Title: Precision measurements in small magnetic fields

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Abstract:

Technische Universität München

Precision measurements and small magnetic fields

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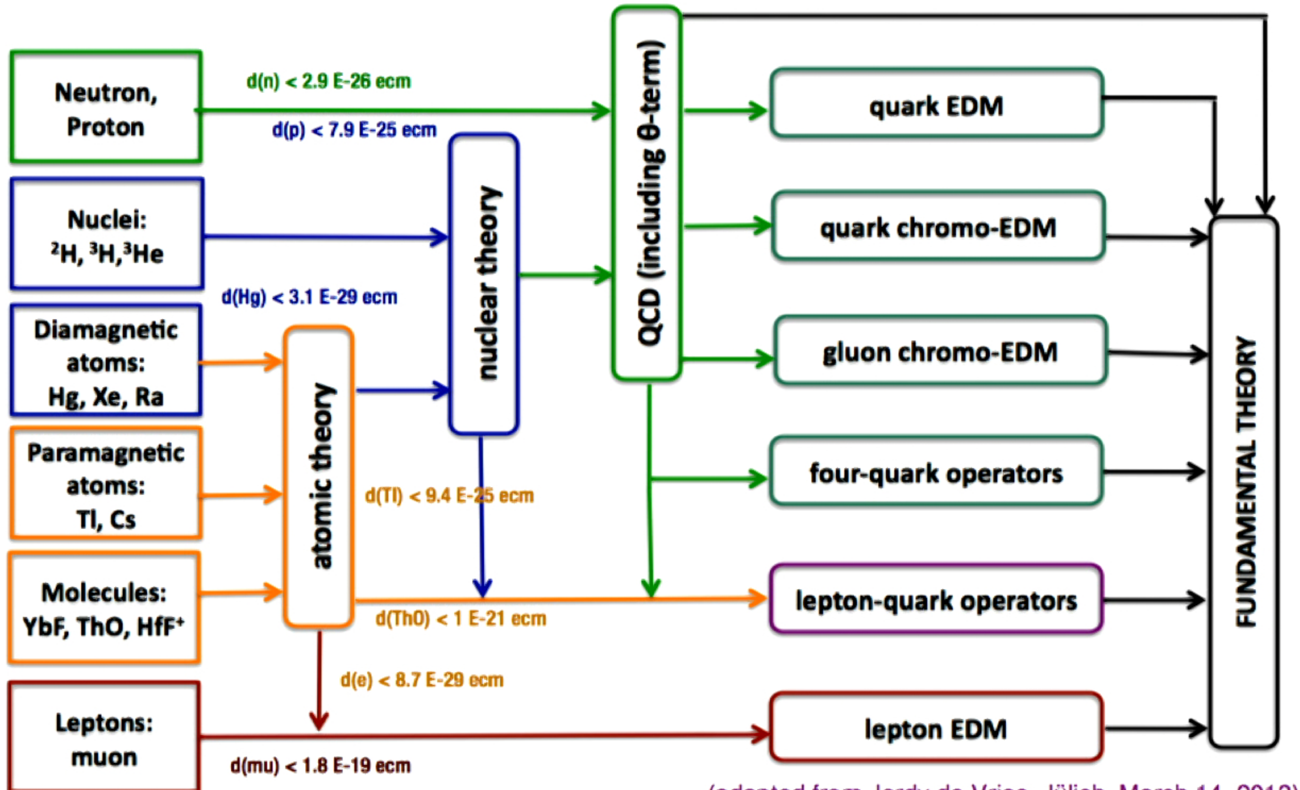
Experimental Techniques in Table-Top Fundamental Physics
Perimeter Institute
23.8.2017

Content

- Motivation: systematics in electric dipole moment experiments, example: neutron EDM - from 10^{-26} ecm -> 10^{-28} ecm
- Status in magnetic shielding & applications
- Xenon EDM and neutron EDM update

Different EDM measurements are needed



(adapted from Jordy de Vries, Jülich, March 14, 2013)

Different EDM measurements are needed

(Under review: T. Chupp, PF, M.J. Ramsey-Musolf, J. Singh, Rev. Mod. Phys.)

e and μ EDM

Nuclear-spin-dependent e-N coupling C_T,

Nuclear-spin independent couplings C_S^0

Intrinsic quark EDMs and chromo EDMs

Meson-nucleon couplings $g_\pi^{0,1,(2)}$

- Paramagnetic atoms

$$d_{para} = \eta_{d_e} d_e + k_{C_S} \bar{C}_S$$

- Polar molecules

$$\Delta\omega^{\not{P}\not{T}}_{para} = \frac{-d_e E_{eff}}{\hbar} + k^{\omega}_{C_S} \bar{C}_S$$

- Diamagnetic atoms

$$d_{dia} = \kappa_S S(\bar{g}_\pi^{0,1}) + k_{C_T} C_T + \ldots$$

- Nucleons

$$d_{n,p} = d^{lr}_{n,p}(\bar{g}_\pi^{0,1}) + d^{sr}_{n,p}(\tilde{d}_{u,d}, d_{u,d})$$

- Fundamental fermions

$$d_e, d_\mu, (d_\tau)$$

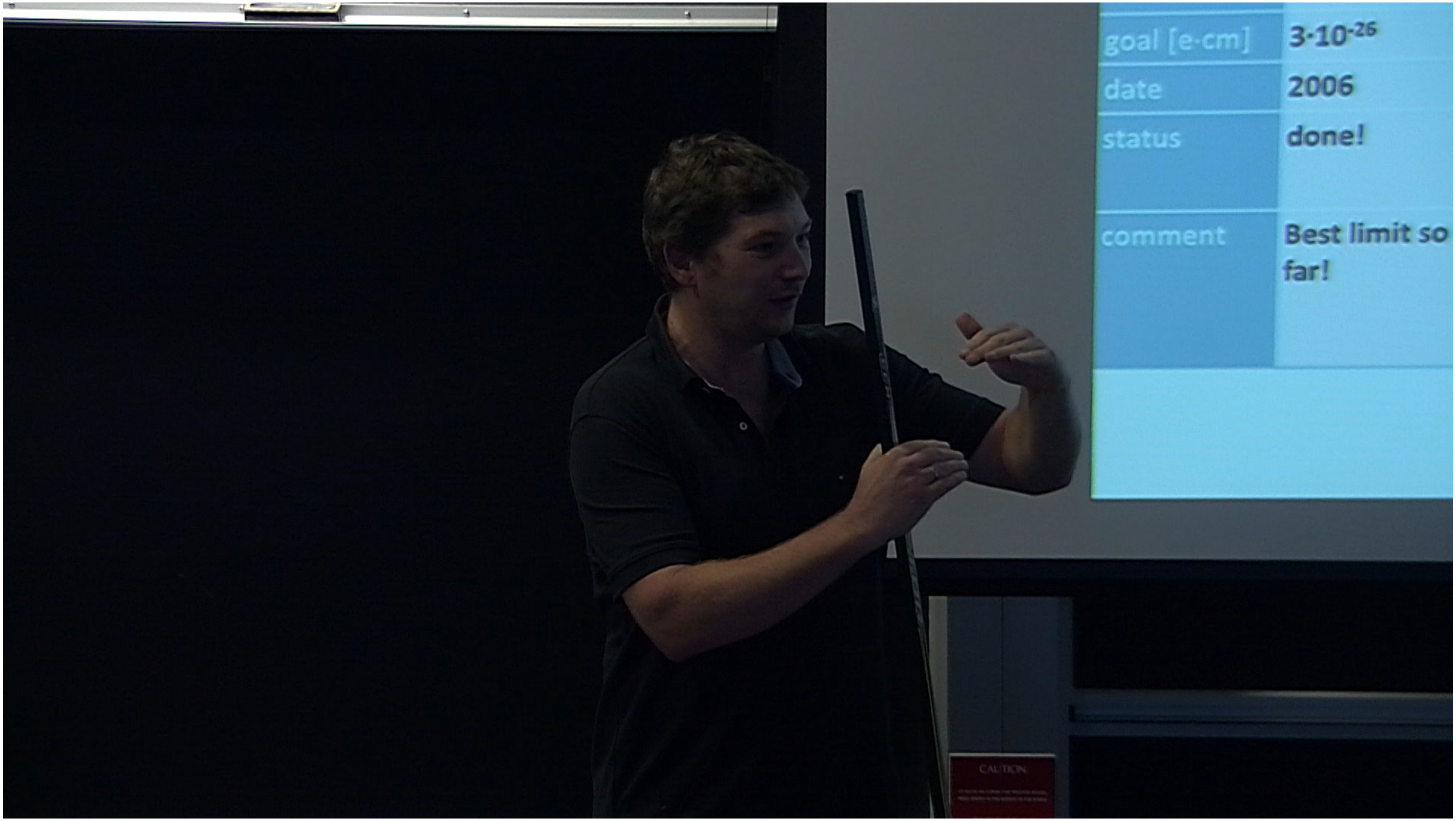
...Higher order effects (e.g.199-Hg) :

$$d_A = (k_T C_T + k_S C_S) + \eta_e d_e + \kappa_S S + \text{h.o. (MQM)}$$

Neutron EDM projects

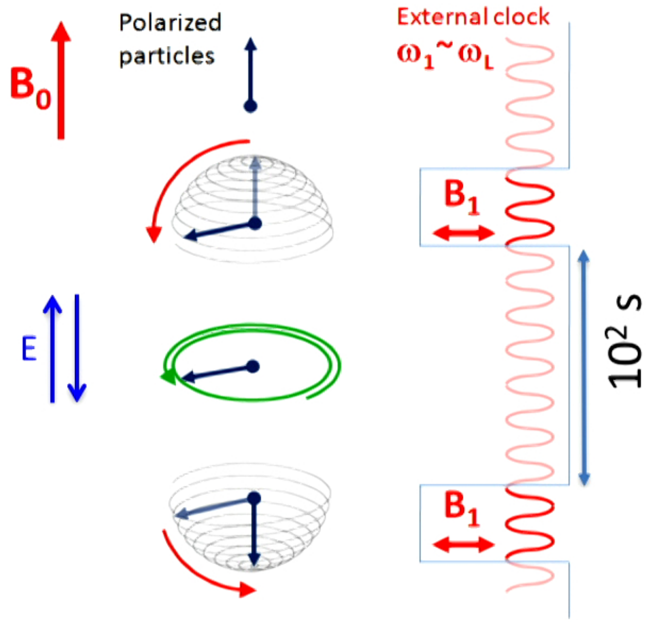
	RAL SUSSEX ILL (Grenoble, FR)	PSI (Villigen, CH)		TUM ILL (Grenoble, Munich)		LANCSE EDM (Los Alamos, US)	SNS EDM (Oakridge, US)	PNPI ILL (Grenoble, FR ⇒ Gatchina, RU)		TRIUMF (Vancouver, CA)	
temperature	**RT**	RT		RT	0.7 K	RT	0.7 K	**RT**		RT	
comag	**Hg**	**Hg**		none		Hg	^{3}He	**none**		Xe+Hg	
source	**reactor, turbine**	**spall., sD_2**		reactor, cold neutrons, ^{4}He		D2	spall, internal ^{4}He	reactor, turbine, ^{4}He		spall., ^{4}He	
nr of cells	**1**	**1**	2	2		1	2	2	>2	1	2
[UCN/cc]	**2**	**3**	5	10	1000	~ 50	125	**4**	10^4	700	
goal [e·cm]	**$3\cdot10^{-26}$**	$1\cdot10^{-26}$	$1\cdot10^{-27}$	$3\cdot10^{-27}$	$< 10^{-27}$	few 10^{-27}	$2\cdot10^{-28}$	**$5\cdot10^{-26}$**	$5\cdot10^{-28}$		$1\cdot10^{-27}$
date	**2006**	**2017**	2019	2018	2021+	2018	2021	**2015**	2022	2017	2019
status	**done!**	using RAL exp.	new	Modifications for Munich ⇒ ILL, D_2 ⇒ He		Source ready	Critical Component Demonstration			Component development phase	
comment	**Best limit so far!**	Source delivery behind expectations		UCN source in Munich delayed since a decade ⇒ go to ILL for now		Will be faster than expected	great concept, high risk				

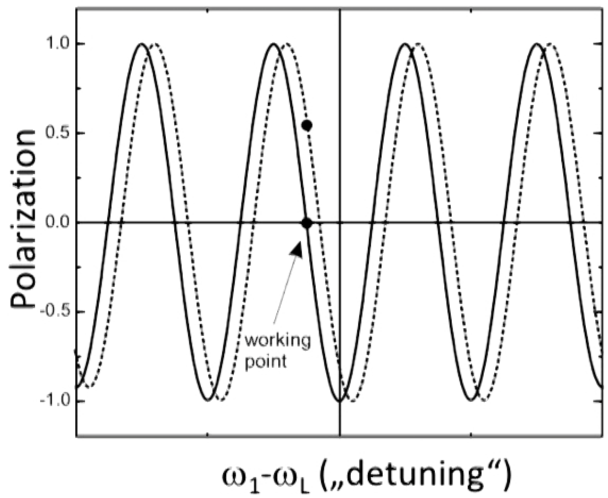
Taken from R. Picker (2016), adapted


goal [e·cm]
3·10-26
date
2006
status
done!
comment
Best limit so far!

Measuring the neutron's EDM: Ramsey's method

(Particle beam or trapped particles)





$$\hbar\omega_L \sim \mu B + dE$$

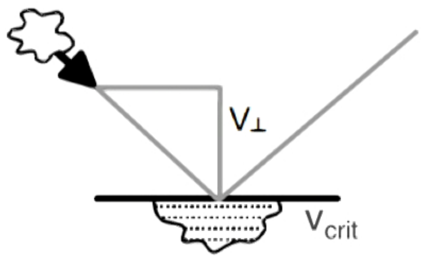
$$\sigma_{d_n} = \frac{h}{2\alpha E T \sqrt{N}}$$

Ultra-cold neutrons (UCN)

T ~ mK, E_{kin} < 200 **NANO**-eV, v < 7 m/s, λ > 50 nm

Strong Interaction:
‚Fermi potential'

$$U_F \propto N \cdot b_c \sim 100 \text{ neV}$$



Optical properties:
- Neutron traps (UCN: $v_{tot} < v_{crit}$)
- Neutron guides (CN: $v_{\perp} < v_{crit}$)

Electromagnetism:

Magnetic moment:
|B| = 60 neV/T
… magnetic traps
... perfect polarization

Weak Interaction:

$$n \to p + e^{-} + \bar{\nu}_e$$

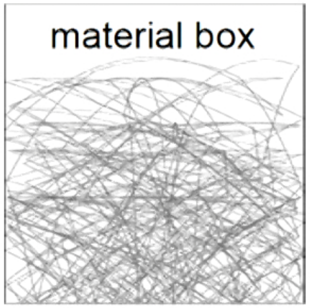
τ ~ 881 s

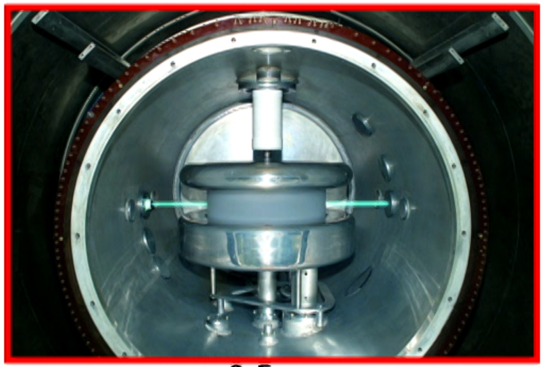
Gravity:

$V = m_n g h$ 100 neV/m

Neutron EDM

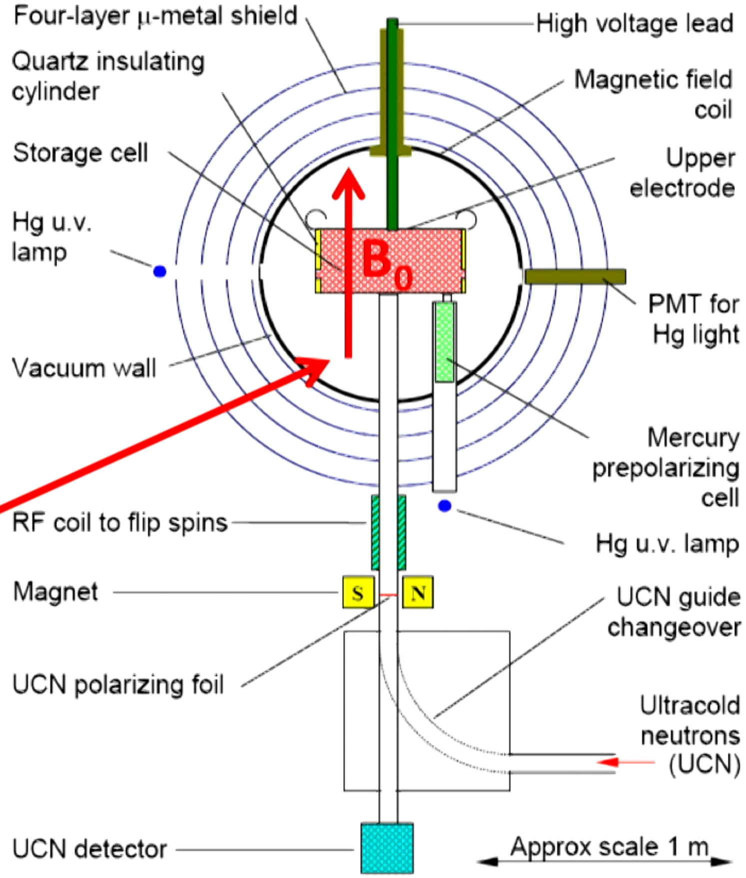
Ultra-cold neutrons (UCN) trapped at 300 K in vacuum
~ 4 UCN / cm³





~ 0.5 m

(RAL/SUSSEX/ILL experiment)



Two species comparison

- Neutrons +^{199}Hg vapor measured simultaneously
- UCN center of mass is affected by gravity
- No cross talk

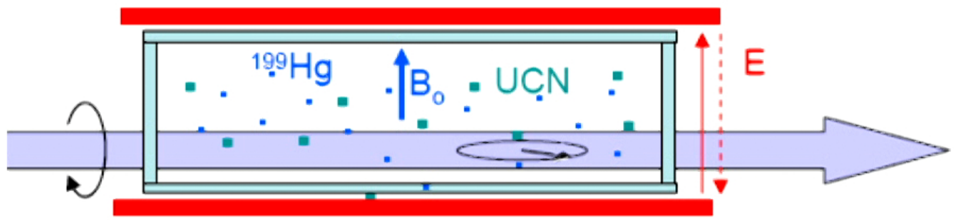
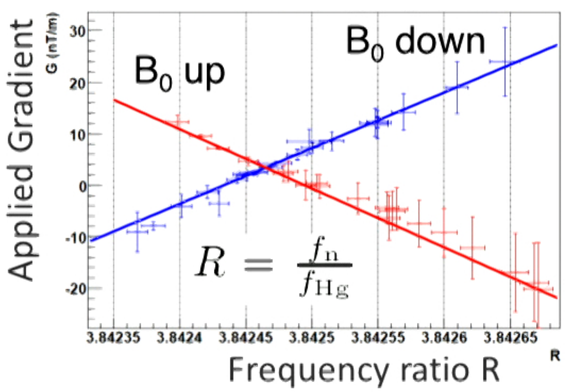


Illustration (2008 data)

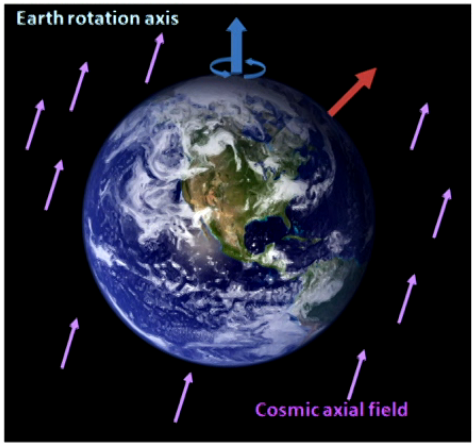


Best limit:
$d_n < 3 \times 10^{-26}$ e cm*

Energy resolution:
$\Delta E \sim 10^{-22}$ eV

Baker et al., Phys. Rev. Lett. 97 (2006) 131801. + re-analysis (2015)

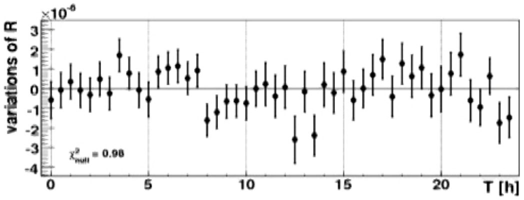
Spin offs: CPT, Lorentz invariance



Background field which couples to spin:

$$V = \frac{\hbar}{2}\gamma_n \, \sigma \cdot \mathbf{B} + \sigma \cdot \tilde{\mathbf{b}}$$

... Would be visible as sidereal or daily modulations



More :

$$V = b_i\sigma_i - \mu_{ij}\,\sigma_i B_j - d_{ij}\,\sigma_i E_j$$

A. Kostelecky et al.

Romalis, Pospelov

$$d_{12} < 15 \times 10^{-25}\ e\,\text{cm} \quad (95\ \%\ \text{C.L.})$$
$$d_{24} < 10 \times 10^{-25}\ e\,\text{cm} \quad (95\ \%\ \text{C.L.})$$

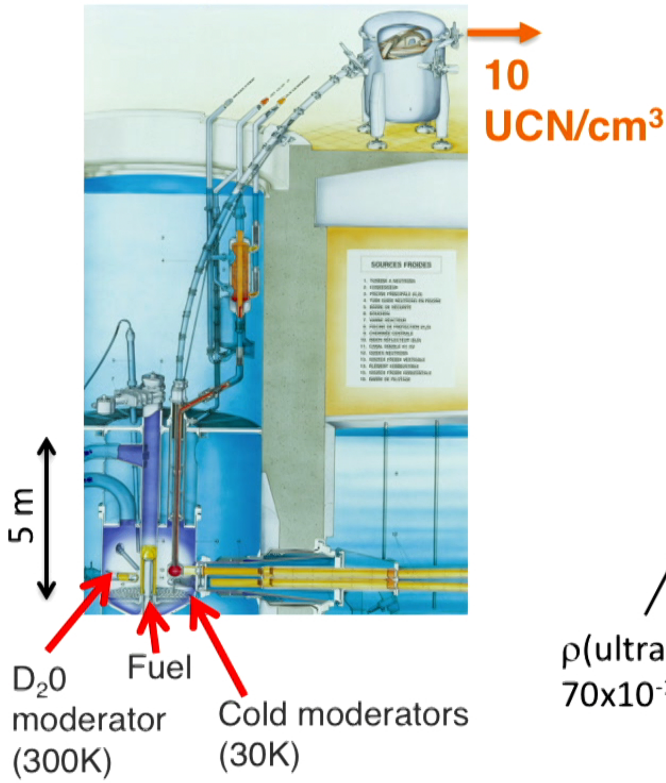
$$\Rightarrow \quad d_{ij} \approx \frac{e\hbar c}{\mathcal{E}_{\rm LV}} \quad \Rightarrow \quad \mathcal{E}_{\rm LV} > 10^{10}\ \text{GeV}$$

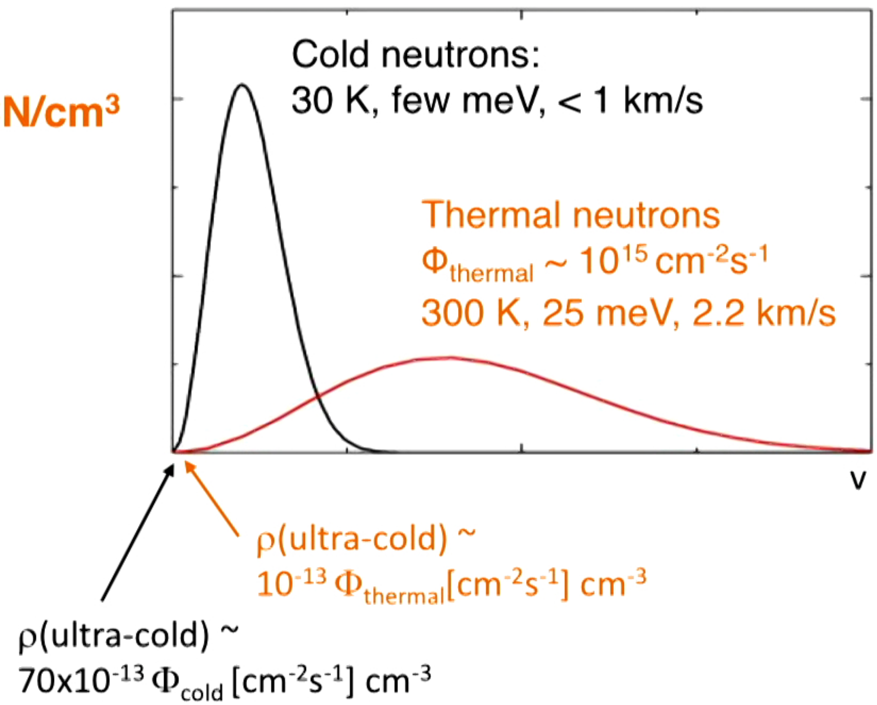
(Dis)advantage: low density of cohabitating species, Discontinued after 2010...

I. Altarev et al., EPL, 92 (2010) 51001
I. Altarev et al., PRL **103**, 081602 (2009)

Where do UCN come from?

Neutron source at Institute Laue-Langevin (Grenoble):



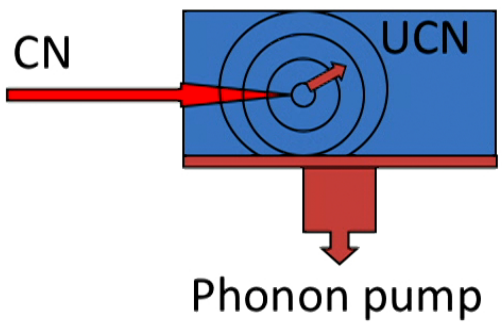


Required to make progress: superthermal UCN production

Golub and Pendlebury, PL62A(1977)337: superfluid He
Golub and Böning, ZPB51(1983)95 : solid D_2

Previously: reactor, lower end of Maxwell spectrum: inefficient, ~ 1 UCN / cm^3

‚Superthermal source‘: conversion instead of moderation: goal: 1000 UCN / cm^3



$$\rho_{UCN} = \Phi_{CN} \Sigma \tau_{UCN}$$

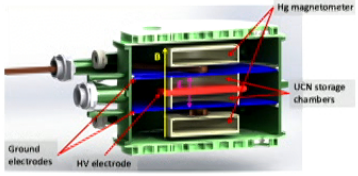
Main options:

	R [cm^{-1}]	τ_{UCN} [s]
D_2	10^{-8}	0.03…0.1
He	1..3 x 10^{-9}	10…1000

Next generation neutron experiments: ~ 10^{-27} - 10^{-28} ecm

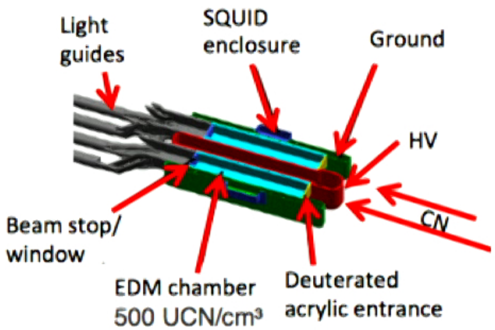
UCN, room temperature: 1000 UCN / cm^3

- Sites: (sD2) FRM, **LANL (new!)**, PSI; (lHe-II) ILL, PNPI, TRIUMF, KEK
- Ramsey, (double chamber)
- Magnetometers: SQUIDs, Cs, ^{3}He, ^{199}Hg, ^{129}Xe, ^{129}Xe
- (co-)magnetometers



UCN, Cryogenic: few 100 UCN/cm^3

- Site: SNS
- UCN source = EDM chamber, double chamber
- Co-magnetometer: spin dependent ^{3}He absorption and scintillation



Other ideas:

Pulse structure and strong peak flux:

- Cold-beam-EDM at long-pulse-neutron source (ESS)? (Piegsa, PRC 2014)
- Large-scale space-like (not time-like) interferometer?

Proton EDM ...

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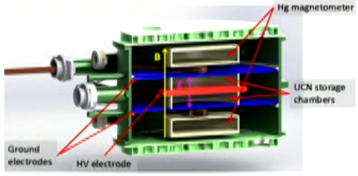

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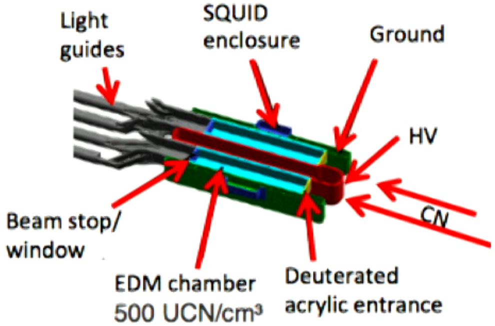

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Proton EDM ...

"Understood" systematic effects

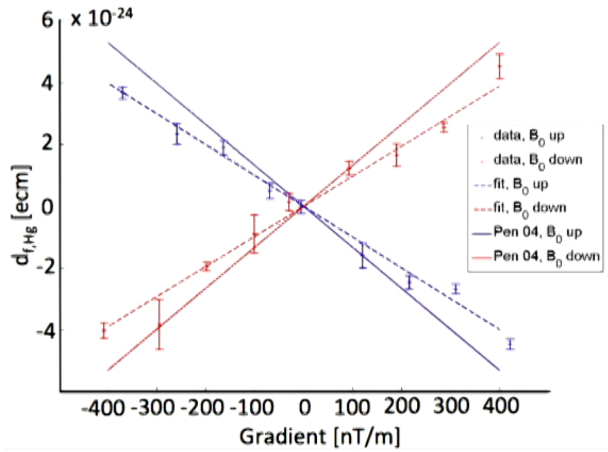
Most critical: Ramsey-Bloch-Siegert shift or ‚geometric phase':

$$\Delta\omega = \frac{\omega_{xy}^2}{2(\omega_0 - \omega_r)}$$

$$\omega_{xy}^2 = \left(\frac{\partial B_{0z}}{\partial z}\alpha\right)^2 + \left(\frac{E\times v}{c^2}\right)^2 + \boxed{2\frac{\partial B_{0z}}{\partial z}\alpha \cdot \frac{E\times v}{c^2}}$$

Magnetic field requirements for 10^{-28} ecm – level accuracy:

- ~ < 0.3 nT/m average gradient at ~ 1 μT ...
  $d_f \sim 4 \cdot 10^{-27}$ ecm (^{199}Hg geom. phase)
  $d_n \sim 1\text{-}2 \cdot 10^{-28}$ ecm (UCN geom. phase)
- Dipoles on trap surface (dirt or **sparks**):
- max 1 dipole with 5 pT in 2 cm distance
- < 10 fT drift stability



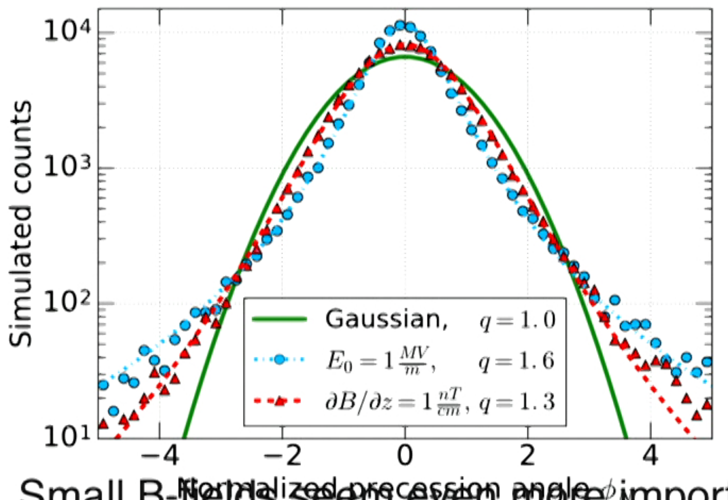
Pendlebury et al., Phys. Rev. A **70**, 032102 (2004)
Further: P. G. Harris et al., Phys. Rev. A 73, 014101 (2006), also: G. Pignol, arXiv:1201.0699 (2012), A. Steyerl et al. Phys. Rev. A 89, 052129 (2014) etc…

The next generation...

What does *really* happen in next-generation experiments?

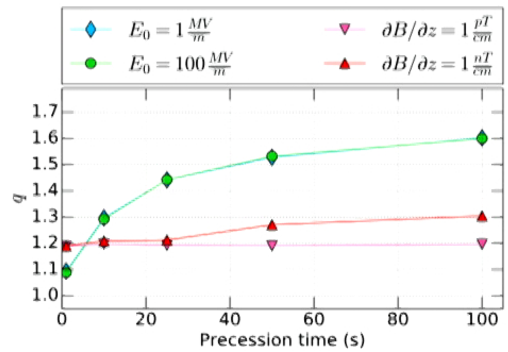
- New class of systematics: **Non-gaussian distributions**
- Skewness -> would lead to yet unexplored frequency shift shifts
- Affects all previously known systematics
- Could appear also in other measurements: g-2? pEDM?

M. Bales, PF, R. Golub, EPL 2017



- Small B-fields seem even more important.

Non-gaussianity build-up with time:



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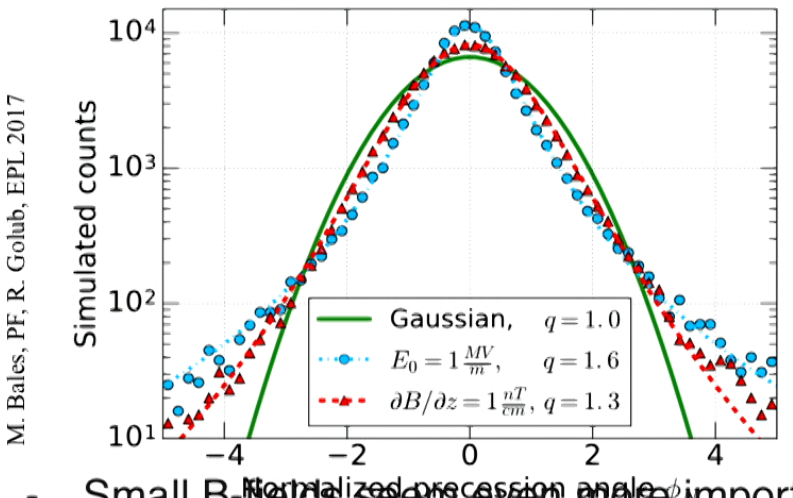

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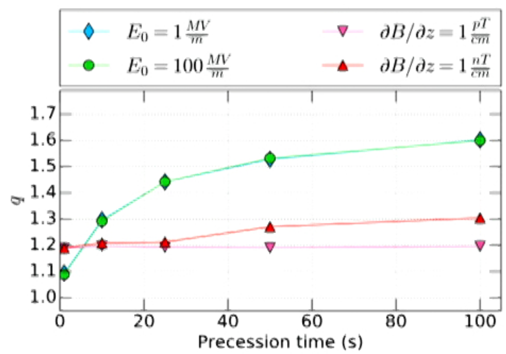


- Small B-fields seem even more important.

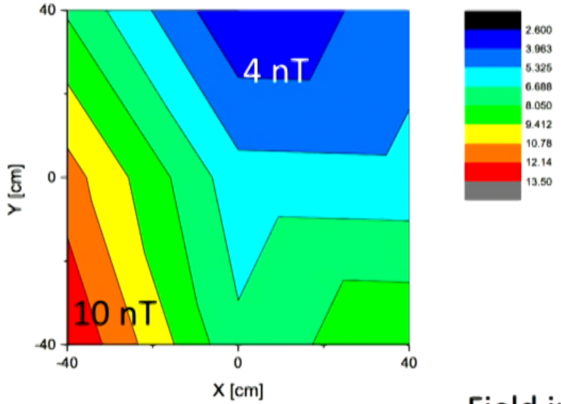
„Small“ fields are easy to achieve

Example: 1 layer, 2 mm thick shell, Magnifer (magnetizable alloy), ~ 2 x 2 x 2.7 m, 80 feed-throughs with > 40 mm diameter

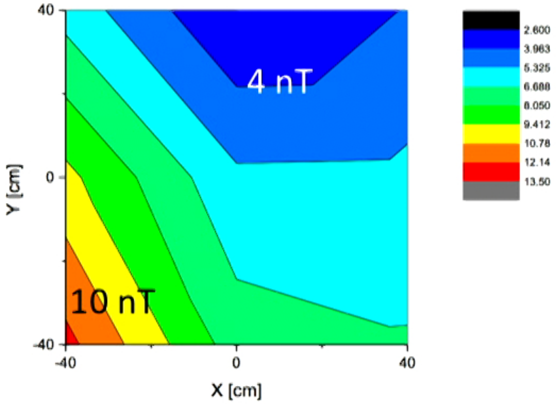
Shielding factor (1 μT external sine-excitation)
@ 10 mHz: 40
@ 1 Hz: 200

Residual field after equilibration: (outside: earth field with 50 μT)

Center plane, centered in room



14 cm above center



Field in nT

State of the art for Shielding factors (SF)

TUM EDM shield

'MSR' = Magnetically Shielded Room

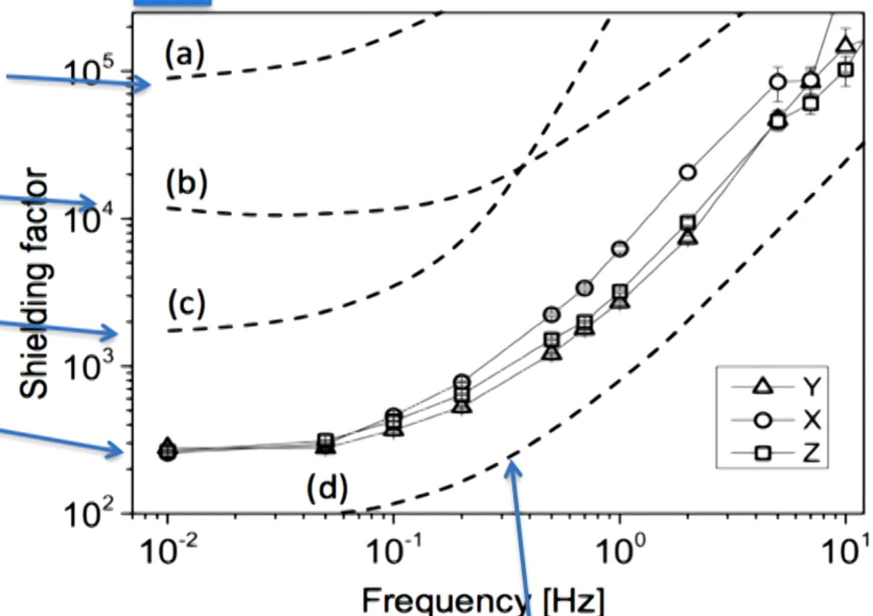
Best shielded room available for users: BMSR-II Berlin, 7+1 layer (~ 1.5 nT residual field)

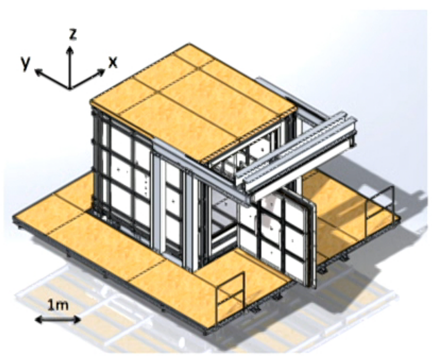
BMSR, Berlin

Boston, 3 layers

Garching, 2 layers (Best 'performing' MSR)

Slope: combination of aluminum and magnetizable material

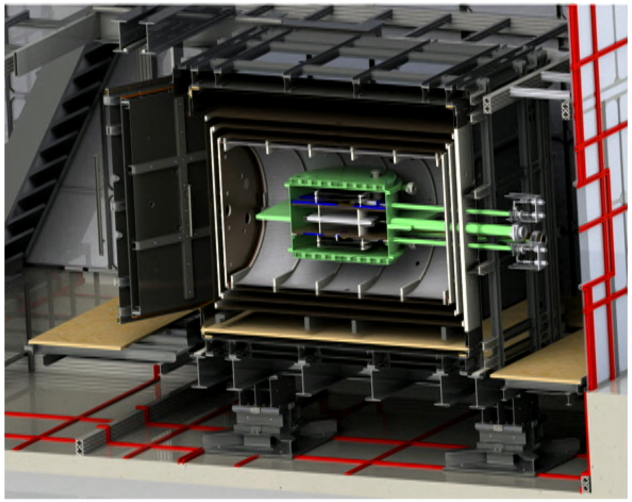




'AK3b' (1.5 x shielding material of Garching MSR)

SF of cuboid EDM shields

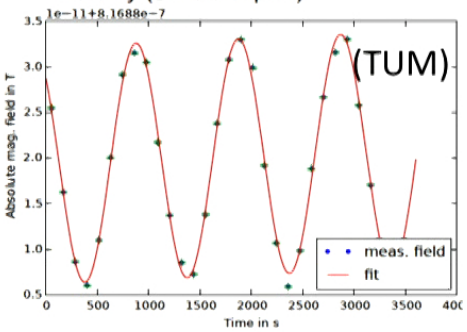
MEASURED: (no active compensation, no innermost shield)
SF (0.001 Hz, longitudinal) = ~ $1 \cdot 10^6$
SF (1 Hz, transversal) = > $15 \cdot 10^6$



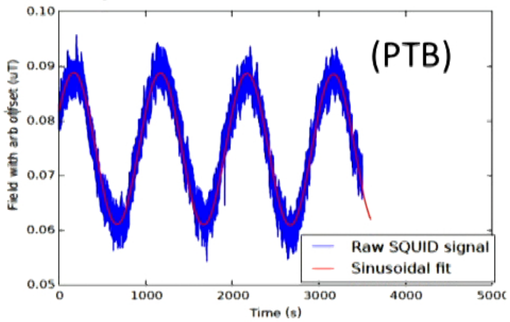
Issue: drifts and bandwidth of magnetic field probes… (an important topic!)

Example: response of 199-Hg magnetometers (12 fT resolution in 100 s) and SQUID to external distortion with 16.25 Microtesla external amplitude:

Mercury (100s samples)



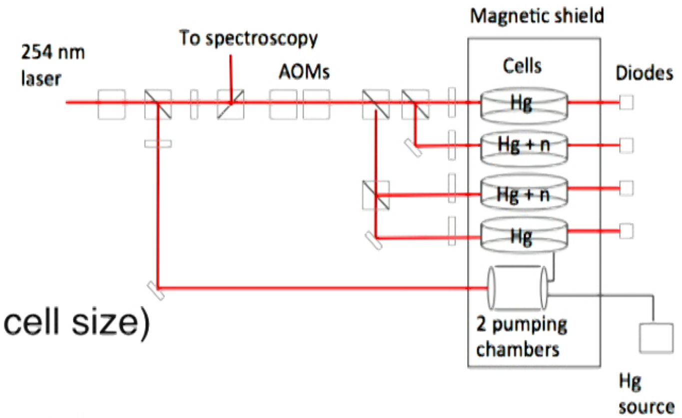
SQUID



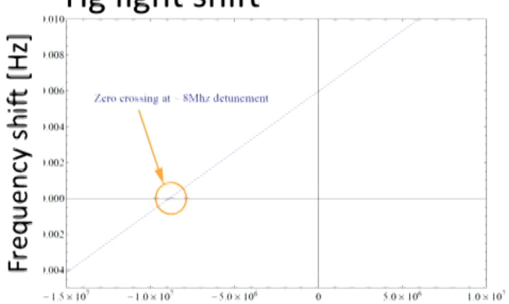
Amplitude: 12.982±0.026pT
Corrected for averaging:
Amplitude=13.2±0.026pT

^{199}Hg magnetometers

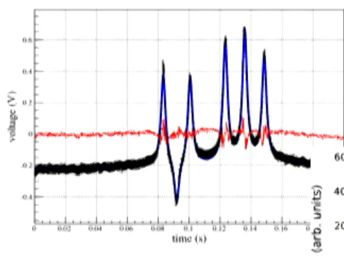
- A bit "similar" to ^{199}Hg EDM experiment
- DDAVLL lock with UV light
- Lock quality: $d_{false,Hg} < 1{\cdot}10^{27}$ ecm
- Several minutes T_2 times demonstrated
- Zero light-shift operation
- few fT resolution in 100 s (finally limited by cell size)
- Low-drift magnetometer

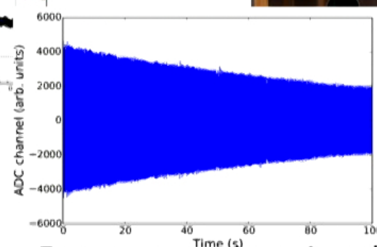


Hg light shift

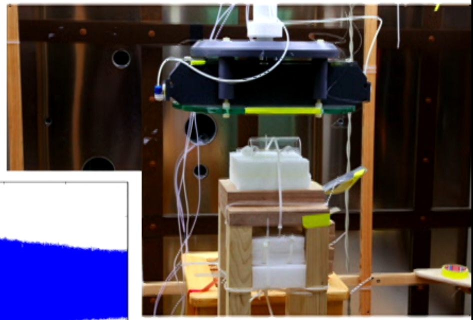


Basis for lock: many different Hg isotope transitions





Free-precession signal

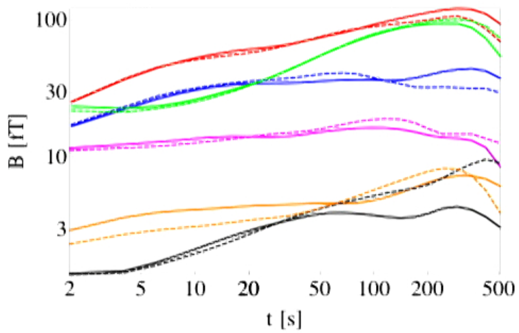


Hg cell

Main problems: drifts, stability and noise

Passive SF of full shield > 6 Millions @ 1 mHz (no active compensation)

Stability, measured with a SQUID



Measured residual field

0.4 m

1 m

	Bx in pT	
Xend-18	Xmitte0	Xend+18
8	50	88
11	59	80
29	80	85
18	48	91
19	51	91
12	43	97
-2	30	91

	By in pT	
Xend-18	Xmitte0	Xend+18
-23	-22	-26
-35	-39	-32
-28	-26	-22
-18	-28	-22
-28	-31	-23
-56	-26	4
-79	-33	15

	Bz in pT	
Xend-18	Xmitte0	Xend+18
-106	-66	-67
-116	-82	-63
-87	-53	-54
-81	-31	-27
-77	-34	-42
-87	-47	-66
-93	-55	-75

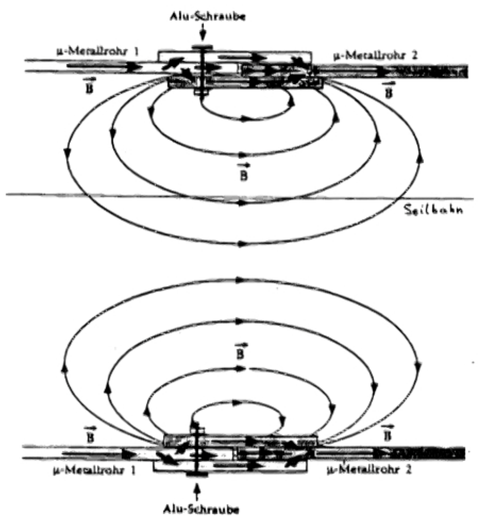
	Bnorm in pT	
Xend-18	Xmitte0	Xend+18
108	86	113
121	108	107
96	100	103
85	64	97
84	69	103
104	69	117
122	71	119

I. Altarev et al., arXiv:1501.07408 / Rev. Sci. Instr (2015)
I. Altarev et al., , arXiv:1501.07861 /J. Appl. Phys. (2015)

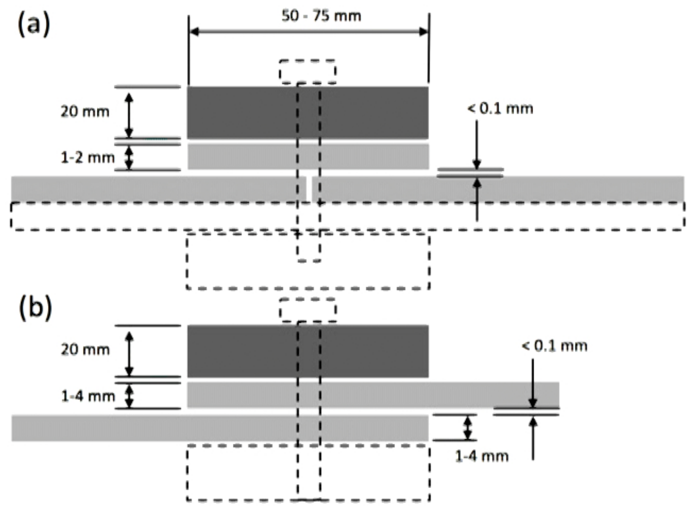
Residual fields inside shields

Imperfections in the shielding material cause gradients (SF is almost irrelevant)

Example: Distortions due to Mu-metal connections, modeled by
D. Dubbers et al. for nnbar (1979)

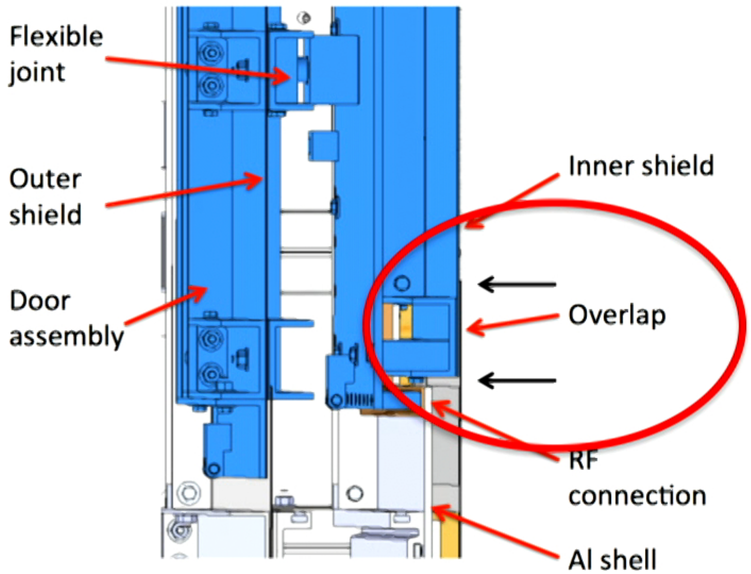


Currently preferred connections of magnetizable materials: ‚clamping'
Crucial: large sheets

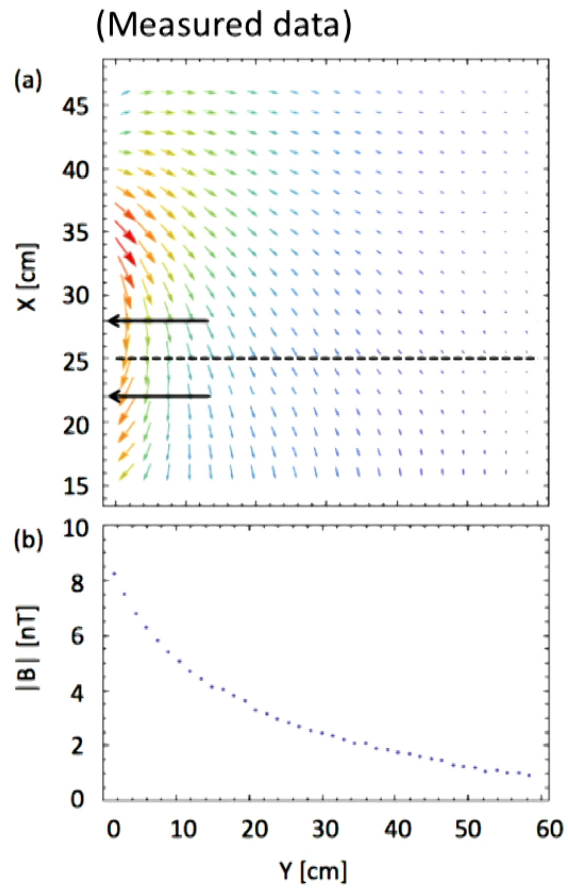


(a) Permanent connection
(b) Door, access hole etc.

Residual fields inside shields

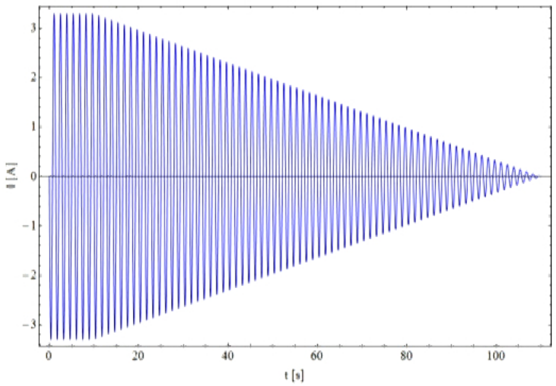


Simple modeling using scalar potentials works very well for qualitative estimates of gradients



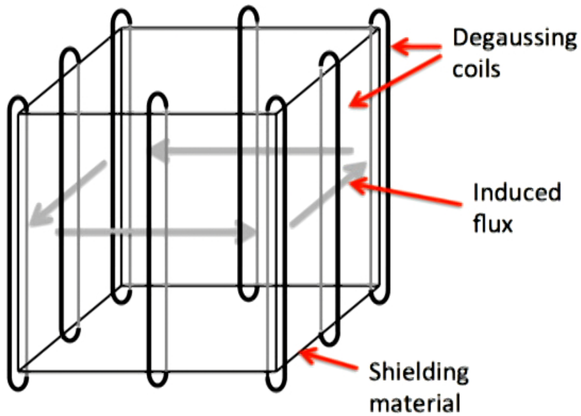
Magnetic equilibration

= Optimal alignment of magnetic domains in ambient field conditions. -> We call it ‘equilibration’, not ‘degaussing’



Parameters: skin depth, frequency, DC offset, symmetry – shape of sine-waves, noise, sufficient current for saturation, increasing slope if not everything can be saturation, envelope functions

Illustration of degaussing coils in one direction in space:

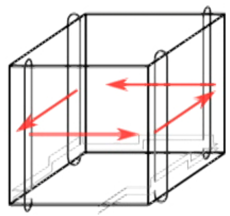


- Wiring can be optimized for each shielding scenario
- Coil positions are NOT bound to edges

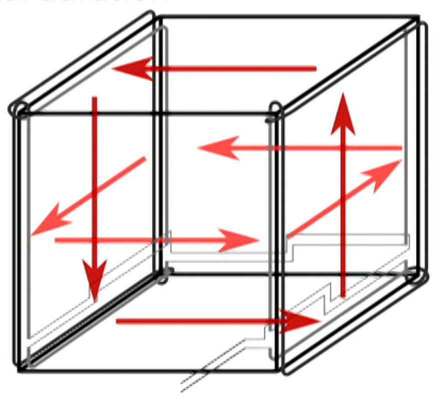
Improvements of equilibration

- Different coils used for equilibration in same shield (2 layer)

a) 3-axes, 100-200 s sequence in each direction x 3 = 300-600 s



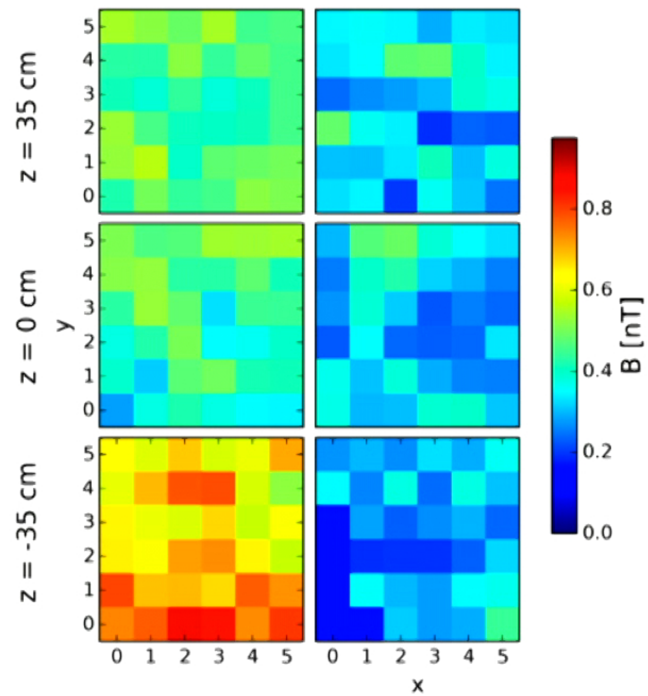
b) New: only 1 set of coils, 30-50 s total duration



Solves most „overlap“ issues

a) Regular coil design

b) New ‘L-shaped‘ coils

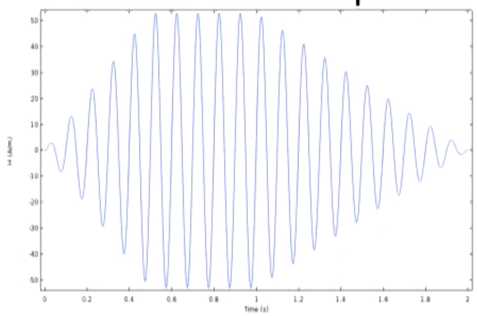


Time-dependent simulations of hysteresis curves

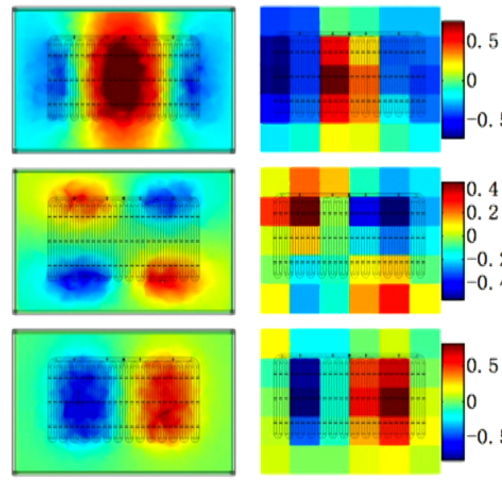
Current status: quantitatively correct time-dependent modeling of real geometries

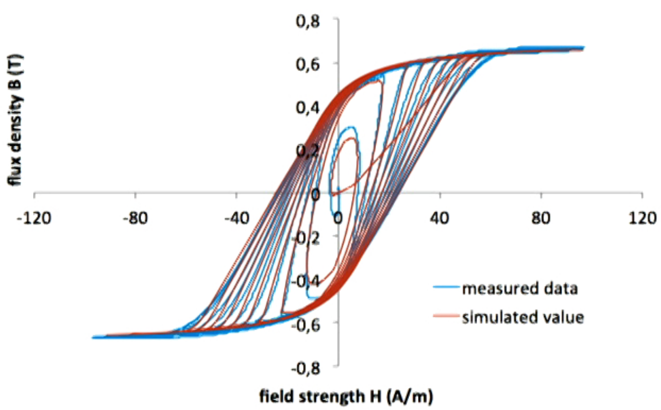
Z. Sun et al., J. Appl. Phys. 119, 193902 (2016)

Schematic current pattern :



Test-geometry:





Joint activity of FM, TUM, PTB, HIT, IBS

Time-dependent simulations of hysteresis curves

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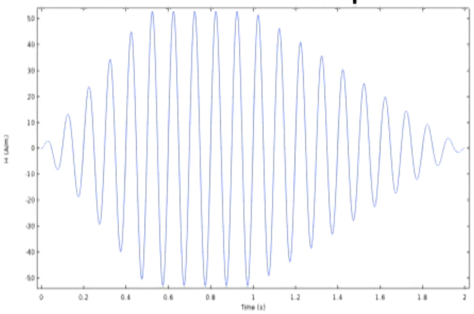
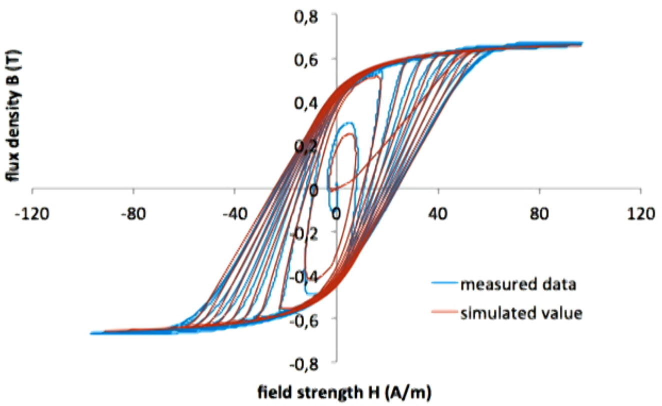
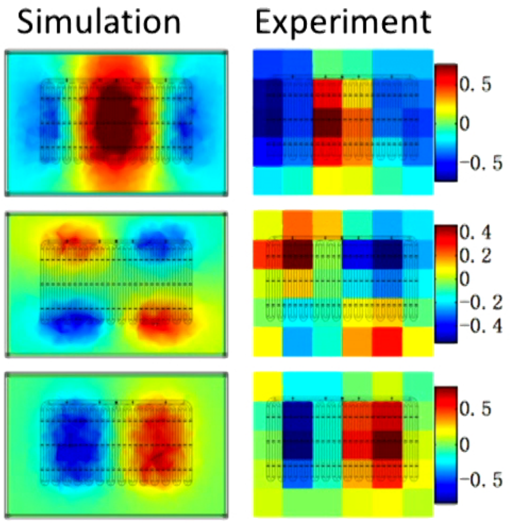


Test-geometry:

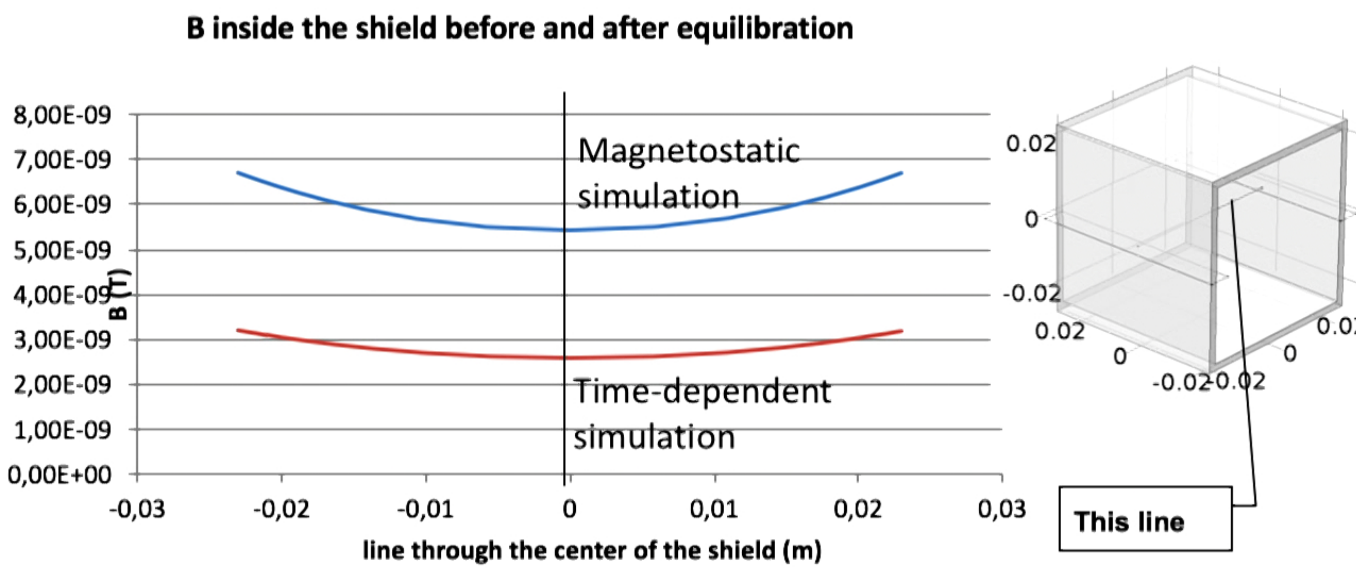




Joint activity of FM, TUM, PTB, HIT, IBS

... Implications (e.g.)

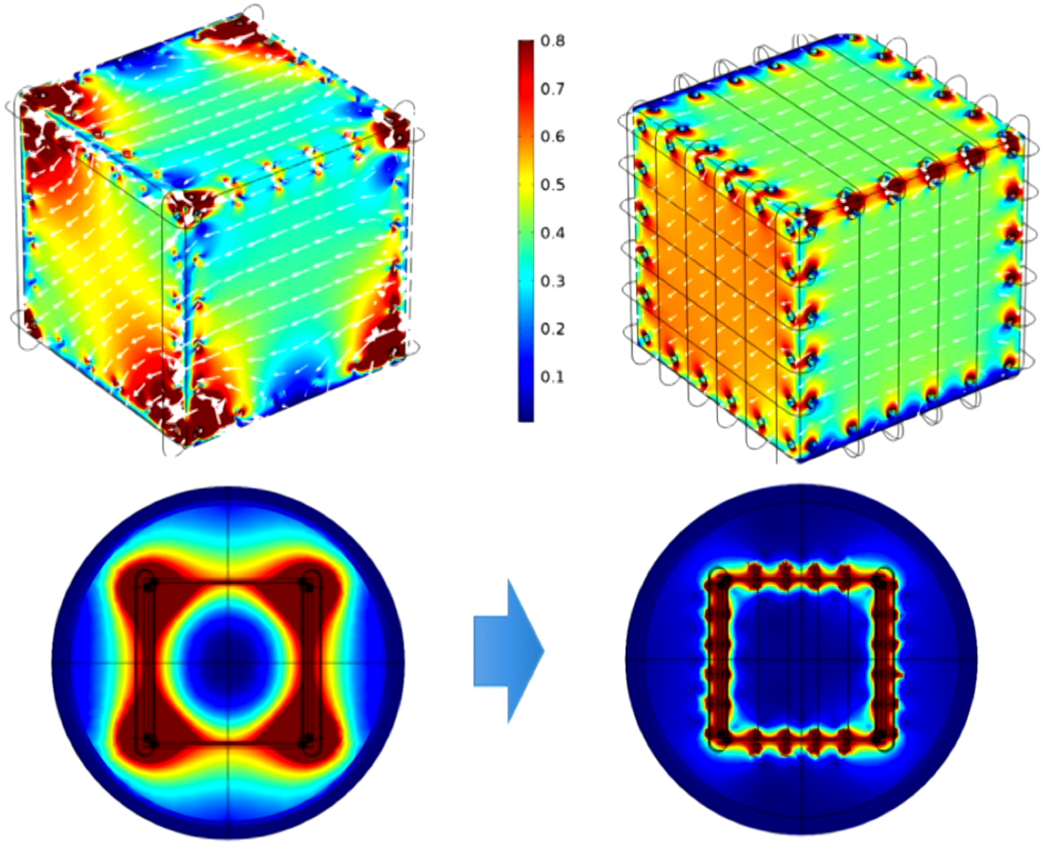
Residual fields in shielded rooms can be lowered and gradients minimized;
Static and time-dependent simulations give quite different results:



(External field: 1 μT)

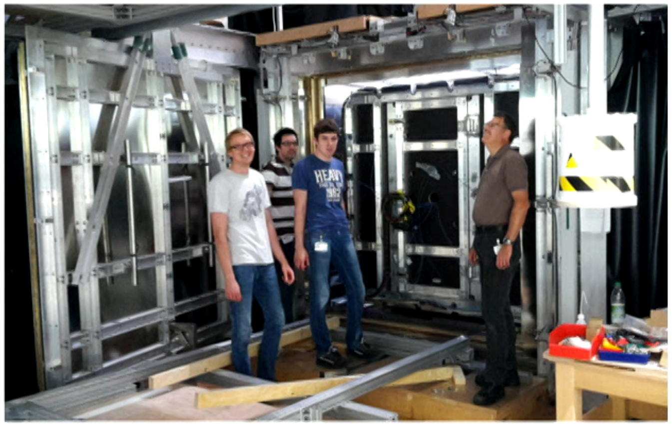
Z. Sun (HIT), in collaboration with TUM

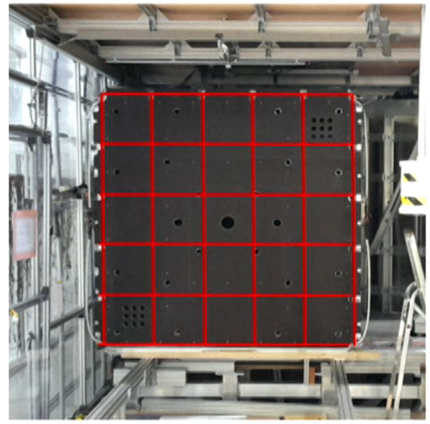
Distributed equilibration coils



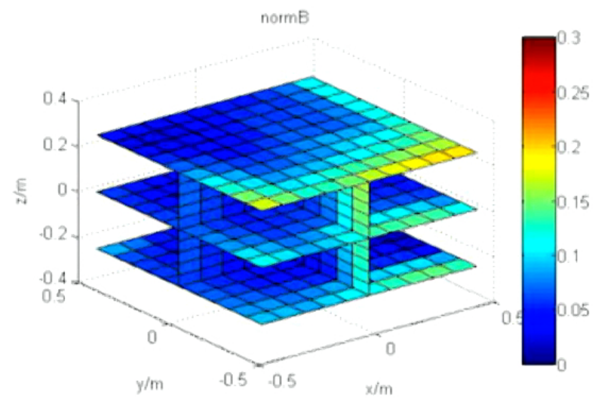
Figures: Z. Sun

... The smallest fields over extended volumes

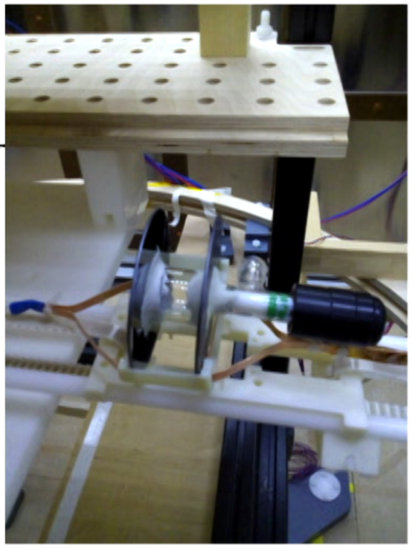




- New wall design
- 2 mm thick, 1 shell
- L-shaped, distributed coils
- Installed temporarily at TUM
- (SF in total ~ 3000 at mHz)
- **0.5 x 0.5 x 0.5 m < 25 pT (Measurements: PTB, HIT, TUM)**



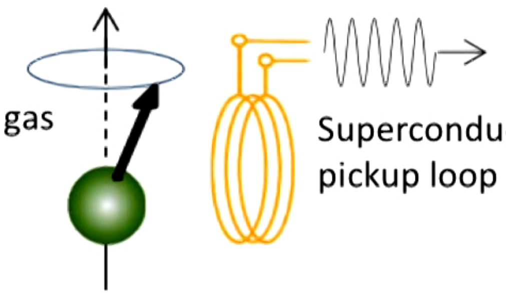
SQUID and He+Xe mixture: ^{129}Xe EDM measurement

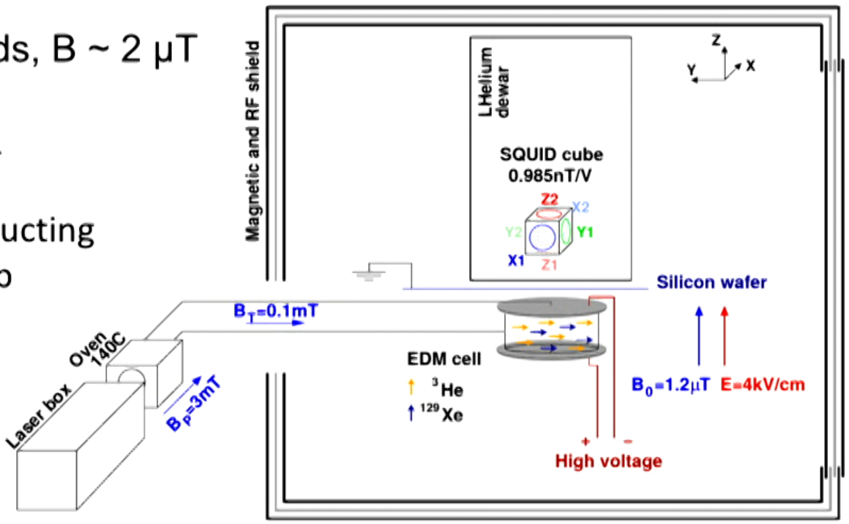


The HeXe experiment:

Jülich, U. Michigan, MSU, PTB, TRIUMF, TUM

- Originates from low-drift magnetometer R&D
- SEOP polarized ^{3}He and ^{129}Xe in cell
- E-fields parallel and antiparallel to B
- Free precession decay, SQUID detection
- Frequency comparison
- ^{3}He is insensitive to EDM
- Placed inside outer nEDM shields, B ~ 2 μT

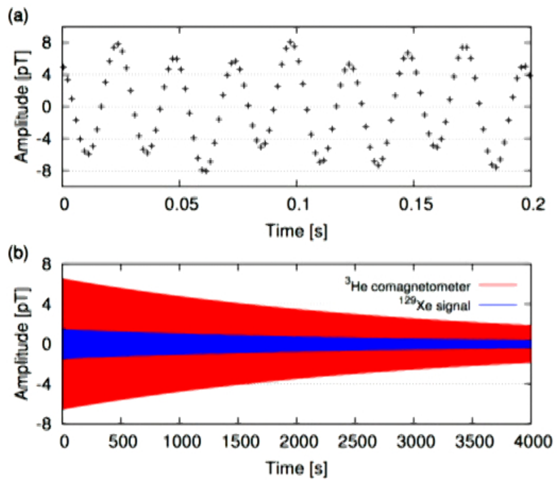




- Now continued at PTB Berlin…

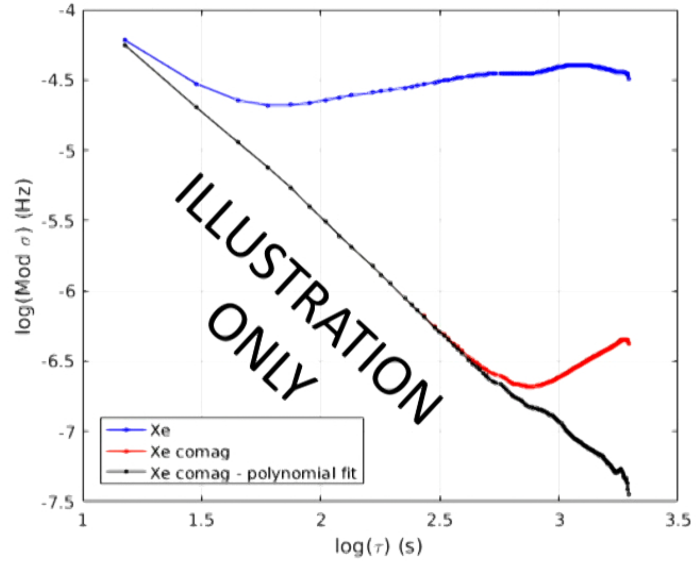
SQUID and He+Xe mixture:
^{129}Xe EDM measurement

Illustration: simultaneous precession of ^{129}Xe and ^{3}He amplitude in cylindrical cell with 5 kV/cm applied:



T2 (transverse spin life-time) are limited by cylindrical cell shape

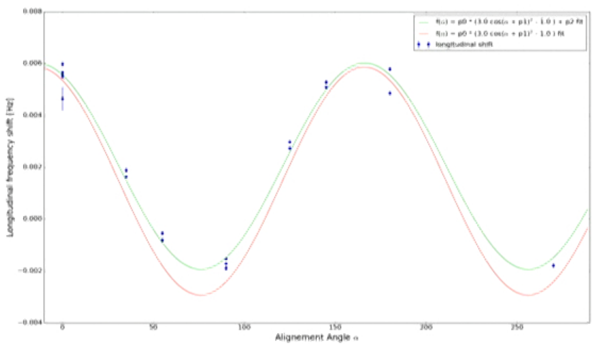
Allan Std. deviation of comagnetometer with HV applied: (7 fT/rt(Hz) SQUID noise level)



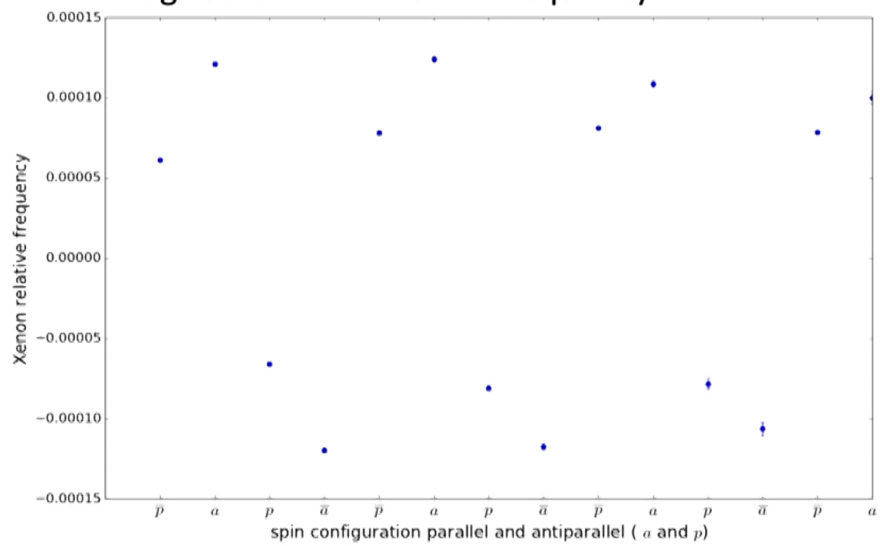
^{129}Xe EDM systematics

- Magnetic field of ^{129}Xe and ^{3}He and self/cross frequency shifts
- Leakage currents
- SQUID back-action
- Flipping precision
- Cell geometry effects (e.g. stem orientation …), phase drifts
- HV cycle length vs. drifts
- (no geometric phase!)
- …

Example: determination of dipole from to cell geometry



Example: effect of helium magnetization on xenon frequency



^{129}Xe EDM analysis

EDM measurement error:

$$\sigma_{\mathrm{d}} = \frac{\hbar}{2E} \frac{\epsilon}{\tau^{3/2} S \sqrt{N}}$$

Noise (ϵ); Duration of one measurement (τ); Signal (S); Number of repetitions (N)

... Current status < 10^{-26} ecm / measurement (~ literature limit for Xe)

... Note: Contains „Cramer-Rao lower bound" for frequency estimation:

$$\sigma_f \propto \tau^{-3/2} \qquad \propto \left[\begin{matrix}\text{Fourier} \\ \text{width}\end{matrix} \propto \frac{1}{T}\right] \times \frac{1}{[\#\,\text{data points} \propto \mathrm{T}]^{\frac{1}{2}}} \propto \frac{1}{T^{\frac{3}{2}}}$$

With: number of data points = sampling rate x time

Side note: progress with SQUIDs

Our wish is to use such a SQUID (and cryostat!) as upgrade:
instantaneous factor 10-100 sensitivity improvement (replacing is VERY simple)

PTB BERLIN: Appl. Phys. Lett. 110, 072603 (2017)

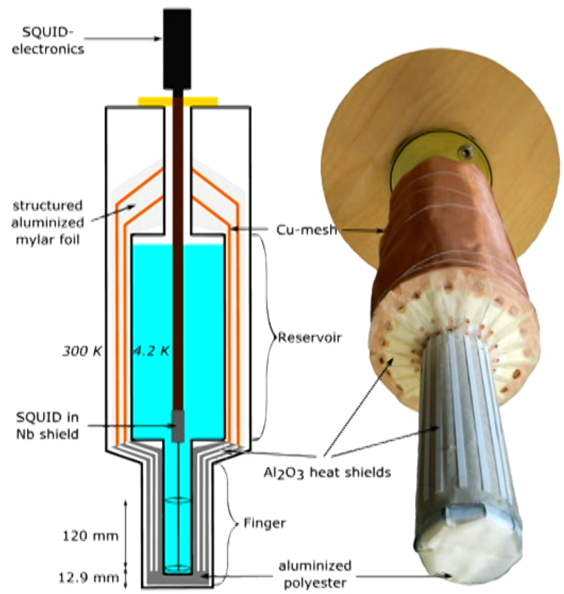


FIG. 1. Left: the schematic setup of LINOD2 in gradiometer configuration. Right: a view of one of the heat shields made from Al_2O_3 strips together with the copper mesh heat shield at the dewar reservoir. The outer shell has been removed.

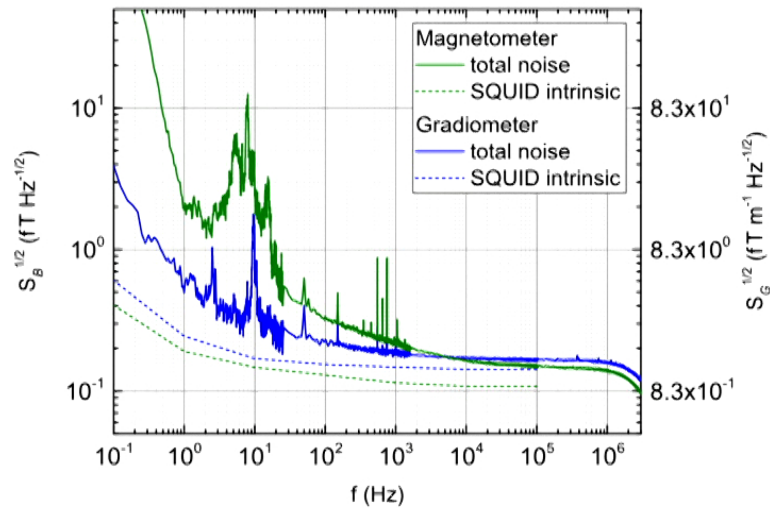
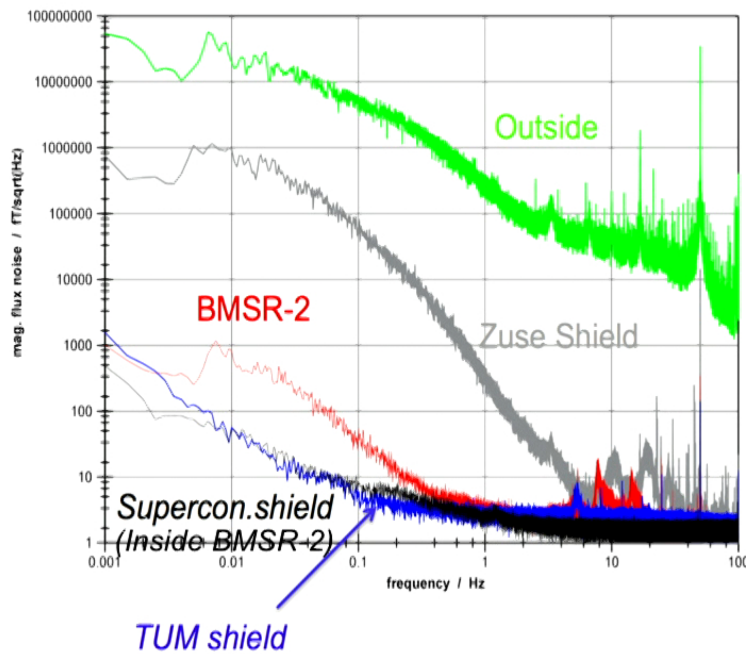
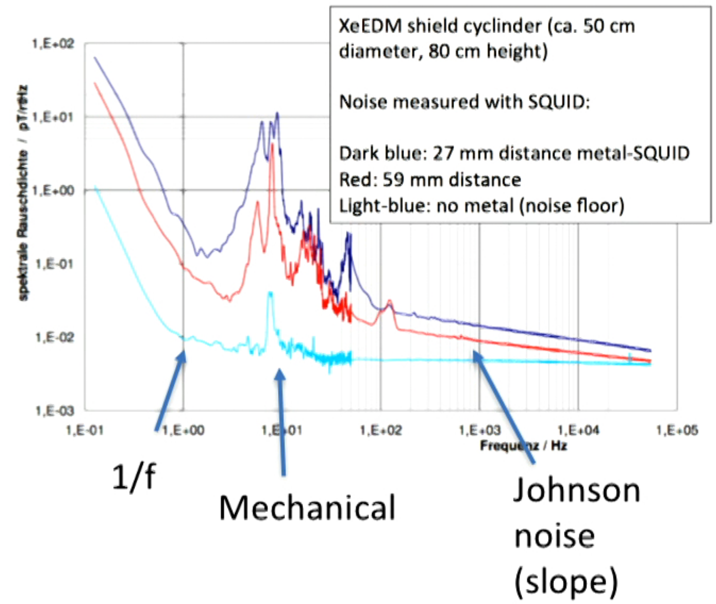


FIG. 2. Measured magnetic flux density noise $S_{B,\mathrm{m}}^{1/2}$ for the two setups with 45 mm diameter pick-up coils: Magnetometer (solid green curve) and gradiometer (solid blue curve). The calculated intrinsic SQUID noise levels $S_{B,\mathrm{i}}^{1/2}$ are given by the dotted curves. For the gradiometer, the noise is referred to the bottom pick-up loop, and the gradient noise is shown on the right.

Noise

Comparison of SQUID measurements inside magnetic shields (permalloy and superconducting):

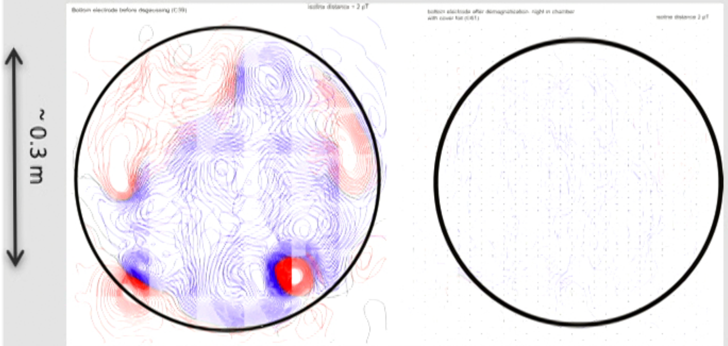




(Measured by PTB, baseline limited by instrument noise)

Drifts

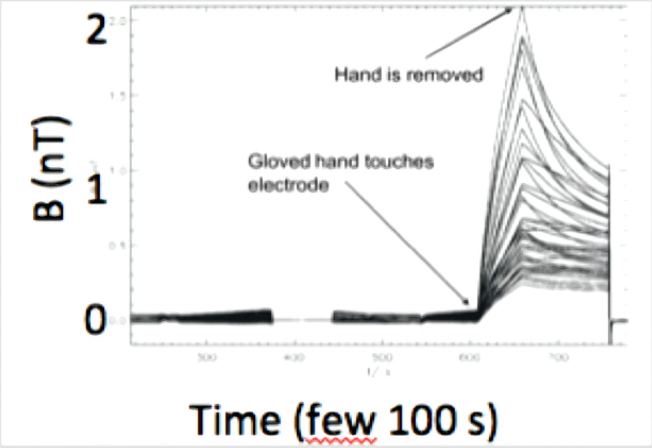
SQUID measurements of Sussex- EDM electrodes @ PTB Berlin
Many materials are problematic



> 200 pT in 3 cm distance: as used in Sussex-EDM experiment

demagnetized: 20 pT pp in 3 cm distance (Larger than nEDM error budget!)

Thermally induced currents in metals:
MUCH more critical than Johnson noise

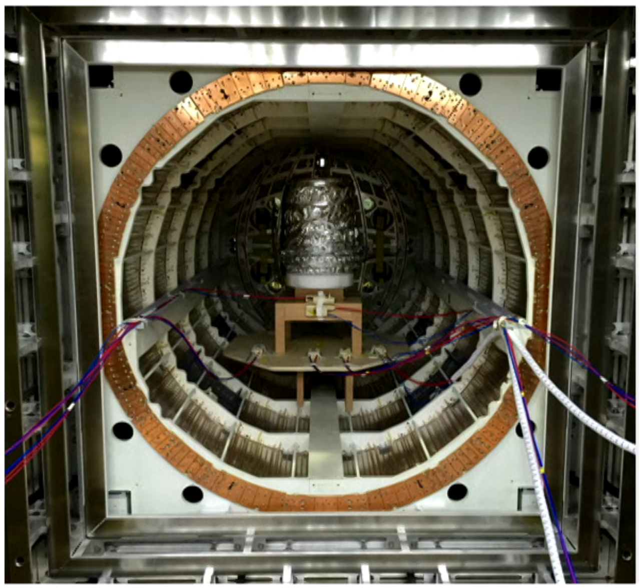


Generating homogeneous fields

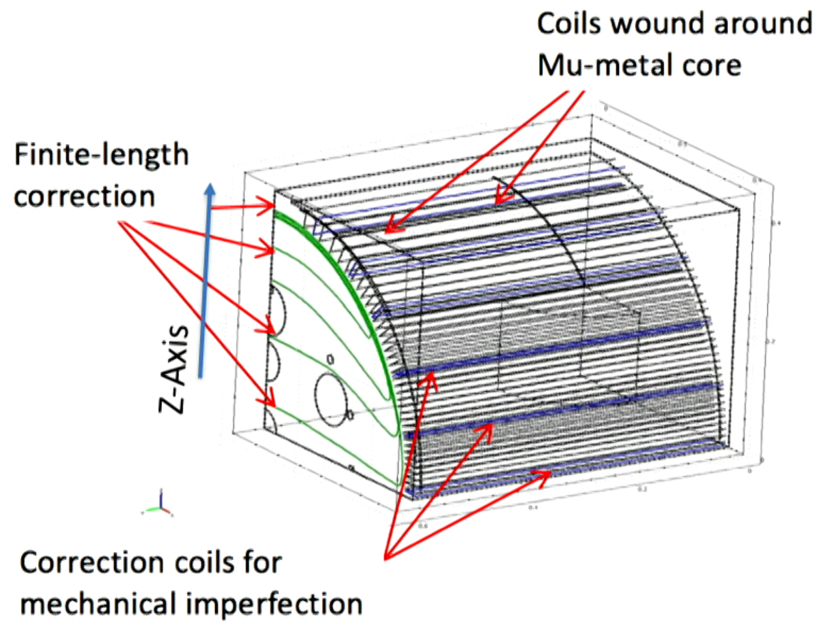
Similar to a 'magic box' configuration: coils are coupled to shields, Approx. cosine-theta coils

1.6 μT Ramsey field coils

I. Altarev et al., WO 2012156278 A1



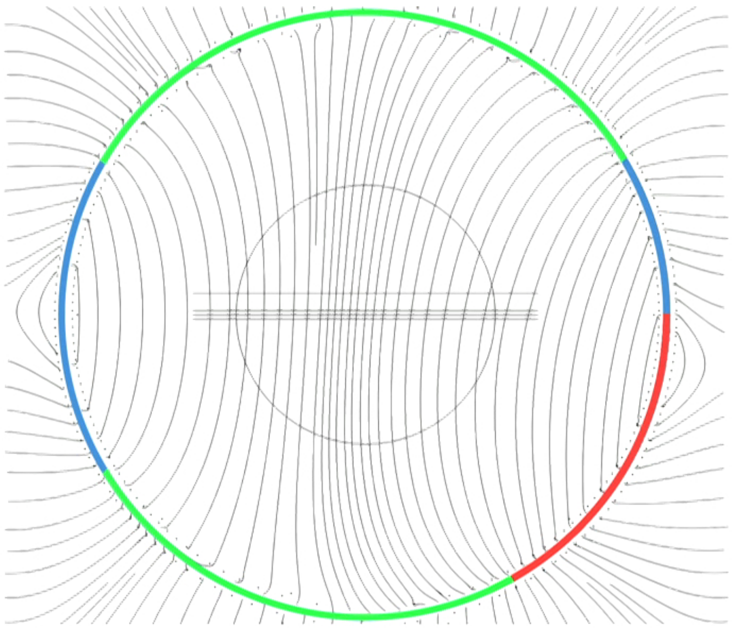
1.5 m



Generating homogeneous fields - what really happens:

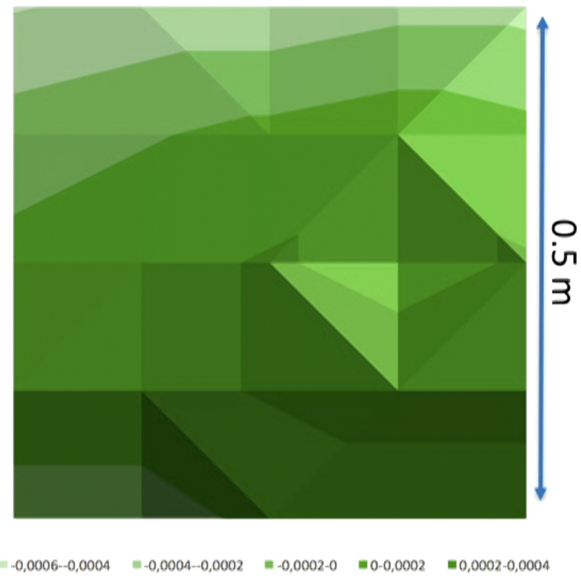
Main issue: the permeability is not uniform in reality, in any shield!

Simulation: permeability varied (strongly) along cylinder used for NMR B0 field coil:



(View into cylinder from front)

Measured: rel. field homogeneity in horiz. plane, after corrections

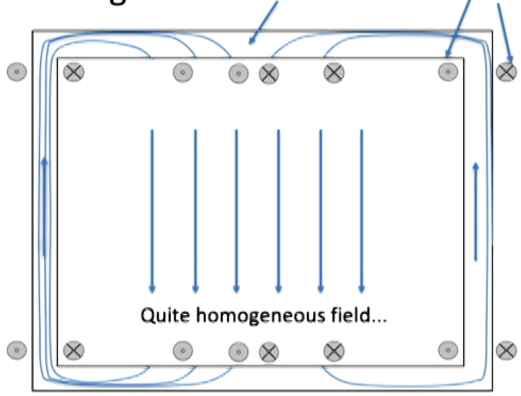


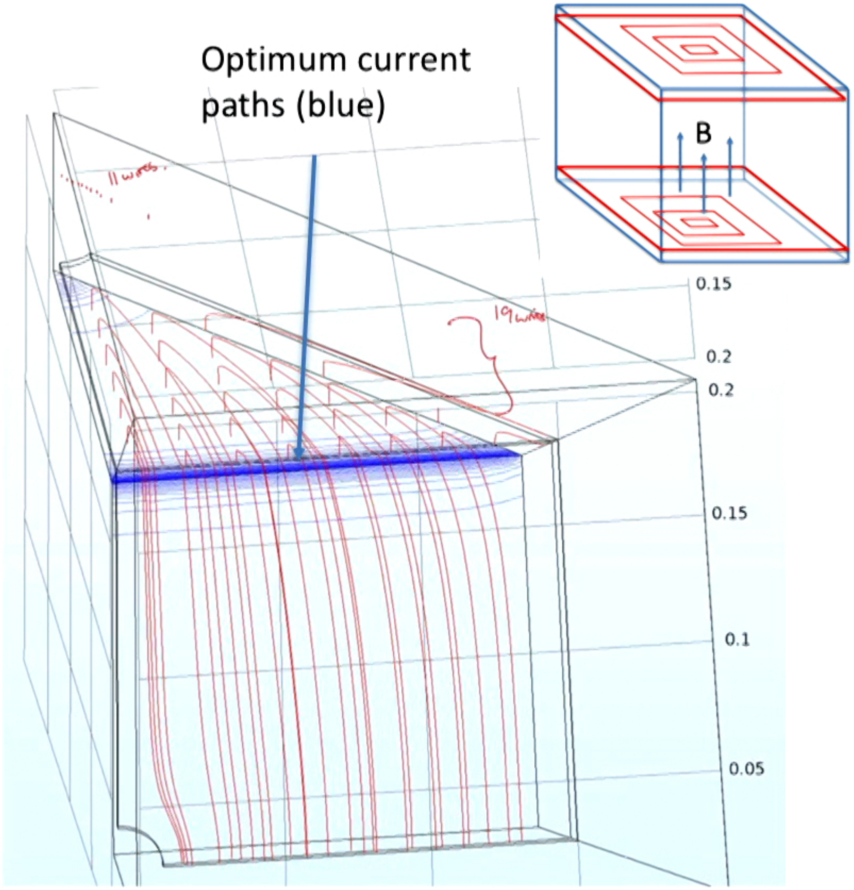
Note: measurements are limited by probe and alignment quality! $< 10^{-4}$ relative tilt resolution

Applications: shields with applied fields inside

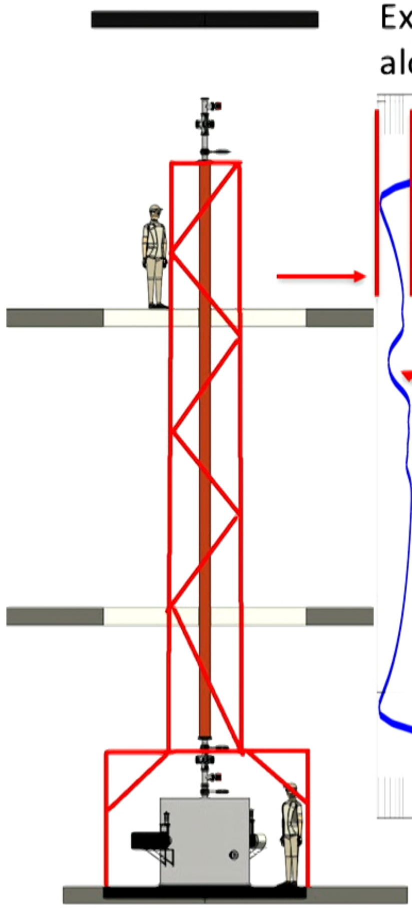
- Again „Magicbox“
- Now used for shielded rooms and experiments: very homogeneous field (compared to Helmholtz coils)
- Reasonably stable in time, if equilibrated

Cut through box:

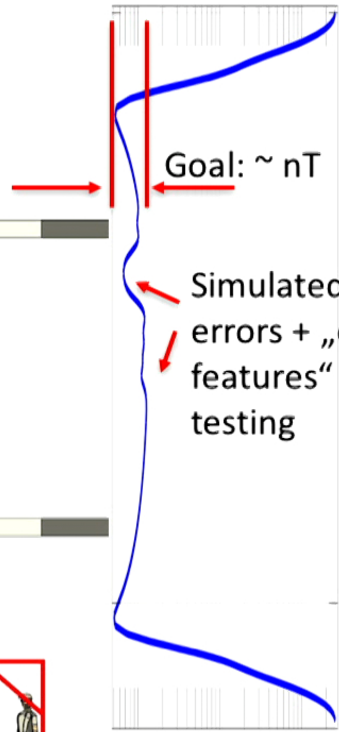




Applications: long shields



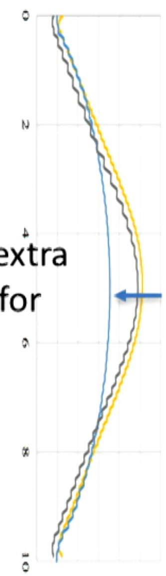
Expected B-field along center:



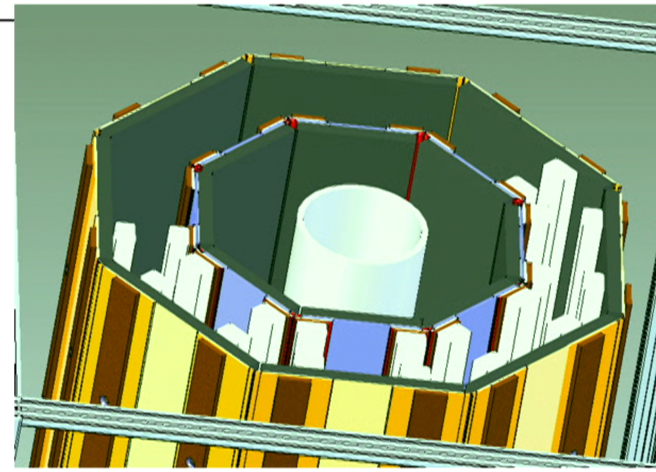
Goal: ~ nT

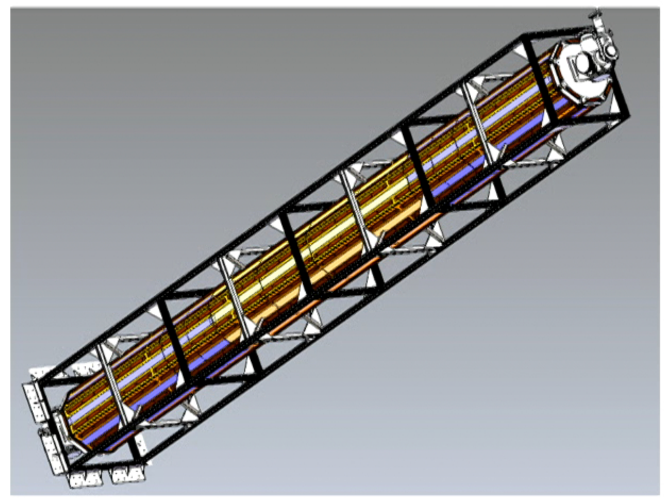
Simulated errors + „extra features“ for testing

Equilibration simulation:



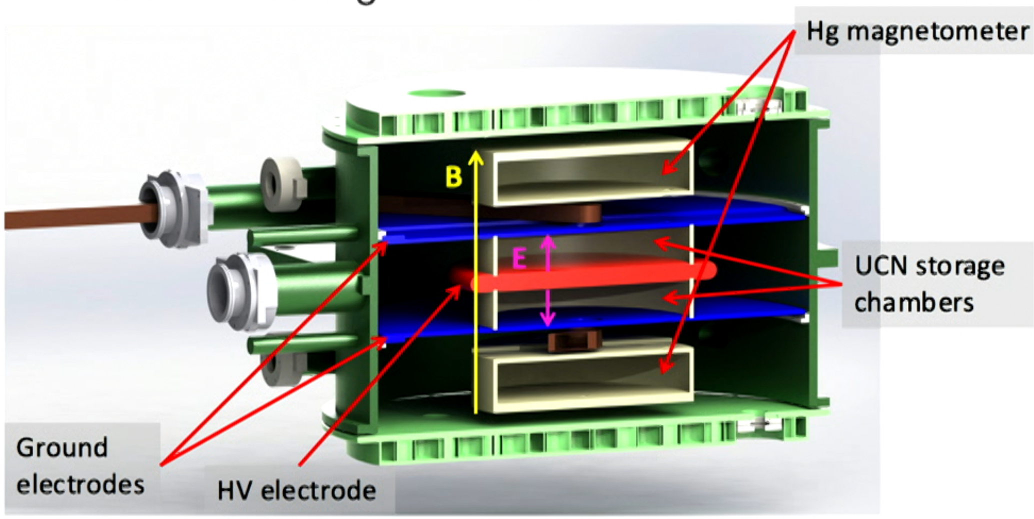
Shield ready by Nov. 2017





Our EDM apparatus

- Contributions from Berkeley, ILL, Jülich, LANL, Michigan, MSU, NCSU, PNPI, PTB, RAL, TUM, UIUC, Yale
- Ramsey experiment with UCN trapped at room temperature, ultimately cryogenic
- Double chamber
- ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUID magnetometers
- Built at TU Munich and waiting for UCN



I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)

... Still no UCN at TUM, but: „life“ in the EDM shield

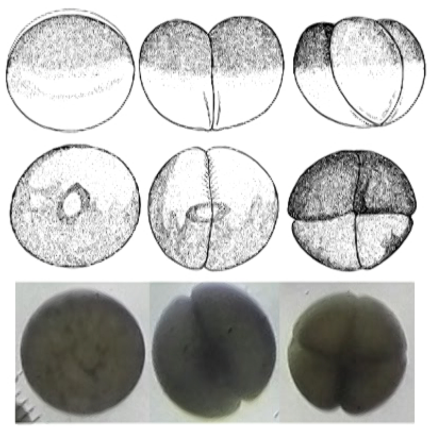
Xenopus laevis (frogs)

1. Stage (0 min) | 2. Stage (30 min) | 3. Stage (120 min)

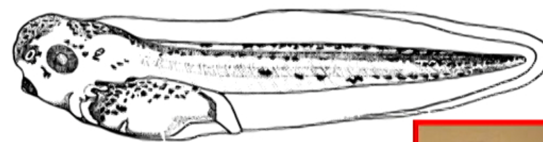
Side view

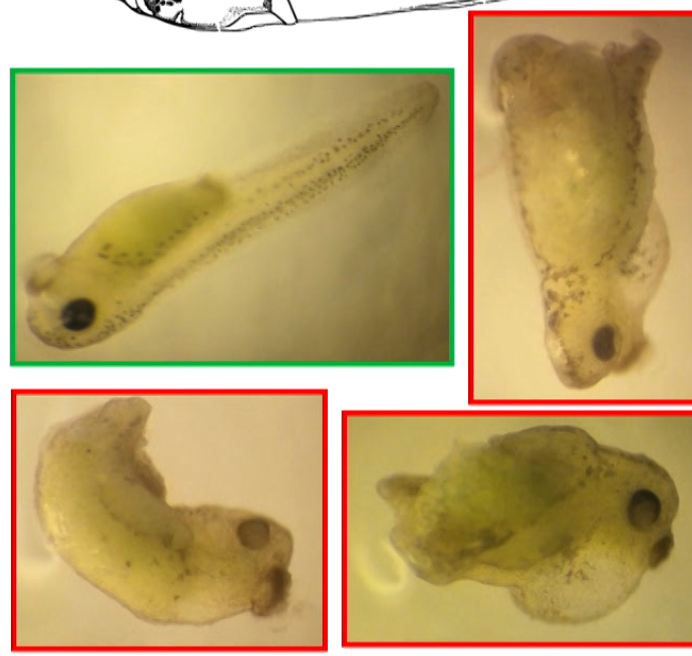
Top view

Microscope



>40. Stage (3 days)



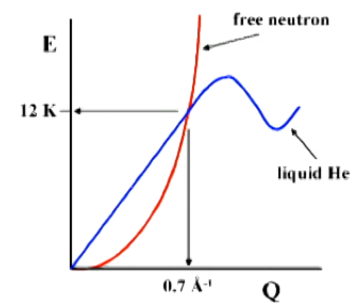


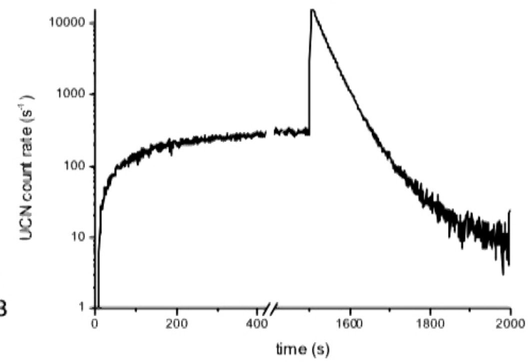
Moving to the ILL research reactor

March 2016:
Our EDM was selected as future flagship experiment for the new ILL Super-SUN source, an 'upgrade' of the currently strongest existing UCN source, after open call for proposals

O. Zimmer et al., Phys. Rev. Lett. **107** (2011) 134801

"Super-SUN" source of UCN:
- Superfluid helium
- Placed at a cold beam
- Very 'soft' spectrum: < 74 neV
- => T > 250 s, demonstrated!
- Scalable
- Suitable to feed EDM experiment with $\sigma_d < 10^{-27}$ ecm
- Designed and built by ~ 1 person*



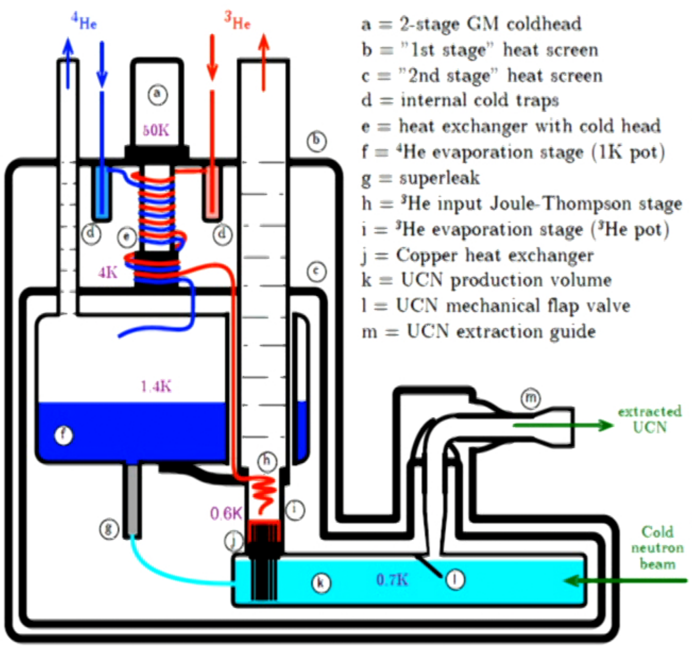


Most recent measured UCN density: 220 / cm^3 (2016)

O. Zimmer

He-based UCN source at ILL

Precursor source “SUN-II”:



- **Fixed number of UCN**
  - Dilution of density in the chambers and guide system
- **Build-up of UCN inside source**
  - Finally: magnetic confinement = polarized UCN in the source
- **Very low energy spectrum**
  - Extremely long storage times
  - In some cases large losses
- **Small systematics**
  - Geometric phase depends on UCN velocity

… Consequences for our experiment: Rebuild all neutron optics …

Physics reach with super-SUN

	SuperSun stage I (2018-2020)		SuperSun stage II (2019-2022)	
UCN density	333	1/cm3	1670	1/cm3
Diluted density	80	1/cm3	400,8	1/cm3
Transfer loss factor	3	*	1,5	
Source saturation loss factor	2		2	
Polarization loss factor	2		1	
Density in cells	6,7	1/cm3	133,6	1/cm3
2 EDM chamber volume	33,2	l	33,2	l
Neutrons per chamber	110556		2217760	
EDM sensitivity				
E	2,00E+04	V/cm	2,00E+04	V/cm
alpha	0,85		0,85	
T	250	s	250	s
N after time T (1/e)	39800		794000	
Number of EDM cells	2		2	
Sensitivity (1 Sigma, 1 cell)	3,9E-25	ecm	8,7E-26	ecm
Sensitivity (1 Sigma, 2 cells)	2,7E-25	ecm	6,1E-26	ecm
Preparation time	150	s	150	s
Measurements per day	216		216	
Sensitivity (1 Sigma, 2 cells) per day	1,9E-26	ecm	4,2E-27	ecm
Sensitivity 100 days	**1,9E-27**	**ecm**	**4,2E-28**	**ecm**
Limit 90% 100 days	**3,00E-27**	**ecm**	**7,00E-28**	**ecm**

Recently reduced to "1" (Transfer loss factor)

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

Compared to current limit: 3.10^{-26} ecm

Summary

- Small fields:
  - Systematics of EDM measurements require very well controlled fields
  - For many applications, small magnetic fields are „easy“ to „generate“, special shapes are still risky
  - Small magnetic fields are being more important in future, e.g. for proton EDM, but also industry
- Scientific projects:
  - p-EDM: move to ILL starts in 3 weeks - finally there is a real perspective to do a measurement!
  - HeXe-EDM: understanding of experiment has significantly improved, at competitive level