PAUL SCHERRER INSTITUT

High RR Lecture Heidelberg

How Neutron EDM-Experiments Really Work II

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Outline of the nEDM lecture

Motivation & History

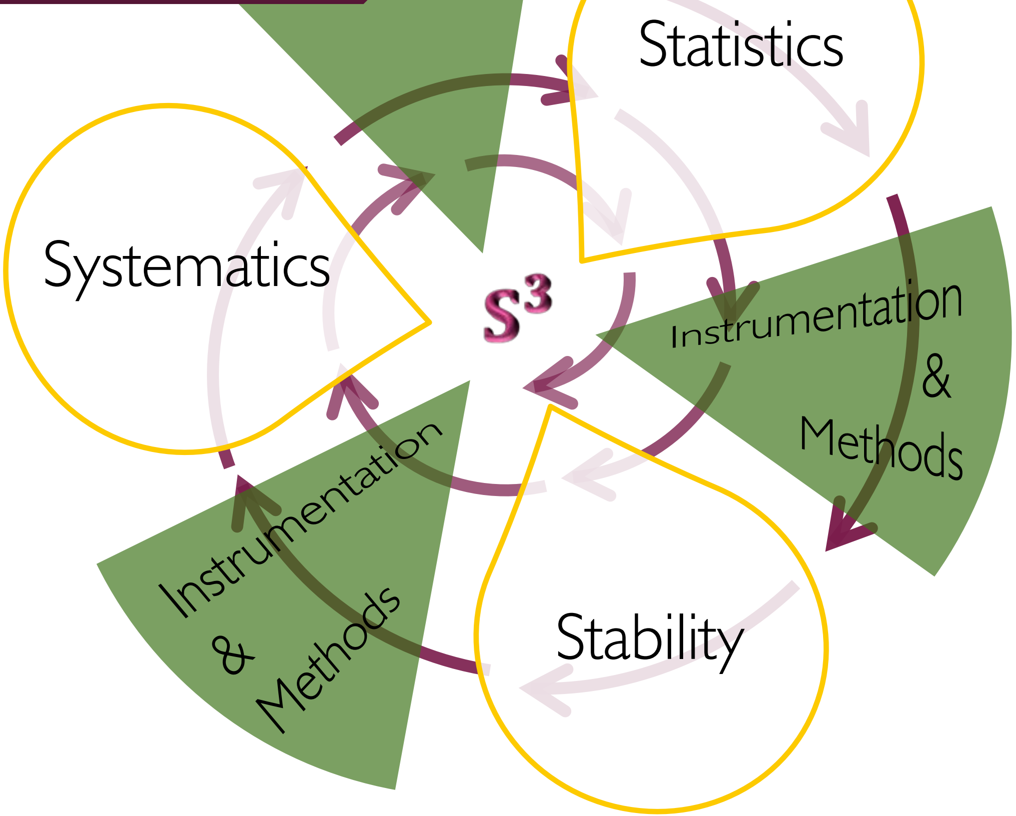
Fundamentales

Lecture I:

Motivation & Fundamentales

Lecture II&III:

The spiral to ultimate sensitivity



From cold to ultracold neutrons

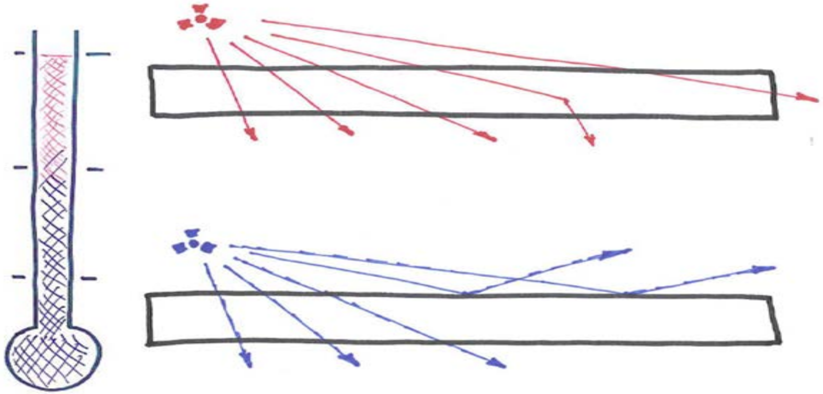
Sensitivity of EDM experiments $\propto \frac{1}{T\sqrt{N}}$

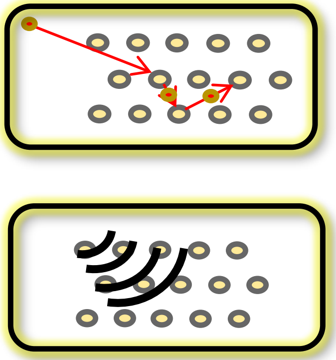
Systematic effect $\propto v \times E$

Store very slow neutrons for long times

- What neutrons can be stored? -How?
- How can I make them?
- What else changes?

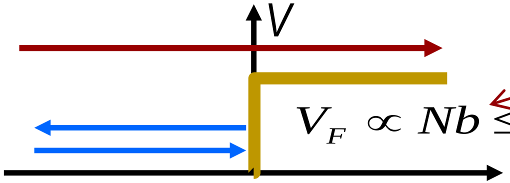
Storable neutrons – UltraCold Neutons (UCN)





Gravity
102 neV/m

Strong
V_F



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

Magnetic
~60 neV/T

Storage properties are material dependent

350 neV ↔ 8 m/s ↔ 500 Å ↔ 3 mK

E. Fermi & W.H. Zinn(1946),
Y. B. Zeldovich, *Sov. Phys. JETP* (1959)389

The optical potential describing the strong interaction

- The Schrödinger equation of a neutron moving in the optical potential $U(\boldsymbol{r})$

$$-\frac{\hbar^2}{2m}\Delta\psi(\boldsymbol{r}) + \frac{2\pi\hbar^2}{m}nb(\boldsymbol{r})\psi(\boldsymbol{r}) = E\psi(\boldsymbol{r})$$

- The neutron optical potential

$$U(r) = \frac{2\pi\hbar^2}{m}bN(\boldsymbol{r})$$

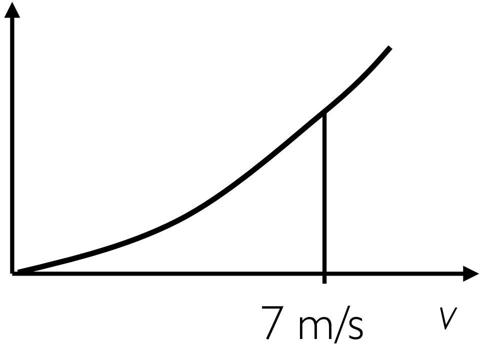
- Neutron optical refractive index

$$n_{\mathrm{r}} = \sqrt{1 - U/E} = \sqrt{1 - \frac{4\pi bN}{k^2}}$$

Ultracold neutrons – storable neutrons

The defining property of UCN is that they *can be confined in material (and magnetic) traps*.
Hence, the maximal velocity depends on the material of the trap for total reflection at all angles of incidence:

$$U_{F,c} > E_{kin} = \frac{1}{2}mv^2 = \frac{h^2}{2m\lambda^2}$$



$E_{kin} < 250$ neV
$v < 7$ m/s
$\lambda > 600$ Å

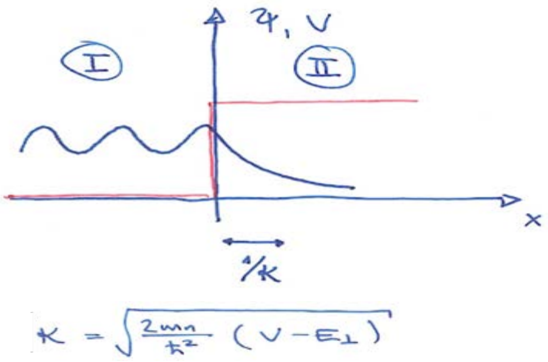
(T < 3 mK)

Material	ρ [10^{28} m^{-3}]	b_c [fm]	ρb_c [10^{-6} Å^{-2}]	$1-n$ [10^{-6}]	$V_{F,c}$ [neV]	ϑ_c [°]
Be	12.3	7.74	9.5	1.52	247	0.099
Al	6.03	3.5	2.1	0.34	54.9	0.047
Si	5.19	4.15	2.2	0.34	55.9	0.047
Ni	9.14	10.3	9.4	1.50	244	0.0992
^{58}Ni	9.14	14.4	13.2	2.09	335	0.117
Ti	5.66	-3.4	-1.9	-0.31	-50	-
Pb	3.30	9.4	3.1	0.49	80	0.057
H_2O	3.35	-1.68	-0.6	-0.090	-14.6	-
D_2O	3.35	19.14	6.4	1.02	167	0.082

Table 3.2: Number densities ρ, bound coherent scattering lengths b_c and Fermi potentials $V_{F,c}$ of some selected materials, taken from [Kle83]. Here, the refractive index n and the critical angle ϑ_c are tabulated for neutrons with a wavelength of 1 Å.

UCN loss mechanisms

- Losses due to **non-ideal traps** (gaps and slits).
- **Inelastic scattering** on walls to energies beyond trap potential 'UCN up-scattering'.
- **Absorption** on trap walls and/or rest gas – e.g. (n,γ)-reaction.
- In magnetic traps due to **spin-flip processes** and depolarization.



Losses due to absorption on trap walls are described in the Schrödinger Equation by a complex wall potential *U*:

$$i\hbar\partial_t\psi = \left(-\frac{\hbar^2\Delta}{2m} + U\right)\psi$$

$$U = V - iW$$

$$|R|^2 = 1 - 2\frac{W}{V}\left(\frac{E_\perp}{V-E_\perp}\right)^{\frac{1}{2}} \equiv 1 - \mu(E,\theta)$$

Loss probability per wall collision

Averaged loss probably per bounce

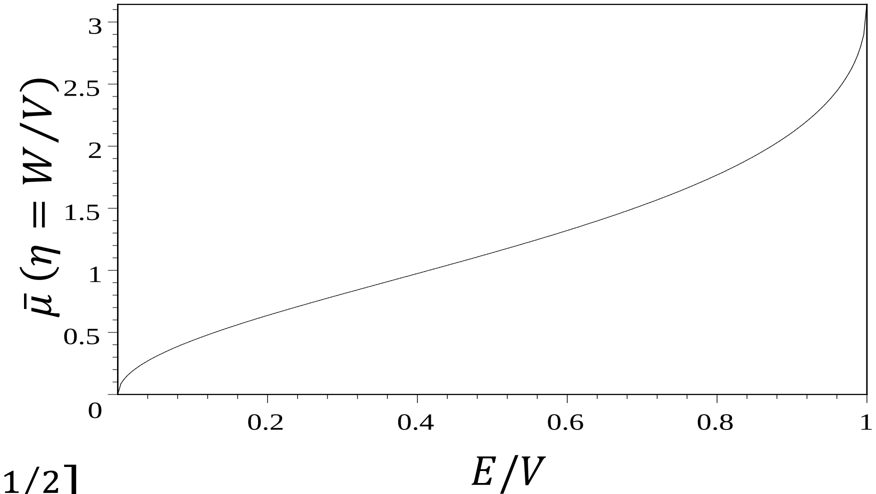
In a real trap many collisions under all possible incident angles will occur. So

$$|R|^2 = 1 - 2\frac{W}{V}\left(\frac{E_\perp}{V-E_\perp}\right)^{\frac{1}{2}} \equiv 1 - \mu(E,\theta) \quad [1]$$

must be average over all incident angles. Rewriting [1] in terms of total energy and incident angle:

$$\mu(E,\theta) = 2\eta\left(\frac{E\cos^2\theta}{V - E\cos^2\theta}\right)$$

averaging this over all incident angles:



$$\bar{\mu}(E) = 2\eta\left[\frac{V}{E}\arcsin\left(\frac{E}{V}\right)^{1/2} - \left(\frac{V}{E} - 1\right)^{1/2}\right]$$

UCN properties of selected materials

Table 2.1 UCN properties of selected materials.

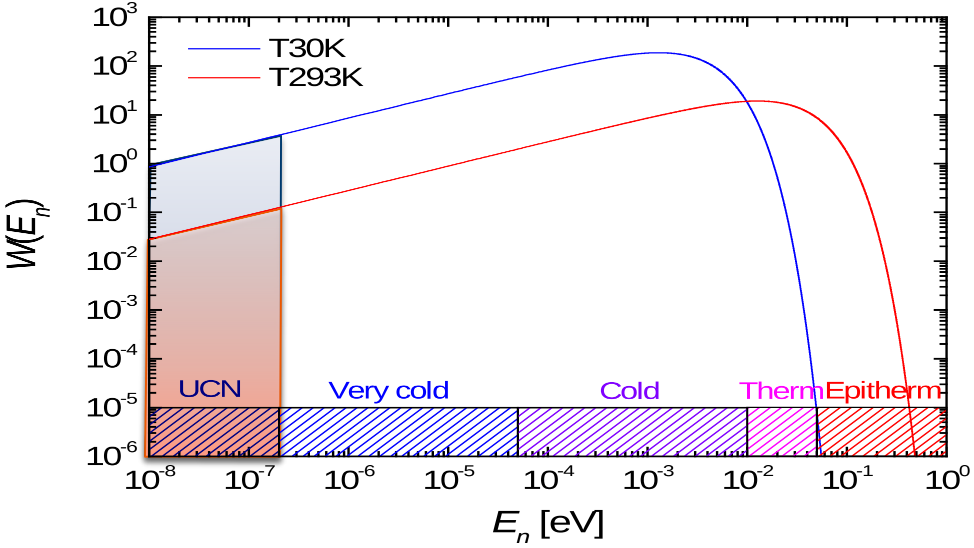
Element	$\rho_{g/cc}$	$N_{form/cc}$ $\times 10^{22}$	$\sum_{form} a_{coh}^{bound}$ $\times 10^{-13}$ cm	V_{neV}	σ_{tot} barns	$f = W/V$ $\times 10^{-5}$
Ni^{58}	8.8	9.0	14.4	335	44	8.6
BeO	3.0	7.25	13.6	261	6.6	1.35
Ni	8.8	9.0	10.6	252	48	12.5
Be	1.83	12.3	7.75	252	1.4[a]	0.5[a]
					0.22[b]	0.08[b]
Cu^{65}	8.5	8.93	11.0	244	28	7.0
Fe	7.9	8.5	9.7	210	30	8.5
C	2.0	10.0	6.6	180	1.4	0.6
Cu	8.5	8.93	7.6	168	43.5	15.5
PTFE (Teflon)	2.2	2.65	17.6	123	—	—
Pb	11.3	3.29	9.6	83	2.0	0.6
Al	2.7	6.02	3.45	54	2.8	2.25
Perspex $(CH_2H_3O)_n$	1.18	1.65	7.88	33.9	—	—
V	6.11	7.1	−0.382	−7.2	50	—
Polyethylene $(CH_2)_n$	0.92	3.9	−0.84	−8.7	—	—
H_2O	1.0	3.34	−1.68	−14.7	—	—
Ti	4.54	5.6	−3.34	−48	58	—

[a] 300 K.
[b] 100 K.

$\rho_{g/cc}$—material density; $N_{form/cc}$—molecular density; $\Sigma_{form} a_{coh}^{bound}$—bound coherent scattering length summed over molecular formula; V_{neV}—effective UCN potential, neV; σ_{tot}—total cross-section at neutron wavelength $\lambda = 18$ Å (1 barn $= 10^{-24}$ cm); f—UCN loss factor, eqn (2.66).

UCN in the Maxwellian distribution

$$N(v)dv = N_0 \left(\frac{m_n}{2\pi k_B T}\right)^{3/2} e^{-\frac{m_n v^2}{2k_B T}} dv$$



Peak velocity:

$$\tilde{v} = \sqrt{\frac{2k_B T}{m_n}}$$

Mean velocity:

$$\bar{v} = \frac{1}{\rho_n}\int_0^\infty v F(v)\, dv = \sqrt{\frac{8k_B T}{\pi m_n}}$$

How many UCN are in a Maxwellian spectrum?

- UCN density in the Maxwellian spectrum:

$$\rho_{UCN} \propto N_0 \left(\frac{V_{F,c}}{k_B T}\right)^{3/2}$$

V_F : Fermi potential of the storage material

T : Temperature of the Maxwellian neutron spectrum (approx. moderator temperature)

N_0 : total thermal neutron flux [n cm^{-2} s^{-1}]

- For T = 300 K, V = 250 neV (typical Ni, Be) : $\rho_{\mathrm{UCN}} \approx 10^{-13} \phi_0 \ \mathrm{cm}^{-3}$
  - ILL (Grenoble): $\phi_0 = 10^{15}$ n cm^{-2} s^{-1} ⇒ $\rho_{\mathrm{UCN,ILL}} \approx 100 \ \mathrm{cm}^{-3}$
  - At the cold source one gains a factor of approx. 20 (temperature).
  - However, the extraction of UCN from reactors involves some ***considerable loss*** so that the available ***densities will always be much less***.

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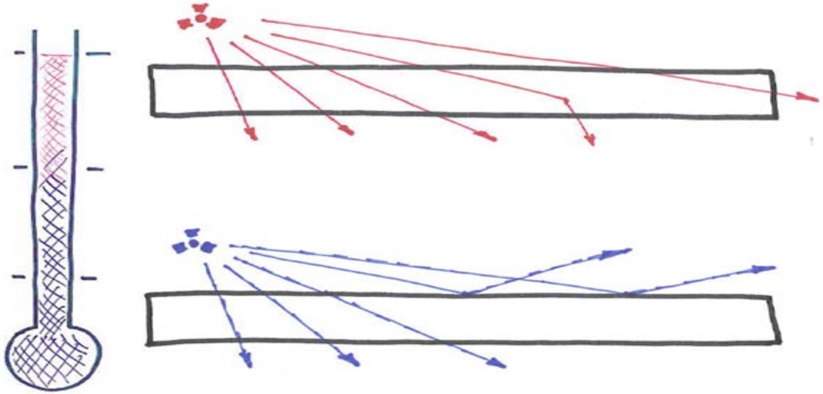
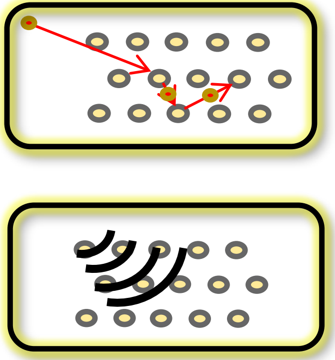
Why not a moderator at 0.5 K ?





- The **lower** the neutron **energy** the **larger** the **wavelength**

- At low temperatures wavelength too large for elastic scattering on one nucleus
  → only coherent scattering of many nuclei
  → classical moderation stops once the wavelength of neutrons is too large

UCN production

Vertical VCN extraction from a reactor with a ***UCN turbine***:

FRM (Steyerl 1969)

ILL – PF2 since the 1970's (10-50 UCN cm^{-3})

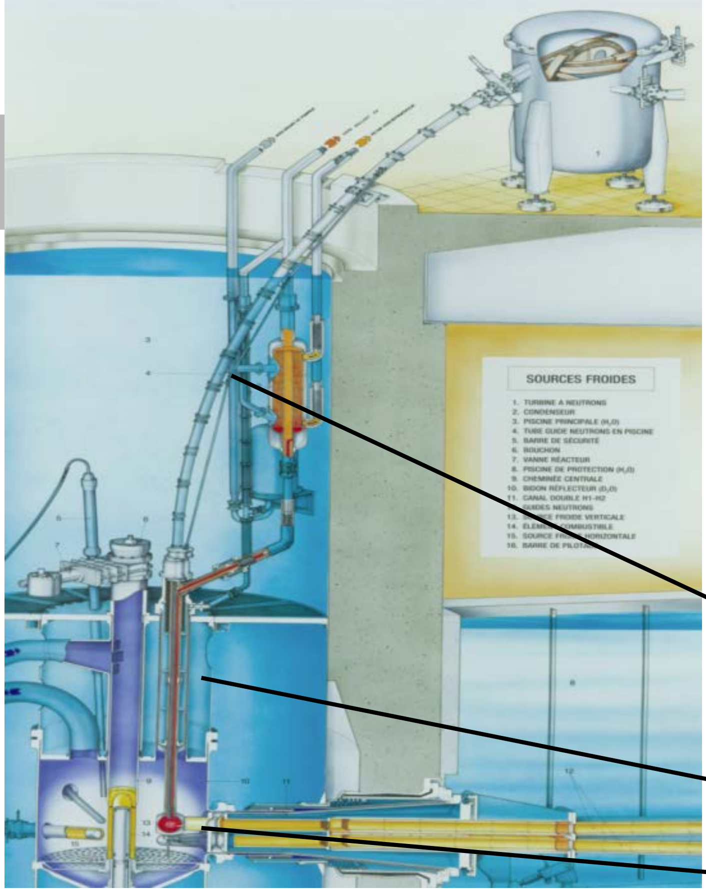
New sources are employing inelastic ''down-scattering'' of cold neutrons to the UCN energy regime using ***superfluid helium*** or ***solid deuterium*** as converter media (superthermal UCN sources):

Paul Scherrer Institute (CH)	Solid Deuterium
Munich (FRM 2)	Solid Deuterium
Mainz	Solid Deuterium
LANL (Los Alamos)	Solid Deuterium
ILL (Grenoble)	Superfluid Helium
Oak Ridge USA (SNS)	Superfluid Helium
Japan & Canada (JPARC + TRIUMF)	Superfluid Helium

⇨ Hope for an increase of UCN density by a factor more than 100 !

UCN turbine – PF2 at ILL (Grenoble)

UCN densities of about 10-50 cm^{-3}



690 concavely curved nickel blades
on wheel with ø = 1.8 m
250 rpm -> v~30 m/s

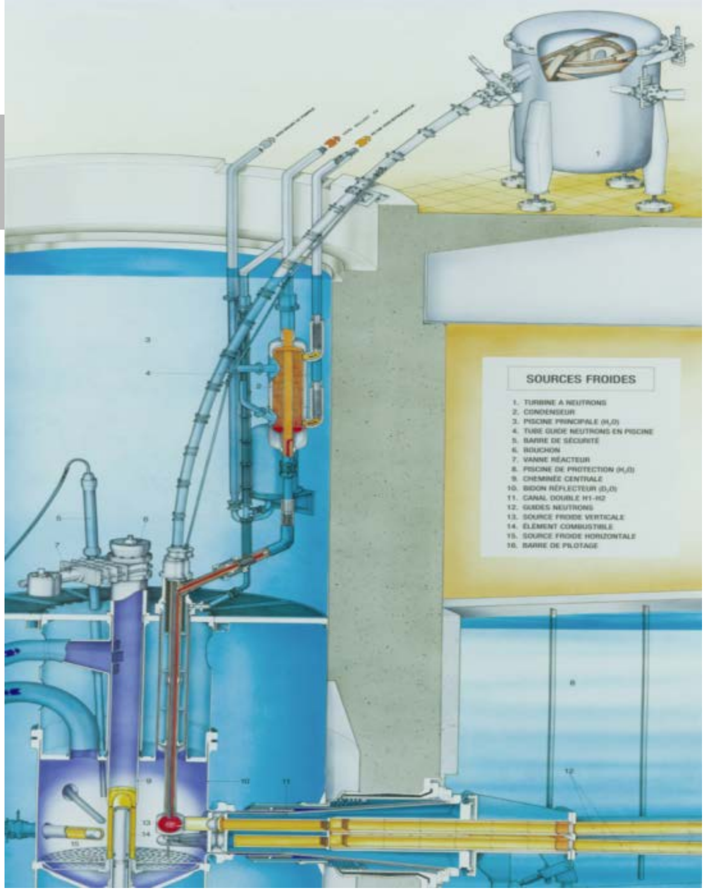
13 m long bent guide
R = 13m, separates VCN
from faster neutrons and γ's

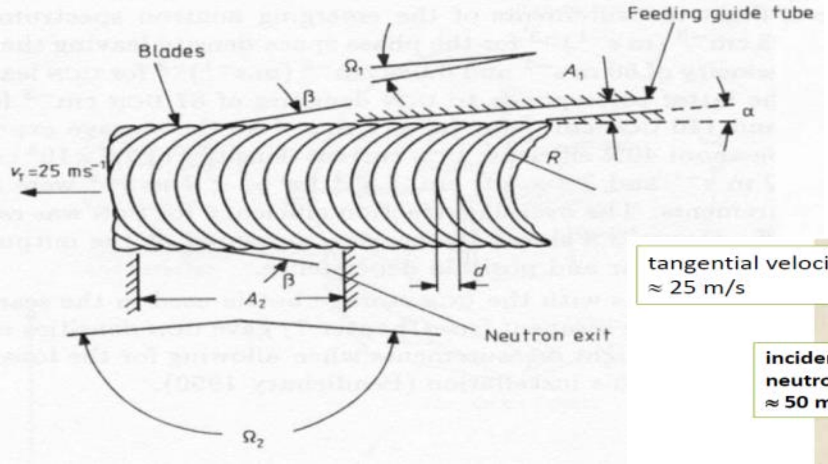
5 m vertical guide dipping in
cold source

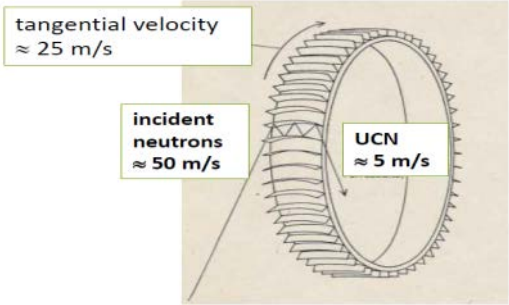
cold source LD_2

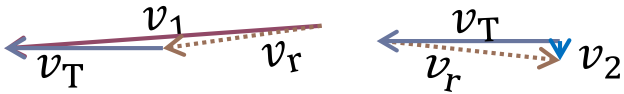
VCN from 17 m long
verticall neutron guide

UCN turbine – PF2 at ILL (Grenoble)



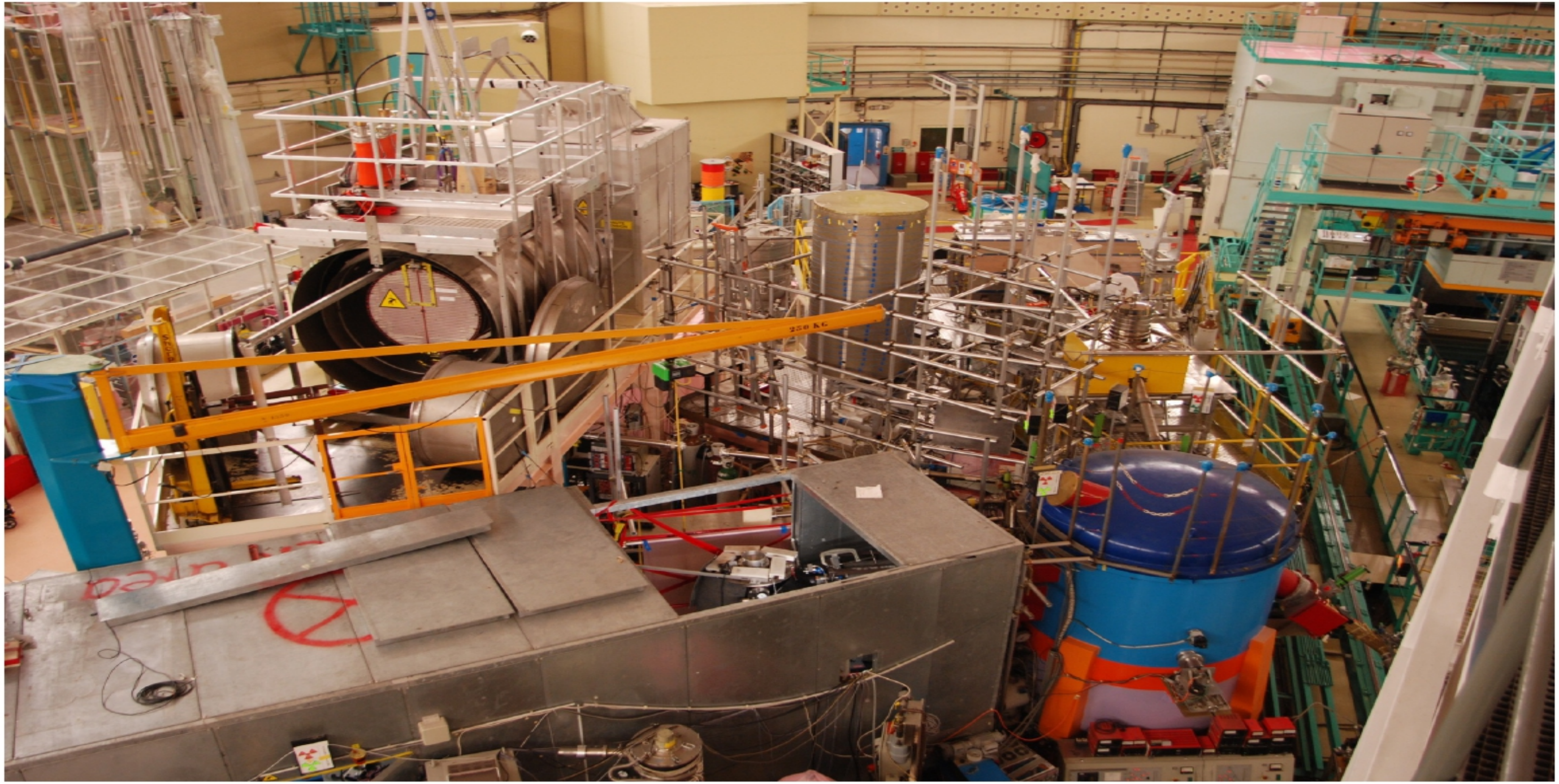




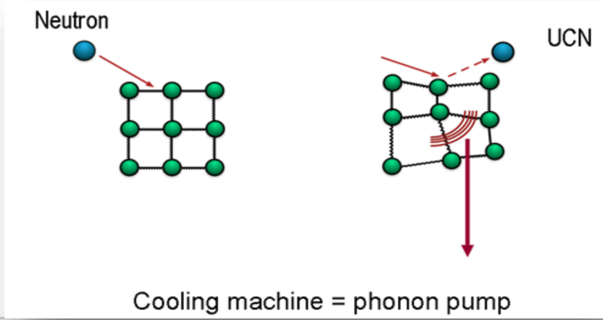


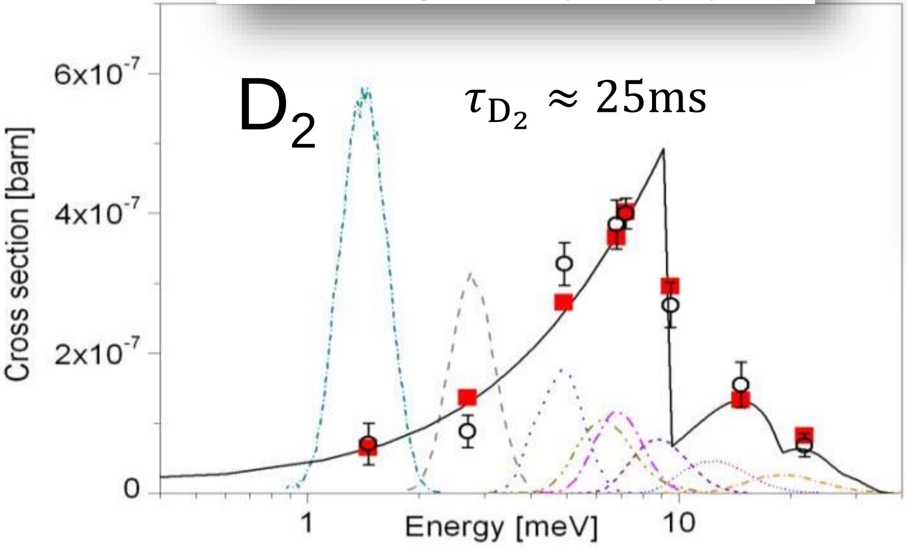
Principle of the neutron turbine. Neutrons with v_I=50 m/s provided by a vertical guide are decelerated by total reflection from moving Ni-coated curved blades. In this process the beam cross-section and divergence increase (Liouville). Here: v_1 = original velocity, v_2 = final velocity, v_T = blade velocity and v_r relative velocity.

UCN turbine – PF2 at ILL (Grenoble)

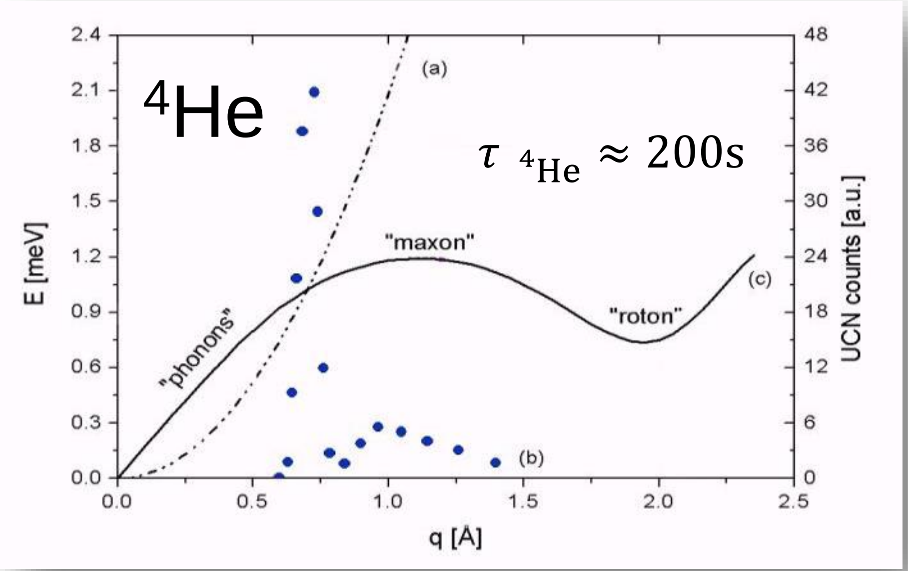


Superthermal UCN production





F. Atchison et al., PRL99(2007)262502



R. Golub & J.M. Pendlebury, PLA62(1977)338
C.A. Baker et al., PLA308(2003)67
PSW, J. Bossy *et al.*,PRC92(2015)024002

Superthermal UCN production

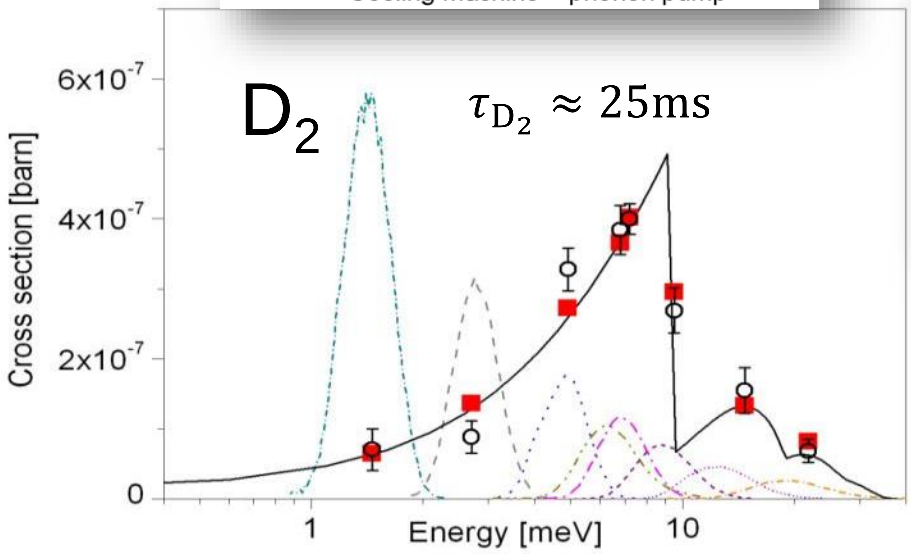
$$\rho = \tau \int \frac{\mathrm{d}\Phi}{\mathrm{d}\lambda} \Sigma(\lambda) \mathrm{d}\lambda$$

macro cross section

differential flux

UCN lifetime in medium

Cooling machine = phonon pump



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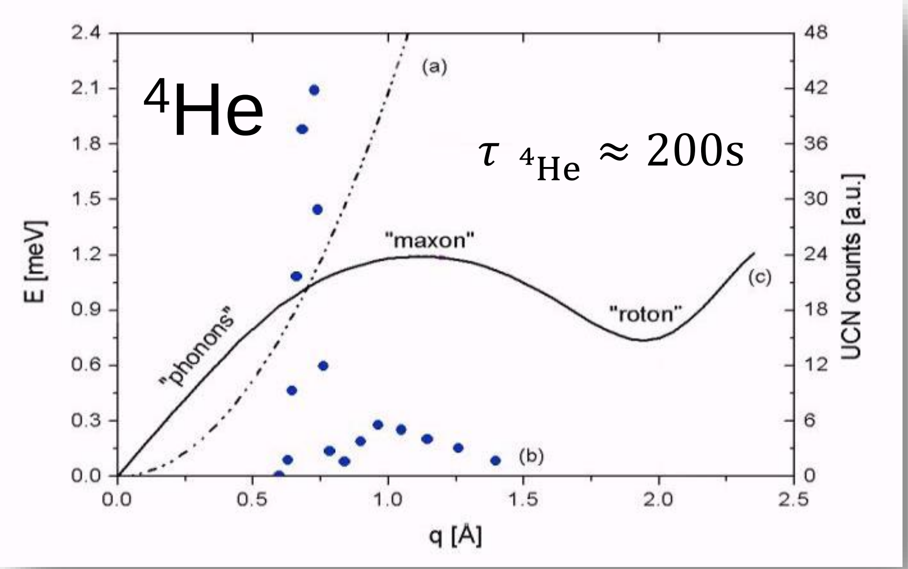

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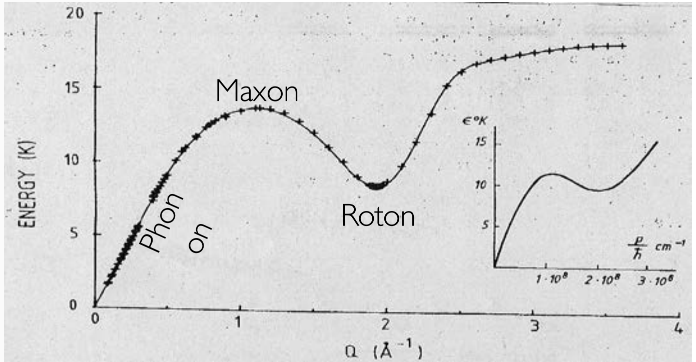
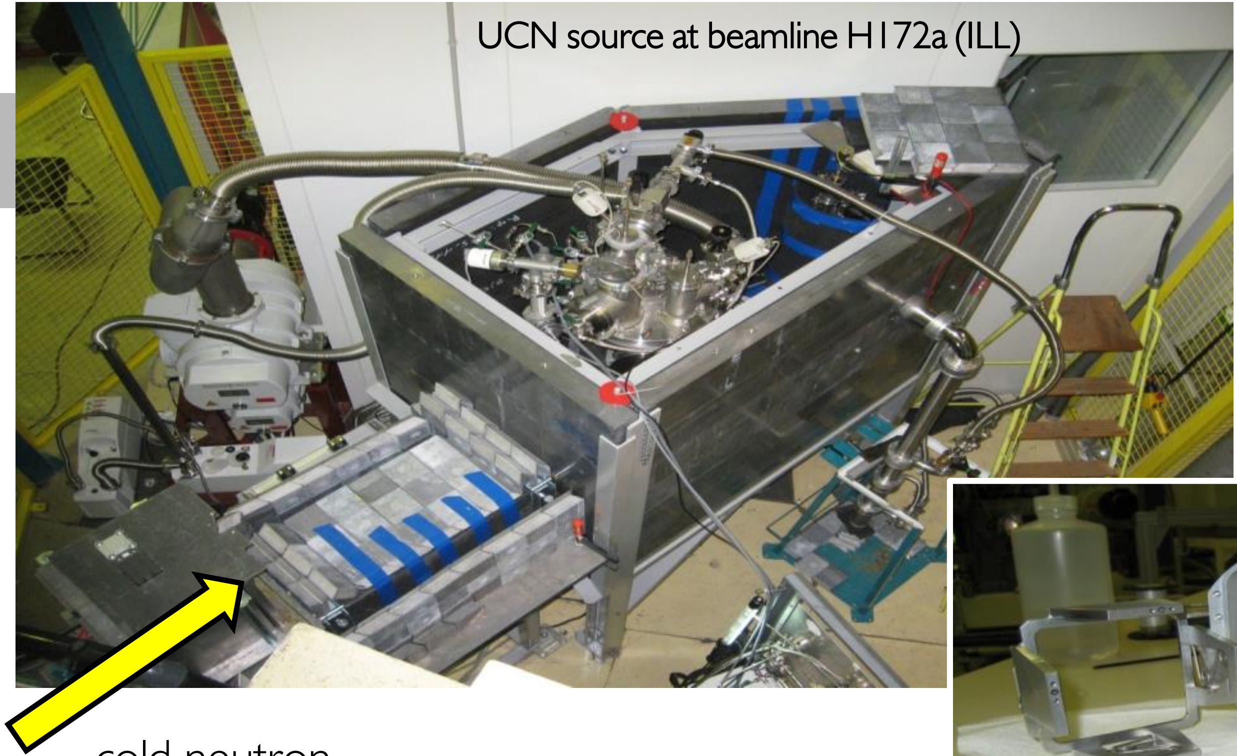
UCN source using Superfluid Helium

- Employs the excitation of phonons by neutrons with a wavelength of 0.89 nm in superfluid helium at temperatures below 1 Kelvin (converter medium).
- Phonon dispersion relation of superfluid helium (obtained from neutron scattering):



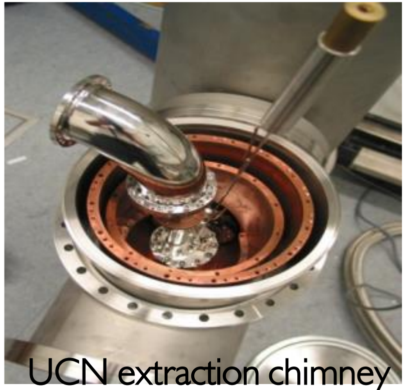
- Energy and momentum conservation during ''down-scattering''.
- In the cold converter the scarcity of low-energy excitations on speaking terms with the trapped UCN suppresses scattering back to higher energies (''up-scattering'') due to the Boltzmann factor.

Superfluid Helium UCN Source at ILL


UCN source at beamline H172a (ILL)

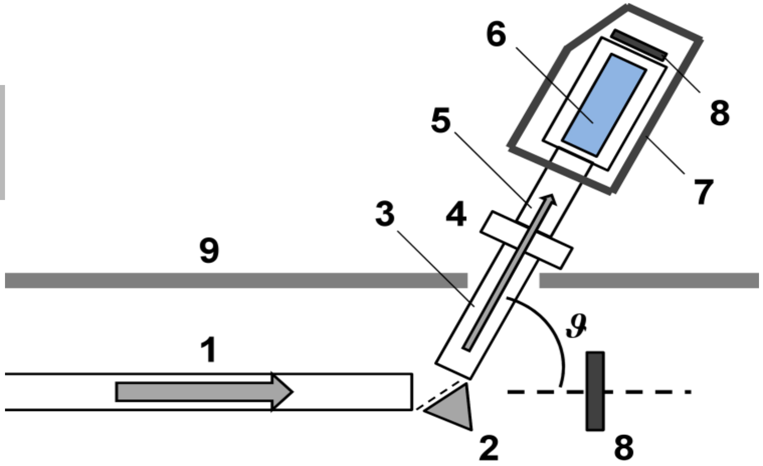
cold neutron beam

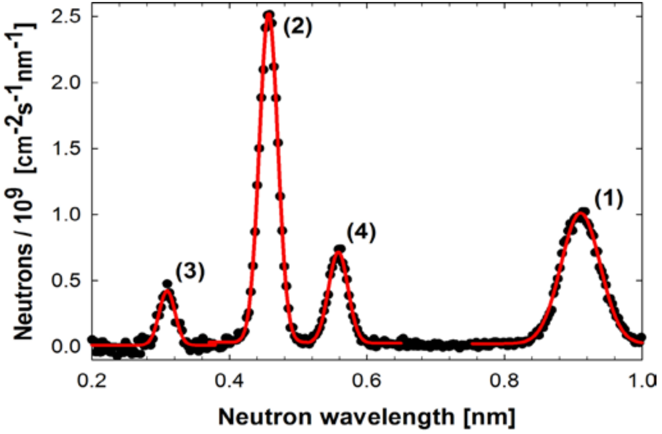
- 5 litres UCN storage volume
- 7 litres of superfluid helium at about 0.7 K
- UCN density 55 cm^{-3} in source

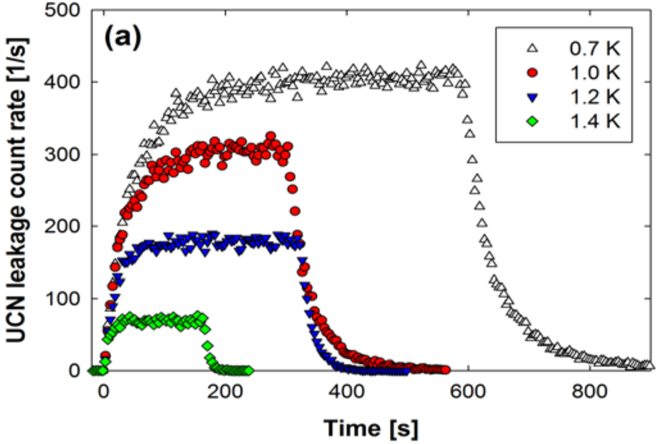

UCN extraction chimney

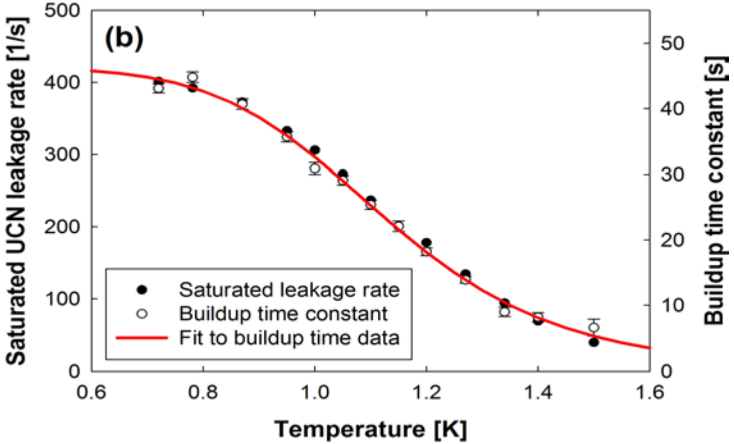

5 litres UCN storage volume made from BeO-ceramics

Superfluid Helium UCN Source at ILL









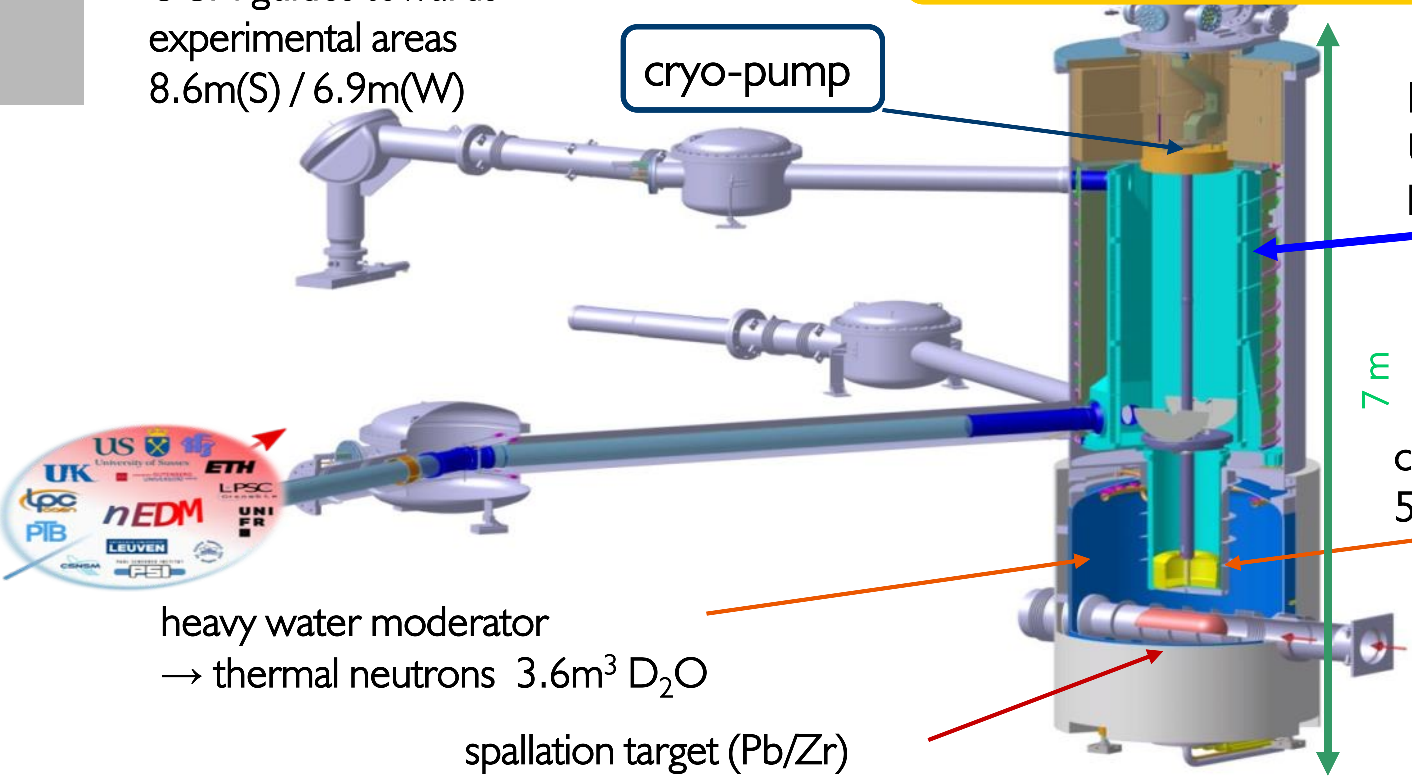
F. Piegsa et al., PRC90 (2014) 01550

Solid Deuterium UCN source at PSI

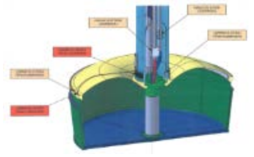
Most intense UCN source

UCN guides towards
experimental areas
8.6m(S) / 6.9m(W)

cryo-pump



DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m^3



cold UCN-converter
5 kg solid D_2 at 5 K

heavy water moderator
→ thermal neutrons 3.6m^3 D_2O

spallation target (Pb/Zr)
(~ 8 neutrons/proton)

pulsed
1.3 MW p-beam
590 MeV, 2.2 mA,
1% duty cycle

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Solid Deuterium UCN source at PSI

UCN storage volume (2000 litres)

UCN valve

solid D2 (converter medium at about 6K)

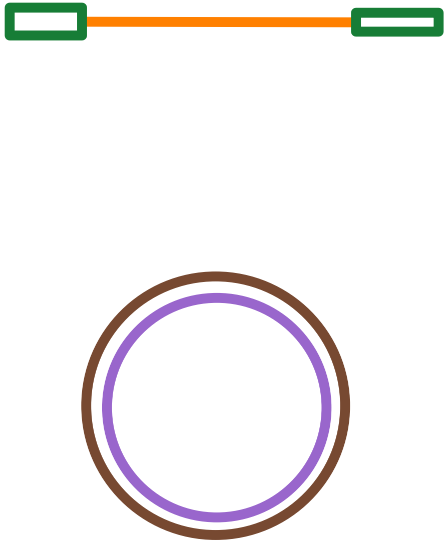
D_2O-moderator

pulsed proton beam
590 MeV, 2.4 mA

Analyzing UCN spins

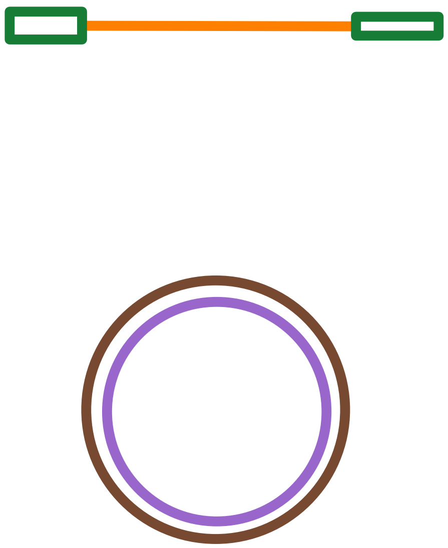
Magnetized Fe foil:

Typically used in UCN experiments by magnetizing with permanent magnets, which produce a $H = 90\ \mathrm{mT}$ magnetic field at the center. As a result, the iron layer is magnetized close to saturation, i.e. close to $B = \mu_r \mu_0 H = 2\ \mathrm{T}$.



How can we detect both spin states?

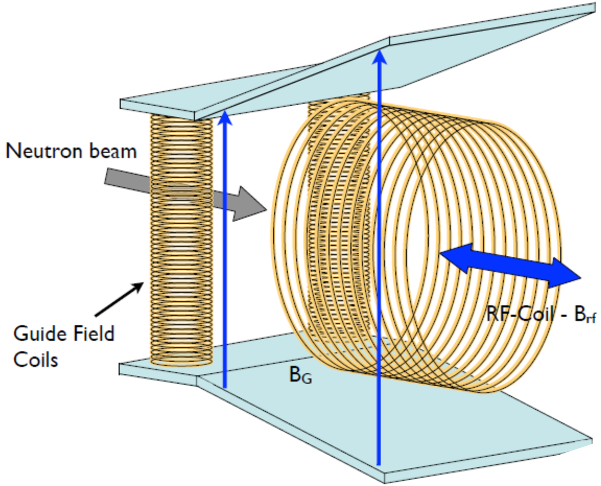
Foil only permits transmission of one spin state

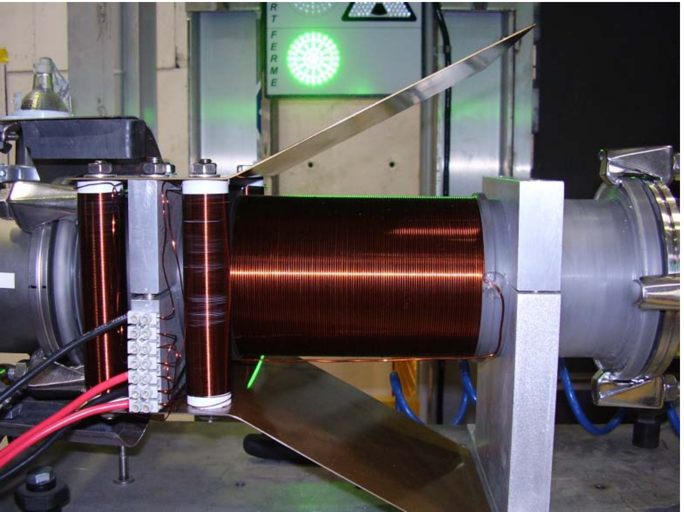


Adiabatic fast passage flipper

Adiabatic-Spinflipper ('Adiabatic Fast Passage'):

A polarized neutron beam passes through a static magnetic field B_G along the *z*-axis, which has a certain gradient along the flight path. Additionally, a linearly polarized rf-field B_1 is irradiated with a frequency ω close to the Larmor frequency $\omega_0=-\gamma_n B_0$. The change of B_G is slow enough such that the spin can follow the effective magnetic field B_e, during the passage of the flipper adiabatically.





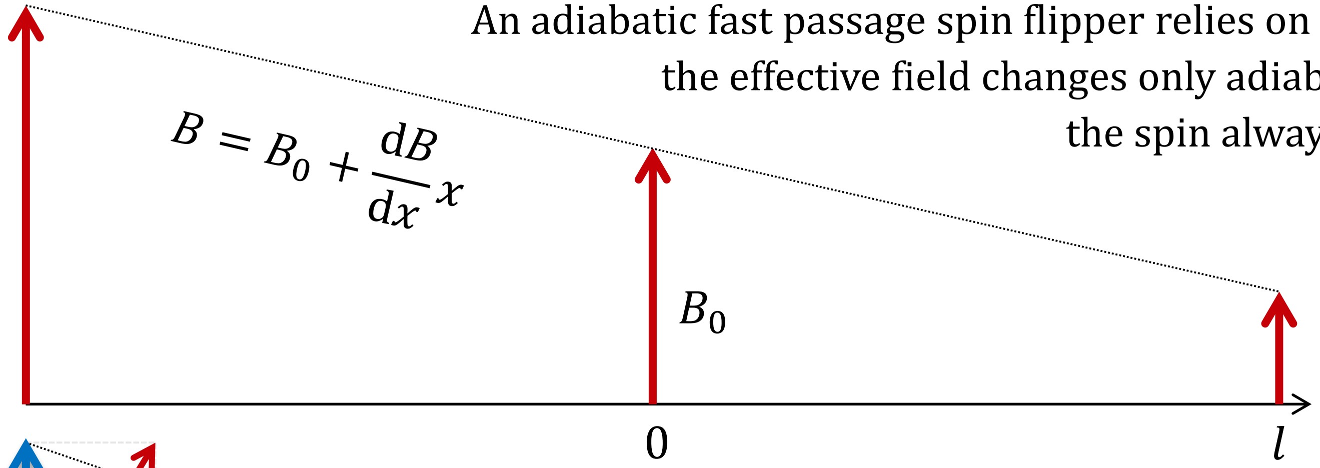
Rf field constant in frequency and magnitude.

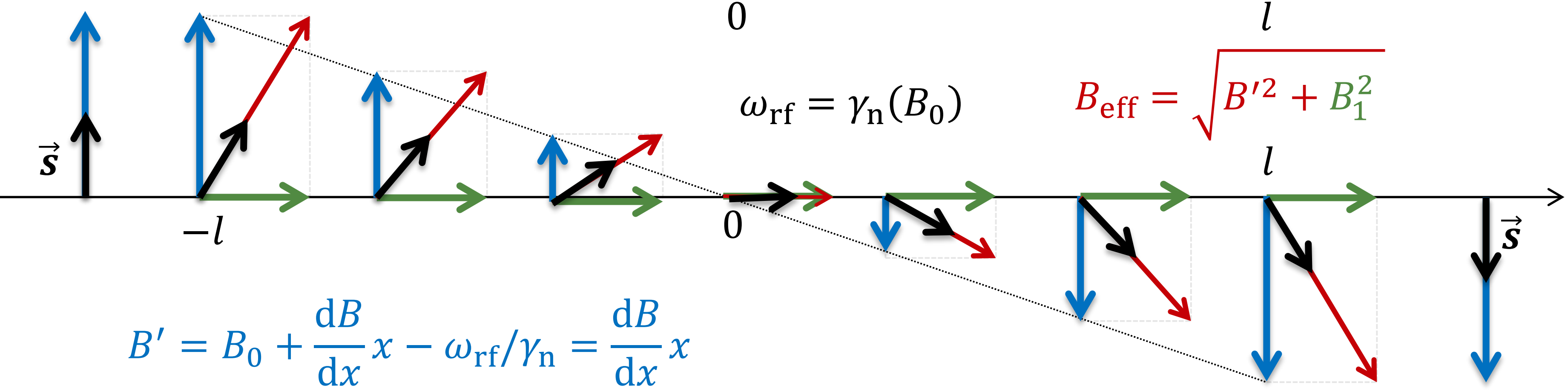
B_G is swept from high to low fields,

through resonance with $\omega_{rf} = \gamma_n B_G(x)$.

Adiabatic fast passage flipper

An adiabatic fast passage spin flipper relies on the condition, that the effective field changes only adiabatically and hence the spin always follows the field.





Adiabatic fast passage flipper

An adiabatic fast passage spin flipper relies on the condition, that the effective field changes only adiabatically and hence the spin always follows the field.

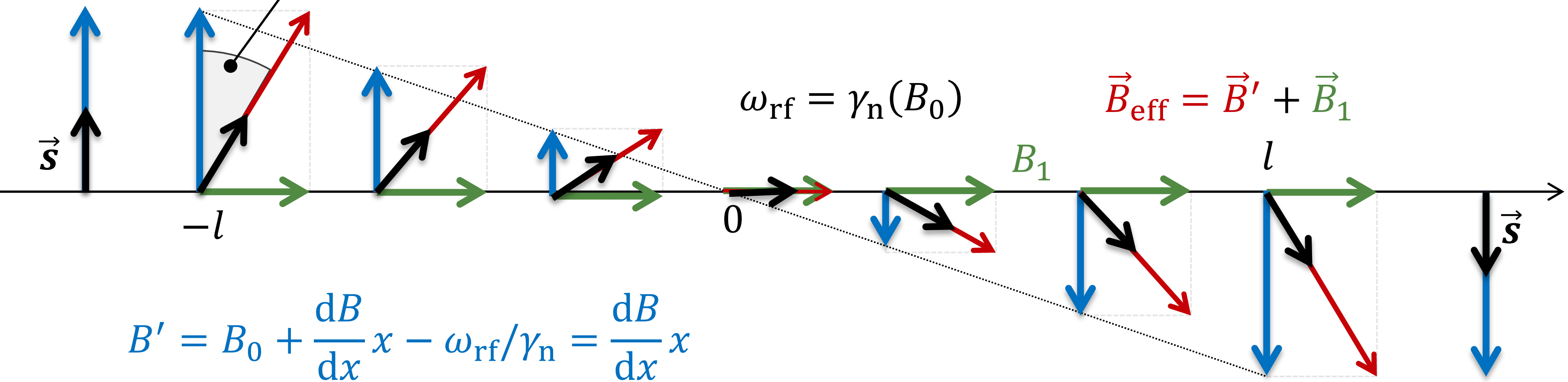
$$10 < \kappa = \frac{\omega_L(x)}{\omega_\theta(x)} = \frac{\gamma_n B_{\mathrm{eff}}}{\mathrm{d}\theta/\mathrm{d}x \cdot v_x^{\max}}$$

$$\theta = \operatorname{asin} \frac{B_1}{\sqrt{B_1^2 + g^2 x^2}}$$

$$\mathrm{d}\theta/\mathrm{d}x = \frac{B_1 g^2 x}{B_{\mathrm{eff}}^3} \sqrt{1 - B_1^2/B_{\mathrm{eff}}^2}$$

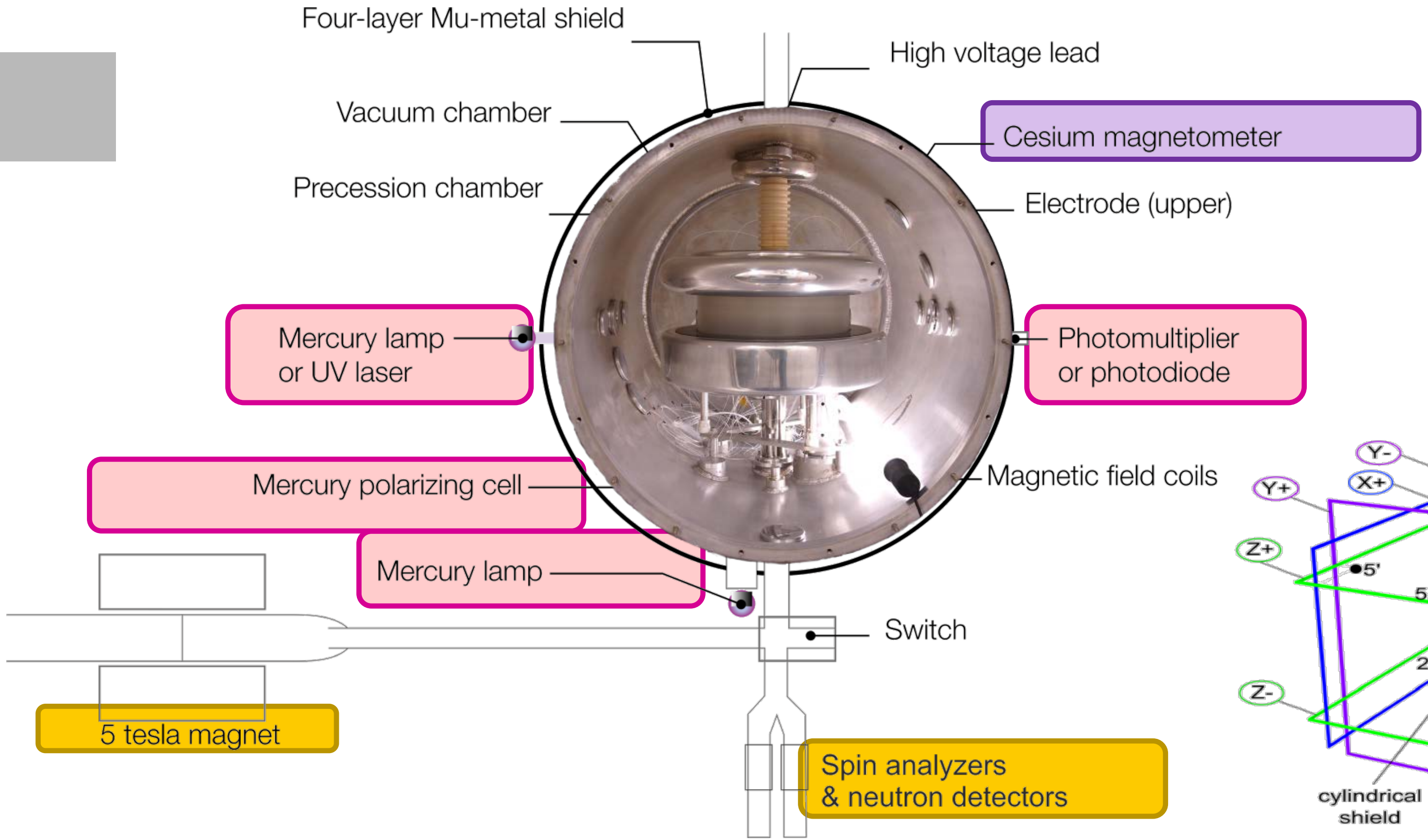
$$\omega_{\mathrm{rf}} = \gamma_n(B_0)$$

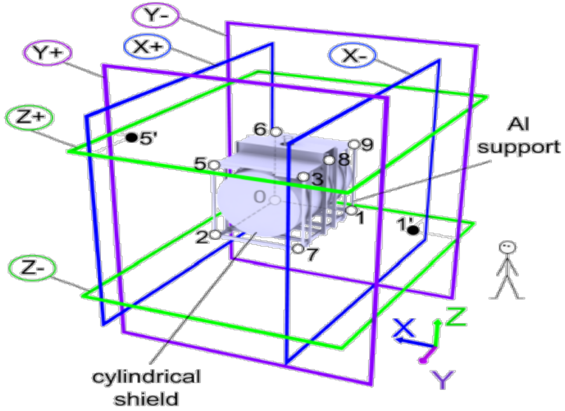
$$\vec{B}_{\mathrm{eff}} = \vec{B}' + \vec{B}_1$$



$$B' = B_0 + \frac{\mathrm{d}B}{\mathrm{d}x} x - \omega_{\mathrm{rf}}/\gamma_n = \frac{\mathrm{d}B}{\mathrm{d}x} x$$

The nEDM spectrometer





Ultracold neutrons (UCN)

For highest sensitivity:

Optimize

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

CN beamline (e.g. ILL - PF1b)

$$\dot{N} \approx 2 \times 10^{9}\ \mathrm{s}^{-1}\ @\ 440\ \mathrm{m/s}$$

$$\alpha \approx 0.99; \quad E \approx 100\mathrm{kV/cm}$$

$$T = l/v = \frac{2\ \mathrm{m}}{440\ \mathrm{m/s}} = 4.5\mathrm{ms}$$

$$\sigma(1\mathrm{s}) = 2 \times 10^{-23} e\mathrm{cm}$$

UCN are neutrons which can be stored in material bottles

UCN (EDM at TRIUMF/PSI)

$$\dot{N} \approx 333\ \mathrm{s}^{-1}$$

$$\alpha \approx 0.9; \qquad E = 15\mathrm{kV/cm}$$

$$T = 200\mathrm{s}$$

$$\sigma(1\mathrm{s}) = 1 \times 10^{-23}\ e\mathrm{cm}$$

Increasing sensitivity

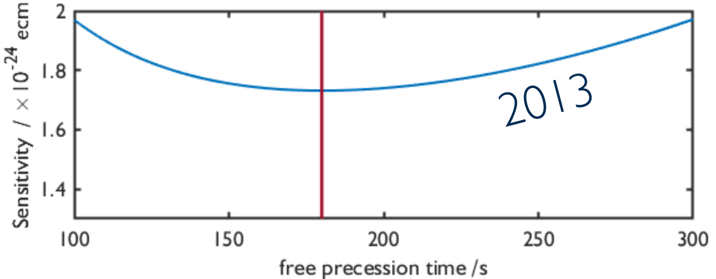
One cycle
300s

Many cycle
300s

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

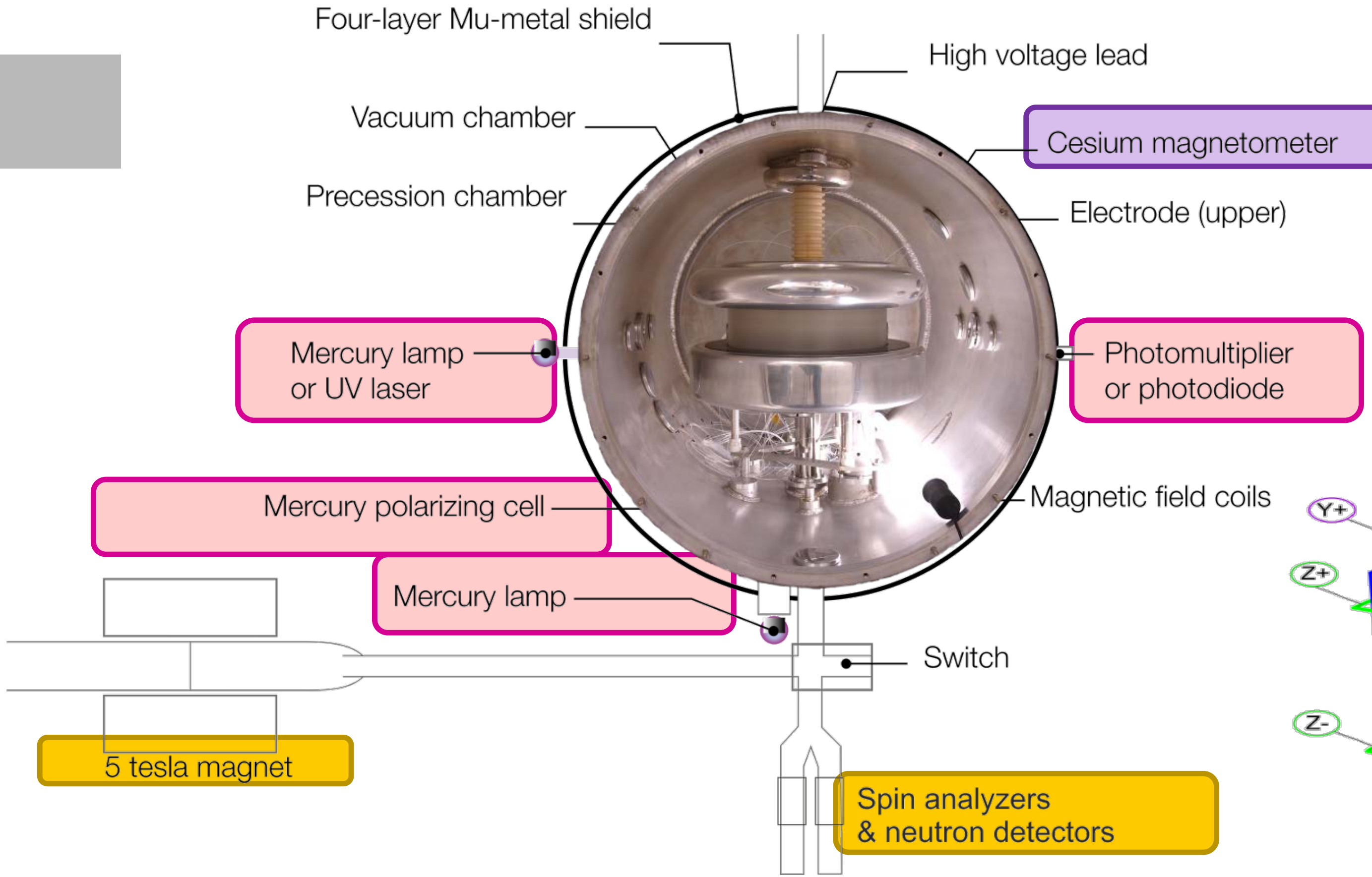
$$\sigma(d_\mathrm{n}) = \frac{\hbar}{2\alpha T E\sqrt{NM}}$$

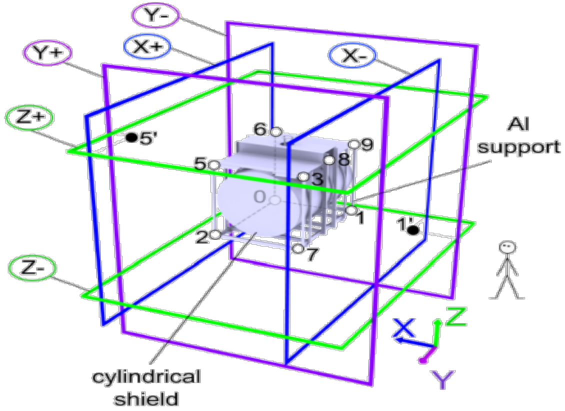
$$\sigma(d_\mathrm{n}) = \frac{\hbar}{E T \alpha_0 \mathrm{e}^{-T/T_2}\sqrt{2N_0\left(\mathrm{e}^{-T/\tau_s} + \mathrm{e}^{-T/\tau_f}\right)}}$$



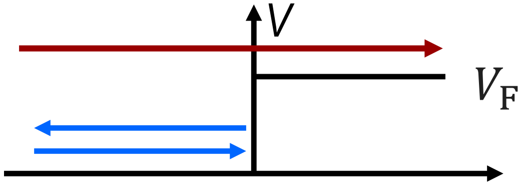
- Highest initial UCN number N_0
- Best possible storage time $\tau_{s,f}$
- Maximum voltage E
- Highest initial polarization α_0
  longest possible T_2

The nEDM spectrometer



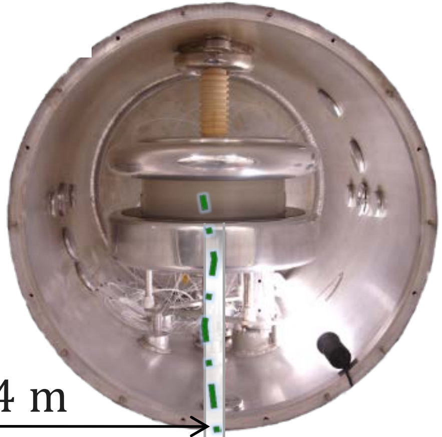


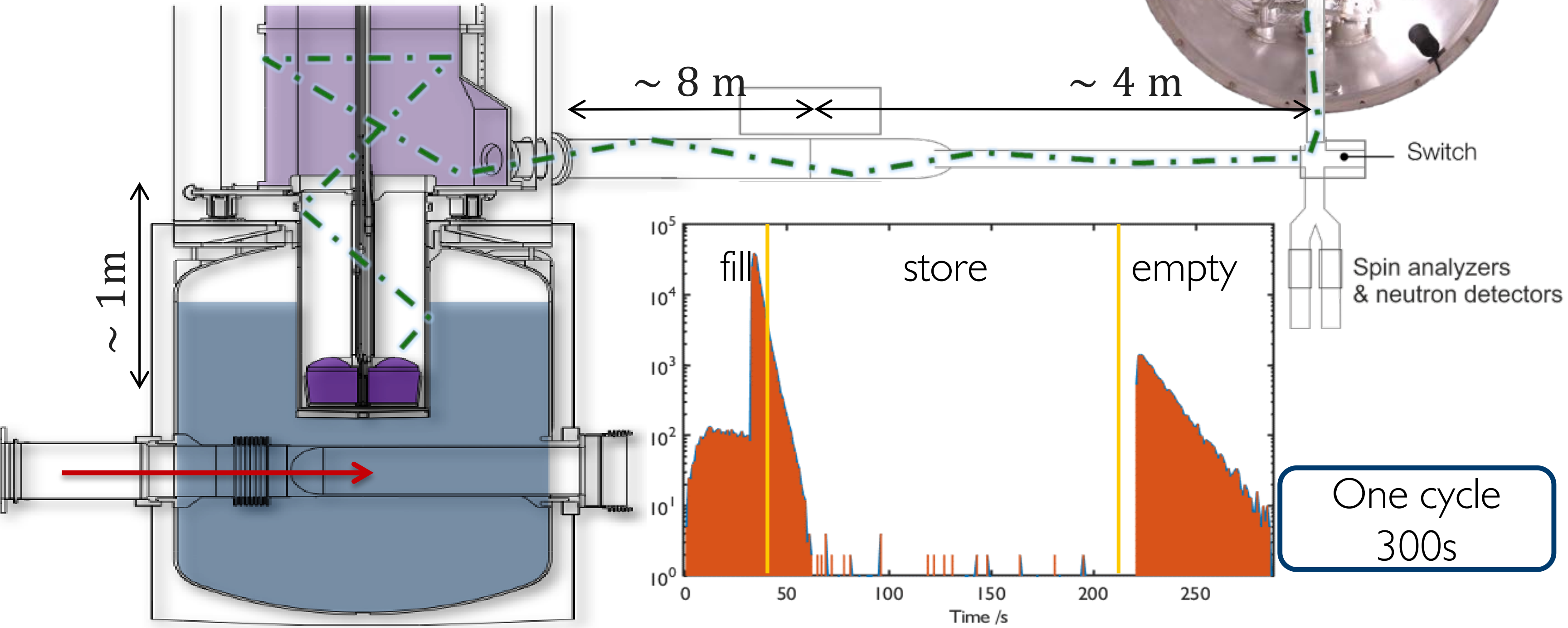
Ultracold neutrons: good for $T\sqrt{N}$



$$V_F = \frac{2\pi\hbar}{m_n} bN \leq 350\text{neV}$$

(8m/s, 3mK)

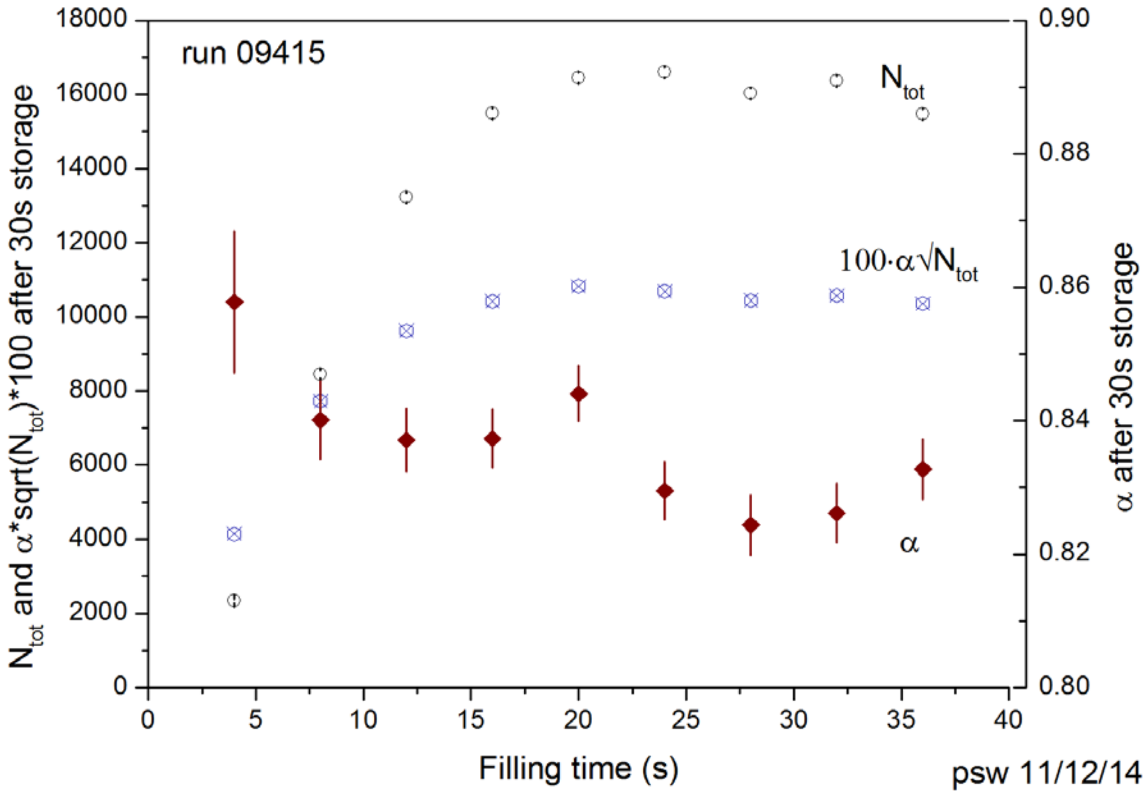




G. Bison et al., EPJA (2020) 56:33

Filling UCN

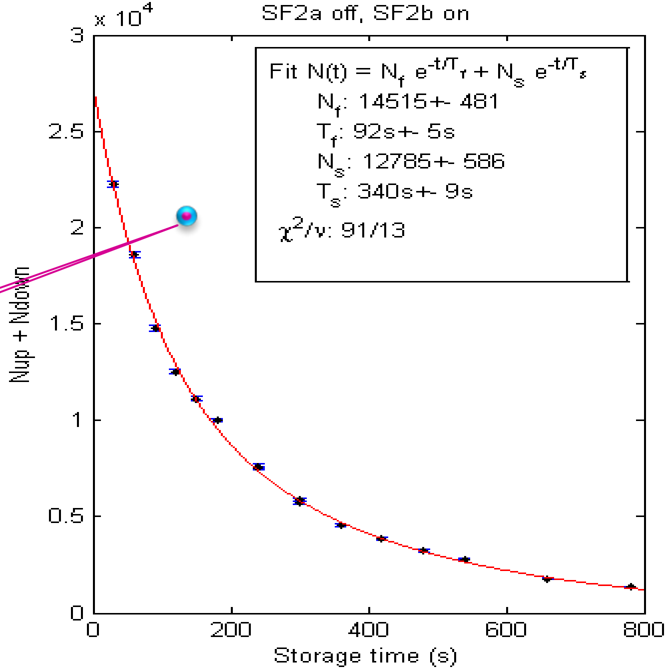
- Optimize product $\alpha\sqrt{N}$



Storage life

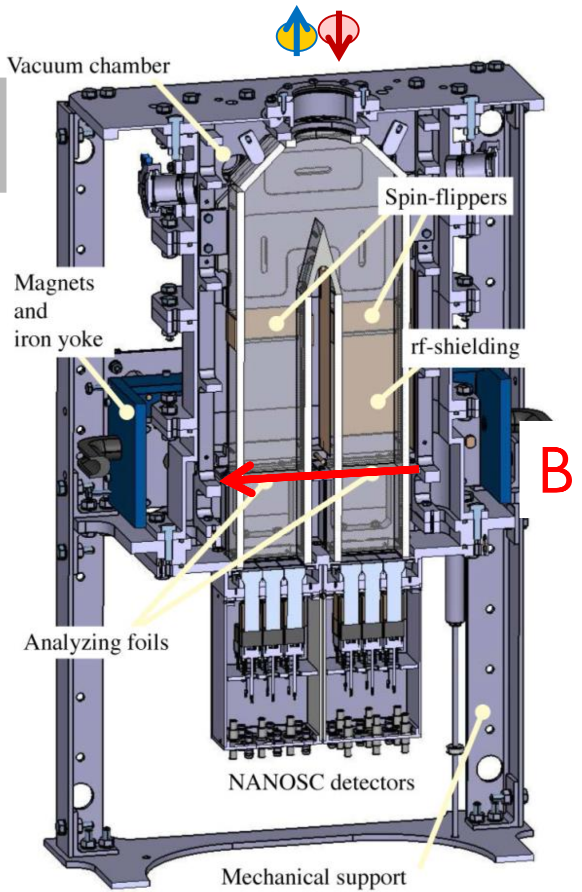
- Chamber made of **dPS** insulator ring and **DLC** electrodes
- Two exp fit:
  $t_s \sim 90s$
  $t_f \sim 340s$
- Max number of UCN measured after 180s storage:

20 800

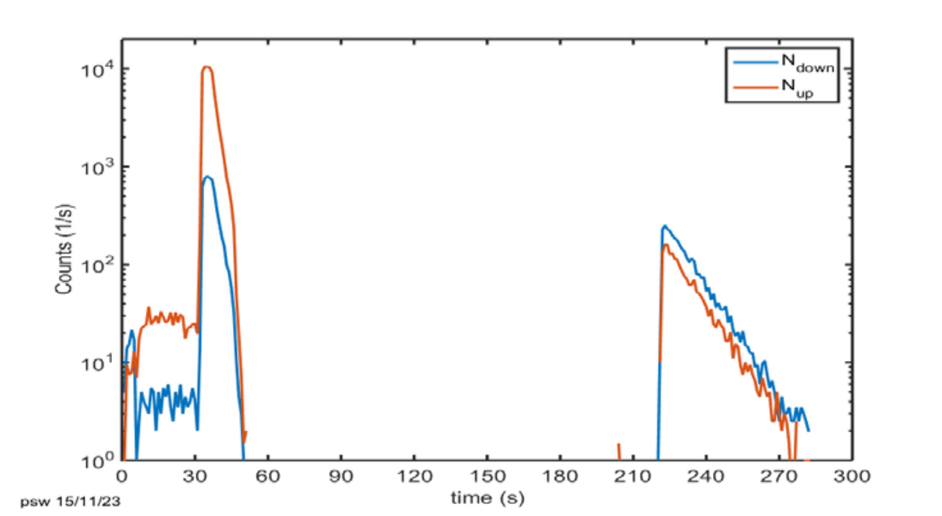


Simultaneous spin detection

$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$



- Spin dependent detection
  - Adiabatic spinflipper
  - Iron coated foil
- ^{6}Li-doped scintillator GS20



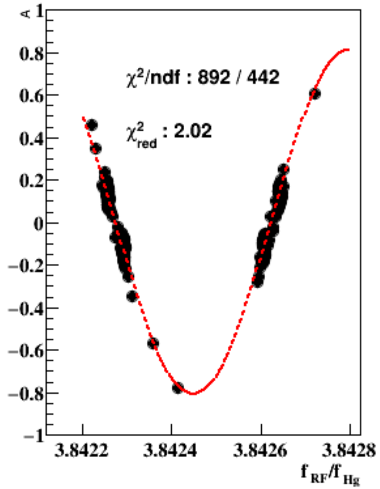
S. Afach *et al.*, EPJA (2015)51: 143

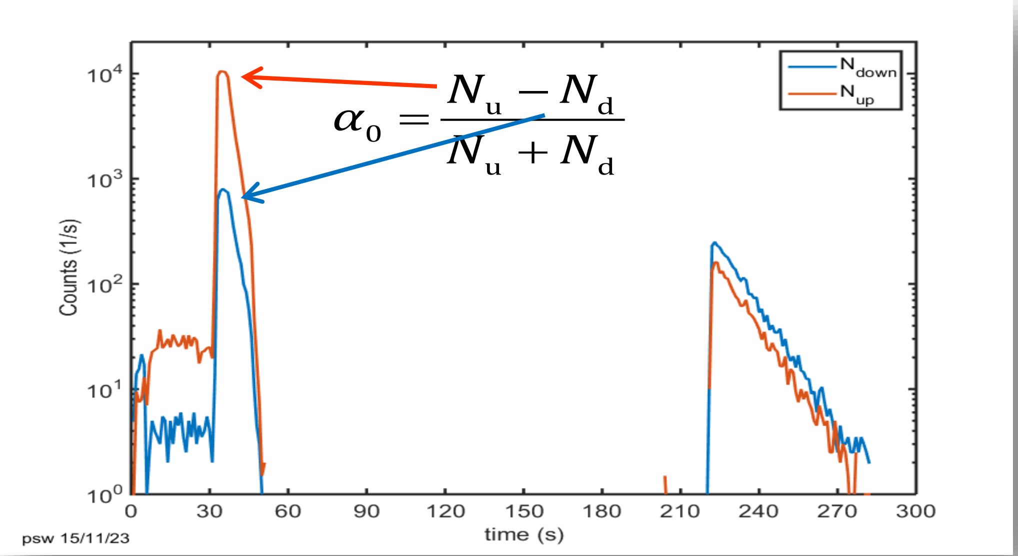
Transverse polarization time

$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

- Initial polarization α_0 measured with USSA 0.86
- Best polarization after 180s free precession 0.80, average 0.75

$$T_2^* = t \cdot \ln\left(\alpha(t)/\alpha_0\right) = 2488\text{s}$$



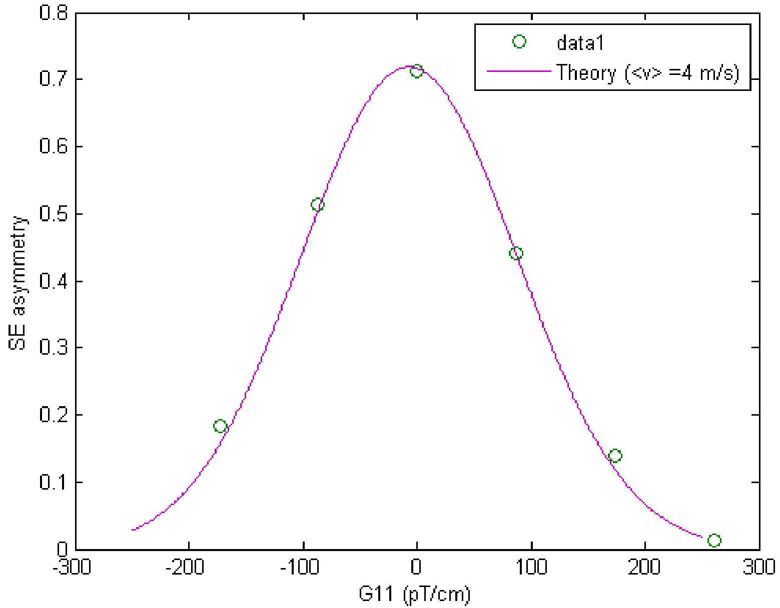


Depolarization $\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$

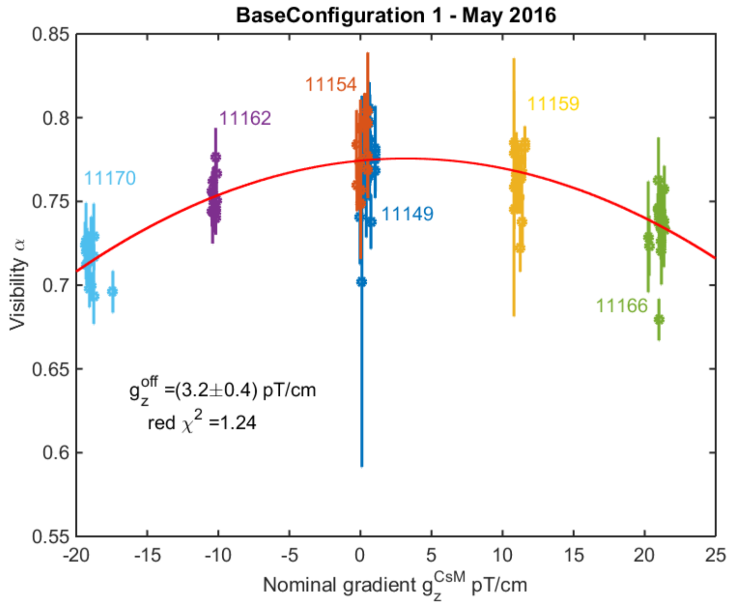
$$\Gamma_2(\epsilon) = a\frac{\gamma_n^2}{v(\epsilon)}\left[\frac{8r^3}{9\pi}\left(\left|\frac{\partial B_z}{\partial x}\right|^2 + \left|\frac{\partial B_z}{\partial y}\right|^2\right) + \frac{\mathcal{H}^3(\epsilon)}{16}\left|\frac{\partial B_z}{\partial z}\right|^2\right]$$

$$\alpha(T) = e^{-\Gamma_2 T} - \frac{\gamma_n^2 g_z^2 T^2}{2} \cdot \langle dh^2\rangle_{\text{eff}}$$

Intrinsic depolarization



Gravitational depolarization



Afach et al., PRD92(2015)052008
Afach et al., PRL115(2015)162502

Increasing sensitivity

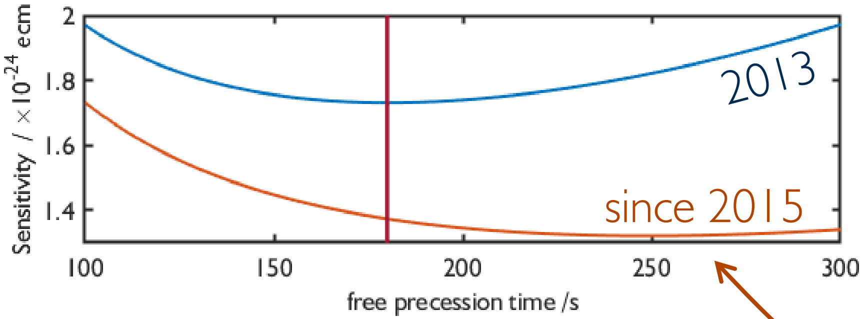
One cycle
300s

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

Many cycles
of 300s

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

$$\sigma(d_n) = \frac{\hbar}{E T \alpha_0 e^{-T/T_2} \sqrt{2 N_0 \left(e^{-T/\tau_f} + e^{-T/\tau_s}\right)}}$$



$N = 20000$, $N(180s) = 11400$

$\tau_{f,s} = 80\text{s}, 180\text{s}$

$E = 11\ \text{kV/cm}$

$\alpha_0 = 0.76$

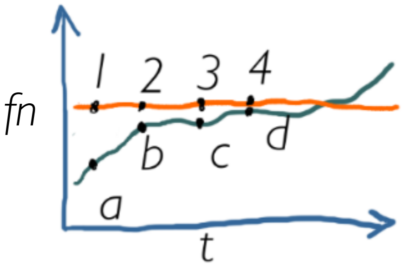
$T = 500\text{s}, 1300\text{s}$

C. Abel et al., PRL 124 (2020) 081803

Sensitivity versus field drifts

- Sensitivity for many cycles

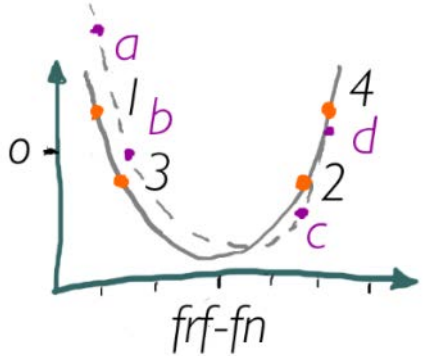
  ideal case: $\sigma(d_\mathrm{n}) = \frac{\hbar}{2\alpha T E\sqrt{NM}}$



- Only if magnetic field is stable enough.

  (Good fit with orange,

  bad fit with purple)



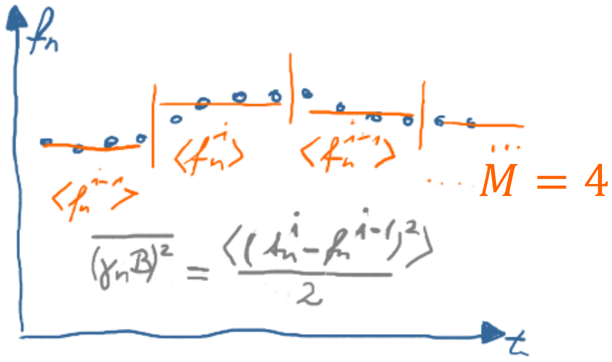
Sensitivity versus Stability

- Sensitivity for many cycles ideal case:

$$\sigma_{\text{stat}}(B) = \frac{1}{\gamma_{\text{n}} \alpha T \sqrt{NM}}$$

- Requires:

$$\overline{\Delta B} \leq \sigma_{\text{stat}}$$



Allan deviation:

$$\sigma_{AD}(M) = \sqrt{\frac{\left\langle \left(f_i(M) - f_{i-1}(M)\right)^2 \right\rangle}{2}}$$

Choose M such that:

$$\sigma_{\text{stat}}(M) \geq \sigma_{AD}(M)$$

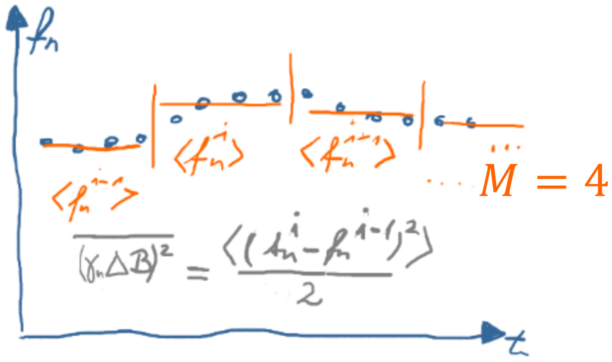
Sensitivity versus Stability

- Many cycles sensitivity ideally:

$$\sigma_{\text{stat}}(B) = \frac{1}{\gamma_n \alpha T \sqrt{NM}}$$

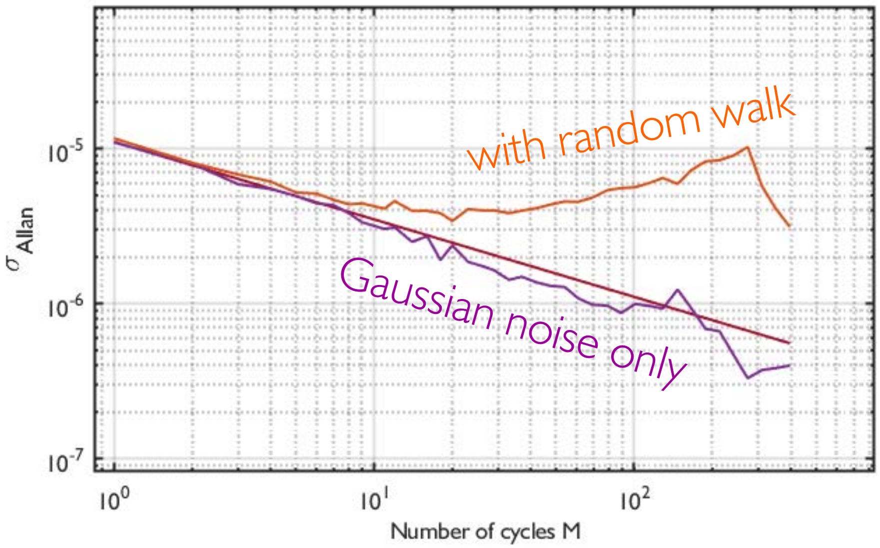
- Require:

$$\sigma_{\text{stat}} \geq \overline{\Delta B}$$



Allan deviation:

$$\sigma_{AD}(M) = \sqrt{\frac{\left\langle \left(f_i(M) - f_{i-1}(M)\right)^2 \right\rangle}{2}}$$



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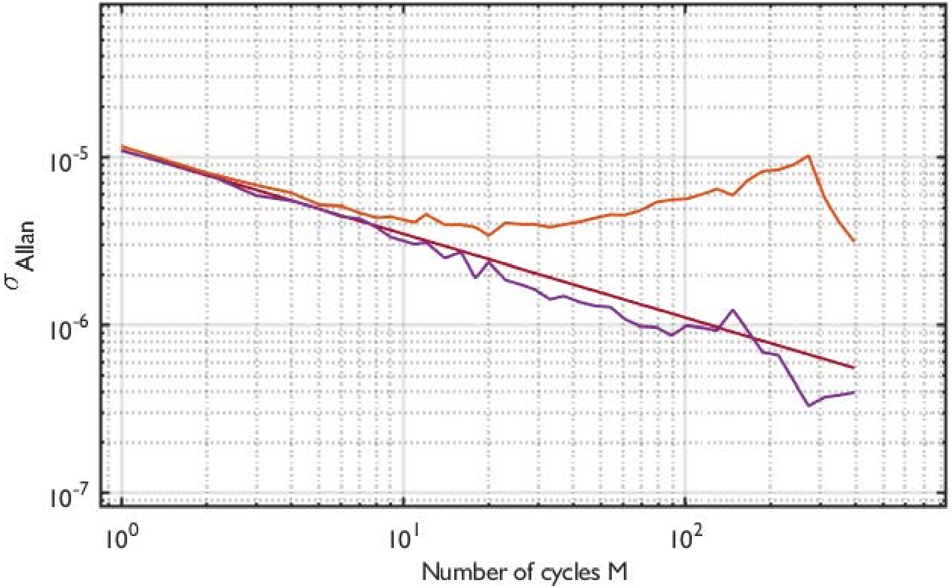
Stability and changing E-fields

$$\Delta f = \frac{4d_n|\vec{E}| - 2\mu\Delta B_0}{h}$$

Options with field changes:

- Change E-field with adequate period (e.g. 10 cycles) (loose time due to E ramps)
- Use a stack of two neutron precession chambers
- Use a comagnetometer

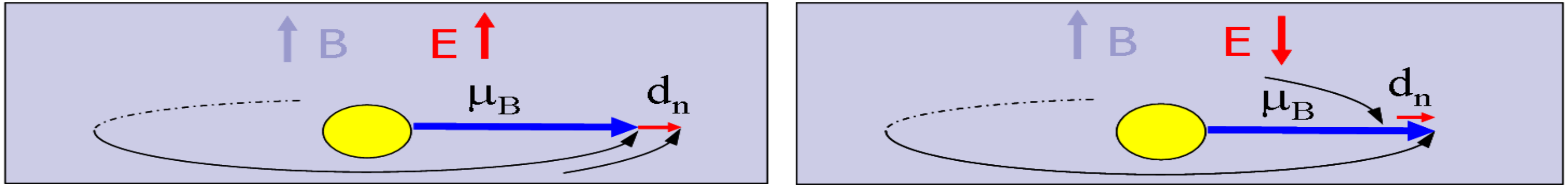


Gatchina's double chamber design

Sussex's co-magnetometer

The measurement technique

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

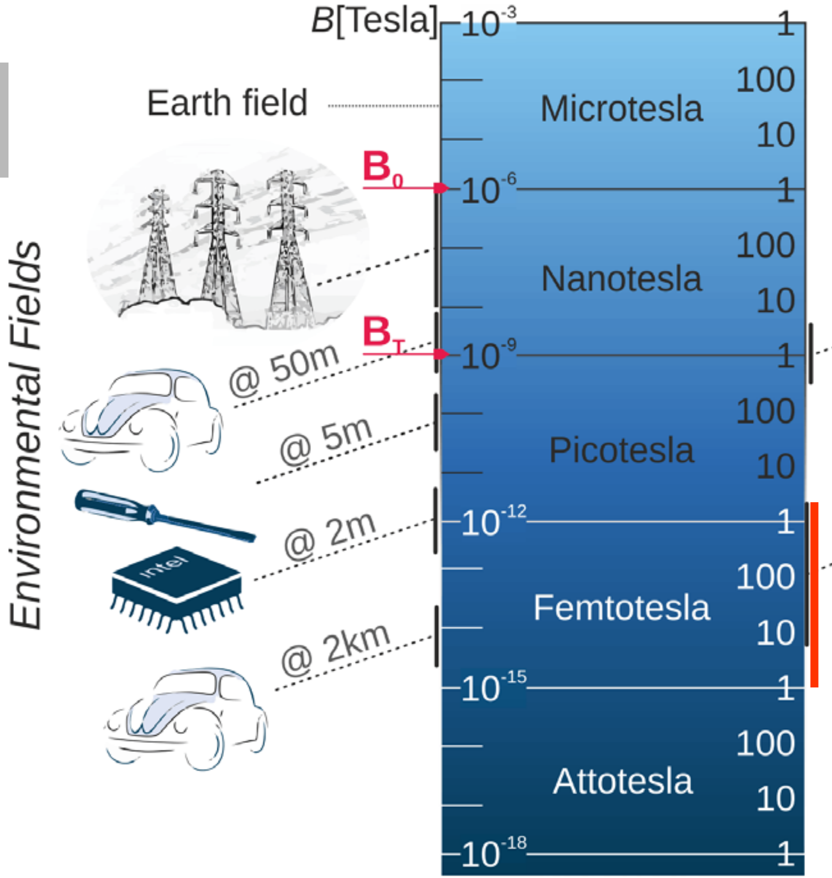


$$\hbar \Delta \omega = 2 d_n \left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow} \right) + 2 \mu_n \left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow} \right)$$

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

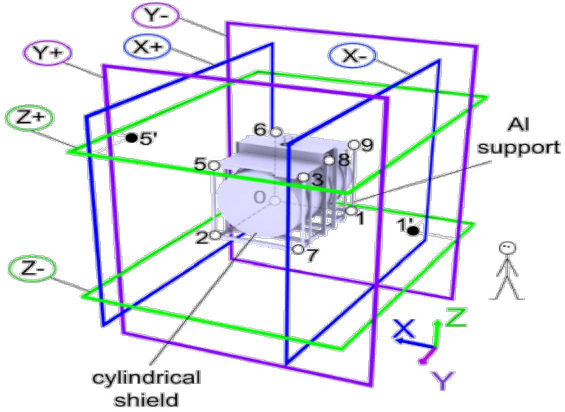
$$\delta f_n = \frac{1}{2\pi\alpha T\sqrt{N}} \approx 11\mu\mathrm{Hz} \xrightarrow{B_0 = 1\mu\mathrm{T}} \delta B \leq 100\mathrm{fT}$$

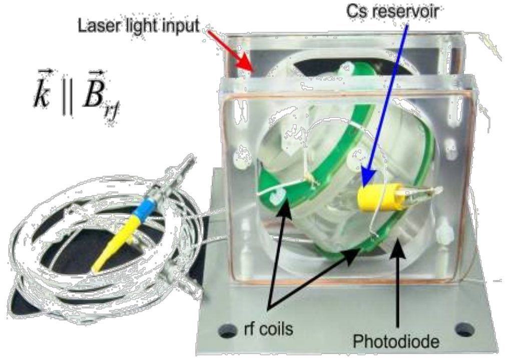
Magnetic fields



$\delta B < 100\mathrm{fT}$

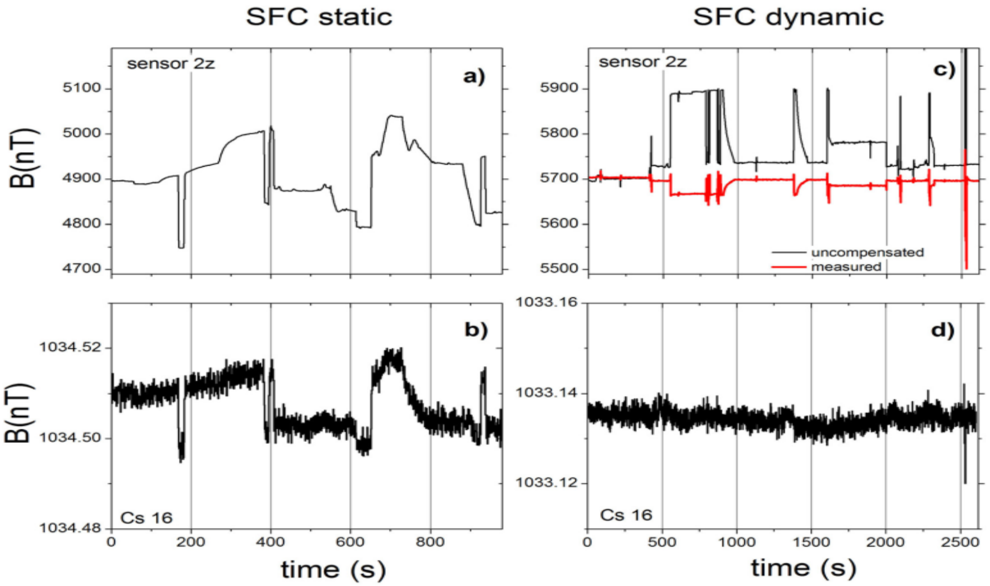
optical pumped magnetometers (CsM/HgM)

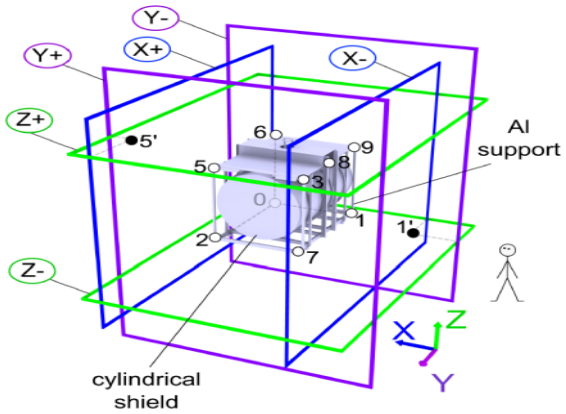




B-Field stability

- Excellent stability
  (dynamic SFC & 4 layer magnetic shield)
  fT





Afach et al., J. Appl. Phys. ***116***, 084510 (2014)

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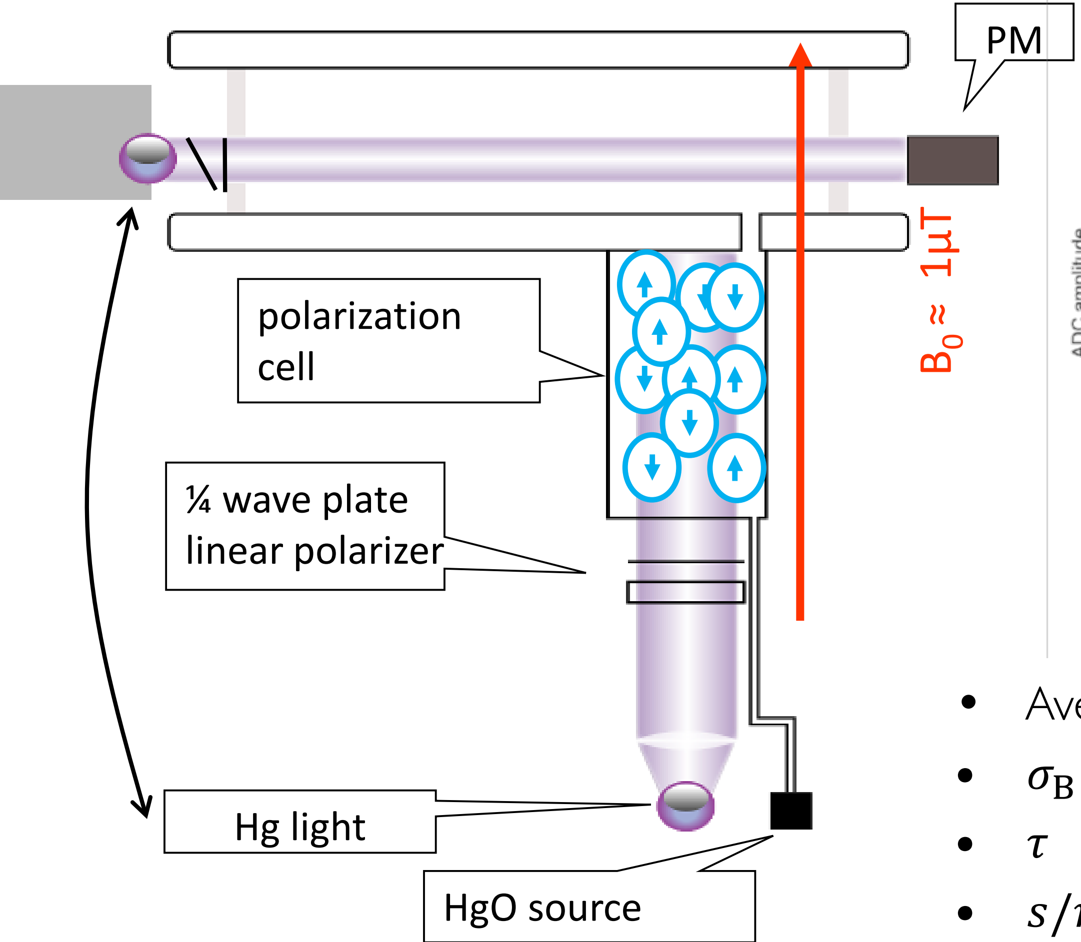
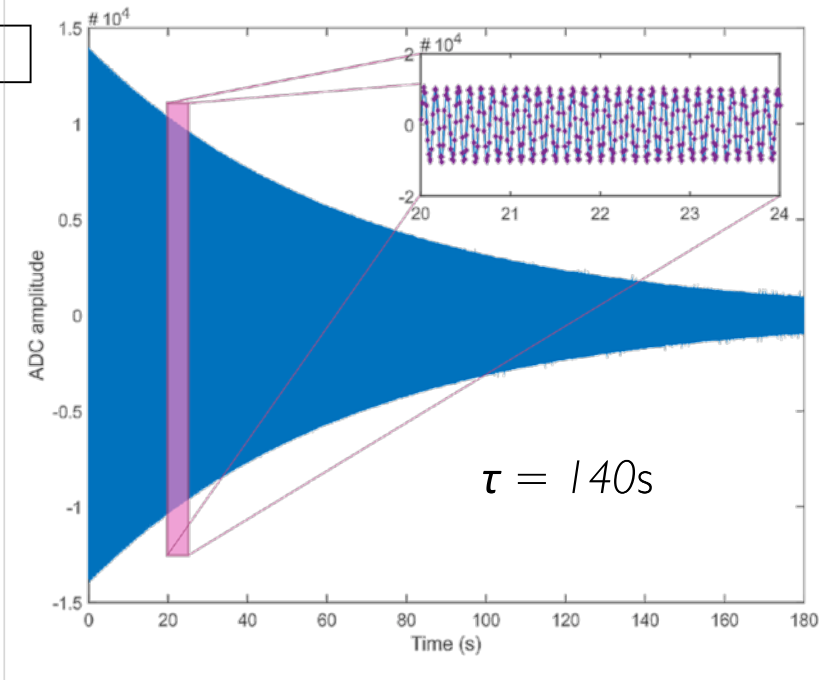
Mercury comagnetometer

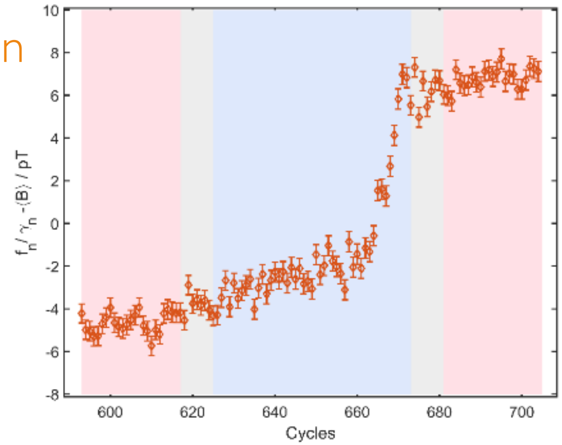




- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100$ fT (CR-limit)
- $\tau > 100$ s wo HV (with ~ 90 s)
- $s/n > 1000$

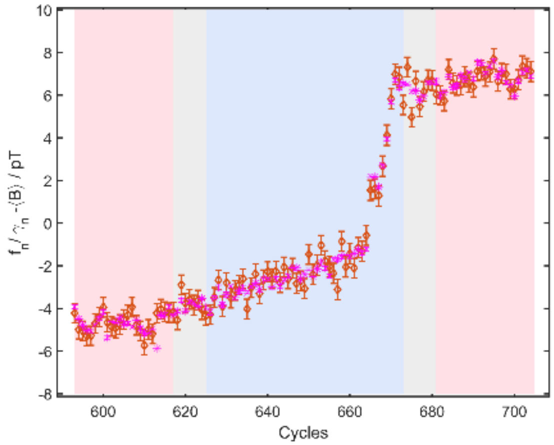
Real data example (stability)

Neutron



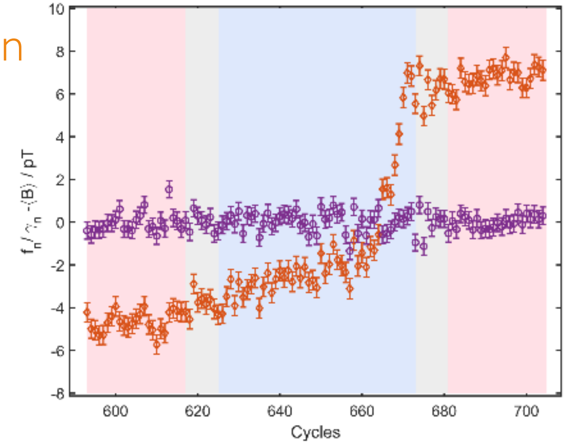
Neutron

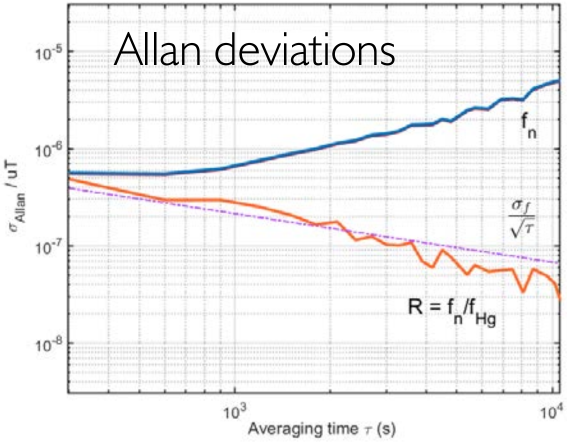
Mercury



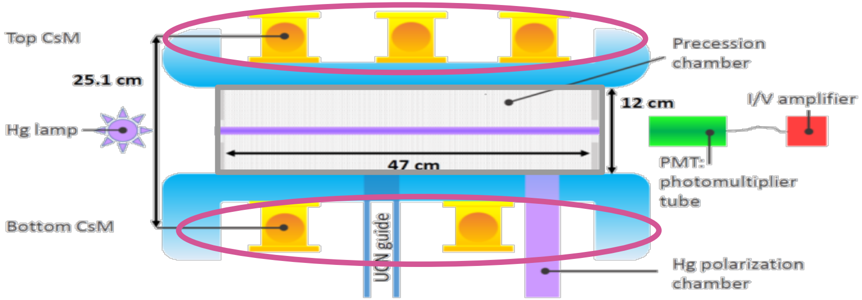
Neutron

R-ratio



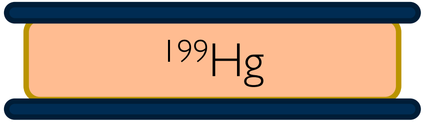


Frequency ratio $R = f_n/f_{Hg}$



- Center of mass offset
- Non-adiabaticity

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



$$\frac{\gamma_n}{2\pi} \approx 30\ \text{Hz}/\mu\text{T}$$

$$\overline{v_{Hg}} \approx 160\ \text{m/s vs. } \overline{v_{UCN}} \approx 3\ \text{m/s}$$

+ further sys.

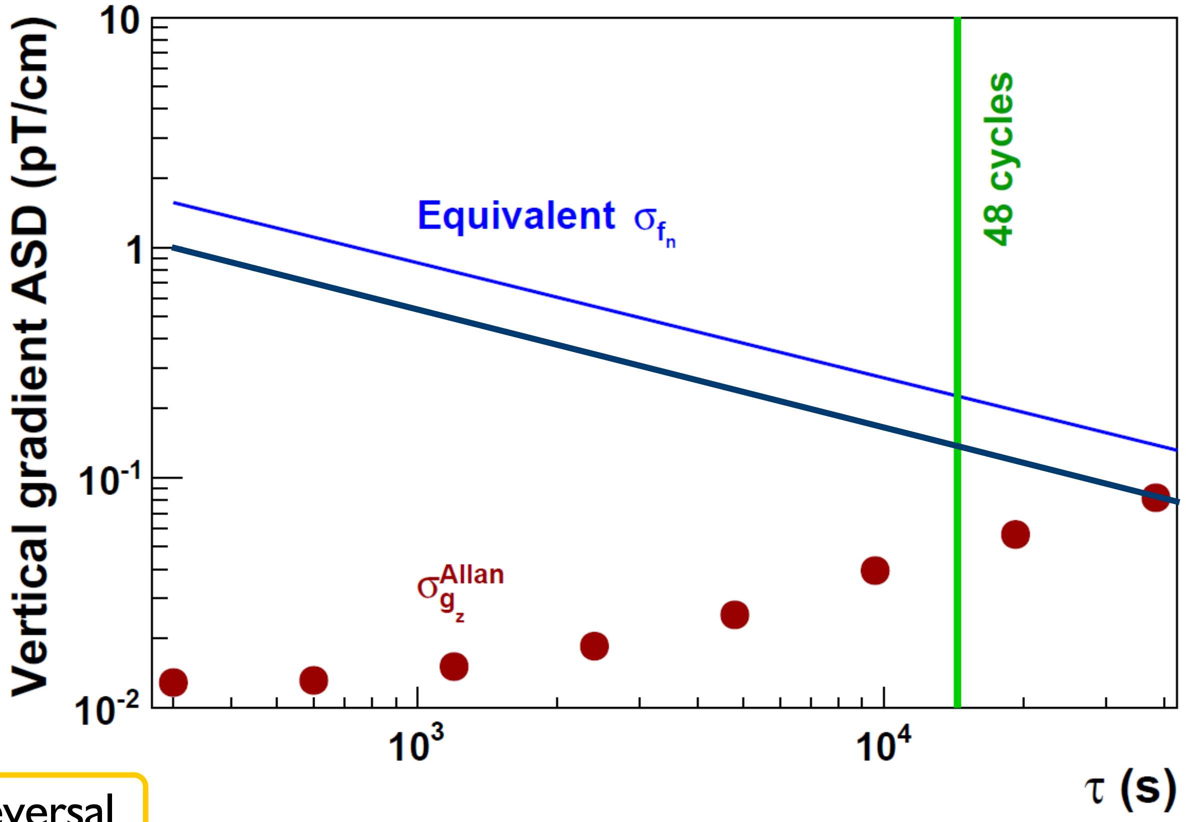
$$R = \frac{\langle f_{UCN} \rangle}{\langle f_{Hg} \rangle} = \frac{\gamma_n}{\gamma_{Hg}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_\perp \rangle}{|B_0|^2} \mp \delta_{Earth} + \delta_{Hg-lightshift} \right)$$

Stability of the effective vertical gradient

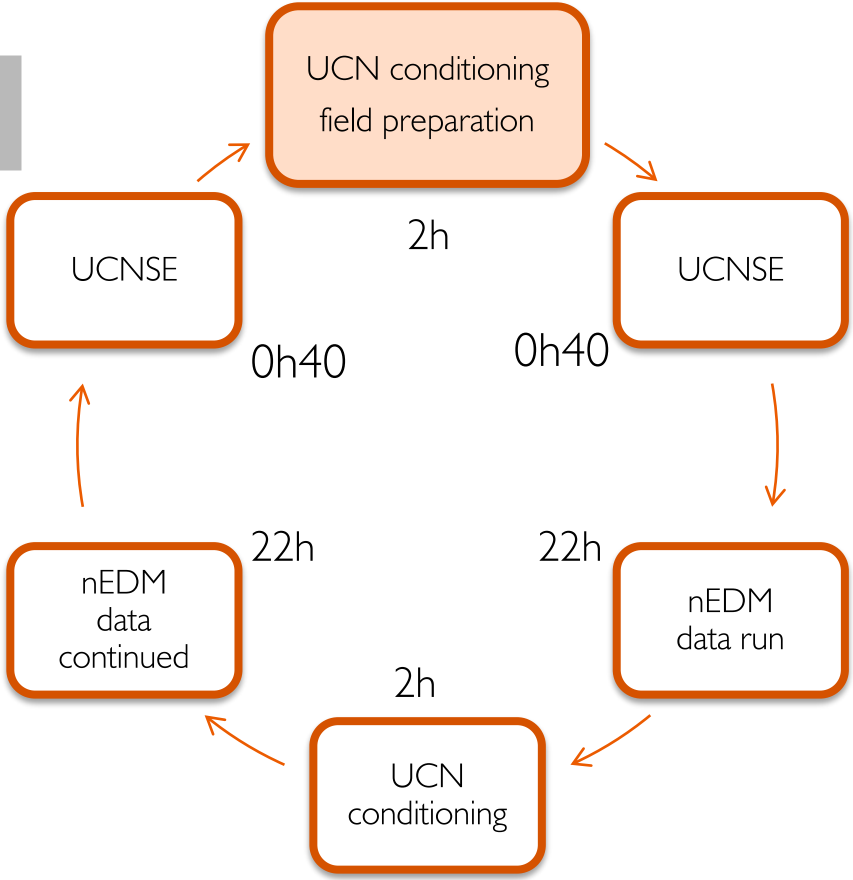
$$\sigma_{f_n} = \frac{1}{2\pi\alpha T\sqrt{N}} = 11.5\mu\text{Hz}$$

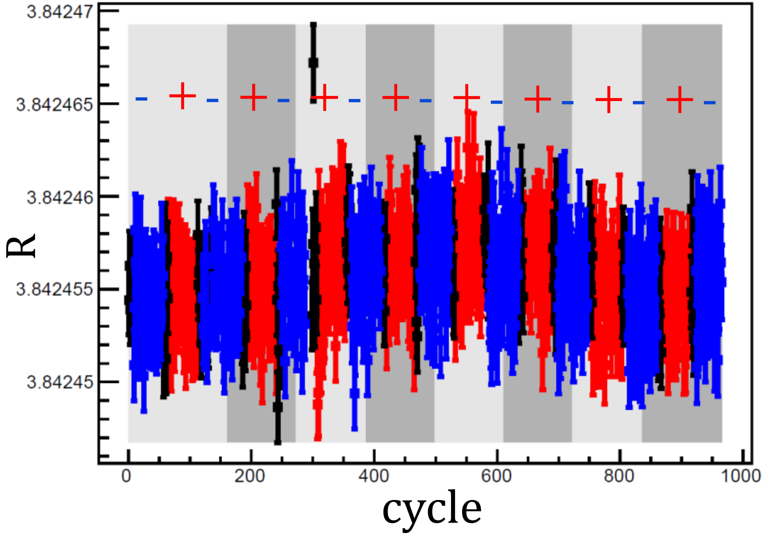
$$\sigma_{equ} = \sigma_{f_n}\frac{B_0}{\gamma_n\,|z|} \approx 1\text{pT/cm}$$

Defines time for electric field reversal



Data taking





$$d_{\mathrm{n}} = \frac{\hbar \langle \omega_{\mathrm{Hg}} \rangle}{4E} (R_{+} - R_{-})$$

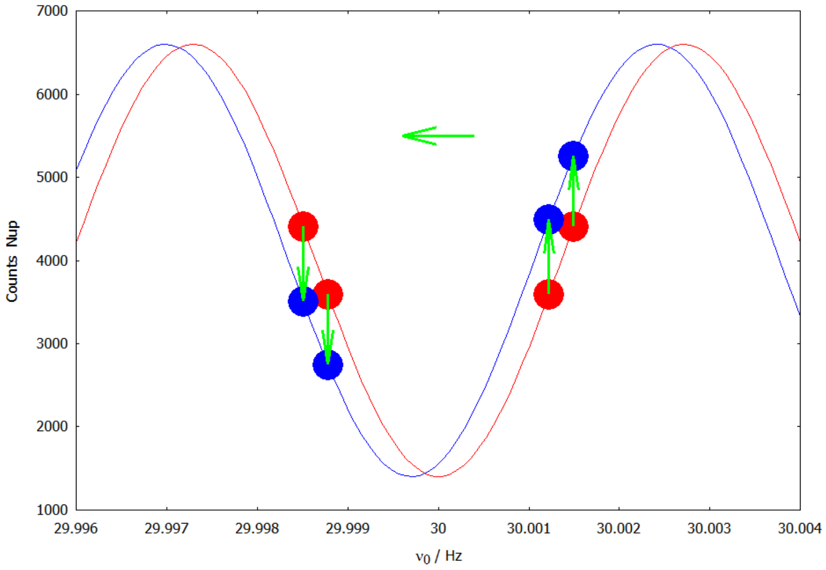
with $R = f_{\mathrm{n}} / f_{\mathrm{Hg}}$

- Shift the central value by adding an unknown offset EDM of **-1.5** to **1.5E-25** ecm to the data

$$\delta N_{\uparrow,\downarrow;i} = \mp \bar{N} \frac{\pi\alpha}{\Delta\nu} \frac{d \cdot E}{h} \sin\phi_i$$

with $$\phi_i = \frac{(\nu_i - \nu_0)}{\Delta\nu}\pi$$

- Keep un-blinded data in a safe place (encrypted)
- Two blinding levels
  - o Primary blinding same for both analysis groups
  - o Secondary blinding layer different for both groups



N.J. Ayres et al. **arXiv:**1912.09244