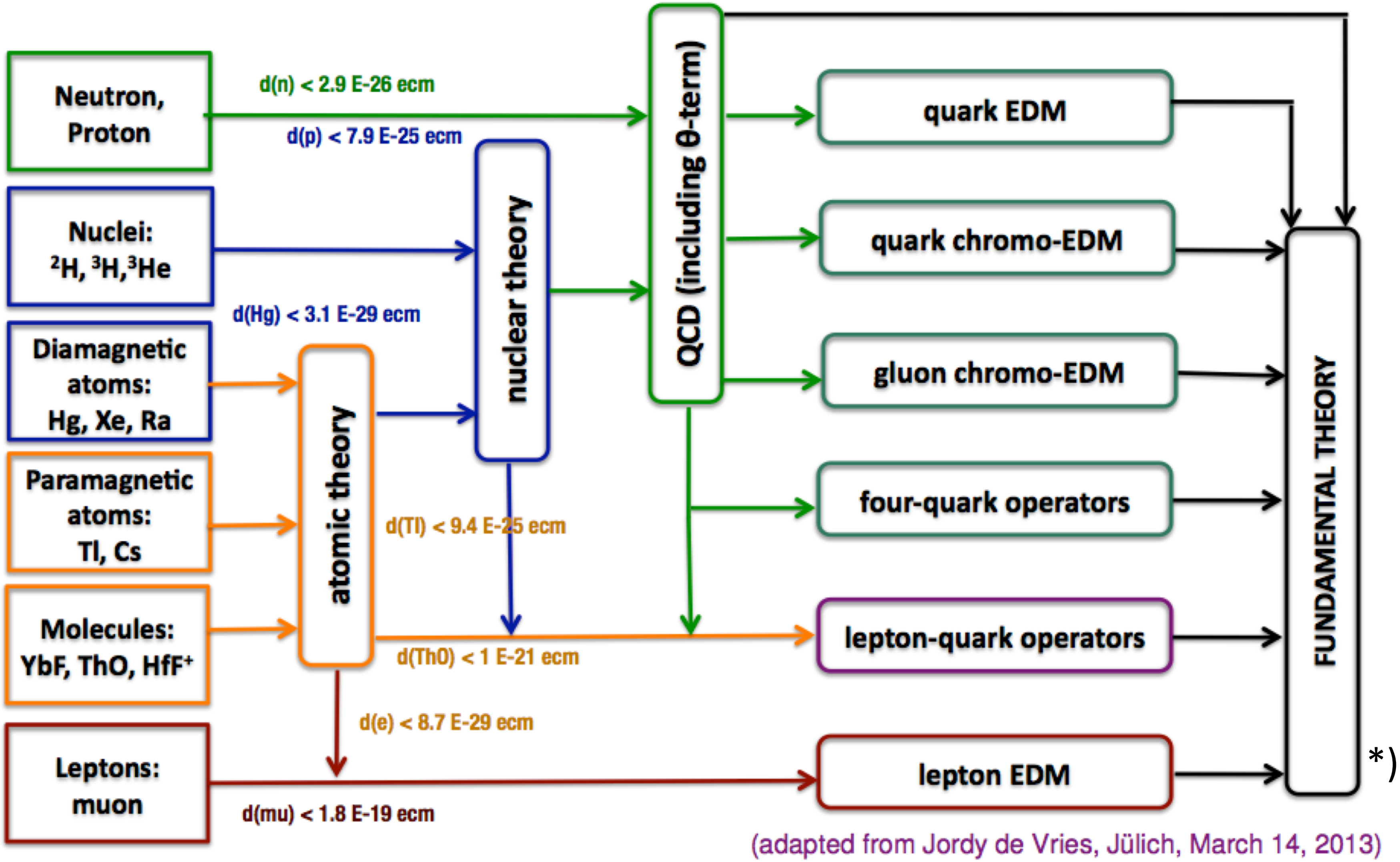
Technische Universität München

Neutron EDM comments
&
The PanEDM Experiment

Peter Fierlinger

SPIN 2018 Conference, Ferrara, Italy

EDM Landscape



*) J.P. Archambault, A. Czarnecki, M. Pospelov, Phys.Rev. D70 (2004) 073006
Mod. Phys. Lett. A11 (1996) 211, D. Ng, J.N. Ng

Different systems and effective parameters

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

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

- Diamagnetic atoms

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

- Nucleons

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

- Fundamental fermions

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

...Higher orders (199-Hg!) :

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

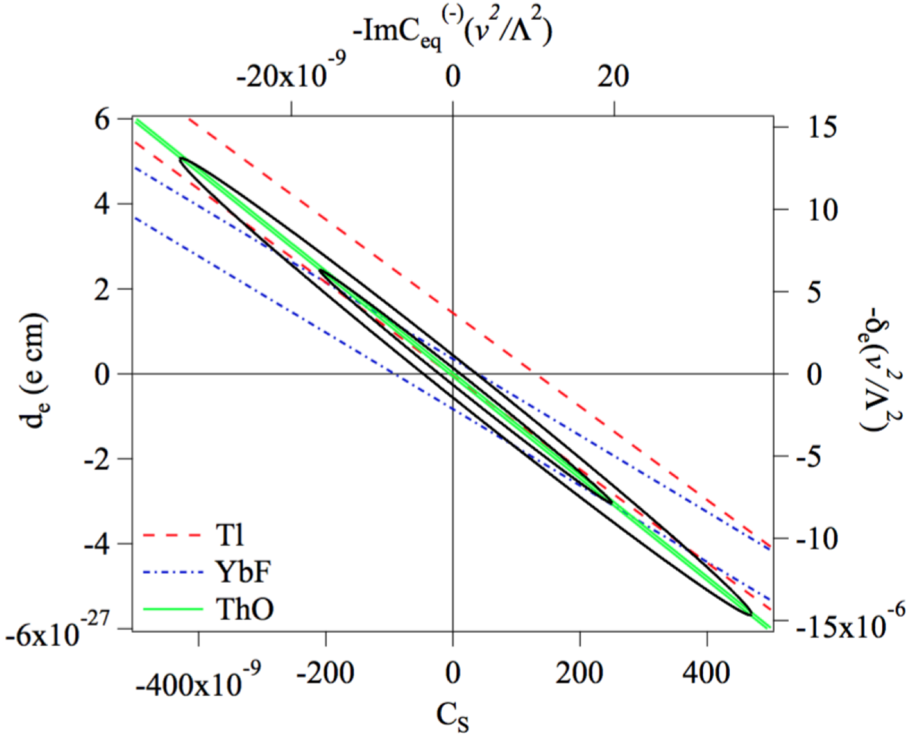
Illustration: combined analyses

Measured limits
(note: 'sole-source' analysis)

System	Result	95% u.l.
	Paramagnetic systems	
Xe^m	...	
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ e-cm	1.4×10^{-23}
	$d_e = (-1.5 \pm 5.6) \times 10^{-26}$ e-cm	1.2×10^{-25}
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ e-cm	1.1×10^{-24}
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$ e-cm	1.9×10^{-27}
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$ e-cm	1.2×10^{-27}
ThO	$\omega^{NE} = 2.6 \pm 5.8$ mrad/s	
	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$ e-cm	9.7×10^{-29}
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}
	Diamagnetic systems	
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$ e-cm	7.4×10^{-30}
^{129}Xe	$d_A = (0.7 \pm 3) \times 10^{-27}$ e-cm	6.6×10^{-27}
^{225}Ra	$d_A = (-0.5 \pm 2.5) \times 10^{-22}$ e-cm	5.0×10^{-22}
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$ e-cm	6.5×10^{-23}
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$ e-cm	3.6×10^{-26}
	Particle systems	
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$ e-cm	1.8×10^{-19}
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$ e-cm	7.9×10^{-17}

+ Paramagn. HfF^+. $d_e < 1.3.10^{-28}$ ecm (90%)

Parameters are not independent: e.g. d_e as function of C_S

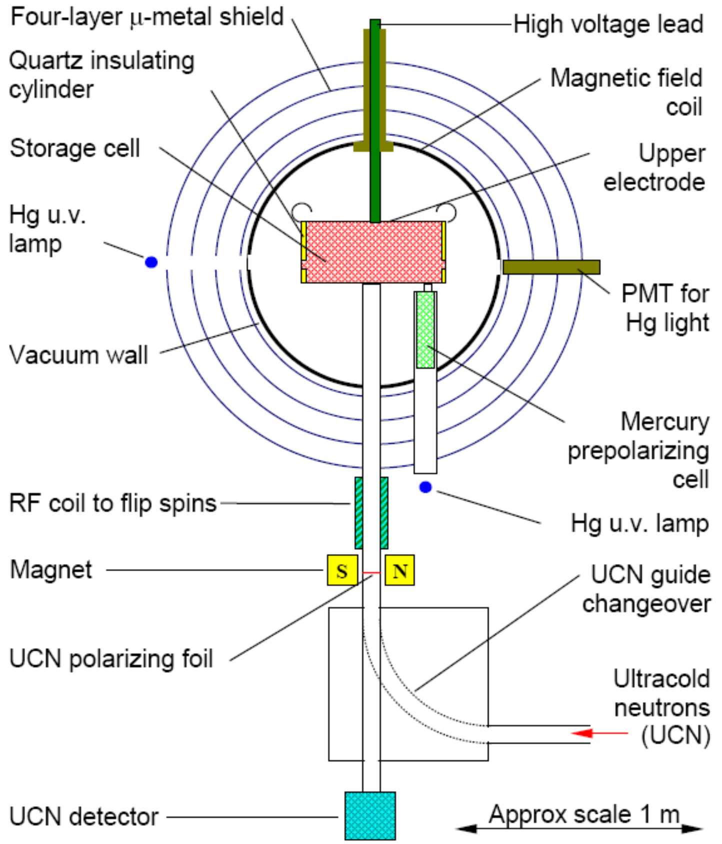


T. Chupp & M.J. Ramsey-Musolf (2015)

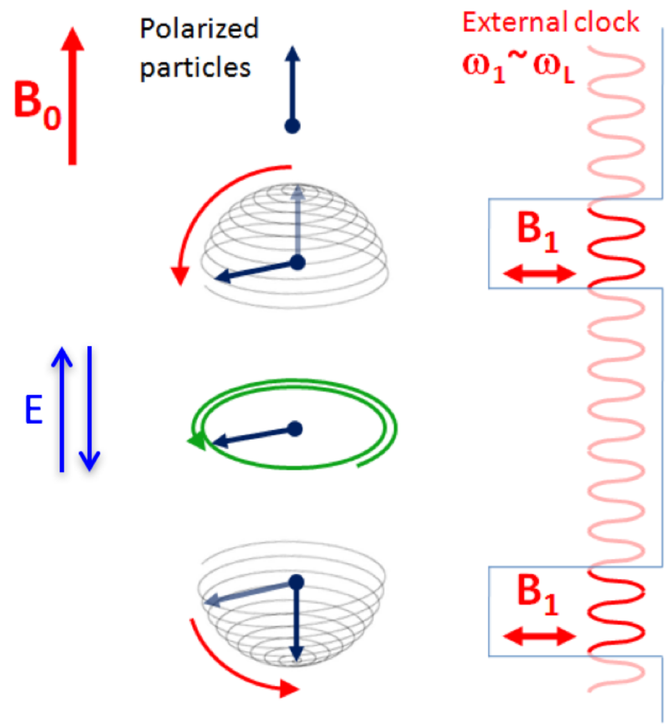
$$d_{\text{para}}^{\text{exp}} = d_e + \frac{\alpha_{C_S}}{\alpha_{d_e}} C_S$$

More measurements needed with different systems...

Ramsey‘s method



(Still) the state of the art: ~ few UCN/ cm^3

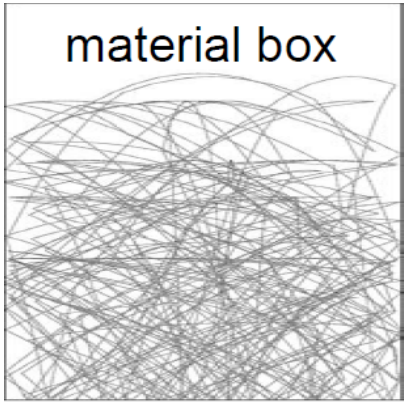


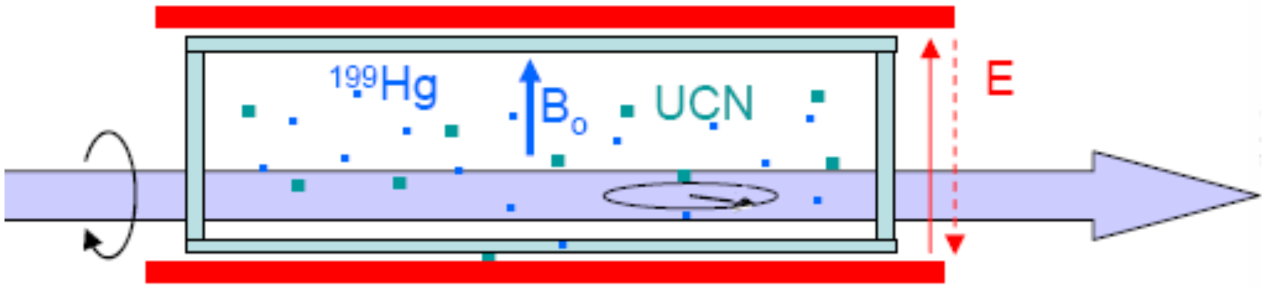
$$\hbar\omega_L \sim \mu B + dE$$

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

Spin-clock with two species

- Neutrons +^{199}Hg vapor measured simultaneously
- UCN center of mass is affected by gravity
  („Slower UCN stay more at bottom")
- Frequency ratio: $R = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right|\left(1 + \frac{(\partial B/\partial z)h}{B}\right)$





... $d_n < 3 \times 10^{-26}$ e cm

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

- Non-trivial: $T_2(z)$, $\Delta\omega(z)$....
- If there is a spatially constant distribution, Spin echo can be applied: energy dependent analysis, T_2 recovery etc...

-> Talk: G.Pignol

Systematics

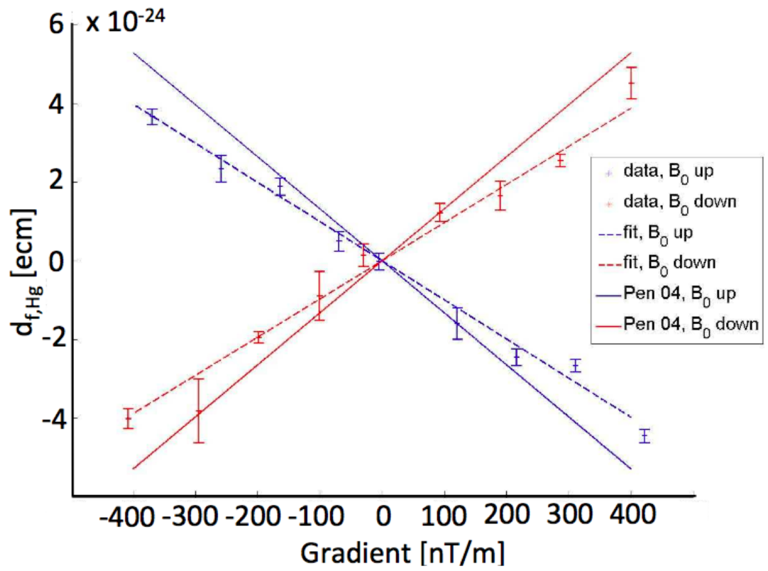
A very critical effect: ‚geometric phase' (GP)

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

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

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

- ~ < 0.3 nT/m gradient
  $d_f \sim 4 \cdot 10^{-27}$ ecm (^{199}**Hg** GP)
  $d_f \sim 1\text{-}2 \cdot 10^{-28}$ ecm (UCN GP)
- Max. 1 dipole with 5 pT in 2 cm distance
- < 10 fT drift stability



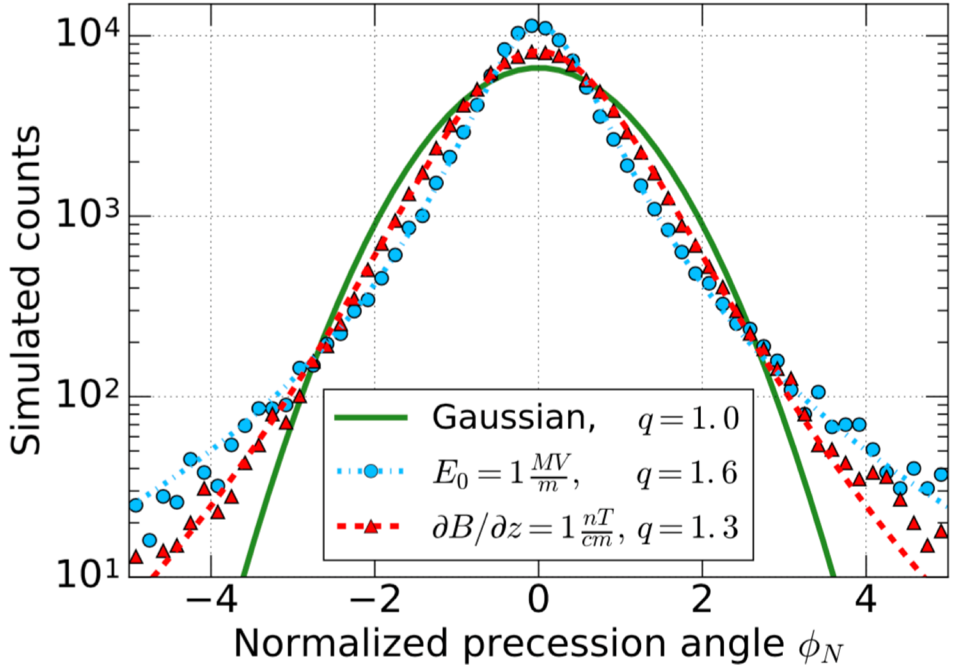
Pendlebury et al., Phys. Rev. A **70**, 032102 (2004) and many more…

New systematics?

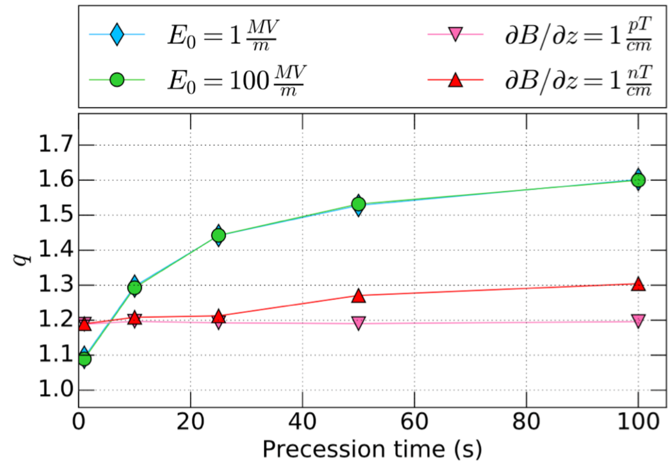
E.g. non-gaussian spin distributions

- Non-ergodic behavior of trapped spins (non-thermalizing systems)
- Any skewness would lead to different frequency shift shifts
- Affects all previously known systematics
- Could appear also elsewhere at increased precision: g-2? pEDM?

M. Bales et al., EPL 2017



Non-gaussianity build-up with time:



... Understanding B-fields seem even more important.

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 beam, ^{4}He		D2	spall, internal ^{4}He	reactor, turbine, ^{4}He		spall., ^{4}He	
nr of cells	**1**	**1**	2	2	> 100	1	2	2	>2	1	2
[UCN/cc]	**2**	**3**	5	10	1000	~ 50	125	**4**	10^4	700	
goal [e·cm]	**$3\cdot10^{-26}$**	$1\cdot10^{-26}$	$1\cdot10^{-27}$	$2\cdot10^{-27}$	$< 10^{-27}$	few 10^{-27}	$2\cdot10^{-28}$	$5\cdot10^{-26}$	$<1\cdot10^{-27}$		$1\cdot10^{-27}$
date	**2006**	**2017**	2019	2019	2021+	2019	2022	2015	2022	2017	2020
status	**done**	RAL exp. **NEW LIMIT SOON** $\sim1.10^{-26}$	new	**Setup at ILL started: ‚PanEDM‘**		**Sucessful source upgrade**	Critical Component Demonstration			**FIRST UCN OBSERVED from prototype source (2017)**	

+ Crystal EDM (Nagoya)
+ Beam EDM (Bern)

Taken from R. Picker (2016), adapted

nEDM progress without ‚better‘ UCN sources?

$$\sigma_d \sim \frac{1}{ET\alpha_0 \mathrm{e}^{-T/T_2}\sqrt{N_0 \mathrm{e}^{-T/\tau_n}}\sqrt{M}}$$

T ... Measurement duration
T_2 .. Spin coherence / τ ...UCN storage time
E ... Electric field strength
α_0 ...Visibility (Polarization)
N_0 .. Number of UCN at start of measurement
M ... Number of repetitions

- **Fast magnetic equilibration: 30 s instead of 300 s**
  I. Altarev et al., J. Appl. Phys. ((2015)
- **Deuterated polyethylene, softer spectrum: T, N increased** I.Altarev et al., Appl. Phys. Lett (2015)
- **Visibility: α > 0.87** T. Zechlau, PD thesis

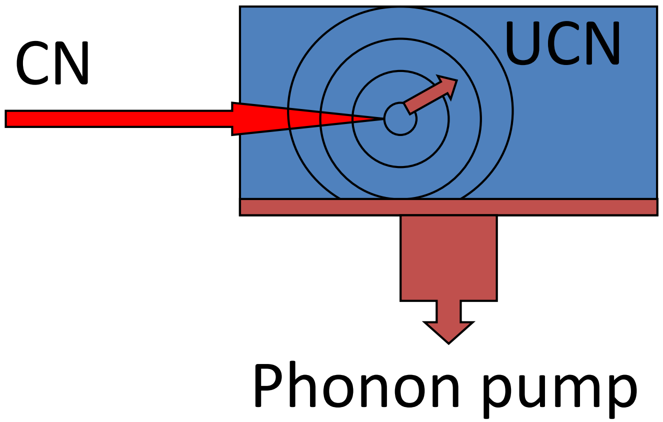
- Larger E ~ x 1.5
- Larger $\alpha(t)$ ~ x 1.1
- Recovery of UCN T_2^* ~ x 1.2
- Knowledge of energy dependence ~ x 1.1
- Faster turnaround and more stable performance: equilibration, new types of co-magnetometers ~ x 1.2

Superthermal UCN production

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

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

All ‚new' approaches: ‚Superthermal' conversion instead of moderation. Goal: 1000 UCN / cm^3



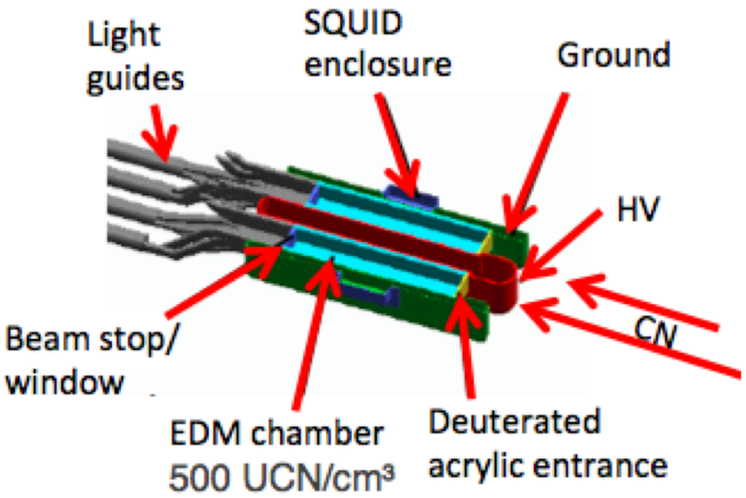
$$\rho_{UCN} = \Phi_{CN} \Sigma \tau_{UCN}$$

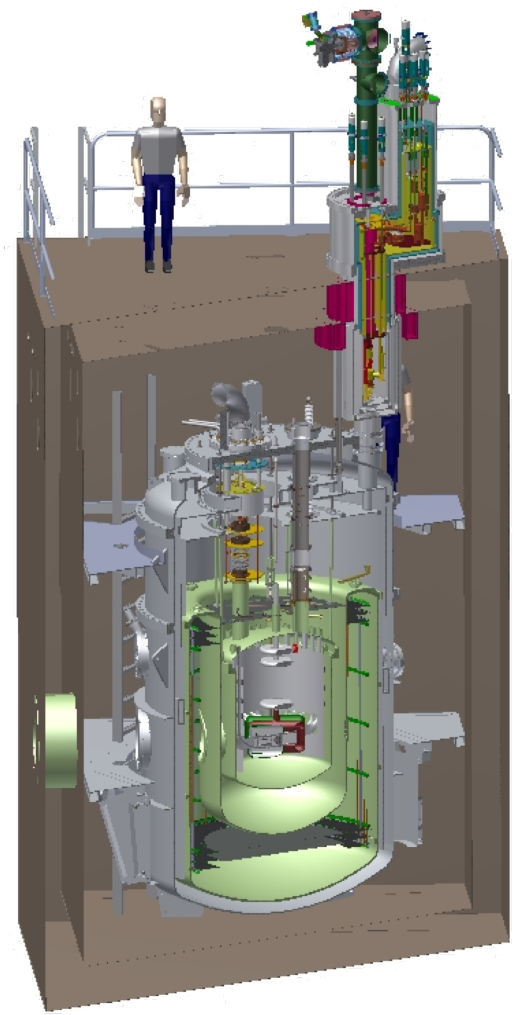
Main options:

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

SNS EDM

- Cryogenic, > 100 UCN/cm^3
- Site: SNS, placed at cold beam
- UCN source = EDM chamber, double chamber
- E = 75 kV/cm
- Co-magnetometer: spin dependent ^{3}He absorption and scintillation, ^{3}He MFP control
- Modulation of spin-dressing frequency to extract EDM

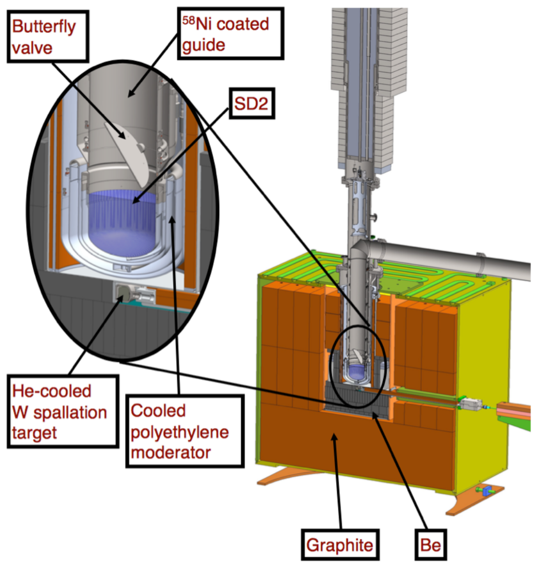


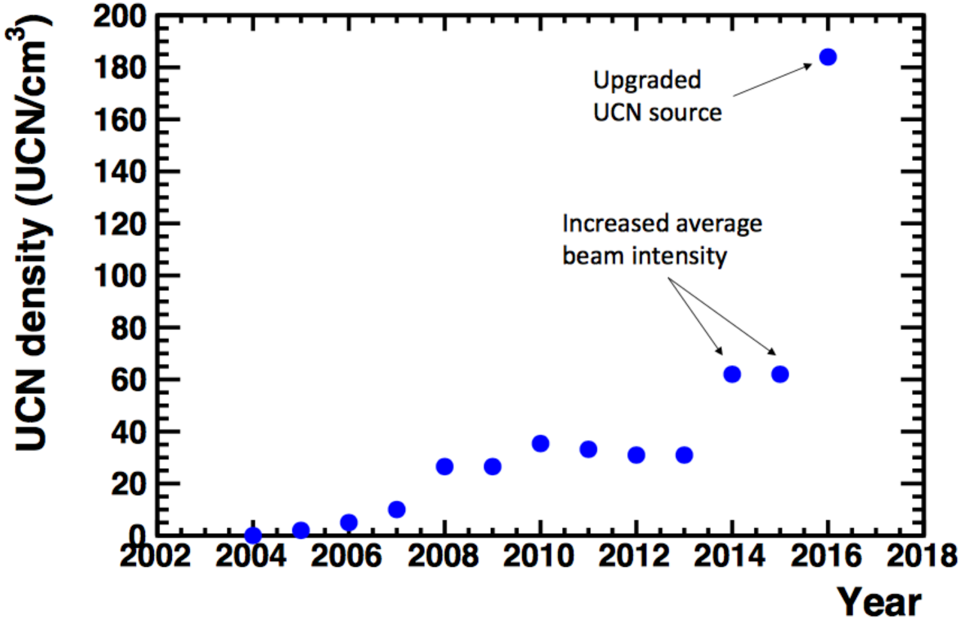


- Full-scale operation in 2022

LANL EDM

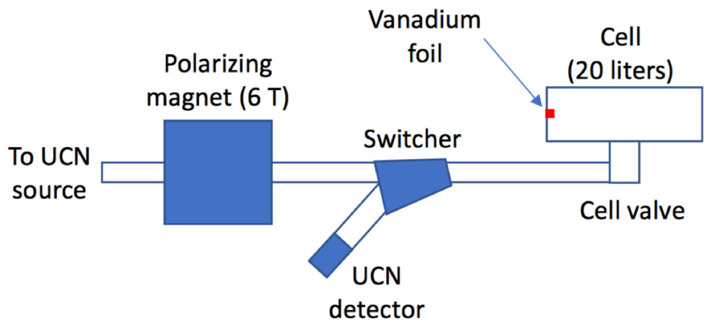
Progress 2017/18: UCN source upgrade





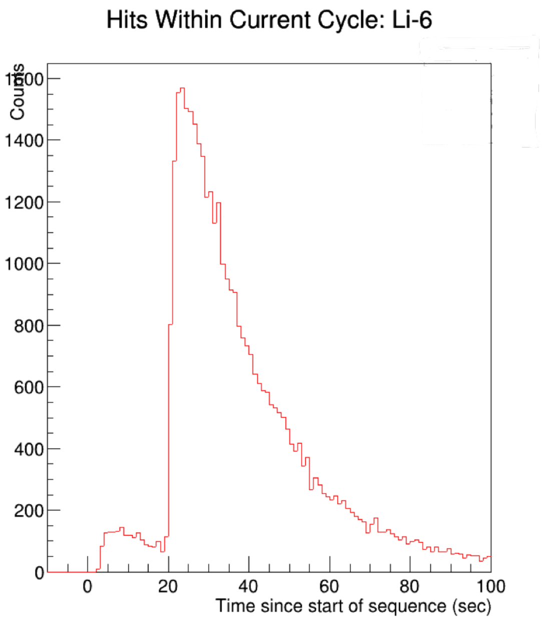
T.M.Ito et al., arXiv:1710.05182

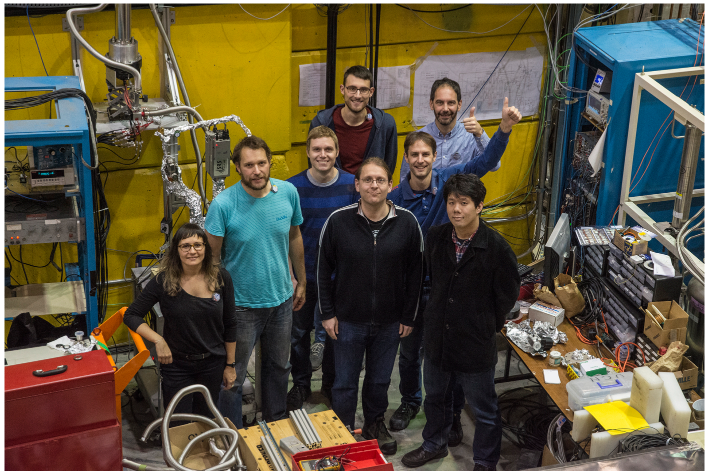
- Room temperature Ramsey experiment
- Initial goal is to demonstrate a stored UCN density sufficient for a several x 10^{-27} e-cm nEDM experiment
- UCN upgrade concluded
- First measurements with Ramsey cell



UCN at TRIUMF

- **First operation of source in 2017: 500000 UCN**
- Behaviour within expectations
- p-Accelerator
- Neutron-production target with a 1 microamp, 480 MeV proton beam for 60 seconds
- Goal: $\sigma_d \sim 10^{-27}$ ecm, room-temp. Ramsey, $^{129}Xe/^{199}Hg$ co-magnetometers





TRIUMF, CFI, BCKDF, MRF and NSERC in Canada, and KEK and RCNP

-> Talk B. Franke

PNPI

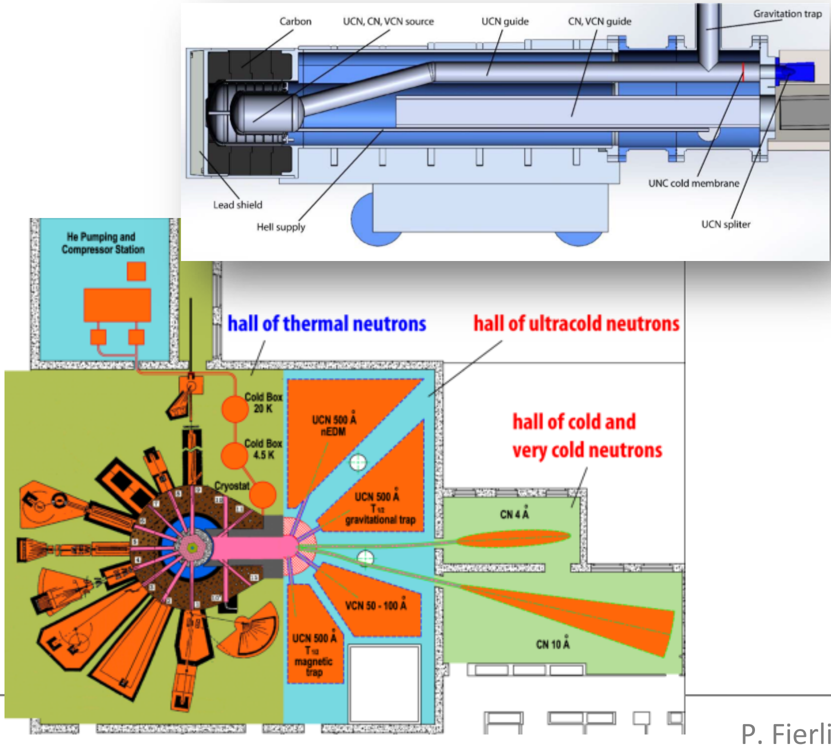
UCN source:

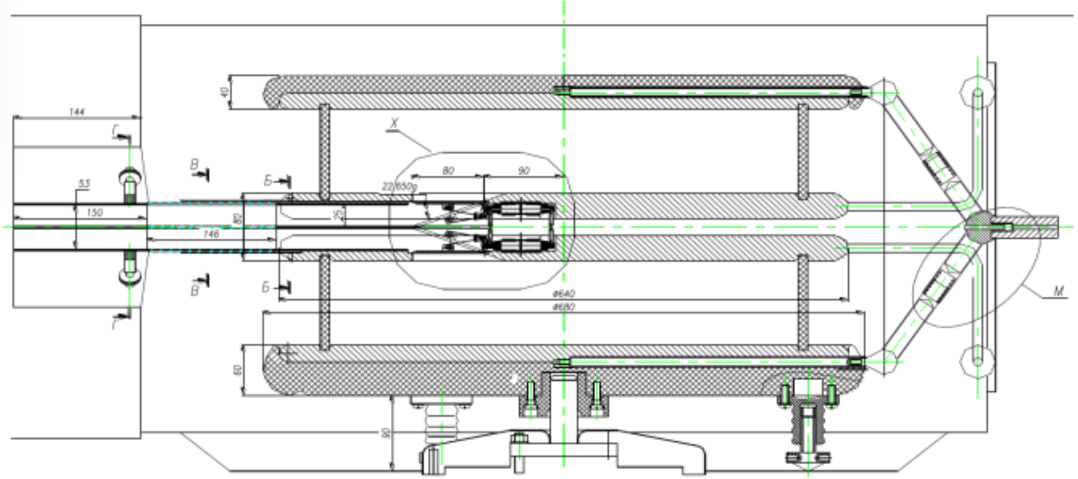
- UCN density $>1\times10^{5}\ \mathrm{cm}^{-3}$
- All hardware exists
- Cooling power test successful
- Permission to operate WWR-M unclear

nEDM:

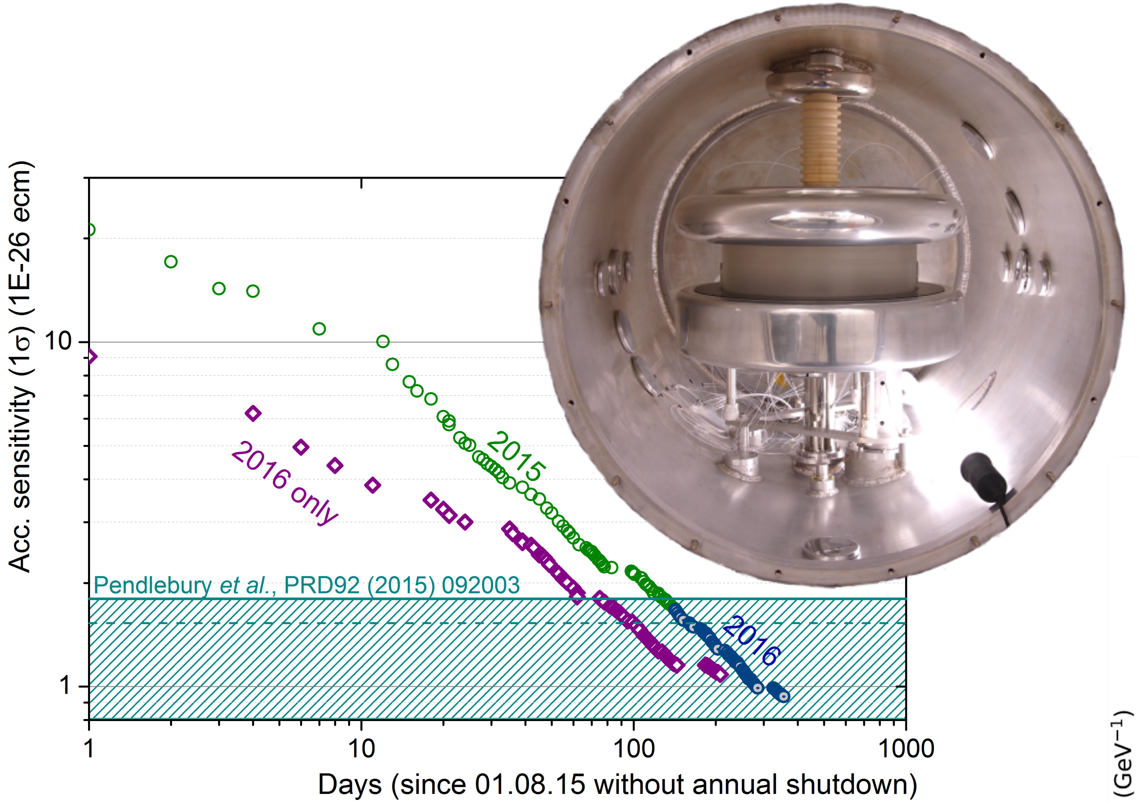
Current: $d_\mathrm{n} < 5.5\times10^{-26} e\mathrm{cm}$
Improvement by factor 3 at new position and with new precession cell

ILL 2020: $d_\mathrm{n} < 2\times10^{-26} e\mathrm{cm}$
Future source at PNPI: $d_\mathrm{n} < 1\times10^{-27} e\mathrm{cm}$





PSI n(2)EDM

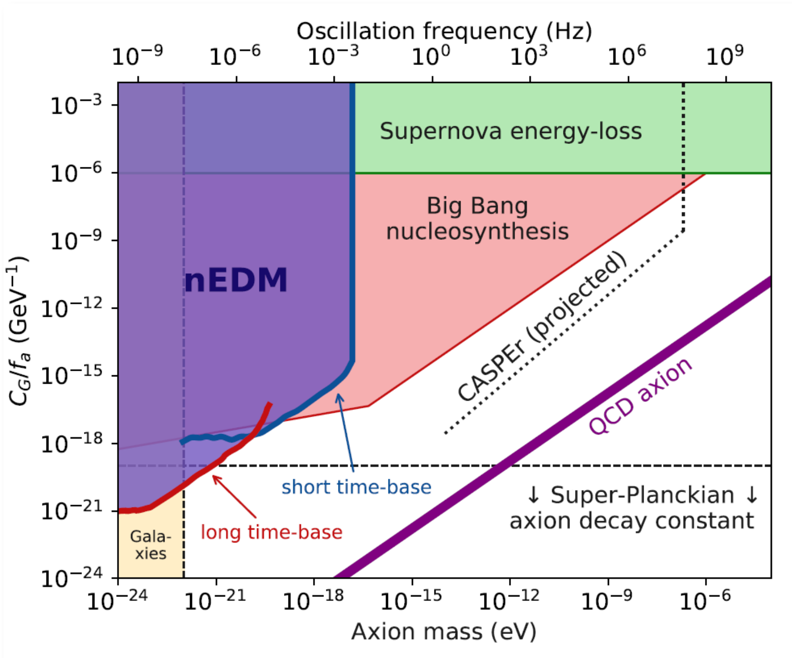


$$\sigma = 0.94\times10^{-26}\mathrm{ecm}$$

- Blinded data
- Two groups
- Result planned for 2018
- n2EDM: Shield being built ~ now

Spin-off physics:

- Limit on ultralight particles with hadronic coupling through ‚oscillating EDMs'

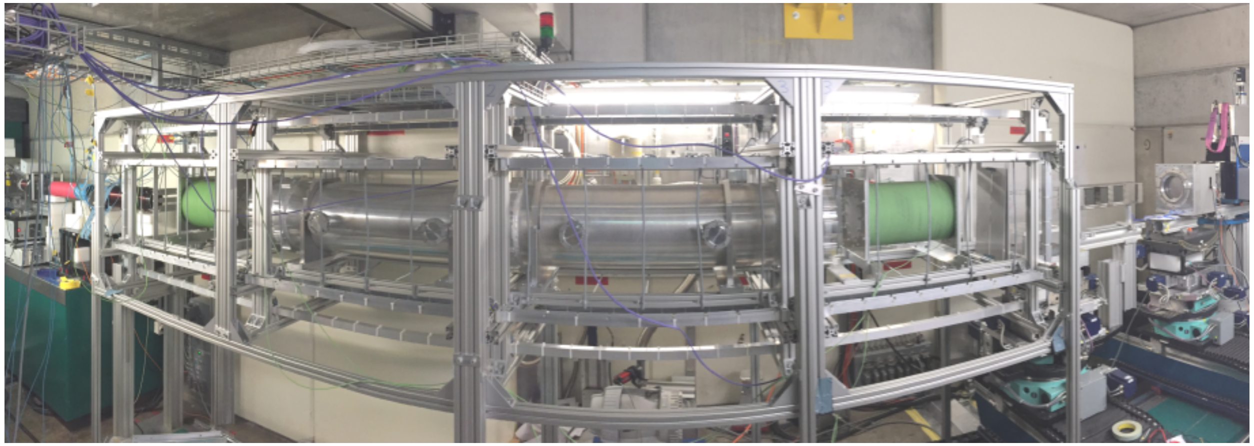


C. Abel *et al.*, PRX7(20017)041034

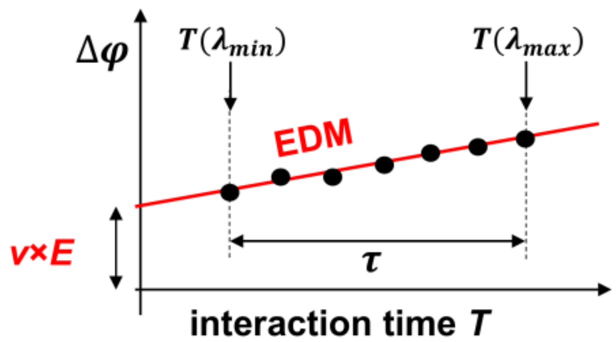
-> Talk: Y. Stadnik

-> Talk: K. Kirch

Pulsed beam



$$\Delta\omega \propto d_n E + \mu_n E \frac{v}{c^2} \sin(\alpha)$$
$$\Leftrightarrow$$
$$\Delta\varphi = \Delta\omega T \propto d_n E T + \mu_n E \frac{L}{c^2} \sin(\alpha)$$



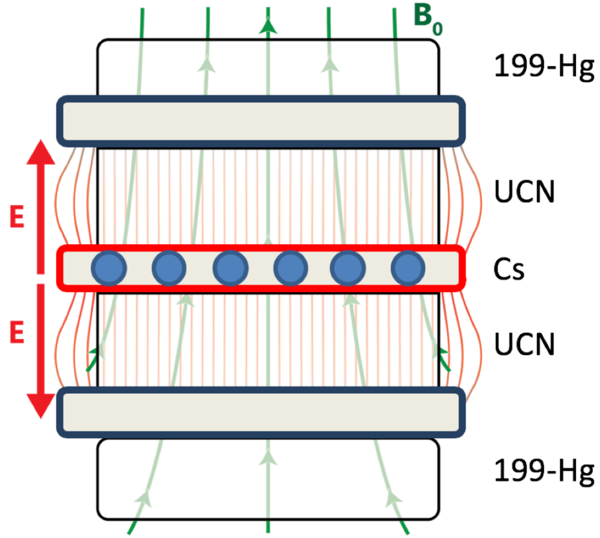
	T	η	E [kV/cm]	N	M (no. cycles)	σ / day [10^{-26} ecm]
@ PF1b/ILL *	8 ms	0.75	50	2 x 2 MHz	1	~ 800
@ ESS	90 ms	0.75	100	2 x 20 - 200 MHz	1	3 - 10
ILL/RAL /Sussex **	130 s	0.45	8.3	14000 per cycle	360	30

- Use neutron source's intrinsic pulses
- Fixed installation
- Lengh: 50m
- $\mathrm{d}N/\mathrm{d}t > 100\ \mathrm{MHz}$

F. Piegsa, PRC (2014)

PanEDM phase I

- Helium-based SuperSUN source at ILL
- Ramsey experiment with UCN trapped at room temperature
- Double chamber in phase I
- ^{199}Hg (few fT in 250 s), Cs (finally good enough), ^{129}Xe, ^{3}He, SQUIDs
- No co-magnetometer (better!)
- Start of data taking scheduled first cycle 2019



… + more surrounding magnetometers, ofcourse

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

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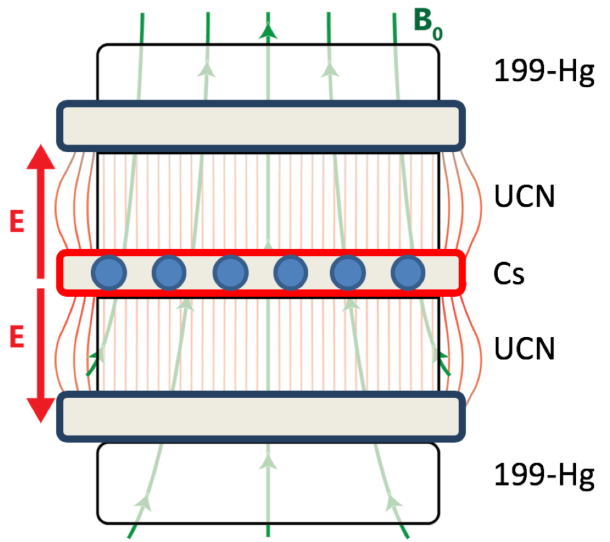

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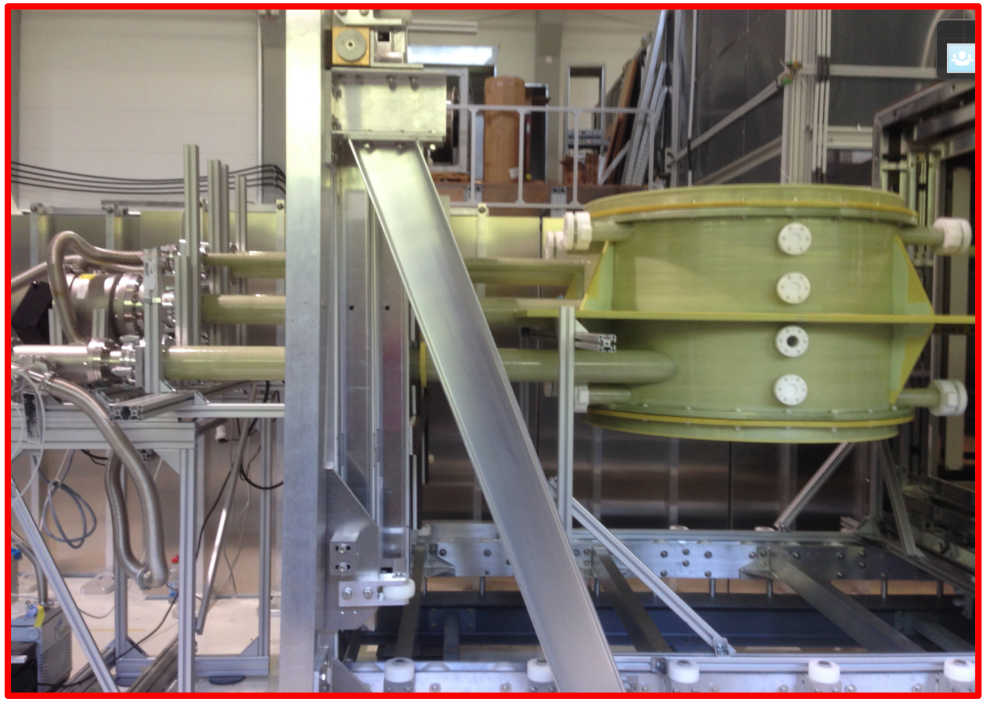

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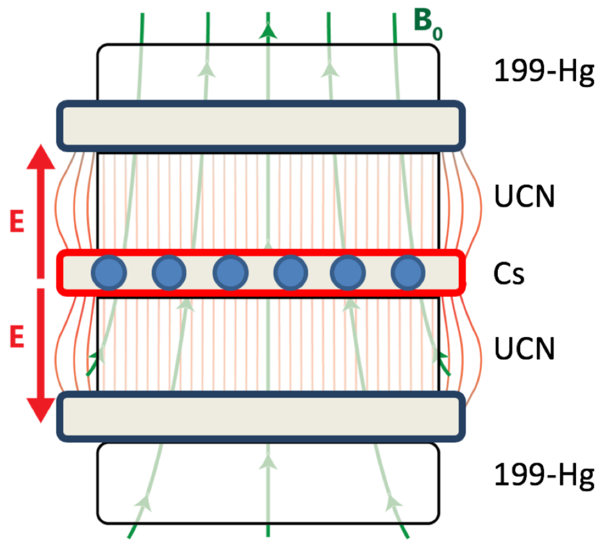

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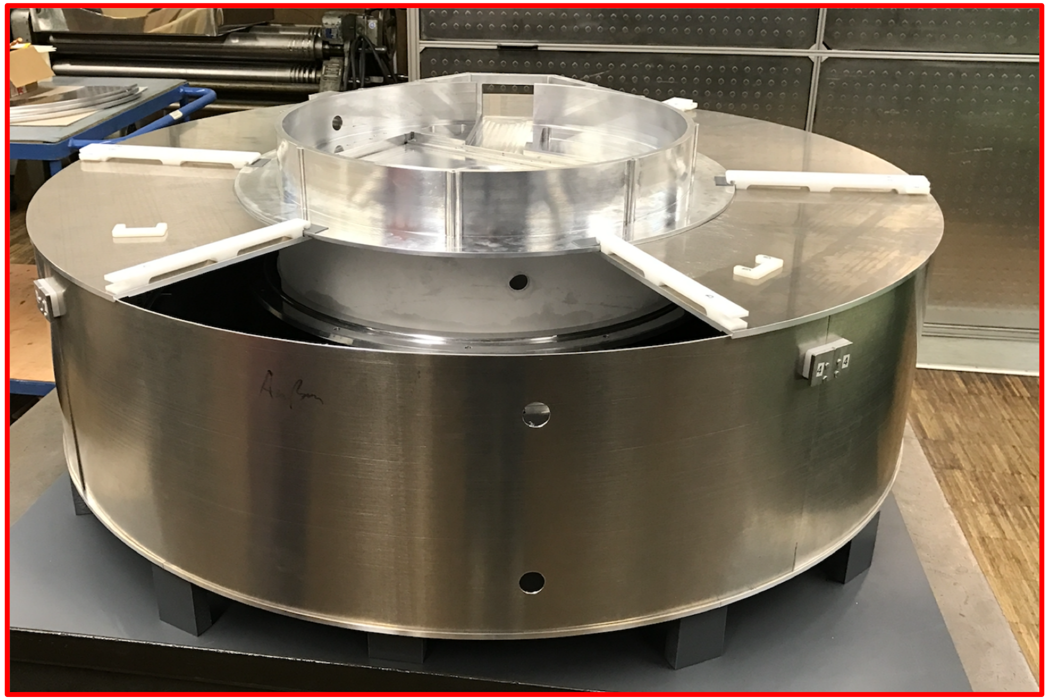
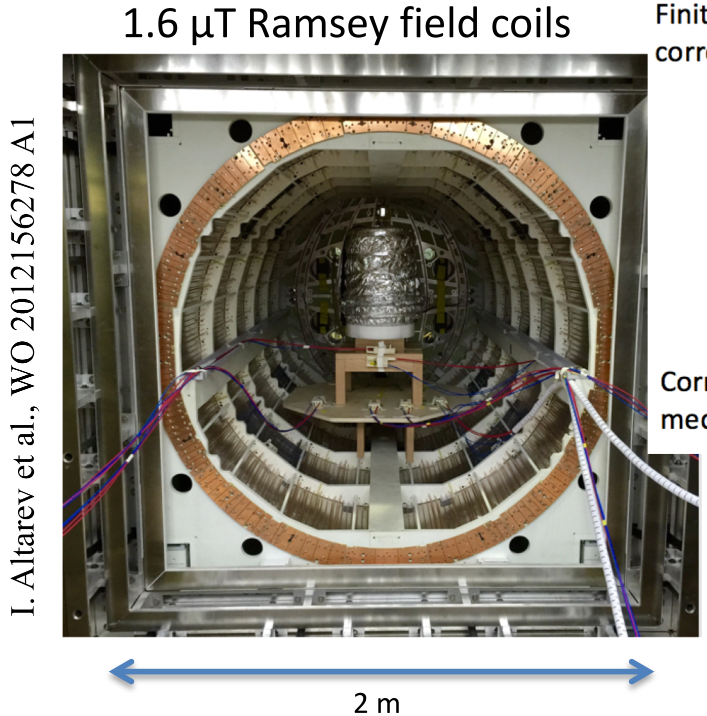
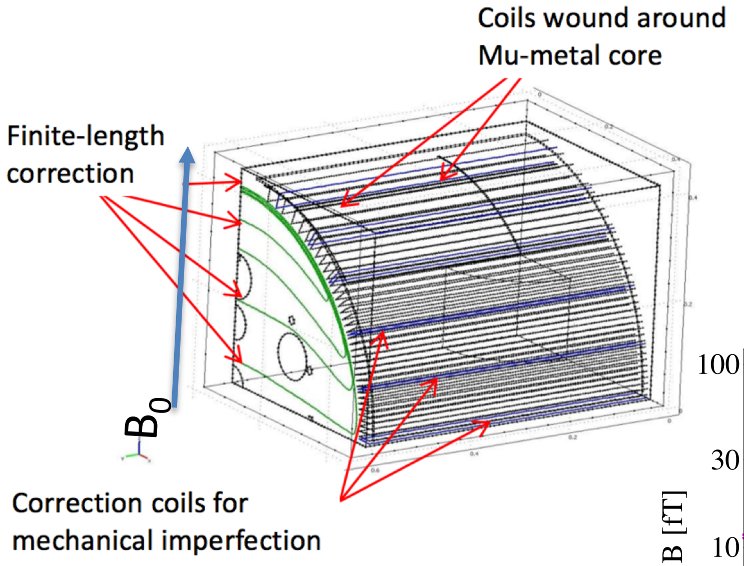


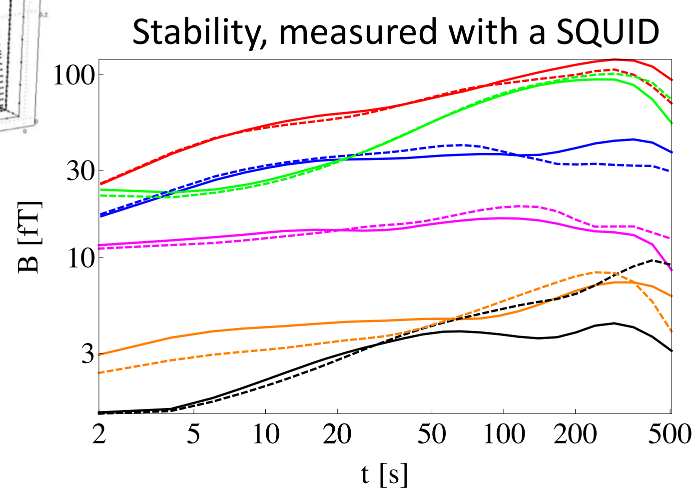
I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)

Magnetic fields

- Double chamber: first order field drifts canceled (limited by B_0 correction coils)
- Damping of ext. distortions ~ $6x10^6$ (passive) at 1 mHz, x 1.5 for gradients
- Background gradient drift < 1 fT in 300 s between cells

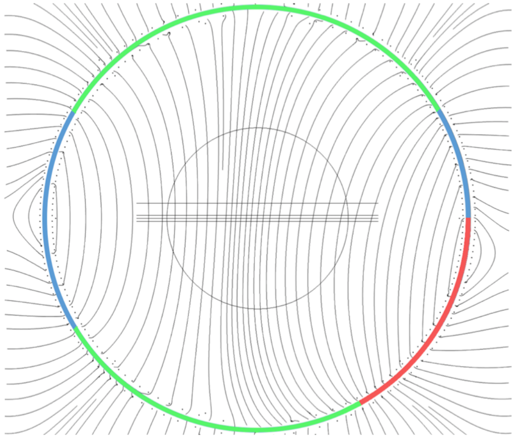






Generated magnetic field

Illustration of the main issue:
Every magnetic field is disturbed by the shields!



(View into cylinder from front)

permeability varied (strongly)
along inner shield cylinder

Result: (could be further optimized when needed)

Residual field [pT]

0.4 m

1 m

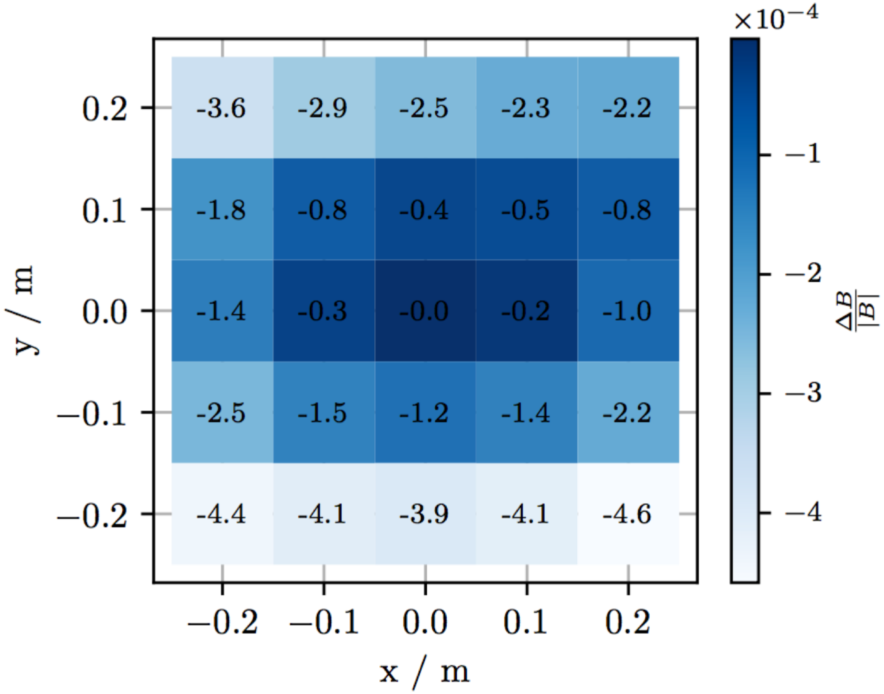
	Bx in pT	
Xend-18	Xmitte0	Xend+18
8	50	88
11	59	80
29	80	85
18	48	91
19	51	91
12	43	97
-2	30	91

	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

(Measurement dominated by sensor cables!)

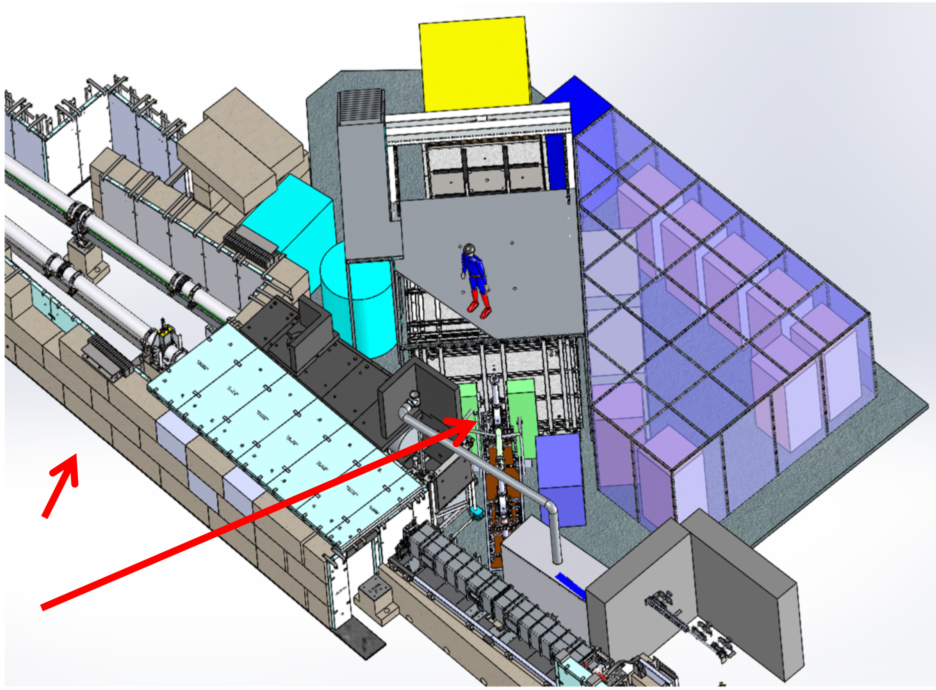
Applied B0 field horiz. plane



- Limited by sensor alignment

Setup at FRM-II in Munich

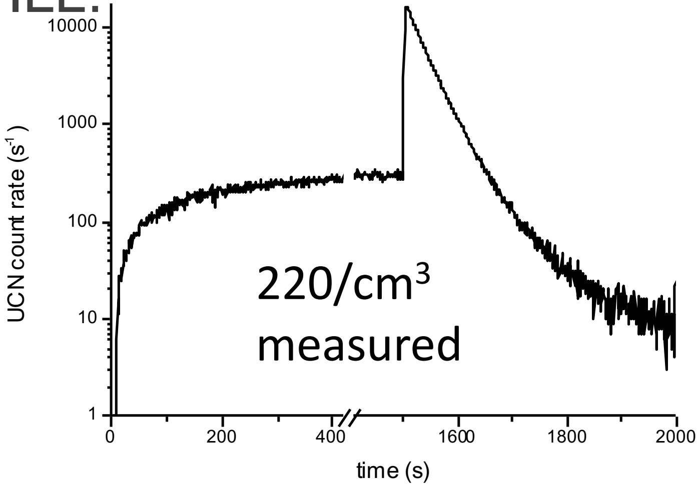
Setup at ILL Grenoble

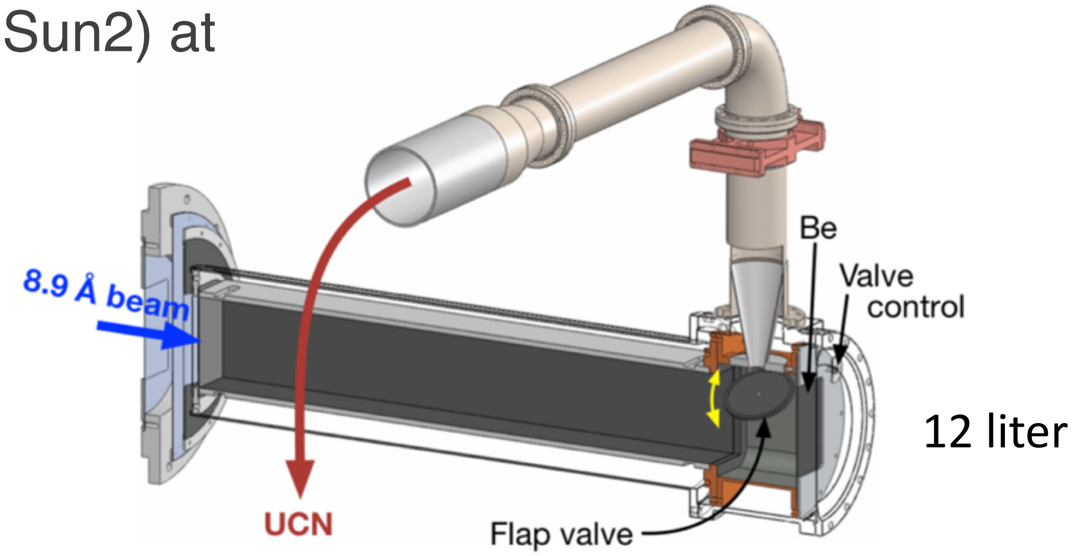


(Re)assembly ongoing now

He-based UCN source at ILL Grenoble

SuperSUN source (based on Sun2) at ILL:



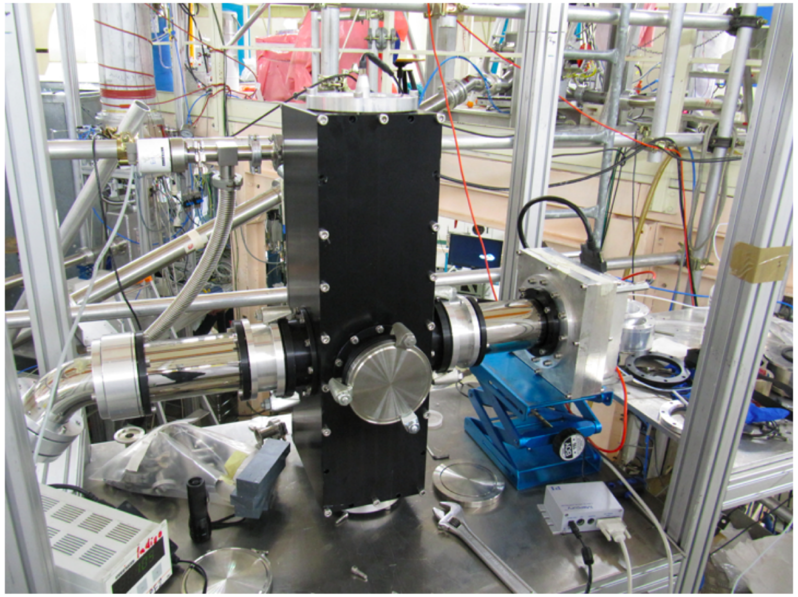


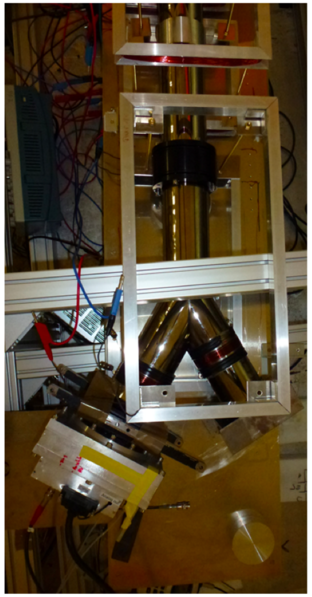
- **Fixed number of UCN:** Dilution of density in chambers and guides
- **Build-up of UCN inside source:** ultimately polarized UCN production
- **Very low energy spectrum:** 79 neV max (stage 1) -> extremely long storage times T = 250 s demonstrated); but bad transport
- **Small systematics:** low UCN velocity

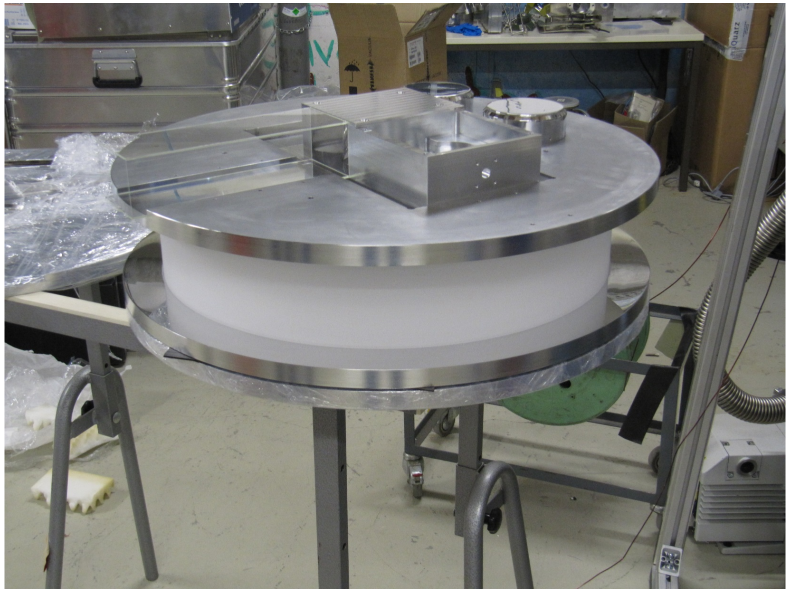
- **Very different to sD2 source:** We have to build all UCN optics new...

Illustration: preceeding UCN tests

- Guides
- Switches, shutters
- Depolarization
- Adiabatic spin transport and spin-flipping
- Simultaneous spin detection
- Deuterated polyethylene coatings
- ‚Dummy'-electrodes and insulator rings
- Results: e.g. 250 s storage demonstrated, $\alpha(300s) > 0.85$







Physics reach PanEDM phase I

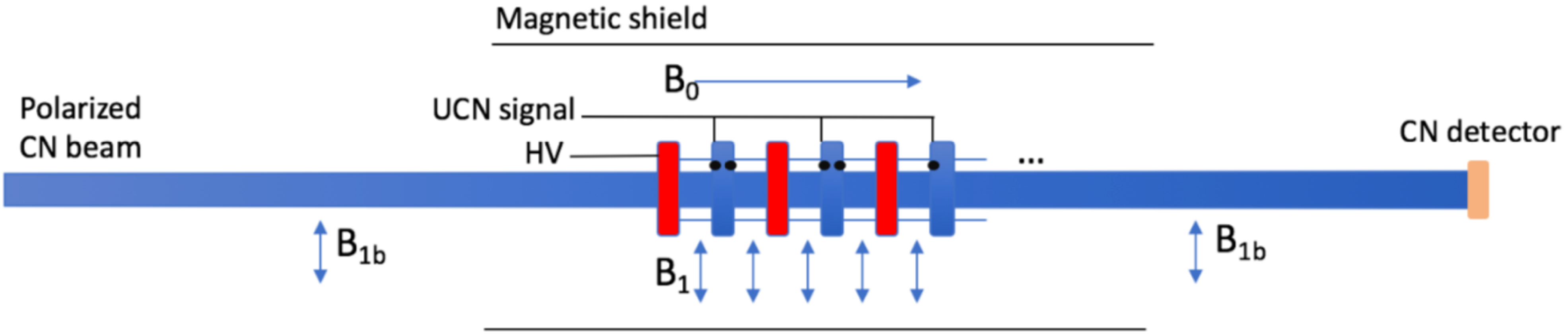
Recently reduced to “1“ due to coil as polarizer

	2019-2020		2020+	
	SuperSun stage I		SuperSun stage II	
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**

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

PanEDM phase II

Concept: Multi-chamber



Reach:

HV	500000	V
Cell "height"	7	cm
E Field	71428,57143	V/cm
alpha	0,95	
T	350	s
Initial UCN density (in situ!)	1000	1/cm3
Volume	2198	cm3
N(t= 0)	2,20E+06	
N after T	*8,14E+05*	
sigma_d =	1,53E-026	ecm / measurement
Cells	100	
sigma_d =	1,53E-027	ecm
Repetitions	10000	
sigma_d =	**1,53E-029**	**ecm**

S. Degenkolb, PF, O. Zimmer

PanEDM phase II

Principle:

- Cold beam produces UCN inside EDM cells in superfluid helium
- Cryogenic = low losses, large HV
- In situ = high density
- Control of systematic: many cells simultaneously
- Magnetic field demonstrated
- UCN source design with 3 m length demonstrated

A key ‘trick’: **in-situ UCN detection**

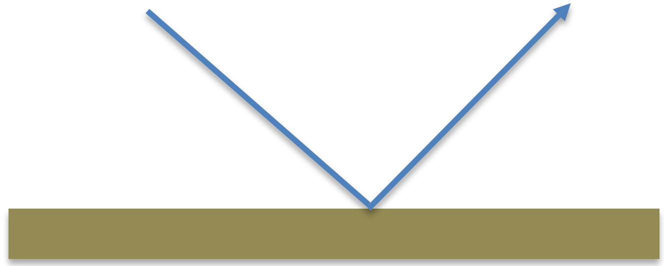
- Only one component needs to be developed & multiplied:
- $1 \cdot 10^{-29}$ ecm feasible without progress at neutron sources!
- No moving parts, (comparably) cheap!

S. Degenkolb, PF, O. Zimmer

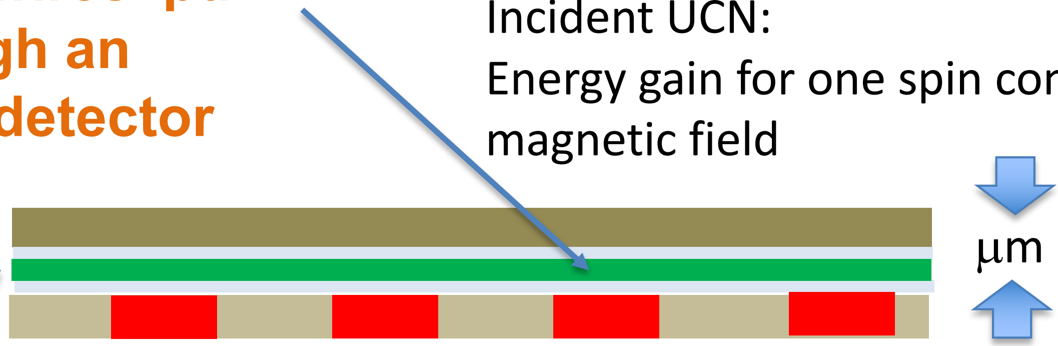
Towards a fully cryogenic measurement

Detection concept:

1) Normal UCN reflection

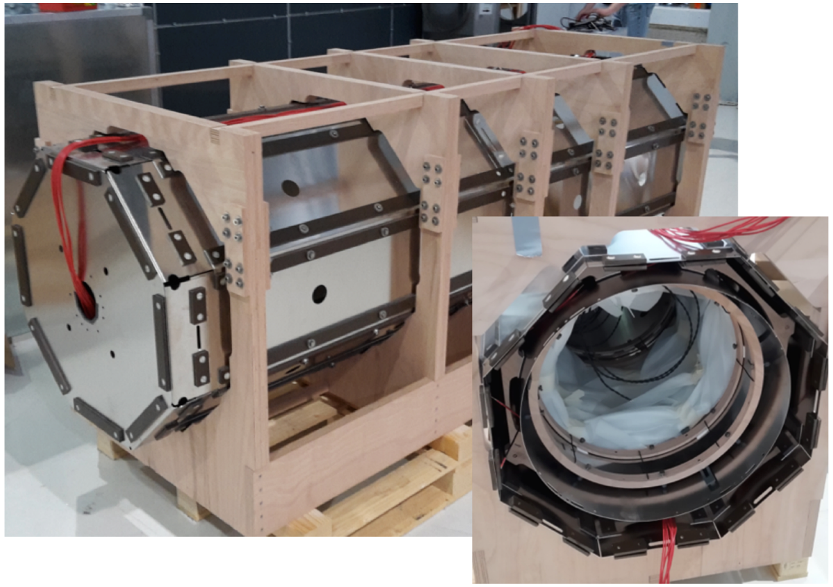


2) Superconducting wires 'pull' one spin state through an electrode surface -> detector



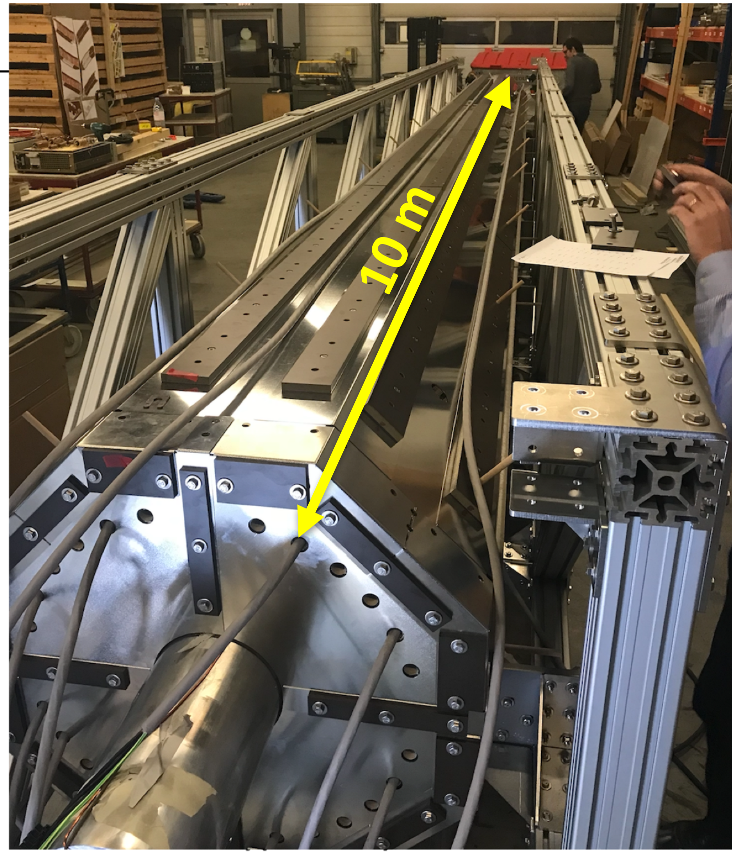
Long magnetic shields

Extended length shielding needed for phase II, but also e.g. for pEDM

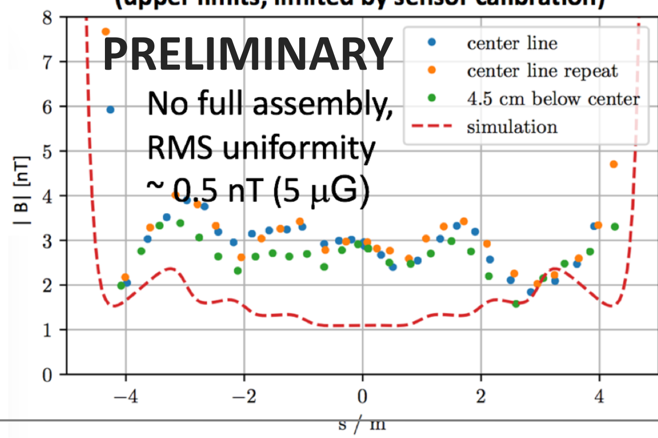


Now demonstrated:
0.1 nT at small radii

Ongoing: characterization of 10 m long shield



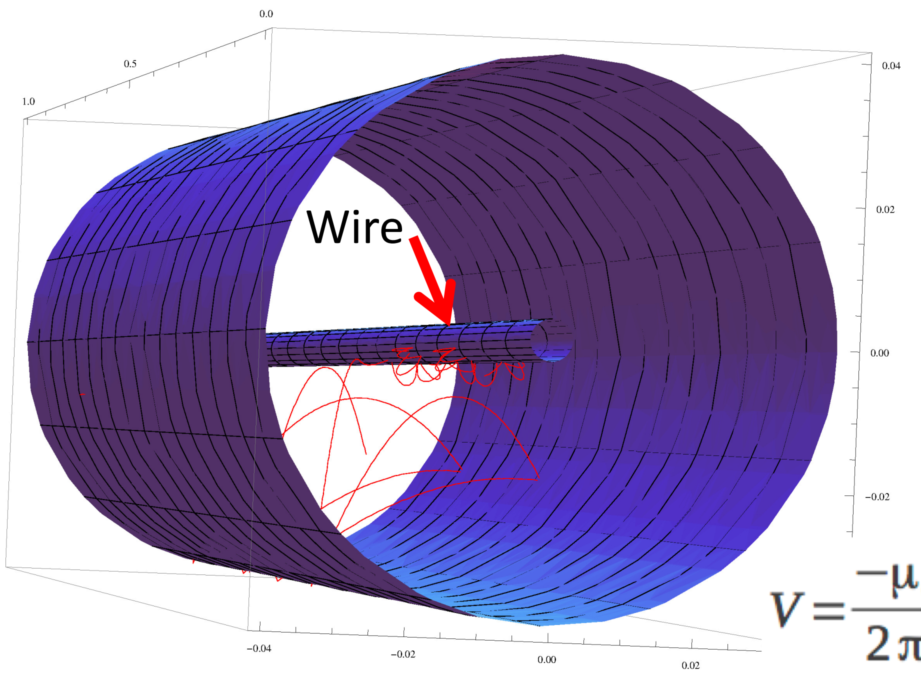
(upper limits, limited by sensor calibration)



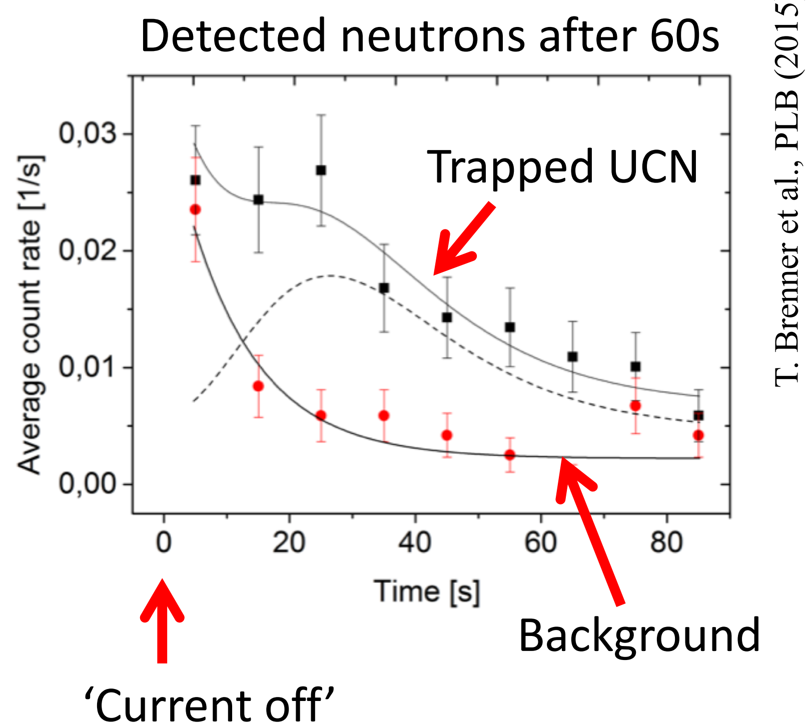
Detector demonstrator: high-field seeker trap

Neutrons trapped on a wire with large current

- First trap for high-field seeking spin-states
- Closed trajectories with (sub)-millimeter distance to a mass without wall collisions
- Easy to detect decay products
- Next step: quantized states around wire

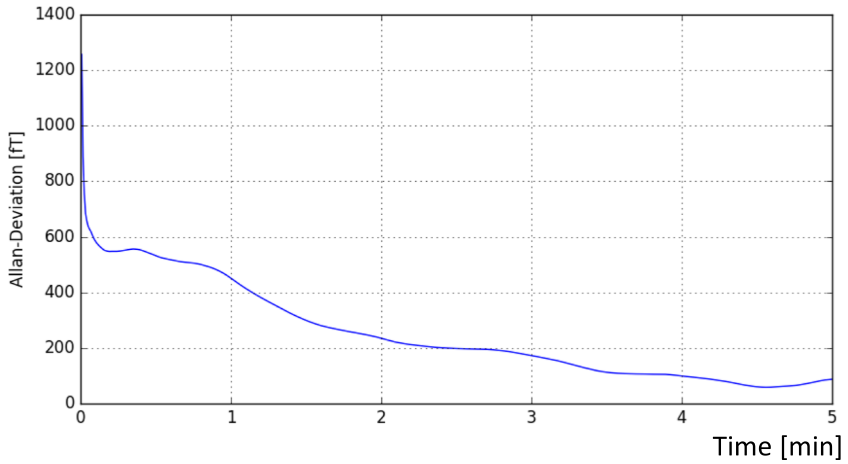


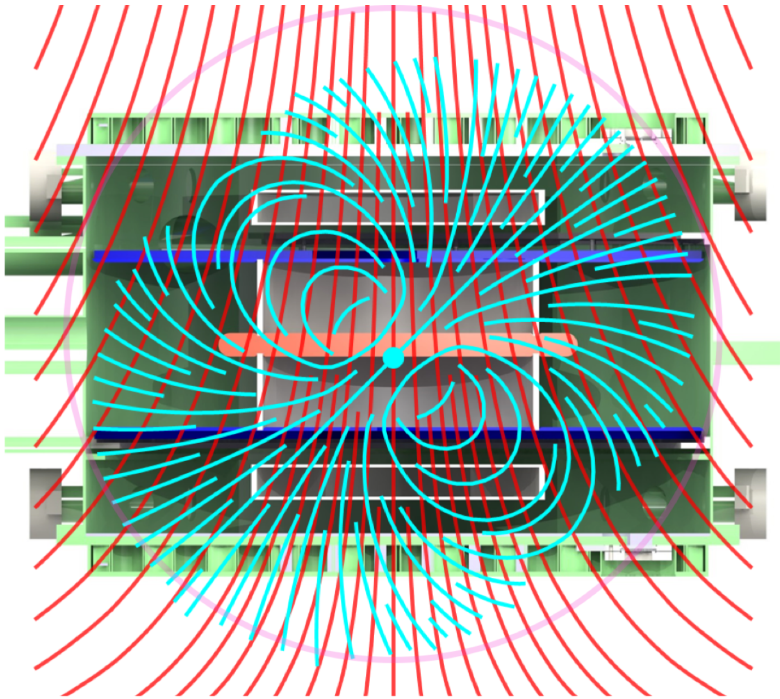
$$V=\frac{-\mu_0 I}{2\pi r}$$



Cs magnetometers

- **Free-space, in-electrode magnetometers at HV:**

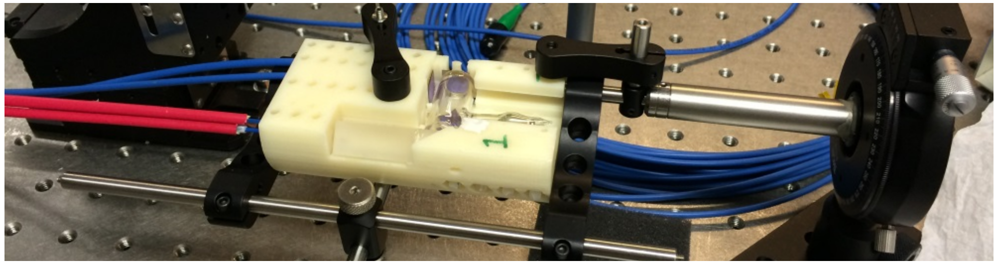




'typical' performance:
< 60 fT without any corrections at typical Ramsey cycle durations

- **Nonmagnetic fiber coupled sensors:**

< 30 fT in 1 s integration



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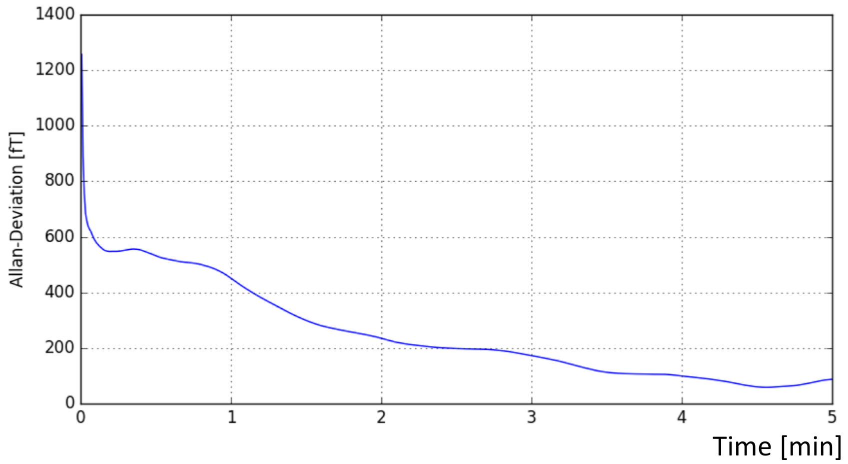

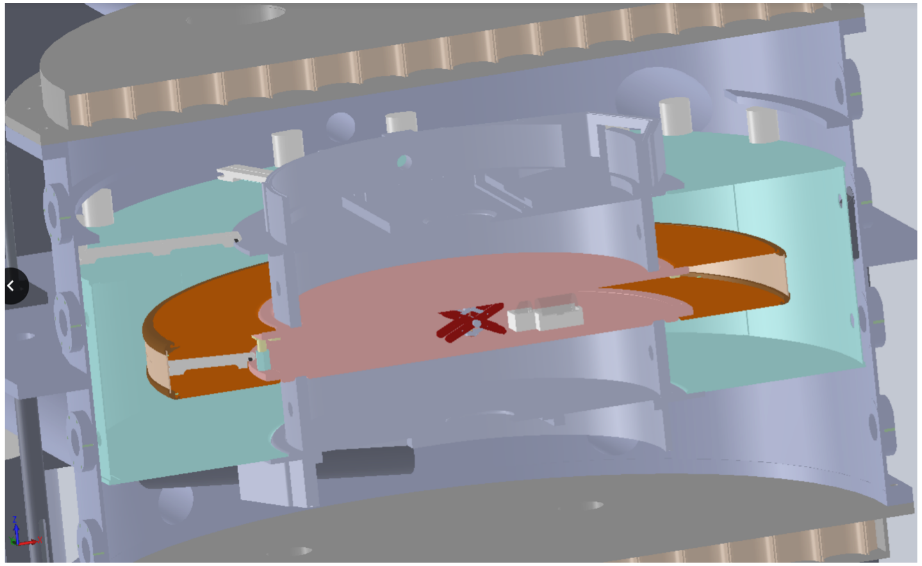

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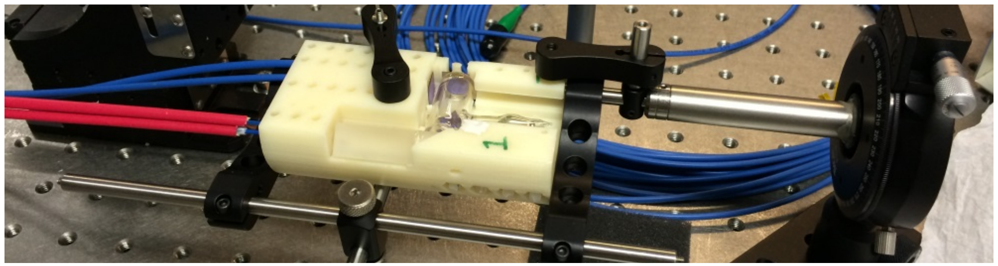
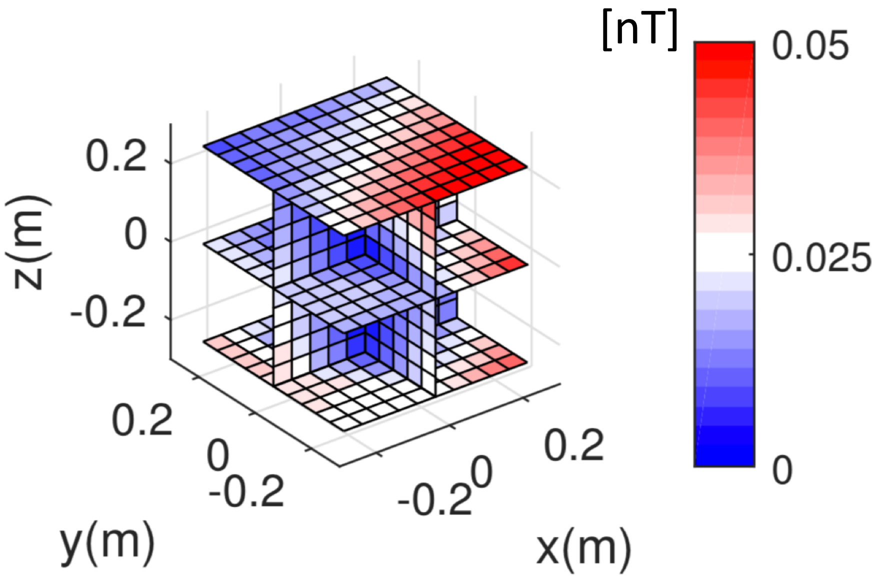
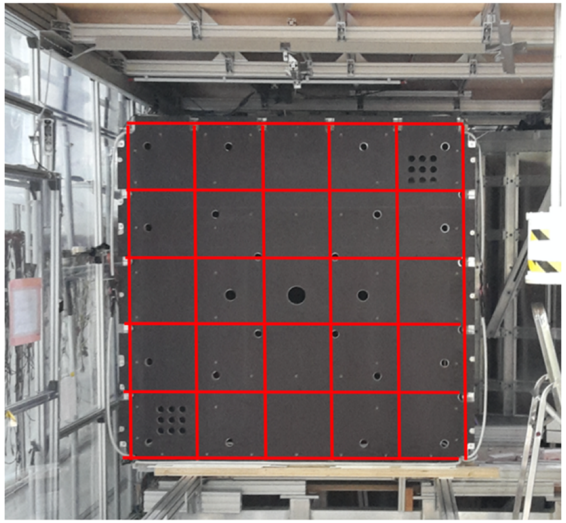
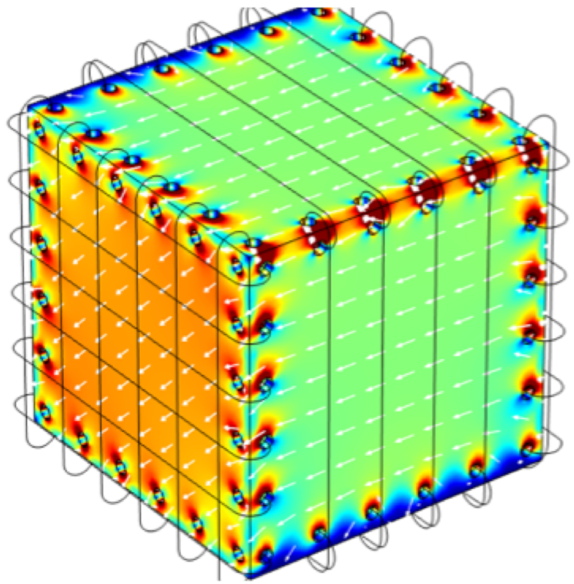


The (so-far) smallest magnetic fields





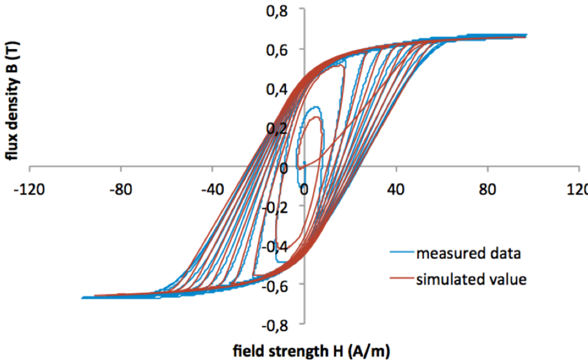


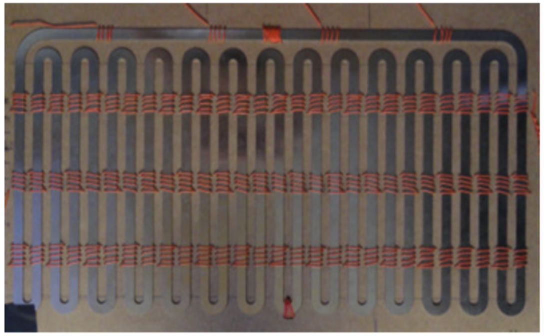
- **0.5 x 0.5 x 0.5 m < 25 pT homogeneity at < 50 pT absolute demonstrated (Measurements: PTB, HIT, TUM)**
- **Even better is feasible: enables 'next generation' of many things**

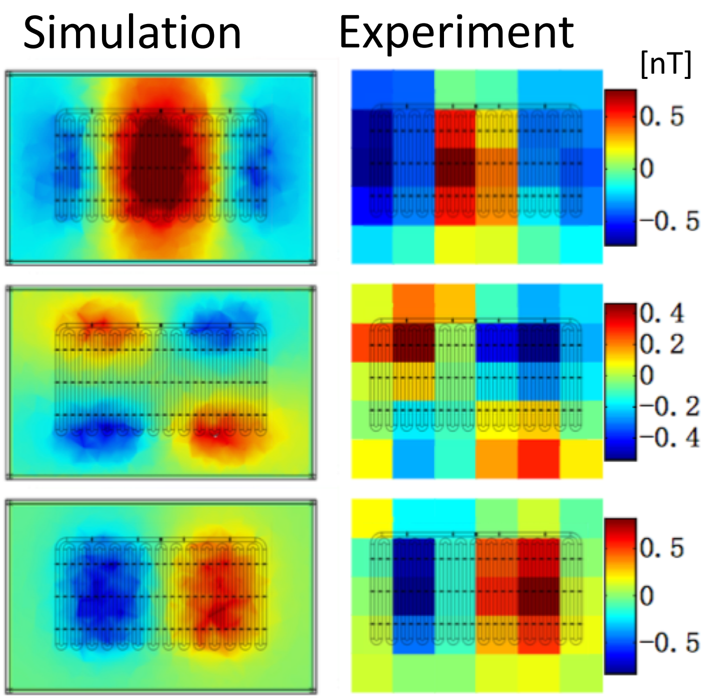
... Calculating small fields

- Time-dependent numerical modeling of hysteresis and magnetic equilibration (Thesis M. Reisner, TUM, follow-up work at HIT, China)
- Quantitative agreement with experiments
- Used in most new field designs, e.g. in atomic fountains, at the ISS, a primordial magnetic field experiment, semi-conductor industry and medicine

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

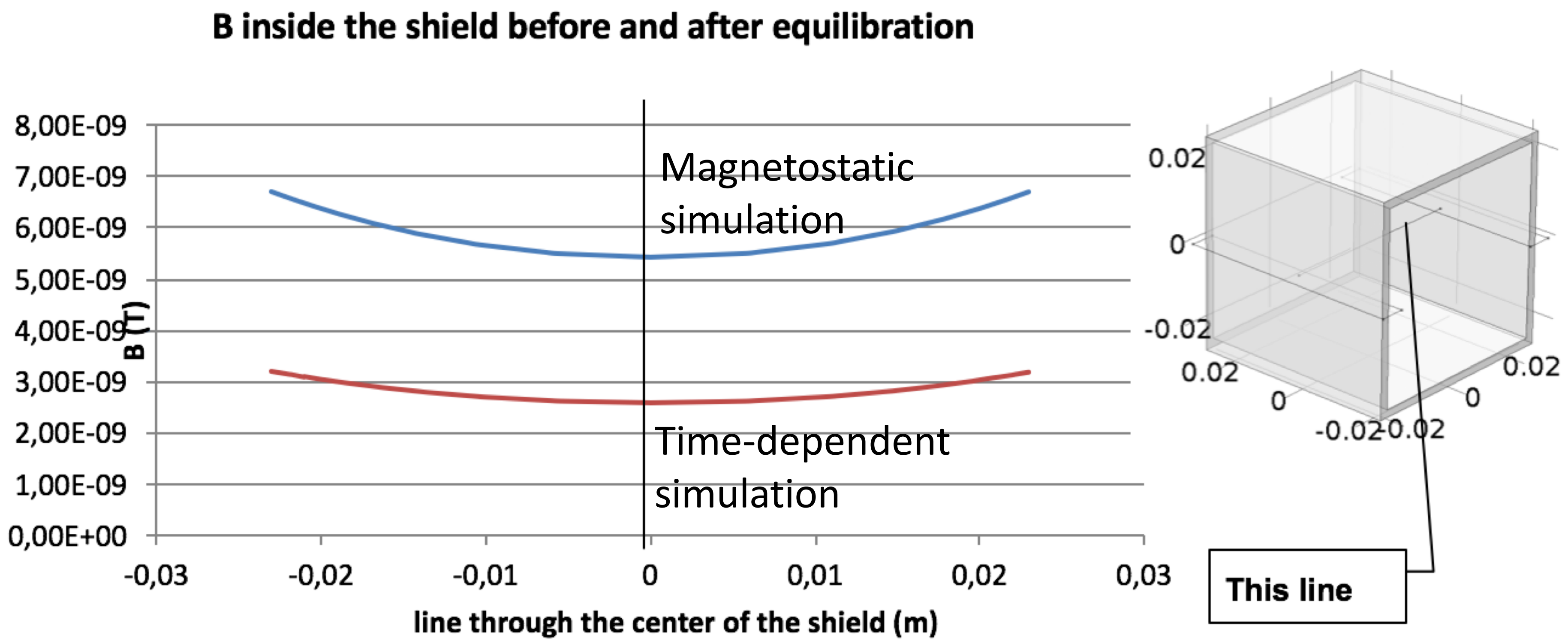






... Implications (e.g.)

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

Side note: SQUIDs at PTB

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)

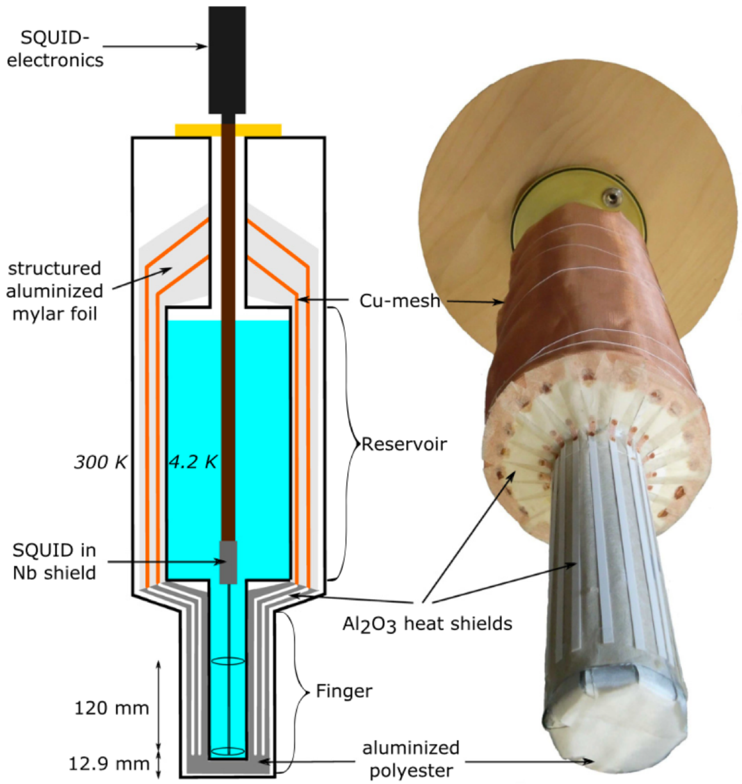


FIG. 1. Left: the schematic setup of LINOD2 in gradiometer configuration. Right: a view of one of the heat shields made from Al_2O_3 strips together with the copper mesh heat shield at the dewar reservoir. The outer shell has been removed.

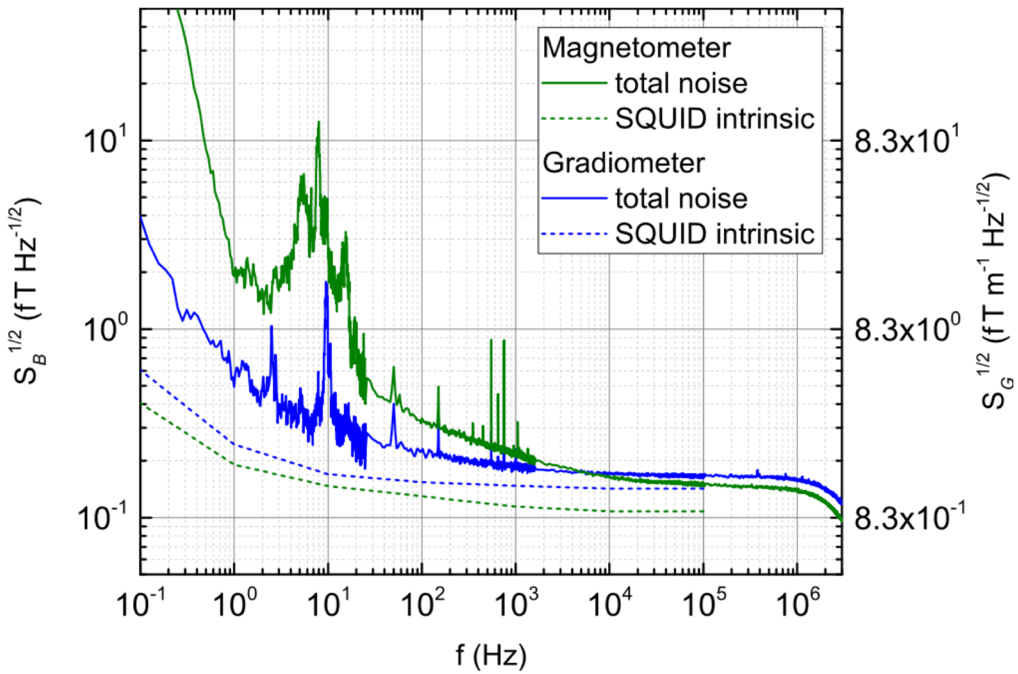


FIG. 2. Measured magnetic flux density noise $S_{B,\mathrm{m}}^{1/2}$ for the two setups with 45 mm diameter pick-up coils: Magnetometer (solid green curve) and gradiometer (solid blue curve). The calculated intrinsic SQUID noise levels $S_{B,\mathrm{i}}^{1/2}$ are given by the dotted curves. For the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

Summary

- Many things from this talk have been covered by other speakers before
- It‘s an exciting time for EDM searchers:
  - Different experiments complement each other.
  - New systematics to be expected
  - Quite some good ideas as countermeasures
  - There will be progress from neutron EDM in reasonable time-scales
- The TUM nEDM experiment is now at ILL: ‚PanEDM‘
  - Phase I will start taking data in spring 2019
  - Phase II will be cryogenic and can reach much further mainly with known technology
- nEDM developments also have spin-offs to other fields

Review paper: T. Chupp et al., RMP (2018) in press

... A discovery while waiting for UCN

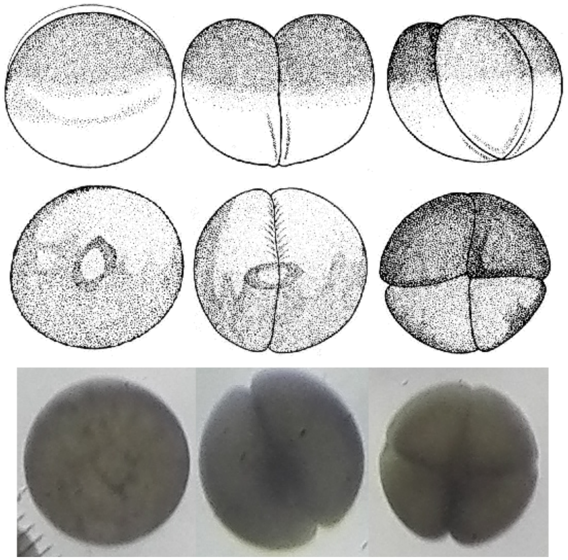
Xenopus laevis (frogs)

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

Side view

Top view

Microscope



>40. Stage (3 days)