement:
5-fold signal increase
(Thesis M. Fertl 2013, ETHZ)

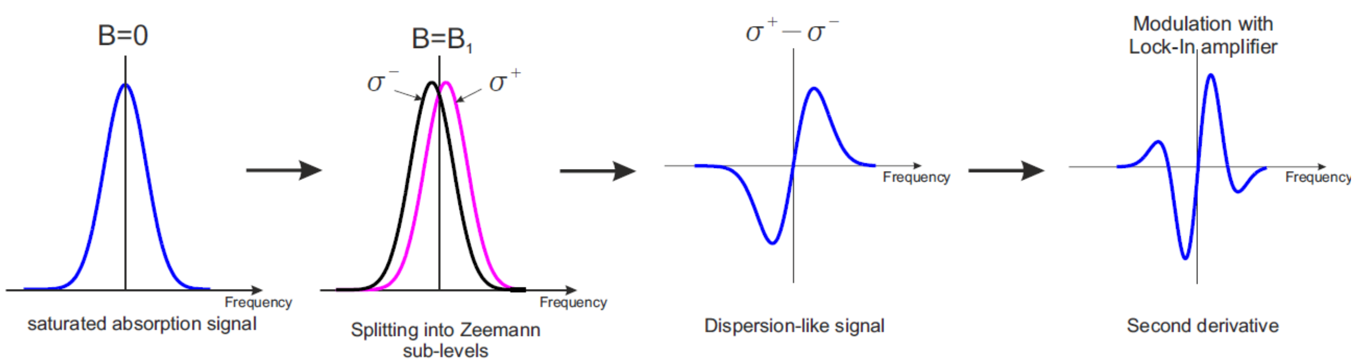
The UV laser



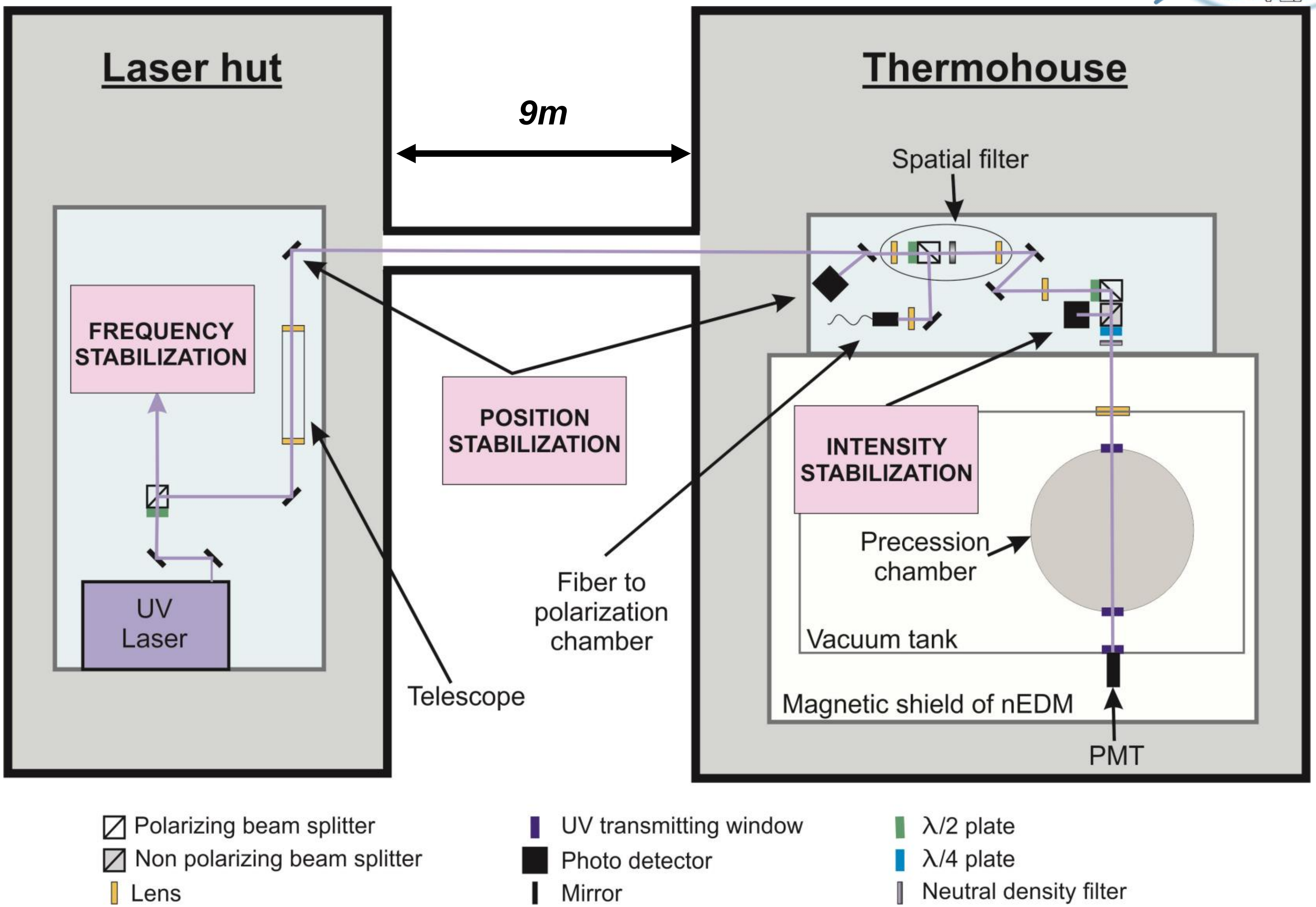
Frequency stabilization

Dichroic atomic vapor laser lock

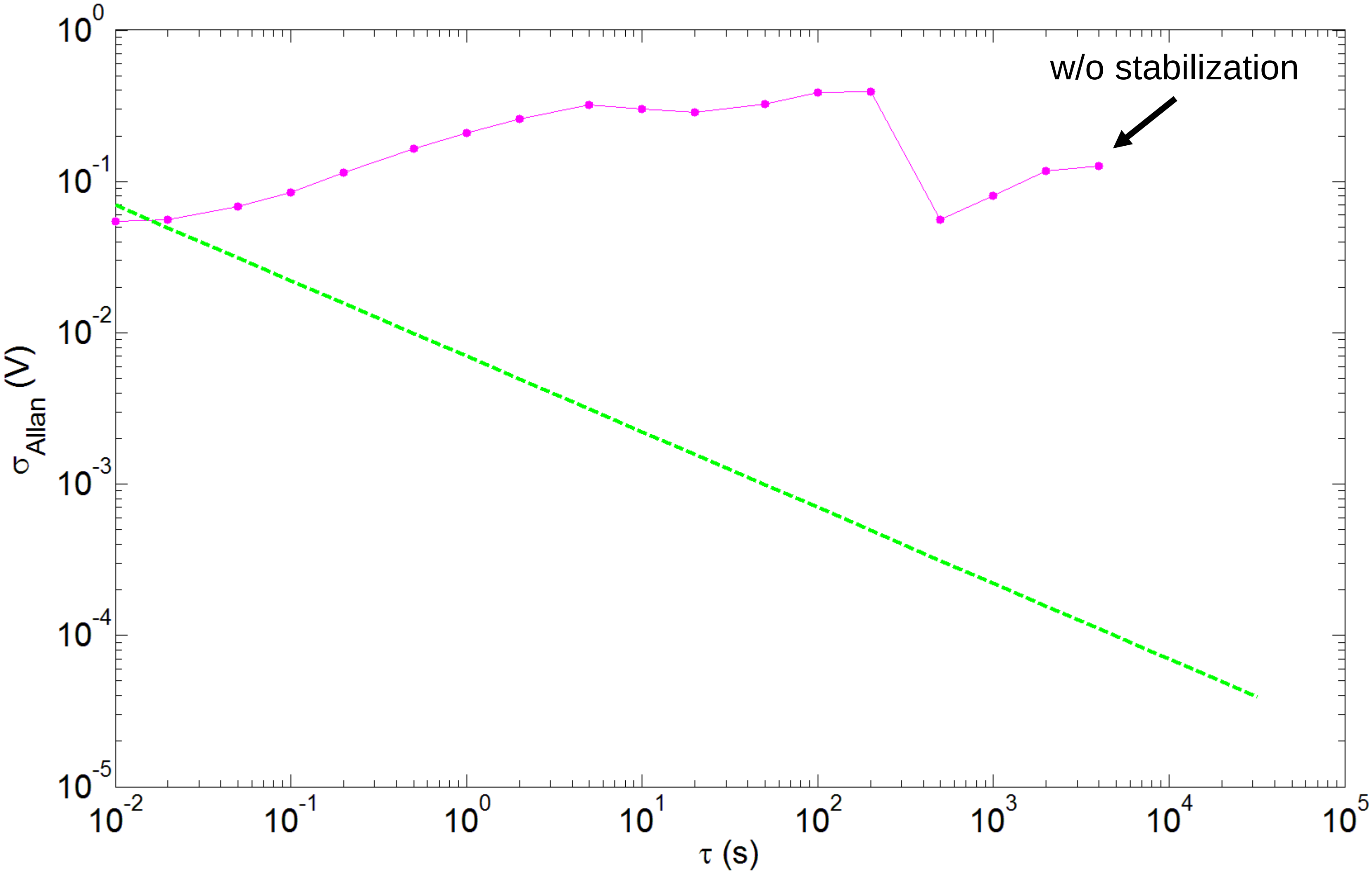




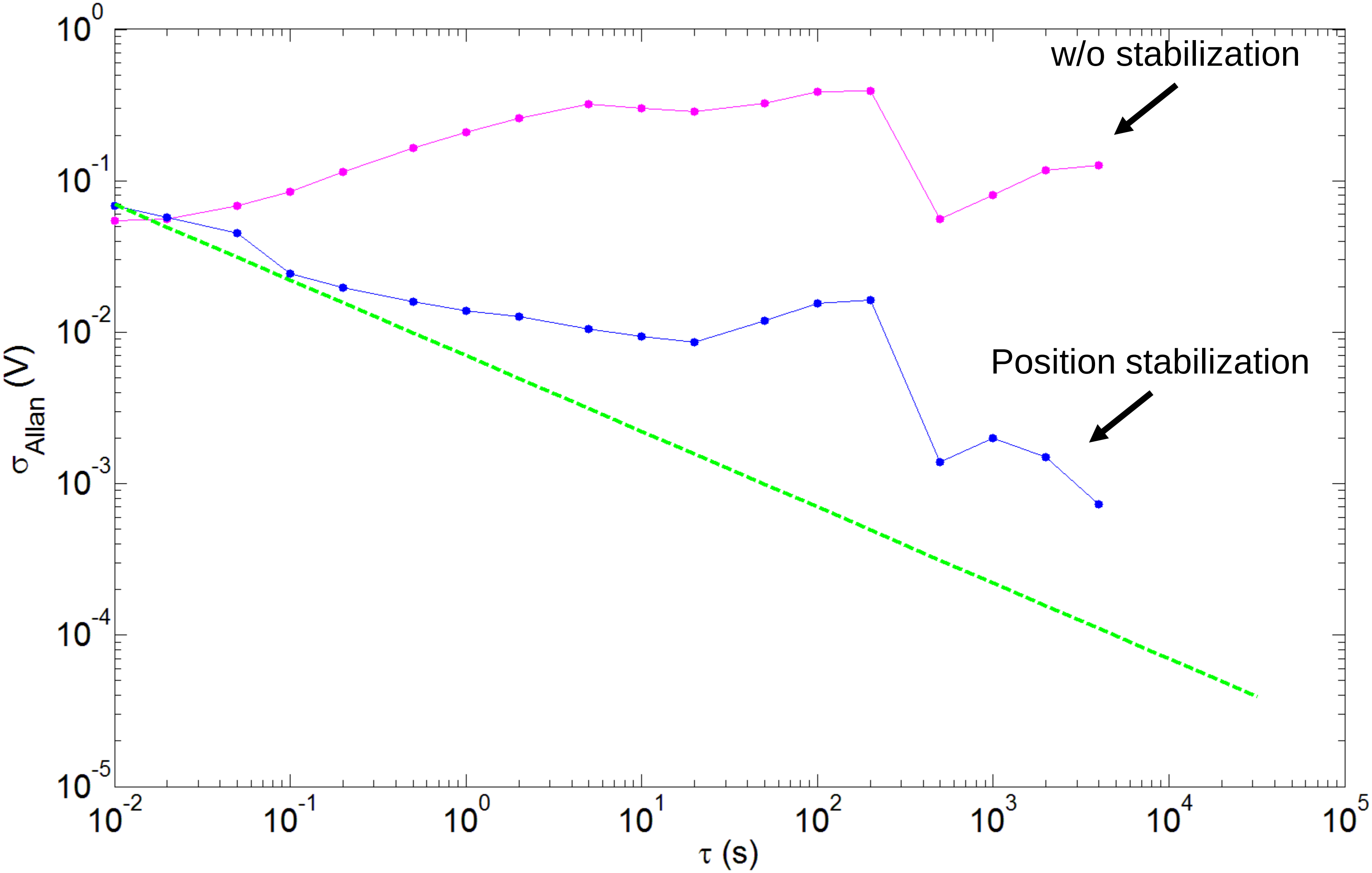
Sketch of the laser system



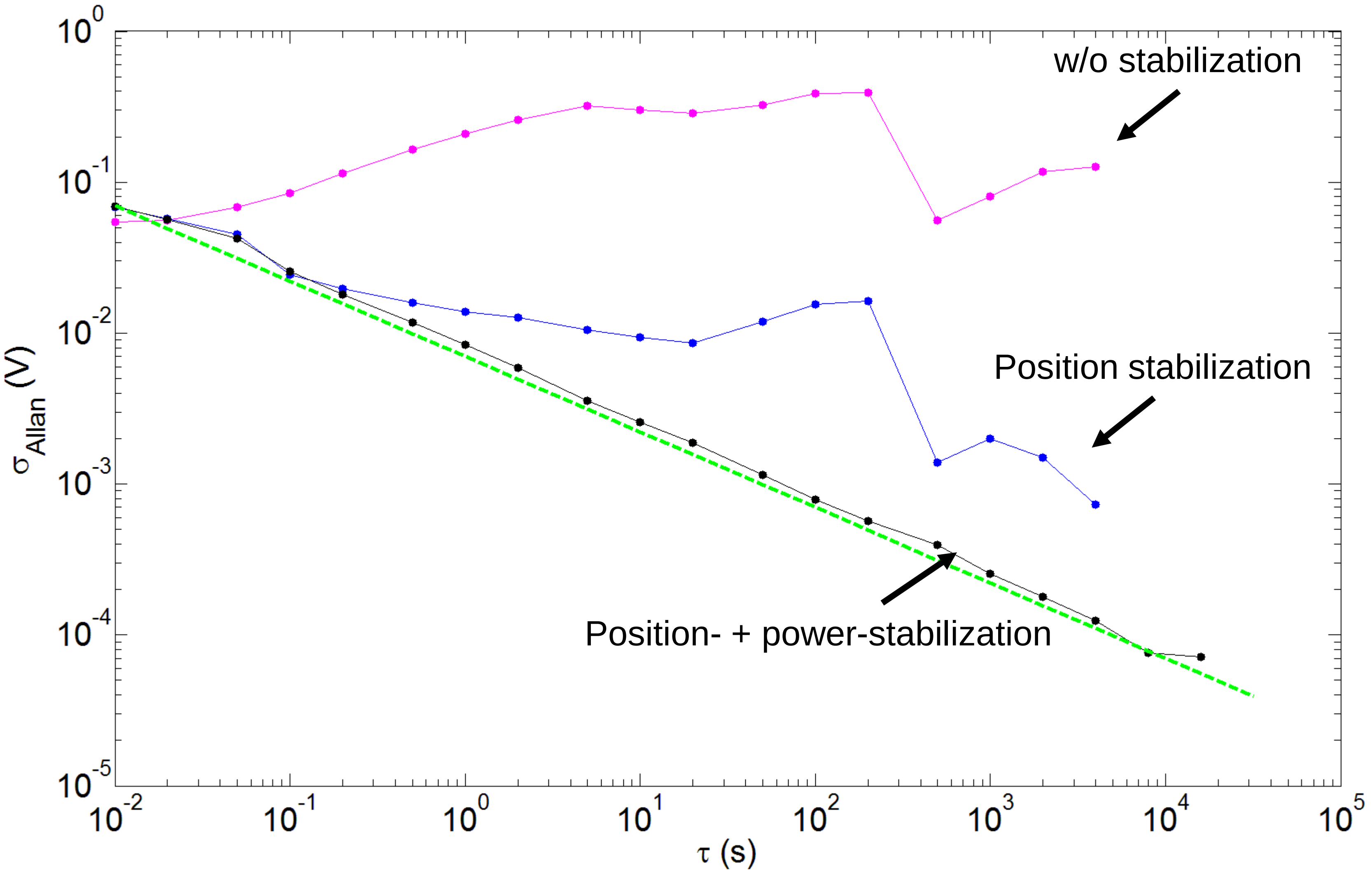
Position- and Power-stabilization



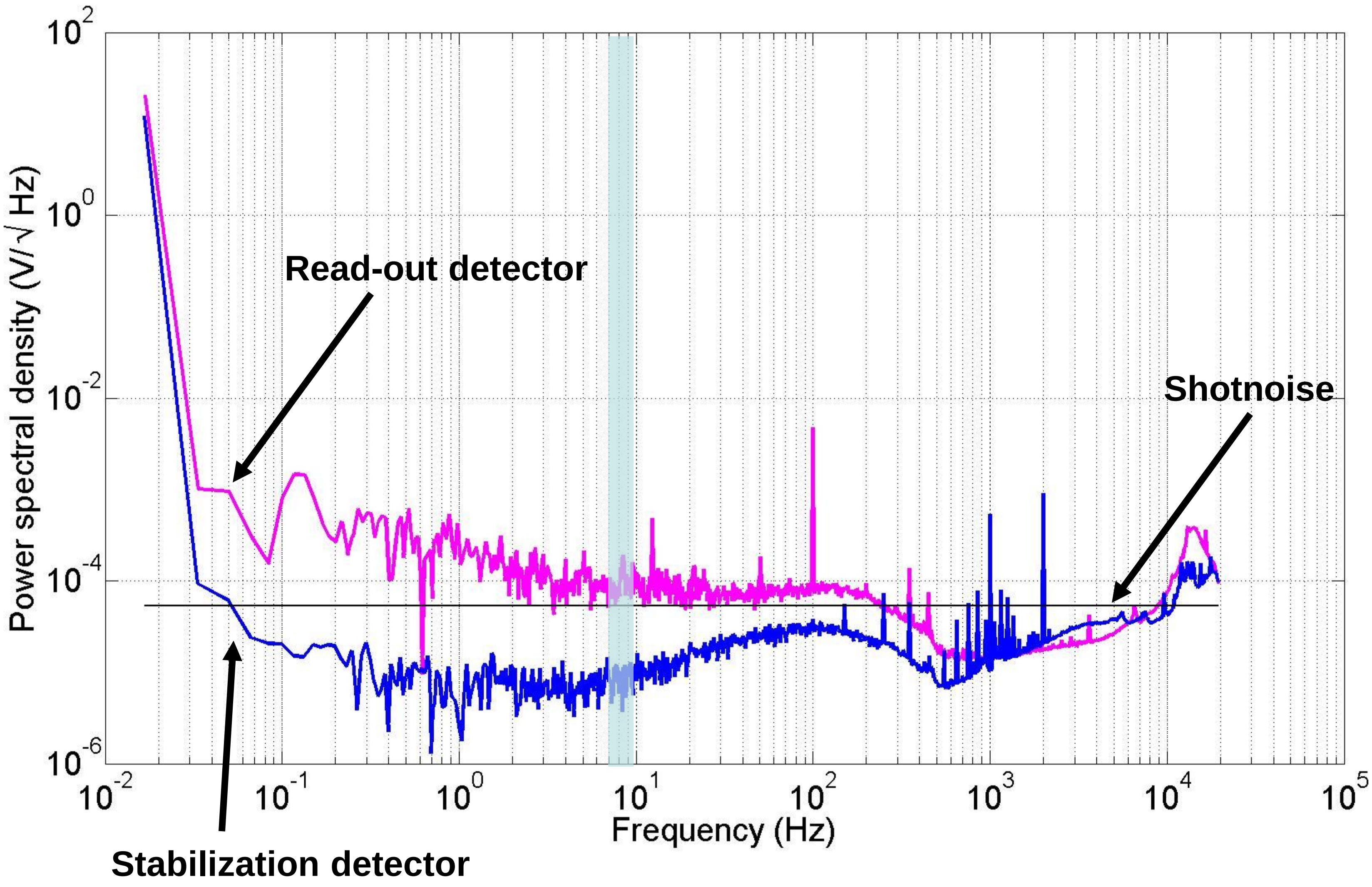
Position- and Power-stabilization



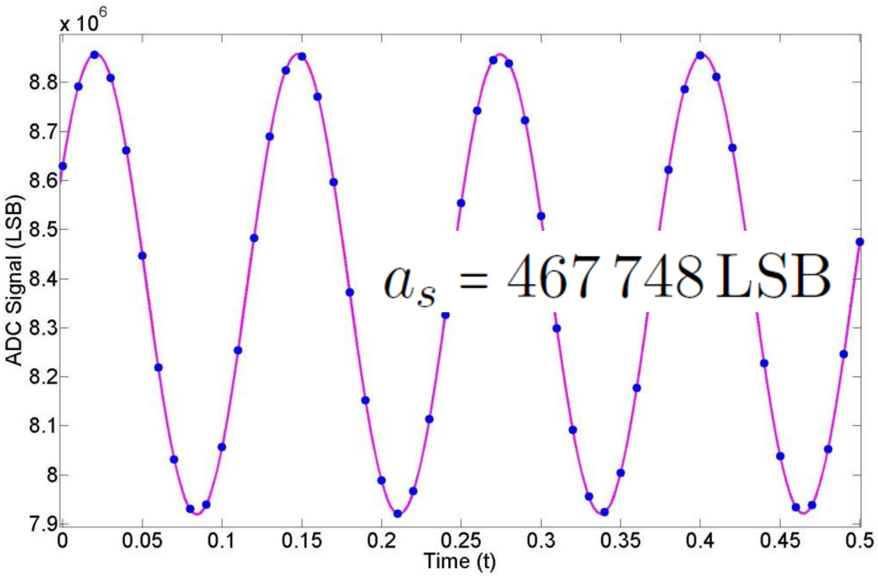
Position- and Power-stabilization



Position- and Power-stabilization



Performance



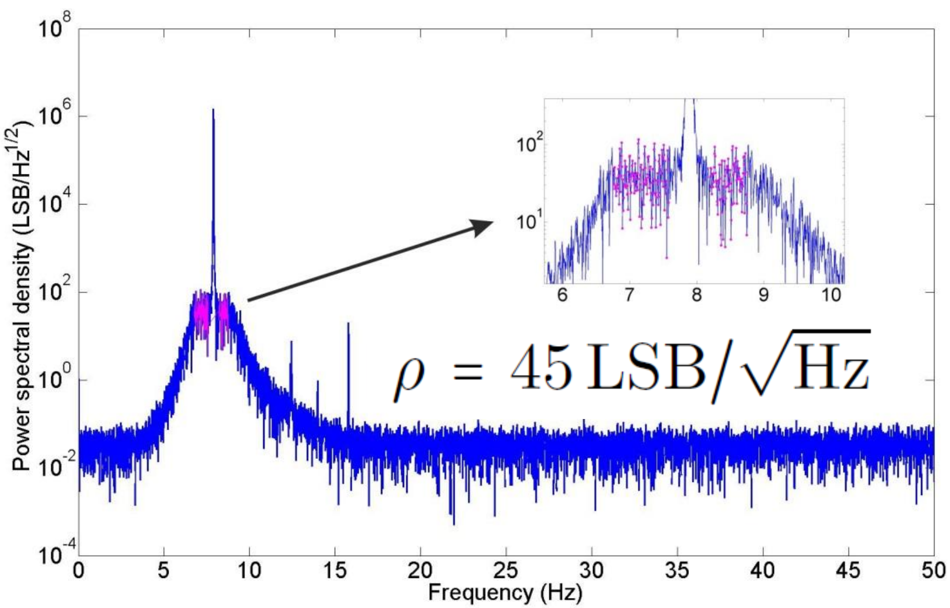
$\rightarrow$ SNDR of $10\,405\,\sqrt{\mathrm{Hz}}$

Cramer-Rao-Lower bound:

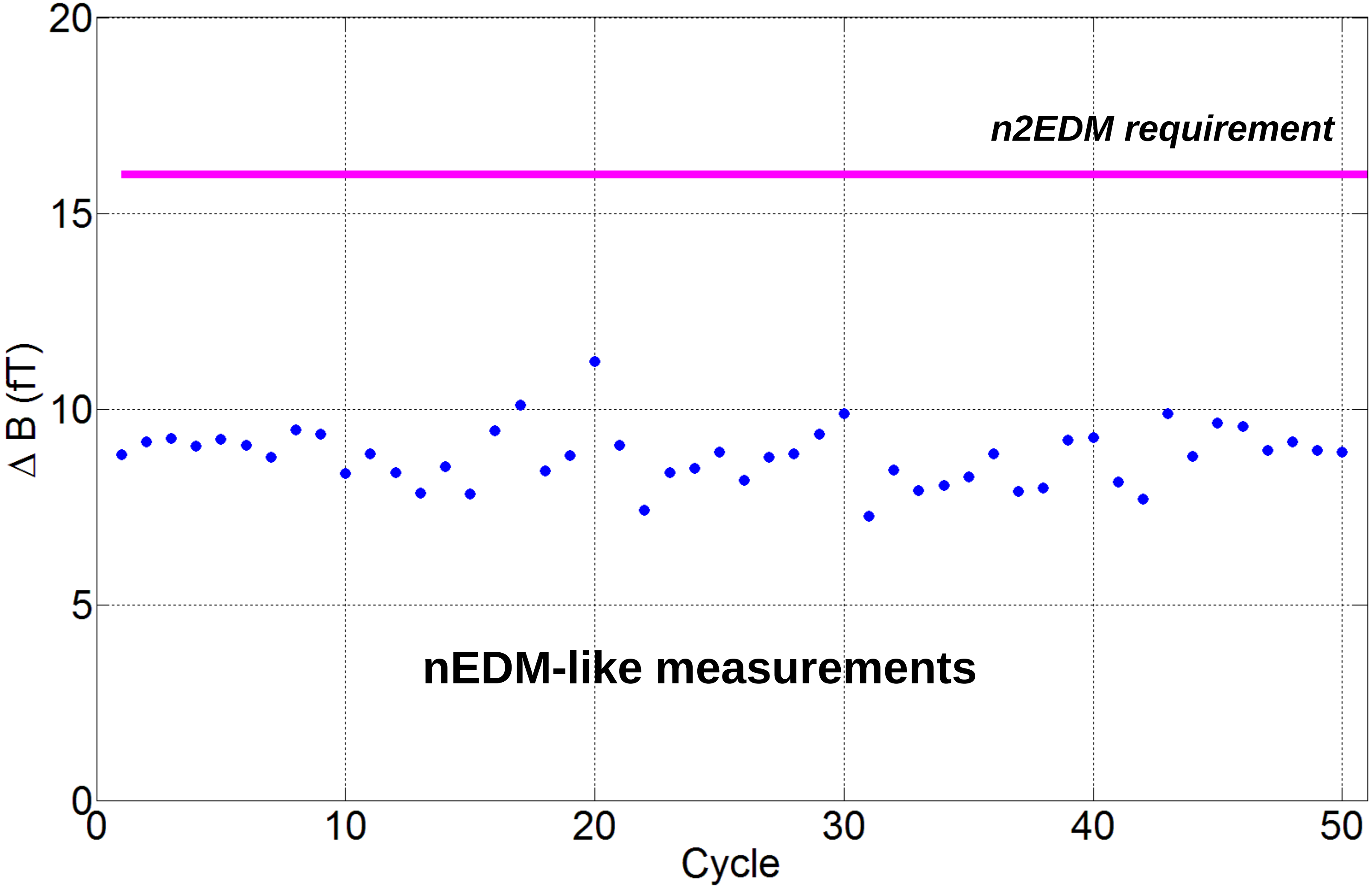
$$\delta B \geq \frac{\sqrt{12}}{\gamma \frac{a_s}{\rho} T^{3/2}} C(r)$$

$$C(r) = \sqrt{\frac{e^{2/r} - 1}{3r^3\left(\cosh\left(2/r\right) - 1\right) - 6r}}$$

$\rightarrow$ $\delta B = 7.5\,\mathrm{fT}$



Performance



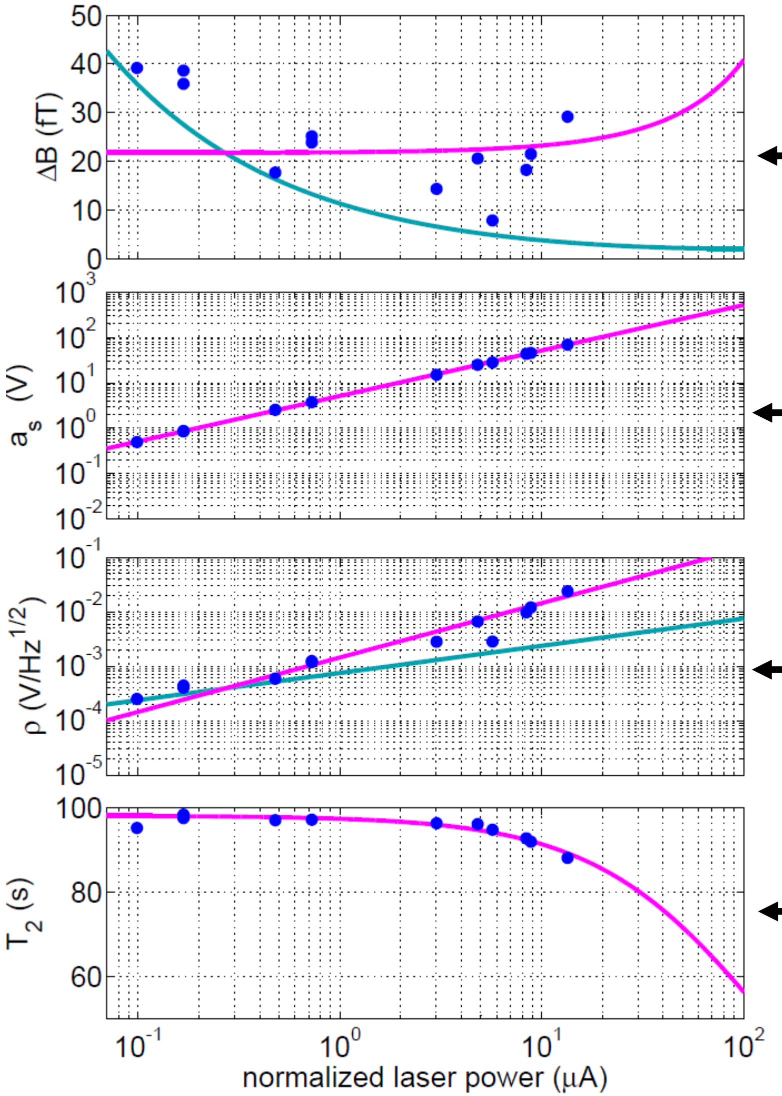
Conclusion

- $$d_n = \frac{1}{2E}\left(h\left(f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow}\right) + \mu_n\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)\right)$$
- Very good performance of the Hg magnetometer in the nEDM experiment :
  99.9% of all nEDM cycles recorded, induced statistical error 2.88% (goal <5%)
- Laser-based Hg magnetometer realized exceeding the performance requirements of n2EDM
  Magnetometric resolution a factor 2 better (shown: 8fT, goal:<16fT)

Thank You!

and
the nEDM collaboration

Laser power optimization



Magnetometric resolution calculated with Cramer-Rao Lower Bound

Amplitude

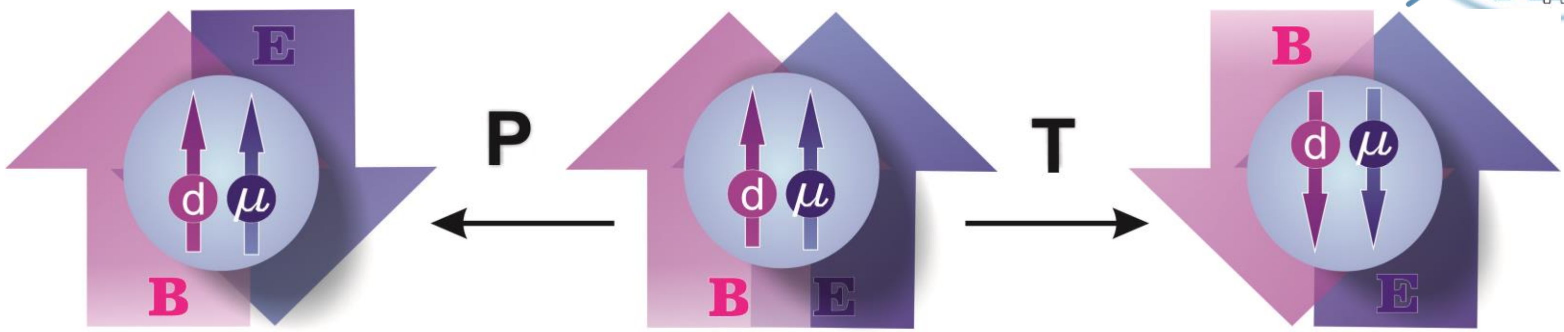
Noise density (Shot noise and technical noise)

Depolarisation by light:

$$T_2 = \frac{1}{\frac{1}{T_i} + \frac{P}{L_P}}$$

Back Up

CP violation and nEDM

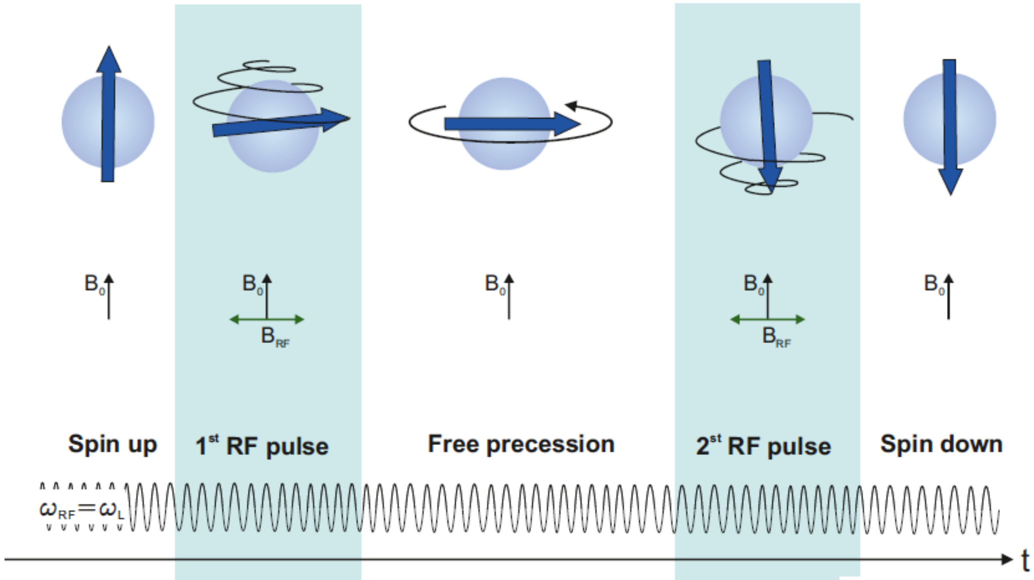


$$\mathcal{H} = -d\frac{\vec{s}}{|\vec{s}|}\vec{E} - \mu\frac{\vec{s}}{|\vec{s}|}\vec{B}$$

$$\hat{P}\mathcal{H} = -d\frac{\vec{s}}{|\vec{s}|}(-\vec{E}) - \mu\frac{\vec{s}}{|\vec{s}|}\vec{B} \neq \mathcal{H}$$

$$\hat{T}\mathcal{H} = -d\frac{-\vec{s}}{|\vec{s}|}\vec{E} - \mu\frac{-\vec{s}}{|\vec{s}|}(-\vec{B}) \neq \mathcal{H}$$

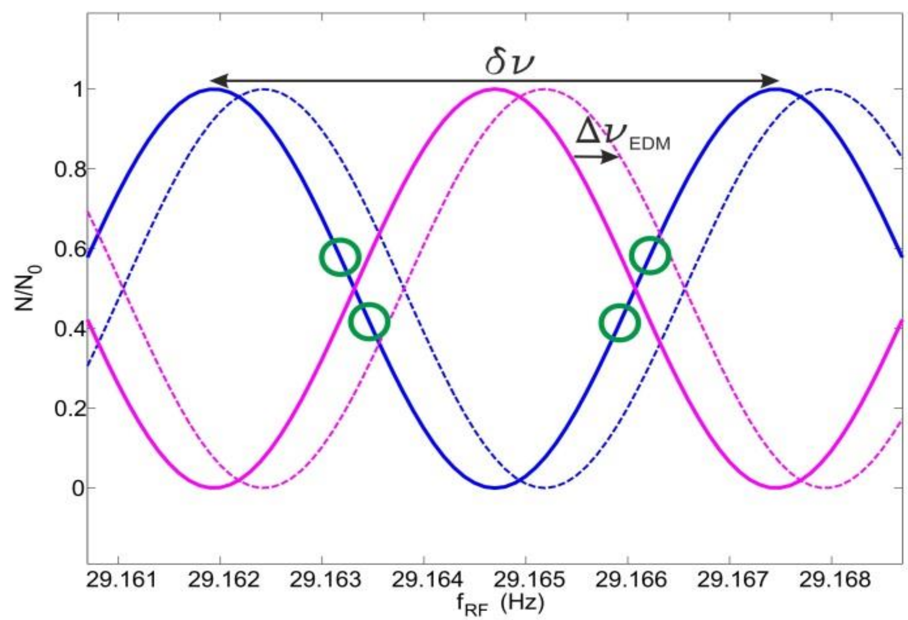
How to measure the nEDM?



$$N_{\uparrow}(\Delta\nu) = \frac{N_0}{2}\left[1 - \alpha\cos\left(\frac{2\pi\Delta\nu}{\delta\nu}\right)\right]$$

$$\Delta\nu = \nu_{\mathrm{rf}} - \nu_{\mathrm{N}}$$

$$\delta\nu = \frac{1}{T_{\mathrm{FP}} + \frac{4T_{\mathrm{rf}}}{\pi}}$$



Sensitivity

$$\sigma(d_\mathrm{n}) = \frac{\hbar}{2\alpha E T_\mathrm{FP}\sqrt{N_0}}$$

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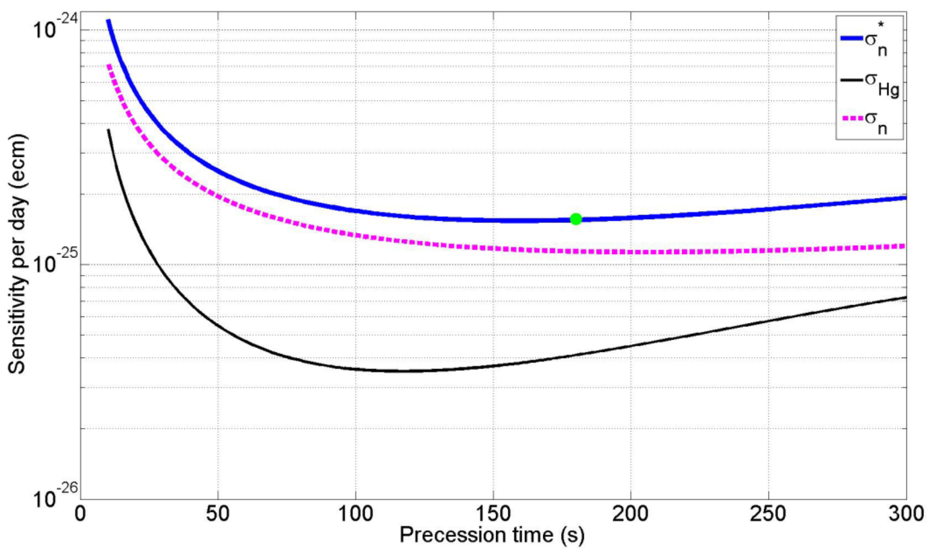

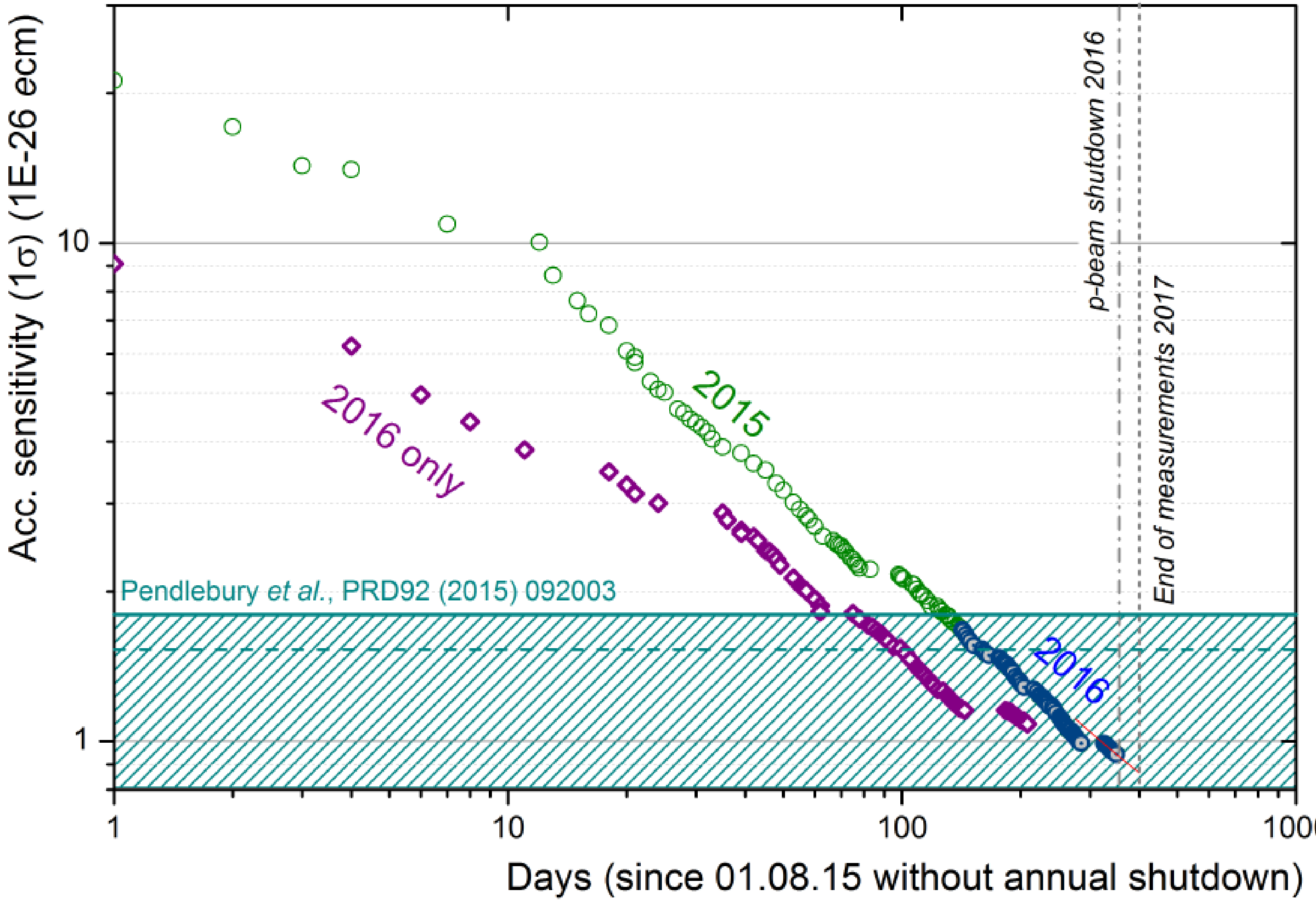
Acc. sensitivity (1σ) (1E-26 ecm)
10
1
1
10
100
1000
Days (since 01.08.15 without annual shutdown)
2015
2016 only
2016
p-beam shutdown 2016
End of measurements 2017
Pendlebury et al., PRD92 (2015) 092003

f_{Hg} vs f_n

$$f_\mathrm{n} = \frac{\gamma_\mathrm{n} B}{2\pi} \approx 30\,\mathrm{Hz}\ @1\,\mu\mathrm{T} \qquad \tilde{v}_\mathrm{UCN} \approx 4\,\mathrm{m/s} \qquad f_\mathrm{n} = \gamma_\mathrm{n} \left\langle |\vec{B}| \right\rangle_\mathrm{V}$$

$$f_\mathrm{Hg} = \frac{\gamma_\mathrm{Hg} B}{2\pi} \approx 8\,\mathrm{Hz}\ @1\,\mu\mathrm{T} \qquad \tilde{v}_\mathrm{Hg} \approx 170\,\mathrm{m/s} \qquad f_\mathrm{Hg} = \gamma_\mathrm{Hg} \left| \langle \vec{B} \rangle_\mathrm{V} \right|.$$

$$R = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}} \left(1 \mp \frac{h}{B_0}\frac{\partial B}{\partial z} + \frac{\langle B_T^2 \rangle}{2B_z^2} \pm \left(\frac{f_\mathrm{Earth}}{f_\mathrm{n}} + \frac{f_\mathrm{Earth}}{f_\mathrm{Hg}} \right) \sin(\lambda) \right)$$

GPE:

$$\delta f_\mathrm{L} = \frac{\gamma^2 D^2}{32\pi\, c^2} \frac{\partial B_0}{\partial z} E \qquad \text{(non adiabatic)}$$

$$\delta f_\mathrm{L} = \frac{v_{xy}^2}{4\pi\, B_0^2\, c^2} \frac{\partial B_0}{\partial z} E \qquad \text{(adiabatic)},$$

GPE for higher orders

General expression valid for any field distribution and volume geometry:
Pignol, G. ; Roccia, S. Phys. Rev. A 85 (2012)

$$d_{\text{false}} = \frac{\hbar\pi}{E}\Delta f(E) = \frac{\gamma^2\hbar\pi}{2c^2}\langle xB_x + yB_y\rangle$$

Magnetic field parametrization: $\vec{B}(\vec{r}) = \sum_{l,m} G_{l,m}\begin{pmatrix}\Pi_{x,l,m}(\vec{r})\\ \Pi_{y,l,m}(\vec{r})\\ \Pi_{z,l,m}(\vec{r})\end{pmatrix}$ ← Harmonic polynomials in x,y,z of degree l

l	m	$\langle xB_x + yB_y\rangle$	$G_{max}(5\cdot10^{-27}\,\text{e}\cdot\text{cm})$
1	0	$-\frac{1}{4}r^2G$	$0.57\,\text{pT/cm}$
3	0	$\frac{1}{16}r^2(2r^2 - H^2)G$	$2.4\cdot10^{-3}\,\text{pT/cm}^3$
5	0	$-\frac{1}{192}r^2(15r^4 + 3H^4 - 20H^2r^2)G$	$8.92\cdot10^{-6}\,\text{pT/cm}^5$

nEDM geometry: H=12cm , r=23.5cm