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An improved search of the nEDM

Paul Scherrer Institut

Philipp Schmidt-Wellenburg on behalf of the nEDM collaboration

Baryon Asymmetry of the Universe

SM expectation:

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

vs.

Observed*:

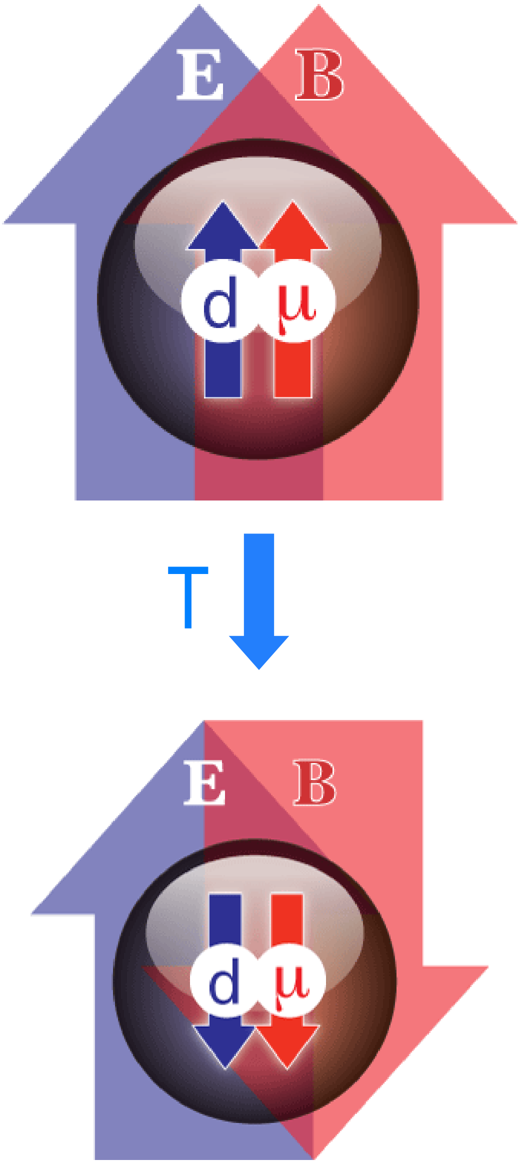
$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-10}$$

Sakharov criteria

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

*WMAP

CP violation and EDM



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

→ CP violation so far only in weak decays

→ Might help explain BAU matter/anti-matter problem

→ Excellent probe for physics beyond the Standard Model (complementary to LHC)

Standard Model: CP violation

- QCD vacuum:

$$L_{\mathrm{eff}} = L_{\mathrm{QCD}} + \theta \frac{\alpha_s}{8\pi} \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

$$\propto \mathbf{E} \cdot \mathbf{B}$$

$$d_n \approx \theta \times 10^{-15}\, e \cdot \mathrm{cm} \rightarrow \theta \approx 10^{-10}$$

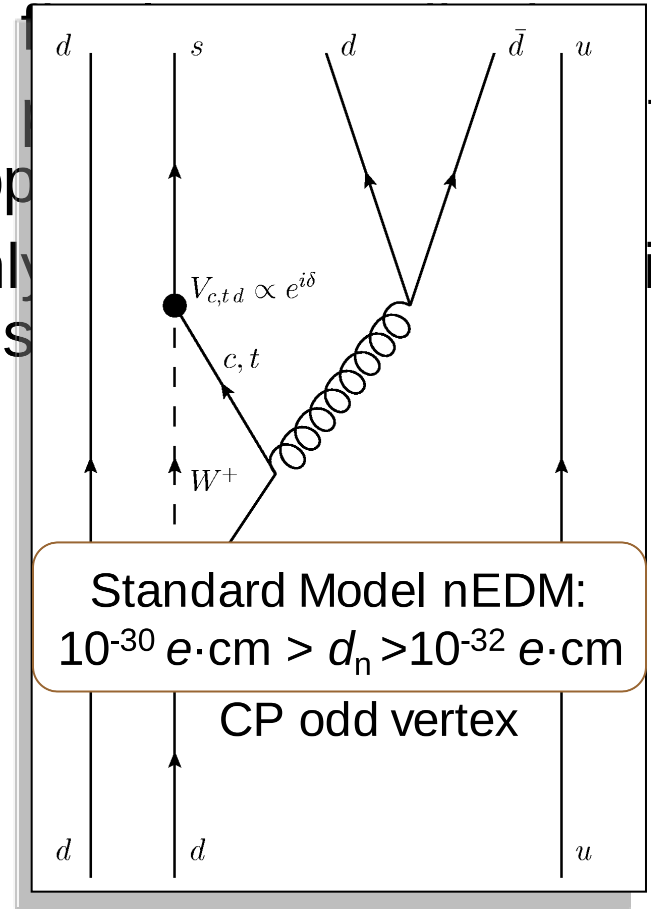
- Phase of CKM matrix:

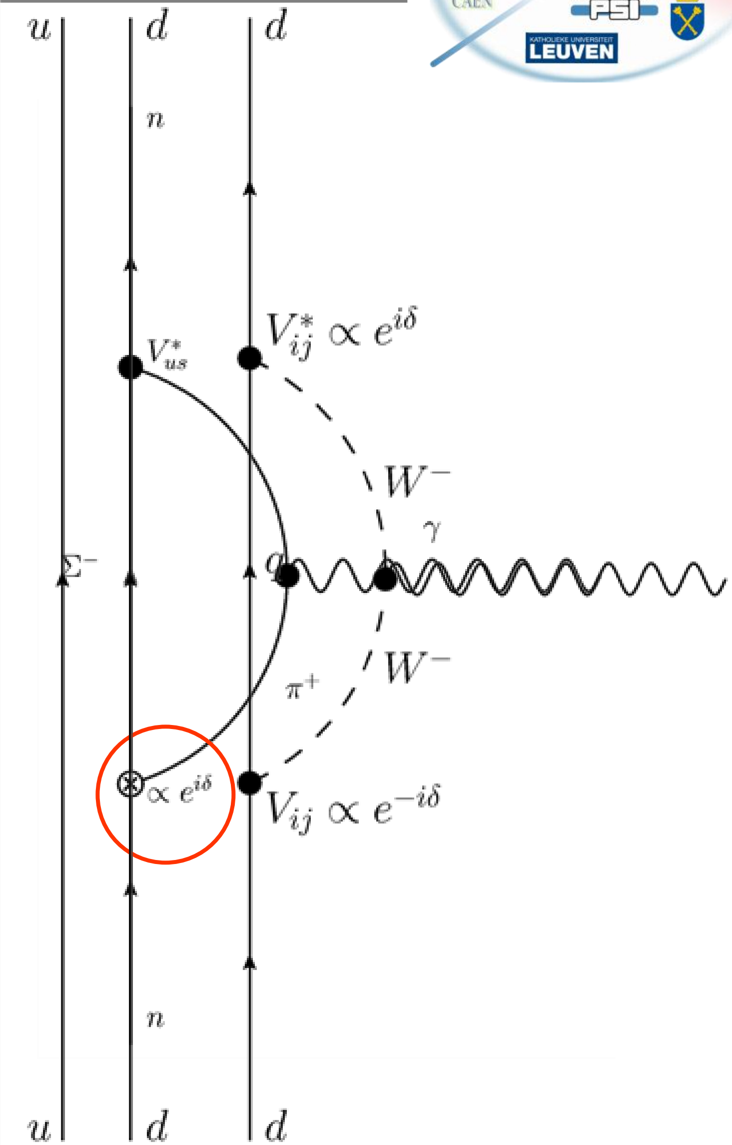
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

Known from neutral K and B meson decays

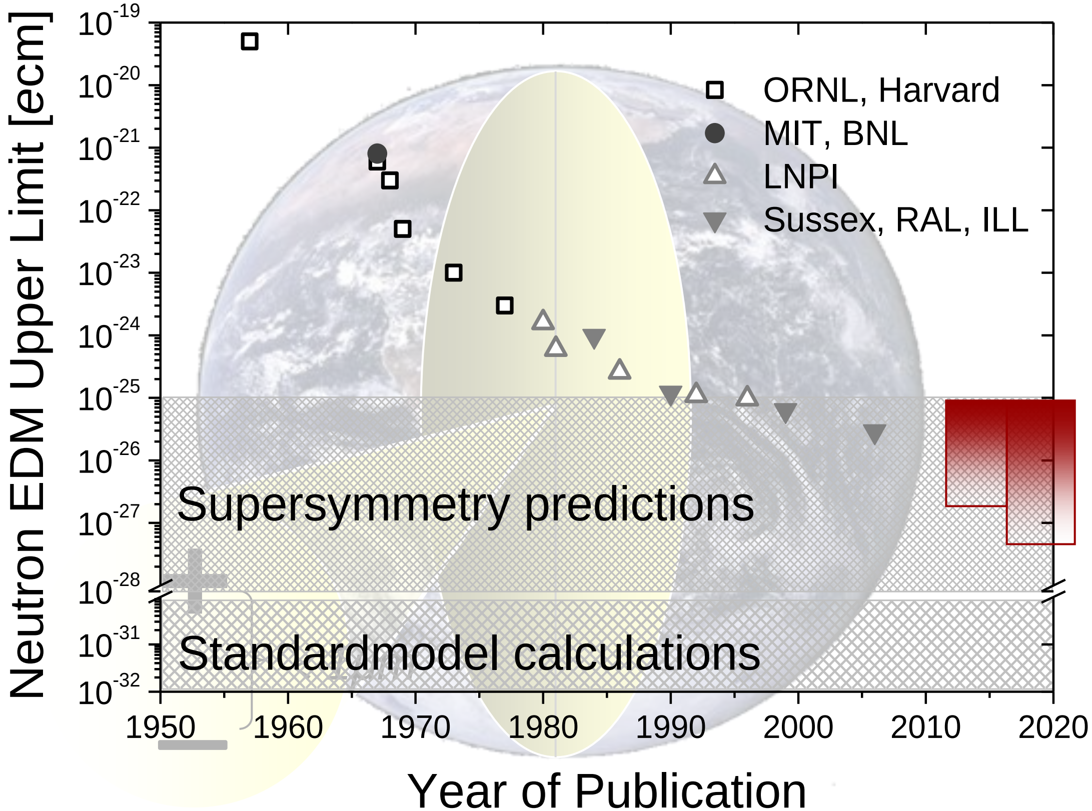
nEDM from CKM Matrix

- No tree level contribution
- No f
- No p   two loop
- Only   ibution → S





A brief history of nEDM searches



Aimed at sensitivities at PSI:

Intermediate:
$d_n < 5 \times 10^{-27}$ **e cm (95% C.L.)**

Finale:
$d_n < 5 \times 10^{-28}$ **e cm (95% C.L.)**

First

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

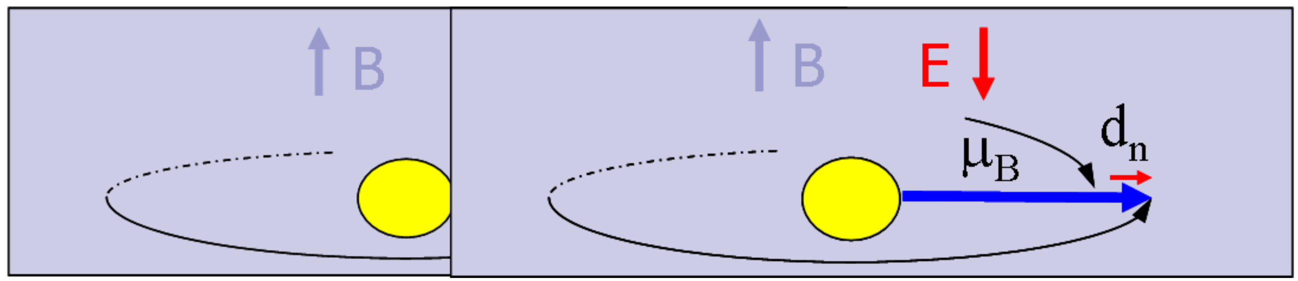
~ 50 years

Last

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

The measurement technique

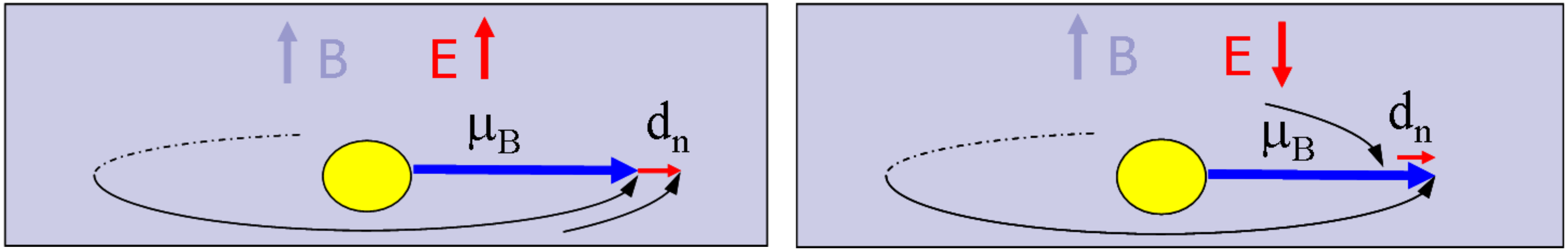
Measure the precession frequencies in a magnetic and electric field:



$$\hbar\omega = 2\mu_n B_{\uparrow\uparrow} + 2d_n E_{\uparrow\uparrow}$$

The measurement technique

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



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

for $d_n < 10^{-26}$ → $\Delta\omega/\omega < 2 \times 10^{-9}$

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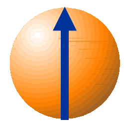
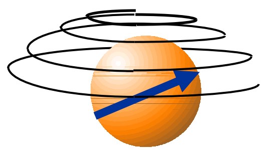
The Ramsey technique

The Ramsey technique of separated oscillating fields

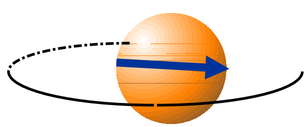
"Spin up" neutron...



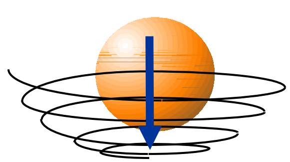
Apply $\pi/2$ spin flip pulse...



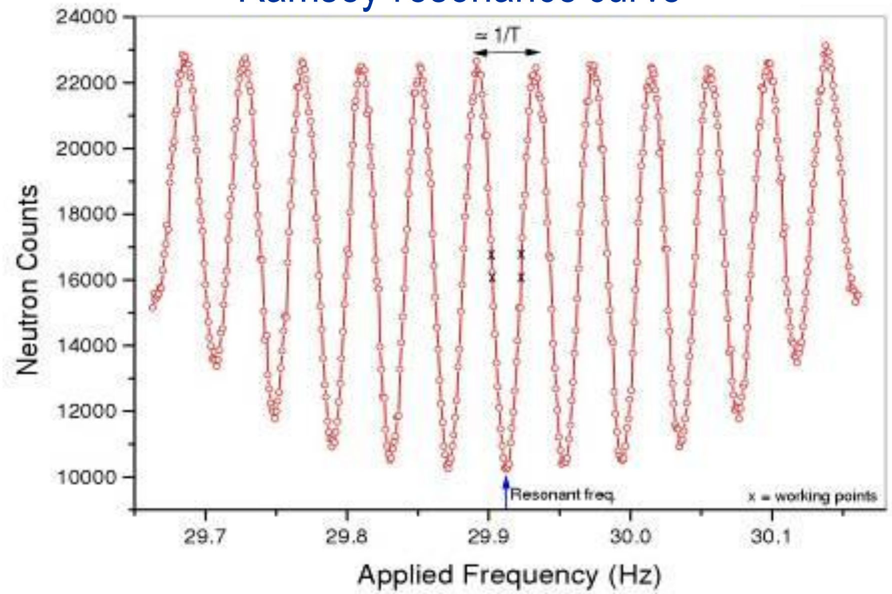
Free precession at ω_L



Second $\pi/2$ spin flip pulse.



Ramsey resonance curve



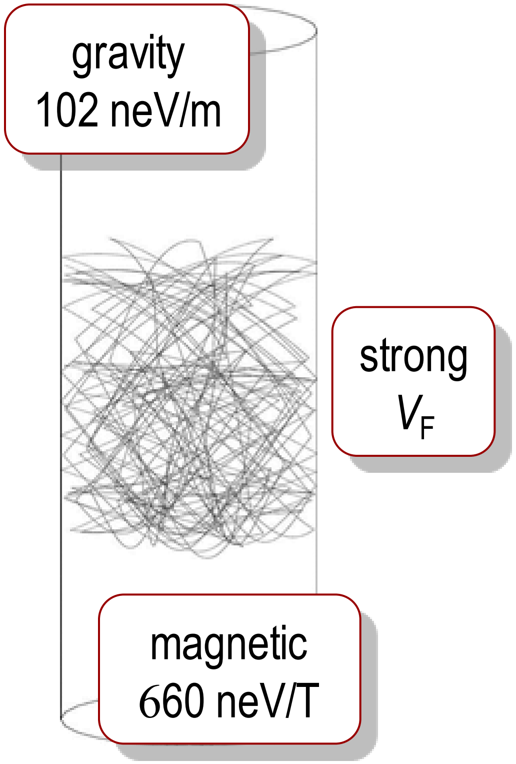
Sensitivity: $$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

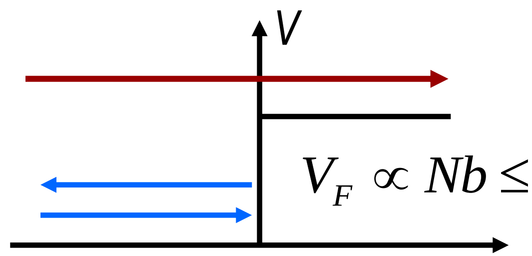
- α Visibility of resonance
- E Electric field strength
- T Time of free precession
- N Number of neutrons

Ultracold neutrons (UCN)

$$\sigma(d_n) \propto \frac{1}{T\sqrt{N}}$$

storable neutrons (UCN)





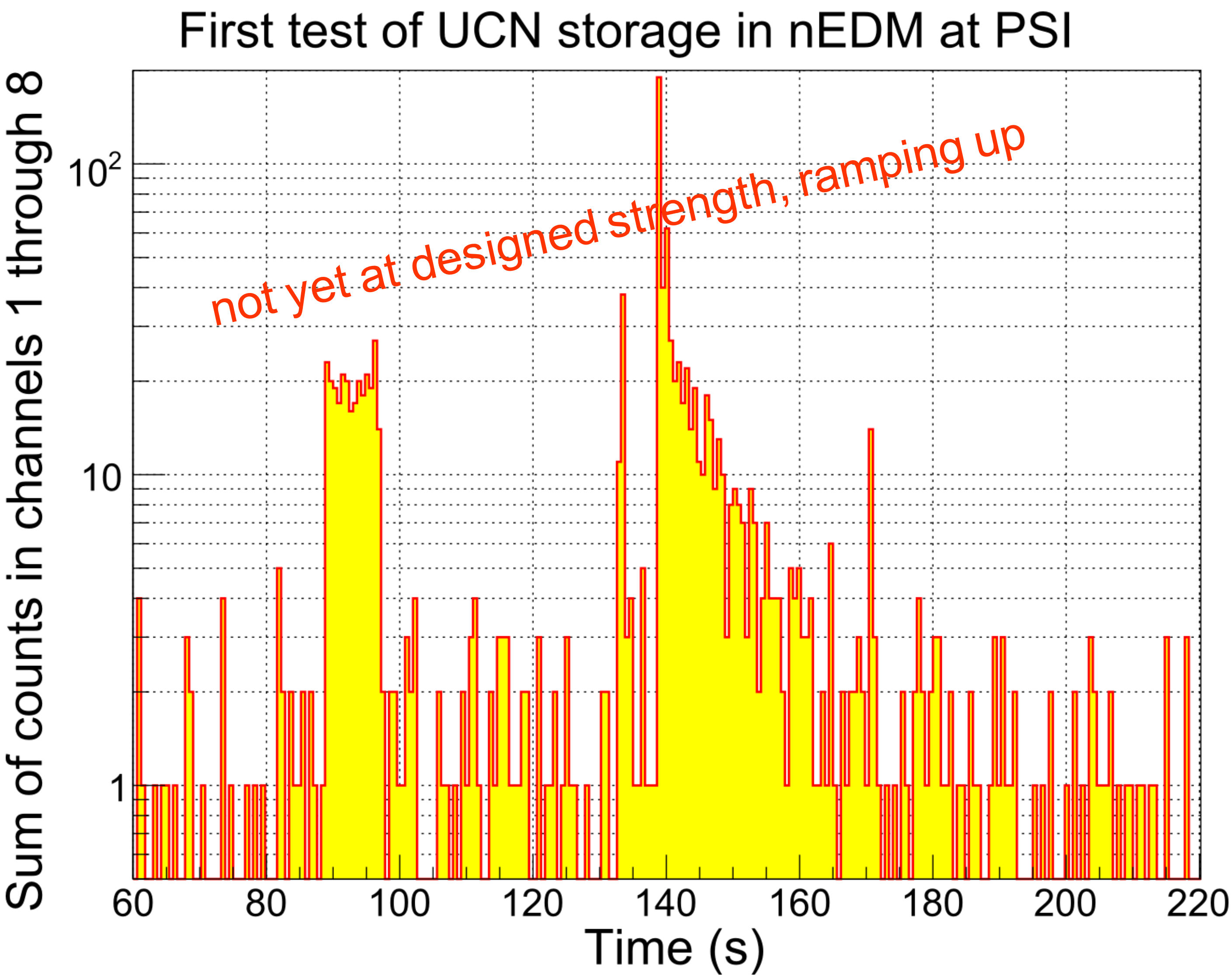
$$V_F \propto Nb \leq 350 \text{ neV}$$

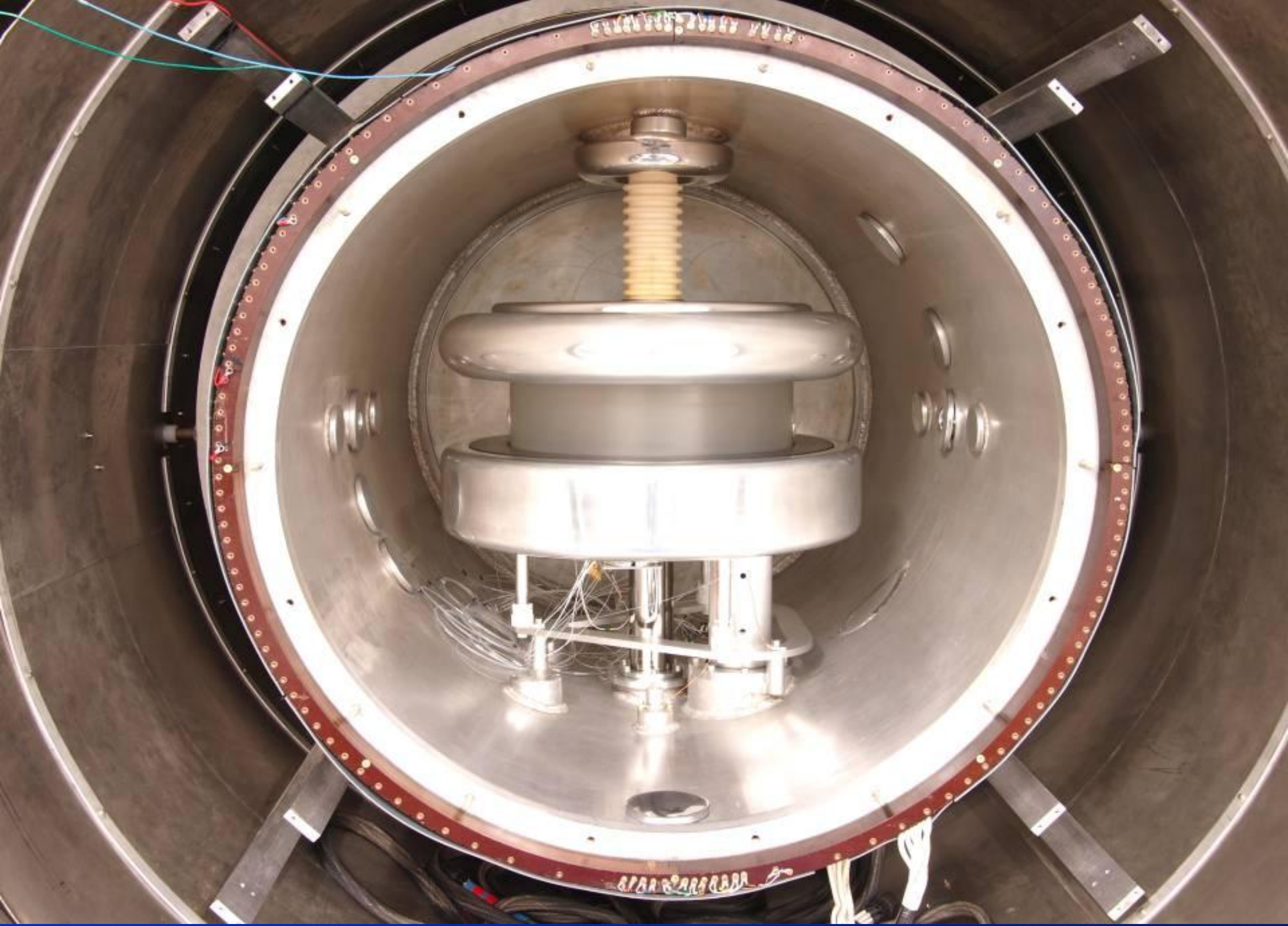
350 neV ↔ 8 m/s ↔ 500 Å ↔ 3 mK

storage properties are material dependent

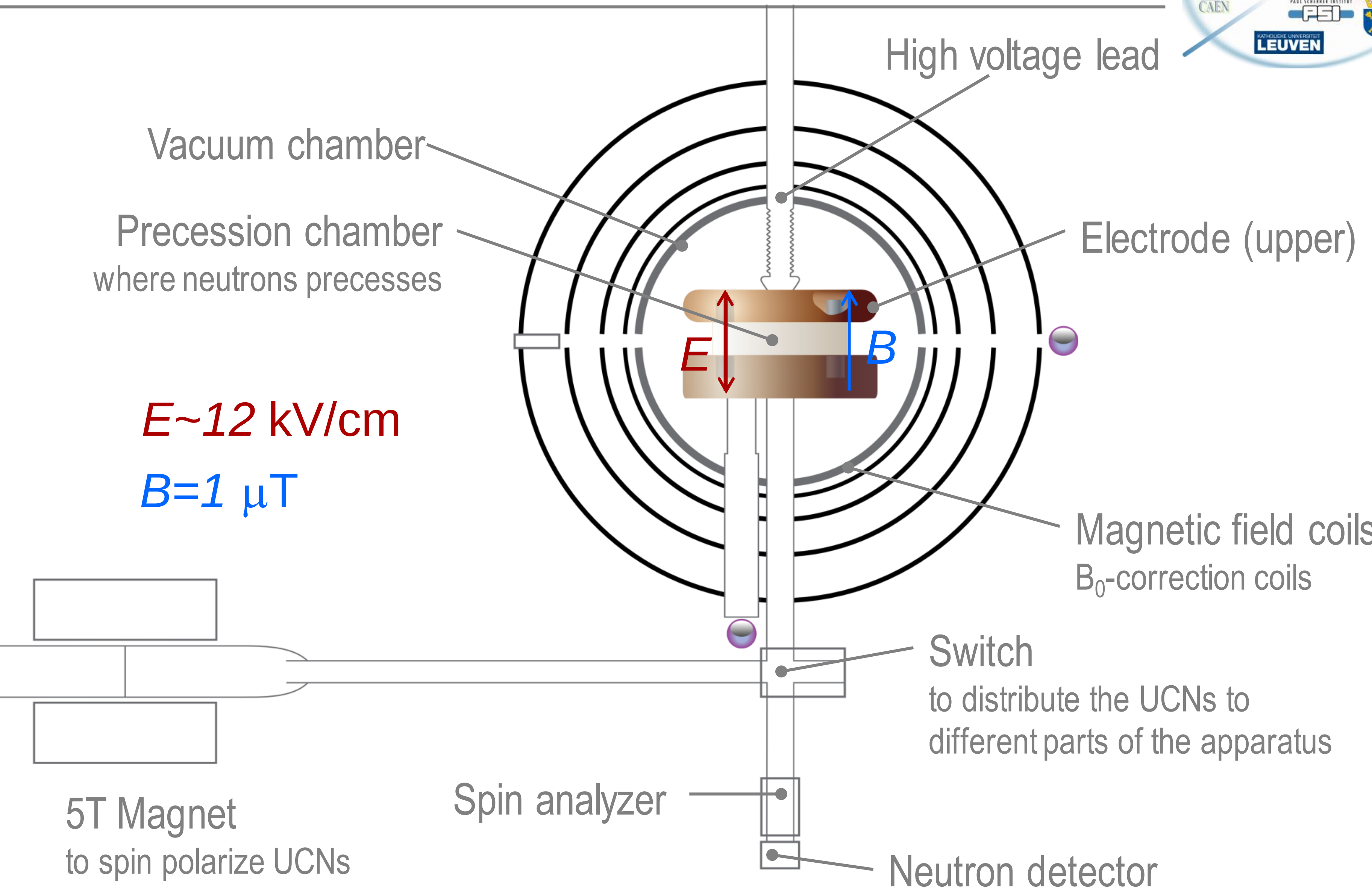
E. Fermi, 1946 , Ya. B. Zeldovich
Sov. Phys. JETP 9, 1389 (1959)

New UCN source @PSI





Apparatus

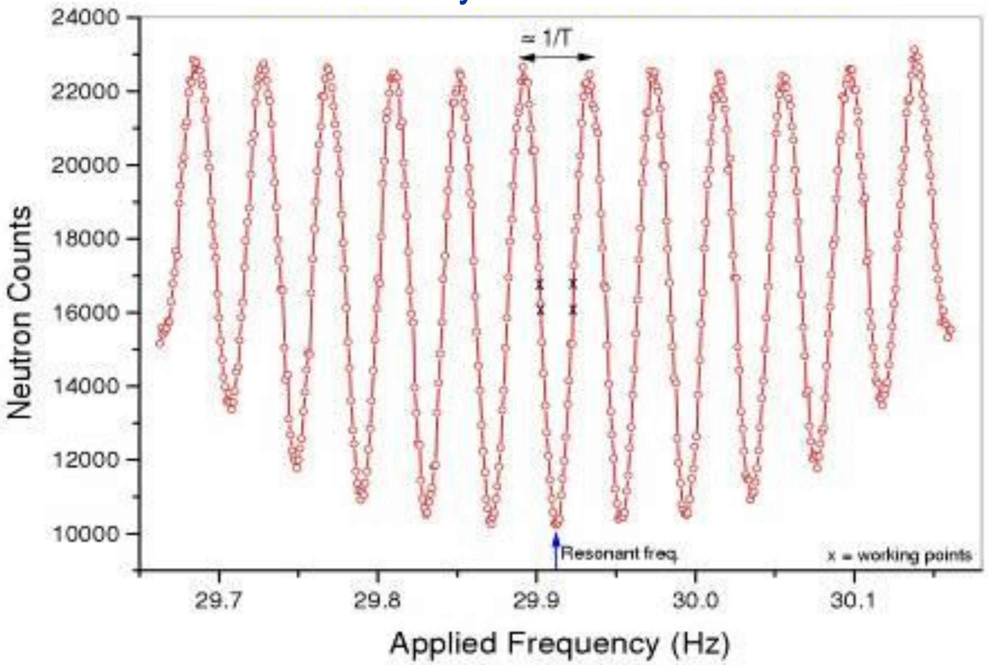


E~12 kV/cm

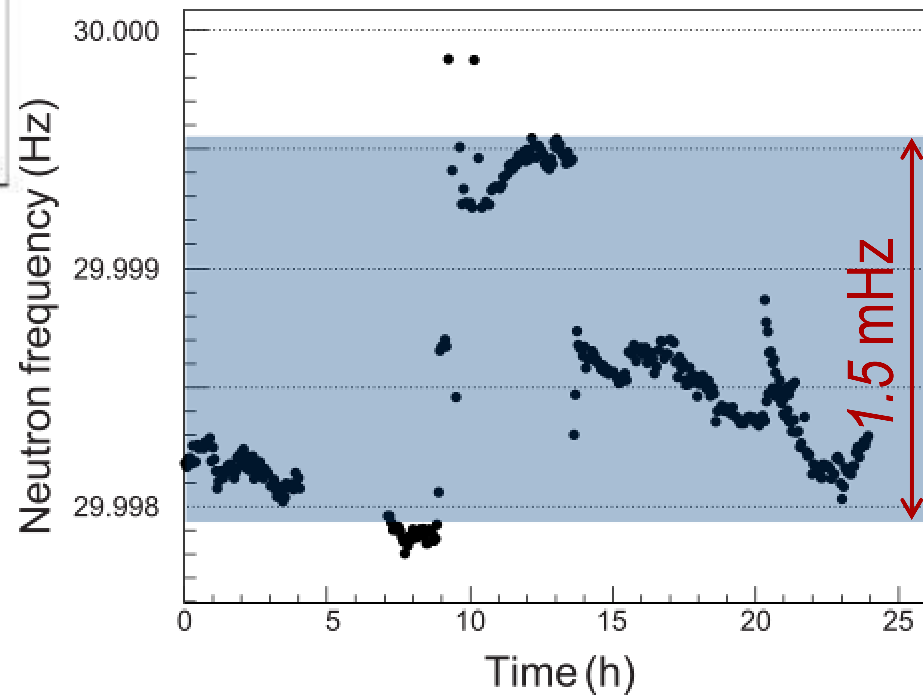
B=1 μT

Measuring frequencies with UCN

Ramsey resonance curve



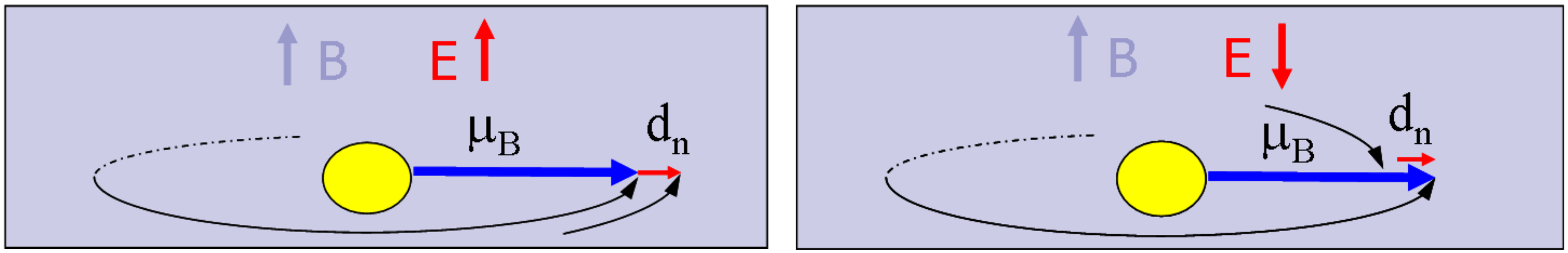
Sensitivity: $\sigma(d_{\mathrm{n}}) = \dfrac{\hbar}{2\alpha E T \sqrt{N}}$



- changing polarity every ~ 1.5h
- comparing frequency +/- polarity
- aimed at sensitivity $\Delta\omega$ [60 nHz

The measurement technique

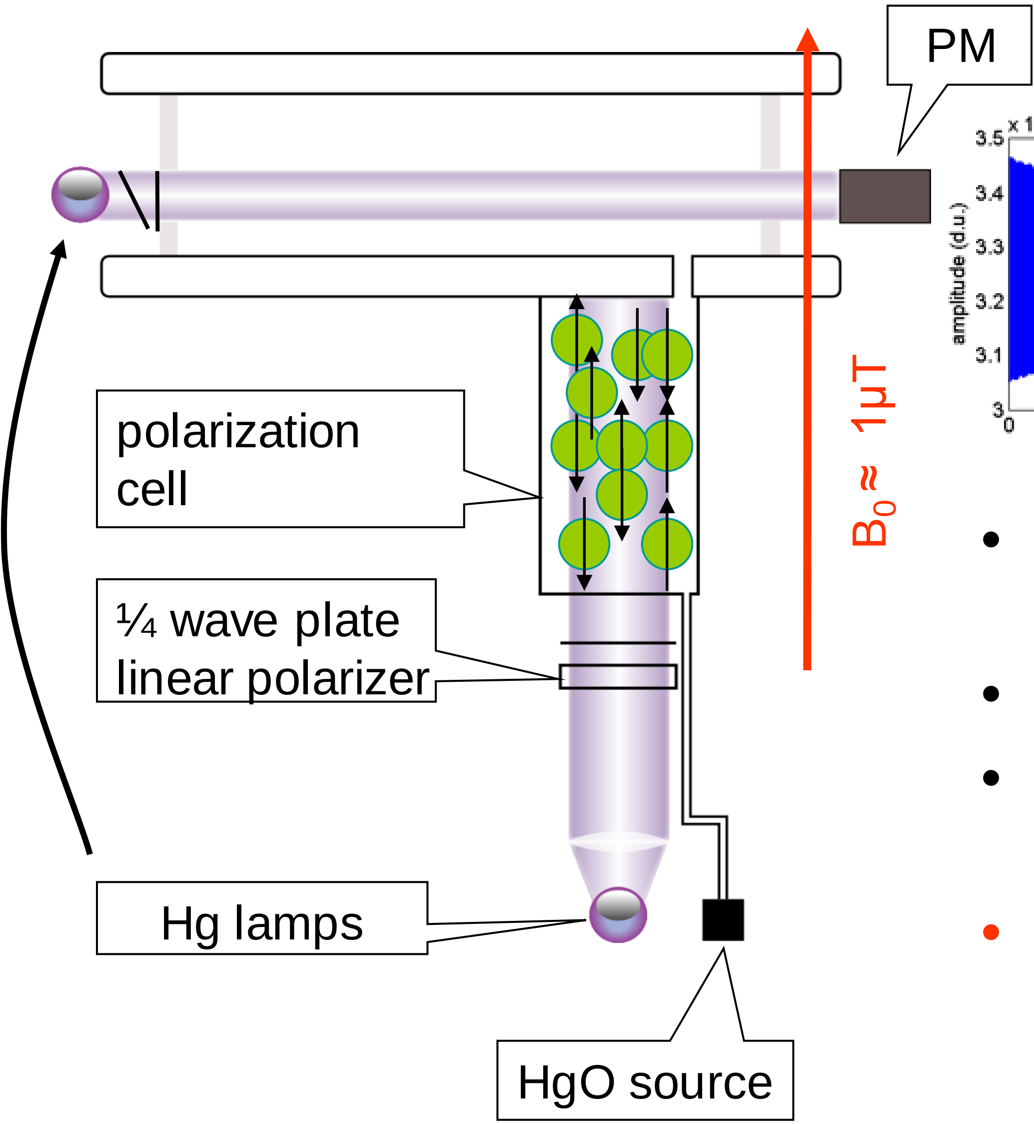
Measure the difference of precession frequencies in parallel/anti-parallel fields:

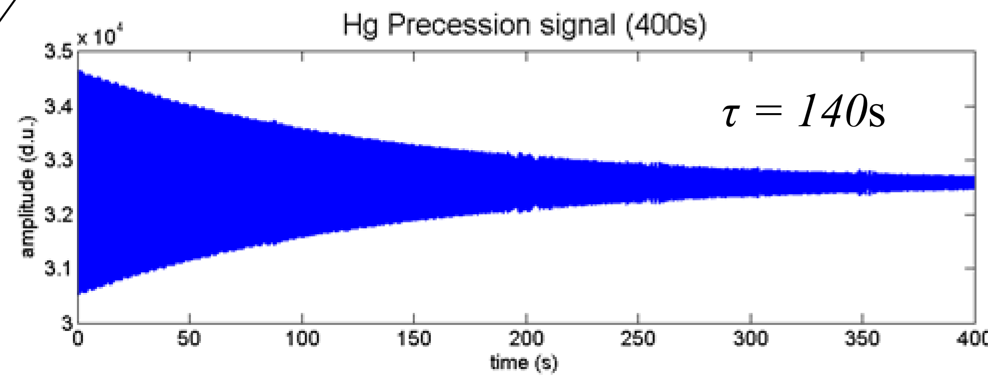


$$\hbar \Delta\omega = 2d_{\mathrm{n}}\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right) + 2\mu_{\mathrm{n}}\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)$$

Active Stabilization and insitu field monitoring

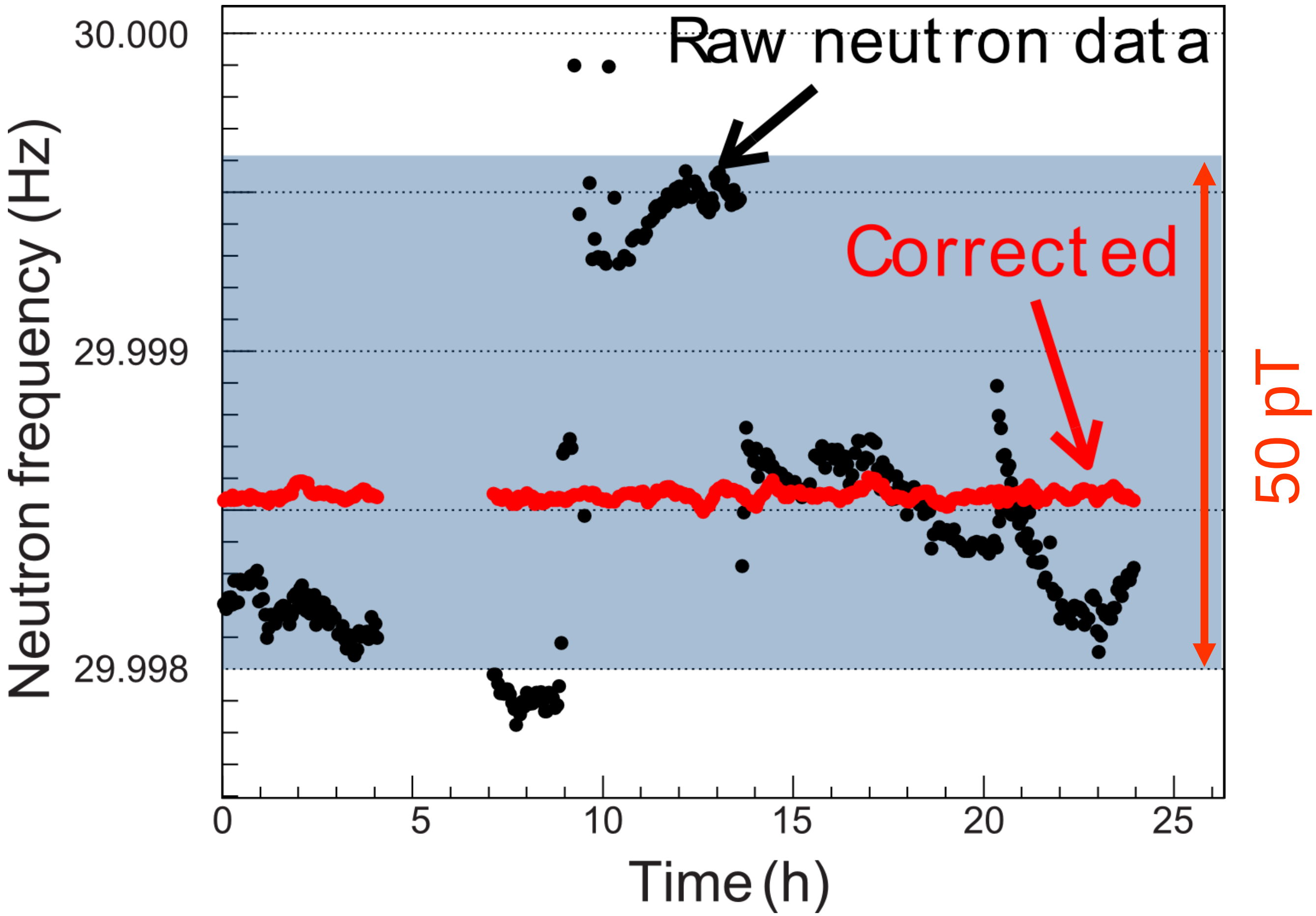
Mercury co-magnetometer





- Average magnetic field (volume and cycle)
- $\sigma(B) \sim 20 - 50$ fT
- Center of mass different than UCN
- Important Systematic effects due to magnetic field gradients

Corrected measurement

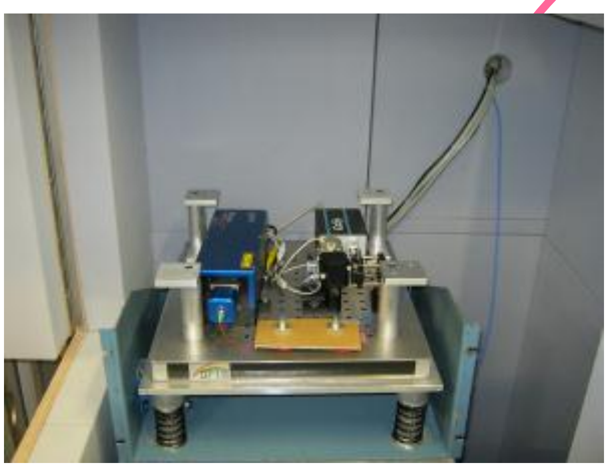


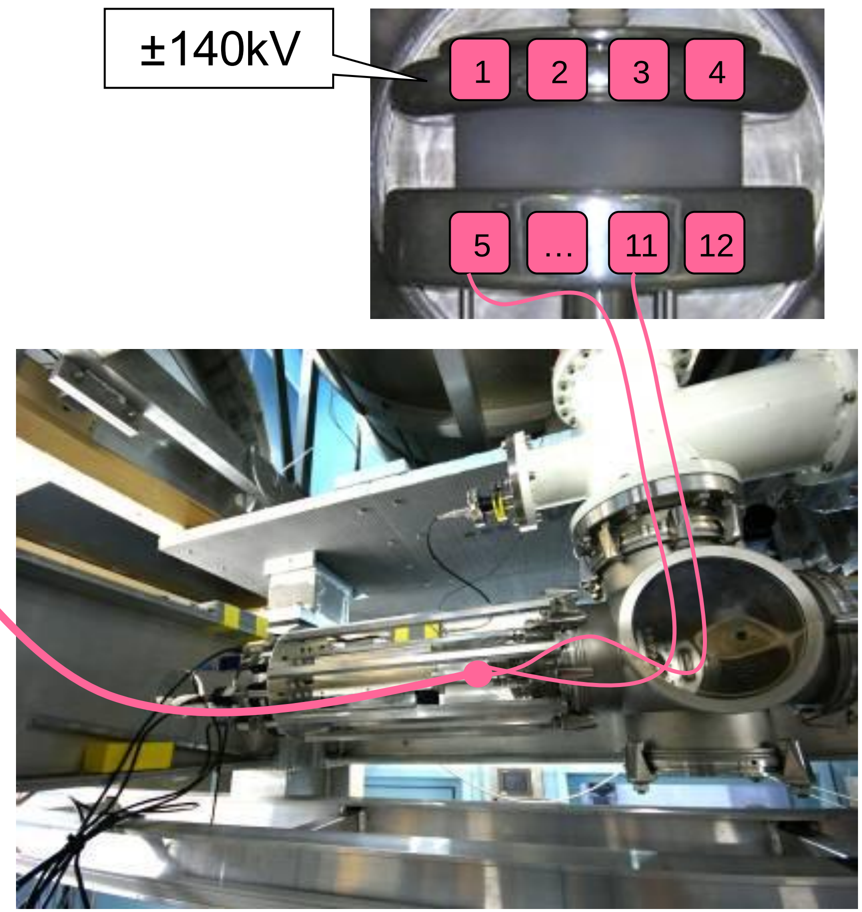
+ 12 Cesium magnetometers for field gradient measurements

Cesium magnetometers

Monitoring of vertical magnetic gradients

- Two cesium magnetometer arrays
- Stabilized laser
- PID phase locked DAQ





Systematic effects

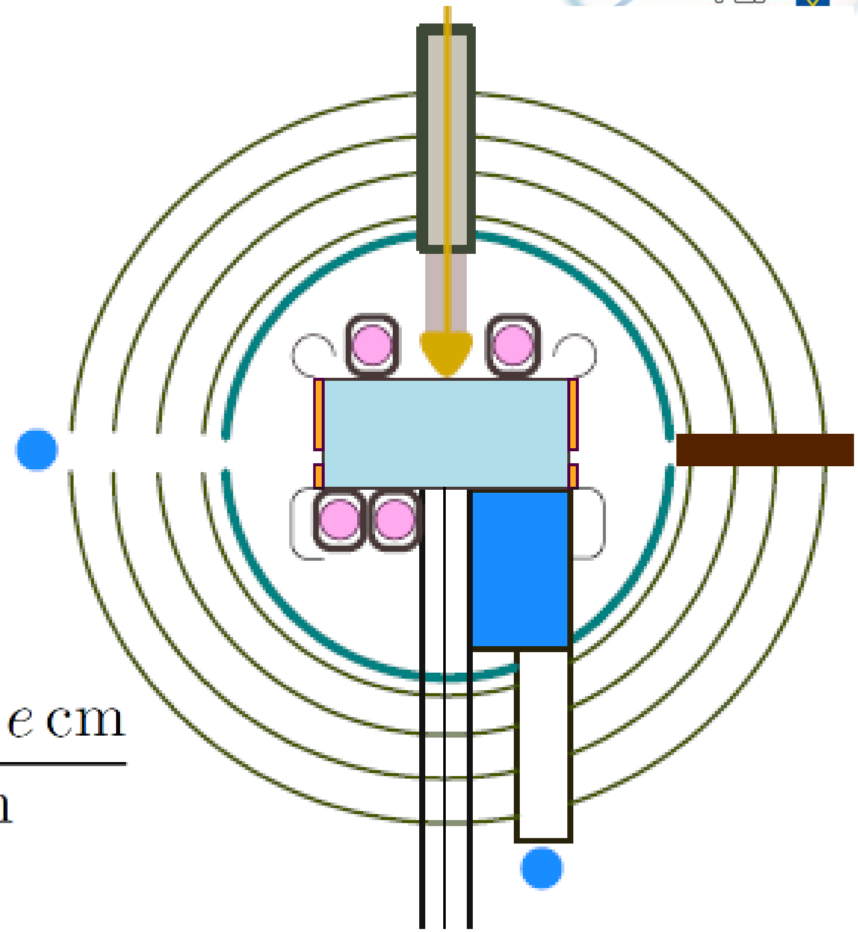
Effect	Shift (see Ref.) [10^{-27} *e* cm]	σ (see Ref.) [10^{-27} *e* cm]	σ (at PSI) [10^{-27} *e* cm]
Door cavity dipole	-5.6	2.00	**0.10**
Other dipole fields	0.0	6.00	**0.40**
Quadrupole difference	-1.3	2.00	**0.60**
v×E translational	0.0	0.03	0.03
v×E rotational	0.0	1.00	**0.10**
Second-order v×E	0.0	0.02	0.02
νHg light shift (geo phase)	3.5	0.80	**0.40**
νHg light shift (direct)	0.0	0.20	0.20
Uncompensated B drift	0.0	2.40	**0.90**
Hg atom EDM	-0.4	0.30	**0.06**
Electric forces	0.0	0.40	0.40
Leakage currents	0.0	0.10	0.10
ac fields	0.0	0.01	0.01
Total	-3.8	7.19	**1.37**

Uncompensated field drift

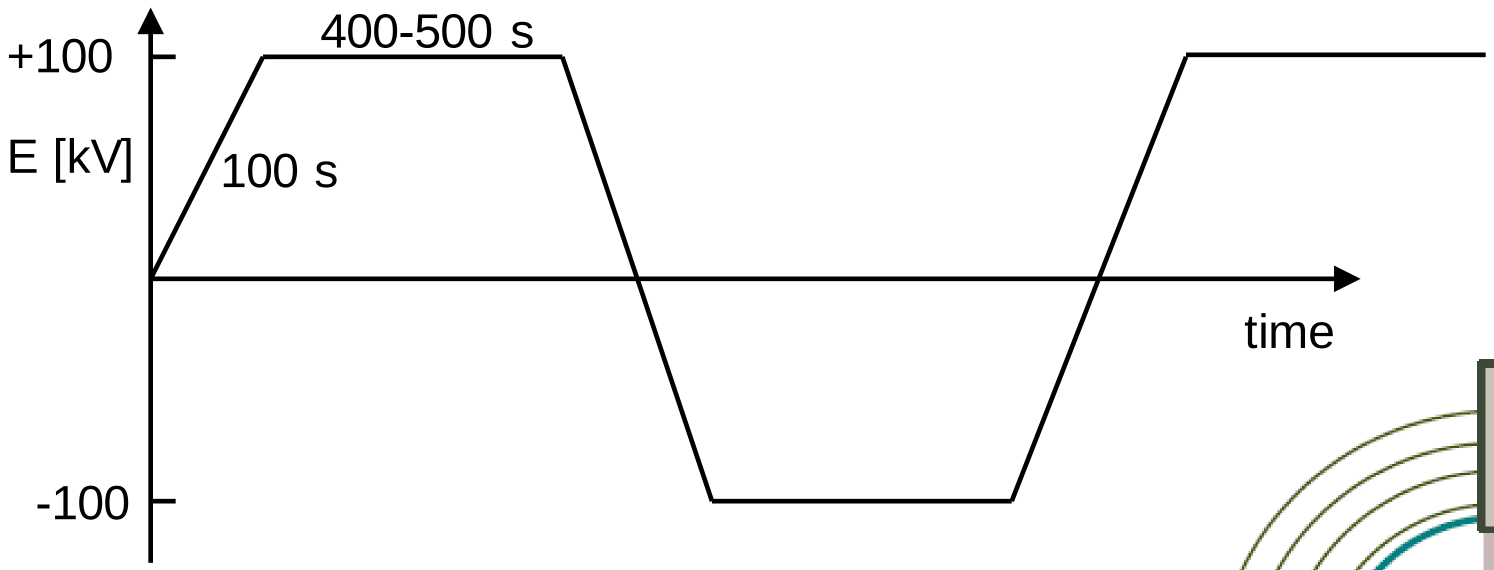
Magnetization through changing polarity

$$\sigma(d_\text{n}) = \boxed{\frac{\hbar\gamma_\text{n}}{2E}\Delta h}\,\delta G$$

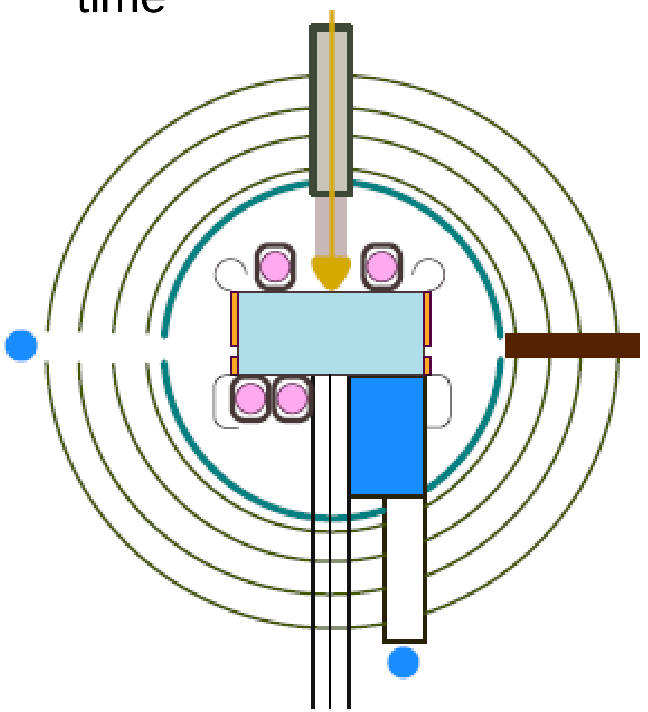
$$\frac{\hbar\gamma_\text{n}}{2E}\Delta h \rightarrow \frac{1.8\times 10^{-27}\,e\,\text{cm}}{1\,\text{fT}/\text{cm}}$$



Uncompensated field drift

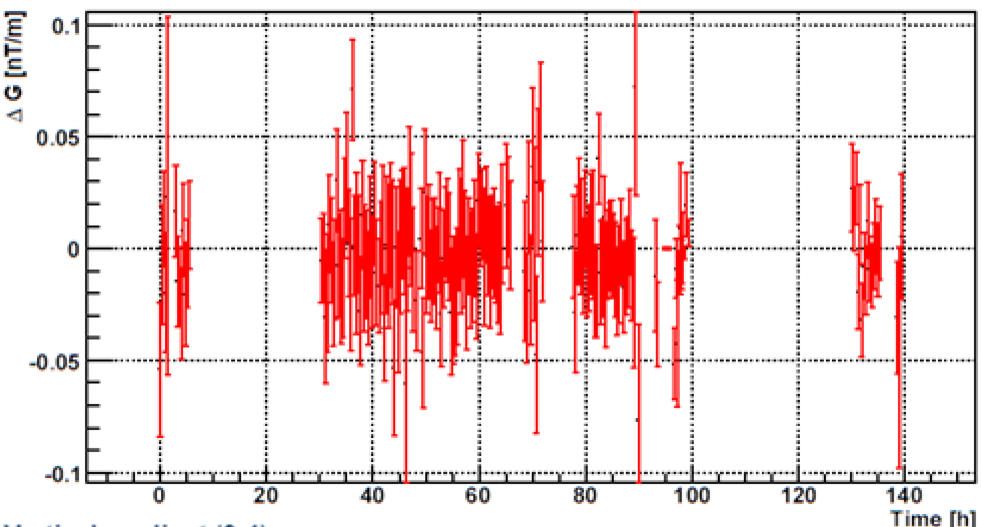


Ramping speed = 1 kV/s
Charging current = 35 nA

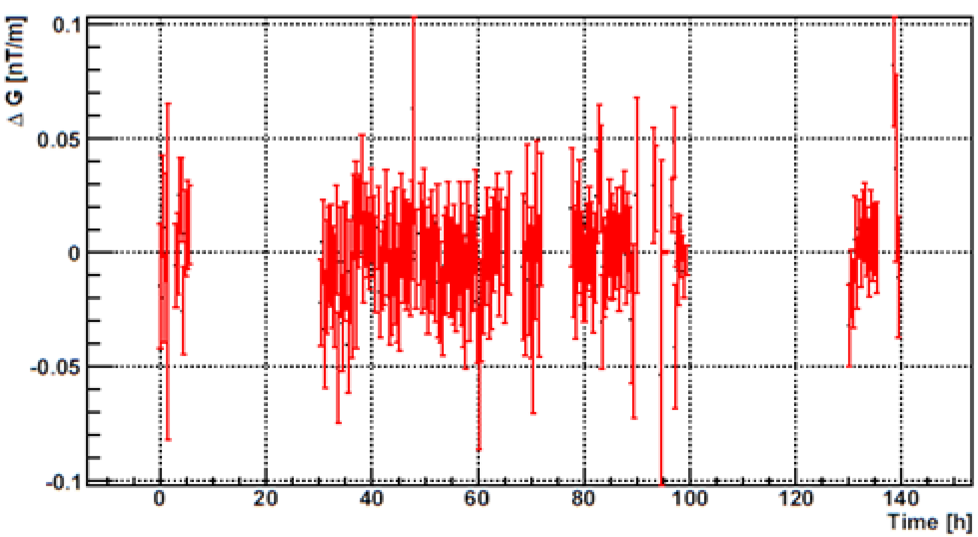


Uncompensated field drift

Vertical gradient (1-2)



Vertical gradient (3-4)



No effect is observed at the level of 2.8 fT/cm

Translates into

$$d_n^{\text{false}} = (-15 \pm 16) \times 10^{-27} \; e \cdot \text{cm}$$

No effect is o rved at the level of 2. /cm

Dedicated runs (daytime)

$$\sigma\left(d_n^{\text{false}}\right) < 0.9 \times 10^{-27} \; e \cdot \text{cm}$$

Conclusion

- UCN source is ramping up
  → first data this year (50 nights)
- Reduction of main systematic effects

$$d_n = (\,?\pm 6_{\text{stat}} \pm\ 4_{\text{sys}})\times 10^{-27}\ e\cdot\text{cm}$$

- Further improvements on systematic effects winter shut-down 2011-2012
- 200 nights of data in 2012-2013

$$d_n = (\,?\pm 2_{\text{stat}} \pm\ 2_{\text{sys}})\times 10^{-27}\ e\cdot\text{cm}$$

The Neutron EDM Collaboration

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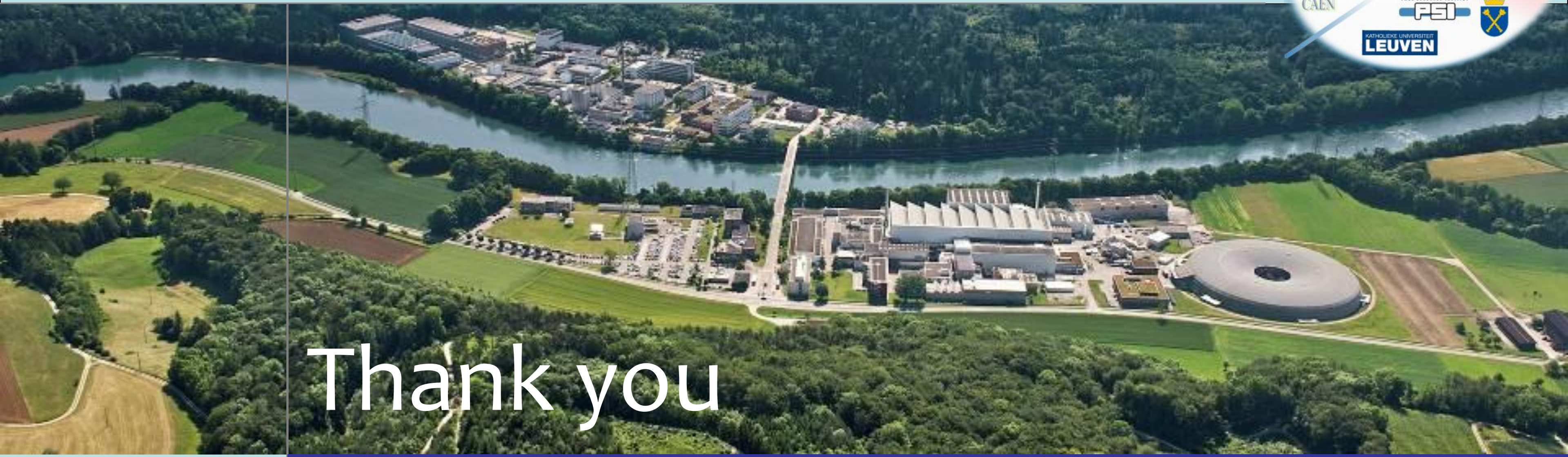

Thank you

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