Searching for a neutron electric dipole moment - European efforts

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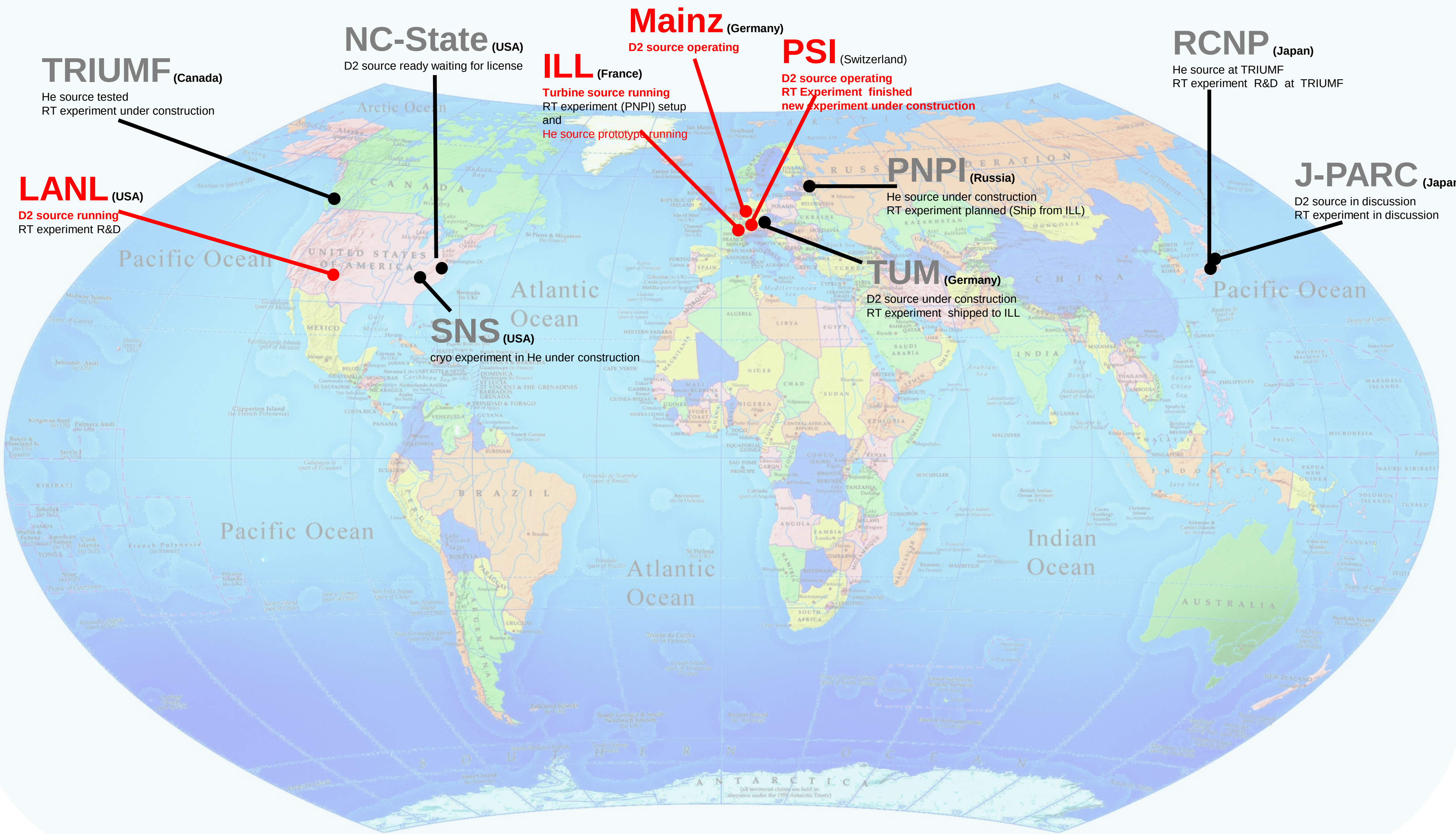
Dec. 7, 2018

Outline

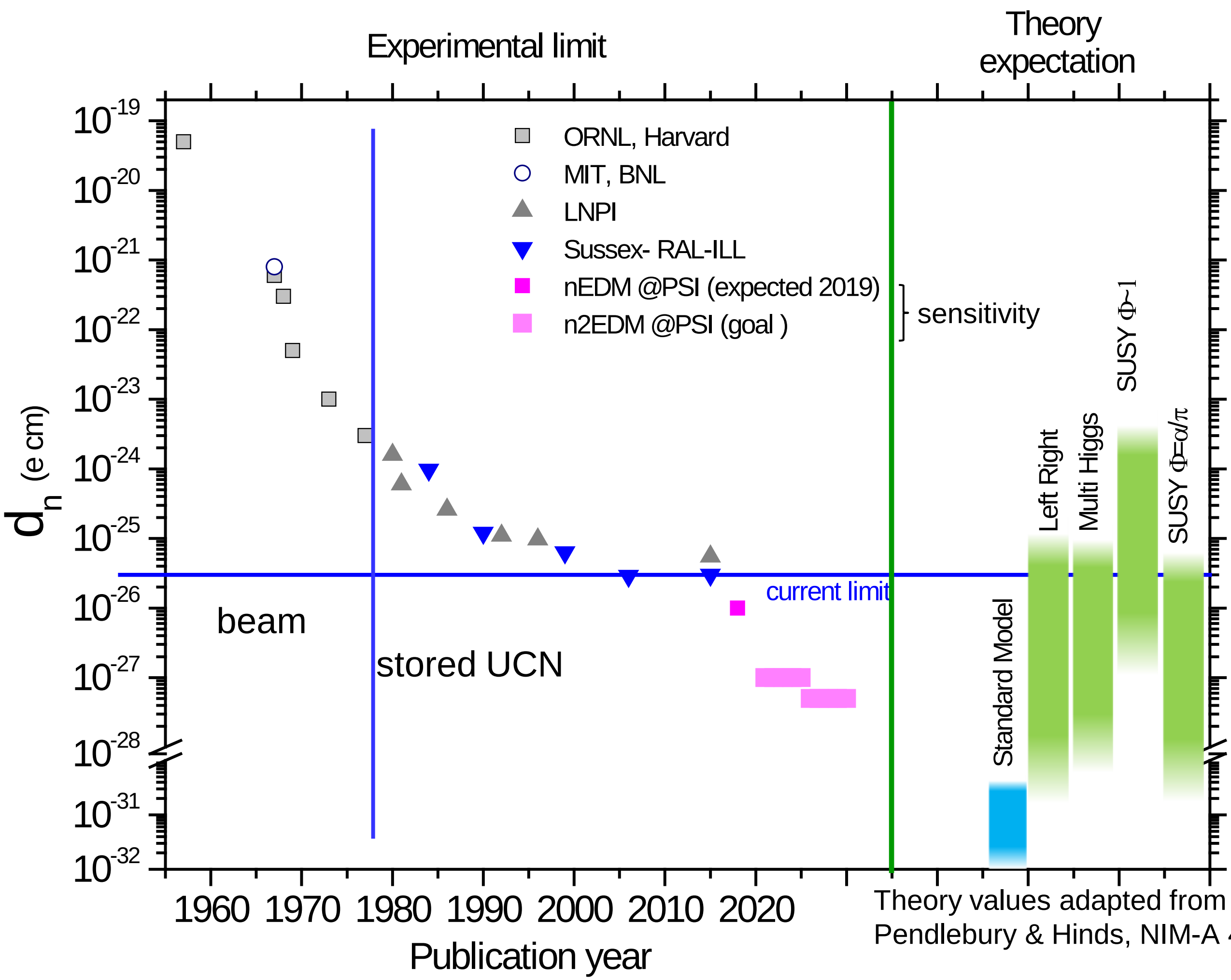
- neutron electric dipole moment & measurement techniques
- ultracold neutrons
- nEDM experiments - European efforts

ULTRACOLD NEUTRON SOURCES AND NEDM EXPERIMENTS: THE WORLDVIEW

PAUL SCHERRER INSTITUT



History of nEDM results



current limit: Baker et al., PRL 2006
revised with largely extended systematics in

PHYSICAL REVIEW D **92**, 092003 (2015)

Revised experimental upper limit on the electric dipole moment of the neutron

J. M. Pendlebury, S. Afach, N. J. Ayres, C. A. Baker, G. Ban, G. Bison, K. Bodek, M. Burghoff, P. Geltenbort, K. Green,[5] W. C. Griffith,[1] M. van der Grinten,[5] Z. D. Grujić,[10] P. G. Harris,[1,†] V. Hélaine,[6,‡] P. Iaydjiev,[5,§] S. N. Ivanov,[5,¶] M. Kasprzak,[10,11] Y. Kermaidic,[12] K. Kirch,[2,3] H.-C. Koch,[10,13] S. Komposch,[2,3] A. Kozela,[14] J. Krempel,[3,2] B. Lauss,[2] T. Lefort,[6] Y. Lemière,[6] D. J. R. May,[1] M. Musgrave,[1] O. Naviliat-Cuncic,[6,**] F. M. Piegsa,[3] G. Pignol,[12] P. N. Prashanth,[11] G. Quéméner,[6] M. Rawlik,[3] D. Rebreyend,[12] J. D. Richardson,[1] D. Ries,[2,3] S. Roccia,[15] D. Rozpedzik,[7] A. Schnabel,[8] P. Schmidt-Wellenburg,[2] N. Severijns,[11] D. Shiers,[1] J. A. Thorne,[1] A. Weis,[10] O. J. Winston,[1] E. Wursten,[11] J. Zejma,[7] and G. Zsigmond[2]

recent review

lanl.arXiv.org > hep-ex > arXiv:1607.06609

High Energy Physics - Experiment

The quest to find an electric dipole moment of the neutron

P. Schmidt-Wellenburg

Weak interaction SM contribution:
$1 - 6 \times 10^{-32}\ ecm$
C.-Y. Seng,PRC(2015)025502

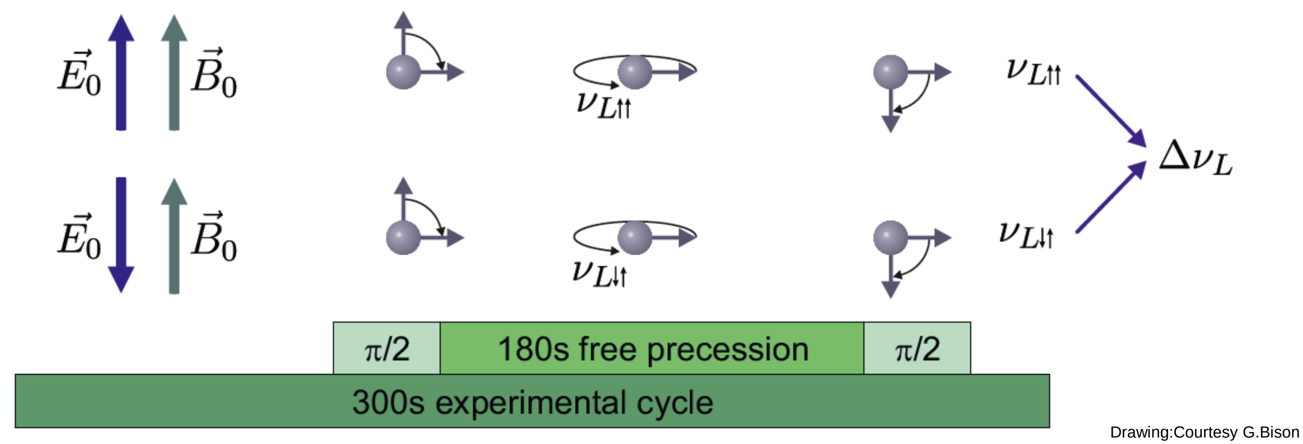
comparable sensitivity goals for all worldwide efforts
new limit from PSI experiment expected soon !

Ramsey method of oscillatory field

Measurement of the difference of neutron precession frequencies in parallel/anti-parallel E and B fields:

$$\mu_n = 60\ \mathrm{neV/T}$$
$$\vec{B} = 1\ \mu\mathrm{T}$$
$$\nu_B \approx 29\,\mathrm{Hz}$$

$$\vec{E} = 11\ \mathrm{kV/cm}$$
$$d_n < 3\times10^{-26}\, e\, cm$$
$$\nu_E < 160\,\mathrm{nHz}$$



$$\nu_n = \frac{2\mu_n}{h}\left|\vec{B}\right| \pm \frac{2d_n}{h}\left|\vec{E}\right|$$

$$d_n = \frac{1}{2E}\left(h\left(f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow}\right) + \mu_n\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)\right)$$

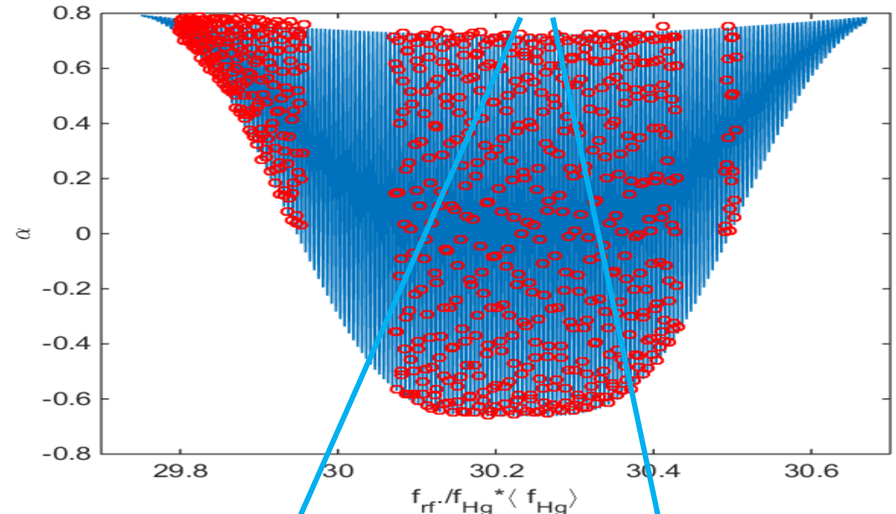
High-precision control and measurement of frequency and magnetic field necessary (fT level)

Experiment sensitivity

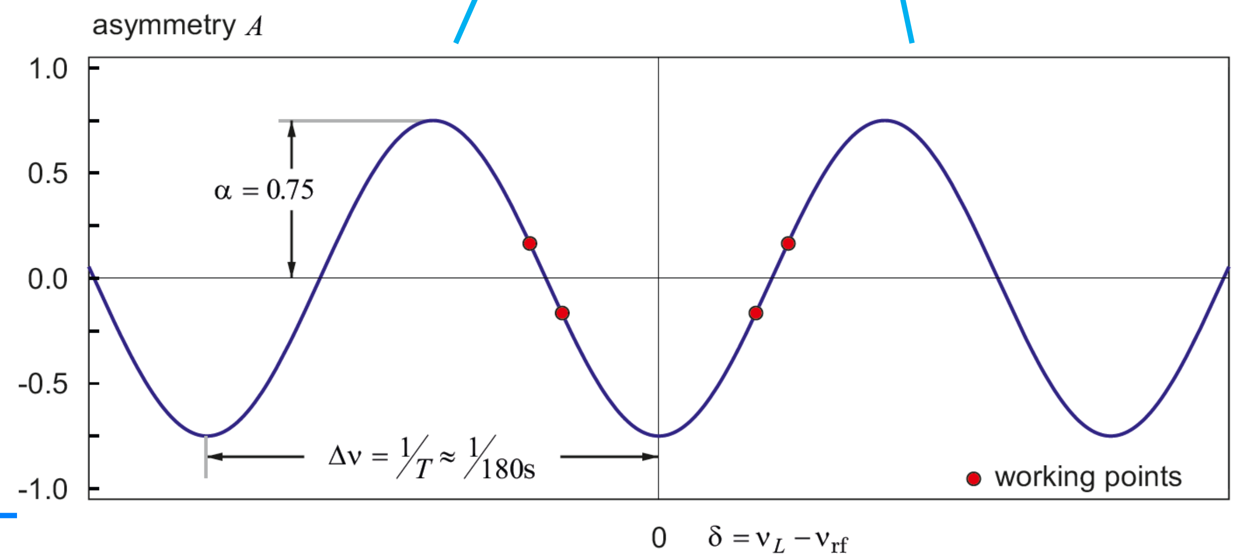
$$\sigma(d_n) = \frac{\hbar}{2\alpha T E \sqrt{N}}$$

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

$$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



$$A(f_{\mathrm{RF}}) = \alpha \cos\left[2\pi(T + 4t/\pi)(f_{\mathrm{RF}} - f_n)\right]$$



nEDM results are still statistically limited

→

the challenge:
design apparatus
to maximize UCN statistics
and all parameters

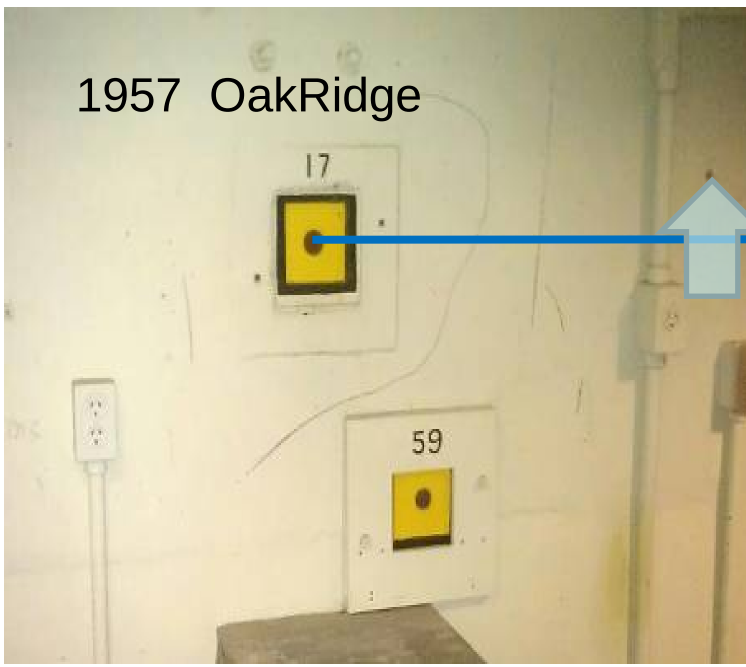
The beam searches

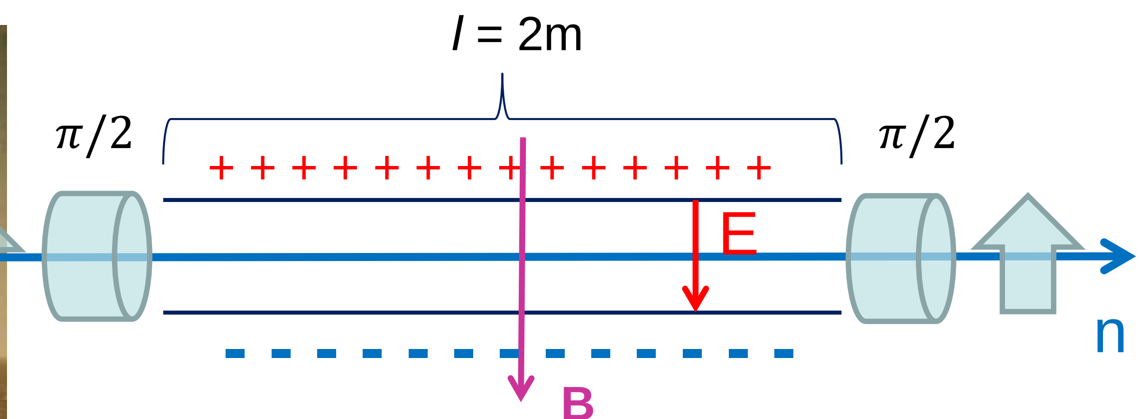
$$\delta(d_\mathrm{n}) = \frac{\hbar}{2\alpha T E\sqrt{\dot{N}}}\frac{1}{\sqrt{t}}$$

$$=8.7\times10^{-22}\frac{e\mathrm{cm}}{\sqrt{\mathrm{Hz}}}\frac{1}{\sqrt{t}}$$

$$T=\frac{l}{v}\approx 0.015\mathrm{s};\ \alpha>0.9;\ E=\frac{100\mathrm{kV}}{\mathrm{cm}};\ \dot{N} = 1\times10^{6}\mathrm{s}^{-1}$$

1 day → $\sigma = 1\times10^{-24}e\mathrm{cm}$





Dominant systematic effect:

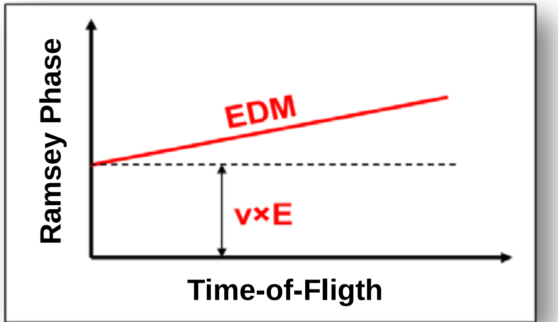
$$B_v = -\frac{\boldsymbol{v}\times\boldsymbol{E}}{c^2}$$

final result: $\sigma(d_\mathbf{n}) = 1.5\times10^{-24}e\mathrm{cm}$
due to misalignment of 0.1 mrad

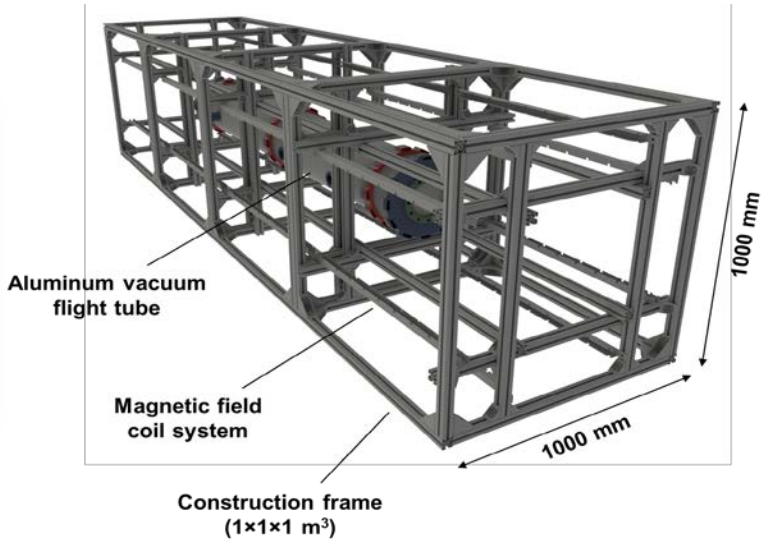
Dres *et al.*, ***PRD*** 15(**1977**) 9

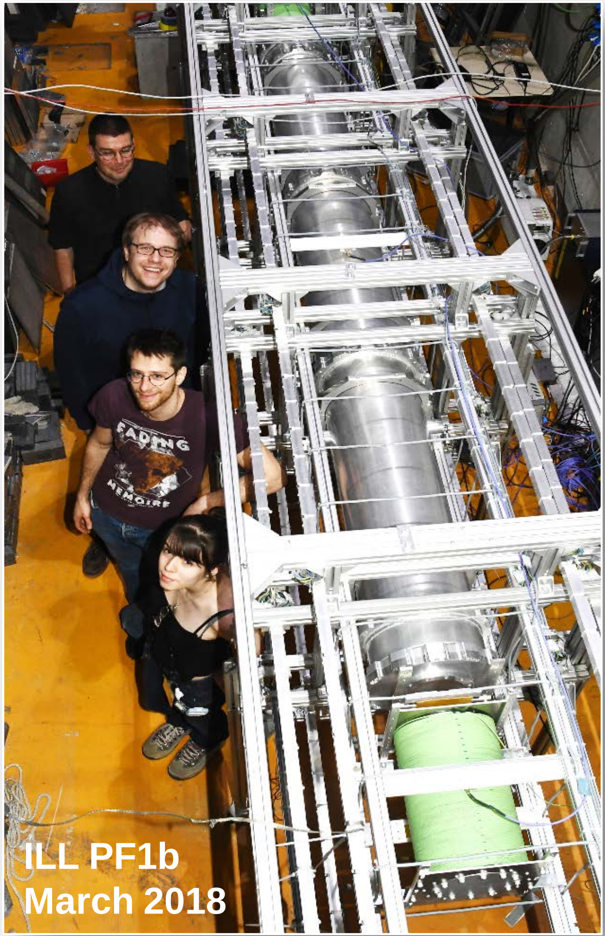
new effort at Univ.Bern: Neutron EDM Experiment using a Pulsed Beam (BEAM-EDM)

- Unique, novel, and complementary EDM approach
- Project based at University of Bern – Start: 10/2016
- Full-scale experiment intended for the ESS / ANNI ($<10^{-26}$ e cm)
- Proof-of-principle experiments at PSI and ILL (10^{-24} e cm)



Piegsa, *PRC* 88, 045502 (2013)





Courtesy: Florian Piegsa

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

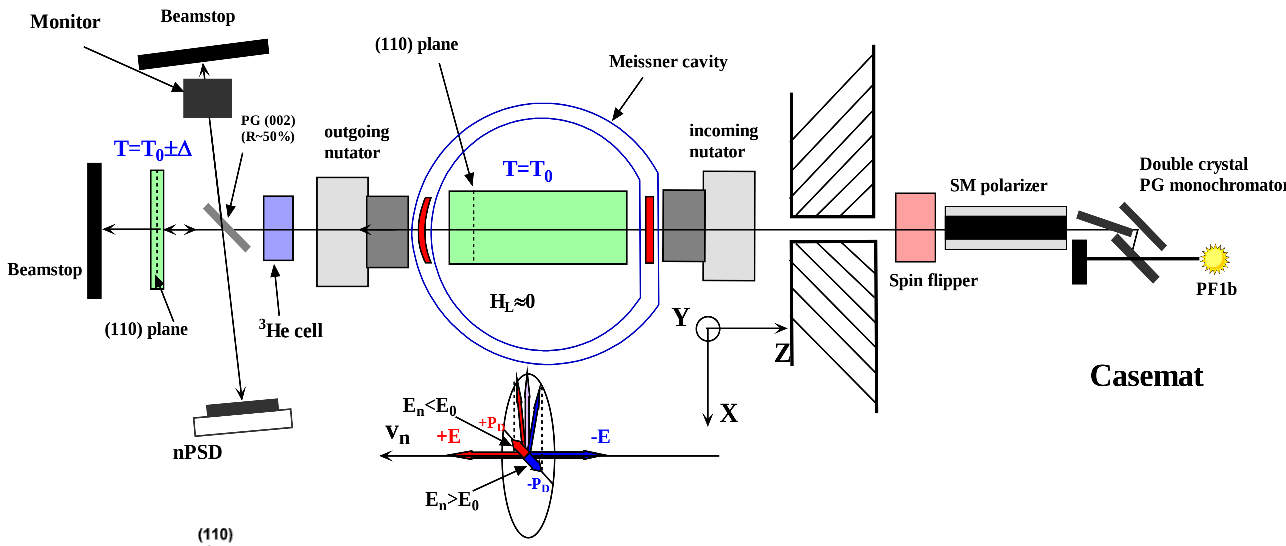
erc European Research Council

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

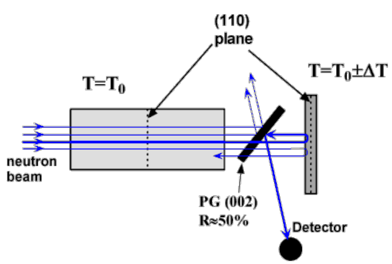
Crystal diffraction neutron EDM

- spin rotation for neutrons close to the Bragg condition for the crystallographic plane in a non-centrosymmetric crystal.
- n exposed to interatomic E-field (up to 10^9 V/cm)
- a non-zero nEDM results in a spin rotation close to Bragg reflex
- Polarization tensor is sensitive to nEDM which would cause a phase shift

New project with sensitivity **2 10^{-25} e cm per day** for quartz crystal and PF1b beam ILL reactor **is ready.**



Information courtesy Vladimir Voronin



$$E_{(11\bar{2}0)} = 2.1 \cdot 10^8 \ V / cm$$

Experimental value for (110) quartz plane

V.V. Fedorov, M. Jentschel, I.A. Kuznetsov et al., Physics Letters B ***694,*** *25 (2010)*

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 (e.g. EDM at PSI)

$$\dot{N} \approx 1000\ \mathrm{s}^{-1}$$
$$\alpha \approx 0.9;$$
$$E = 15\mathrm{kV/cm}$$
$$T = 200\mathrm{s}$$
$$\sigma(1\mathrm{s}) = 4 \times 10^{-24}\ e\mathrm{cm}$$

UCN < 300neV ~ 8m/s ~ 3 mK

$$\lambda = \frac{h}{m \cdot v}$$

> 50 nm !

$$E_{\mathrm{kin}} = \frac{mv^2}{2} = \frac{3}{2}kT$$

How to increase the statistical sensitivity

$$\sigma(d_\mathrm{n}) = \frac{\hbar}{2ET\alpha\sqrt{N}} = \frac{\hbar}{2ET\alpha_0 e^{-T/T_2}\sqrt{N_0 e^{-T/\tau_n}}}$$

$E \leq 20\mathrm{kV/cm}$: Limited by insulator

$\alpha \to 1$: Polarization of neutrons

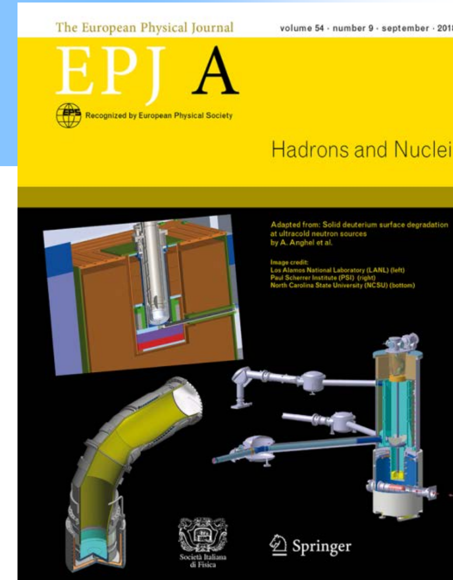
$T \to \tau_\mathrm{n}$: Minimize losses

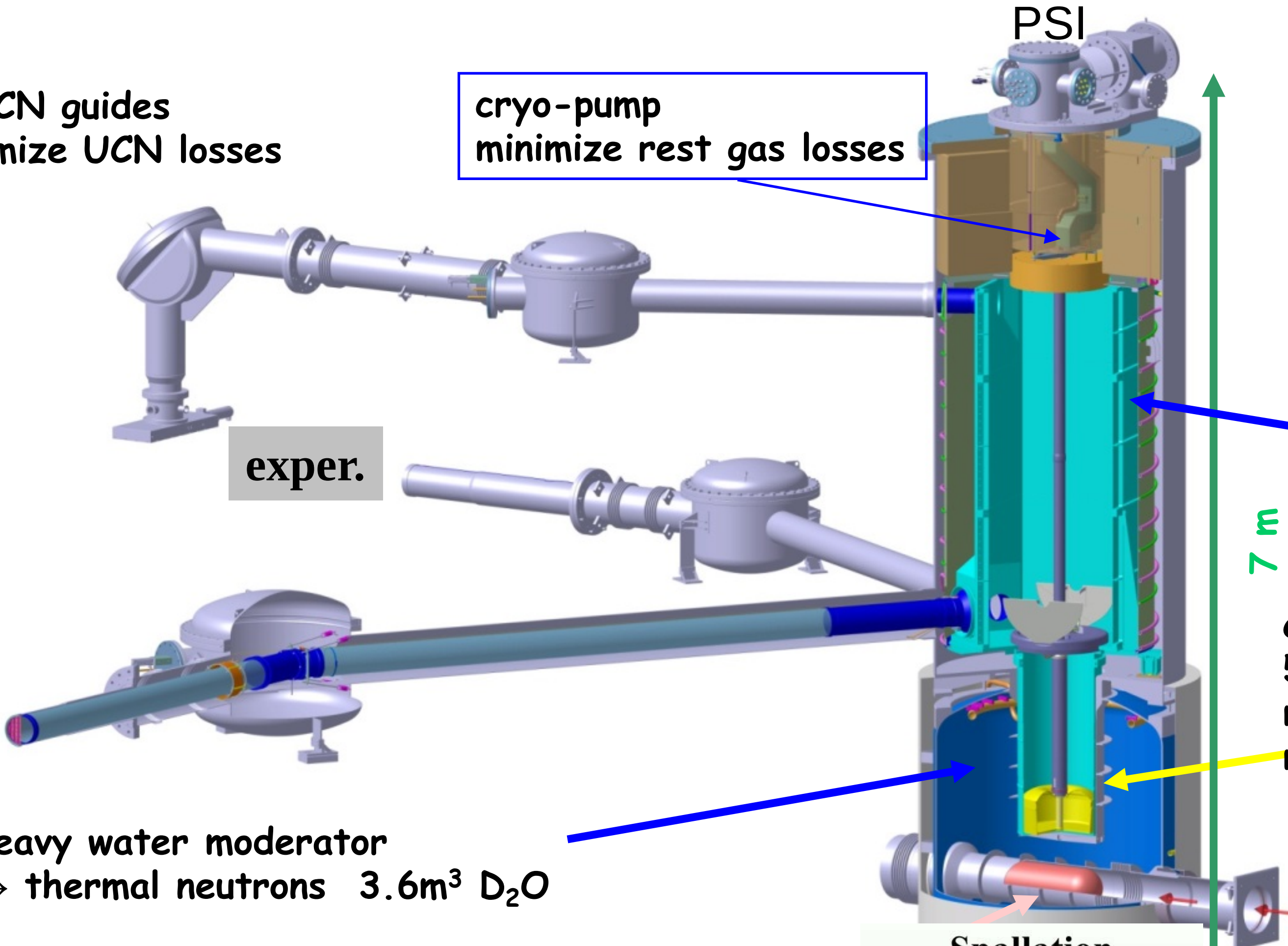
$\sqrt{N_0}$: Limited by transport losses

$T_2 \to \infty$: Magnetic field inhomogeneity

- Make T_2, α large → large high performance magnetically shielded rooms and homogeneous magnetic field
- Make $\sqrt{N_0}$ large → improve UCN sources
  - better extraction of UCN from converter
  - higher UCN production rates
  - adaptation / improvement of UCN transport
- Make $ET\sqrt{N}$ large → cryogenic UCN storage experiment

Example: solid deuterium based sources- LANL - NCSU - MAINZ - PSI





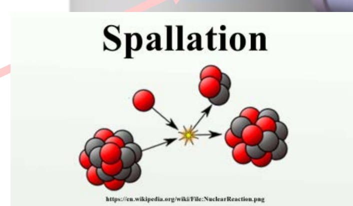
long UCN guides
- minimize UCN losses

cryo-pump
minimize rest gas losses

DLC coated
UCN storage vessel
minimize UCN losses

cold UCN-converter
5 kg solid D_2 at 5 K
mazimize UCN production
minimize losses

heavy water moderator
→ thermal neutrons $3.6 m^3$ D_2O



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

pulsed
1.3 MW p-beam
590 MeV, 2.2 mA,
3% duty cycle

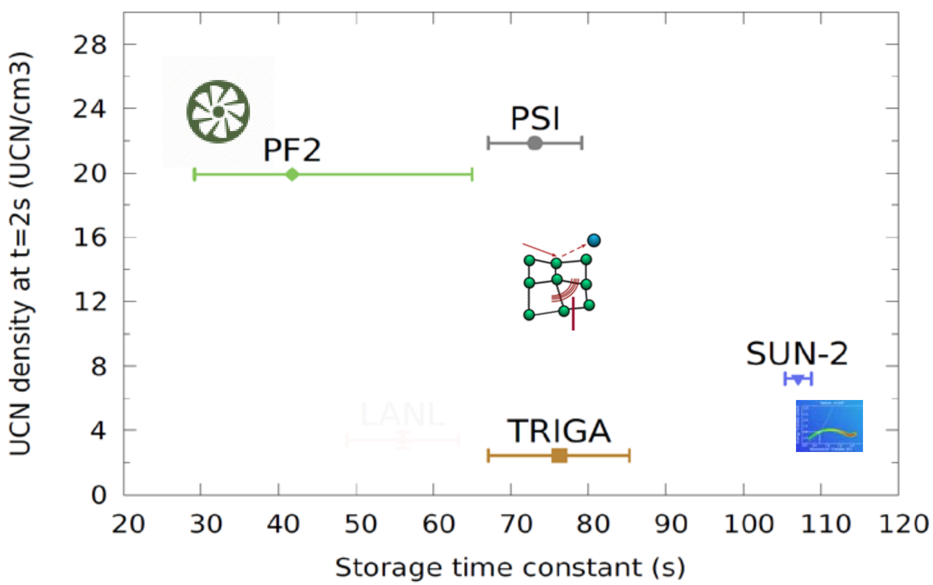
Worldwide efforts for higher UCN intensities

PHYSICAL REVIEW C 95, 045503 (2017)

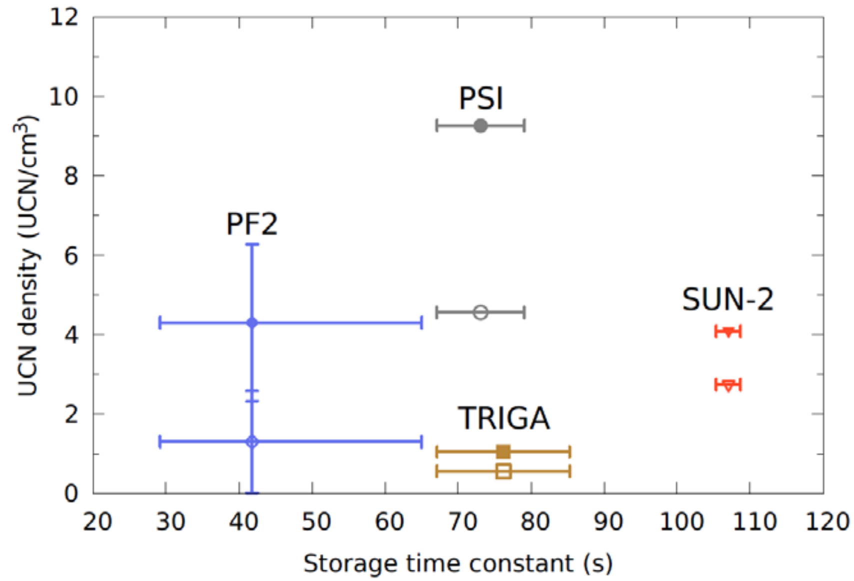
Comparison of ultracold neutron sources for fundamental physics measurements

UCN density after storage in 20 l external stainless-steel bottle

storage times = 2s



storage times = 50s, 100s



Comparison of ultracold neutron sources for fundamental physics measurements
G.Bison et al., Phys.Rev.C95 (2017) 045503

Suggestion of "standard" method and device for UCN density measurement and comparison:
G.Bison et al., Nucl.Instrum.Meth. A 830 (2016) 449

Volume 102B, number 1 PHYSICS LETTERS 4 June 1981

A NEW UPPER LIMIT ON THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON

I.S. ALTAREV, Yu.V. BORISOV, N.V. BOROVIKOVA, A.B. BRANDIN,
A.I. EGOROV, V.F. EZHOV, S.N. IVANOV, V.M. LOBASHEV [1],
V.A. NAZARENKO, V.L. RYABOV, A.P. SEREBROV and R.R. TALDAEV
Leningrad Nuclear Physics Institute of the Academy of Sciences of the USSR, Leningrad, USSR

Received 24 March 1981

New measurements have reduced the upper limit for the electric dipole moment of the neutron to $|d| < 6 \times 10^{-25} e$ cm (90% confidence level).

Pioneering efforts by the PNPI - Lobashev group using for the first time a double UCN storage chamber

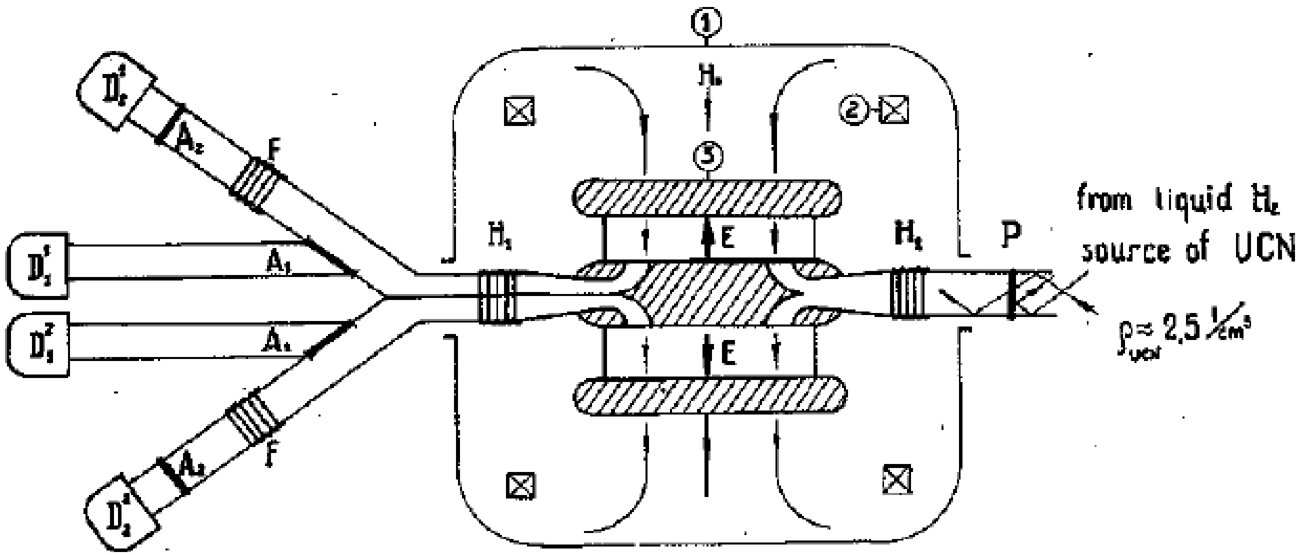


Fig. 1. 1: magnetic shield, 2: coils, 3: chambers of storage of UCN, P: polariser, A_1, A_2: analysers, D_1^1, D_1^2, D_2^1, D_2^2: detectors; H_0 is the constant magnetic field, H_1 is the oscillating magnetic field, E is the electric field.

PRL 97, 131801 (2006) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2006

Improved Experimental Limit on the Electric Dipole Moment of the Neutron

C. A. Baker,[1] D. D. Doyle,[2] P. Geltenbort,[3] K. Green,[1,2] M. G. D. van der Grinten,[1,2] P. G. Harris,[2] P. Iaydjiev,[1,*] S. N. Ivanov,[1,†] D. J. R. May,[2] J. M. Pendlebury,[2] J. D. Richardson,[2] D. Shiers,[2] and K. F. Smith[2]
[1]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[2]*Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom*
[3]*Institut Laue-Langevin, BP 156, F-38042 Grenoble Cedex 9, France*
(Received 9 February 2006; revised manuscript received 29 March 2006; published 27 September 2006)

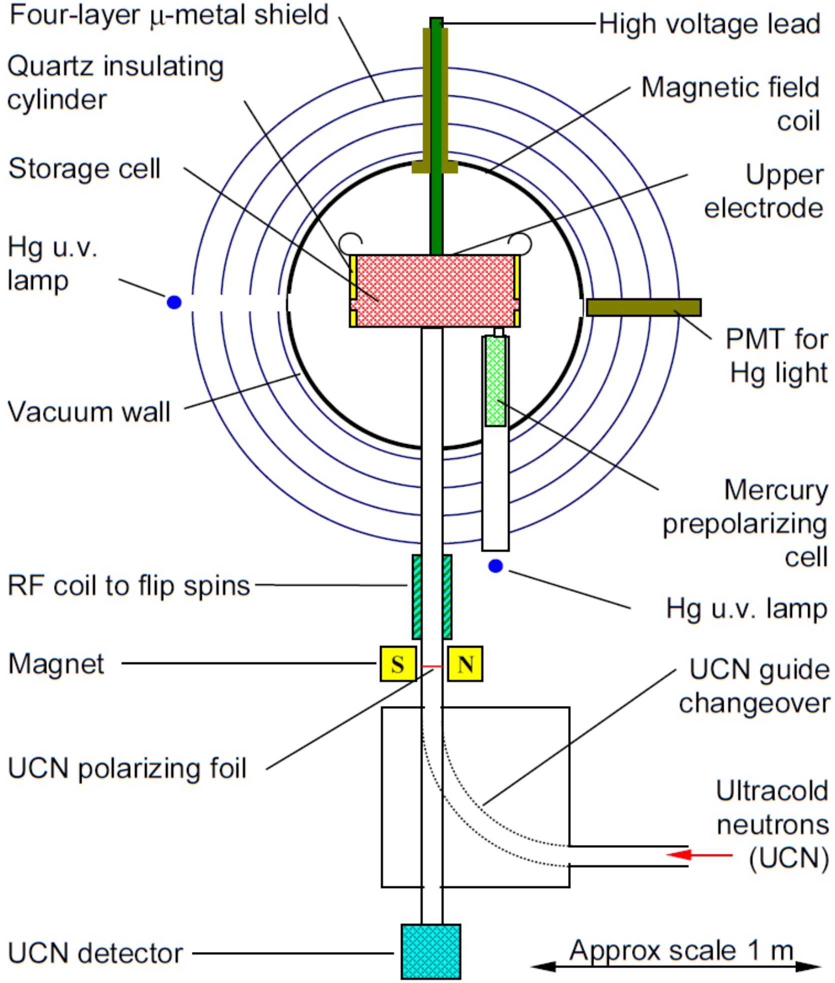


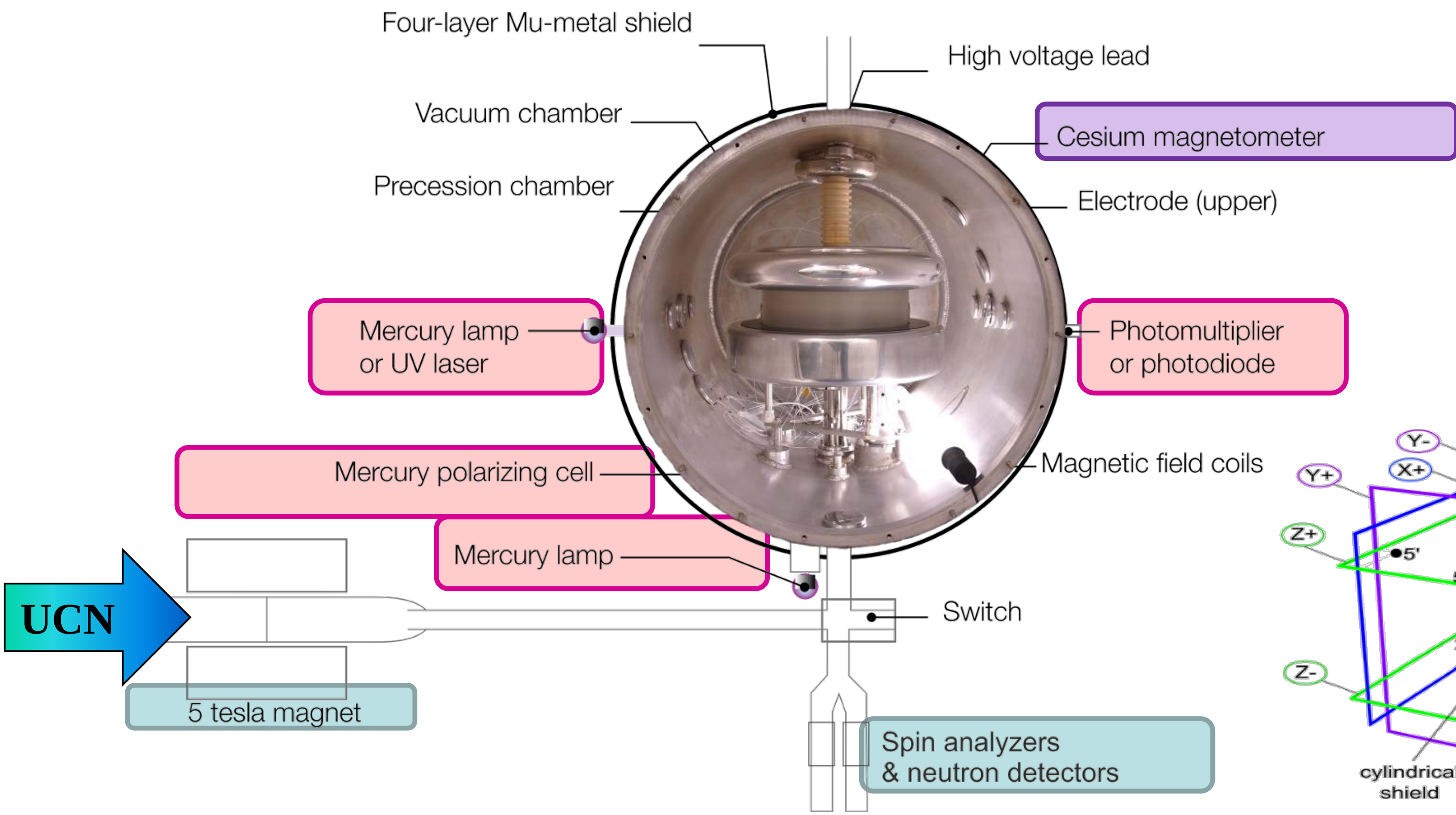
FIG. 1: (Color online) Experimental apparatus

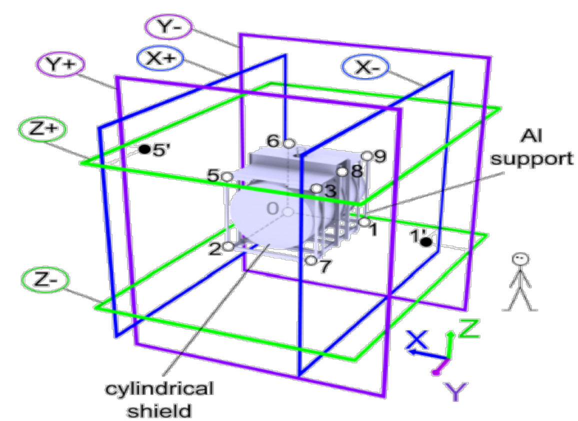
Pioneering efforts by the RAL-Sussex-ILL collaboration using

for the first time a cohabiting magnetometer - polarized 199-Hg

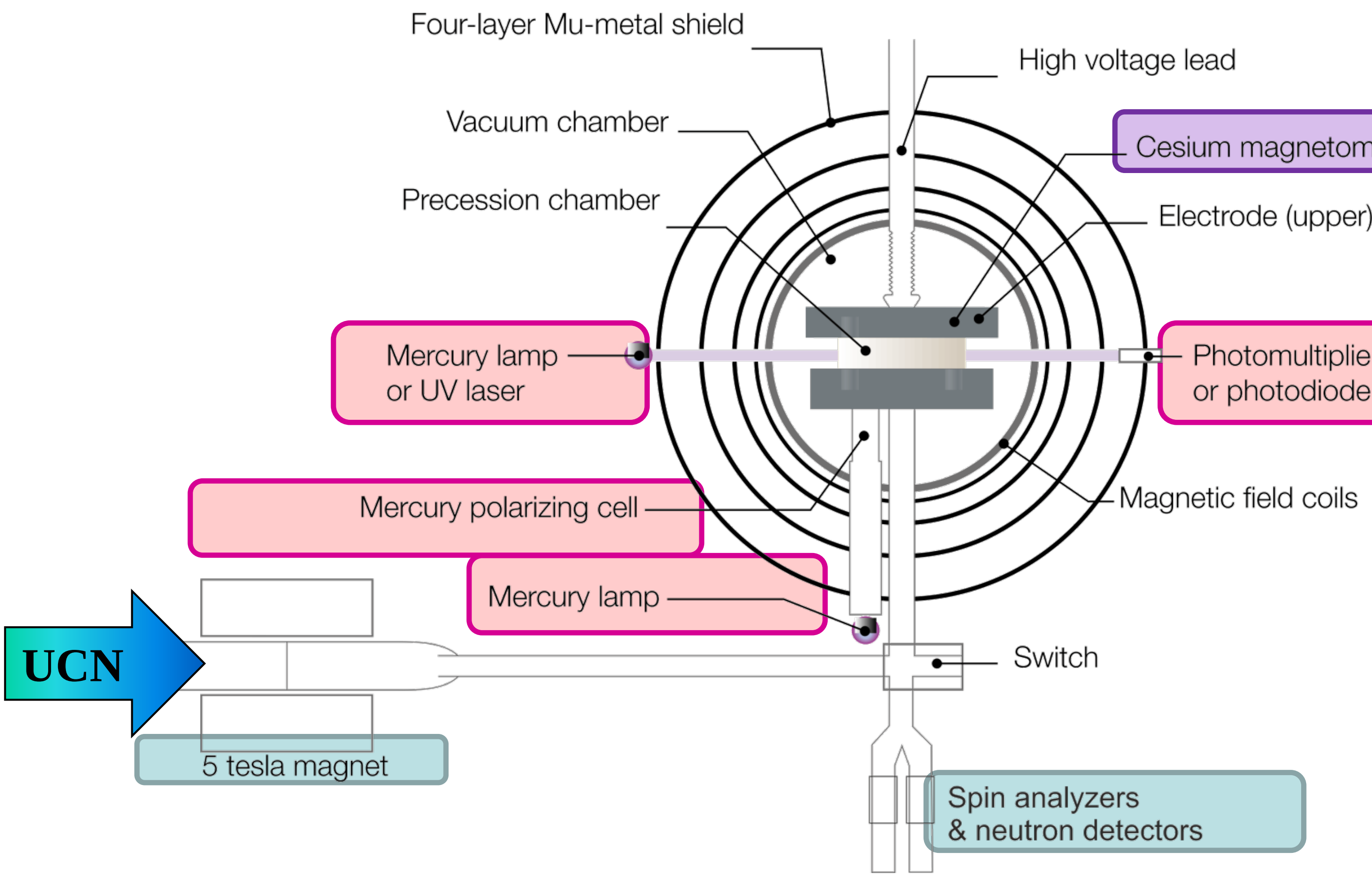
set the present limit

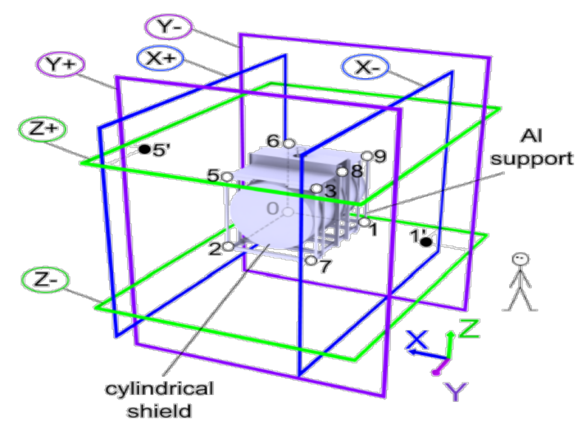
Several improvements and upgrades to the original nEDM apparatus at PSI





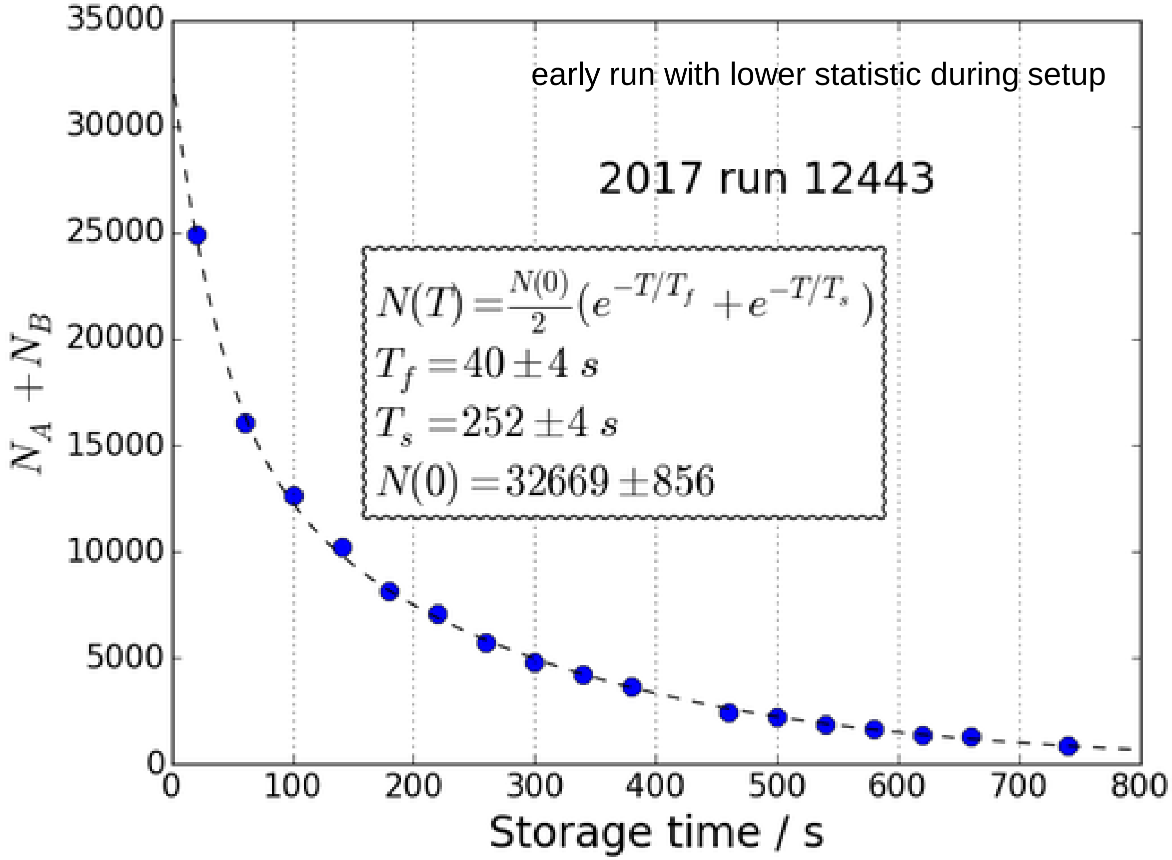
Several improvements and upgrades to the original nEDM apparatus at PSI

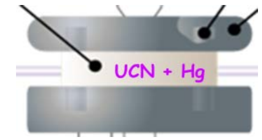




UCN source

How to improve: optimize UCN storage time and UCN statistics

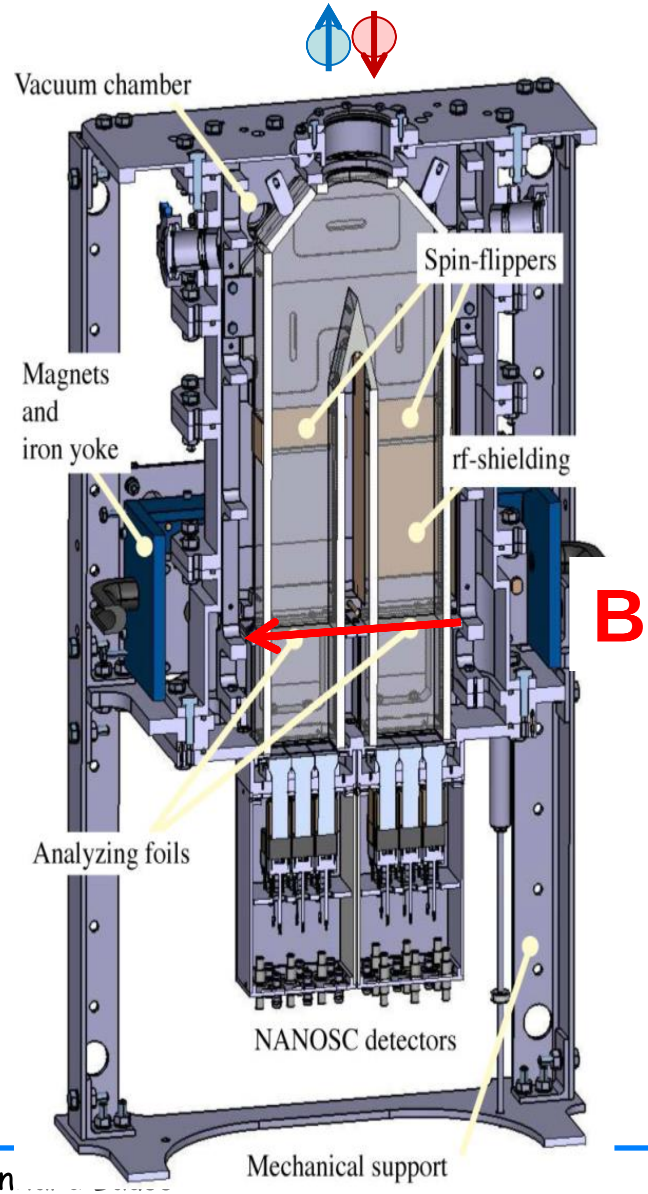




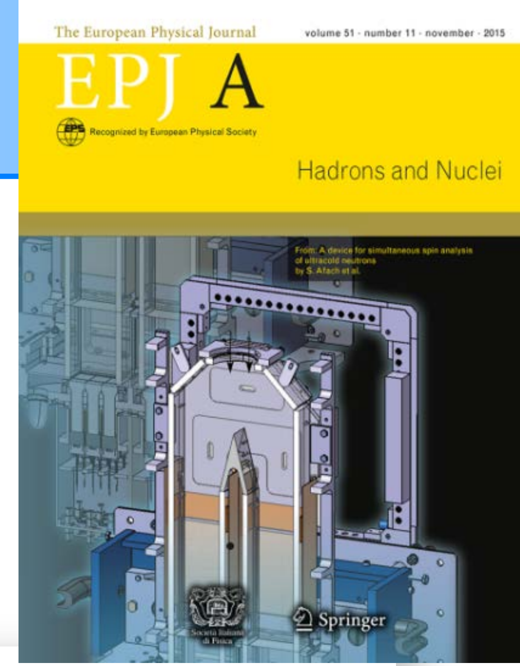
Chamber made of dPS insulator ring and DLC electrodes

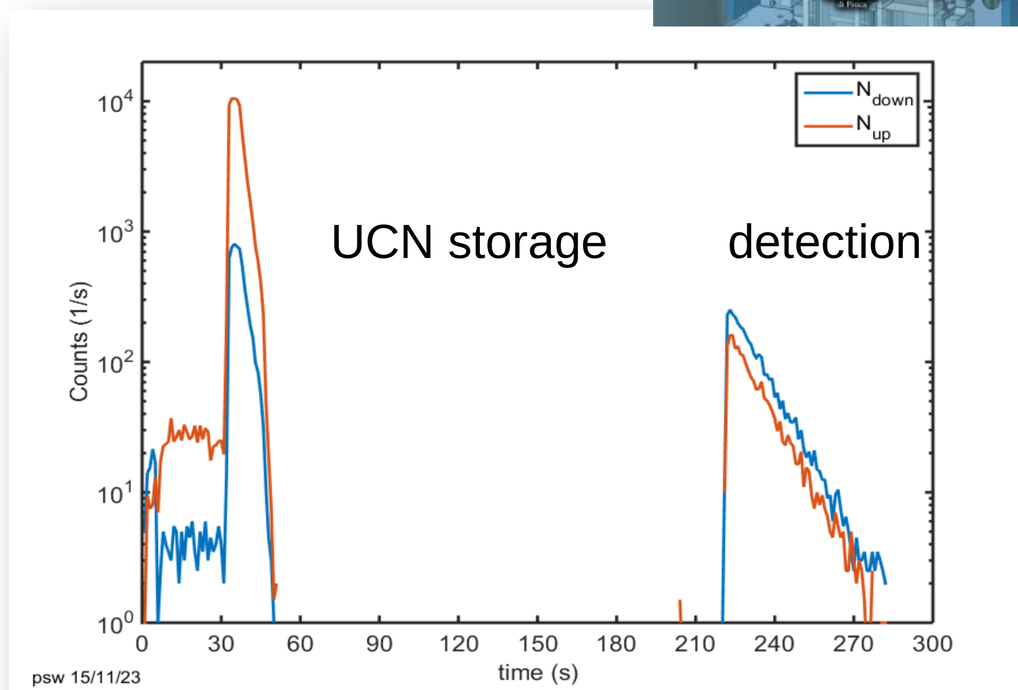
$$\sigma(f) = \frac{\hbar}{2\alpha T E \sqrt{N}}$$

Simultaneous spin detection (also pioneered at PNPI)



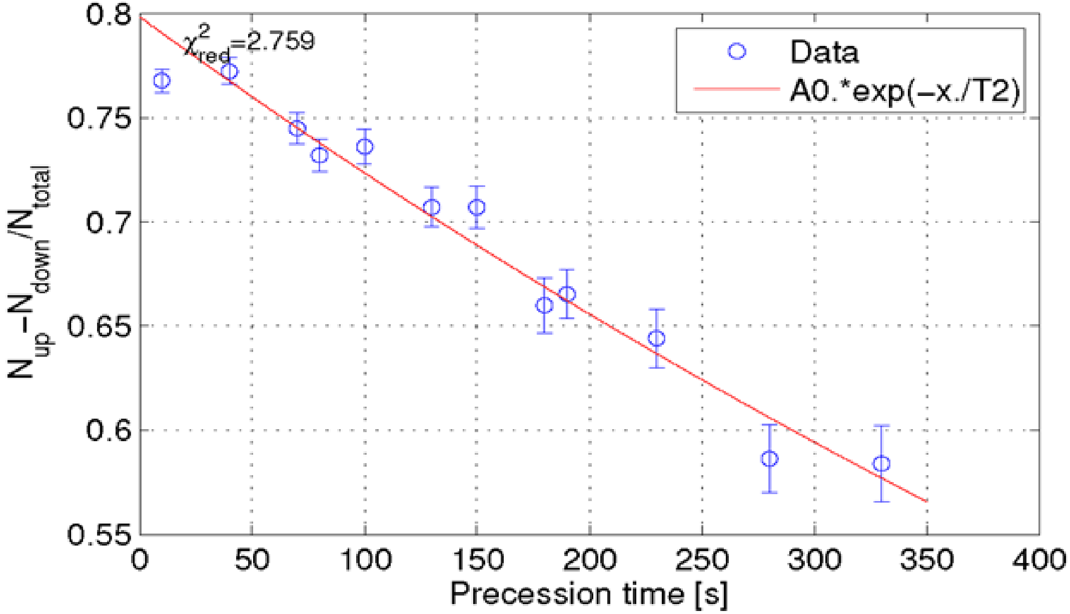
- o Spin dependent detection
  - Adiabatic spinflipper
  - Iron coated foil
- o ^{6}Li-doped scintillator GS20





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

Neutron transversal depolarization time



T2 ~ 1000s

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

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

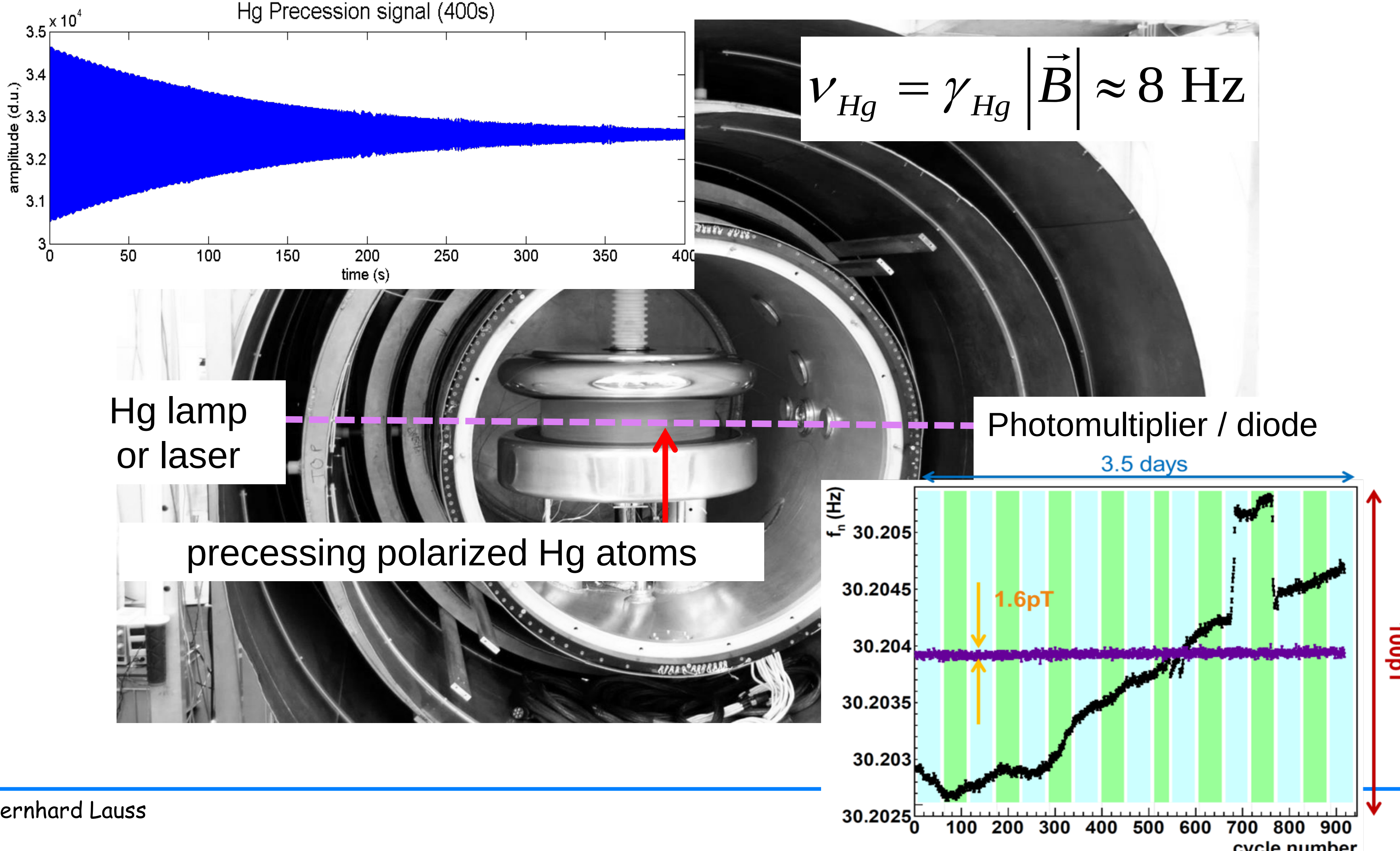
$$\Gamma_2(\epsilon) = a\frac{\gamma_n^2}{v(\epsilon)}\left[\frac{8r^3}{9\pi}\left(\left|\frac{\partial B_z}{\partial x}\right|^2 + \left|\frac{\partial B_z}{\partial y}\right|^2\right) + \frac{\mathcal{H}^3(\epsilon)}{16}\left|\frac{\partial B_z}{\partial z}\right|^2\right]$$

in addition we found gravitational depolarization

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

magnetic field homogeneity 10^{-3} -> 10^{-4}
new variometer method of B-field homogenization

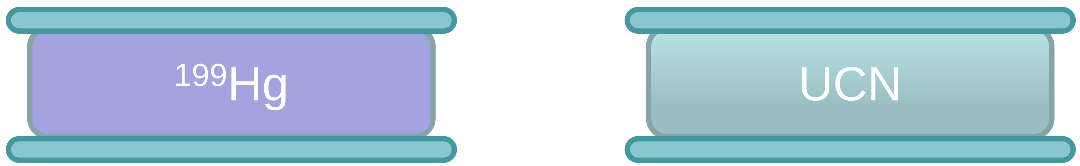
Hg co-magnetometer



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

Center of mass offset δh
Non-adiabaticity -> new systematic effects
motional (false) EDM

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



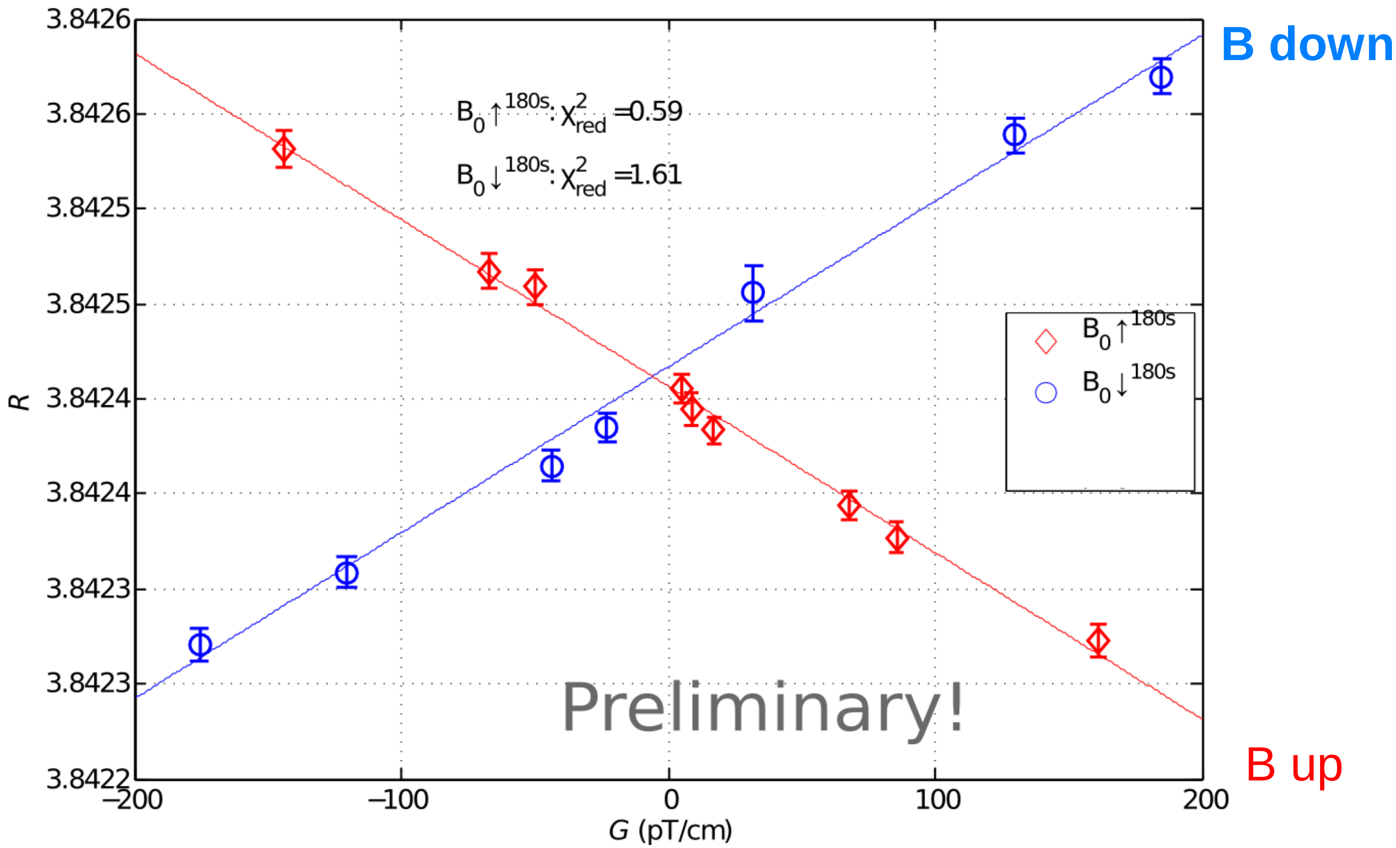
$$\frac{\gamma_{\mathrm{n}}}{2\pi} \approx 30\ \mathrm{Hz}/\mu\mathrm{T}$$

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

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

Measure R as function of dB/dz

extracting the neutron frequency / R-curve



$$R = \frac{f_n}{f_{Hg}} \approx \frac{\gamma_n}{\gamma_{Hg}} \left(1 \mp \frac{Gh}{B_0} \pm \delta_{B_\perp}{}^{\uparrow\downarrow} \pm \delta_{Hg_{Light}}{}^{\uparrow\downarrow} + \delta_{Earth}\right)$$

+ new physics

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

Eur. Phys. J. D (2015) 69: 225
DOI: 10.1140/epjd/e2015-60207-4

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Measurement of a false electric dipole moment signal from ^{199}Hg atoms exposed to an inhomogeneous magnetic field

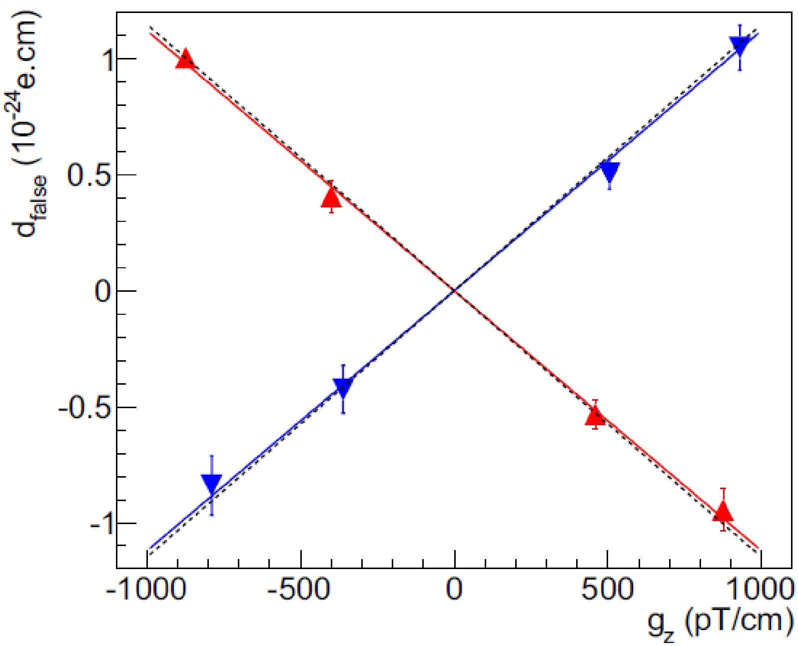


Fig. 5. Motional false mercury EDM versus the vertical gradient g_z for $B_0^{\uparrow}$ (red up triangles) and $B_0^{\downarrow}$ (blue down triangles). The solid lines correspond to a linear fit, and the dashed line to the theory discussed in Section 2. The horizontal error bars are smaller than the symbol size.

$$d_n^{\text{false}} = \frac{\partial B_z}{\partial z} 1.5\times 10^{-29}\, e\cdot\text{cm}\frac{\text{cm}}{\text{pT}}$$

$$d_{\text{Hg}}^{\text{false}} = \frac{\partial B_z}{\partial z}\cdot 1.15\times 10^{-27}\, e\cdot\text{cm}\frac{\text{cm}}{\text{pT}}$$

$$d_{\text{Hg}\to\text{n}}^{\text{false}} = -\frac{\partial B_z}{\partial z}\cdot 4.4\times 10^{-27}\, e\cdot\text{cm}\frac{\text{cm}}{\text{pT}}$$

However, it is important also to take higher order gradients into account.

Important:
Cs magnetometry to map online

B-field decomposition

TABLE I. Associated Legendre polynomials up to $l = 5$.

l	m	$P_l^m(\cos\theta)$
1	0	$\cos\theta$
1	1	$-\sin\theta$
2	0	$\frac{1}{2}(3\cos^2\theta - 1)$
2	1	$-3\cos\theta\sin\theta$
2	2	$3\sin^2\theta$
3	0	$\frac{1}{2}\cos\theta(5\cos^2\theta - 3)$
3	1	$-\frac{3}{2}(5\cos^2\theta - 1)\sin\theta$
3	2	$15\cos\theta\sin^2\theta$
3	3	$-15\sin^3\theta$

+ higher orders

arXiv.org > physics > arXiv:1811.06085

Physics > Instrumentation and Detectors

Magnetic field uniformity in neutron electric dipole moment experiments

C. Abel, N. Ayres, T. Baker, G. Ban, G. Bison, K. Bodek, V. Bondar, C. Crawford, P.-J. Chiu, E. Chanel, Z. Chowdhuri, M. Daum, B. Dechenaux, S. Emmenegger, L. Ferraris-Bouchez, P. Flaux, P. Geltenbort, K. Green, W. C. Griffith, M. van der Grinten, P.G. Harris, R. Henneck, N. Hild, P. Iaydjiev, S. N. Ivanov, M. Kasprzak, Y. Kermaidic, K. Kirch, H.-C. Koch, S. Komposch, P. A. Koss, A. Kozela, J. Krempel, B. Lauss, T. Lefort, Y. Lemiere, A. Leredde, P. Mohanmurthy, D. Pais, F. M. Piegsa, G. Pignol, G. Quéméner, M. Rawlik, D. Rebreyend, D. Ries, S. Roccia, D. Rozpedzik, P. Schmidt-Wellenburg, A. Schnabel, N. Severijns, R. Virot, A. Weis, E. Wursten, G. Wyszynski, J. Zejma, G. Zsigmond

(Submitted on 13 Nov 2018)

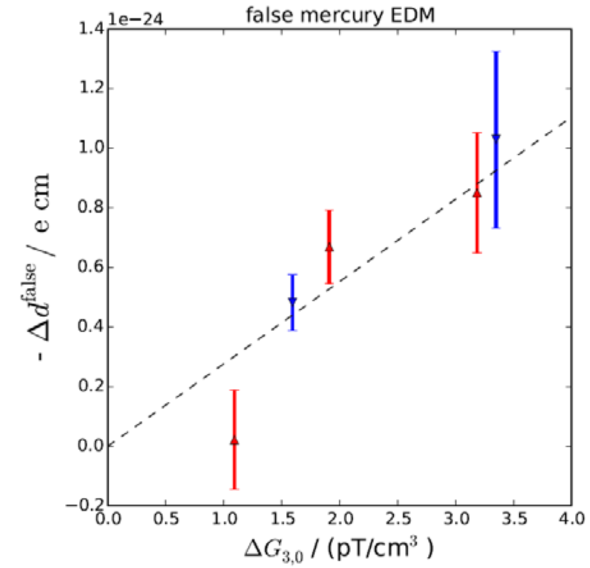


FIG. 3. Experimental verification of motional false EDM of mercury induced by a change of the cubic gradient $G_{3,0}$. The frequency shift correlated with electric field reversals was measured at ± 120 kV. Red triangles pointing upwards (blue downwards) correspond to runs for which the B_0 field points upwards (downwards). The dashed line corresponds to the theoretical expectation.

magnetic impurities: example: Electrode maps

Local dipoles -> mapping of electrodes and co-magnetometer

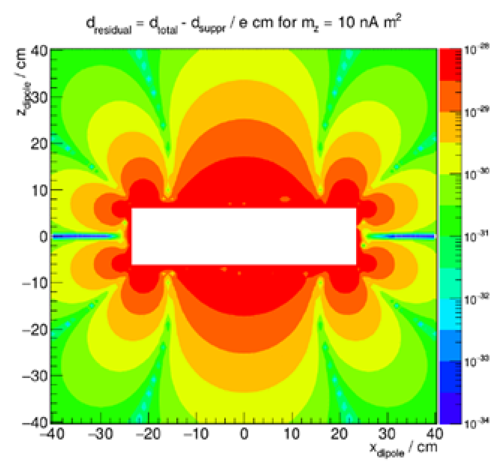
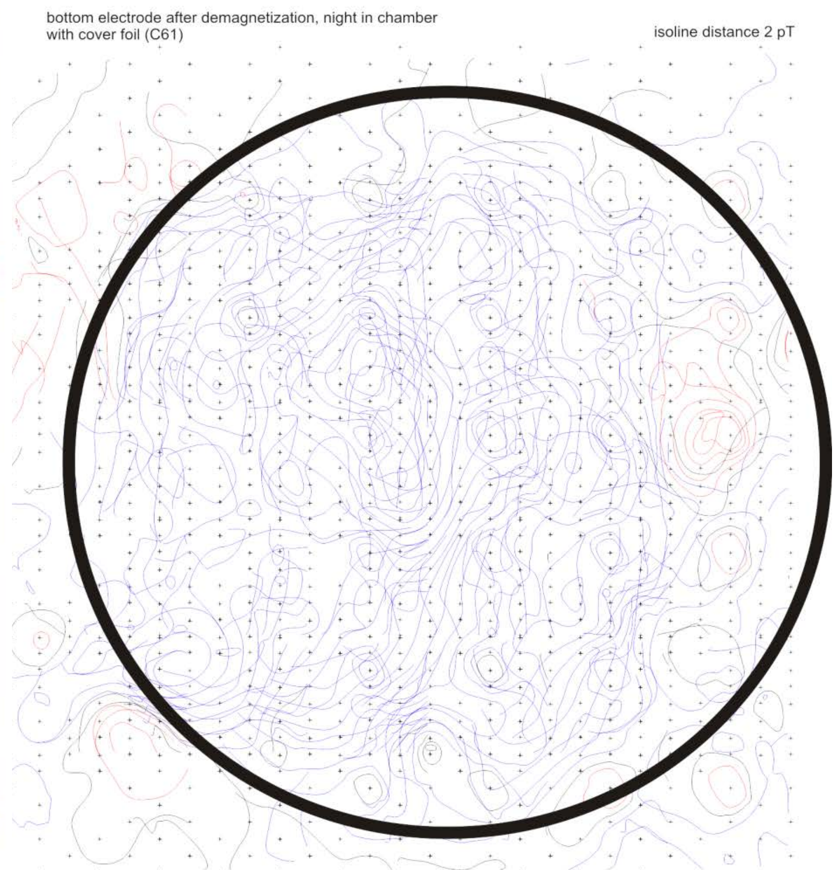


FIG. 6. Absolute residual false EDM created by a dipole located in the vertical plane $y = 0$, with a magnetic moment aligned with z and with $m_z = 10$ nA m^2, as a function of the position (x, z) of the dipole. The white area corresponds to the volume of the chamber (diameter 47 cm and height 12 cm).

@PTB Berlin

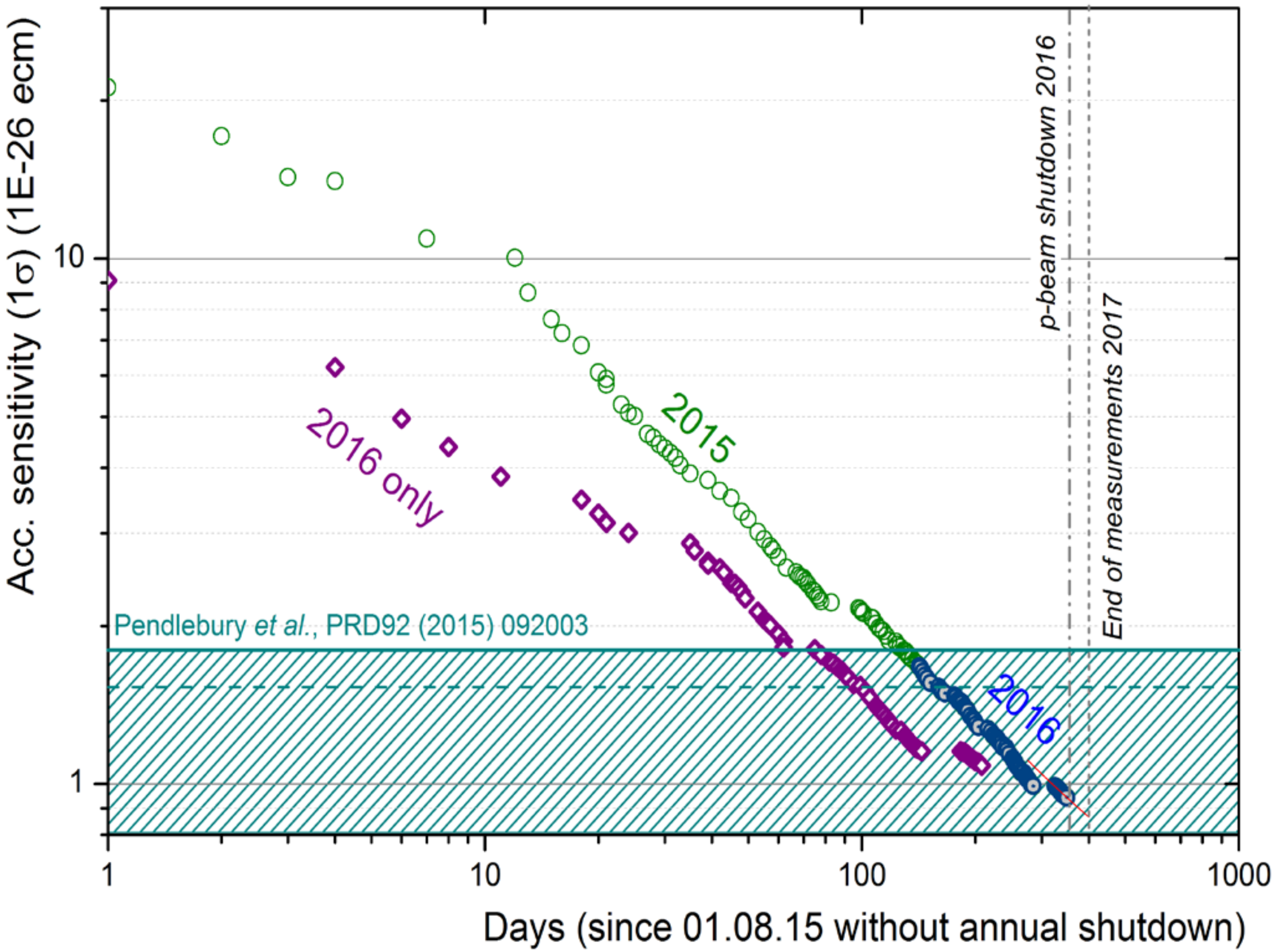
after degaussing



Maximum peak to peak: ~20 pT, or $d_{f,dipole} \leq 4x\ 10^{-28}$ ecm!

PSI experiment finished data taking in Oct.2017

→ record statistical sensitivity
→ apparatus dismounted
→ analysis is ongoing (double blinded)



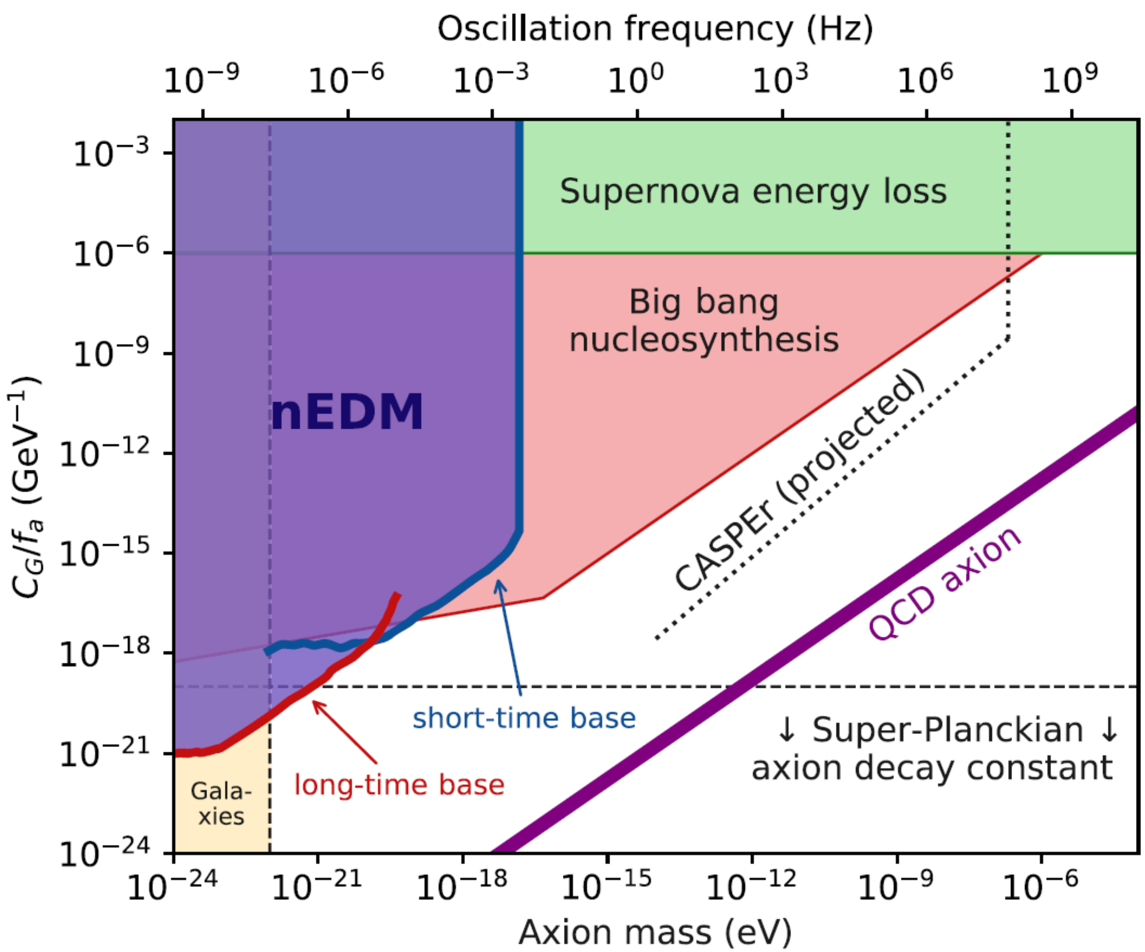
$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

54362 cycles
(exclude runs with issues)

$$\sigma = 0.94 \times 10^{-26}\text{ecm}$$

(before cuts)

Example physics results on the way with blinded data: PSI EDM together with RAL-Sussex data limit on ultra-light axions from oscillating nEDM



Oscillating EDM could come from the interaction of ultra-light axions which could be the dark matter in the Universe

nEDM places the first laboratory limit

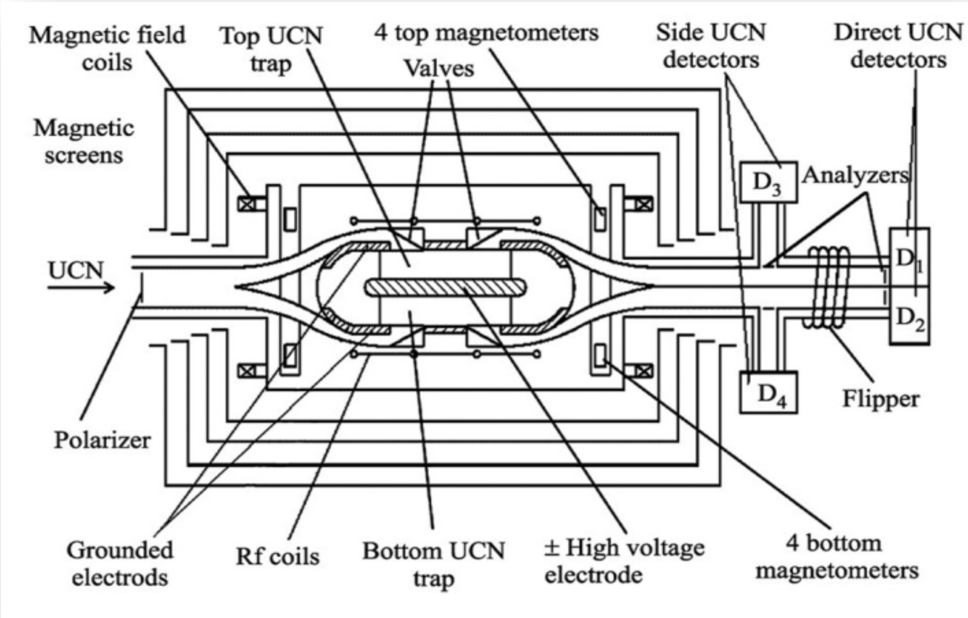
C. Abel et al, PHYSICAL REVIEW X 7, 041034 (2017)

New generation UCN storage apparatus various efforts worldwide

European projects
currently under construction

- PNPI @ILL and @PIK
- TUM @FRMII / moved to ILL
- n2EDM@PSI my generic example

nEDM @ PNPI (&ILL)



courtesy: Anatolii Serebrov

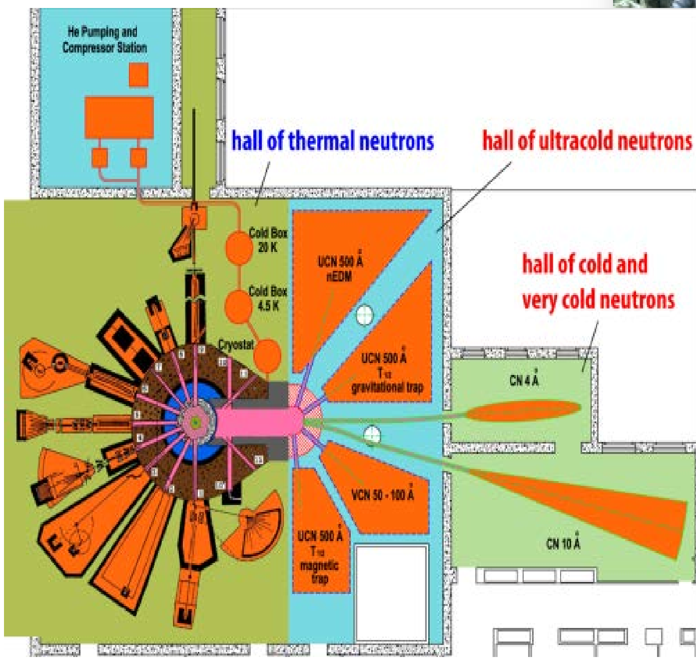
Reinforcement of platform for earthquake safety is under way - start measurements as soon as allowed by ILL safety

Current: $d_n < 5.5 \times 10^{-26} e\text{cm}$
Improvement by factor 3
at new position and with new precession cell

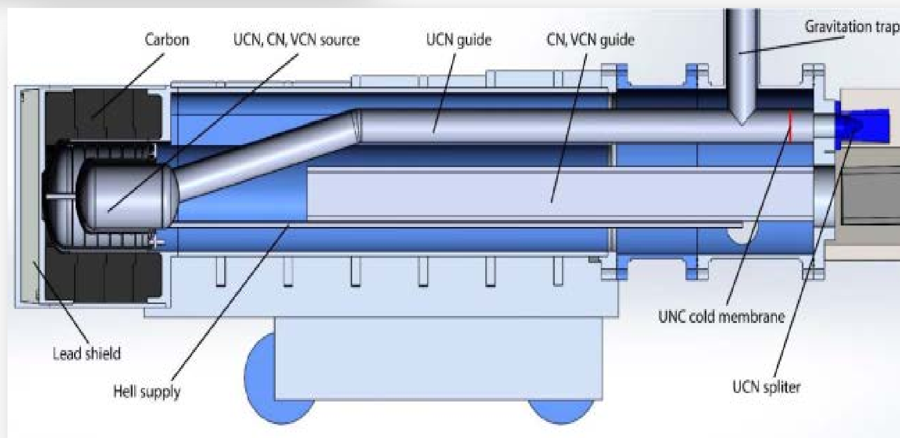
ILL > 2020: $d_n < 2 \times 10^{-26} e\text{cm}$
future source at PNPI: $d_n < 1 \times 10^{-27} e\text{cm}$

PNPI UCN source at WWR-M reactor

WWR-M reactor



- UCN density $>1 \times 10^4\ \mathrm{cm}^{-3}$
- All hardware exists
- Necessary cooling power test succesful
- Unclear whether and when WWR-M will get permission to operate



courtesy: Anatolii Serebrov

n2EDM@PSI the generic example

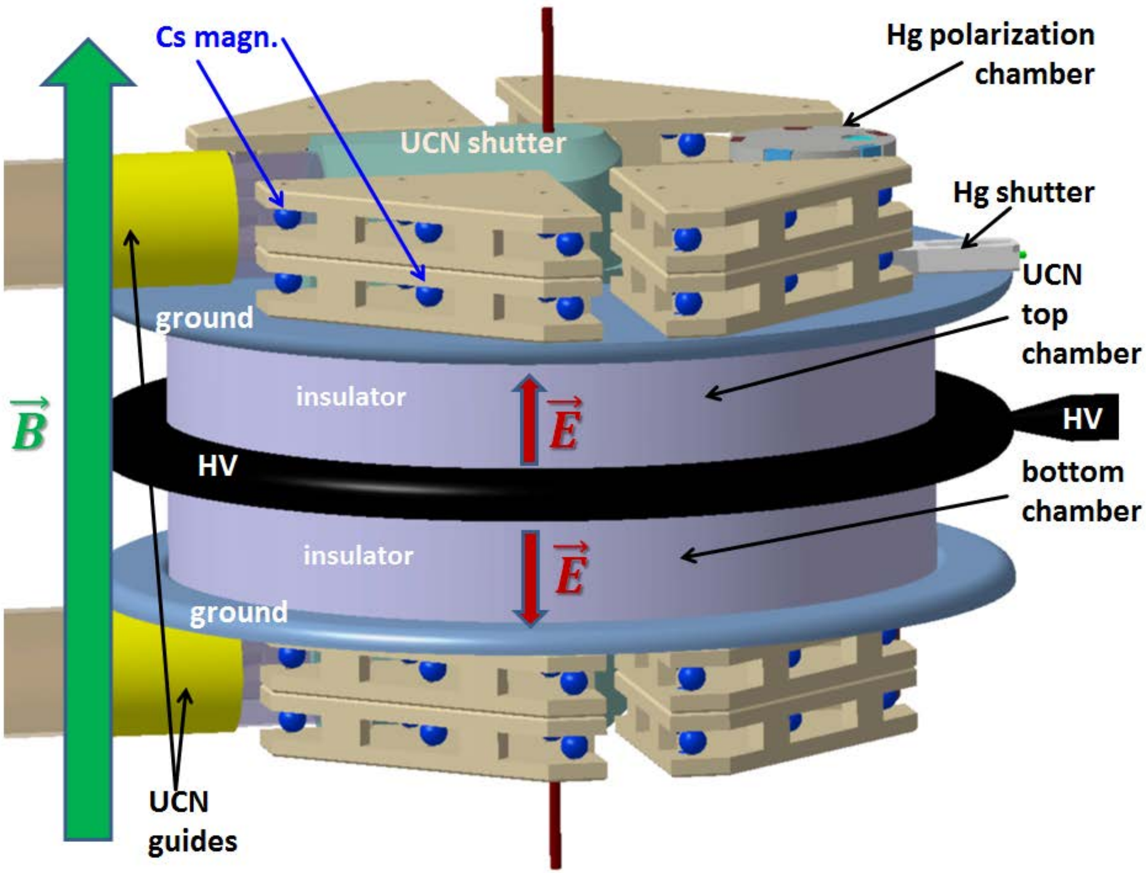
PSI Strategy:

Maximize UCN statistics with adequate adaption of systematics.

Construct a baseline apparatus ready in 2020 and upgrade from there.

Goal: $d_n \sim 1 \times 10^{-27}$ e cm for baseline apparatus

Main features of the new apparatus baseline setup



Inspired by the pioneering Gatchina double-chamber setup **I.Altarev et al. JETP Lett.44(1986)460** and several years of our **own upgrade and operating experience** with the present nEDM setup

- 2 neutron precession chambers with ID=80cm
- coating R&D ongoing

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

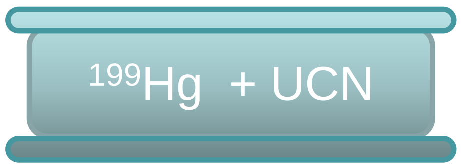
- Surrounded by calibrated Cs arrays on ground potential (>50 sensors)

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

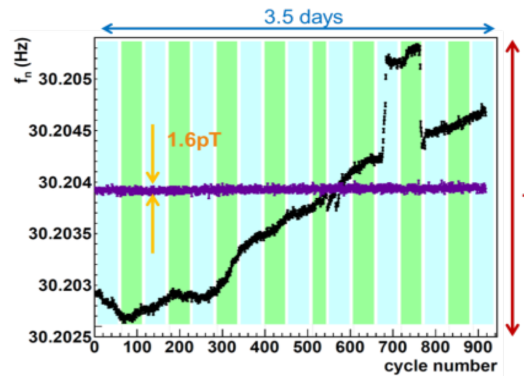
Analysis: Frequency ratio R = f_n/f_{Hg}

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

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



Δh



single chamber

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

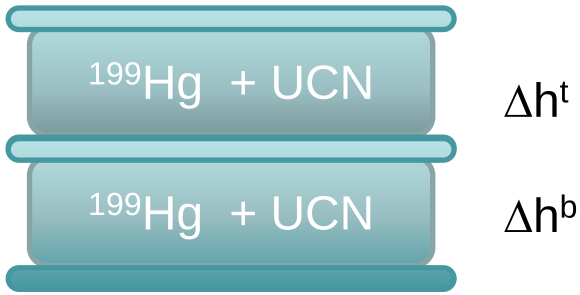
center of mass difference h

single chamber analysis - B and G fluctuations compensated by comagnetometer but gradient fluctuations introduce error term proportional to gravitational shift

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

Analysis: based on R as function of dB/dz extrapolate to 0

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



double chamber

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 896, 11 July 2018, Pages 129-138

Demonstration of sensitivity increase in mercury free-spin-precession magnetometers due to laser-based readout for neutron electric dipole moment searches

G. Ban [a], G. Bison [b], K. Bodek [c], M. Daum [b], M. Fertl [b, d, 1], B. Franke [b, d, 2], Z.D. Grujić [e], W. Heil [g], M. Horras [b], M. Kasprzak [e, 3], Y. Kermaidic [f, 4], K. Kirch [b, d], H.-C. Koch [e, g, 3], S. Komposch [b, d], A. Kozela [h], J. Krempel [d], B. Lauss [b], T. Lefort [a] ... G. Zsigmond [b]

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

$$R^T - R^B = \frac{2E}{\pi\hbar f_{\mathrm{Hg}}} d_{\mathrm{n}} + \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(h^T - h^B\right)\frac{G}{B_0}$$

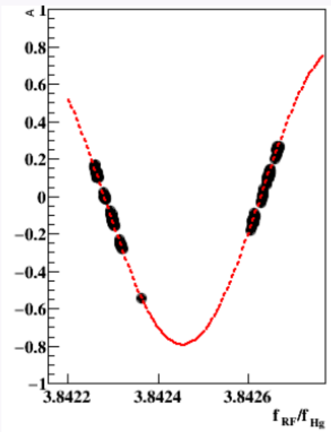
Analysis: based on (R^T - R^B) as function of dB/dz extrapolate to 0

Selected requirements for the given statistics goal

Vertical uniformity $\partial B_z/\partial z$	0.7 pT/cm
Horizontal uniformity $\partial B_z/\partial x, y$	8 pT/cm

Same frequency for the pi/2 pulses for both chambers:

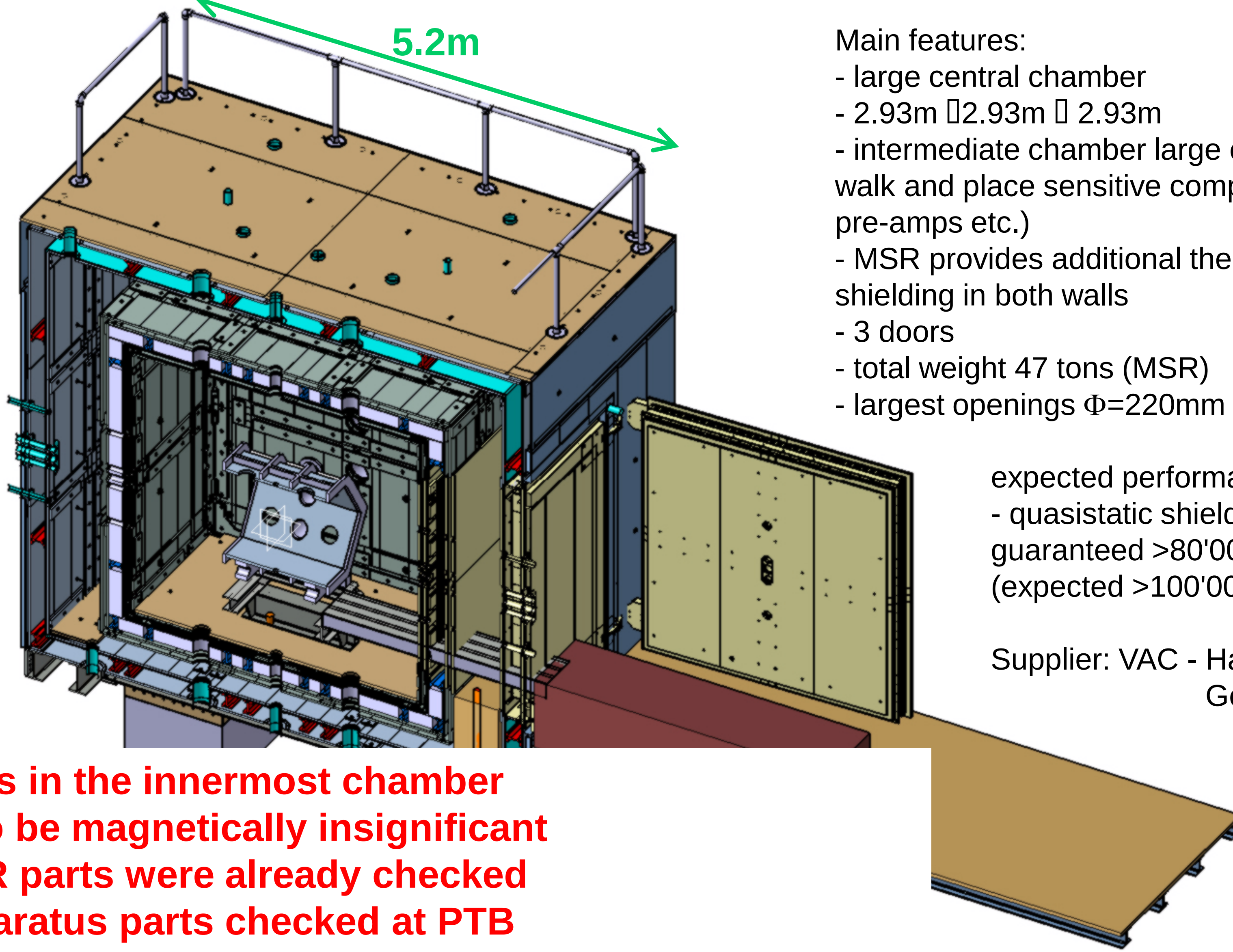
Larmor frequency should be the same in both chambers.
$\boldsymbol{\partial_z B_z}$ must be small.



$\boldsymbol{\partial_{x,y} B_z}$ should be small enough not to induce intrinsic depolarization of UCNs and decrease the visibility α.

$$T_2^{hgr} \approx \frac{9\pi v}{D^3\gamma_n^2(\partial B_z/\partial x)^2}$$

Precession chamber inside a large magnetically shielded room (MSR)



Main features:
- large central chamber
- 2.93m × 2.93m × 2.93m
- intermediate chamber large enough to walk and place sensitive components (e.g. pre-amps etc.)
- MSR provides additional thermal shielding in both walls
- 3 doors
- total weight 47 tons (MSR)
- largest openings Φ=220mm

expected performance:
- quasistatic shielding factor guaranteed >80'000 (expected >100'000)

Supplier: VAC - Hanau, Germany

all parts in the innermost chamber have to be magnetically insignificant
all MSR parts were already checked
all apparatus parts checked at PTB


Area B-field mapping
10
12
035
039

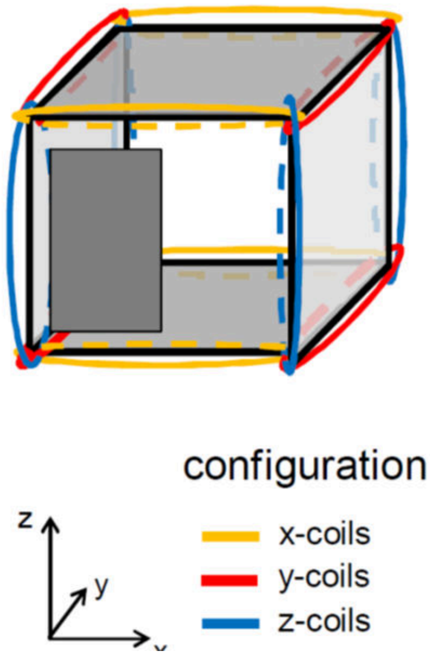

Support setup
10
12
13
035
039

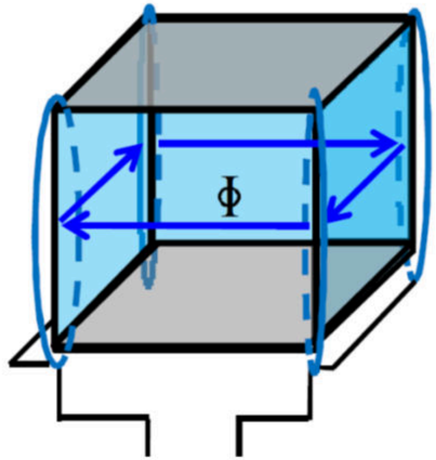

MSR setup
10
12
obrist
obrist
obrist


Finshed outer MSR cabin
10
obrist
obrist
obrist

Important: minimizing the remanent feld

B-field equilibration scheme and coils layout based on PTB-Berlin experience
published in J.Voigt et al. Metrol.Meas.Sys. 20,2 (2013) 239
innermost layer more complex coil scheme

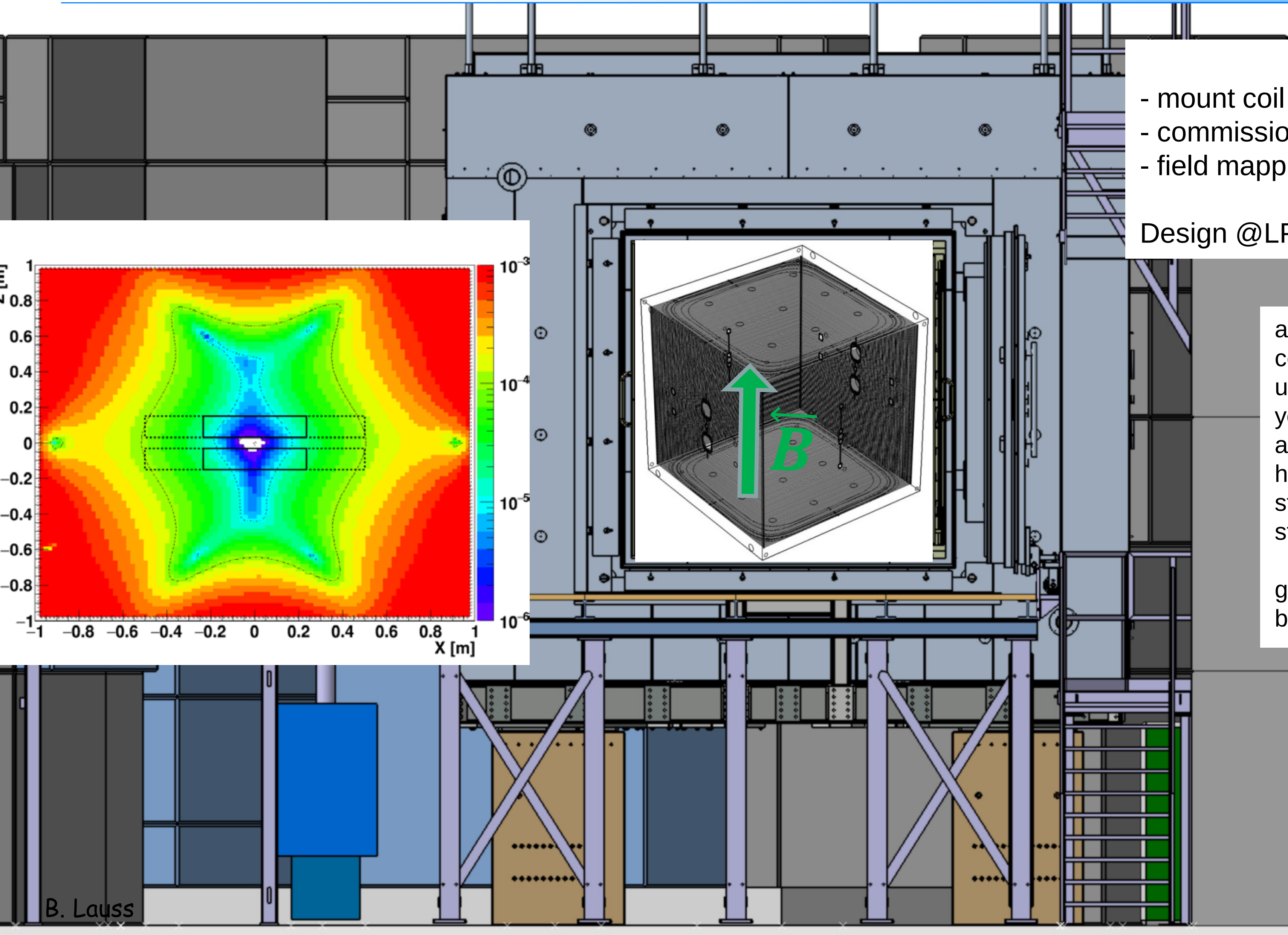




planned minimization from outside to inside for each layer and direction possible

- innermost room has additional 2 coils on all sides and in all 3 directions to drive magnetic flux in all walls and wall centers

Field coil system - 1μT



- mount coil system
- commission individual coils
- field mapping

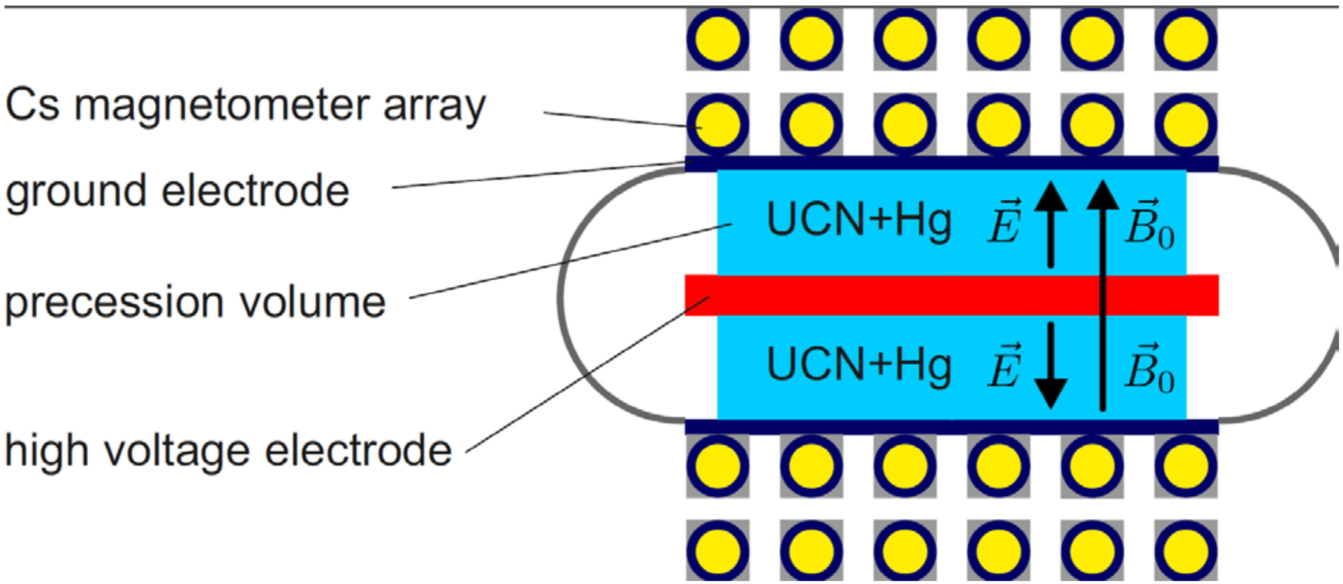
Design @LPC CAEN

adapted box-shape B0 coil which uses MSR as return yoke provides adequate homogeneity and stability via current stabilization

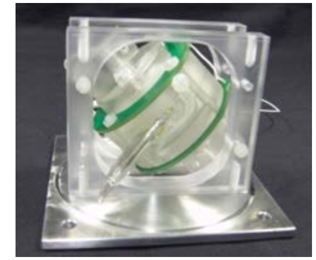
goal is uniformity better than 10^{-4}

PhD
Pierrick Flaux

Cs magnetometer array



work of Georg Bison



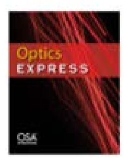
Cs sensor

- homogenisation & control of B field
- (higher) gradient measurement and control in all directions
- measurement of correlations with E-fields
- crucial for systematics control

Highly stable atomic vector magnetometer based on free spin precession

S. Afach, G. Ban, G. Bison, K. Bodek, Z. Chowdhuri, Z. D. Grujić, L. Hayen, V. Hélaine, M. Kasprzak, K. Kirch, P. Knowles, H.-C. Koch, S. Komposch, A. Kozela, J. Krempel, B. Lauss, T. Lefort, Y. Lemière, A.

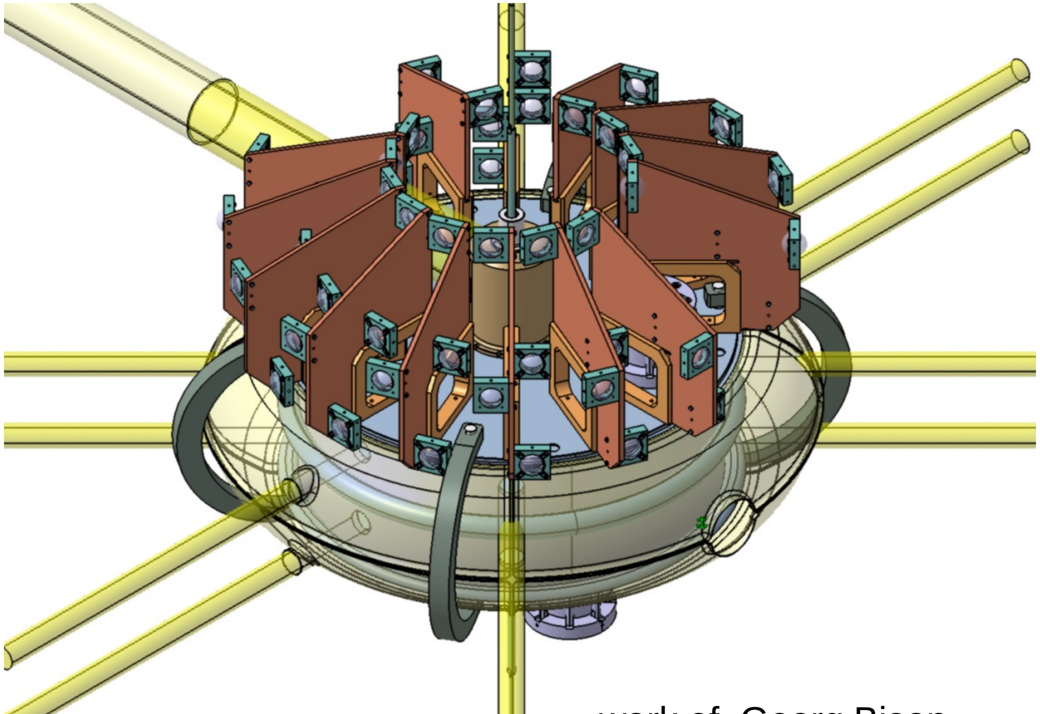
#243536 Received 24 Jun 2015; revised 4 Aug 2015; accepted 4 Aug 2015; published 13 Aug 2015
(C) 2015 OSA 24 Aug 2015 | Vol. 23, No. 17 | DOI:10.1364/OE.23.022108 | OPTICS EXPRESS 22109



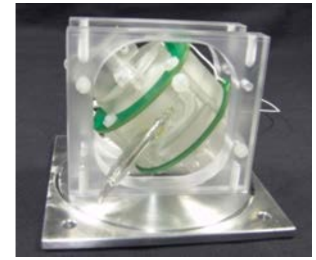
- develop ^{3}He magnetometry further for absolute B measurement and sensor calibration

Cs magnetometer array

techn. design



Cs sensor



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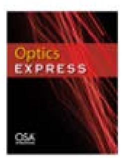
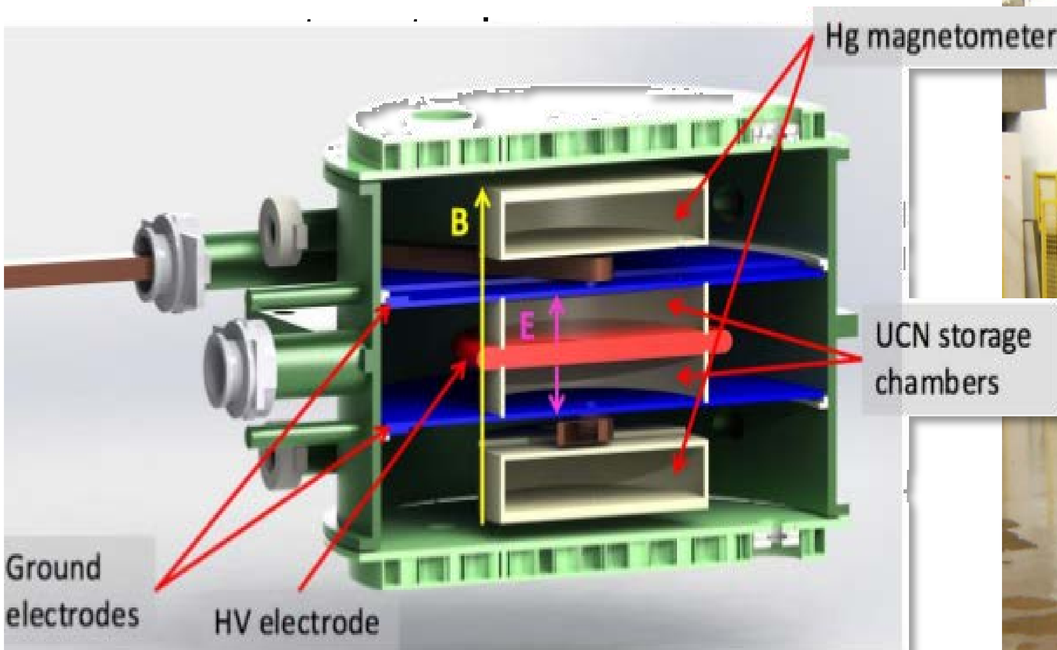


- develop ^3He magnetometry further for absolute B measurement and sensor calibration

ILL / TUM project

ILL/TUM effort:
Berkeley, ILL, Jülich, LANL, Michigan, MSU, NCSU, PTB, RAL, TUM, UIUC, Yale

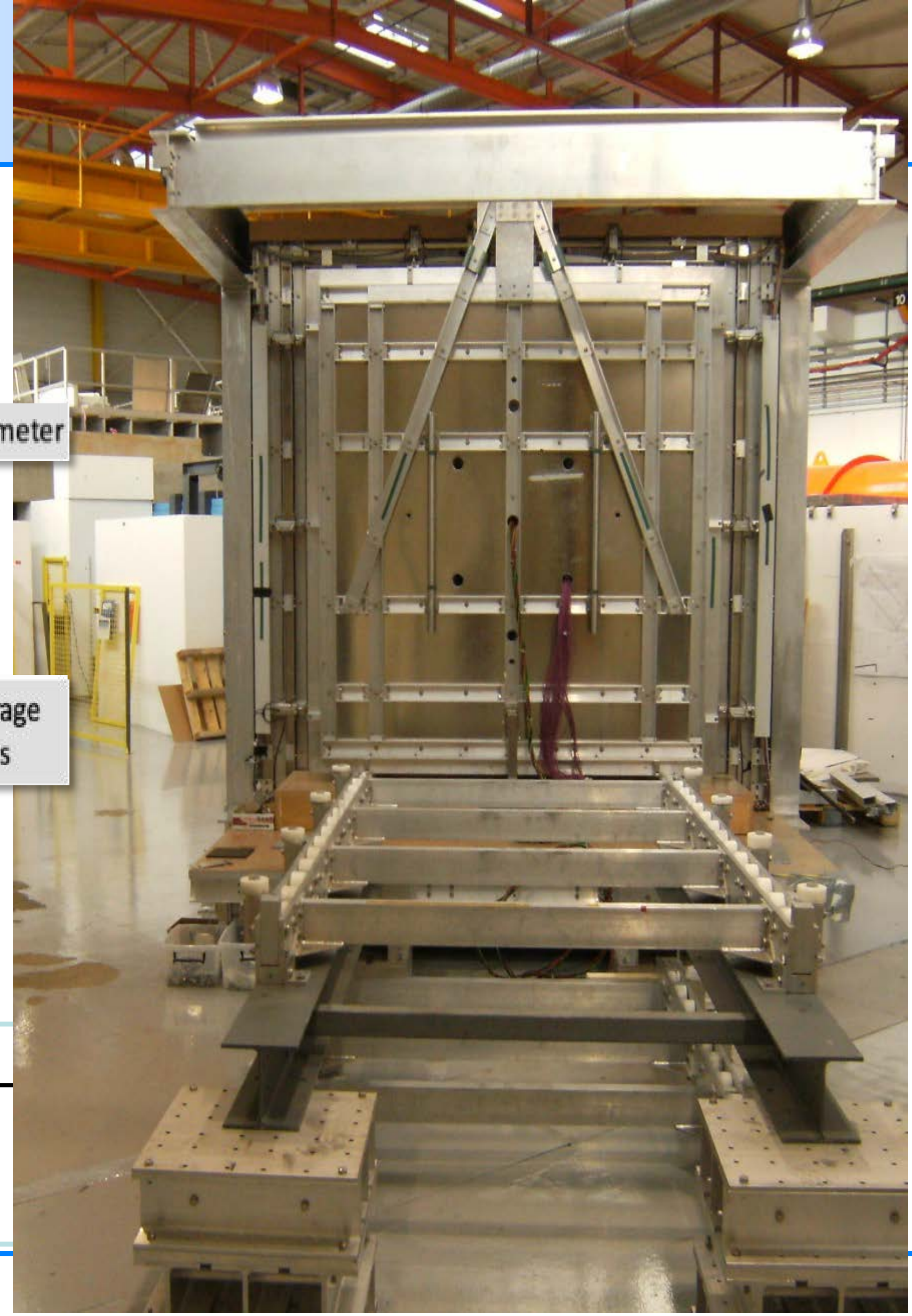


Transparency courtesy Skyler Degenkolb

New UCN source based on He-II at ILL

Phase 1 (from 2019) $1.9 \times 10^{-27} e\text{cm}$

Phase 2 (later) $4.2 \times 10^{-28} e\text{cm}$



Summary

Several effort to search for a neutron EDM in Europe

- prototype beam EDM at U Bern
- crystal EDM at ILL

stored UCN

- PSI: ongoing analysis of blinded data set with $\sim 1\cdot 10^{26}$ *ecm* statistical sensitivity - result 'soon'.
Installation of new setup n2EDM ongoing - factor 10 sensitivity improvement for baseline setup

- ILL / PNPI waiting for reinforced platform to start measuring
- ILL / TUM installation of MSR and apparatus ongoing,
UCN source ready at ILL 2019 ? - UCN source at TUM ?

- PNPI PIK reactor / waiting for reactor start ?

thank you

cordial thanks for providing transparencies to
Anatoli Serebrov, Vladimir Voronin, Skyler Degenkolb
Florian Piegsa, Philipp Schmidt-Wellenburg, Georg Bison

the collaboration

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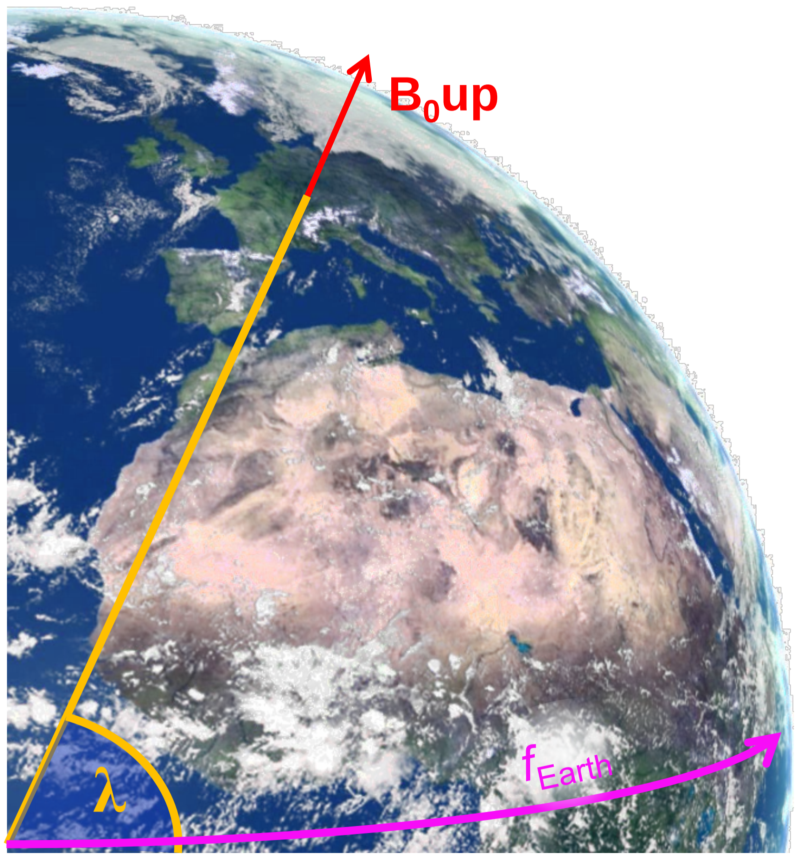
S. Emmenegger, K. Kirch[1], J. Krempel	*Eidgenössische Technische Hochschule*, ***Zürich***

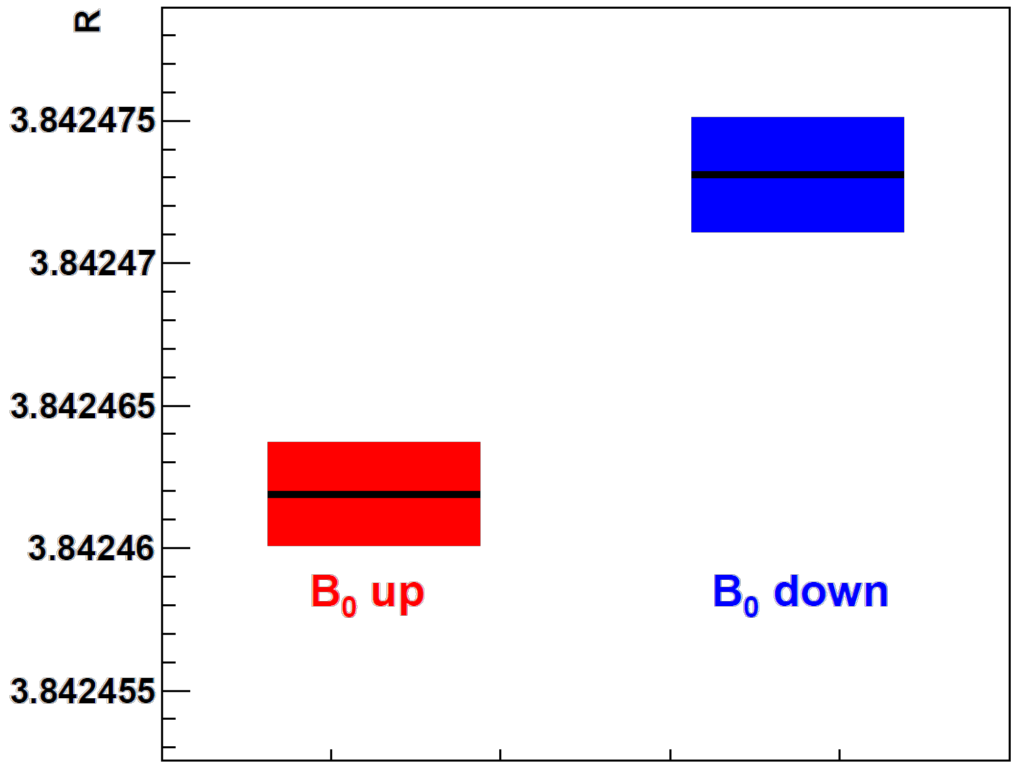
also at: [1]*Paul Scherrer Institut*, [2]*Eidgenössische Technische Hochschule*

R-curve analysis / earth rotation Foucault's UCN pendulum

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

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





*S. Lamoreaux PRL98(2007)149101

R-curve analysis / earth rotation
Foucault's UCN pendulum

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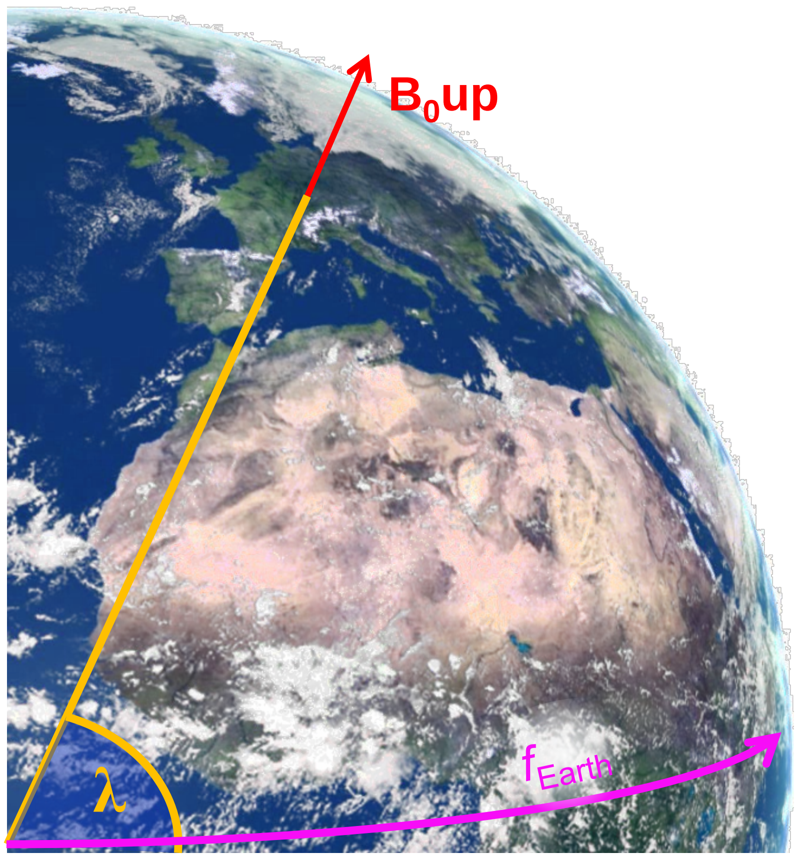
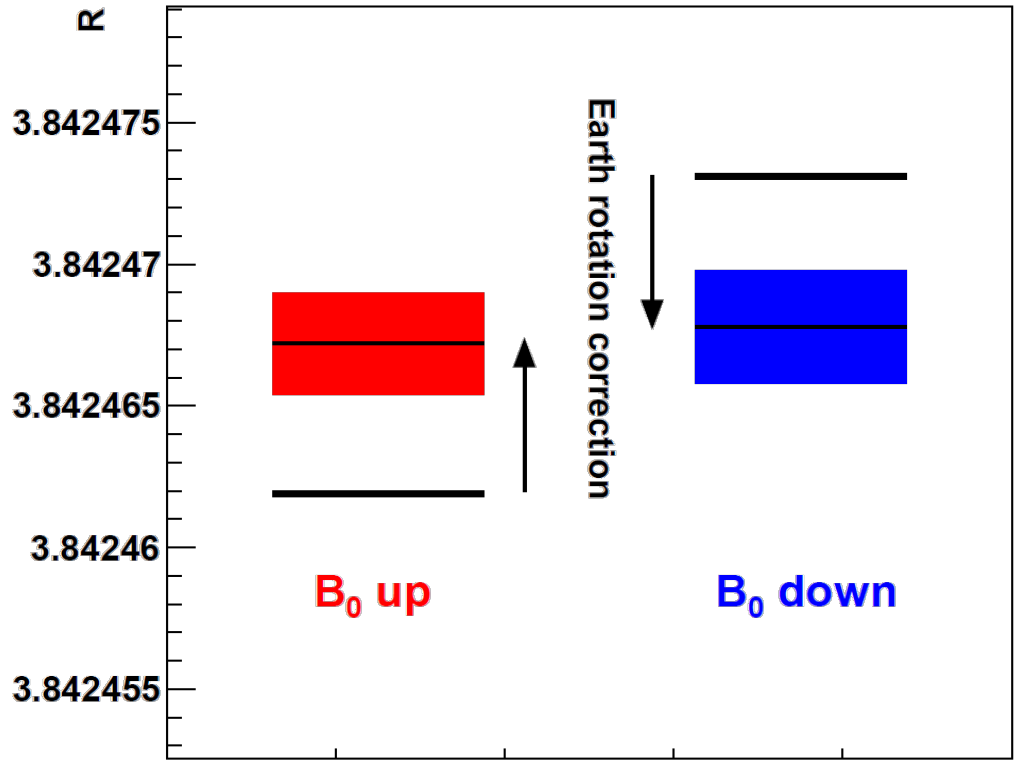


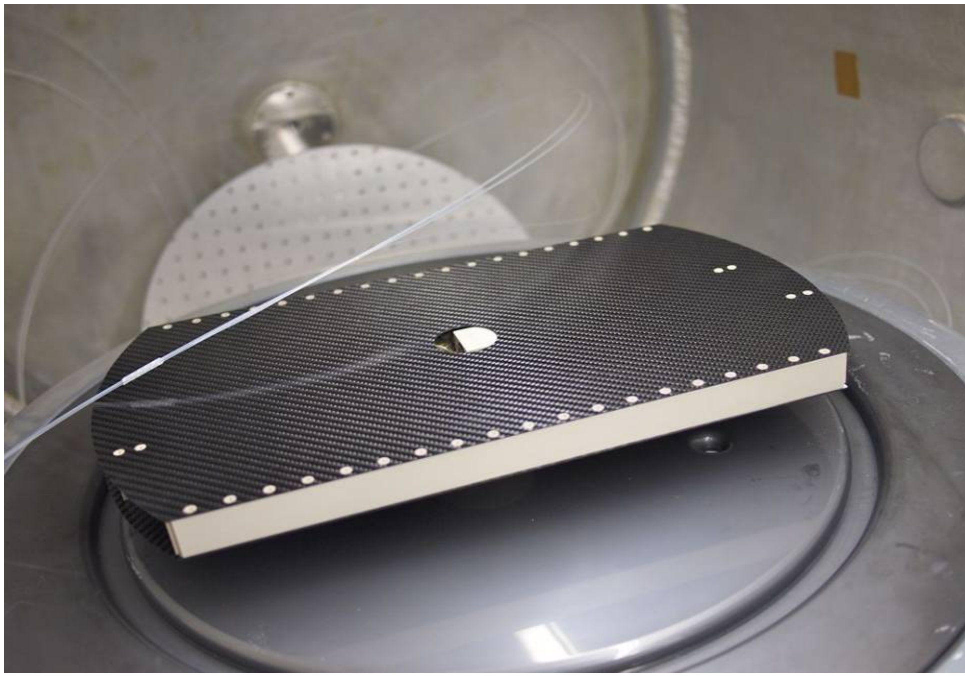
checks B-field control

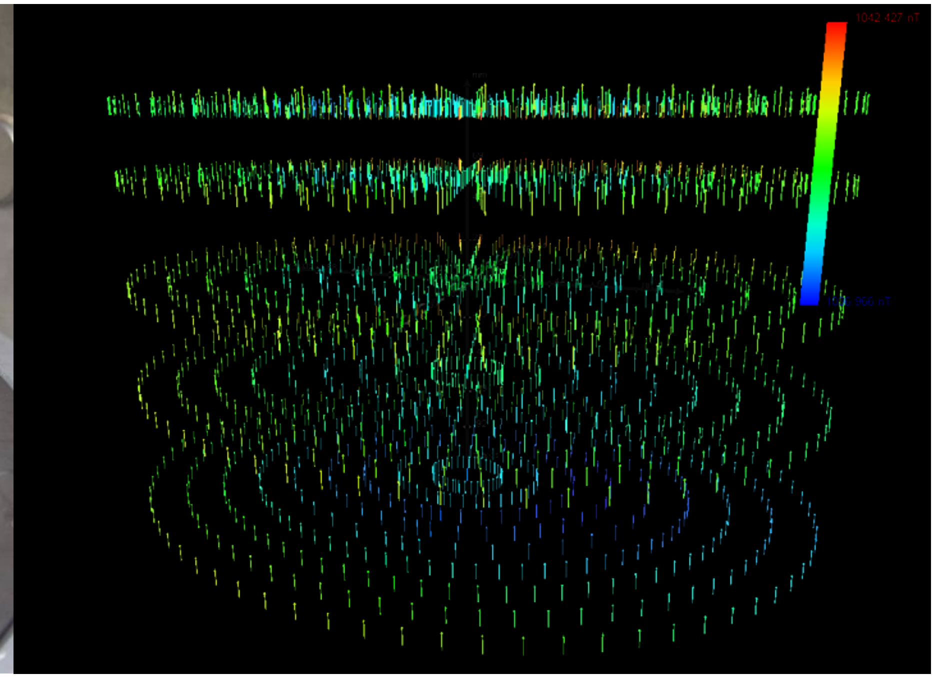


*S. Lamoreaux
PRL98(2007)149101

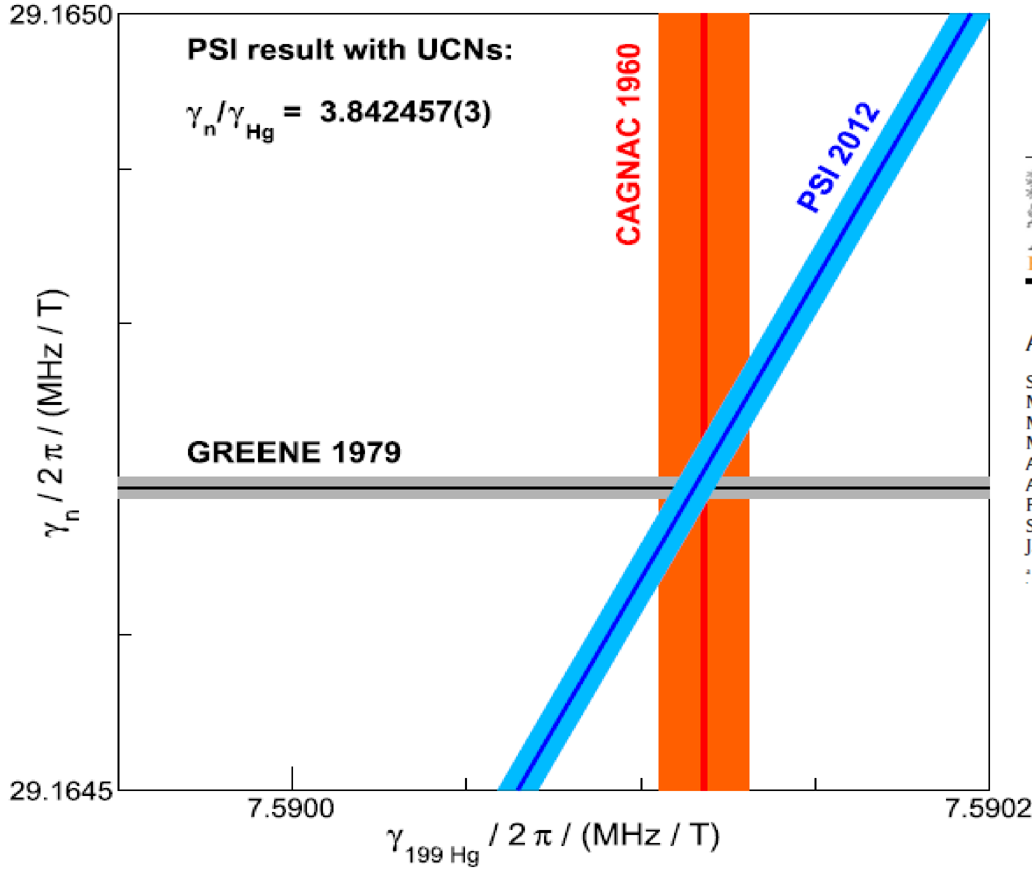
Internal mapper

- The spatial homogeneity of the magnetic field is characterized with a movable robot → map the magnetic field of each trimcoil and the main field





Example physics results on the way: neutron/Hg magnetic moment



Physics Letters B 739 (2014) 128–132

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A measurement of the neutron to ^{199}Hg magnetic moment ratio

CrossMark

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Fig. 4. 1-sigma allowed regions in the γ_n, γ_{Hg} plane. Our final value for the neutron to mercury magnetic moment ratio (18) here labeled as "PSI 2012" forms the diagonal band. The horizontal band is the neutron magnetic moment (1) value from Greene et al. and the vertical band is from the measurement of the mercury magnetic moment (2) by Cagnac.