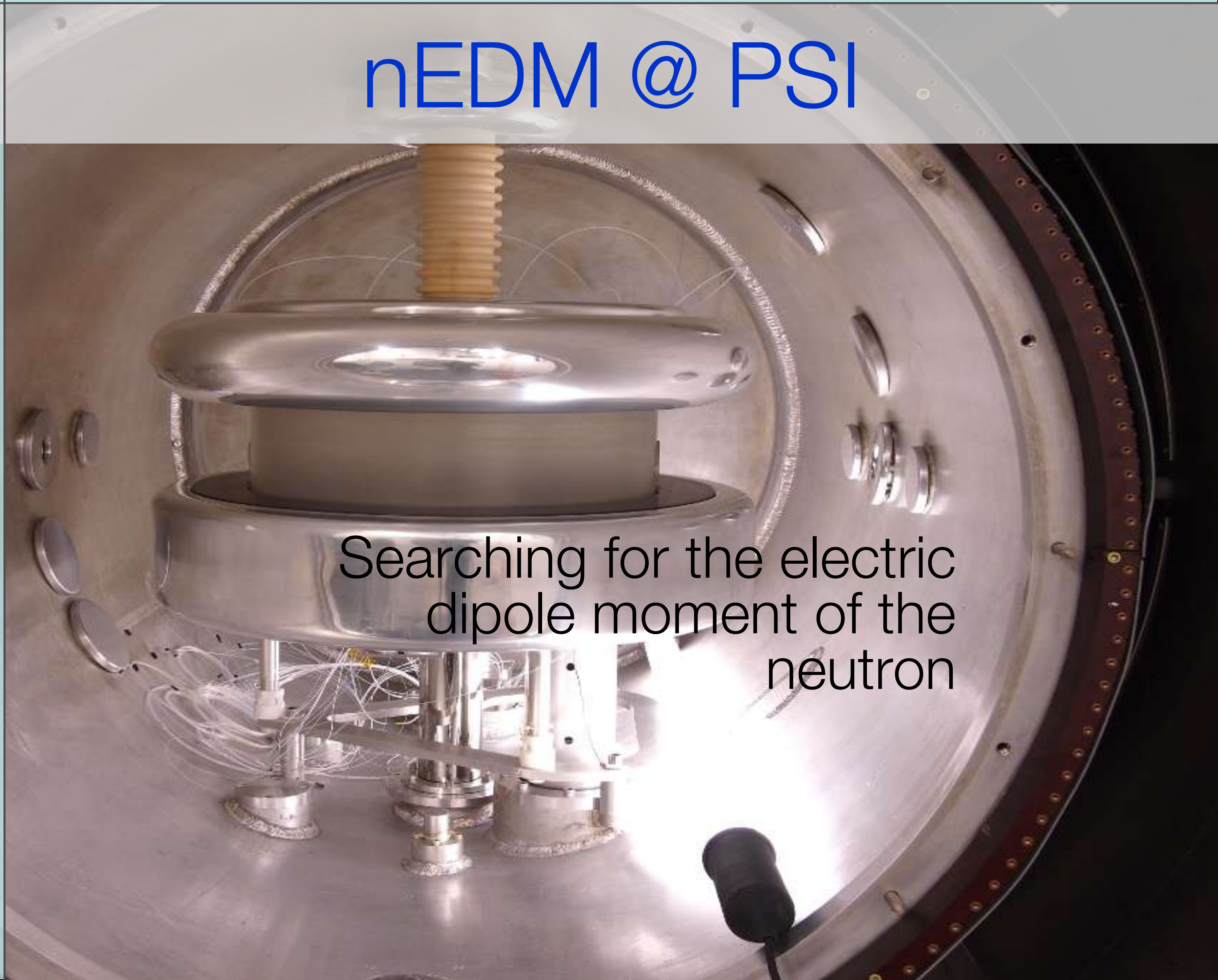
nEDM @ PSI



Searching for the electric dipole moment of the neutron

Event
Date
Name

The collaboration

- Eight countries
- 48 Members
- 11 PhD students

PSI in Switzerland

Outline

Introduction

- Why search for an nEDM?
- How do we search for it?

Status at PSI

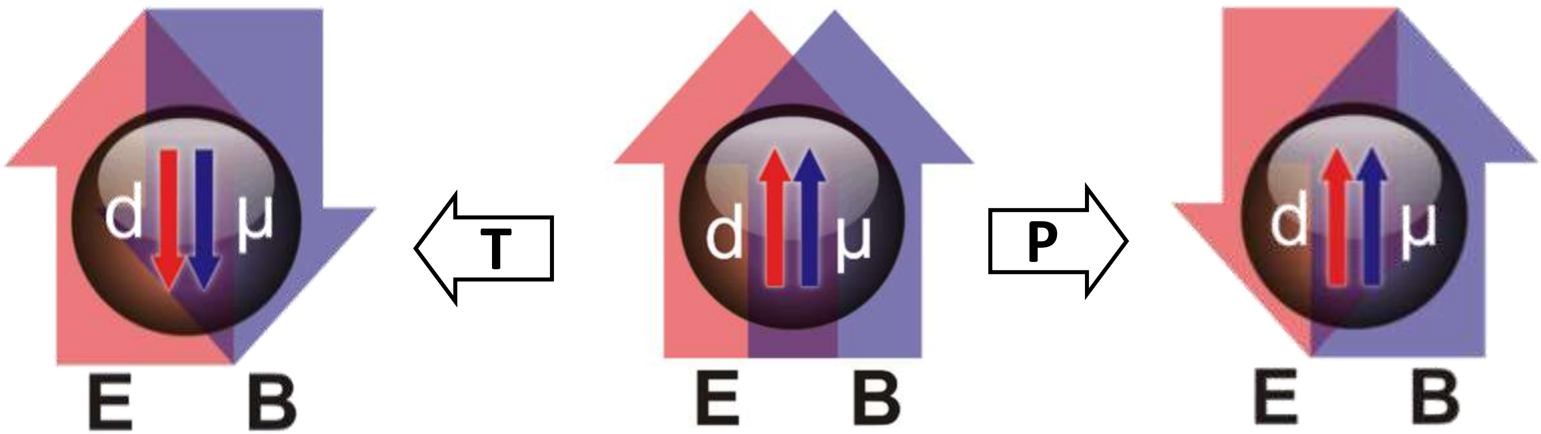
- The UCN source
- Statistical sensitivity

Neutron/mercury gyromagnetic ratio

- Magnetometry
- Preliminary Results

CP violation and EDM

$$H = -\left(d\frac{\vec{\sigma}}{|\vec{\sigma}|}\times\vec{E} + \mu\frac{\vec{\sigma}}{|\vec{\sigma}|}\times\vec{B} \right)$$



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

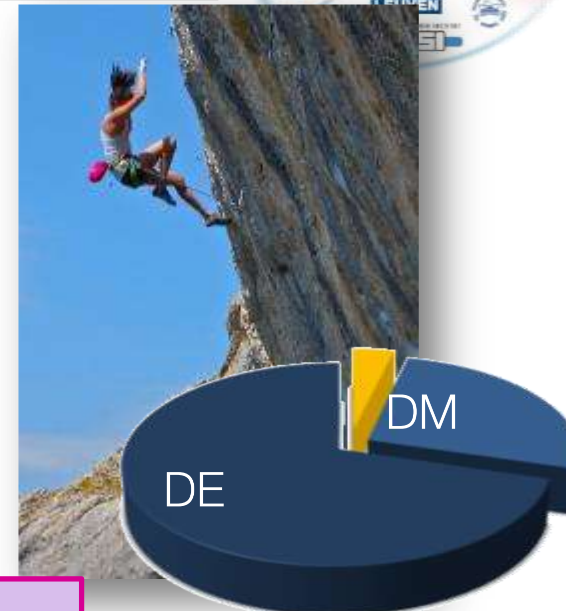
Phenomena not explained by Standard Model

- ***Gravity***

  The Standard model does not explain Gravity.

- ***Dark matter /Dark energy***

  Only about 4% of the Universe's energy content are explained by the SM.



- ***Matter/Anti-matter asymmetry***

  Observed asymmetry and SM expectation disagree by a factor 10^8

- ***g-2 of muon and muonic hydrogen***

  The g-2 value for muon disagrees by 3.3σ

  The proton radius from muonic hydrogen disagrees by 7σ

Baryon Asymmetry of the Universe

SM expectation:

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-18}$$

vs.

Observed*:

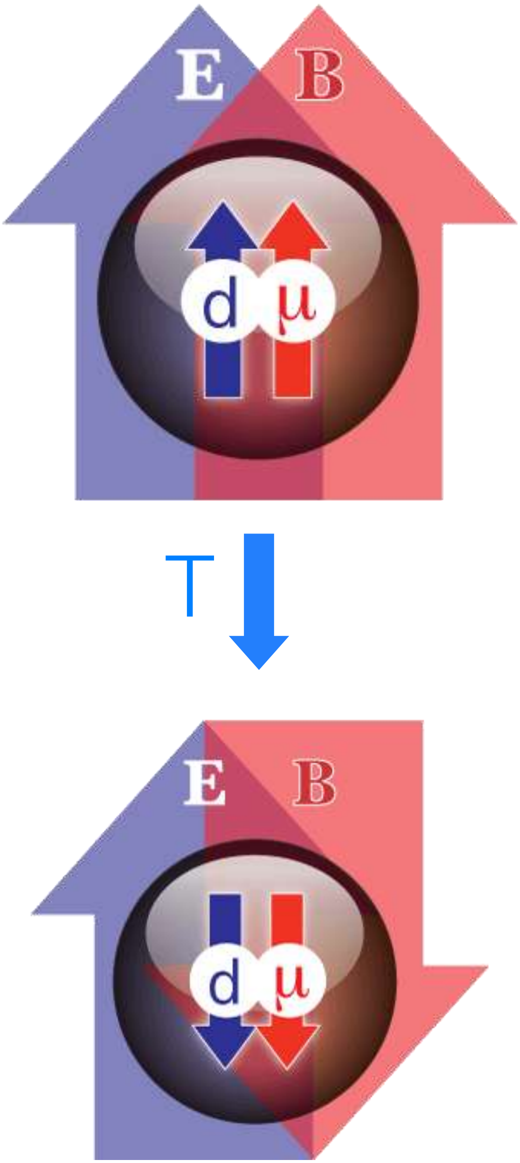
$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-10}$$

Sakharov criteria

1. *Baryon number violation*
2. *C and CP violation*
3. *Thermal non-equilibrium*

*WMAP + COBE (2003)
(6.19 ± 0.15) x 10^{-10}
[E. Komatsu et al. 2011 ApJS 192]

CP violation and EDM



A nonzero neutron EDM violates P, T and, assuming CPT conservation, also CP.

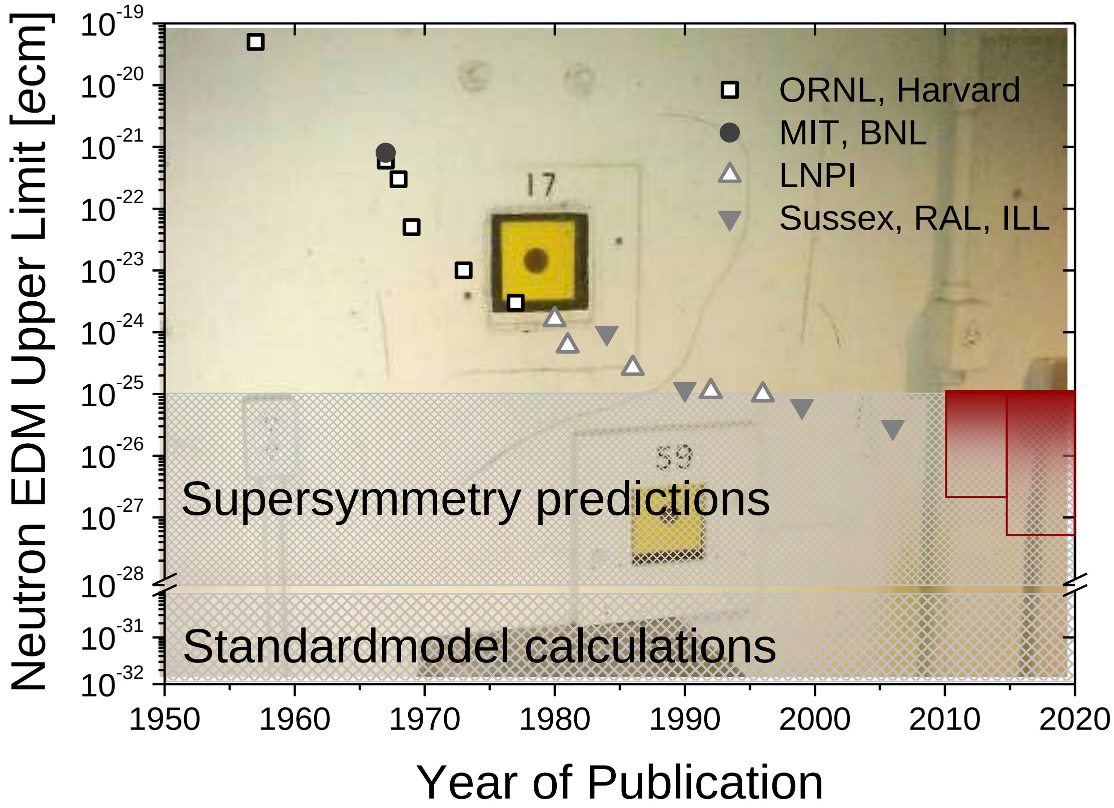
→ ~~CP~~ so far only in weak interaction

→ Excellent probe for physics beyond the Standard Model

→ Might explain BAU (matter/anti-matter problem)

→ Sensitive to the θ-term in QCD

A brief history of nEDM searches



Aimed at sensitivities at PSI:
Intermediate:
$d_n < 5 \times 10^{-27}$ e cm (95% C.L.)
Final:
$d_n < 5 \times 10^{-28}$ e cm (95% C.L.)

First

Smith, Purcell, Ramsey
$d_n < 5 \times 10^{-20}$ e cm
PR 108 (1957) 120

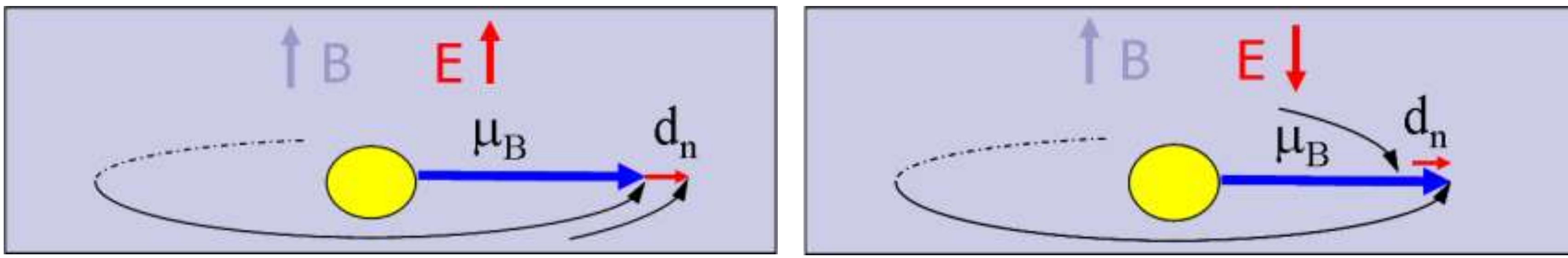
~ 50 years

Last

RAL-Sussex-ILL
$d_n < 2.9 \times 10^{-26}$ e cm (90% C.L.)
C.A.Baker et al., PRL 97 (2006) 131801

The measurement technique

Measure the difference of precession frequencies in parallel/anti-parallel fields:



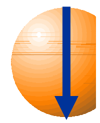
$$\hbar \Delta\omega = 2d_n\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_n\cancel{\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}$$

for $d_n < 10^{-26}$ → $\Delta\omega < 60$ nHz

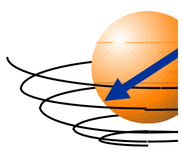
$\omega_L \approx 30$Hz

The Ramsey technique

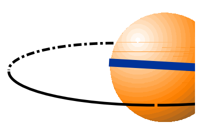
Spin "down" neutron...



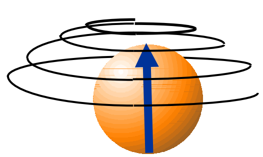
Apply π/2 spin flip pulse...

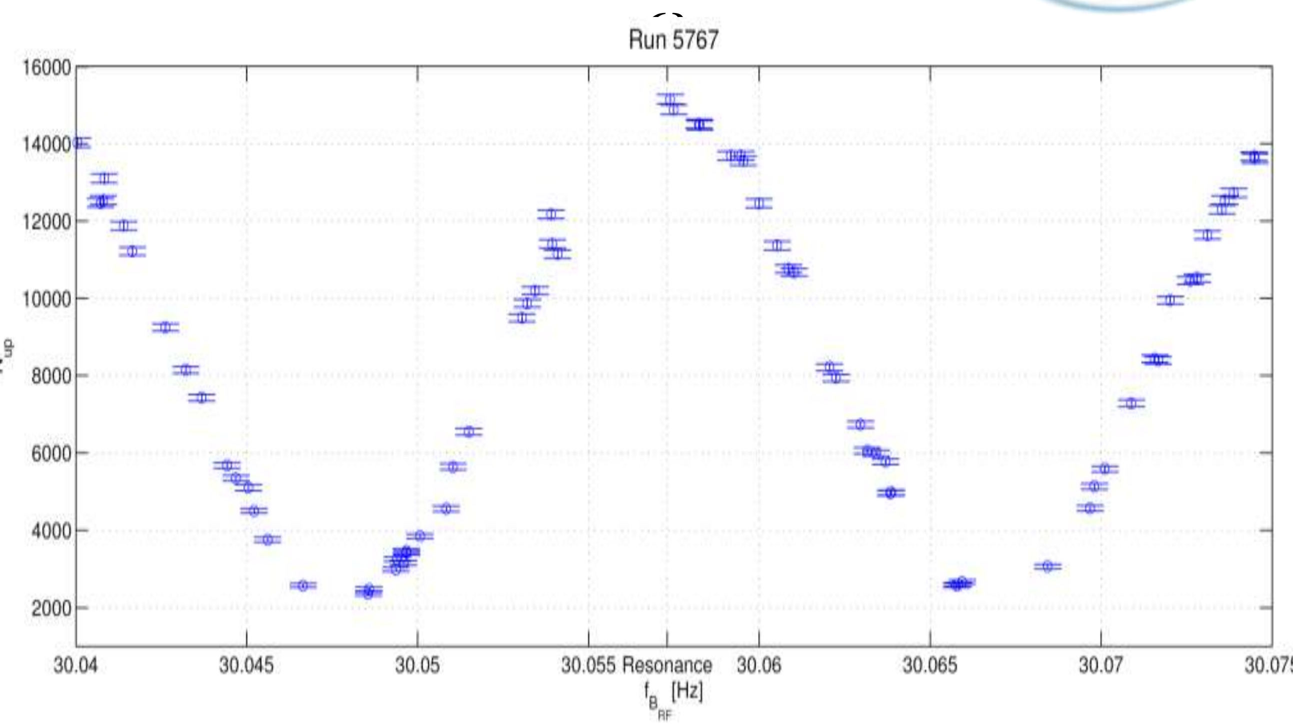


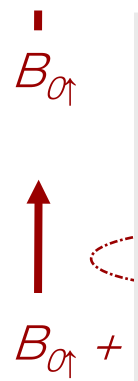
Free precession at ω $_L$



Second π/2 spin flip pulse.







Sensitivity: $$\sigma(f) = \frac{\hbar}{2\alpha T E \sqrt{N}}$$

α	Visibility of resonance
T	Time of free precession
N	Number of neutrons
E	Electric field strength

Overview

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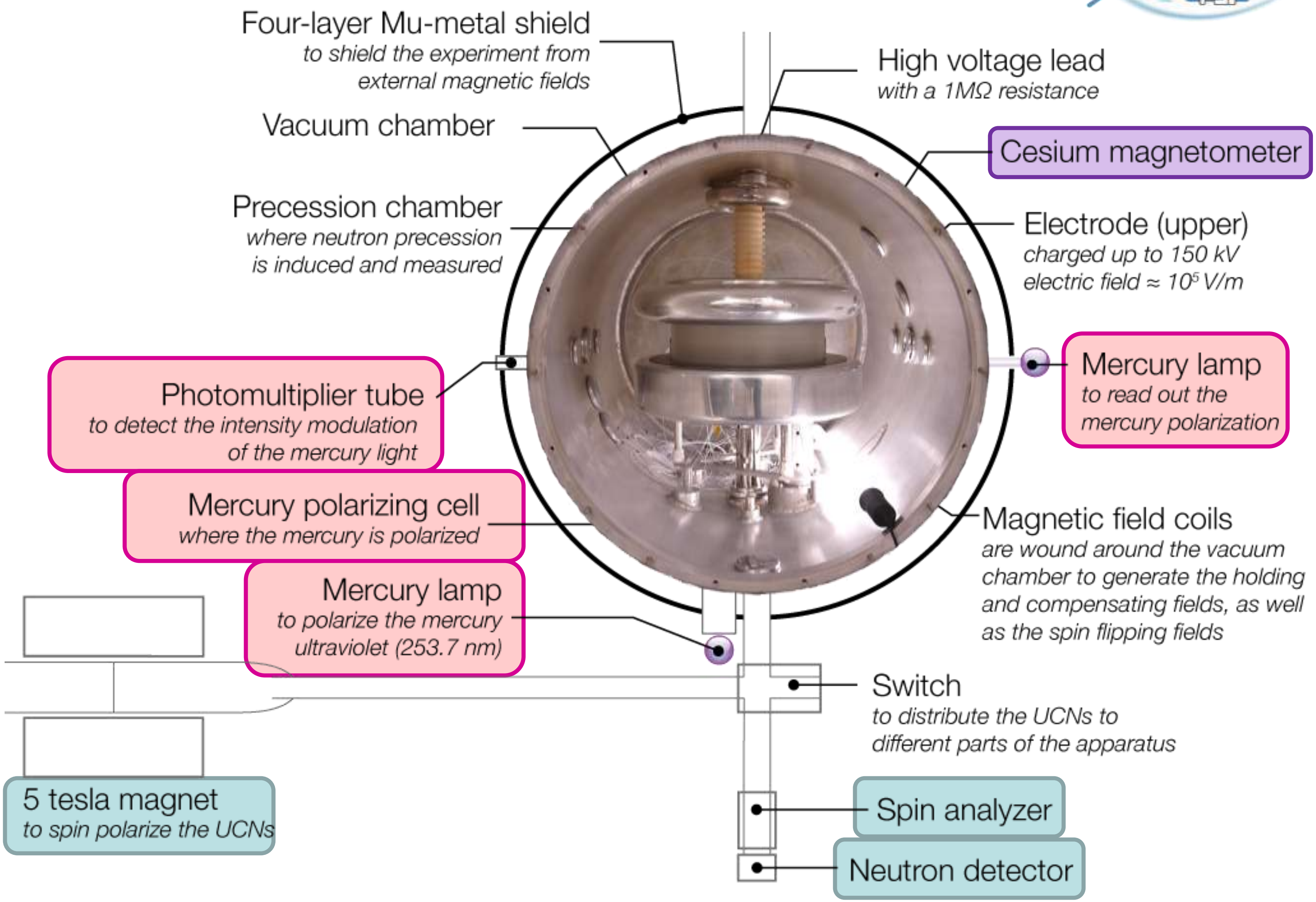
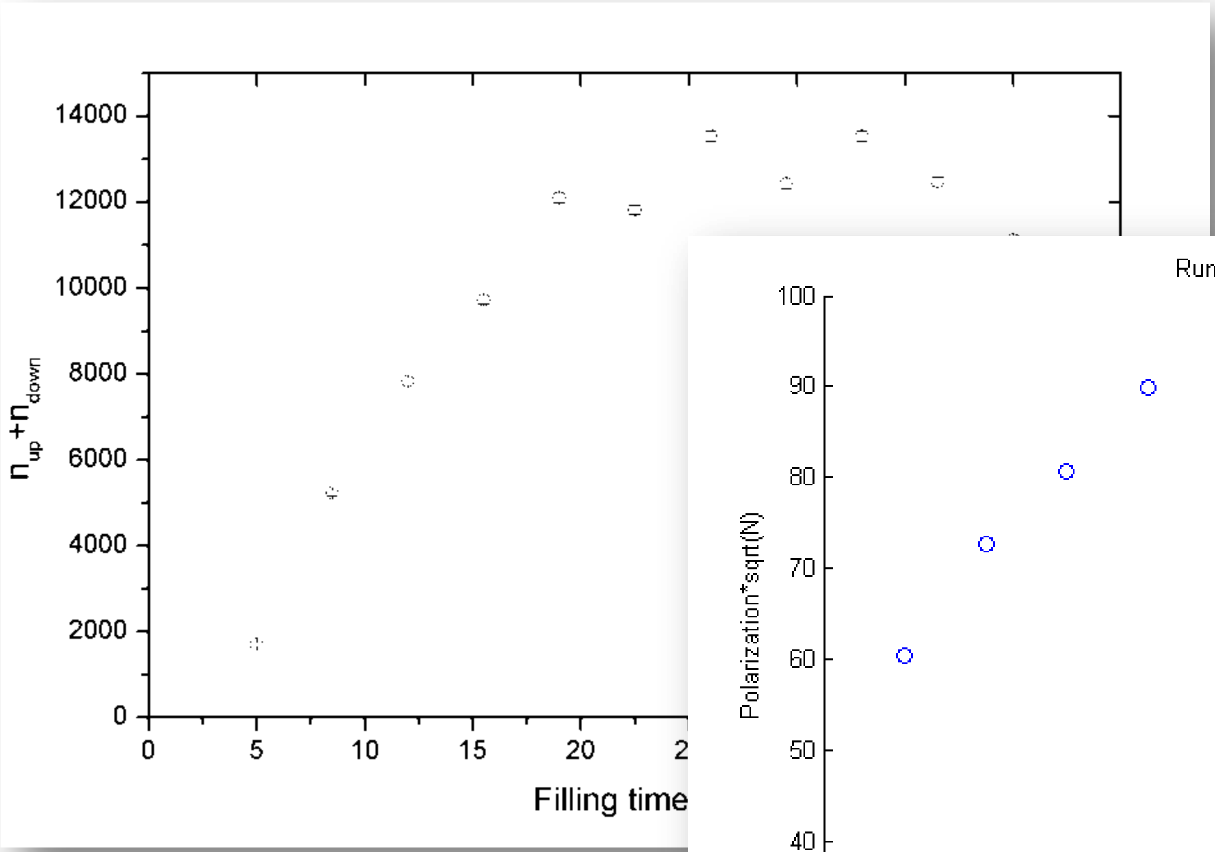
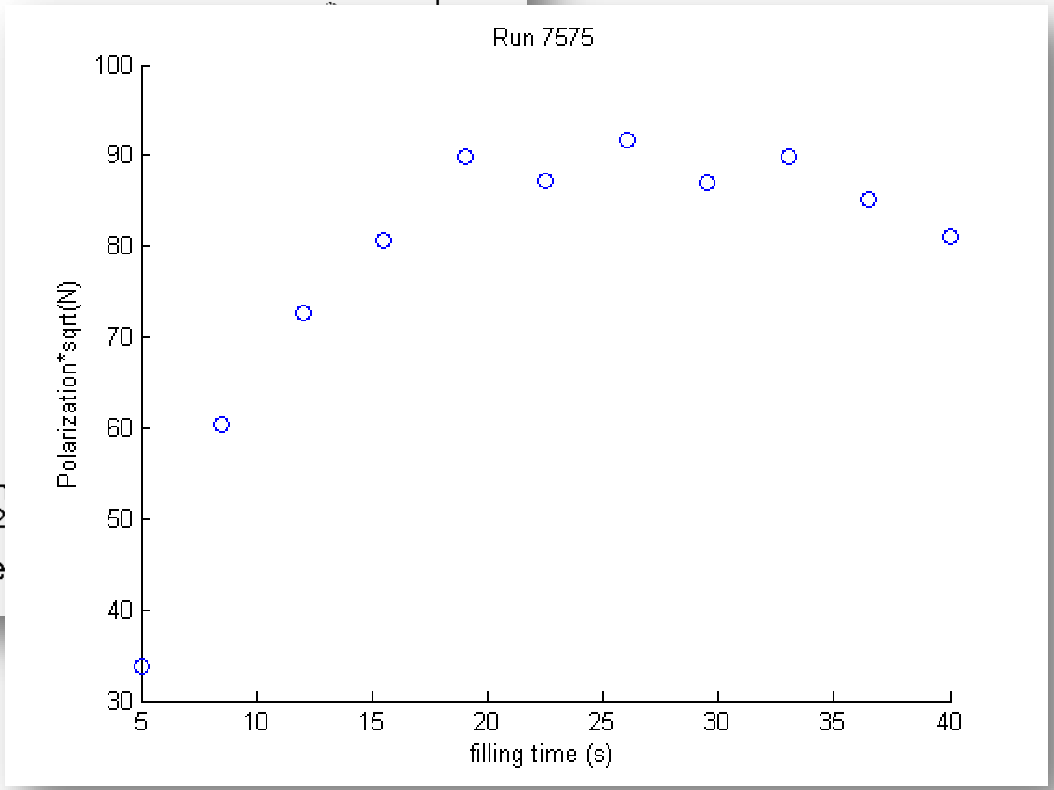
The nEDM spectrometer



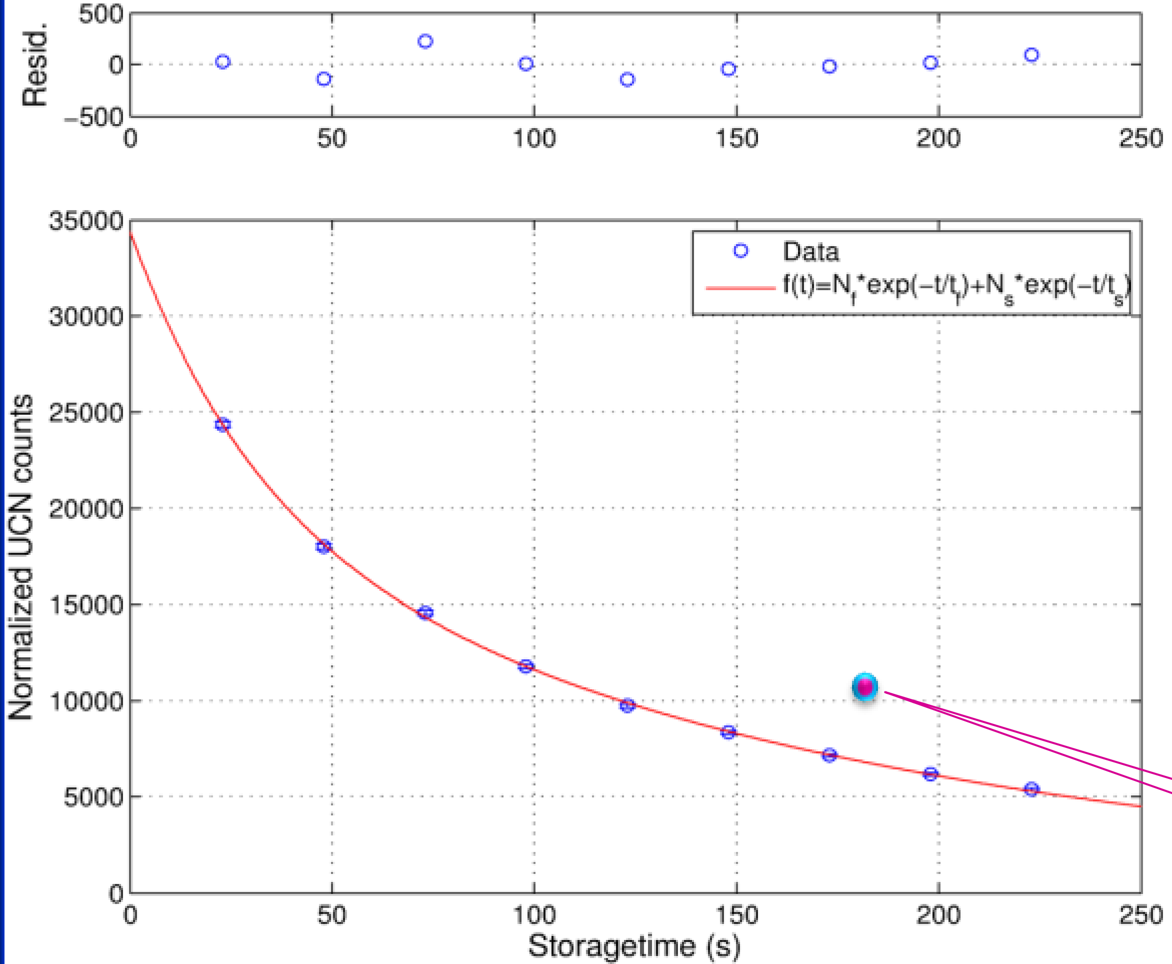
Filling UCN

- Optimize product $\alpha\sqrt{N}$



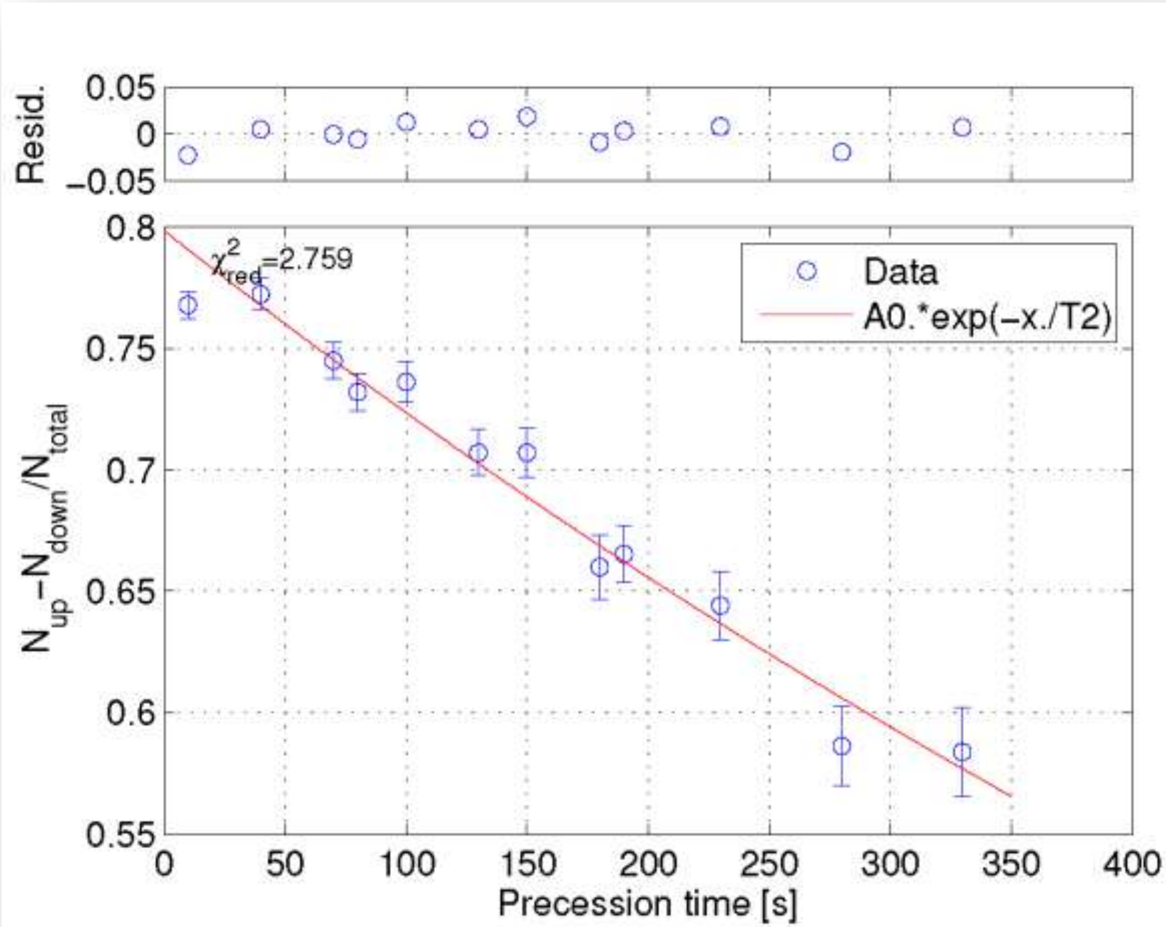


Storage life time



- Chamber made of dPS insulator ring and DLC electrodes
- Two exp fit:
  t_s~30s
  t_f ~180s
- Max no. UCN measured after 180s storage: 10 500

Transversal depolarization

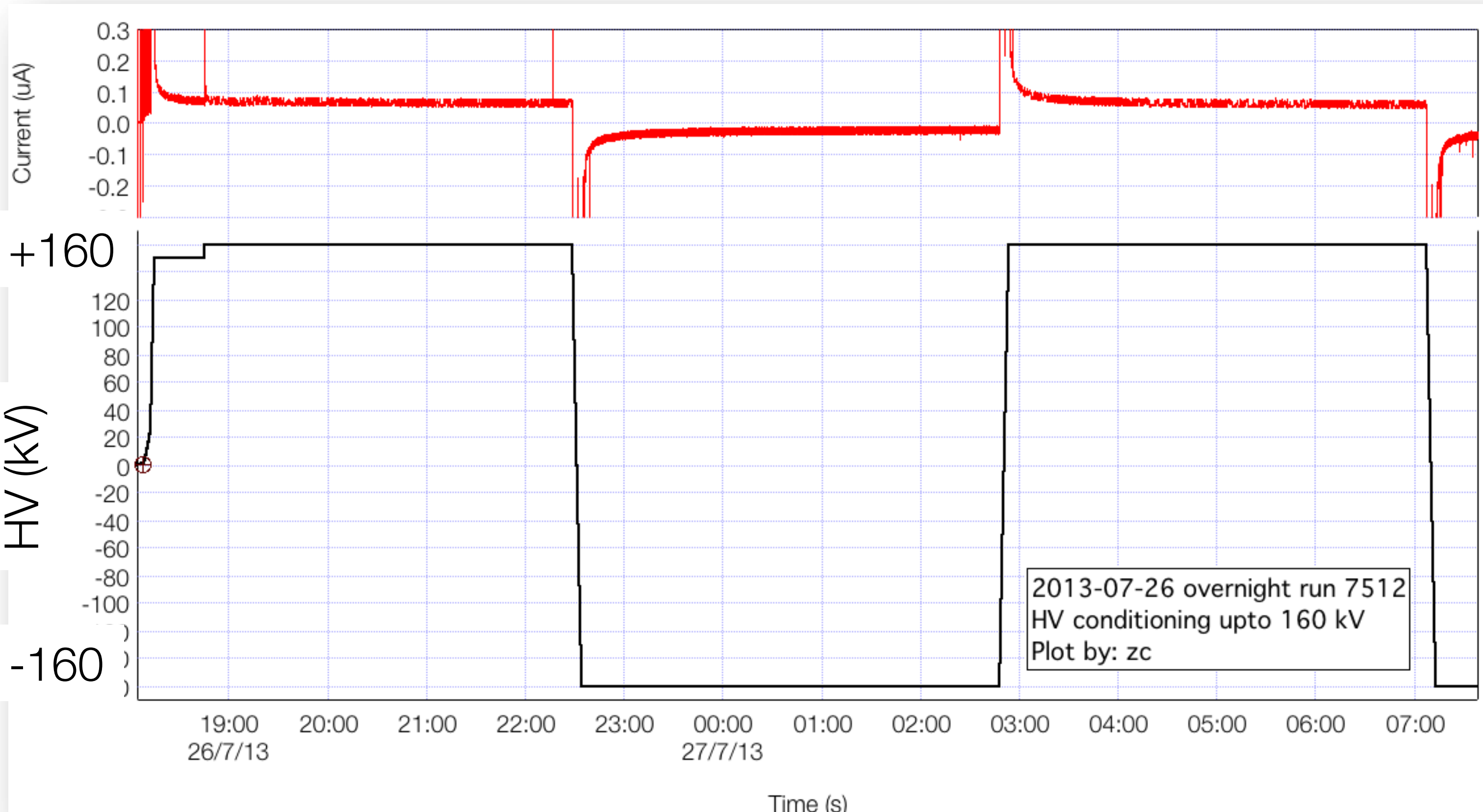


Best @ PSI
$T_2(B_0\downarrow)$: 1158 ± 94s
$T_2(B_0\uparrow)$: 836 ± 63s

2013:
$T_2(B_0\downarrow + B_0\uparrow)$~600s

→ Excellent magnetic field homogeneity

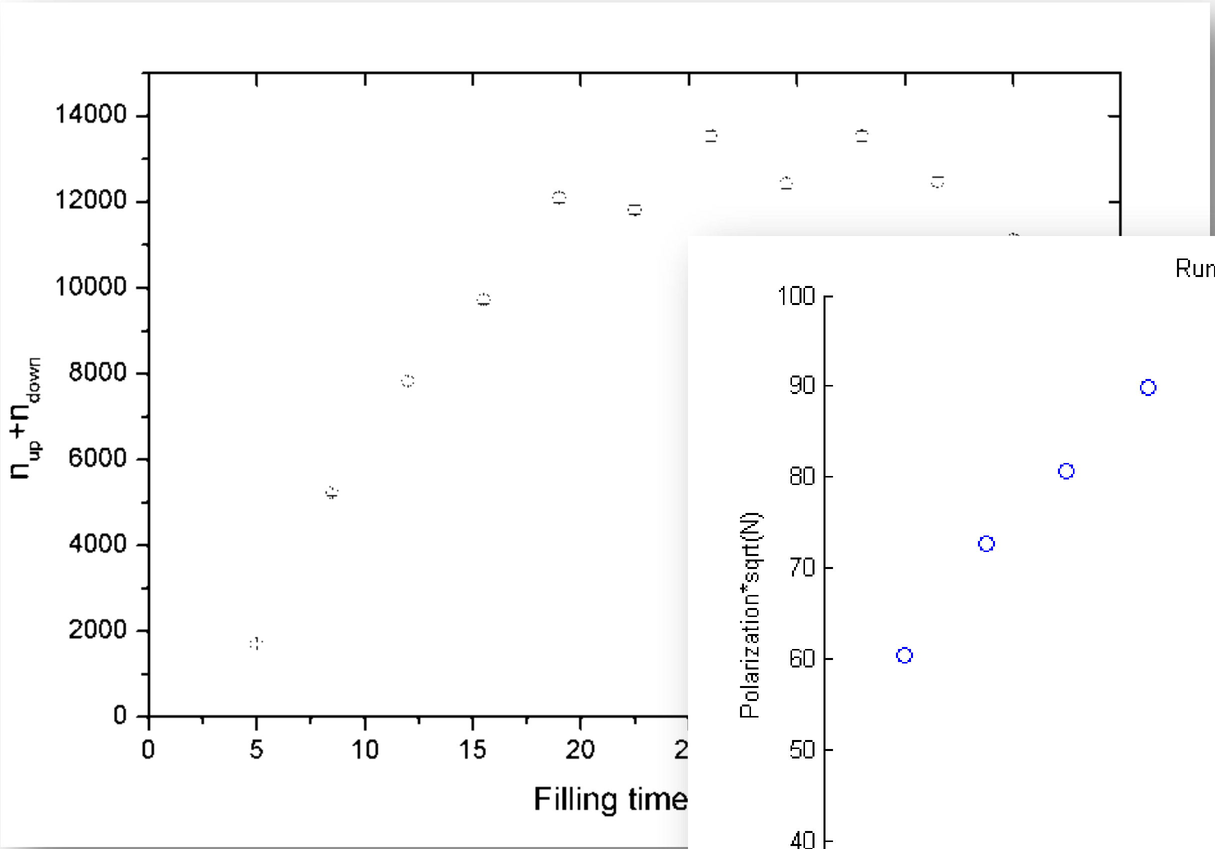
HV performance

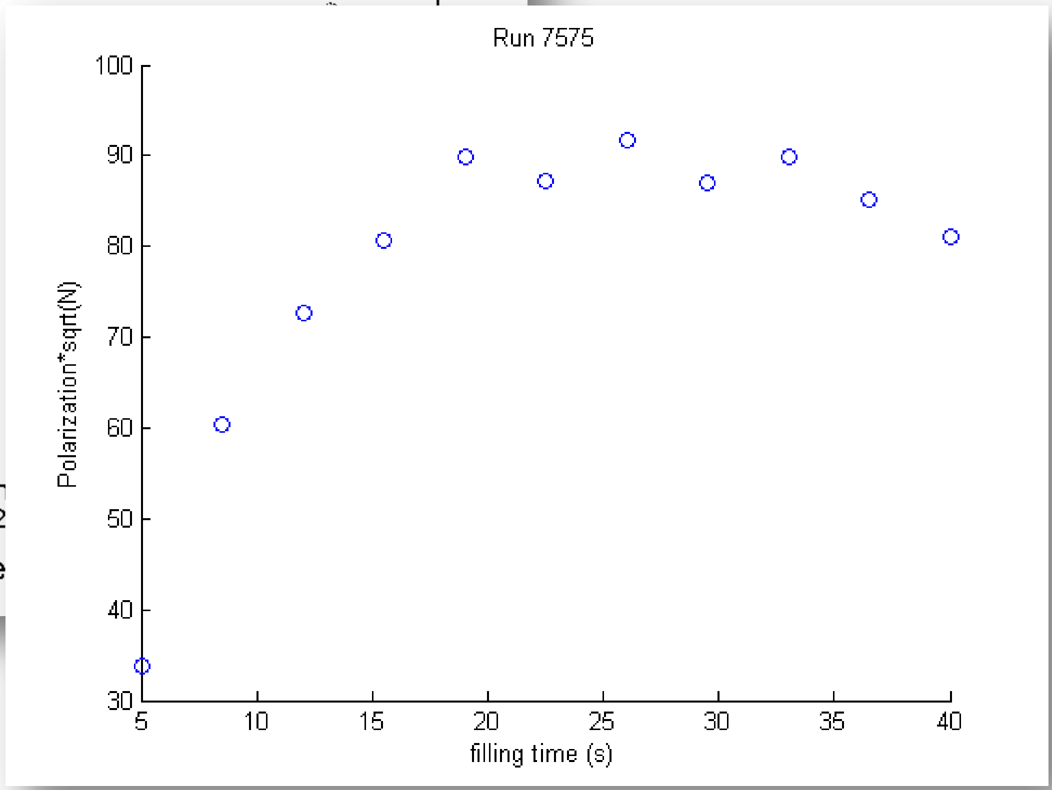


- Best HV performance 144 kV → 12.0 kV/cm
- Average E-Field while data taking: 10.3 kV/cm

Filling UCN

- Optimize product $\alpha\sqrt{N}$





Neutron EDM sensitivity

$$\sigma = \frac{\hbar}{2\alpha TE\sqrt{N}}$$

	RAL/Sx/ILL*		PSI 2012		PSI 2013	
	best	avg	best	avg	best	avg
E-field	8.8	8.3	8.33	7.9	12	10.3
Neutrons	14 000	14 000	9 000	5 400	10 500	6 500
T_{free}	130	130	200	200	200	180
T_{duty}	240	240	360	360	340	340
A	0.6	0.453	0.65	0.57	0.62	0.57
σ/d (10^{-25}ecm)	2.3	3.0	2.3	3.5	1.5	2.8

2013 data taking: 3266 cycles
25 days
Stopped by switch break down
2013 accumulated sensitivity 6×10^{-26} e.cm

* Best nedm limit:
Baker *et al.*, PRL**97**(2006)

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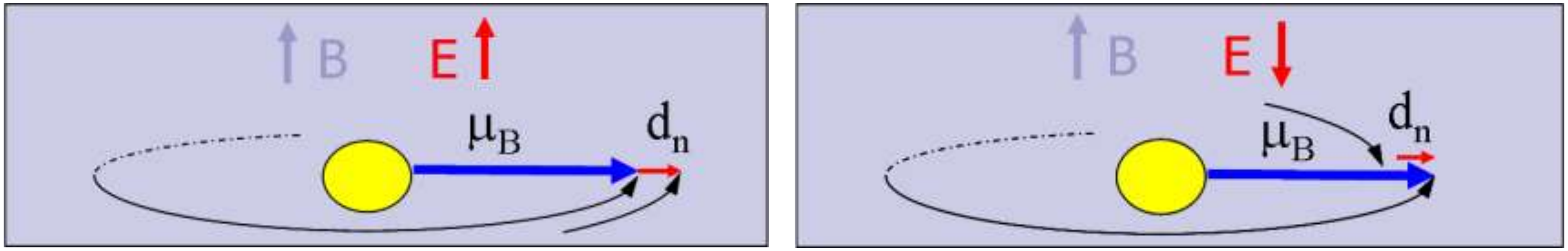
The measurement technique

Measure the difference of precession frequencies in parallel/anti-parallel fields:

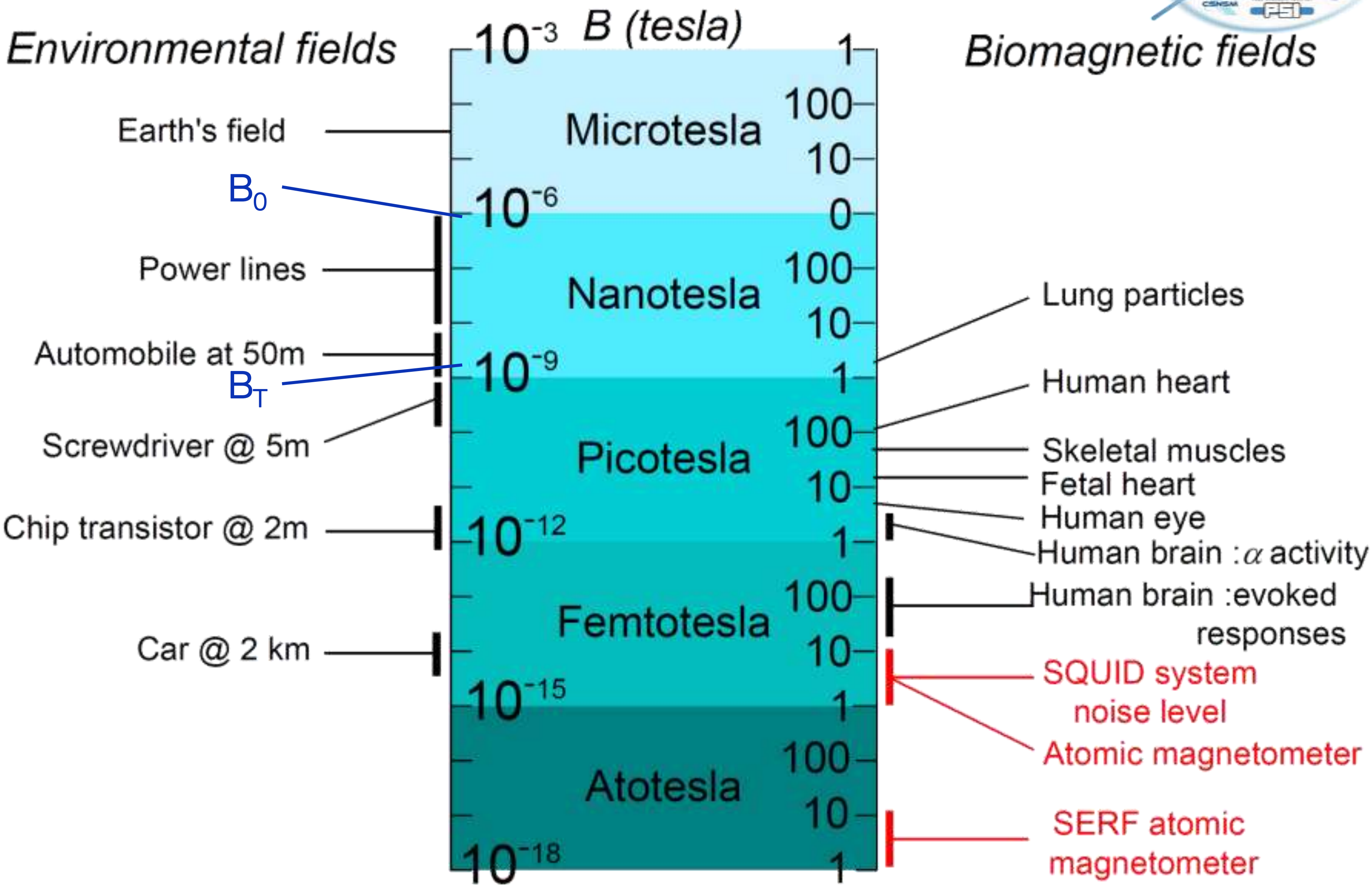


$$\hbar\Delta\omega = 2d_n\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_n\boxed{\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}$$

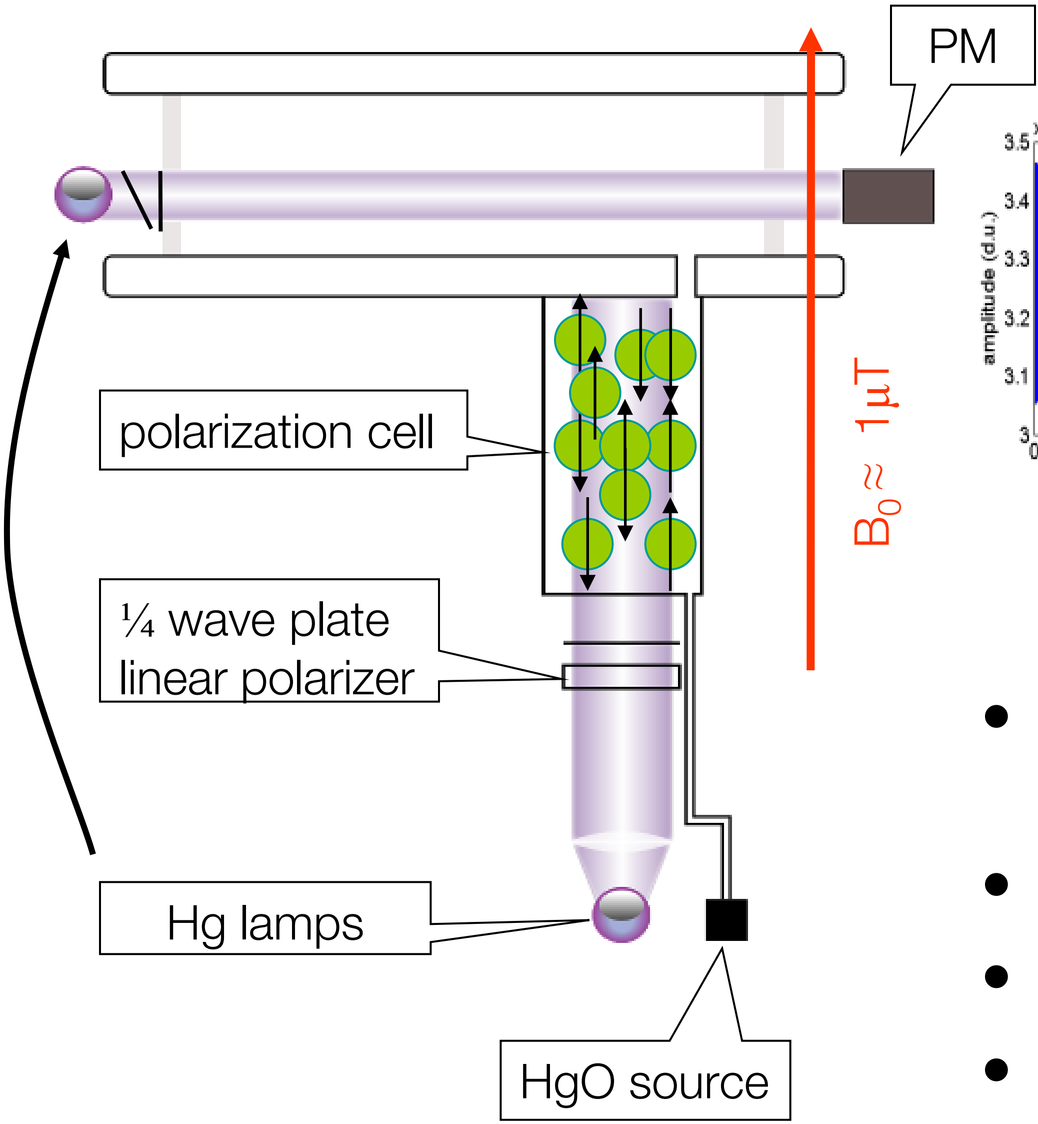
Statistical accuracy of a magnetometer correcting for a change in B should be better than the neutron sensitivity per cycle:

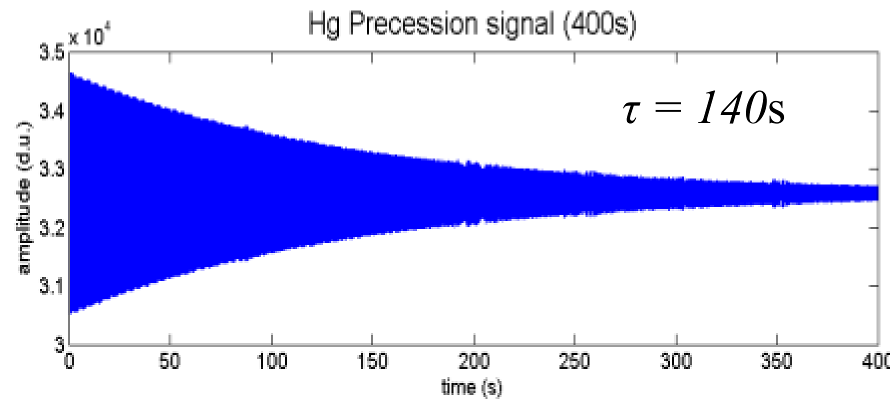
$$\delta f_n = \frac{1}{2\pi\alpha T\sqrt{N}} \approx 11\mu\text{Hz} \xrightarrow{B_0=1\mu\text{T}} \delta B \approx 400\text{fT}$$

Magnetic fields



Mercury co-magnetometer



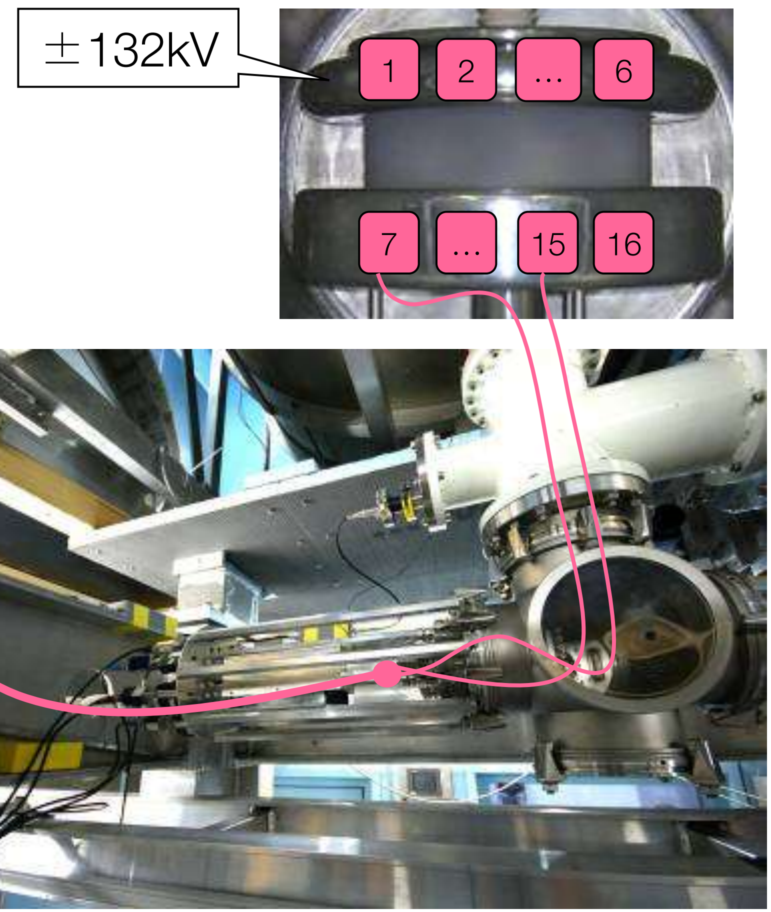


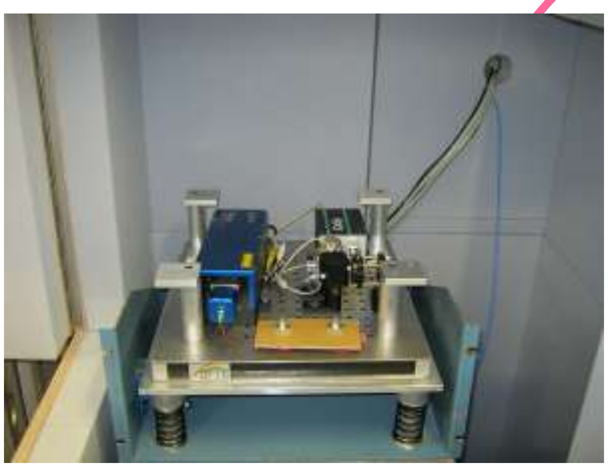
- Average magnetic field (volume and cycle)
- σ_B ~ *400* fT
- τ > 100 s without HV
- s/n ~ 500 without HV

Cesium gradiometer

Monitoring of vertical magnetic gradients

- Six HV CsM
- Ten ground CsM
- Stabilized laser
- PID phase locked DAQ

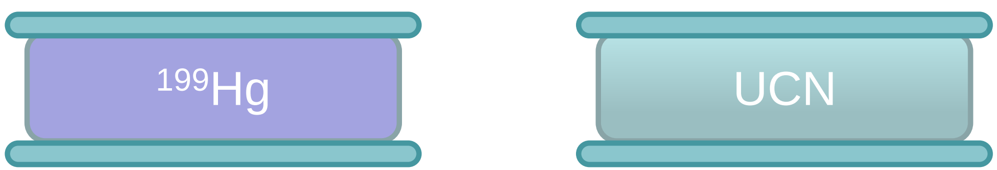




Frequency ratio $R = f_n/f_{Hg}$

- There are two drawbacks using the HgM as field monitor:
  - Center of mass offset
  - Non-adiabaticity

$$\frac{\gamma_{Hg}}{2\pi} \approx 8\ \mathrm{Hz/\mu T}$$



$$\frac{\gamma_{n}}{2\pi} \approx 30\ \mathrm{Hz/\mu T}$$

	best	avg	best	avg	best	avg
E-field	8.8	8.3	8.33	7.9	12	10.3
Neutrons	14 000	14 000	9 000	5 400	10 500	6 500
T_{free}	130	130	200	200	200	180
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A	0.6	0.453	0.65	0.57	0.62	0.57

CsM - array

+ further sys.

$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} = \frac{\gamma_n}{\gamma_{Hg}} \left(1 \mp \boxed{\frac{\partial B}{\partial z}} \frac{\Delta h}{|B_0|} + \boxed{\frac{\langle B^2{}_\perp \rangle}{|B_0|^2}} \mp \delta_{Earth} + \delta_{Hg-lightshift} \right)$$

Field maps

Gradients from CsM

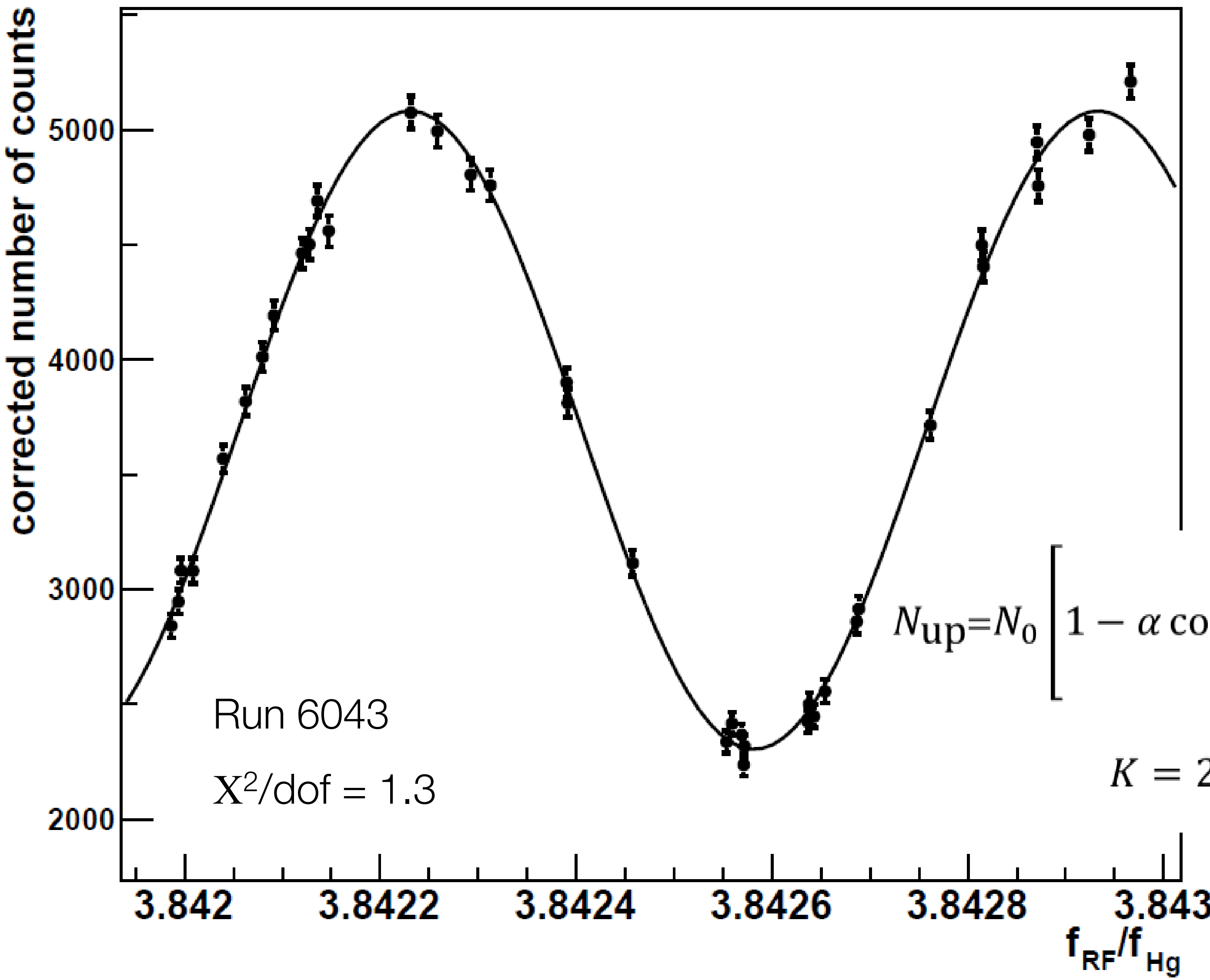
- Field parameterized by 9 parameters (next-to-linear)

$$B(x,y,z) = B_0 + g_x x + g_y y + g_z z + g_{xx}(x^2 - z^2) + g_{yy}(y^2 - z^2) + g_{xy} xy + g_{xz} xz + g_{yz} yz$$

- The parameters are adjusted to 12 magnetometers readings using least squares
- Residuals are about 30 pT (500 pT using linear model)
- Jackknife procedure to estimate the error on the gradient G

$$\boxed{\Delta G = 8\ \mathrm{pT/cm}}$$

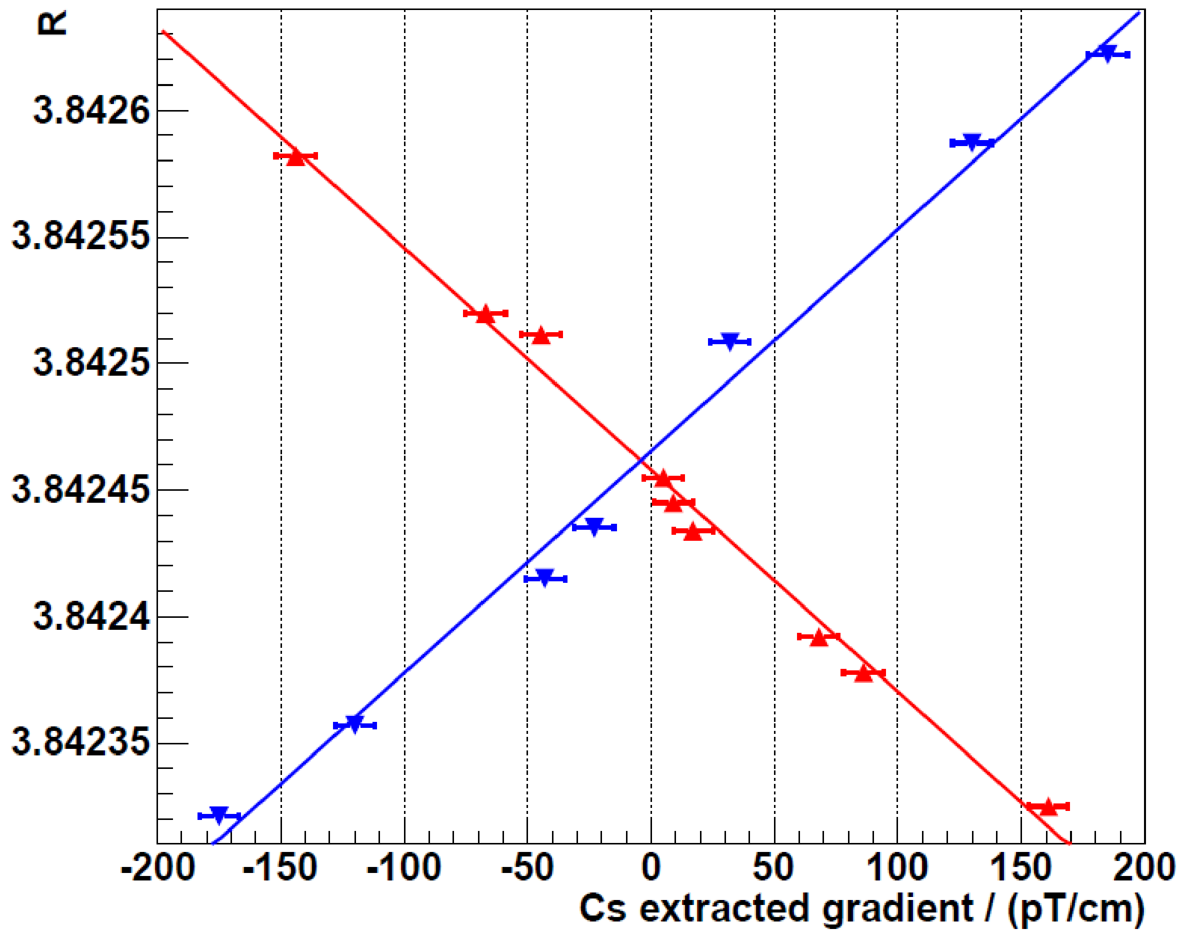
Extracting R



$$N_{\rm up} = N_0 \left[1 - \alpha \cos\left(K \left(\frac{f_{\rm RF}}{f_{\rm Hg}} - R \right) \right) \right]$$

$$K = 2\pi \left(T + \frac{4t}{\pi} \right) \langle f_{\rm Hg} \rangle$$

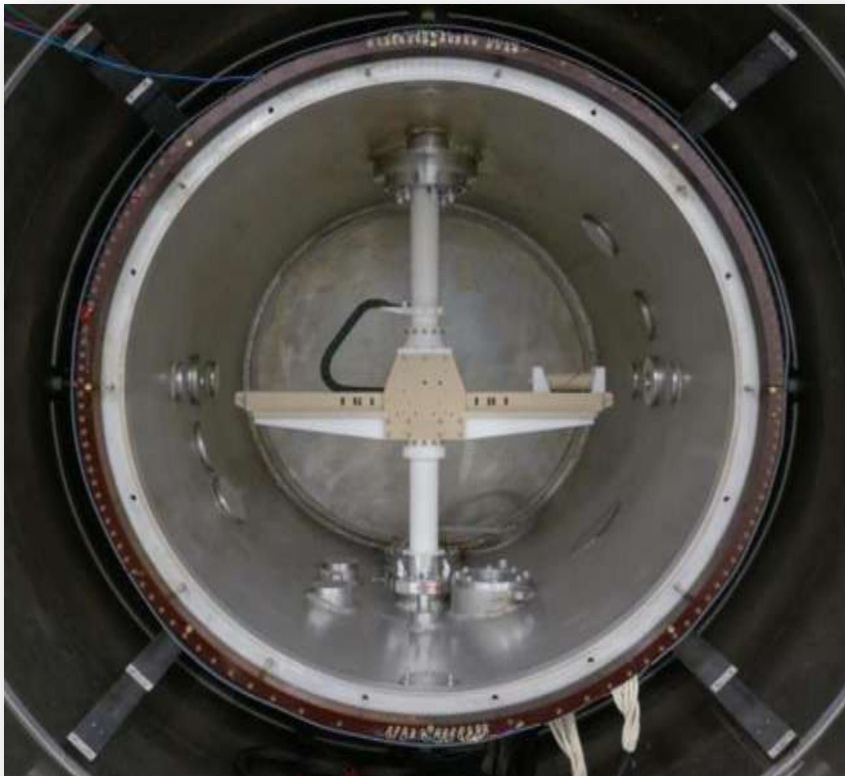
R vs gradient



$$h = -0.235(5)\,\mathrm{cm}$$
$$R_0^{\uparrow} = 3.8424580(23)$$
$$R_0^{\downarrow} = 3.8424653(27)$$

$$R = \frac{\langle f_{\mathrm{UCN}}\rangle}{\langle f_{\mathrm{Hg}}\rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(1 \mp \frac{\partial B}{\partial z}\frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp}\rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}}\right)$$

Transversal fields



UCNs:

Adiabatic regime:

$$f_n \propto \langle |\vec{B}| \rangle = B_0 + \frac{\langle B_T^2 \rangle}{2B_0}$$

Mercury:

Non-adiabatic regime:

$$f_{\mathrm{Hg}} \propto | \langle \vec{B} \rangle | = B_0$$

- Mapping with fluxgate and vector cesium magnetometer
- -20<z<20, -10<r<30, $\Delta\varphi = 5°$

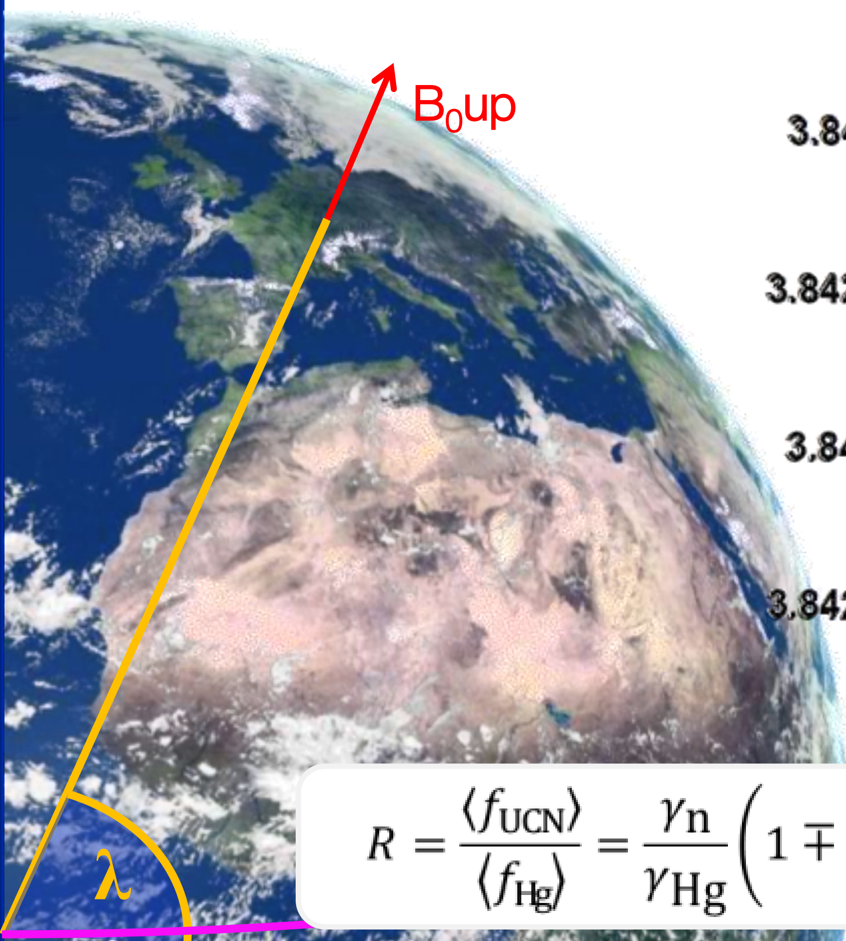
$$\delta R_{\mathrm{Transverse}} = (3 \pm 1) \times 10^{-6}$$

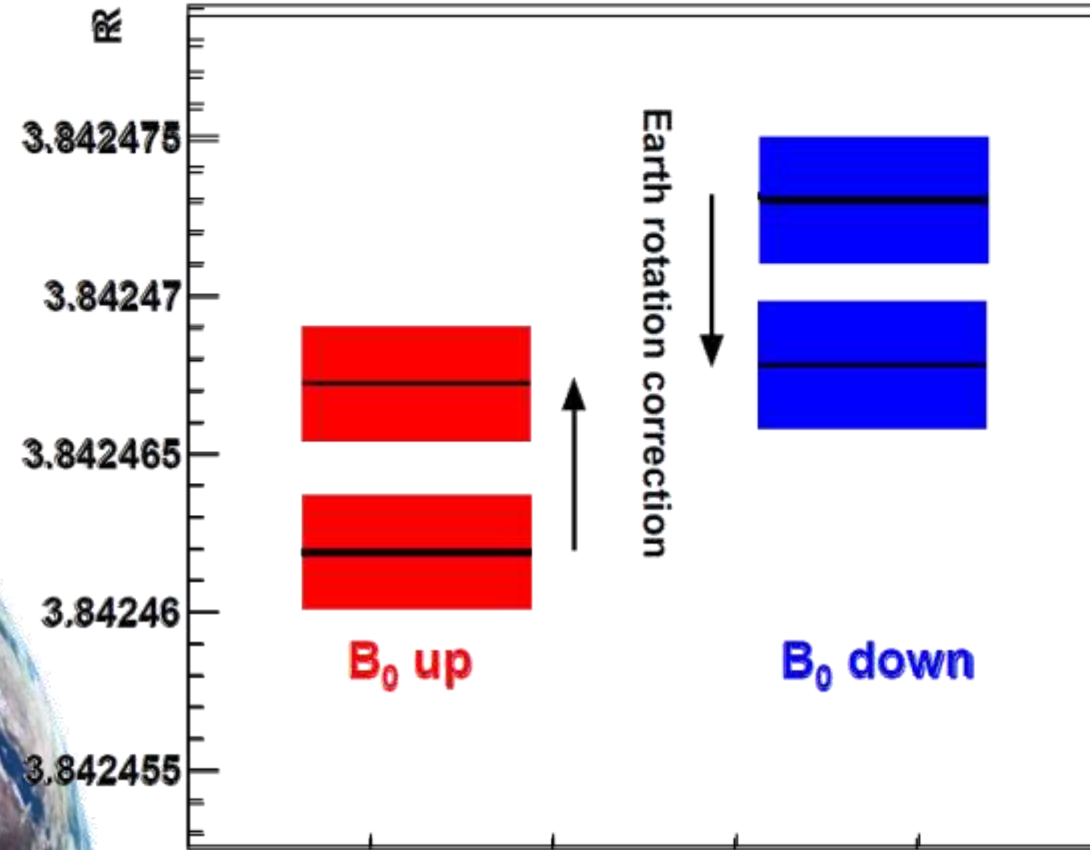
$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B_T^2 \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}} \right)$$

Earth rotation correction

$$\delta_{\mathrm{Earth}} = \mp \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(\frac{f_{\mathrm{Earth}}}{f_{\mathrm{n}}} + \frac{f_{\mathrm{Earth}}}{f_{\mathrm{Hg}}}\right)\sin(\lambda)$$

$$= \mp 5.3\times 10^{-6}$$

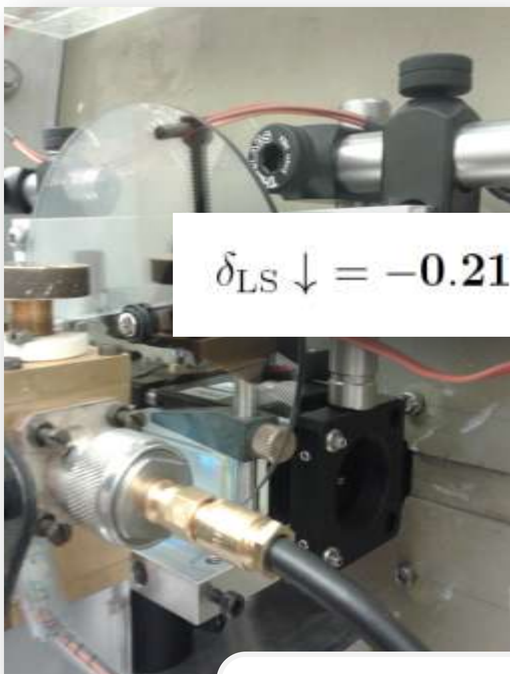


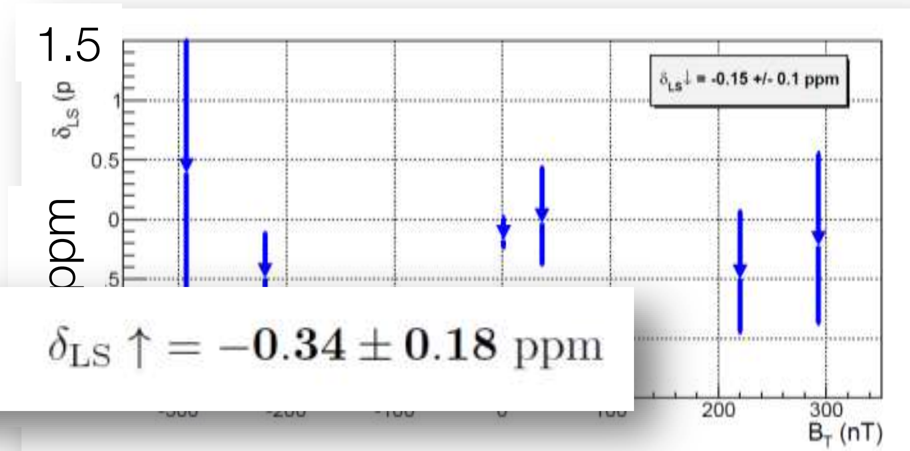


$$R = \frac{\langle f_{\mathrm{UCN}}\rangle}{\langle f_{\mathrm{Hg}}\rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(1 \mp \frac{\partial B}{\partial z}\frac{\Delta h}{|B_0|} + \frac{\langle B^2_{\perp}\rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}}\right)$$

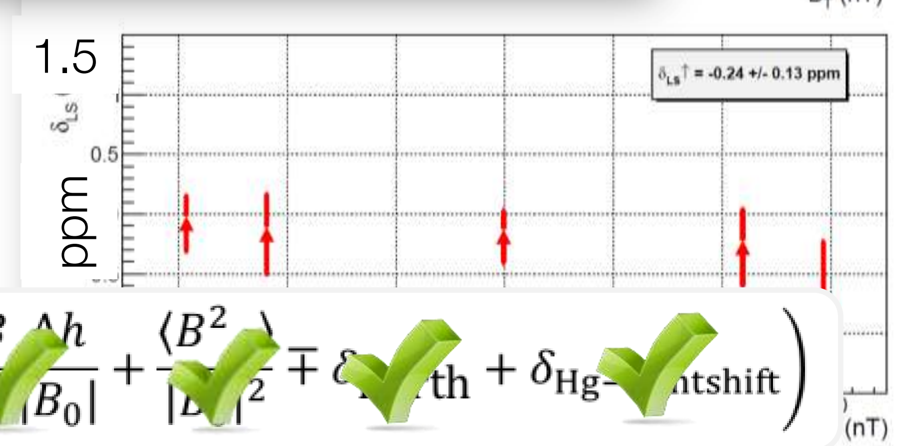
Hg lightshift

- While probing the precessing Hg-atoms a change in frequency occurs proportional to the intensity of the light beam.





$$\delta_{\rm LS}\downarrow = -0.21 \pm 0.14\ \text{ppm} \qquad \delta_{\rm LS}\uparrow = -0.34 \pm 0.18\ \text{ppm}$$

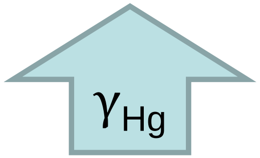


$$R = \frac{\langle f_{\rm UCN}\rangle}{\langle f_{\rm Hg}\rangle} = \frac{\gamma_{\rm n}}{\gamma_{\rm Hg}}\left(1 \mp \frac{\partial B}{\partial z}\frac{\Delta h}{|B_0|} + \frac{\langle B_\perp^2\rangle}{|B_0|^2} \mp \delta_{\rm Earth} + \delta_{\rm Hg-lightshift}\right)$$

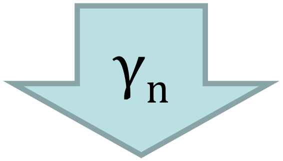
Preliminary result

- Light shift not yet included

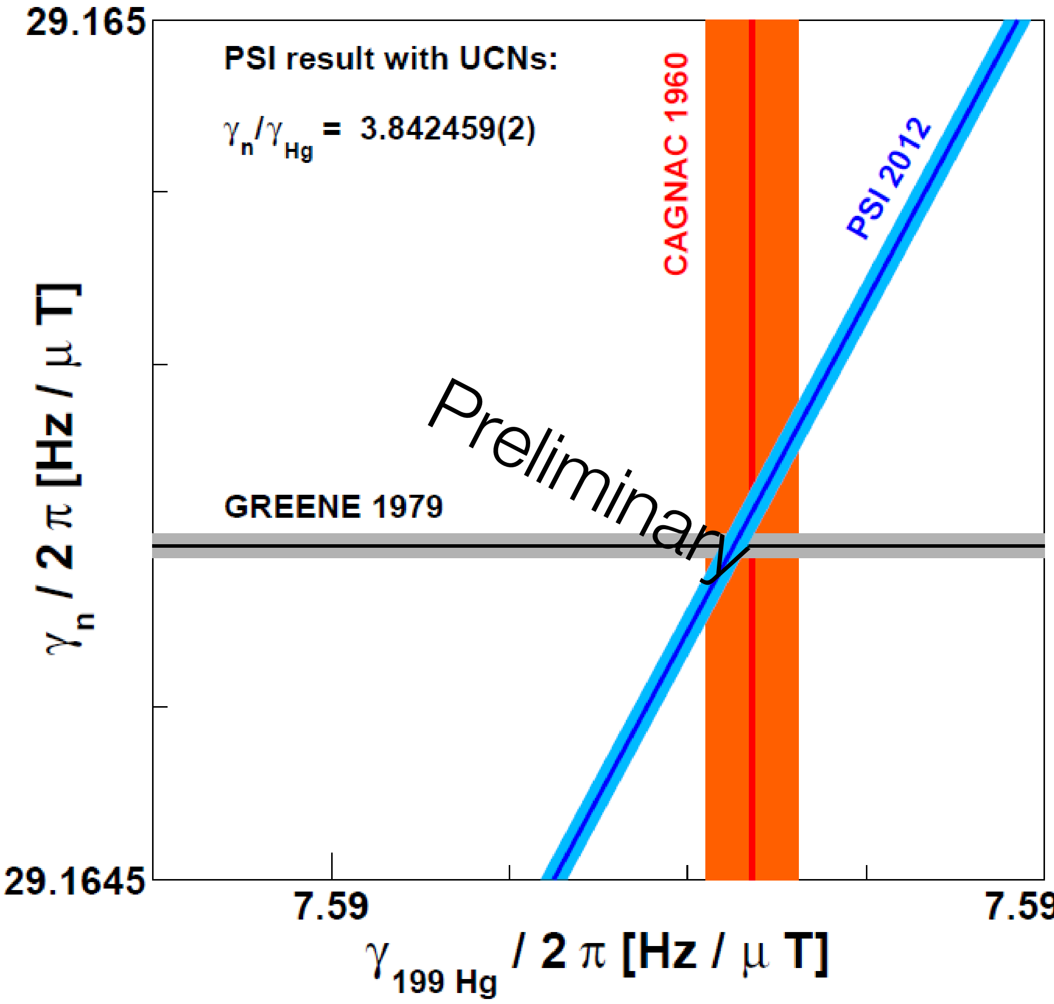
$$\frac{\gamma_n}{2\pi} = 29.164713(13) \quad \mathrm{MHz/T}$$



$$\gamma_n/\gamma_{Hg} = 3.8424585(19).$$



$$\frac{\gamma_{Hg}}{2\pi} = 7.5901130(9) \quad \mathrm{MHz/T}$$



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Conclusion

- The UCN source delivers sufficient statistics for data taking, potential improvements are being identified
- The nEDM experiment is taking data, operational reliability has been improved during shutdown 2014
- As a test of magnetic field control we have measured the most precise gyromagnetic ratio of mercury-199 and neutron.
- We expect with 300 data-days until 2016 a statistical sensitivity of $\sigma \lesssim 10^{-26}\, e\cdot\mathrm{cm}$

Thank you for your attention.