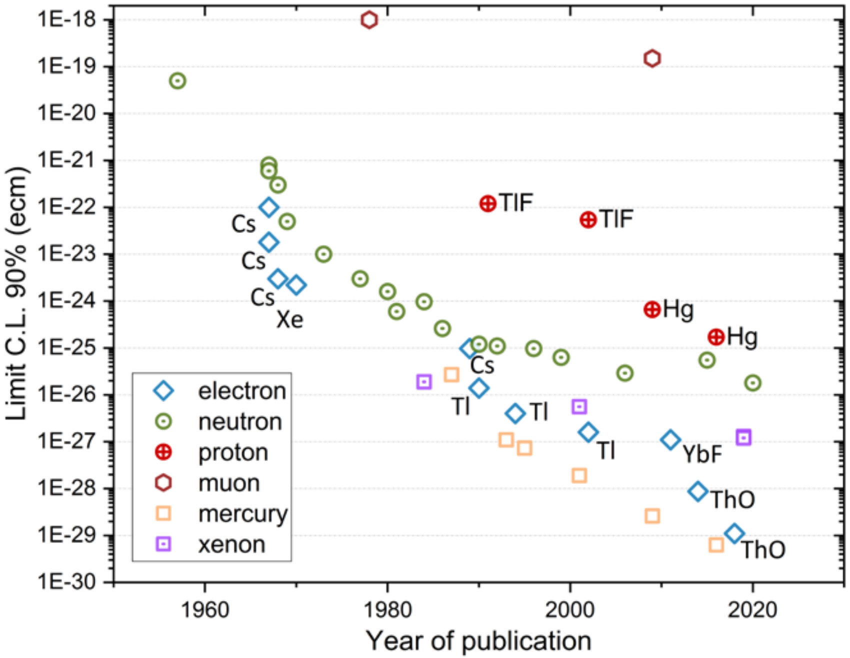
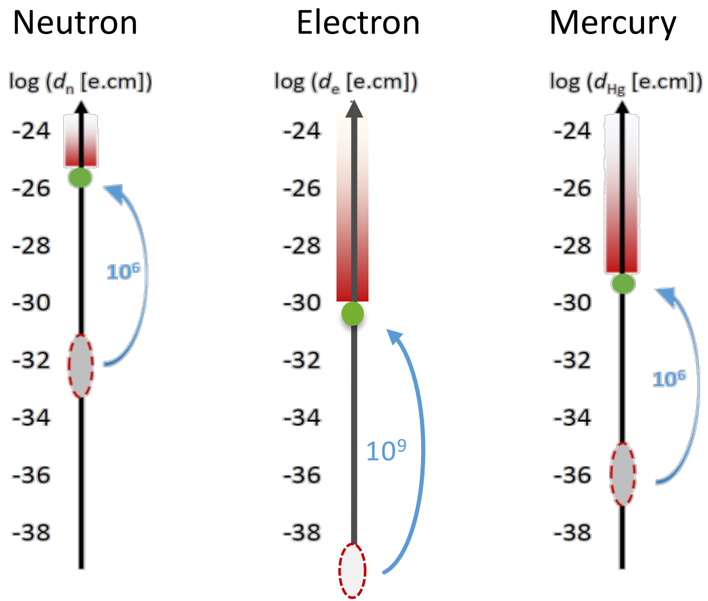
nEDM @ PSI

P. Schmidt-Wellenburg

Challenges and opportunities in future searches for the electric dipole moment of the neutron

A brief history of EDM searches





First neutron

Smith, Purcell, Ramsey

$d_n < 5 \times 10^{-20}$ e cm

PR 108 (1957) 120

~ 63 years

Best

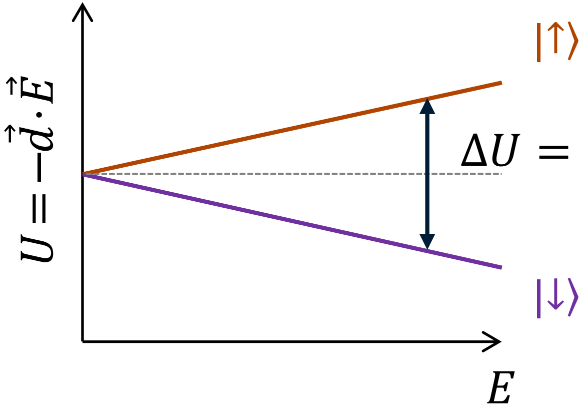
PSI

$d_n < 1.8 \times 10^{-26}$ e cm (90% C.L.)

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

EDM measurement basics

Measure the energy splitting



$$\Delta U = \hbar\omega_e = 2dE$$

Best to measure the associated frequency ω_e

$$f_e = \frac{2dE}{h} \approx 53\text{nHz}$$

Corresponds to about 1 turn in a year

Systematic effect: classical Larmor precession

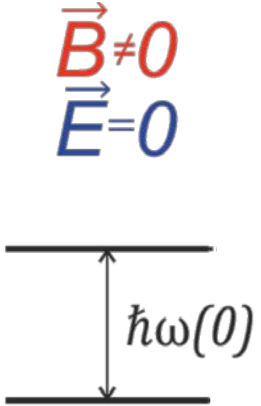
$$f_L = \frac{2\mu B}{h} \approx 0.3\text{mHz}$$

Corresponds to 1 turn in 1 h in the best MSR $B \sim \boldsymbol{O}(10\text{pT})$

Use a magnetic field as reference

$+\hbar/2$

$-\hbar/2$



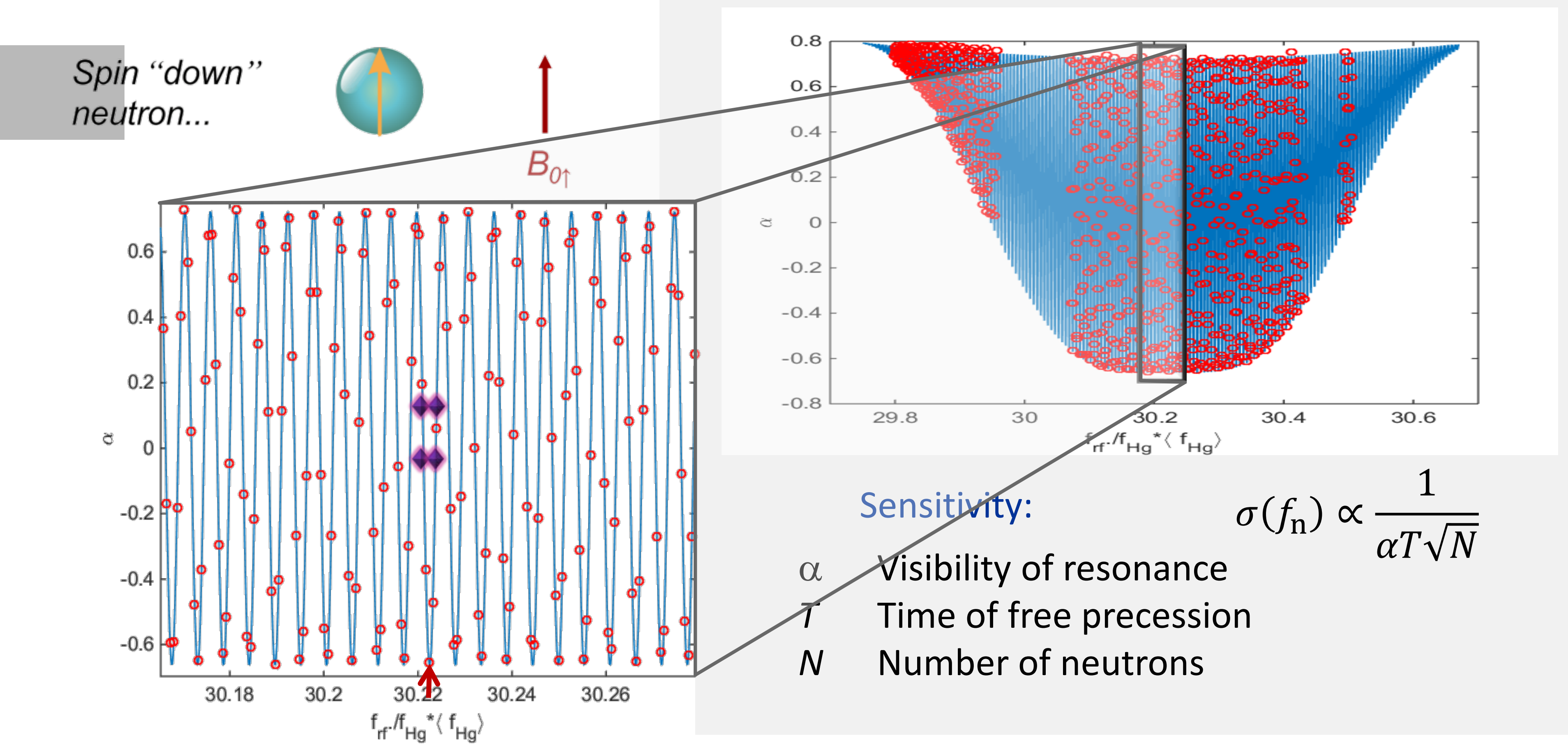
I $\quad f^{\uparrow} = \frac{2}{h}(\mu B + dE)$

II $\quad f^{\downarrow} = \frac{2}{h}(\mu B - dE)$

II-I $\quad \Delta f = \frac{2}{h}(\mu \Delta B - 2dE)$

$$d = \frac{h\Delta f}{4E}$$

Ramsey's technique to measure f



Sensitivity:

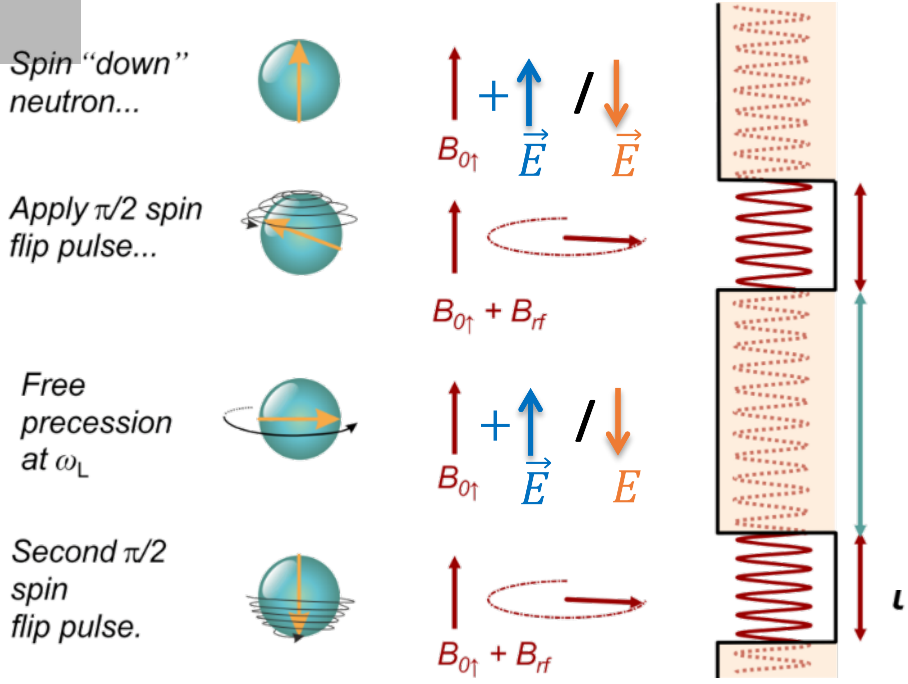
$$\sigma(f_n) \propto \frac{1}{\alpha T \sqrt{N}}$$

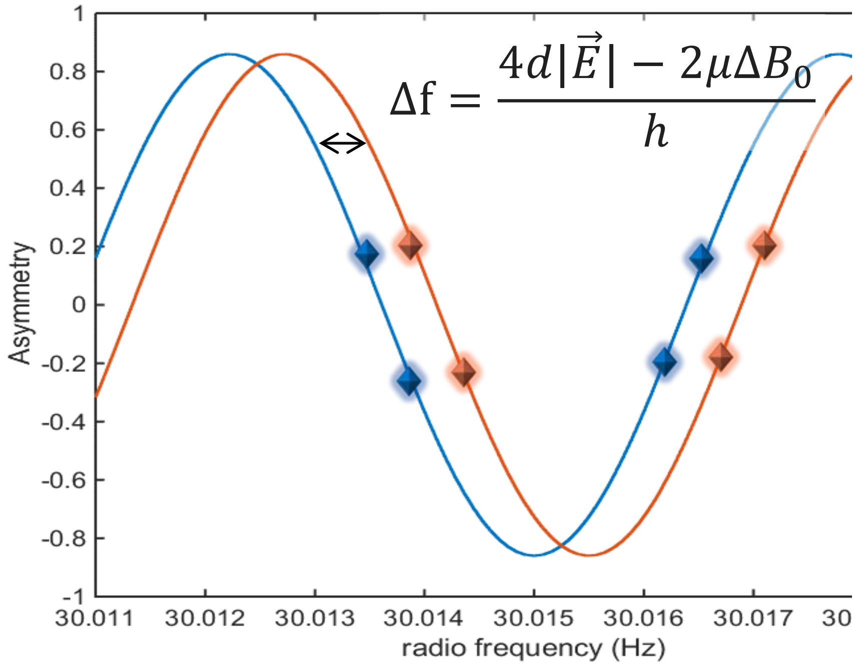
α Visibility of resonance

T Time of free precession

N Number of neutrons

Coupling of the spin to an electric field





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

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

Sensitivity for an EDM

$$\sigma(d) \propto \frac{1}{PE\sqrt{N}TA}$$

P: Initial polarization

E: Electric field strength

N: Number of particles

T: *Observation time*

A: *Analyzing power*

Statistical sensitivity, systematic error and limit

$$d_n = (\ 0.0\ \pm\ 1.1_{\mathrm{stat}}\ \pm\ 0.2_{\mathrm{syst}}) \times 10^{-26}\ e\mathrm{cm}$$

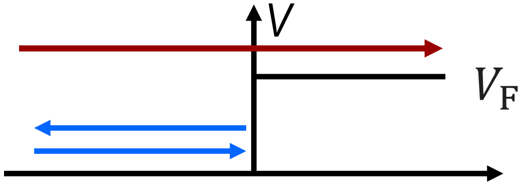
Limit: $d_\mathrm{n} < 1.8 \times 10^{-26} e\mathrm{cm}\ (\mathrm{C.L.}\ 90\%)$

For a limit better than $1 \times 10^{-26} e\mathrm{cm}$ we need to design an apparatus with a statistical sensitivity of better than $0.5 \times 10^{-26} e\mathrm{cm}$ as some unthought systematic could always appear.

C. Abel et al., PRL124(2020)081803

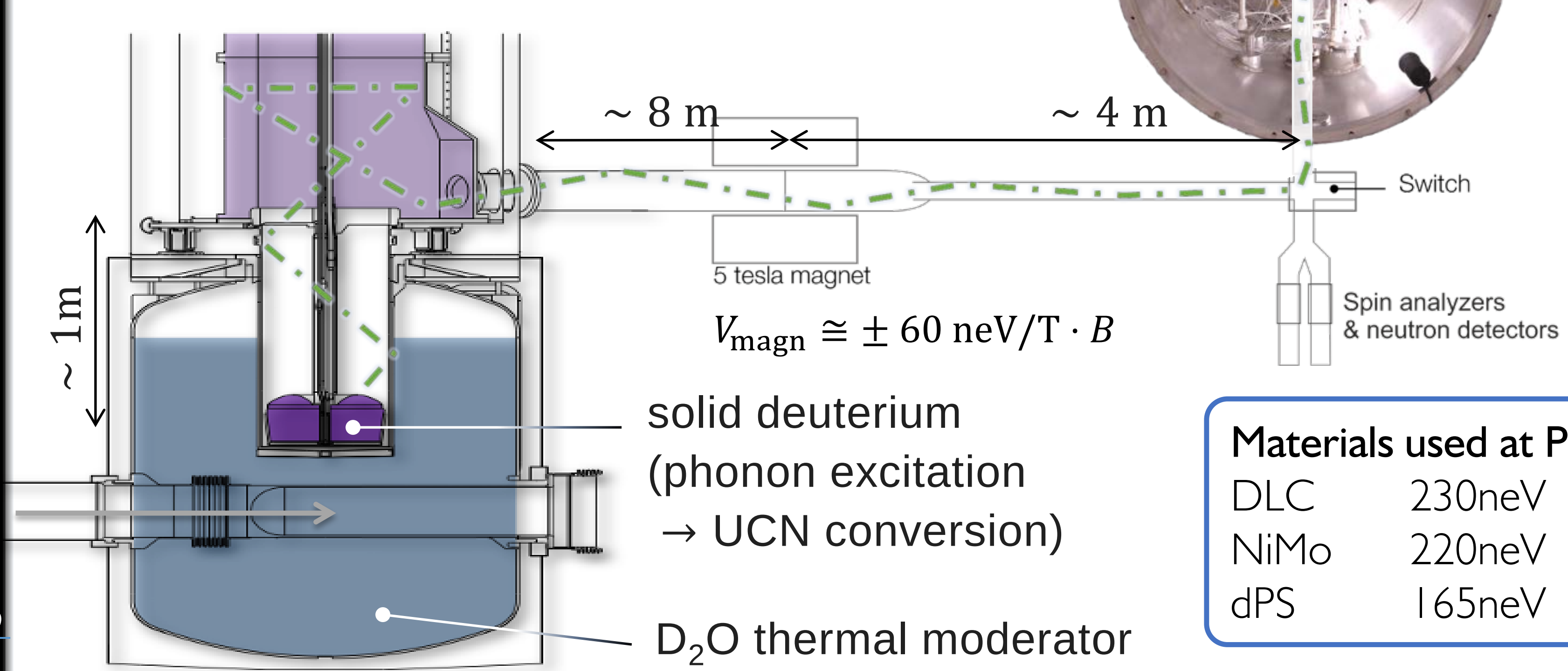
Ultracold neutrons: good for $T\sqrt{N}$

$$\sigma(d) \propto \frac{1}{PE\sqrt{N}TA}$$



$$V_{\mathrm{F}} = \frac{2\pi\hbar}{m_{\mathrm{n}}} bN \leq 350\mathrm{neV}$$

(8m/s, 3mK)



$V_{\mathrm{magn}} \cong \pm 60\ \mathrm{neV/T} \cdot B$

solid deuterium
(phonon excitation
→ UCN conversion)

D_2O thermal moderator

Materials used at PSI:

DLC	230neV
NiMo	220neV
dPS	165neV

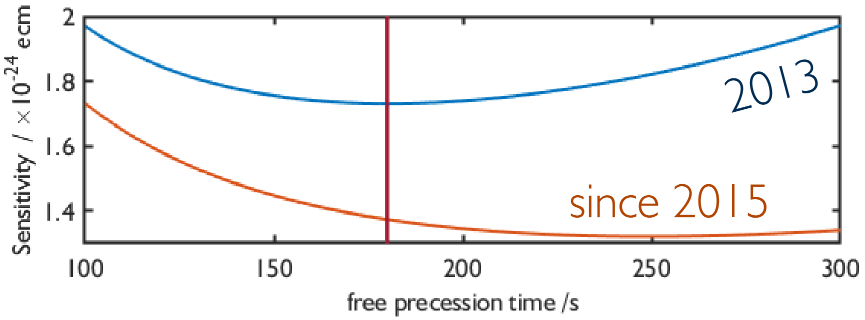
Increasing sensitivity

One cycle
300s

Many cycle
300s

$$\sigma_1(d_\mathrm{n}) = \frac{\hbar}{E T \alpha_0 \mathrm{e}^{-T/T_2} \sqrt{N_0\left(\mathrm{e}^{-T/\tau_s} + \mathrm{e}^{-T/\tau_f}\right)/2}}$$

$$\sigma_M(d_\mathrm{n}) = \frac{\sigma_1(d_\mathrm{n})}{\sqrt{M}}$$



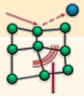
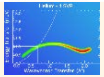
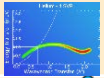
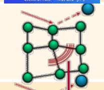
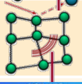
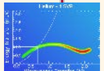
- $N_0 \;= 20000$ (polarized)
- $\tau_{f,s} = 80\mathrm{s},\; 180\mathrm{s}$
- $E \;= 11\ \mathrm{kV/cm}$
- $\alpha_0 \;= 0.86 \quad (T_2 \;=\; 1300\mathrm{s})$

What seems possible in a single shot?

Number of neutrons N:

Higher density and/or larger volume → more neutrons

New UCN sources:
- superthermal sources based on D_2 or sfHe
- Transport losses/dilution
- Ramsey cell = source (see SNS talk)

Location	Type	Density	Year of operation
Mainz		3	2007
Grenoble			
PF2		20	1986
SUN2		8	2012
SuperSun		7/130	2021/202?
LANL		80	yes
PSI		22	yes
TRIUMF			

What seems possible in a single shot?

Number of neutrons N:

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New UCN sources:
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- Transport losses/dilution
- Ramsey cell = source (see SNS talk)

Needs matching of source volume to experiment volume, other wise too strong dilution.
Neutron spin coherence function of cell radius → good control of gradients:

$$\frac{1}{T_{2,\mathrm{mag}}} = \frac{8R^3\gamma_n^2}{9\pi v}\left(G_{1,-1}^2 + G_{1,1}^2\right) + \frac{\mathcal{H}^3\gamma_n^2}{16v}G_{1,0}^2$$

C. Abel et al., PRA99(2019)042112

PAUL SCHERRER INSTITUT

What seems possible in a single shot?

100 times larger (SuperSun,TRIUMF, SNS)

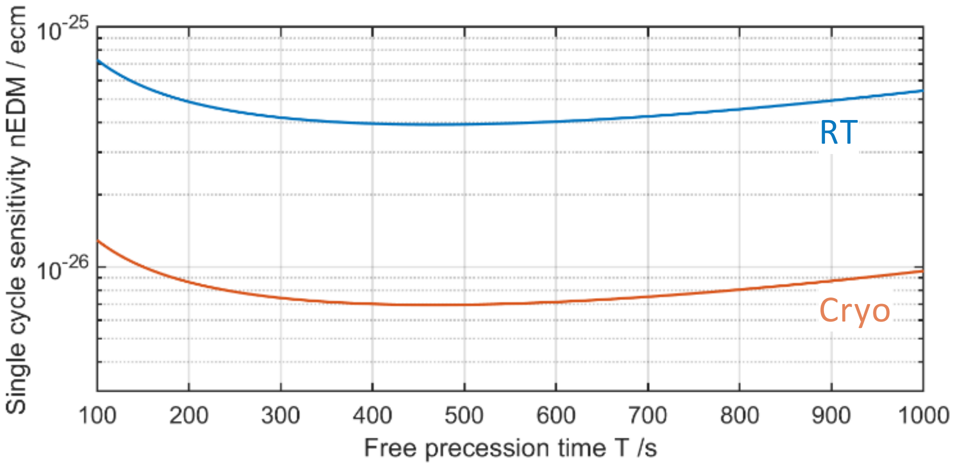
Number of neutrons N: 10^7

Electric field RT: 20 kV/cm **Cryogenic:** 80kV/cm

8 times larger (SNS, former CryoEDM)

Coherence time T_2: 3000 s

Storage times t_s,t_f: (100, 300) **s**



After 4 years with 200 days each:

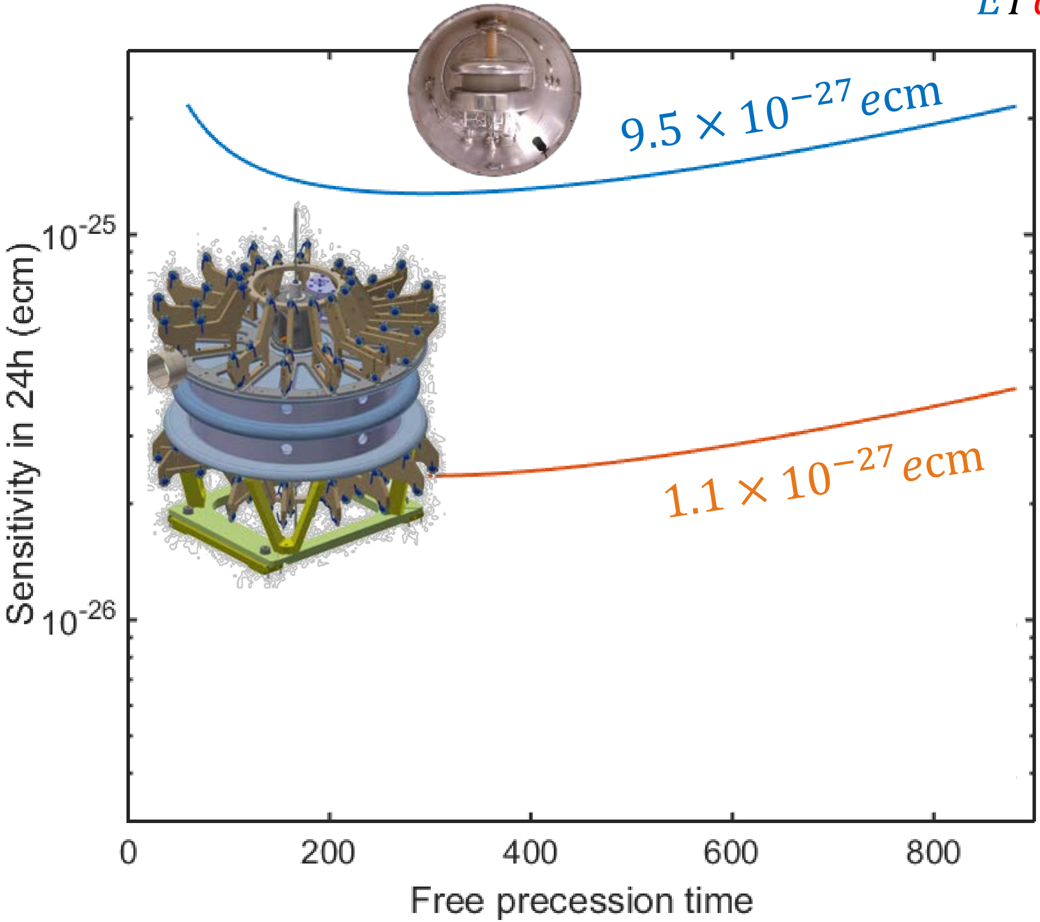
$$\sigma_{\mathrm{RT}} \approx 1 \times 10^{-28} e\mathrm{cm}$$

$$\sigma_{\mathrm{Cryo}} \approx 0.2 \times 10^{-28} e\mathrm{cm}$$

C. Abel et al., PRA99(2019)042112

Sensitivity:

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



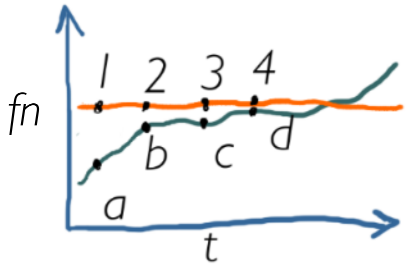
Performance in 2015/2016

Prospect TDR (start 2021)
$E = 15\ \mathrm{kV/cm},\ N = 8 \times N_{2016}$

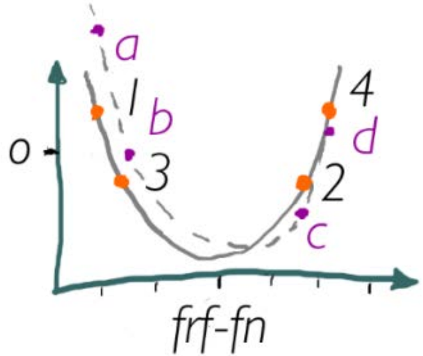
Sensitivity versus field drifts

- Sensitivity for many cycles ideal case:

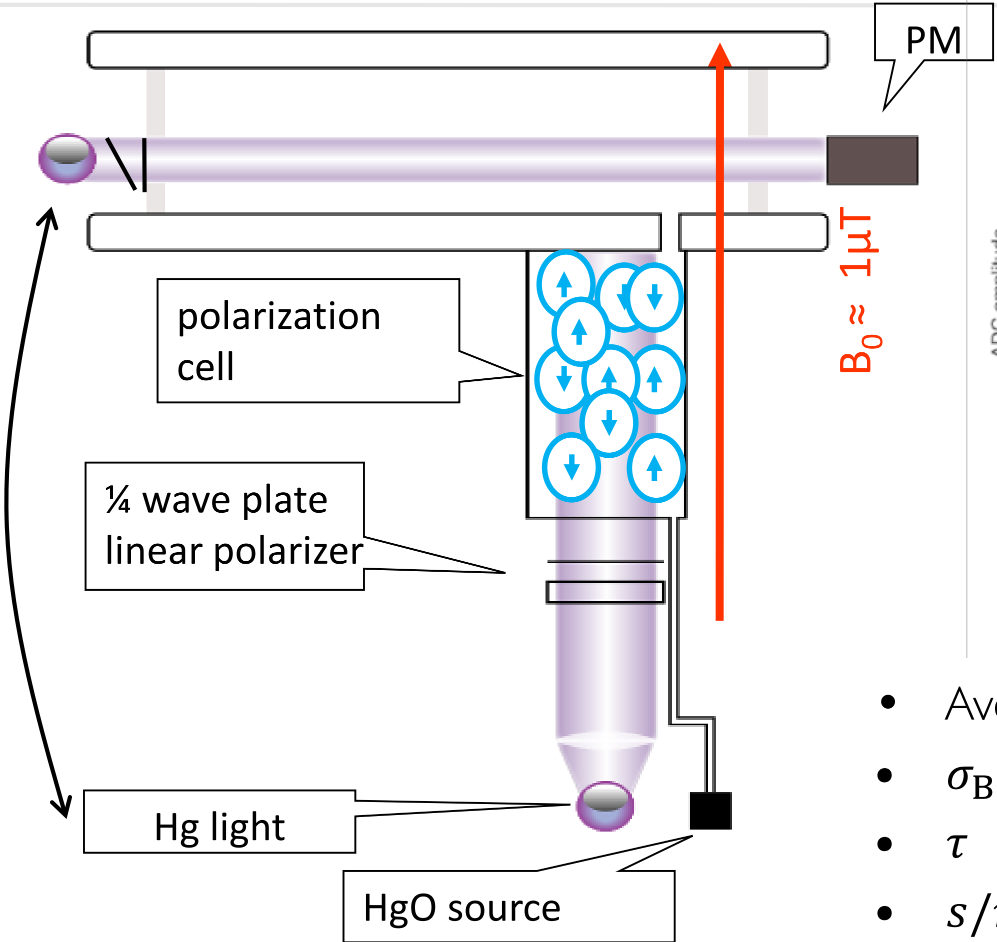
$$\sigma(d_{\mathrm{n}}) = \frac{\hbar}{2\alpha TE\sqrt{NM}}$$

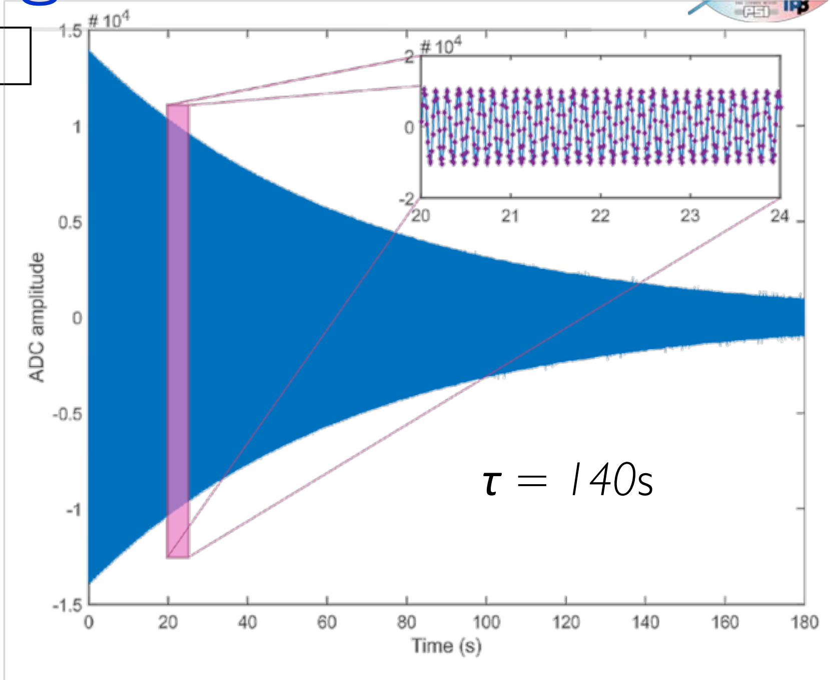


- Only if magnetic field is stable enough.
  (Good fit with orange,
  bad fit with purple)



Mercury comagnetometer

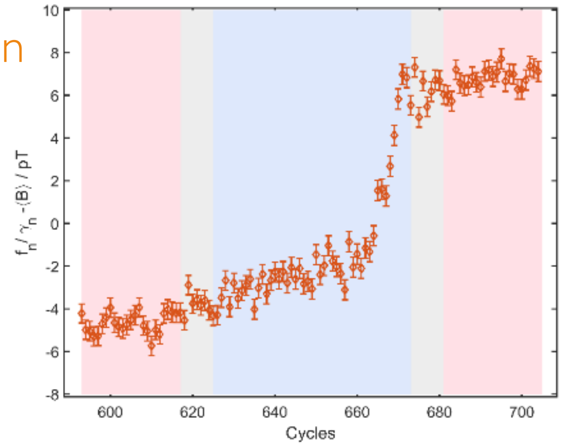




- Average magnetic field (volume and cycle)
- $\sigma_B \leq 100$ fT (CR-limit)
- $\tau > 100$ s wo HV (with ~ 90 s)
- $s/n > 1000$

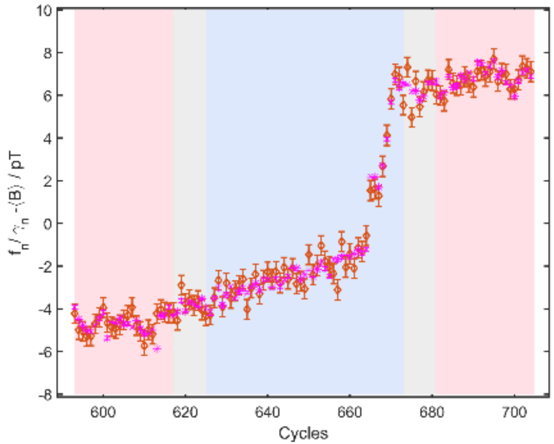
Real data example (stability)

Neutron



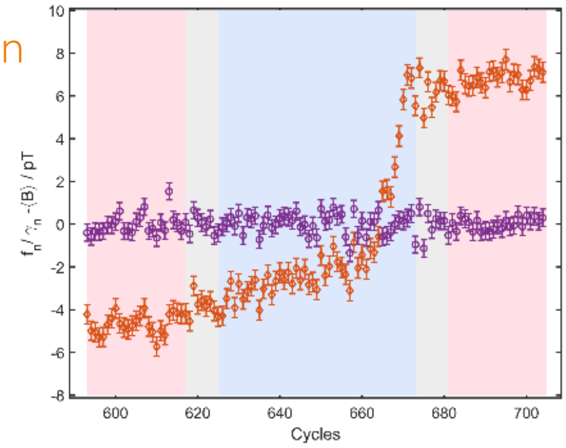
Neutron

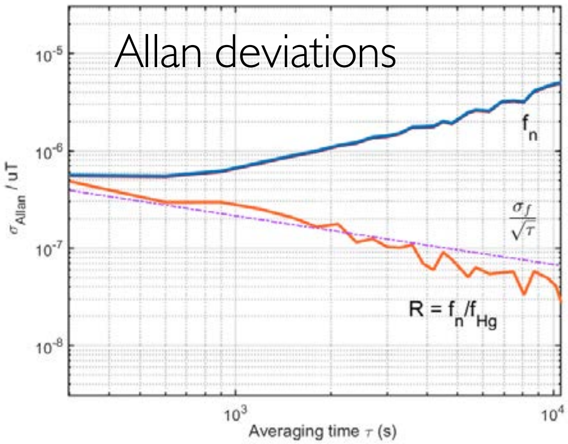
Mercury



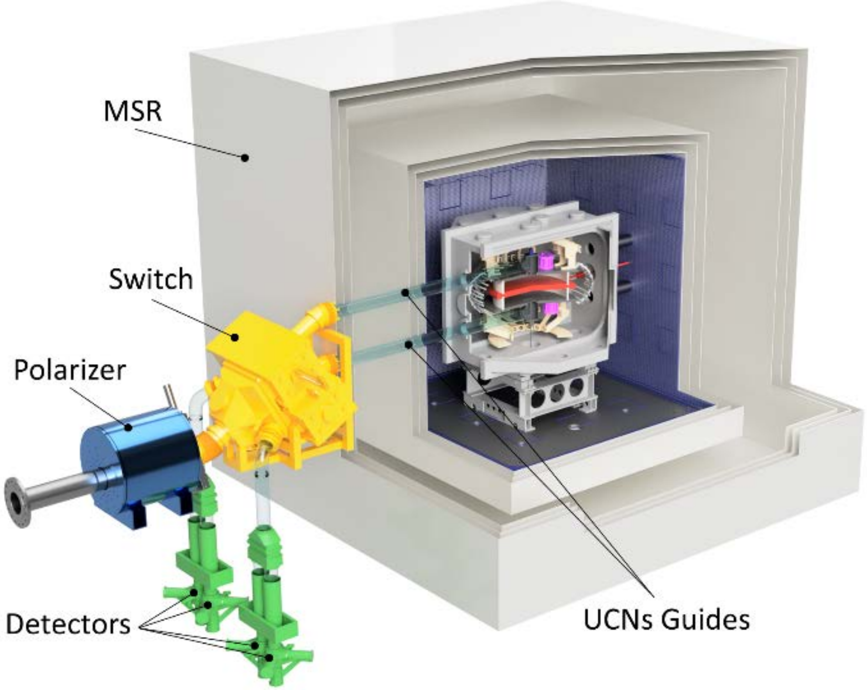
Neutron

R-ratio





The n2EDM at PSI



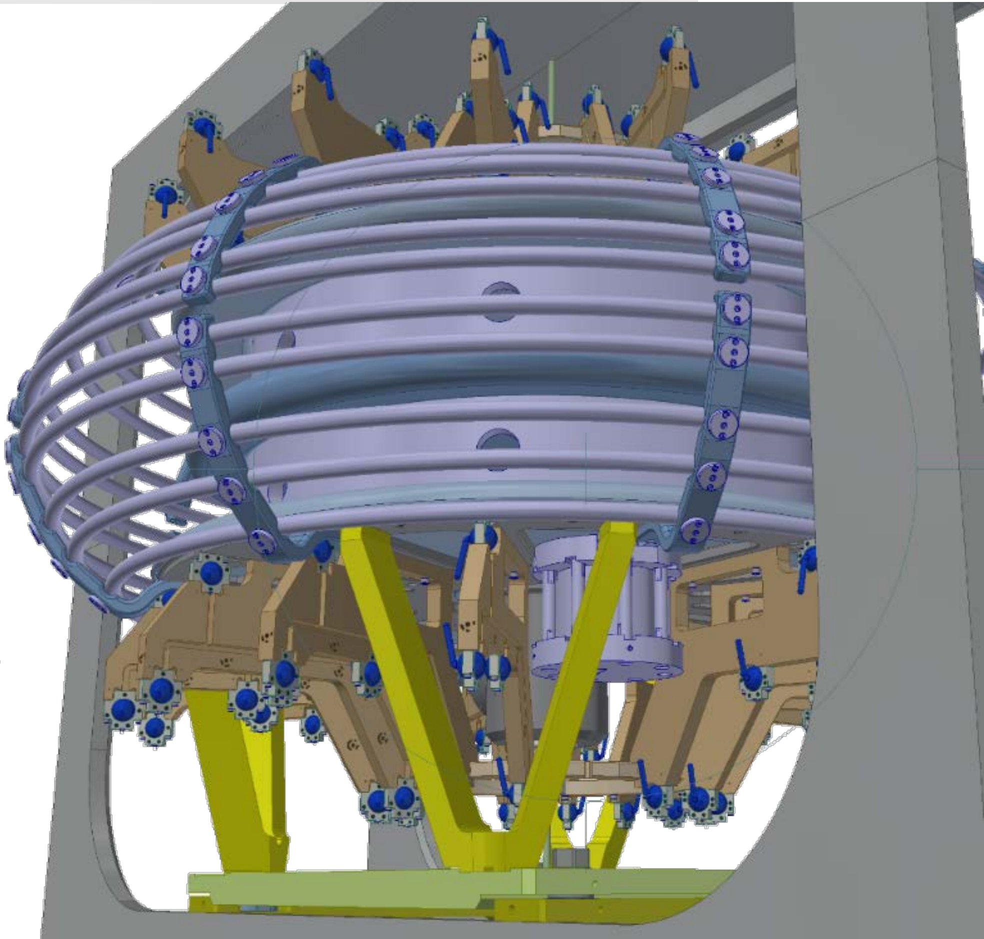
Large active magnetic shield

Stabilization of magnetic environment to $\pm$ 1µT around MSR in 10µHz range

- Bz, By, Bx
- 5 linear gradients
- About 520 Wire Paths
- Total of 54km Wires
- 2.6t of wire
- 840m Cable Trays
- Several kW Heat

Double chamber with Cs-OPM

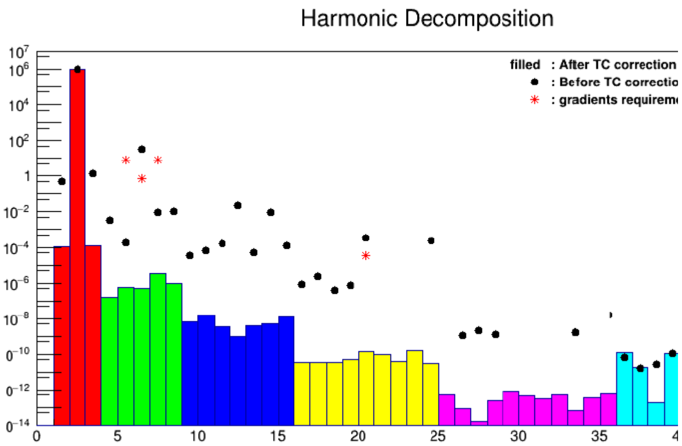
- Two large chamber
  N=120000
- Hg co-gradiometer
  Cancels many systematics
  but leads to **motional false EDM**
- Order 100 Cs-OPM
  Field optimization & extraction
  higher order gradients to correct
  for **motional false EDM**



Excellent B-field uniformity

Magnetic-field generation

- Optimized main magnetic field coil
- 64 correction coils



Harmonic polynomials

MAGNETIC-FIELD UNIFORMITY IN NEUTRON … PHYSICAL REVIEW A **99**, 042112 (2019)

TABLE IV. The basis of harmonic polynomials sorted by degree in cylindrical coordinates.

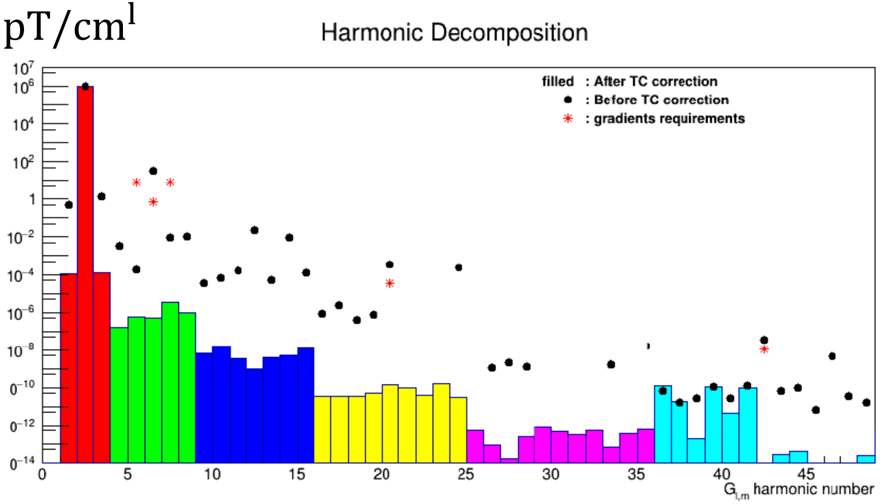
l	m	Π_ρ	Π_ϕ	Π_z
0	−1	$\sin\phi$	$\cos\phi$	0
0	0	0	0	1
0	1	$\cos\phi$	$-\sin\phi$	0
1	−2	$\rho\sin 2\phi$	$\rho\cos 2\phi$	0
1	−1	$z\sin\phi$	$z\cos\phi$	$\rho\sin\phi$
1	0	$-\frac{1}{2}\rho$	0	z
1	1	$z\cos\phi$	$-z\sin\phi$	$\rho\cos\phi$
1	2	$\rho\cos 2\phi$	$-\rho\sin 2\phi$	0
2	−3	$\rho^2\sin 3\phi$	$\rho^2\cos 3\phi$	0
2	−2	$2\rho z\sin 2\phi$	$2\rho z\cos 2\phi$	$\rho^2\sin 2\phi$
2	−1	$\frac{1}{4}(4z^2-3\rho^2)\sin\phi$	$\frac{1}{4}(4z^2-\rho^2)\cos\phi$	$2\rho z\sin\phi$
2	0	$-\rho z$	0	$-\frac{1}{2}\rho^2+z^2$
2	1	$\frac{1}{4}(4z^2-3\rho^2)\cos\phi$	$\frac{1}{4}(\rho^2-4z^2)\sin\phi$	$2\rho z\cos\phi$
2	2	$2\rho z\cos 2\phi$	$-2\rho z\sin 2\phi$	$\rho^2\cos 2\phi$
2	3	$\rho^2\cos 3\phi$	$-\rho^2\sin 3\phi$	0
3	−4	$\rho^3\sin 4\phi$	$\rho^3\cos 4\phi$	0
3	−3	$3\rho^2 z\sin 3\phi$	$3\rho^2 z\cos 3\phi$	$\rho^3\sin 3\phi$
3	−2	$\rho(3z^2-\rho^2)\sin 2\phi$	$\frac{1}{2}\rho(6z^2-\rho^2)\cos 2\phi$	$3\rho^2 z\sin 2\phi$
3	−1	$\frac{1}{4}z(4z^2-9\rho^2)\sin\phi$	$\frac{1}{4}z(4z^2-3\rho^2)\cos\phi$	$\rho(3z^2-\frac{3}{4}\rho^2)\sin\phi$
3	0	$\frac{3}{8}\rho(\rho^2-4z^2)$	0	$\frac{1}{2}z(2z^2-3\rho^2)$
3	1	$\frac{1}{4}z(4z^2-9\rho^2)\cos\phi$	$\frac{1}{4}z(3\rho^2-4z^2)\sin\phi$	$\rho(3z^2-\frac{3}{4}\rho^2)\cos\phi$
3	2	$\rho(3z^2-\rho^2)\cos 2\phi$	$\frac{1}{2}\rho(\rho^2-6z^2)\sin 2\phi$	$3\rho^2 z\cos 2\phi$
3	3	$3\rho^2 z\cos 3\phi$	$-3\rho^2 z\sin 3\phi$	$\rho^3\cos 3\phi$
3	4	$\rho^3\cos 4\phi$	$-\rho^3\sin 4\phi$	0

C. Abel et al., PRA 99(2019)042112

Excellent B-field uniformity

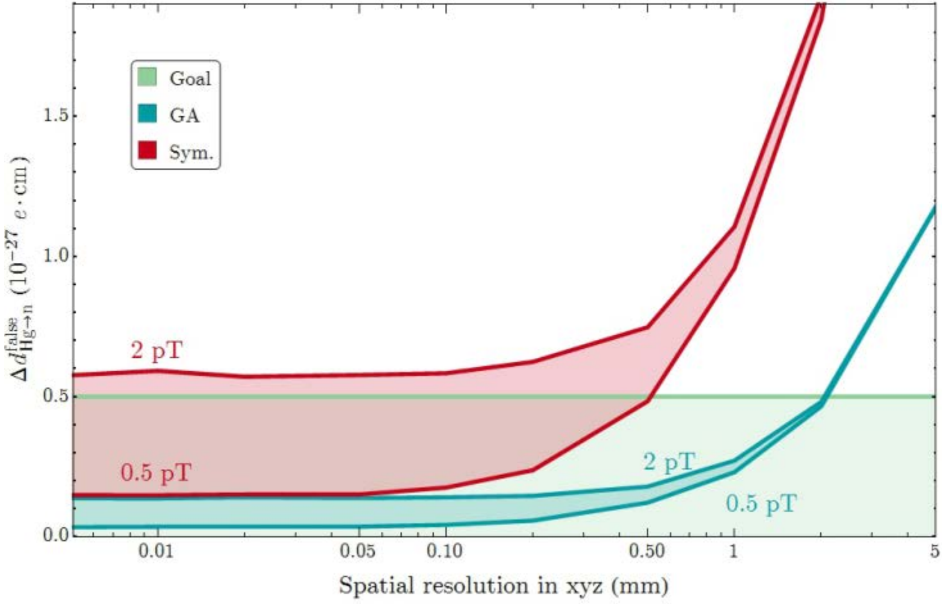
Magnetic-field generation

- Optimized main magnetic field coil
- 64 correction coils



Magnetic-field measurement

- Order 100 CsM sensors
- Optimal placement



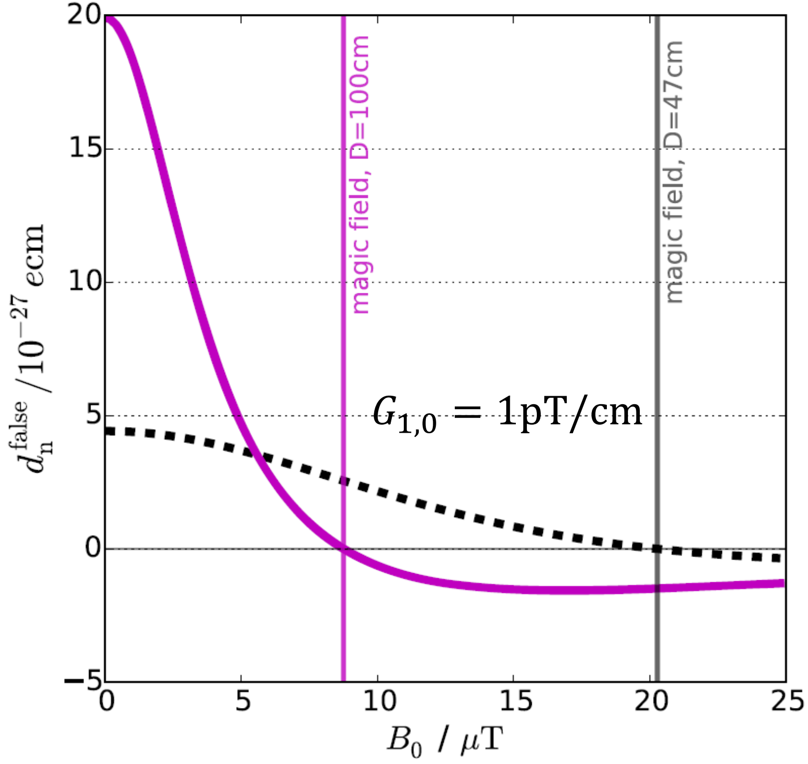
Going magic

Larger cell → more neutrons

False EDM from Hg:

$$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}} = \frac{\hbar\gamma_{\text{n}}\gamma_{\text{Hg}}}{2c^2}\langle xB_x + yB_y\rangle = \frac{\hbar\gamma_{\text{n}}\gamma_{\text{Hg}}}{32c^2}D^2G_{\text{eff}}$$

Go to magnetic field ($\omega = \gamma B$) where false EDM is zero:

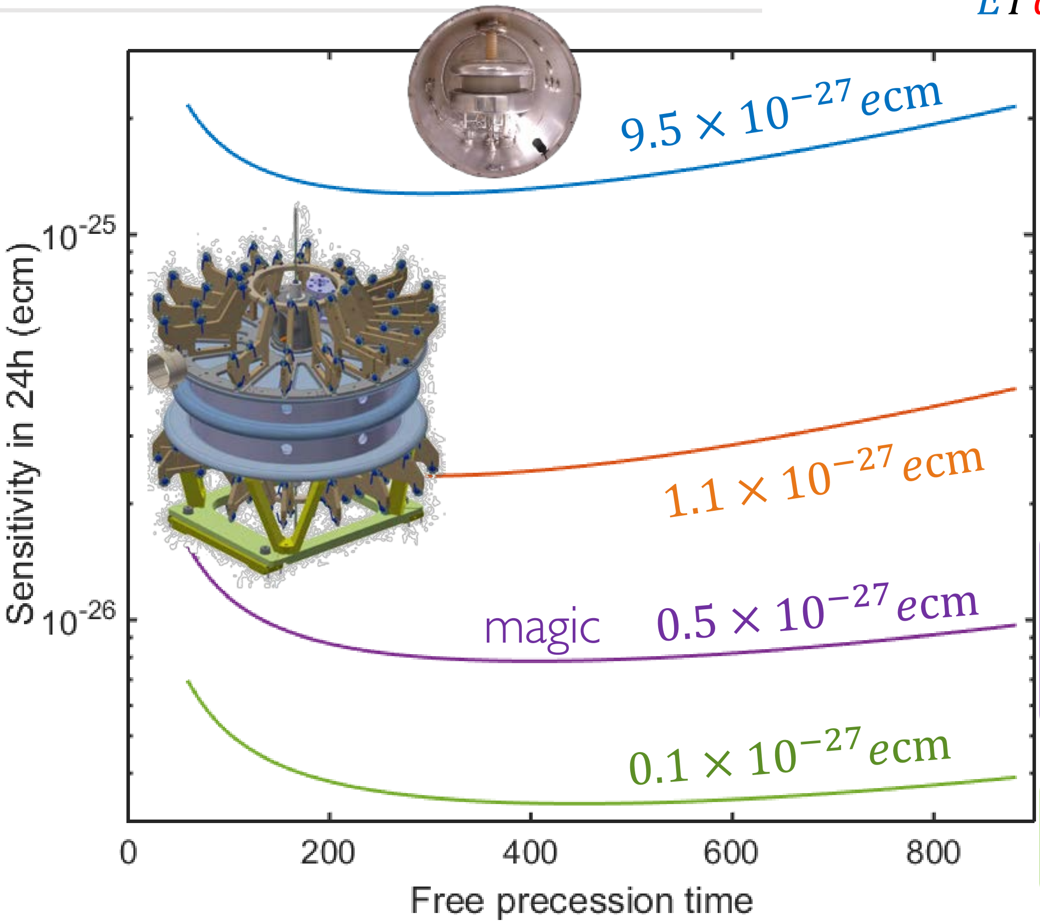


G. Pignol PLB793 (2019) 440

$$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}} = \frac{\hbar\gamma_{\text{n}}\gamma_{\text{Hg}}}{2c^2}\int_0^\infty \langle B_x(0)v_x(t) + B_y(0)v_y(t)\rangle \cos\omega t \text{d}t$$

Outlook:

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



Performance in 2015/2016

Prospect TDR (start 2021)
$E = 15\,\mathrm{kV/cm},\ N = 8 \times N_{2016}$

Possible final performance at PSI
$E = 18\,\mathrm{kV/cm}$, improved UCN source, optimal magnetic field tuning

New source? At ESS? Cyryogenic?
$E = 20\mathrm{kV/cm},\ N = 128 \times N_{2016}$

The collaboration

- 16 Institutions
- 8 Countries
- 84 authors
- 34 PhD degrees

Measurement of the Permanent Electric Dipole Moment of the Neutron

C. Abel,[1] S. Afach,[2,3] N. J. Ayres,[1,3] C. A. Baker,[4] G. Ban,[5] G. Bison,[2] K. Bodek,[6] V. Bondar,[2,3,7] M. Burghoff,[8] E. Chanel,[9] Z. Chowdhuri,[2] P.-J. Chiu,[2,3] B. Clement,[10] C. B. Crawford,[11] M. Daum,[2] S. Emmenegger,[3] L. Ferraris-Bouchez,[10] M. Fertl,[2,3,12] P. Flaux,[5] B. Franke,[2,3,d] A. Fratangelo,[9] P. Geltenbort,[13] K. Green,[4] W. C. Griffith,[1] M. van der Grinten,[4] Z. D. Grujić,[14,15] P. G. Harris,[1] L. Hayen,[7,e] W. Heil,[12] R. Henneck,[2] V. Hélaine,[2,5] N. Hild,[2,3] Z. Hodge,[9] M. Horras,[2,3] P. Iaydjiev,[4,n] S. N. Ivanov,[4,o] M. Kasprzak,[2,7,14] Y. Kermaidic,[10,f] K. Kirch,[2,3] A. Knecht,[2,3] P. Knowles,[14] H.-C. Koch,[2,14,12] P. A. Koss,[7,g] S. Komposch,[2,3] A. Kozela,[16] A. Kraft,[2,12] J. Krempel,[3] M. Kuźniak,[2,6,h] B. Lauss,[2] T. Lefort,[5] Y. Lemière,[5] A. Leredde,[10] P. Mohanmurthy,[2,3] A. Mtchedlishvili,[2] M. Musgrave,[1,i] O. Naviliat-Cuncic,[5] D. Pais,[2,3] F. M. Piegsa,[9] E. Pierre,[2,5,j] G. Pignol,[10,a] C. Plonka-Spehr,[17] P. N. Prashanth,[7] G. Quéméner,[5] M. Rawlik,[3,k] D. Rebreyend,[10] I. Rienäcker,[2,3] D. Ries,[2,3,17] S. Roccia,[13,18,b] G. Rogel,[5,l] D. Rozpedzik,[6] A. Schnabel,[8] P. Schmidt-Wellenburg,[2,c] N. Severijns,[7] D. Shiers,[1] R. Tavakoli Dinani,[7] J. A. Thorne,[1,9] R. Virot,[10] J. Voigt,[8] A. Weis,[14] E. Wursten,[7,m] G. Wyszynski,[3,6] J. Zejma,[6] J. Zenner,[2,17] and G. Zsigmond[2]

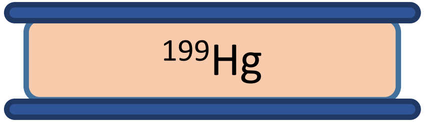
Backup

Use R-value as proxy for $G_{1,0}$

- Center of mass offset
- Non-adiabaticity

$$R_\pm = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \left|\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\right| \left(1 \pm \delta_\mathrm{EDM} \pm \delta_\mathrm{EDM}^\mathrm{false} + \delta_\mathrm{Q} + \delta_\mathrm{G} + \delta_\mathrm{T} + \delta_\mathrm{E} + \delta_\mathrm{LS} + \delta_\mathrm{I} + \delta_\mathrm{P} + \delta_{AC}\right)$$

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



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

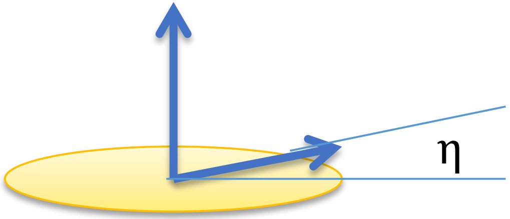
$\overline{v_\mathrm{Hg}} \approx$ 160 m/s vs. $\overline{v_\mathrm{UCN}} \approx$ 3 m/s

$$R \cdot \left|\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\right| - 1 = \delta_\mathrm{G} + \delta_\mathrm{T} = \pm\frac{\langle z\rangle G_{1,0}}{B_0} + \frac{\langle B_\mathrm{T}^2\rangle}{2B_0^2}$$

Needs to be known for each measurement

Pseudo magnetic field from incoherent scattering length

$$B^* = -\frac{4\pi\hbar}{m_n\gamma_n} \, n b_i P \sqrt{\frac{I}{I+1}}$$

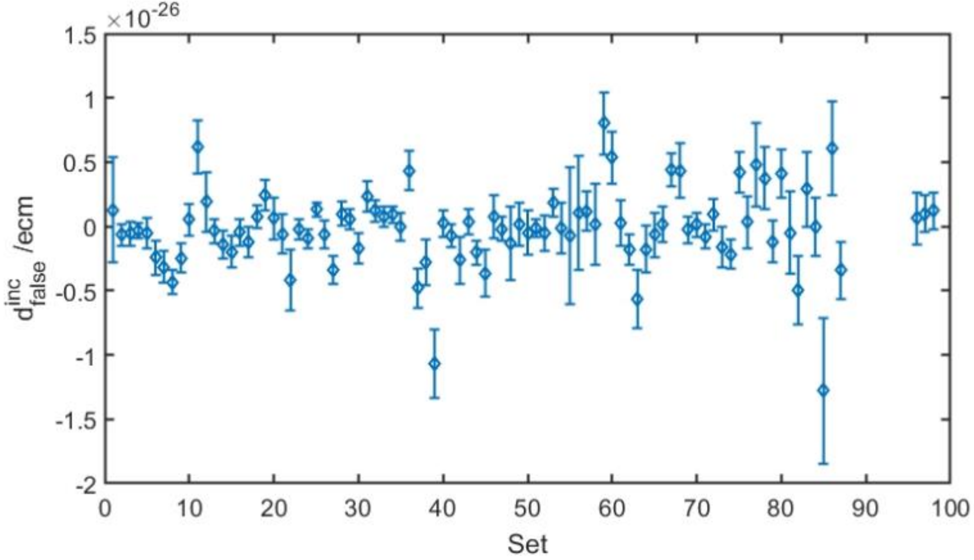


$$\delta\eta = \eta(+E) - \eta(-E)$$

- $b_i = \pm 15.5 \text{ fm}$
- nP (^{199}Hg × polarization) extracted from data cycle by cycle

$$d_n^{\text{false}} = \hbar \frac{\gamma_n}{4E} B^* \cdot \delta\eta$$

$$< 7 \times 10^{-28} ecm$$



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Correcting systematic by G_g and $\hat{G}$

The crossing point analysis takes care of a large part of the motional false EDM:

$$d_{n\leftarrow Hg}^{false} = \frac{\hbar\gamma_n\gamma_{Hg}}{32c^2}D^2\left[G_g + G_{30}\left(\frac{D^2}{16}+\frac{H^2}{10}\right) + G_{50}\left(\frac{H^4}{28}-\frac{D^2H^2}{96}-\frac{5D^4}{256}\right)\right]$$

Corrected by crossing point fit

$$\hat{G} := \hat{G}_{30} + \hat{G}_{50}$$

Corrected set for set using map analysis

Ingredients needed for baryon genesis

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

Anomalous B-violating processes

SM Sphalerons:

$$\Gamma(A + B \rightarrow C) \neq \Gamma(\bar{A} + \bar{B} \rightarrow \bar{C})$$

EDMs

SM CKM CPV:

Prevent washout by inverse processes

LHC: scalars

SM EWPT:

(Requires Higgs mass <80meV)

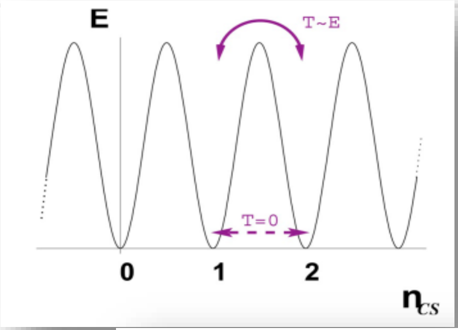
Ingredients for EW baryogenesis

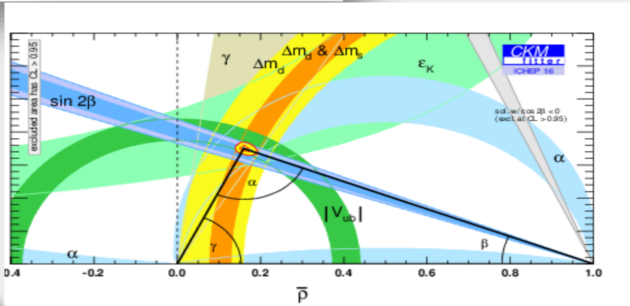
1. *Baryon number violation*
2. *C and CP violation*
3. *Thermal non-equilibrium*

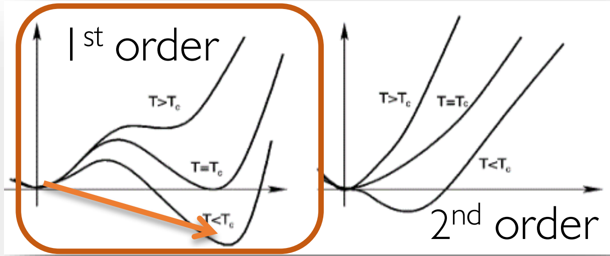
possible

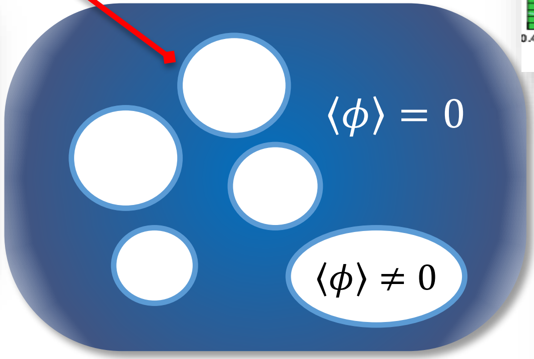
too weak

Higgs too heavy





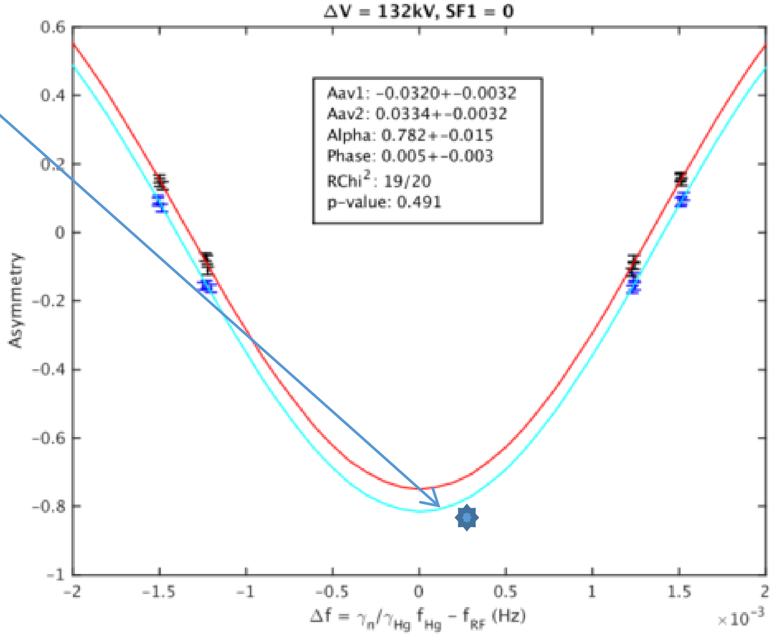




Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

Frequency for each cycle

- Single point fits to avoid loss of cycles (same equation, but all parameters know but ϕ_1)
- In the end the relative change of frequency is relevant for the nEDM analysis the global parameter are all covariant.



Data point below cosine: $A_i < (A_{\mathrm{SF2}} - \alpha)$

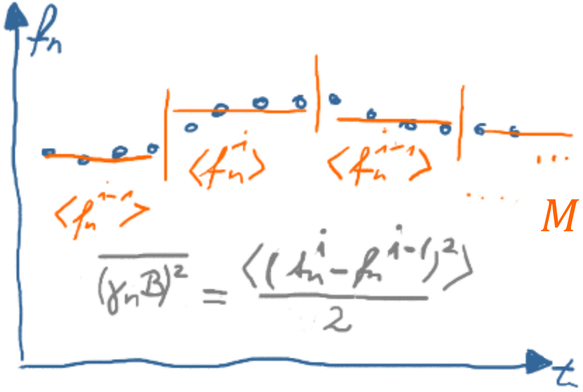
Sensitivity versus Stability

- Sensitivity for many cycles ideal case:

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

- Requires:

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



$M = 4$

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:

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

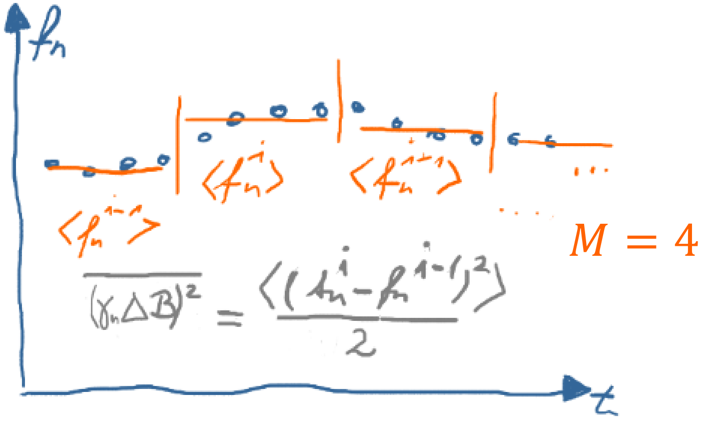
Sensitivity versus Stability

- Many cycles sensitivity ideally:

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

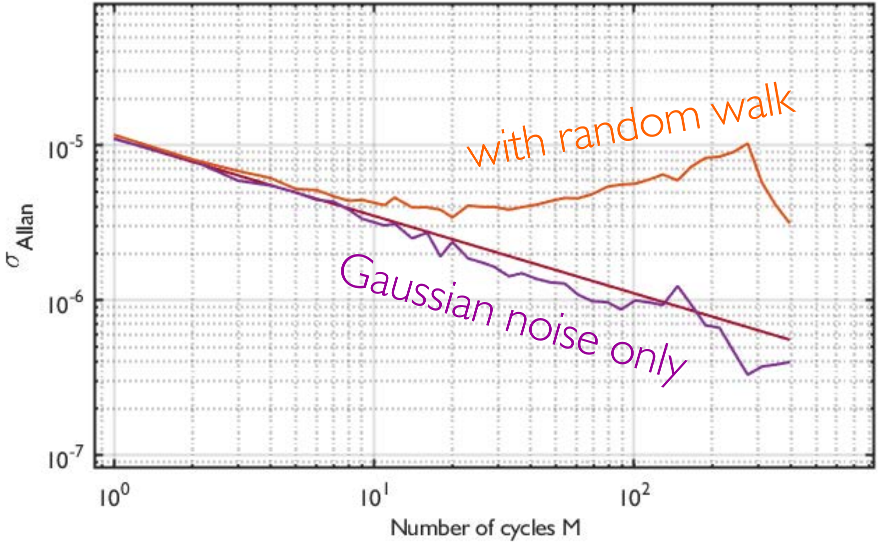
- Require:

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



Allan deviation:

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



The full covariant matrix C

$$A_i = A_{\mathrm{av}} - \alpha\cos\left(\frac{\omega_{\mathrm{rf}} - \omega_{\mathrm{cor}}}{\Delta\nu} + \phi\right) \rightarrow \; f = \frac{\Delta\nu}{\pi}\left[\mathrm{acos}\left(\frac{(A_{\mathrm{av}} - A_i)}{\alpha}\right) + \phi\right]$$

$$C = C_\alpha + C_{A_i} + C_{A_{av}} + C_\phi$$

$$C_{A_{\mathrm{av}},ij} = \frac{\mathrm{d}f}{\mathrm{d}A_{\mathrm{av},i}} \cdot \frac{\mathrm{d}f}{\mathrm{d}A_{\mathrm{av},j}} \cdot \delta A_{\mathrm{av},i}\,\delta A_{\mathrm{av},j}$$

$$= \frac{\Delta\nu^2 \delta A_{\mathrm{av},i}\,\delta A_{\mathrm{av},j}}{\pi^2}\left(\alpha^2 - \left(A_{\mathrm{av},i} - A_i\right)^2\right)^{-1/2}\left(\alpha^2 - \left(A_{\mathrm{av},j} - A_j\right)^2\right)^{-1/2}$$

Remember there are four different A_{av}

The full covariant matrix C

$$A_i = A_{\rm av} - \alpha\cos\left(\frac{\omega_{\rm rf}-\omega_{\rm cor}}{\Delta\nu} + \phi\right) \rightarrow f = \frac{\Delta\nu}{\pi}\left[\operatorname{acos}\left(\frac{(A_{\rm av}-A_i)}{\alpha}\right) + \phi\right]$$

$$C = C_\alpha + C_{A_i} + C_{A_{av}} + C_\phi$$

$$C_{\alpha,ij} = \frac{\mathrm{d}f}{\mathrm{d}\alpha_i}\cdot\frac{\mathrm{d}f}{\mathrm{d}\alpha_j}\cdot\delta\alpha^2 = \frac{\Delta\nu^2\delta\alpha^2}{\alpha^2\pi^2}\frac{(A_{\mathrm{av},i}-A_i)}{\sqrt{\alpha^2-(A_{\mathrm{av},i}-A_i)^2}}\frac{(A_{\mathrm{av},j}-A_j)}{\sqrt{\alpha^2-(A_{\mathrm{av},j}-A_j)^2}}$$

$$C_{\phi,ij} = \frac{\mathrm{d}f}{\mathrm{d}\phi_i}\cdot\frac{\mathrm{d}f}{\mathrm{d}\phi_j}\cdot\delta\phi\delta\phi = \frac{\Delta\nu^2\delta\phi^2}{\alpha^2\pi^2}$$

Remember there are four different $A_{\rm av}$

R value and error on R

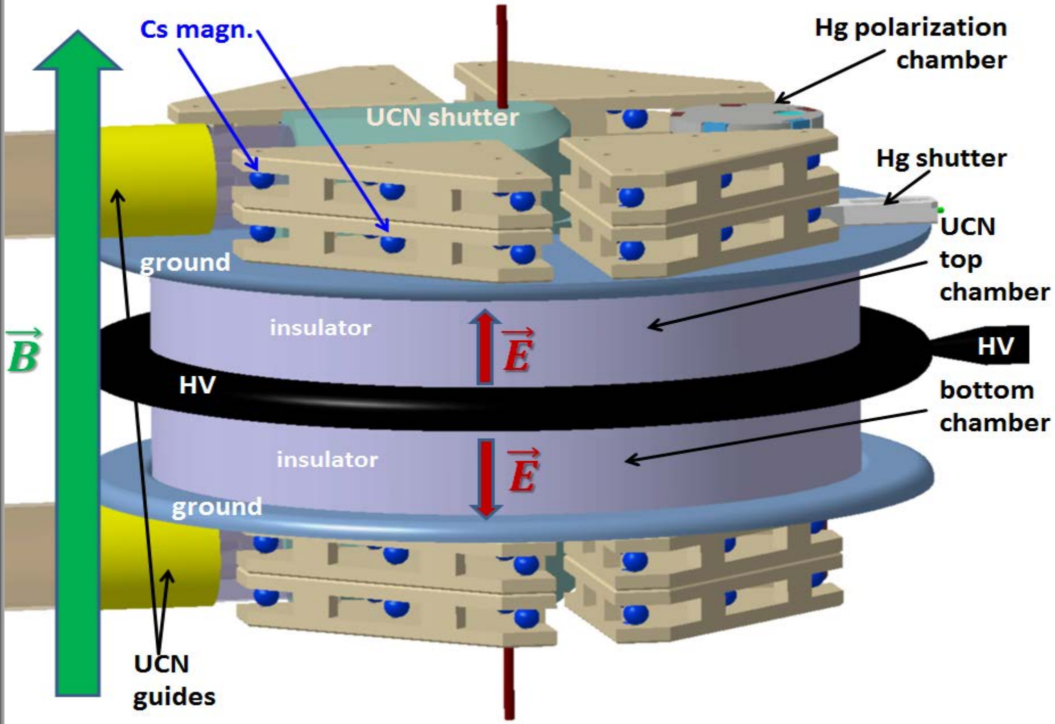
- Calculate R
- Divide covariance matrix by matrix $f'_{\mathrm{Hg},ij}$ (element for element)
- Add diagonal matrix with statistical error for each R value

$$R = \frac{f_\mathrm{n} \mp \gamma_n/2\pi\langle z\rangle g_z}{f_\mathrm{Hg}}$$

$$f_{\mathrm{Hg},ij} = f_{\mathrm{Hg},i} \cdot f_{\mathrm{Hg},j}$$

$$\sigma_R^2 = \frac{\sigma_{f_\mathrm{n}}^2}{f_\mathrm{Hg}^2} + \left(\frac{\gamma_n/2\pi\langle z\rangle\,\delta g_z}{f_\mathrm{Hg}}\right)^2 + \left(\frac{\sigma_\mathrm{Hg}\cdot(f_\mathrm{n}\mp\gamma_n/2\pi\langle z\rangle\,\delta g_z)}{f_\mathrm{Hg}^2}\right)^2$$

Main features of the new instrument



$$\sigma(d_n) \approx 1 \times 10^{-27} ecm$$

Inspired by Gatchina double-chamber setup
I.Altarev et al. JETP Lett.44(1986)460
and based on **years of experience with** our **own operating experiment:**

- 2 neutron precession chambers

- Hg co-magnetometer in both chambers with laser read out

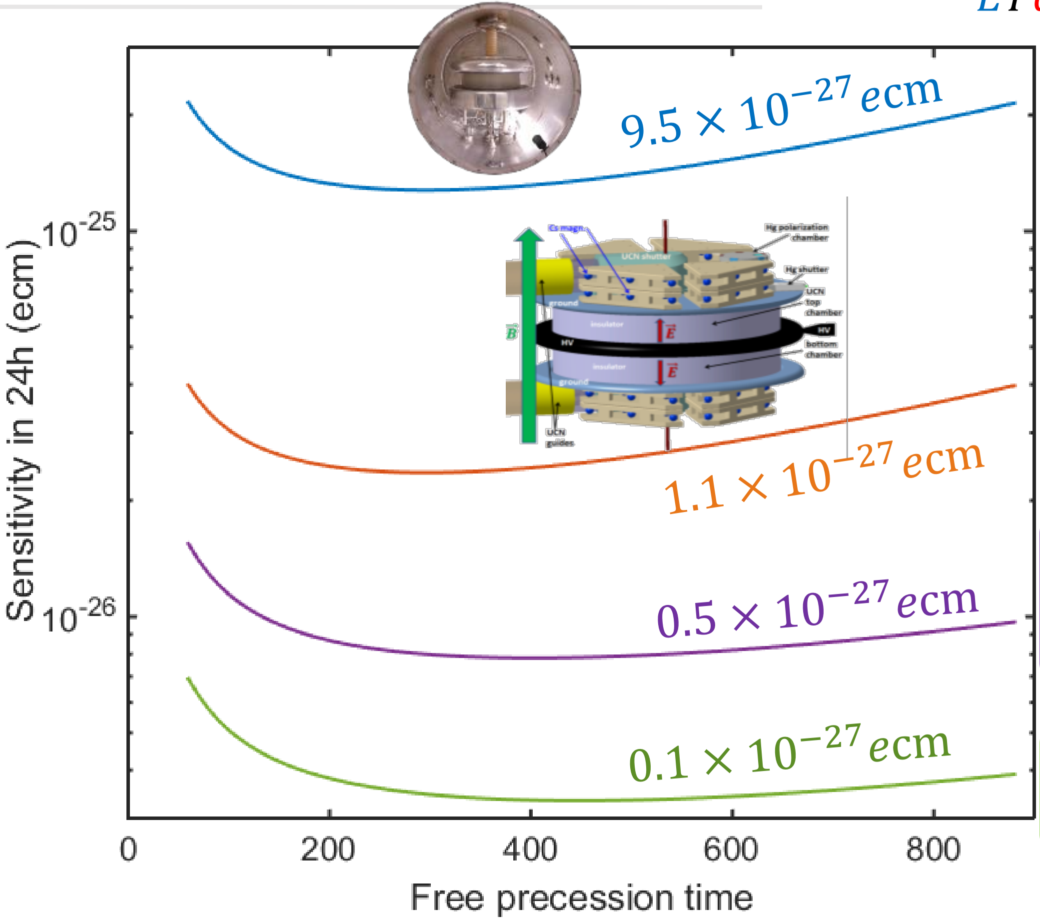
- Baseline scenario: UCN chamber with materials and coatings as present chamber, but larger diameter of storage volume - upgrades in development

- Surrounded by calibrated Cs arrays on ground potential (~ 100 sensors)

- large NiMo (^{58}NiMo) coated UCN guides

Sensitivity:

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



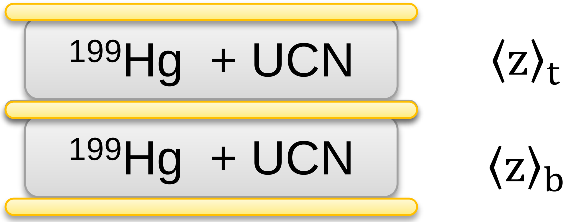
Performance in 2015/2016

Prospect TDR (start 2021)
$E = 15\ \mathrm{kV/cm},\ N = 8 \times N_{2016}$

Possible final performance at PSI
$E = 18\ \mathrm{kV/cm}$, improved UCN source, optimal magnetic field tuning

New source? At ESS?
$E = 20\mathrm{kV/cm},\ N = 128 \times N_{2016}$

Analysis: Frequency ratio $R = f_{\mathrm{n}}/f_{\mathrm{Hg}}$

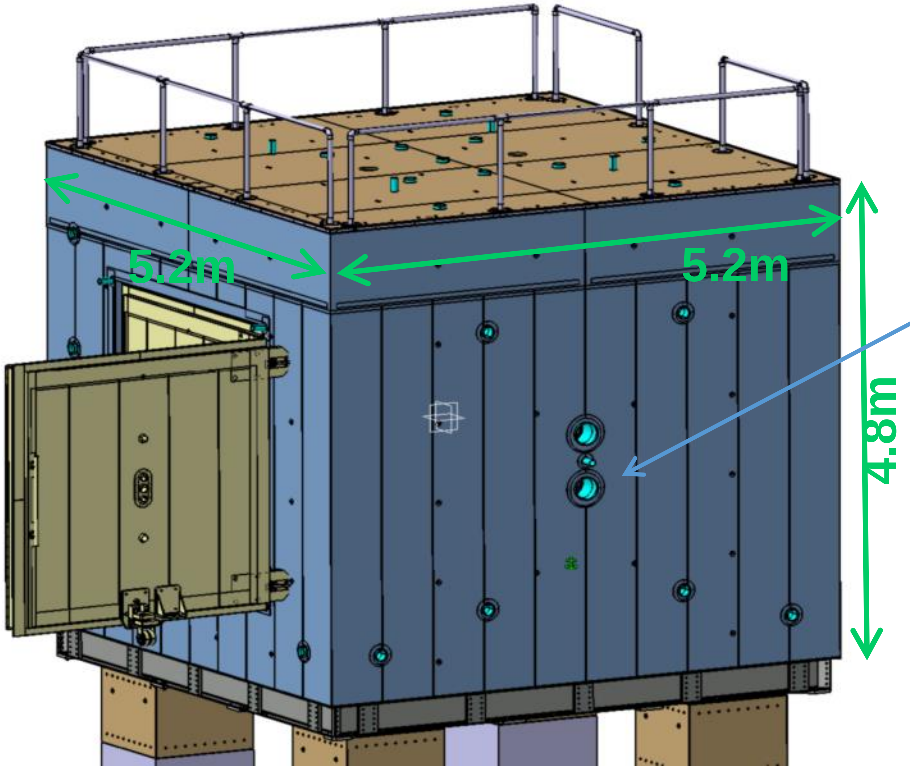


double chamber - linear $\partial B/\partial z$ is almost perfectly compensated but due to different h_t and h_b gradient fluctuations still cause an error on a lower level though

$$R^{\mathrm{T}} - R^{\mathrm{B}} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(2\delta_{\mathrm{EDM}} \quad + \left(\langle z \rangle_{\mathrm{T}} - \langle z \rangle_{\mathrm{B}}\right)\frac{g}{B_0} + \cdots\right)$$

Analysis: based on (R^T - R^B) as function of dB/dz extrapolate to 0

Magnetically Shielded Room



setup features:
- (2 + 4) layers mu-metal
- Al eddy current shield
- 78 openings for experiment use
- largest openings ID=220mm
for 2 UCN guides
for 2 main pumping ports

expected performance:
- quasi-static shielding factor guaranteed >70'000 (expected >100'000)
- central B-field < 0.5nT
- central gradient < 0.3 nT/m

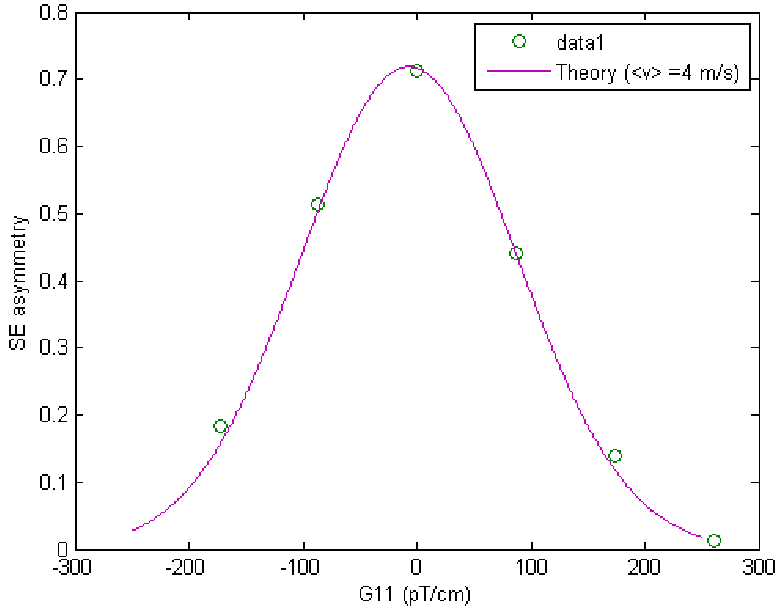
Depolarization

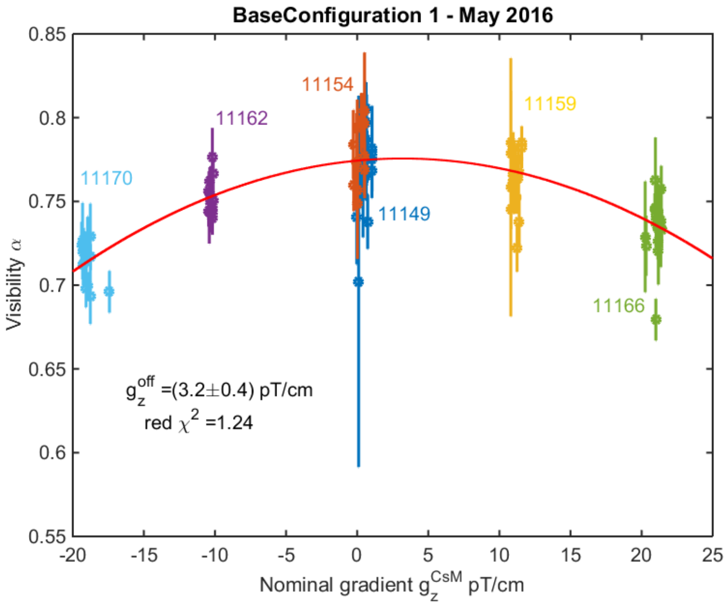
$$\Gamma_2(\epsilon) = a\frac{\gamma_n^2}{v(\epsilon)}\left[\frac{8r^3}{9\pi}\left(\left|\frac{\partial B_z}{\partial x}\right|^2 + \left|\frac{\partial B_z}{\partial y}\right|^2\right) + \frac{\mathcal{H}^3(\epsilon)}{16}\left|\frac{\partial B_z}{\partial z}\right|^2\right]$$

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

Intrinsic depolarization

Gravitational depolarization



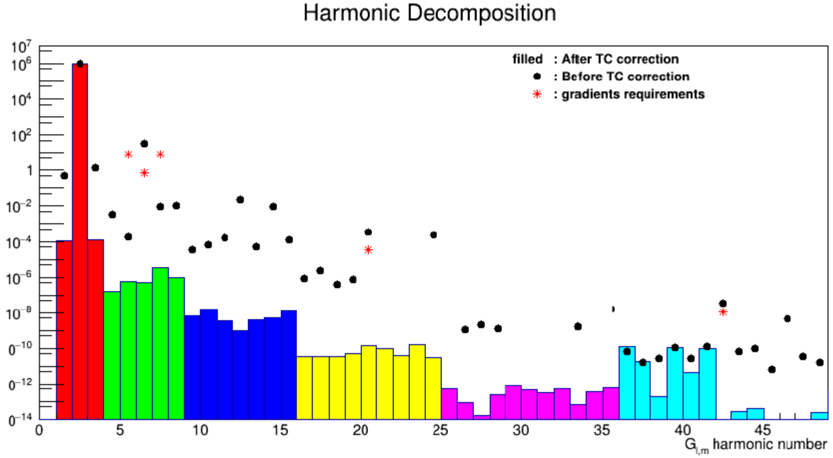


Afach et al., PRD92(2015)052008
Afach et al., PRL115(2015)162502

Excellent B-field uniformity

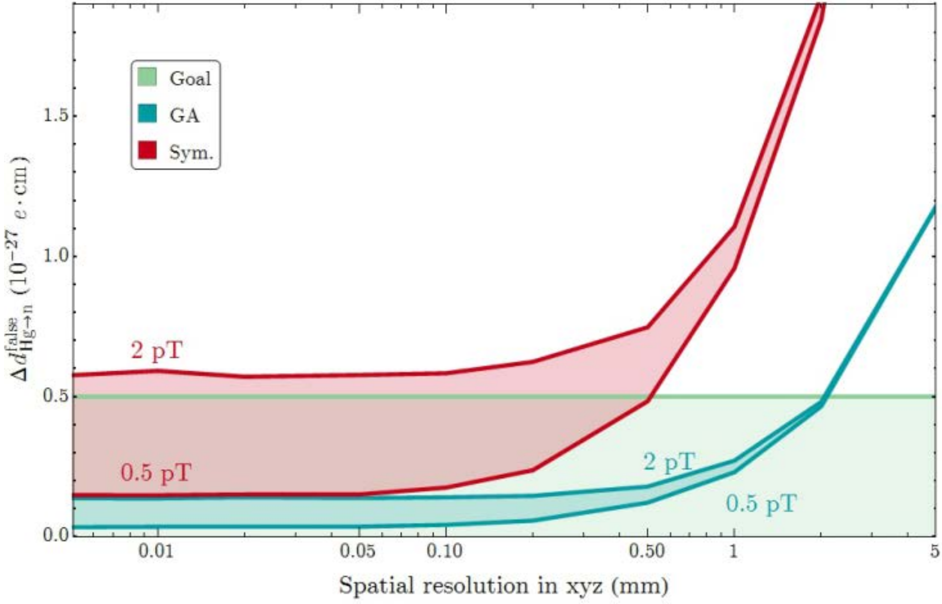
Magnetic-field generation

- Optimized main magnetic field coil
- 64 correction coils



Magnetic-field measurement

- Order 100 CsM sensors
- Optimal placement



Today's status of n2EDM

Status of setup:

- MSR installed and commissioning has started
- Installation of coil system, vacuum tank and precession chambers next
- Area and environmental setup ongoing

Maximize field uniformity

- Use variometer method field information
- Use known sensitivity of each CsM to changes of any of 30 trim coils
- Use field information from offline field maps for $\langle B_{\mathrm{T}}^2 \rangle$

Initial polarization

$$\alpha_0 = 0.86$$

Best polarization after **180 s** free precession

$$\alpha_{180} = 0.81$$

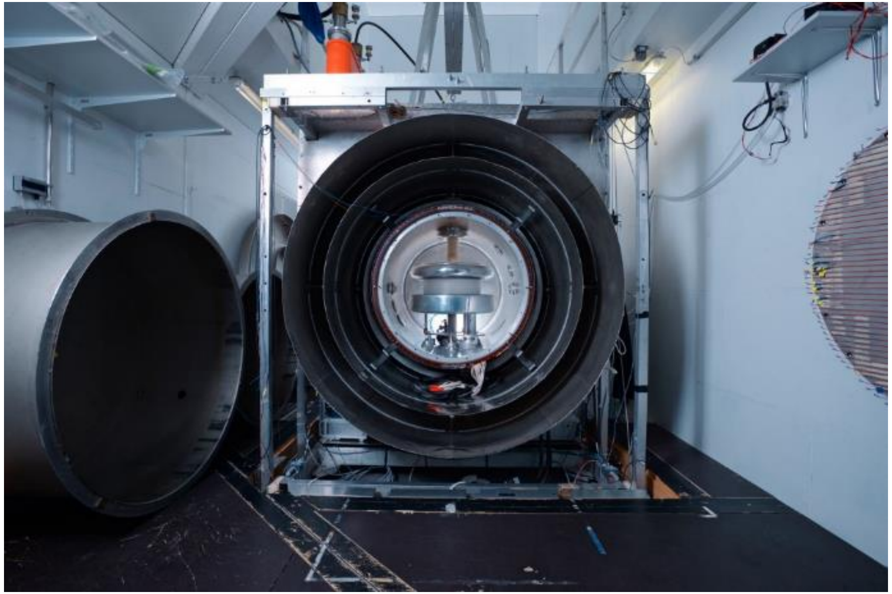
Average:

$$\overline{\alpha_{180}} = 0.75$$

$$\mathrm{T}_2 = -180\mathrm{s} \,/\, \ln\left(\frac{\alpha_{180}}{\alpha_0}\right) = 3000s$$

$$\overline{T_2} = -180\mathrm{s} \,/\, \ln\left(\frac{\overline{\alpha_{180}}}{\alpha_0}\right) = 1315s$$

The history of the Sussex tin can



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The history of the Sussex tin can

1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997

Last beam result

Setup of tin can

1st result u. UCN

Move to turbine

2nd result

Installation of HgM

Move to the Paul Scherrer Institute

1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

ILL data taking

3rd result

4th result

UCN source startup & nEDM upgrade

PSI data

Dismantling nEDM

Installing n2EDM