Search for a nEDM at PSI

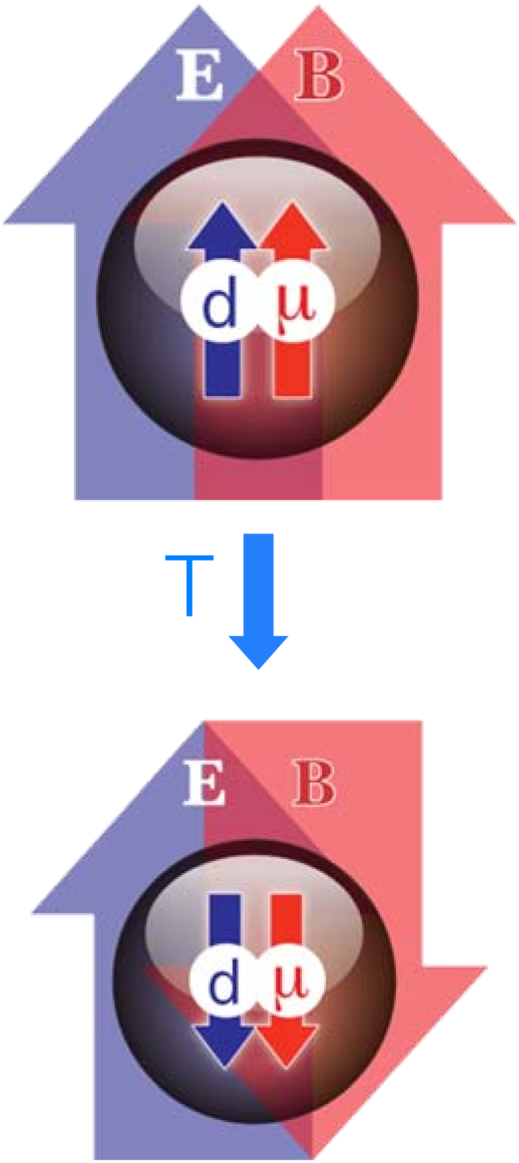
P. Schmidt-Wellenburg
on behalf
of the PSI nEDM
collaboration

Mahabaleshwar,
20.02.2013
Philipp Schmidt-Wellenburg

The collaboration

- 6 countries
- 14 institutions
- 44 members

CP violation and EDM



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

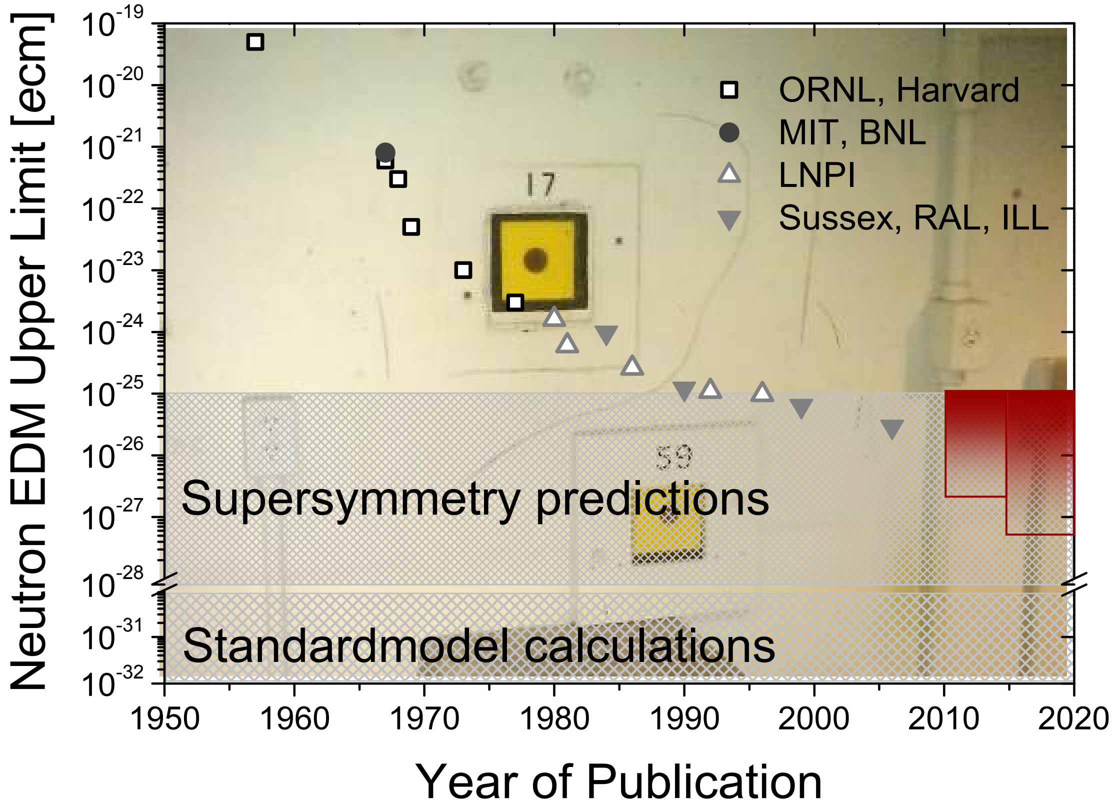
→ ~~CP~~ so far only in weak decays

→ 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

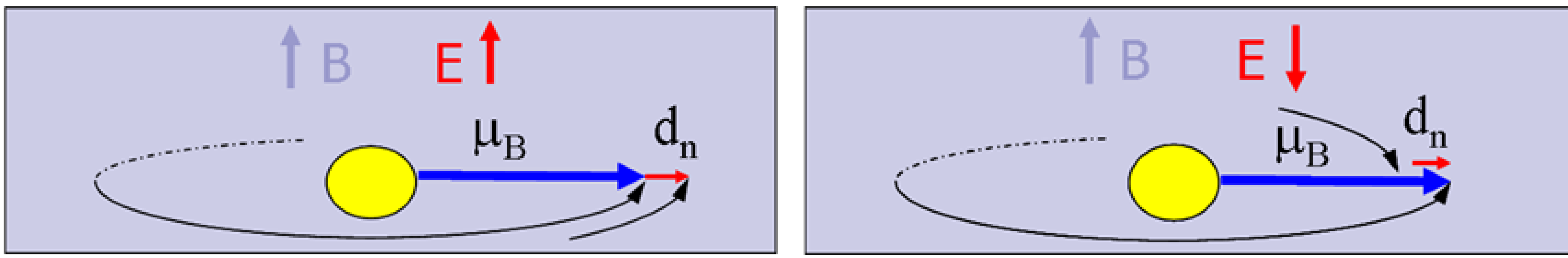
~ 50 years

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:



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

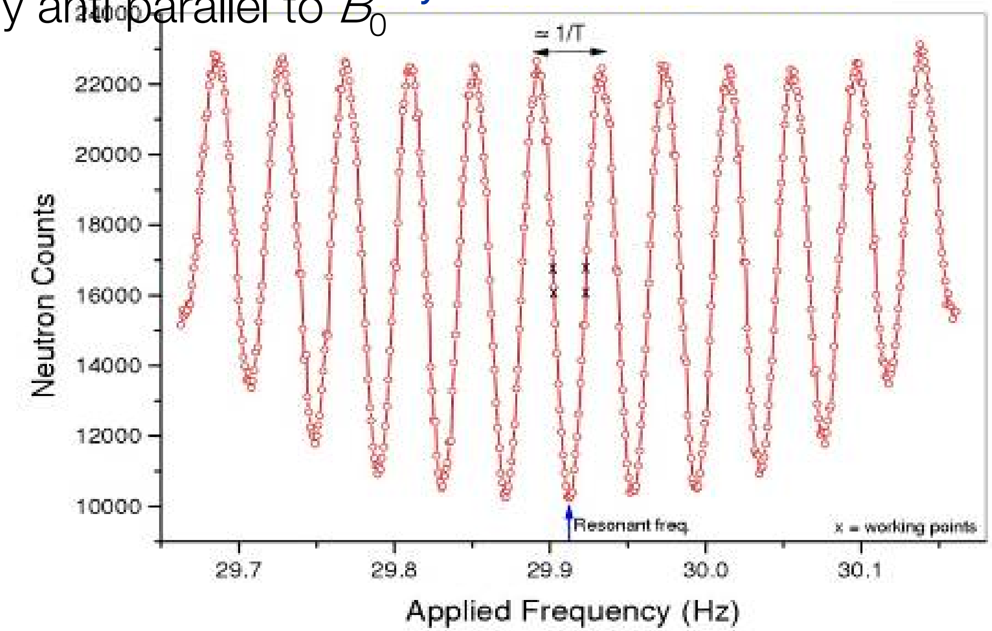
for $d_n < 10^{-26}$ → $\Delta\omega$ < 60 nHz

ω_L=30Hz

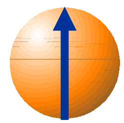
The Ramsey technique

Electric field E parallel respectively anti-parallel to B_0

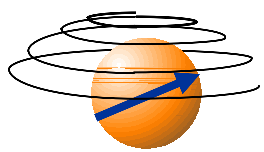
Ramsey resonance curve



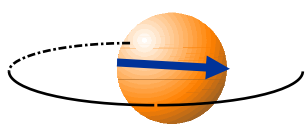
"Spin up" neutron...



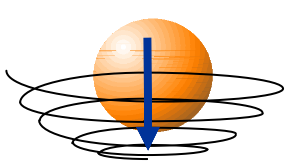
Apply $\pi/2$ spin flip pulse...



Free precession at ω_L



Second $\pi/2$ spin flip pulse.



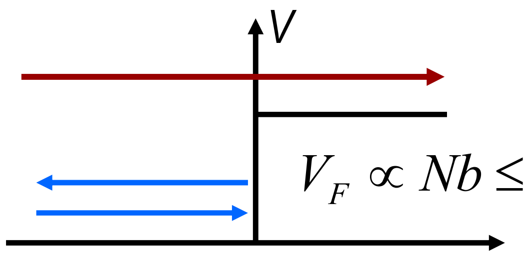
Sensitivity: $$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

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

Ultracold neutrons (UCN)

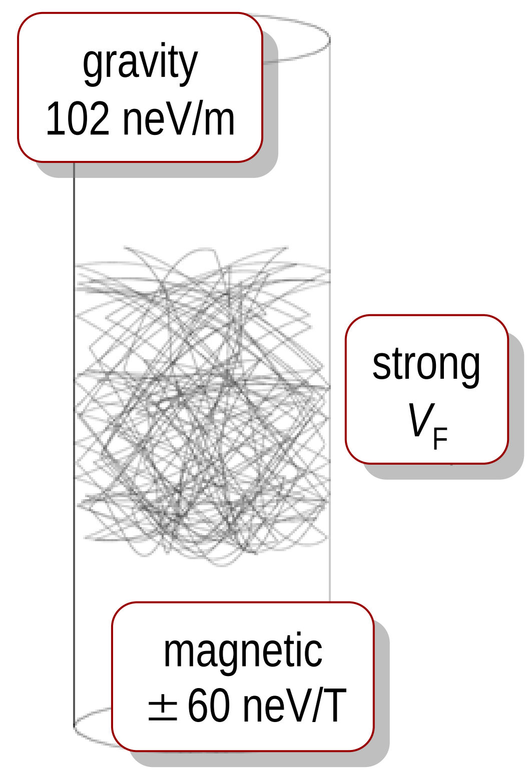
$$\sigma(d_n) \propto \frac{1}{T\sqrt{N}}$$

⇒ storable neutrons (UCN)



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

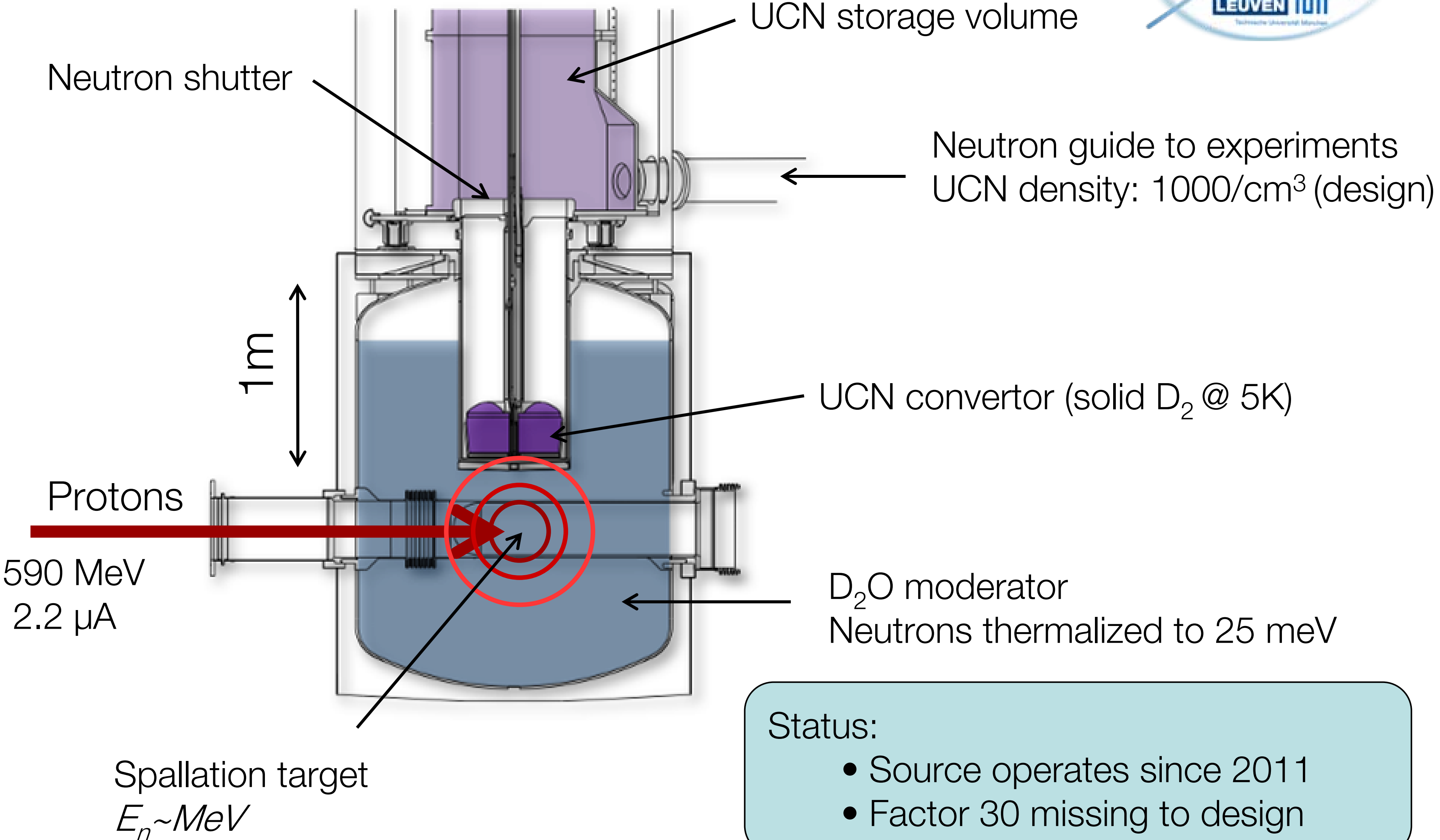
storage properties are material dependent



350 neV ↔ 8 m/s ↔ 500 Å ↔ 3 mK

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

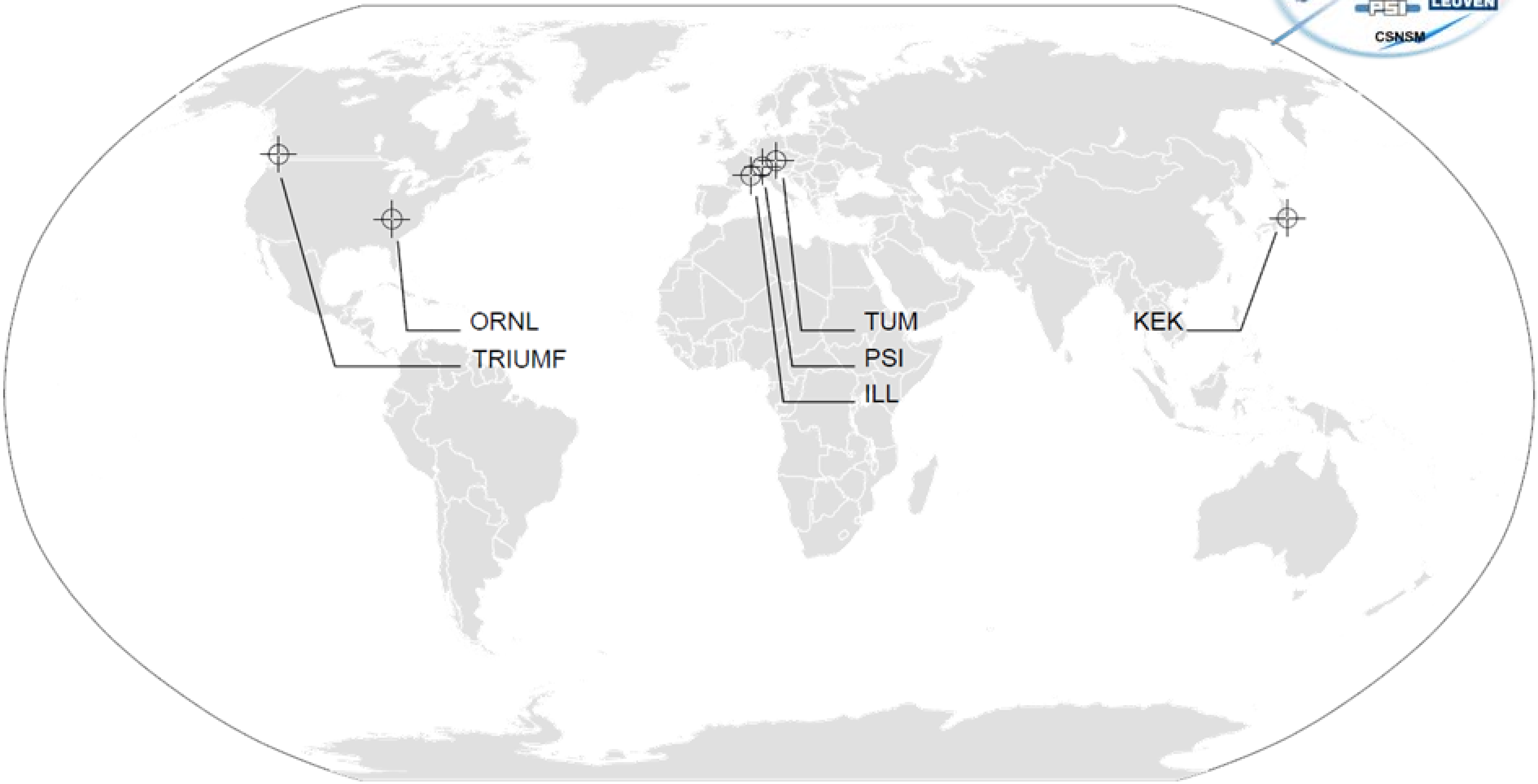
PSI UCN source



Status:

- Source operates since 2011
- Factor 30 missing to design

Competitors



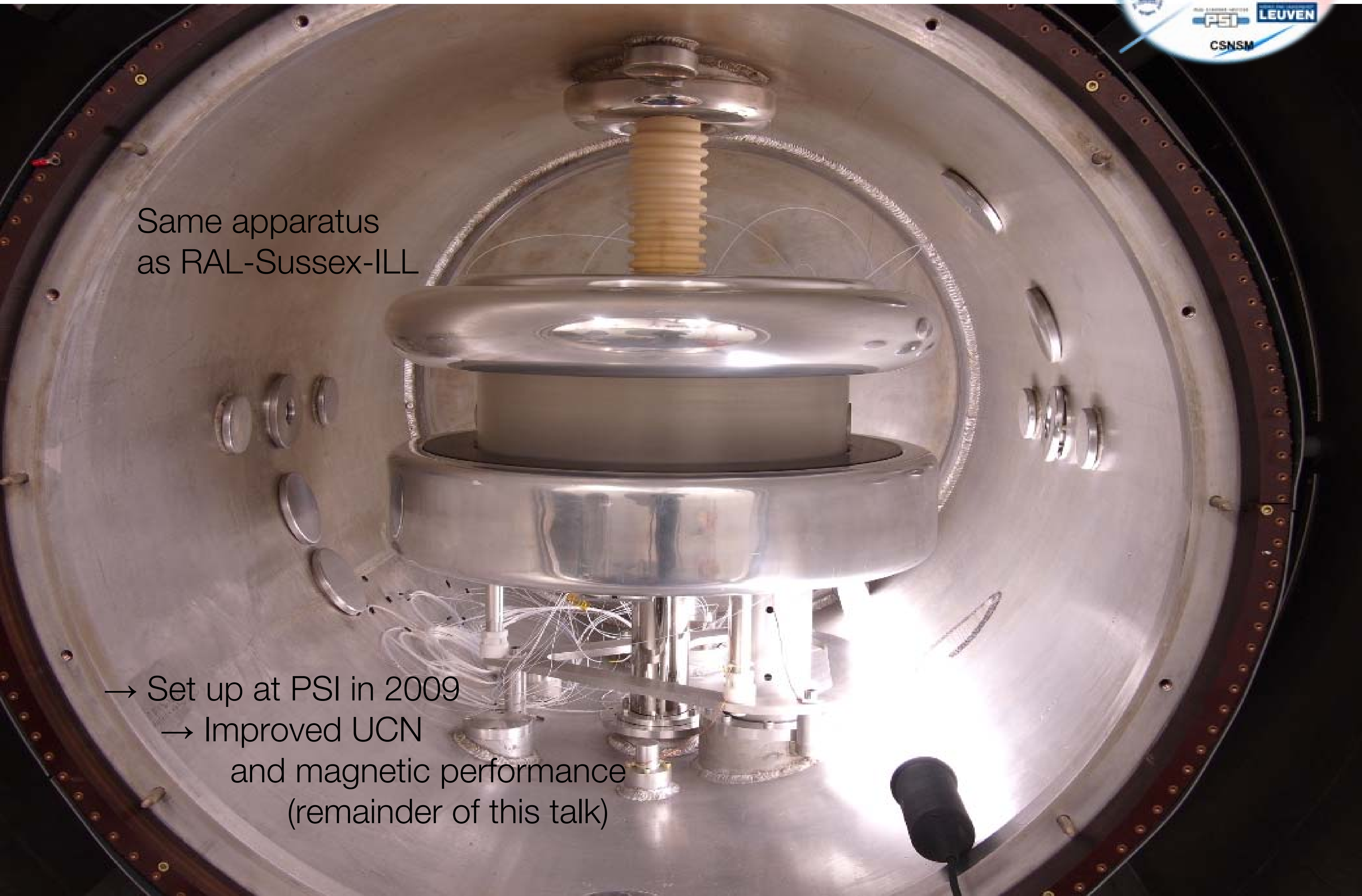
In vacuum:

TRIUMF, PSI, TUM, ILL, KEK

In superfluid helium (cryo EDM):

ILL, ORNL

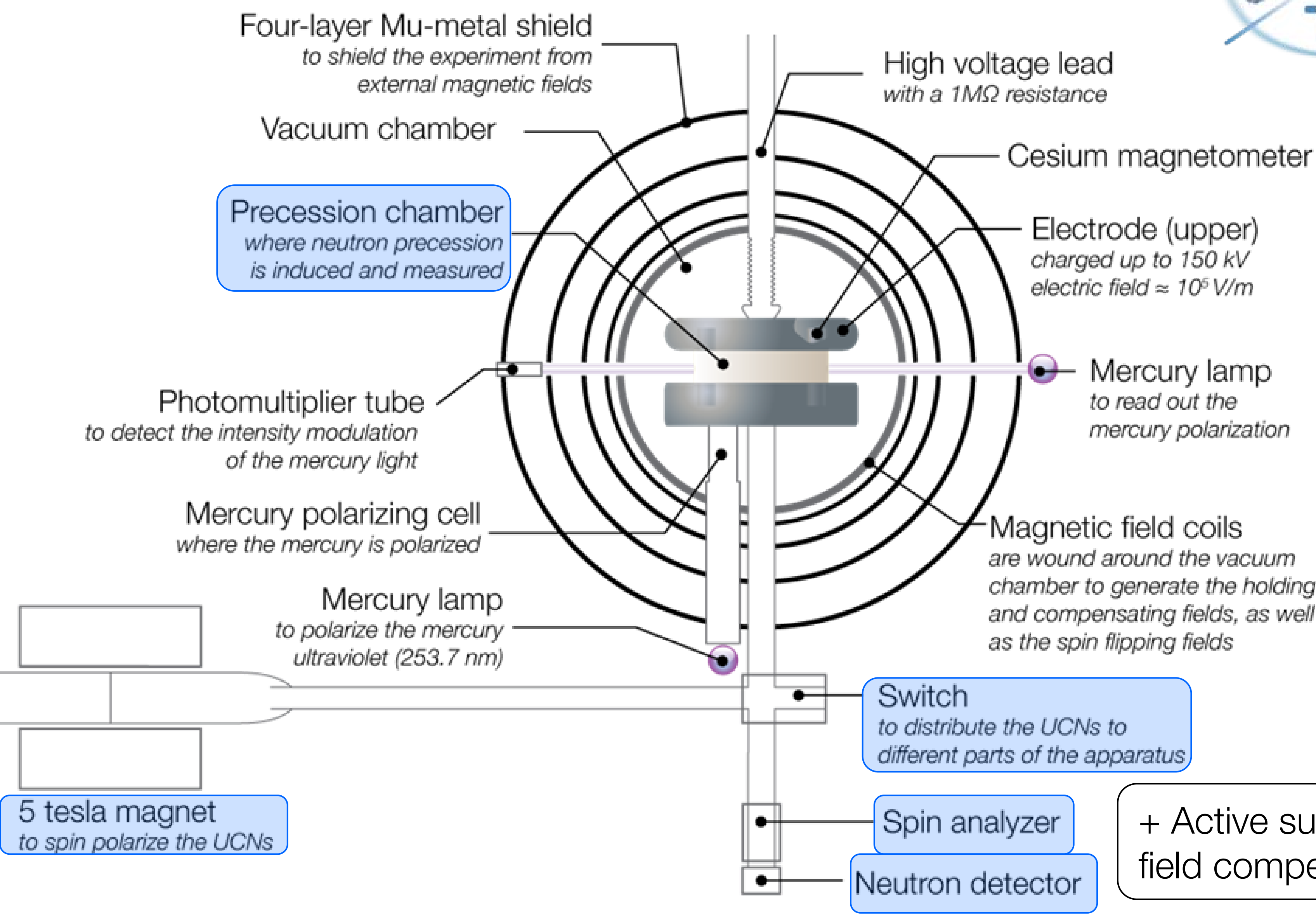
The spectrometer at PSI



Same apparatus
as RAL-Sussex-ILL

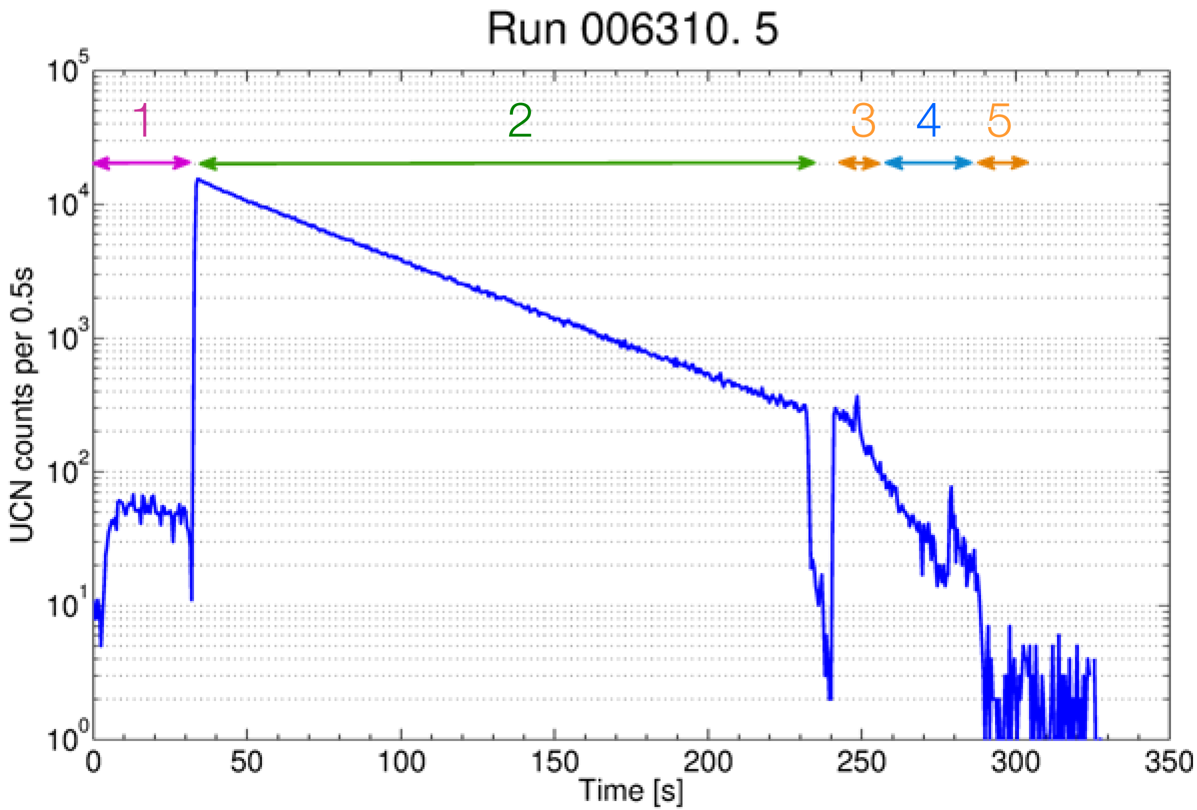
→ Set up at PSI in 2009
→ Improved UCN
and magnetic performance
(remainder of this talk)

Apparatus overview

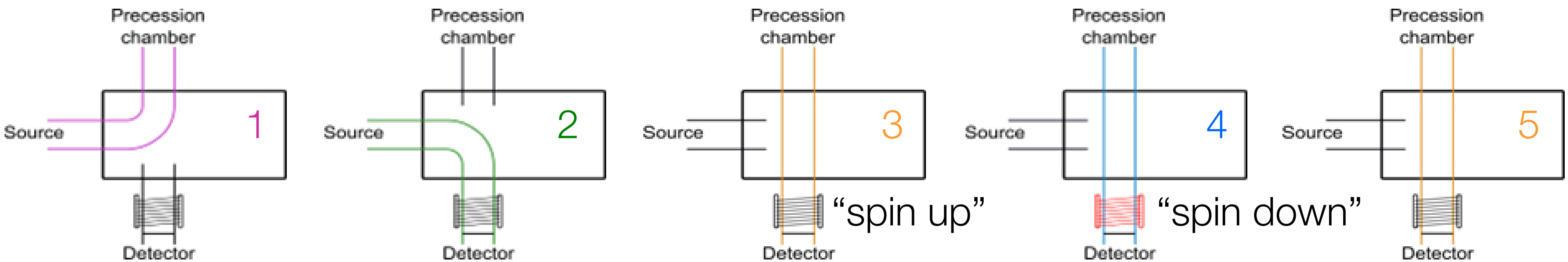


+ Active surrounding field compensation

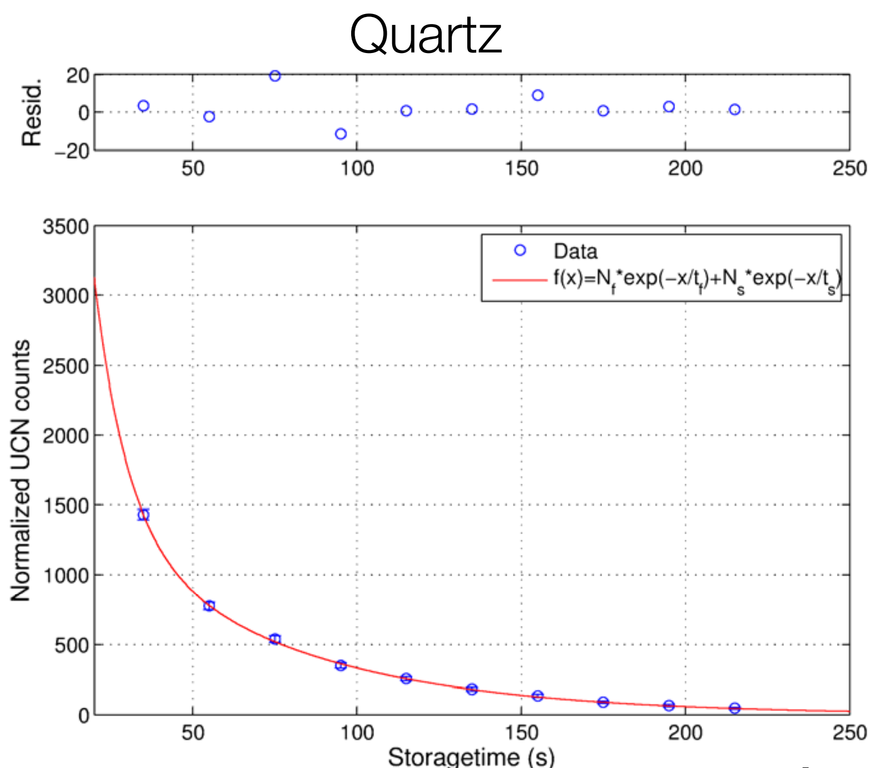
UCN counts vs. time

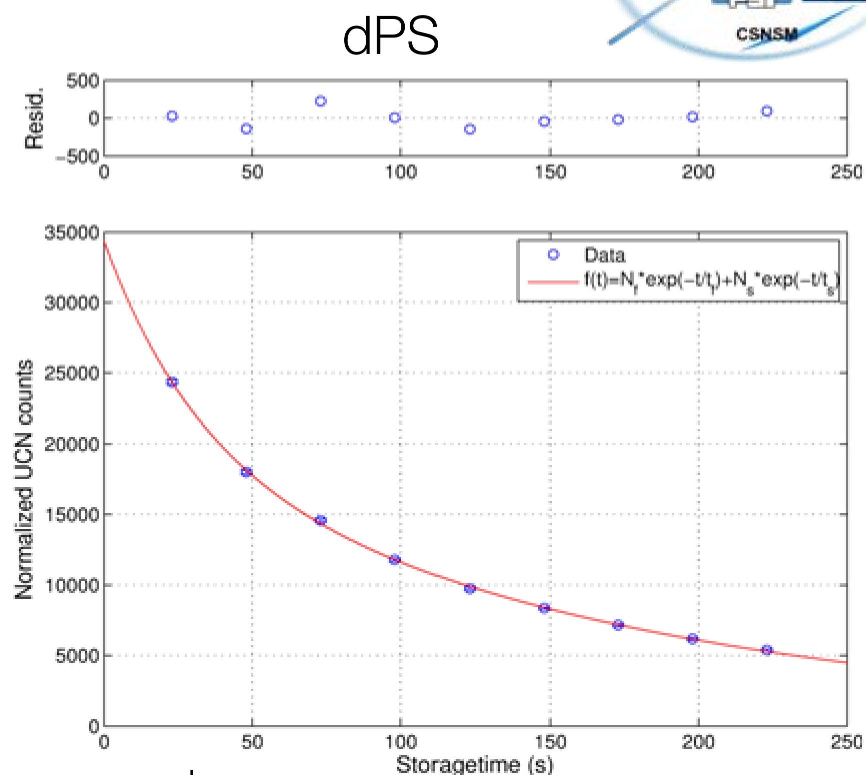


Segmented ^{6}Li doped glass scintillators + PMT



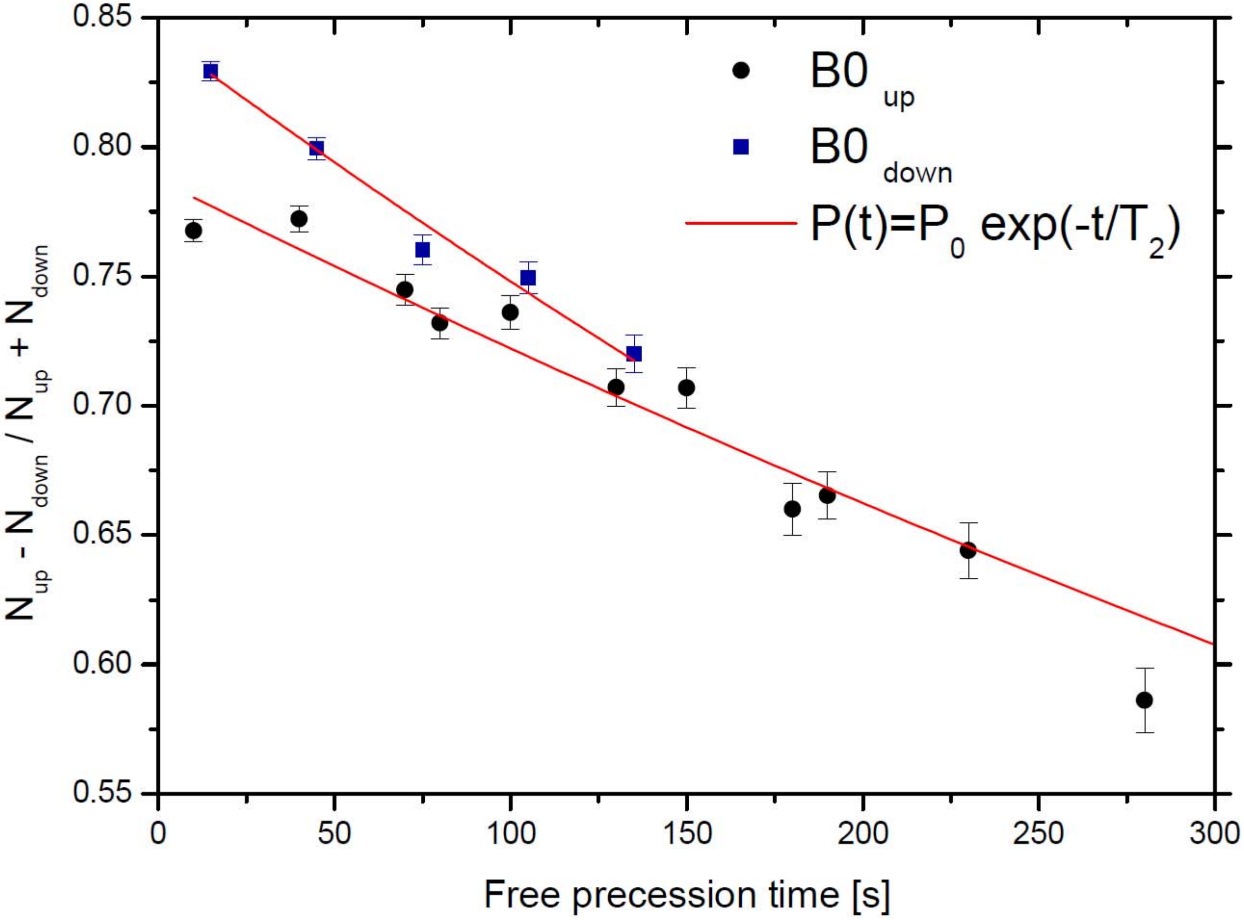
Storage life time





	t_{fast}	t_{slow}
Quartz	10 ± 4	57 ± 5
dPS (10.2012)	31 ± 6	167 ± 13
dPS (12.2012)	27 ± 6	190 ±11
dPS (2011)	56 ± 14	182 ± 33

Transversal depolarization

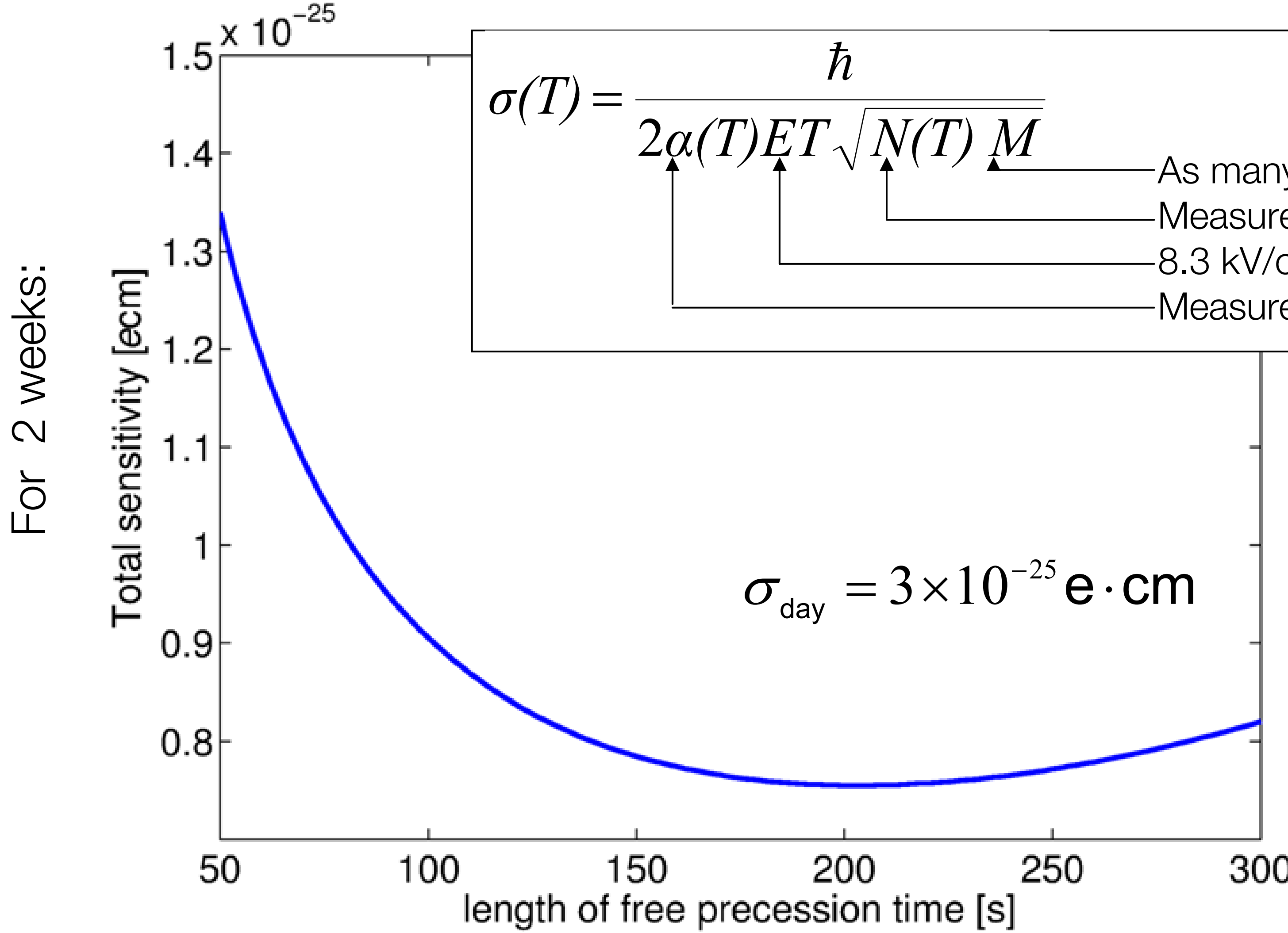


$T_2(B_0\downarrow)$: 1158 ± 94s
$T_2(B_0\uparrow)$: 836 ± 63s

→ Excellent magnetic field homogeneity

Statistical sensitivity

Expected sensitivity as function of free precession time T:



$$\sigma(T) = \frac{\hbar}{2\alpha(T) E T \sqrt{N(T)\, M}}$$

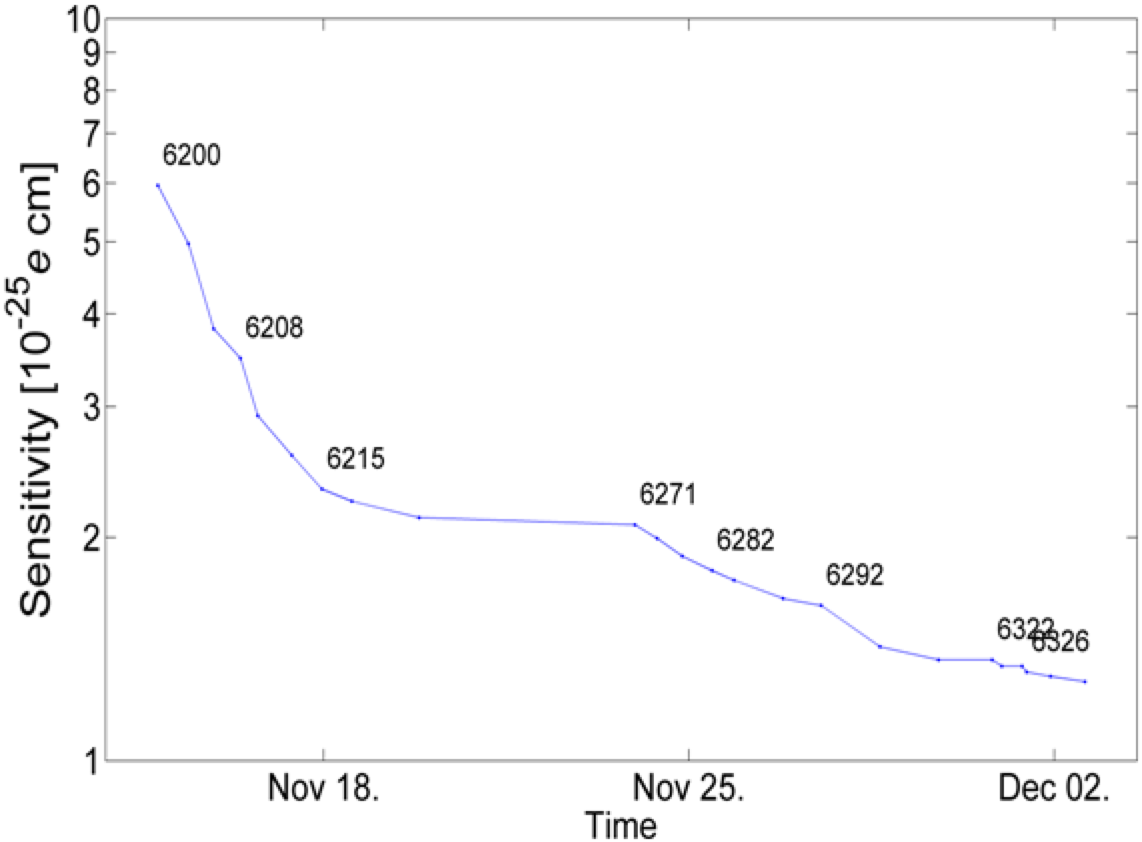
$$\sigma_{\text{day}} = 3\times10^{-25}\ \text{e}\cdot\text{cm}$$

nEDM data 2012

Total recorded: ~ 3 weeks of nEDM data

Parameters:

- Source:
  3 sec pulses, every 360 sec
- E = 8.3 kV/cm
  - ---0++++++0---
  - +++0-------0+++
- free precession time: 200s
- Gradient with trim coils
  0, ±250, ±500 uA
  O(10) pT/cm



After *removing data* with no neutrons, sultan ramps, poor Hg quality, …

Net sensitivity: 1.28 x 10^{-25} *e*cm

Sensitivity comparison

- UCN density still factor 20-30 below design
- Apparatus has already better sensitivity than best runs of RAL/Sussex/ILL:

	RAL/Sx/ILL	PSI	relative
E (kV/cm)	11	8.33	0.755
Neutrons	14000	8000	0.76
T_{free} (s)	130	200	1.54
T_{duty} (s)	240	360	0.82
α	0.453	0.68	1.56

11-12

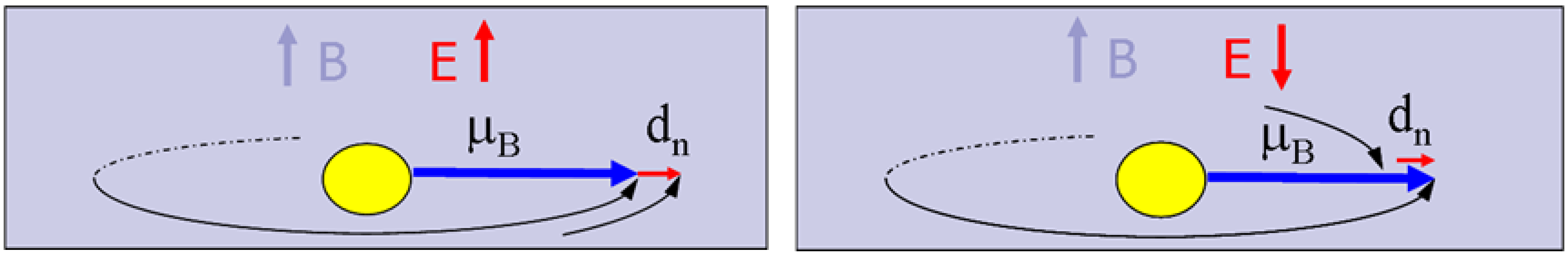
0.8

~ 1.13

1.85

Magnetic field stability

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



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

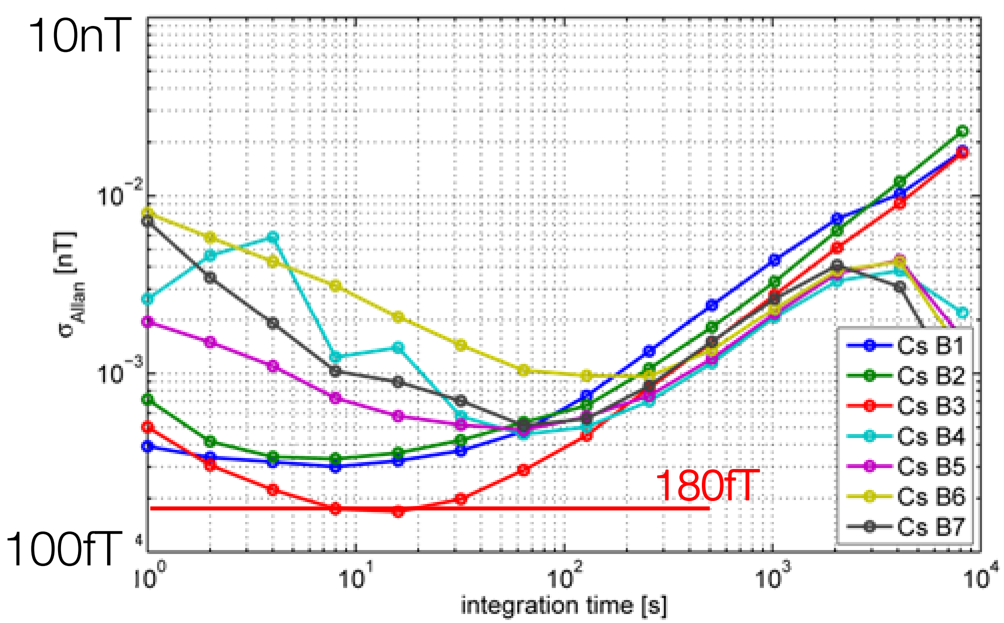
Two possible scenarios:

- Magnetic field changes stochastically → decrease of sensitivity
- Magnetic field change is function of electric field reversal → systematic effects

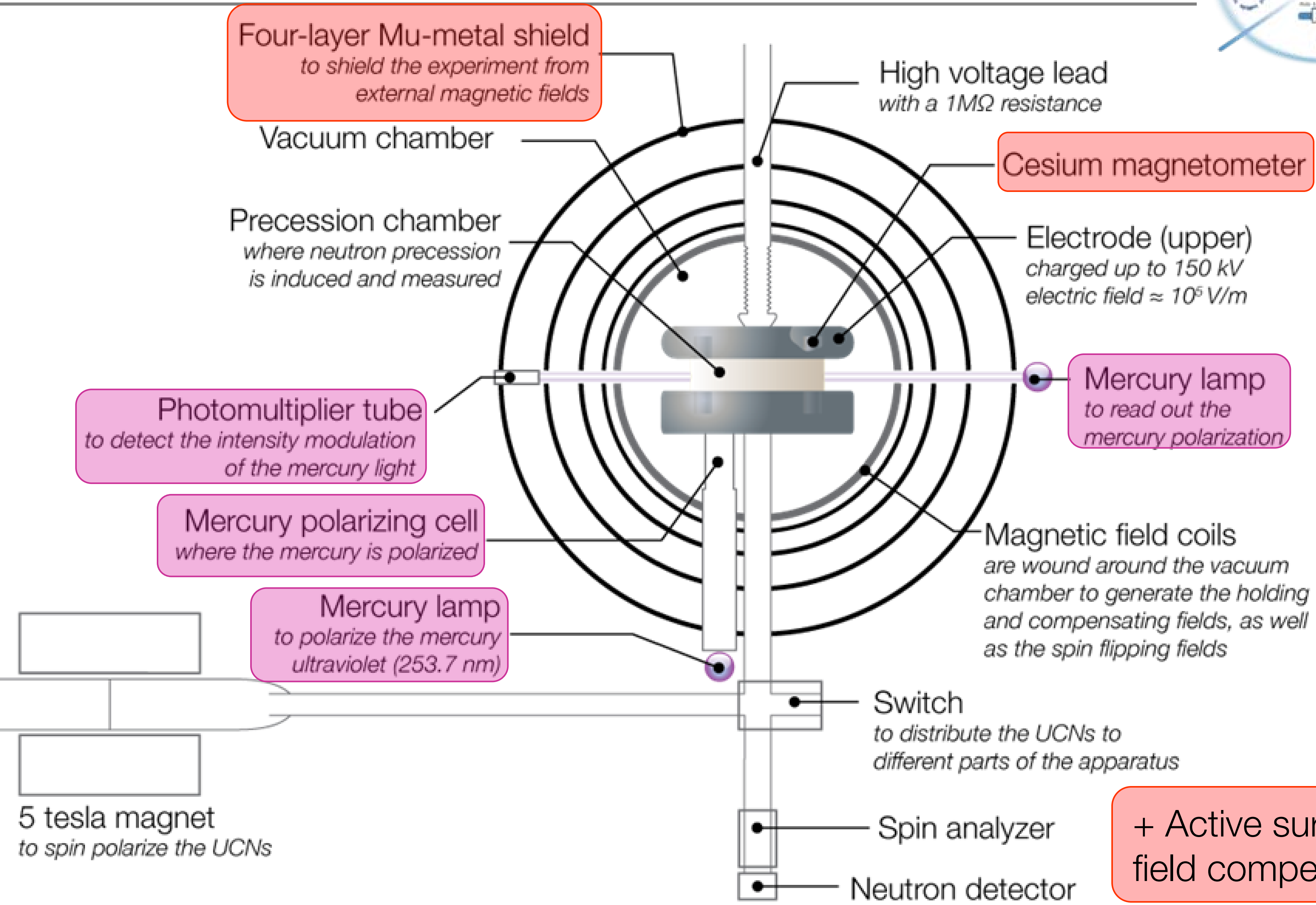
Magnetic field stability

- Magnetic shield: attenuation ~ 10000

$$\Delta B < \frac{2E \cdot \sigma}{\mu_n} = 160 \text{ fT}$$



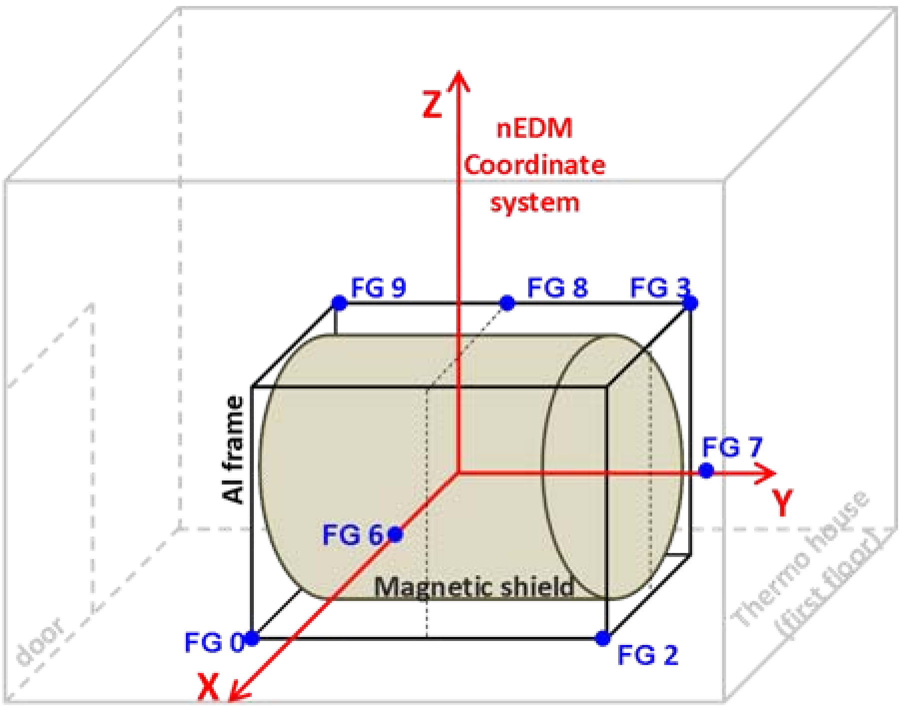
Apparatus

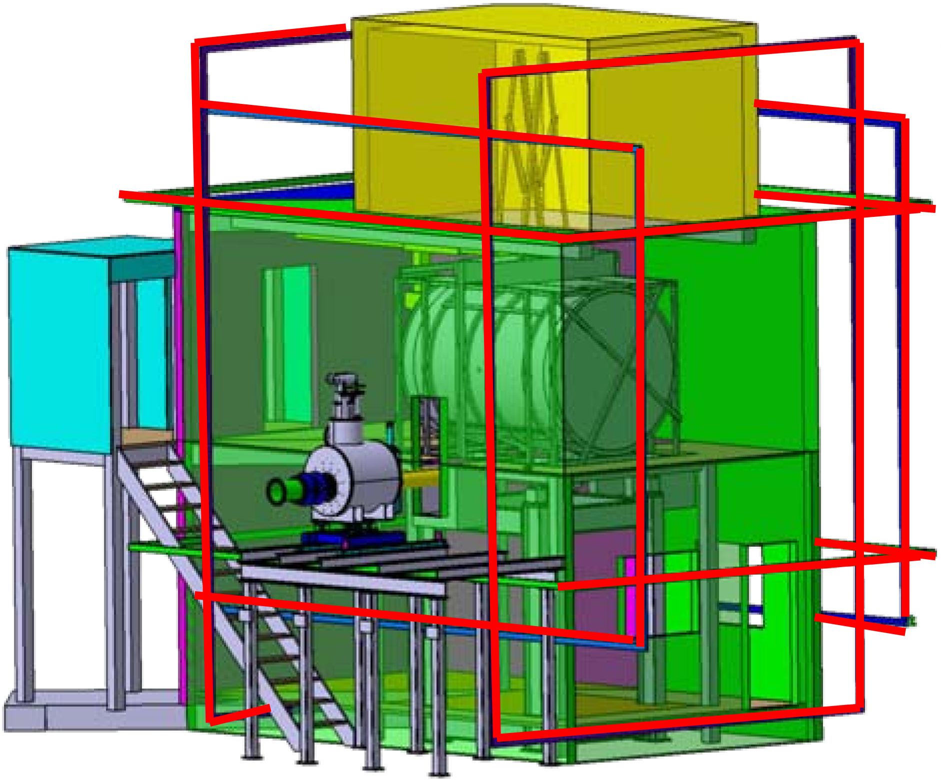


+ Active surrounding field compensation

SFC with response matrix

Use measured response of fluxgate on changes in coils currents for feedback.



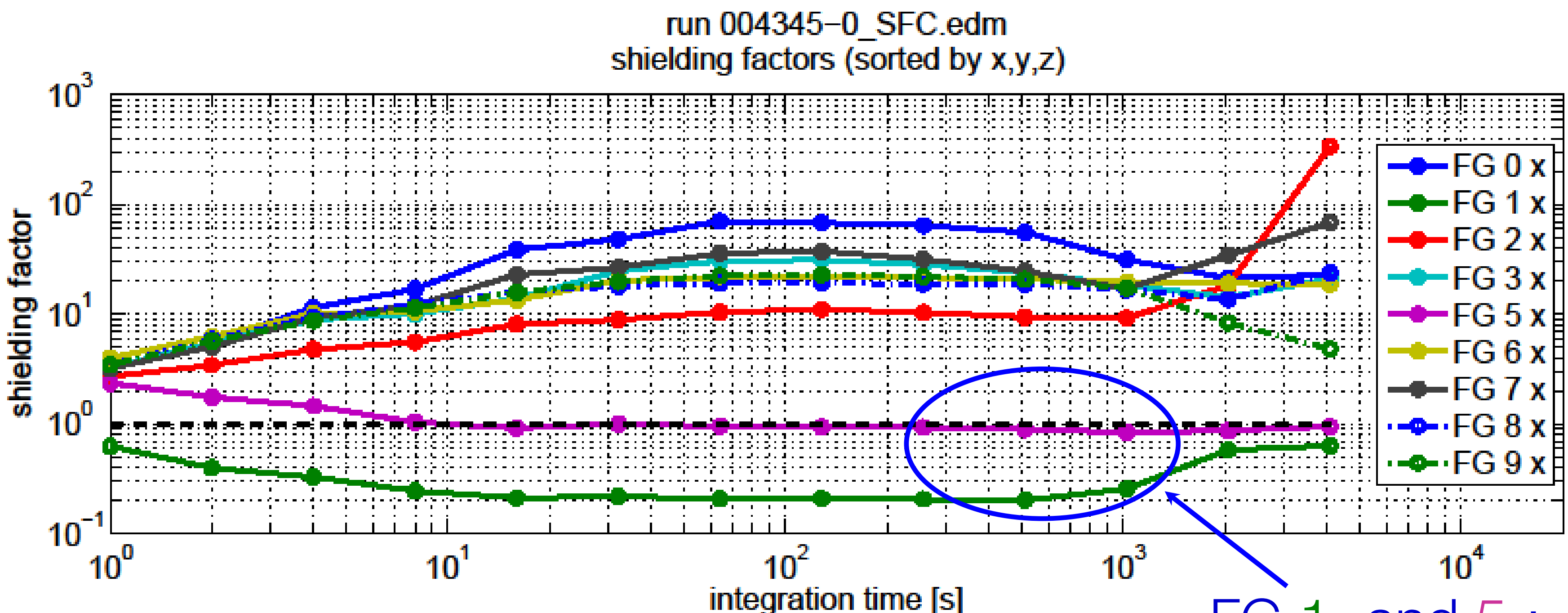


Measure changes in magnetic field ΔB_i → Apply currents $\Delta I_i = -M_{ij}^{-1} \cdot \Delta B_i$ to each coil

SFC performance

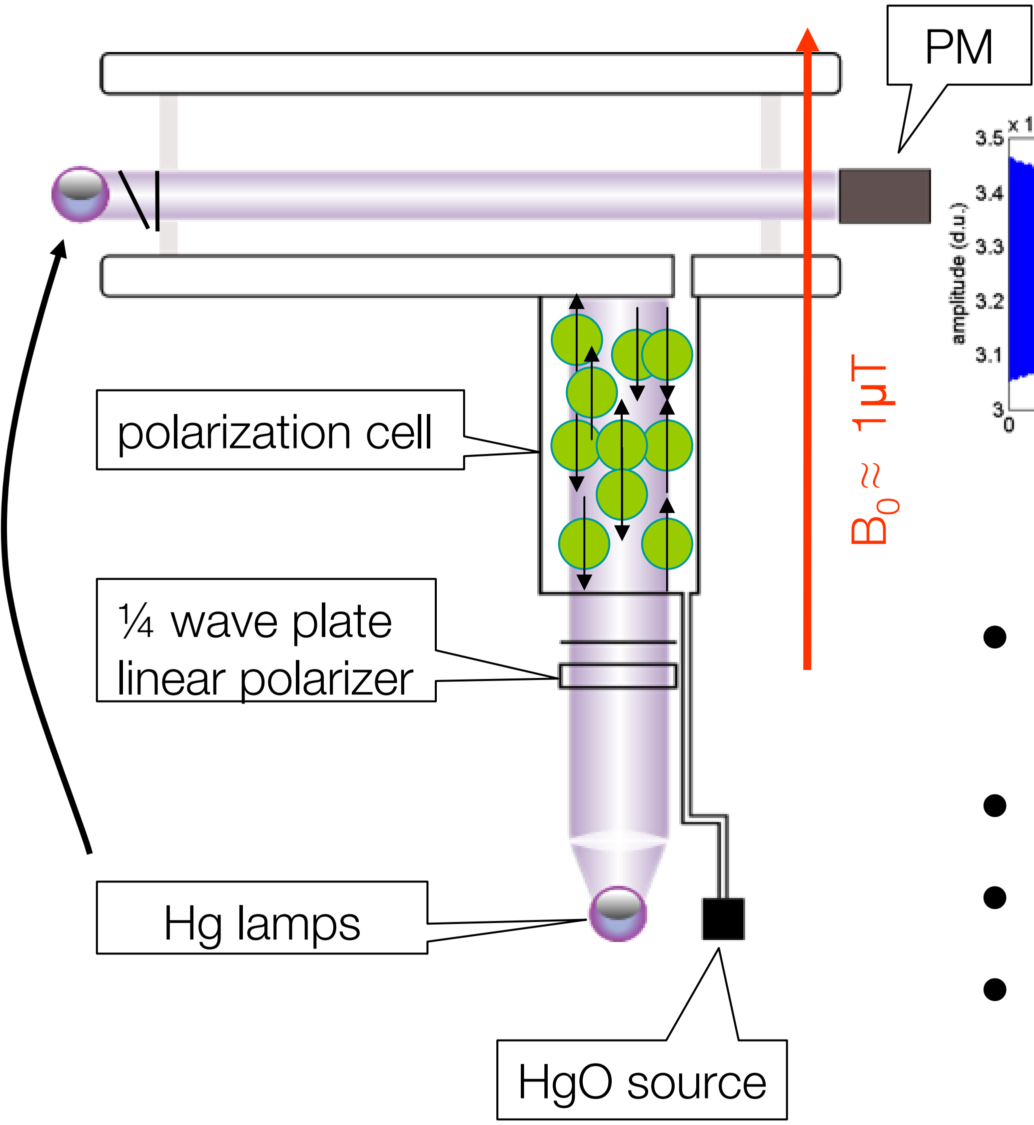
Feedback with *inverted & regularized* (6 x 12) Matrix;
i.e. twelve sensors close to shield are taken into account

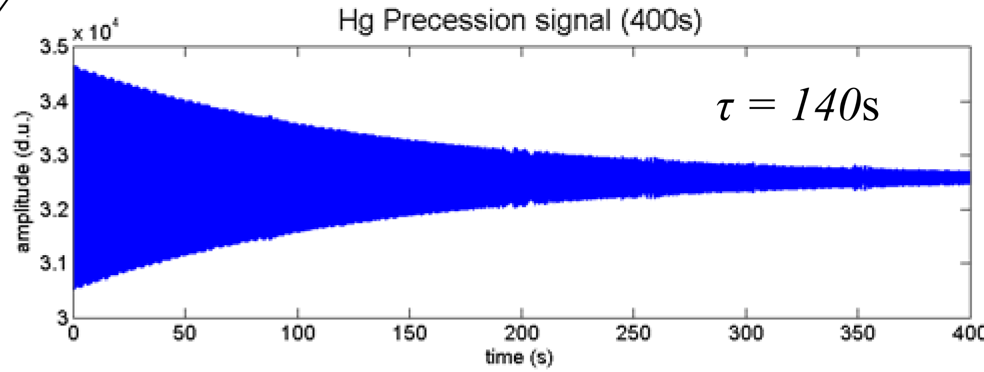
(for x-direction shown below: sensors 0_x, 3_x, 6_x, and 9_x were used)



FG 1_x and 5_x:
former feedback sensors, far away

Mercury co-magnetometer





- Average magnetic field (volume and cycle)
- $\sigma_B \sim 20 - 50$ fT
- $\tau > 100$ s without HV
- s/n ~ 2500 without HV

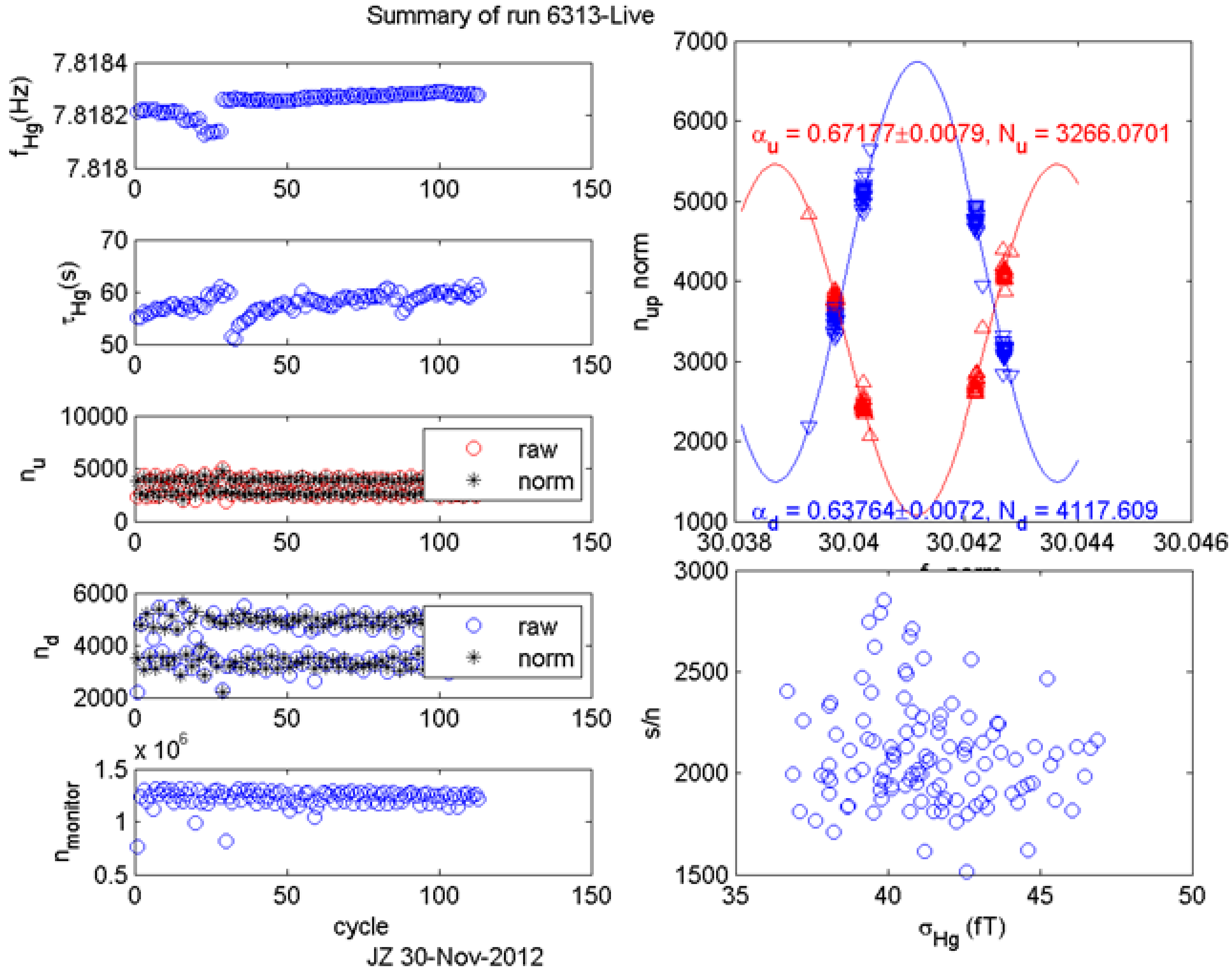
Hg during nEDM runs

- Three weeks data taking
  (day and night)
- 26 runs
- 2470 cycles
- Hg sensitivity:

  $\sigma_{cyc} = 45$ fT

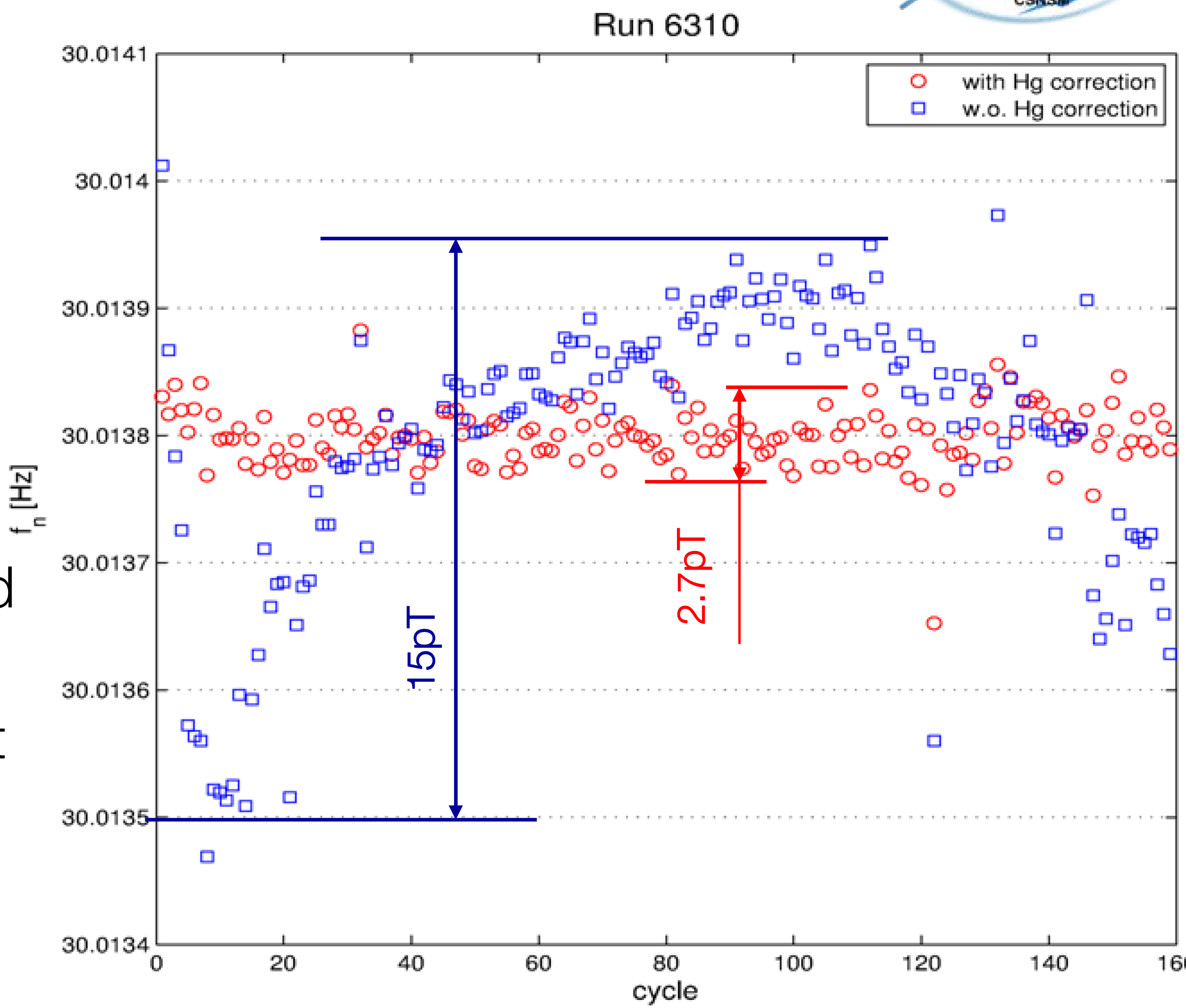
  $\tau \geq 50$s

  s/n ~ 2200



Correcting for drifts

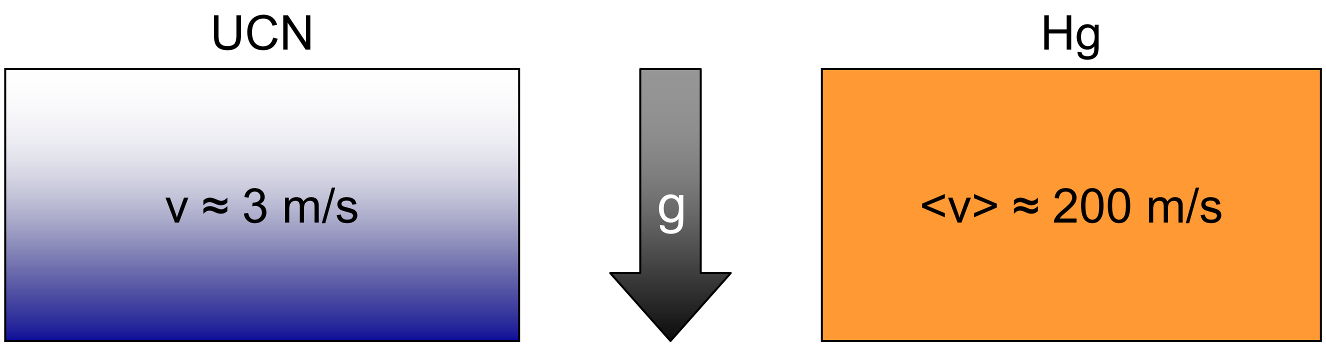
- HgM corrects drifts of magnetic field
- Changes in magnetic field gradients can not be corrected
- Gradients give rise to important systematic effects



Uncompensated field drifts

Measure online the free precession of polarized ^{199}Hg atoms **in the same volume at the same time** as the UCN to correct for magnetic field drifts.

BUT:



Difference in the center of mass of UCN and Hg $\Delta h \approx 2.4\text{mm}$.

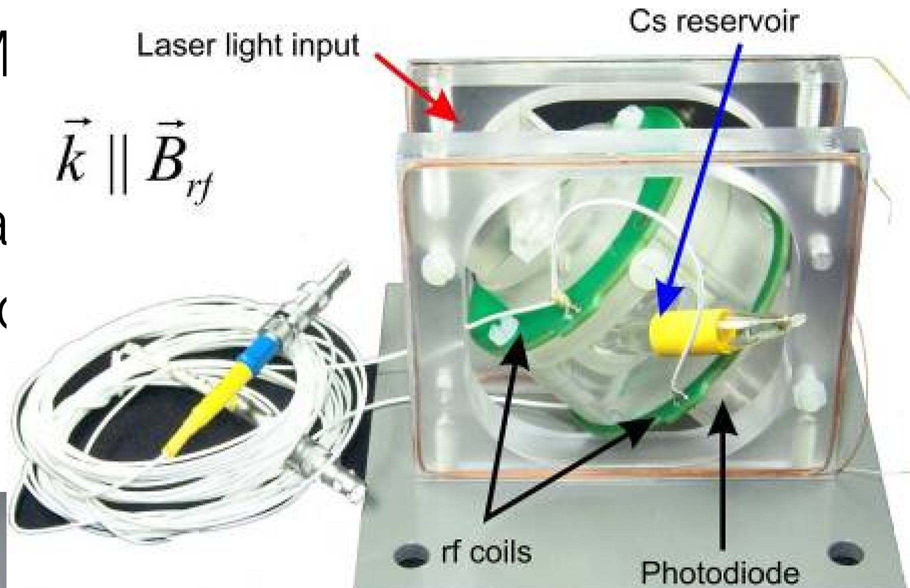
Any change in the vertical magnetic field gradient will not be compensated:

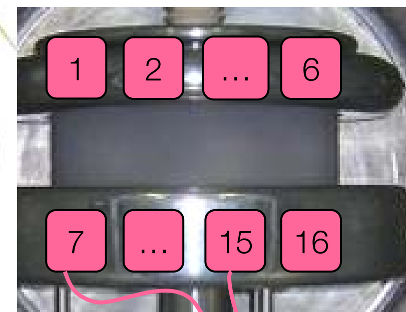
$$f_n = f_{Hg} \frac{\gamma_{Hg}}{\gamma_n} \left(1 + \frac{\partial B}{\partial z} \frac{\Delta h}{B} \right)$$

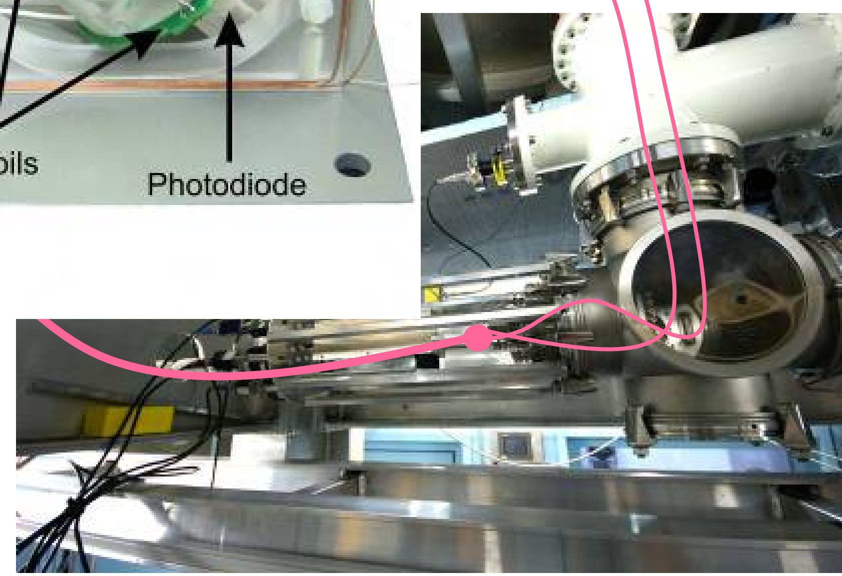
Cesium magnetometers

Monitoring of vertical magnetic gradients

- Six HV CsM
- Ten ground
- Stabilized la
- PID phase l



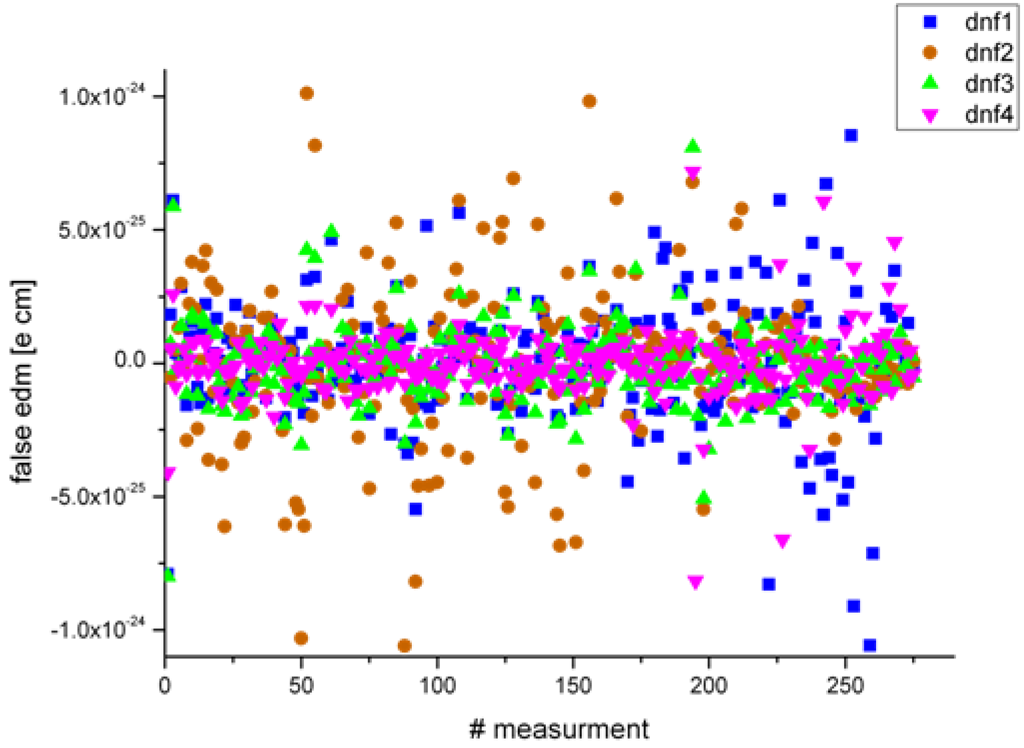


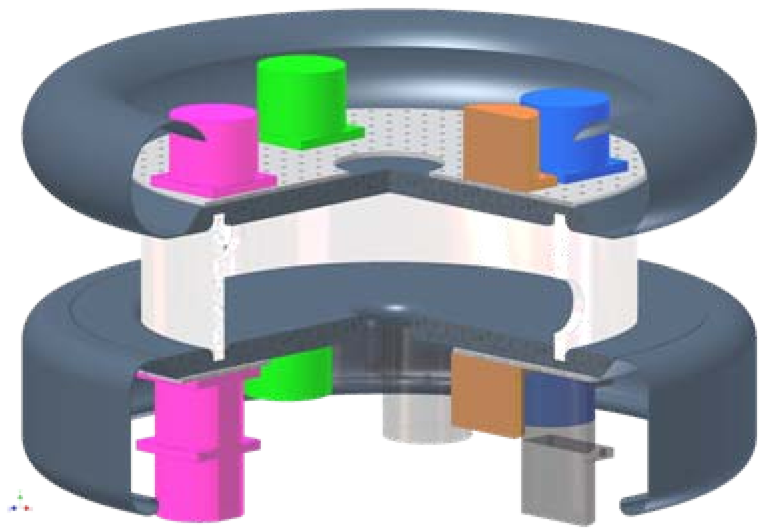


Uncompensated field drifts

For gradients correlated with electric field changes
(e.g. create a magnetization with charging currents)
this would result in a EDM like signal!

Use Cs magnetometers to measure the gradient → check for this systematic





Systematic effects

→ Field mapping.

→ Online Cs-OPM measurement.

→ Combine online information and field maps.

→ Material control for magnetic impurities with large squid array.

Direct Effects	Goal	Status
Uncompensated B-Drifts	0±0.9	2.9±8.6
Leakage Current	0±0.1	0.00±0.05
$V \times E$ UCN	0±0.1	0±0.1
Electric Forces	0±0.4	0±0.4
Hg EDM		0.02±0.06
Hg Direct Light Shift	0±0.4	0±0.008
Indirect Effects		
Hg Light Shift		0±0.05
Quadrupole Difference	0±0.6	1.3±2.4
Dipoles	0±0.5	
At the surface		0±0.4
Other Dipoles		0±3
Total	0±1.3	4.2±9.4

$\times 10^{-27}$ecm

Conclusion

- UCN performance of the apparatus is already excellent
  - HV will most probably be further improved to 12kV/cm
  - Alpha might be further increased to 80%
- It was shown that on a day to day comparison the apparatus now has a higher statistical sensitivity than any other experiment before
- Magnetic field stability meets statistical requirements
- Magnetometer operate at their best
- Systematic studies are ongoing and most effects have been understood sufficient

Outlook

- Measure 120 days in 2013
  → $\sigma_d < 2\times10^{-26}$ *e*cm
  (without further improvement of source, etc.)
- Hope for gradual improvement of UCN source for 2013-2016
  → $d_n < 5\text{x}10^{-27}$ *e*cm (95% C.L.)
- In parallel the collaboration builds a new experiment with an intrinsic 10 times higher sensitivity
  → Online 2016/2017

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The Neutron EDM Collaboration

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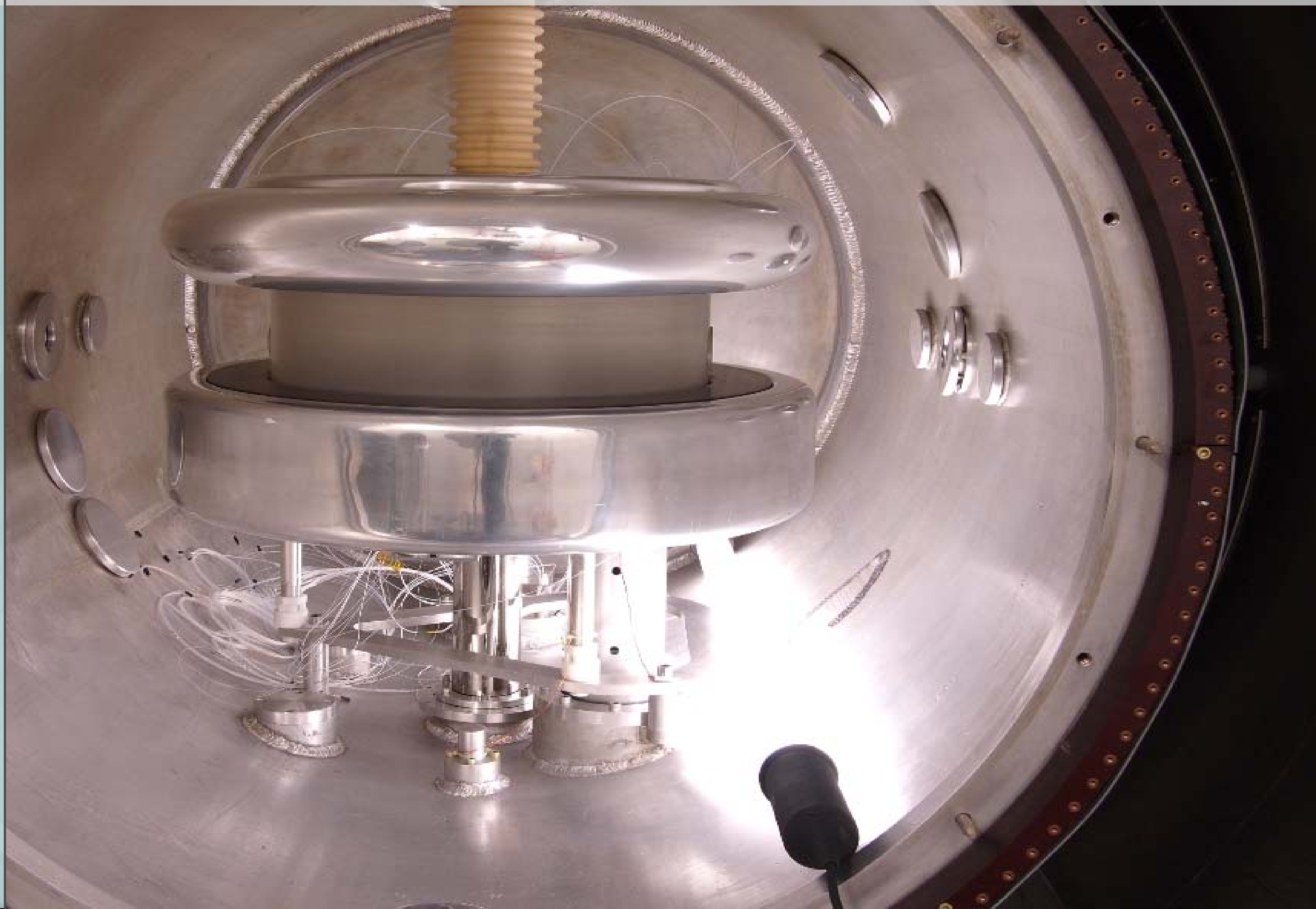
Backup



Mahabaleshwar, 20.02.2013 Philipp Schmidt-Wellenburg