Technische Universität München

Recent progress with small magnetic fields

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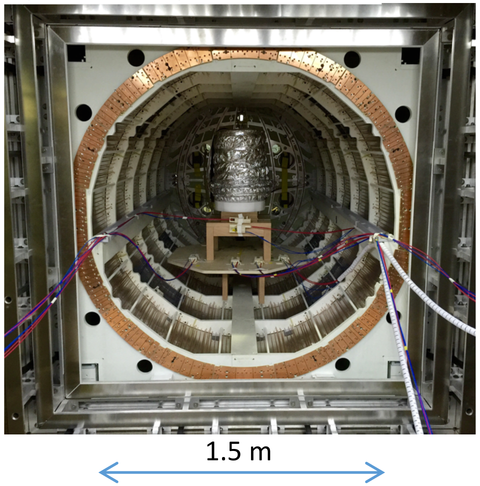
with inputs from Z. Sun (HIT, China)

State of the art

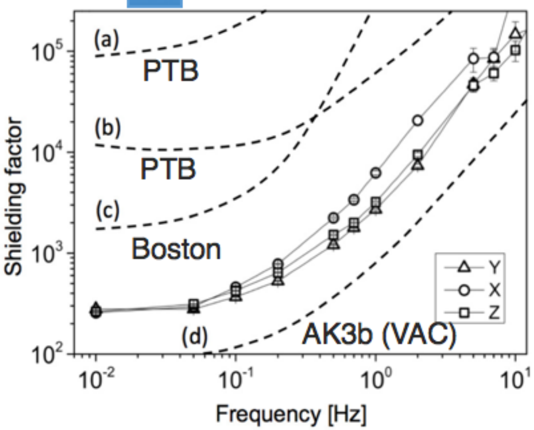
SLOW NEUTRONS
DFG SPP 1491

Passive SF > 6 Millions @ 1 mHz
(without using ext. compensation)
'Gradient' < 100 pT/m in 1 m^3
Abs(B) < 100 pT
Stability < 5 fT in 1000 s

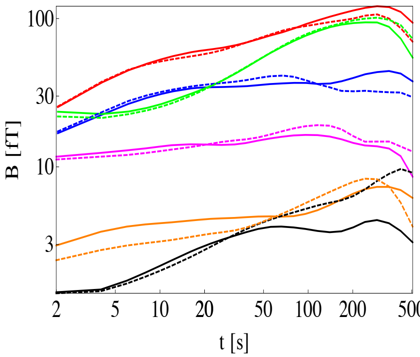
µT Ramsey field coils



nEDM @ TUM



Typical SQUID Allan deviation



Field homogeneity maps [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

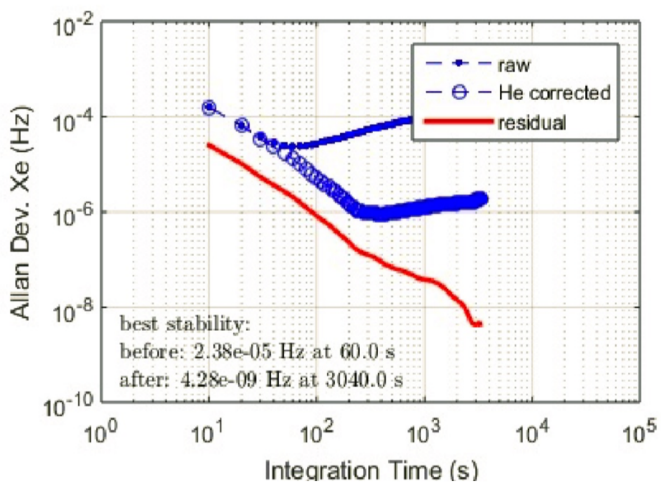
	Bz in pT	
Xend-18	Xmitte0	Xend+18
-106	-66	-67
-116	-82	-63
-87	-53	-54
-81	-31	-27
-77	-34	-42
-87	-47	-66
-93	-55	-75

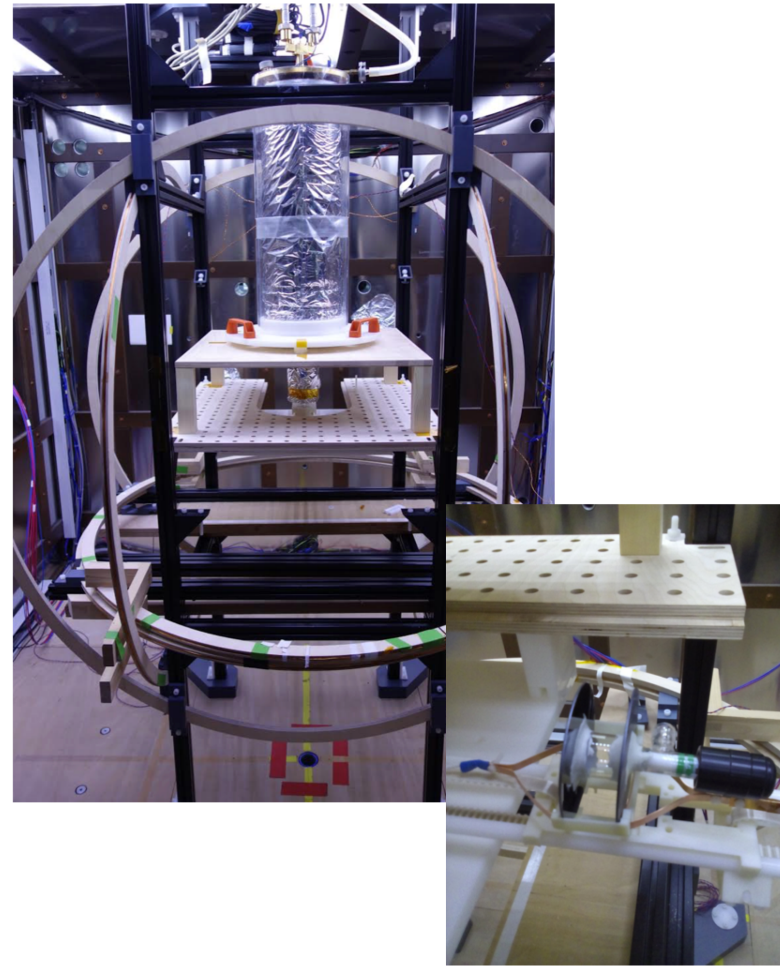
(Measurement dominated by sensor cables!)

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

Magnetometer stability is not trivial: e.g. SQUID and He+Xe cell

Illustration: simultaneous precession of ^{129}Xe and ^{3}He amplitude in cylindrical cell with 5 kV/cm applied (preliminary data for illustration only!)





Many new systematic effects observed at this level of precision: EDM experiments are difficult...

Side note: Progress with SQUIDs

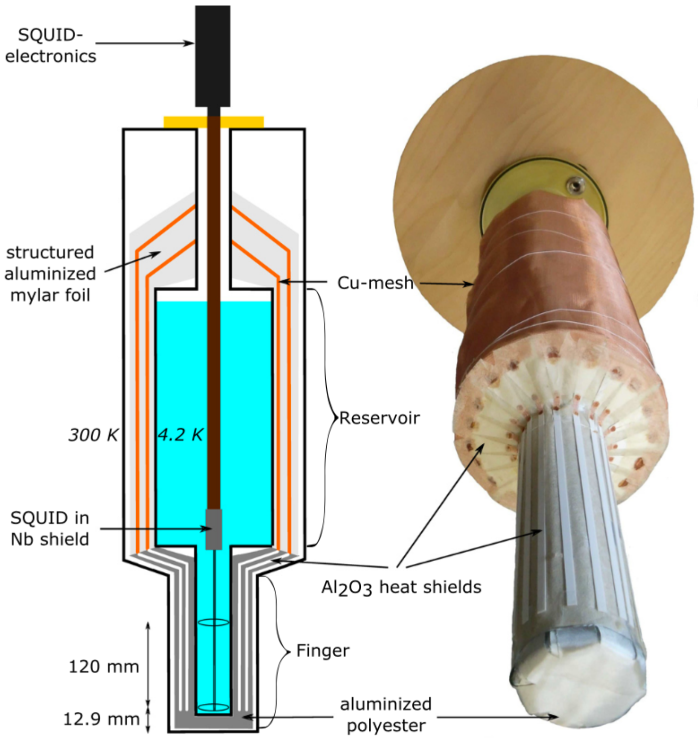


FIG. 1. Left: the schematic setup of LINOD2 in gradiometer configuration. Right: a view of one of the heat shields made from Al_2O_3 strips together with the copper mesh heat shield at the dewar reservoir. The outer shell has been removed.

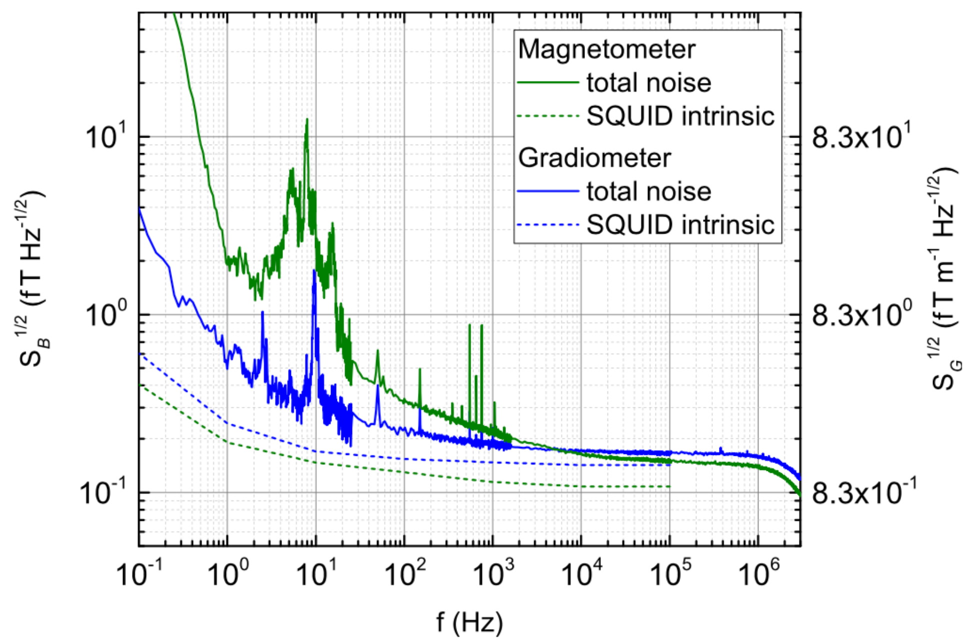
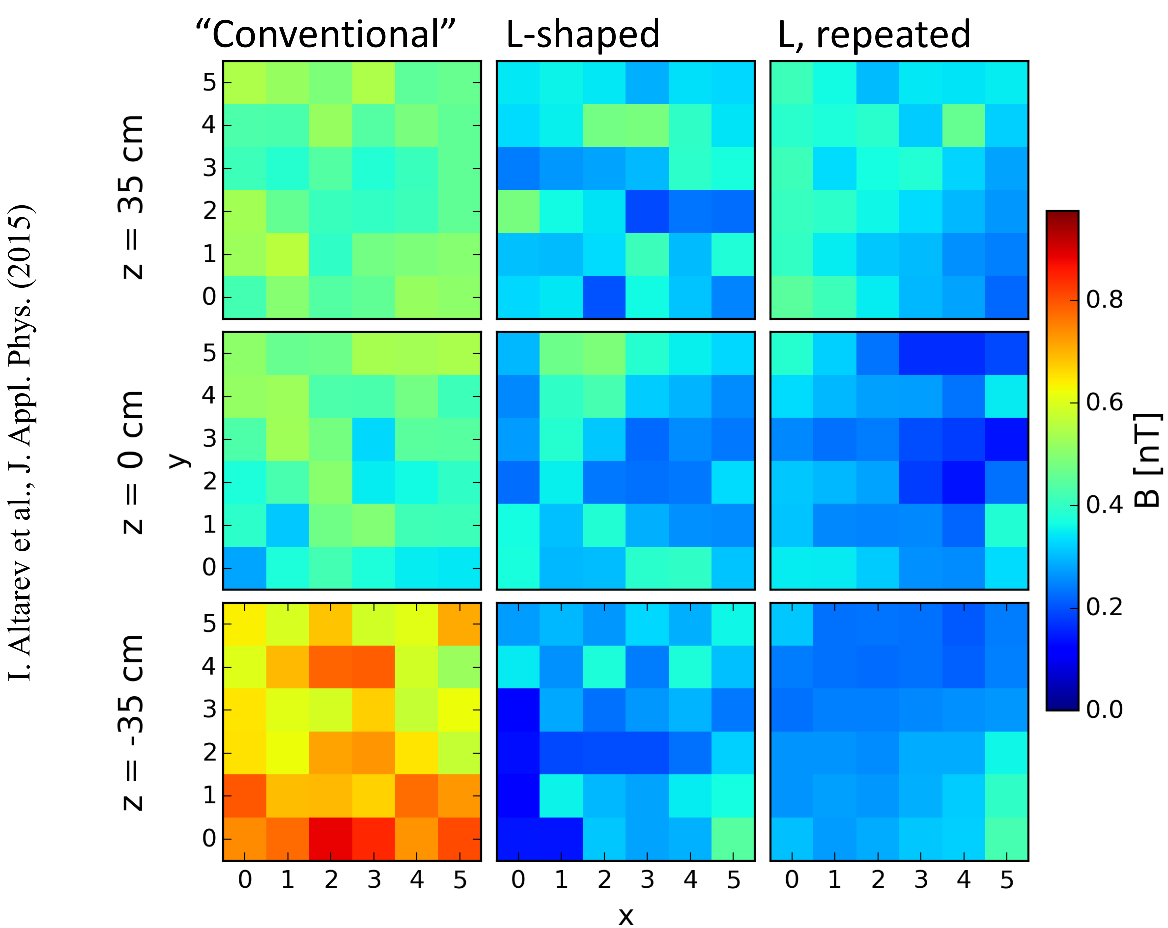


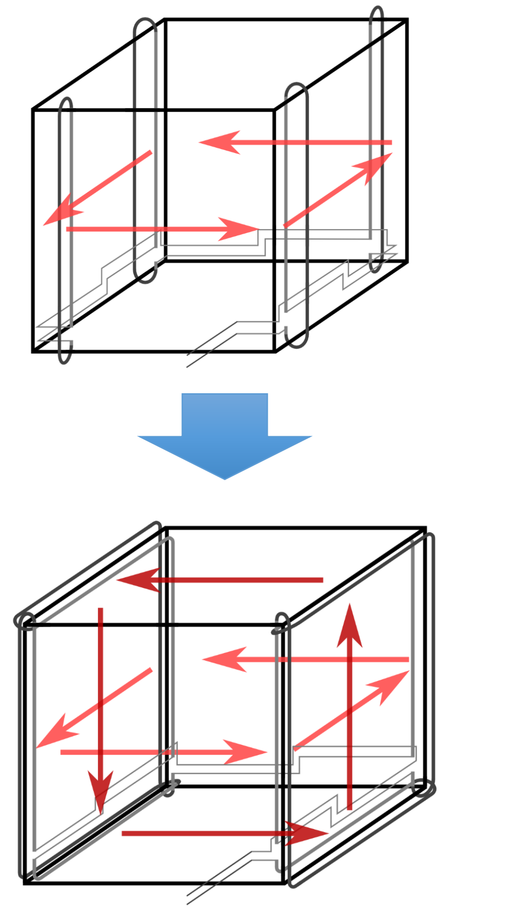
FIG. 2. Measured magnetic flux density noise $S_{B,\mathrm{m}}^{1/2}$ for the two setups with 45 mm diameter pick-up coils: Magnetometer (solid green curve) and gradiometer (solid blue curve). The calculated intrinsic SQUID noise levels $S_{B,\mathrm{i}}^{1/2}$ are given by the dotted curves. For the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

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

Improved magnetic equilibration

Ultra low magnetic fields and gradients: ‚**L-shaped**‘ coils, 10 x improved speed to state of the art, also better result





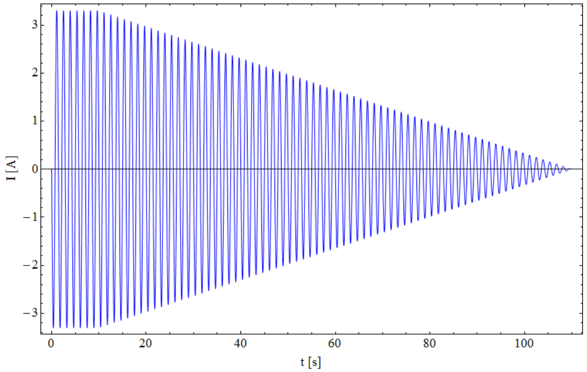
Remanent field (relatively) independent of shielding factor!

Time-dependent simulations of hysteresis curves

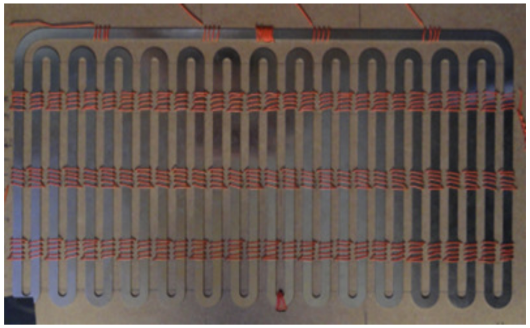
Current status: Quantitatively correct time-dependent modeling of real geometries

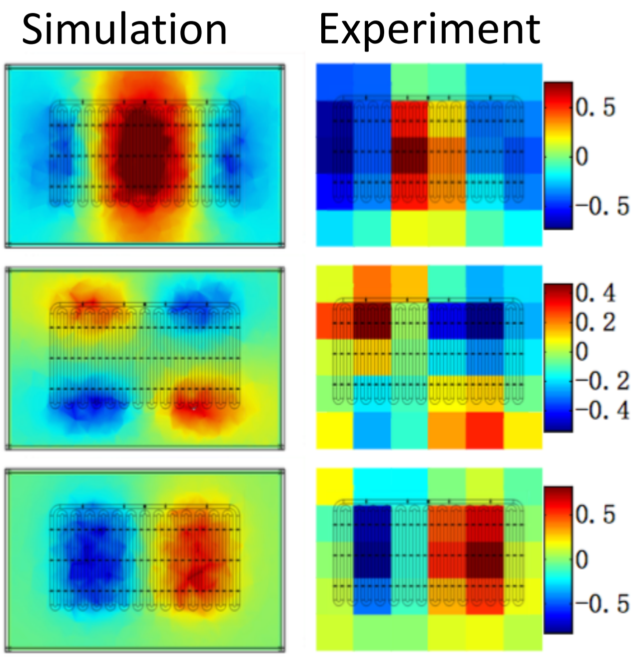
Z. Sun et al., J. Appl. Phys. 119, 193902 (2016)

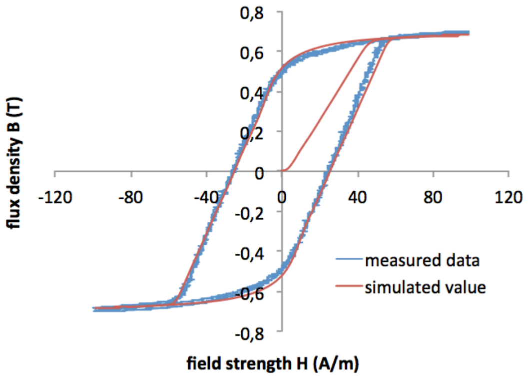
A typical current pattern :

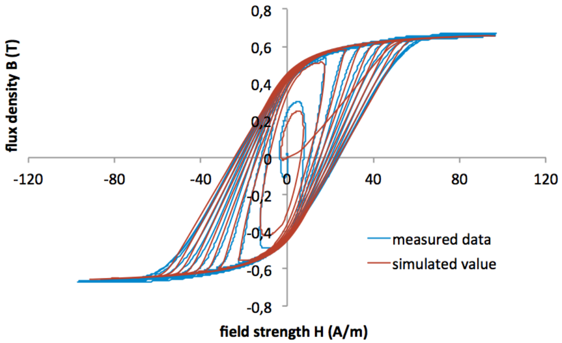


Test-geometry:





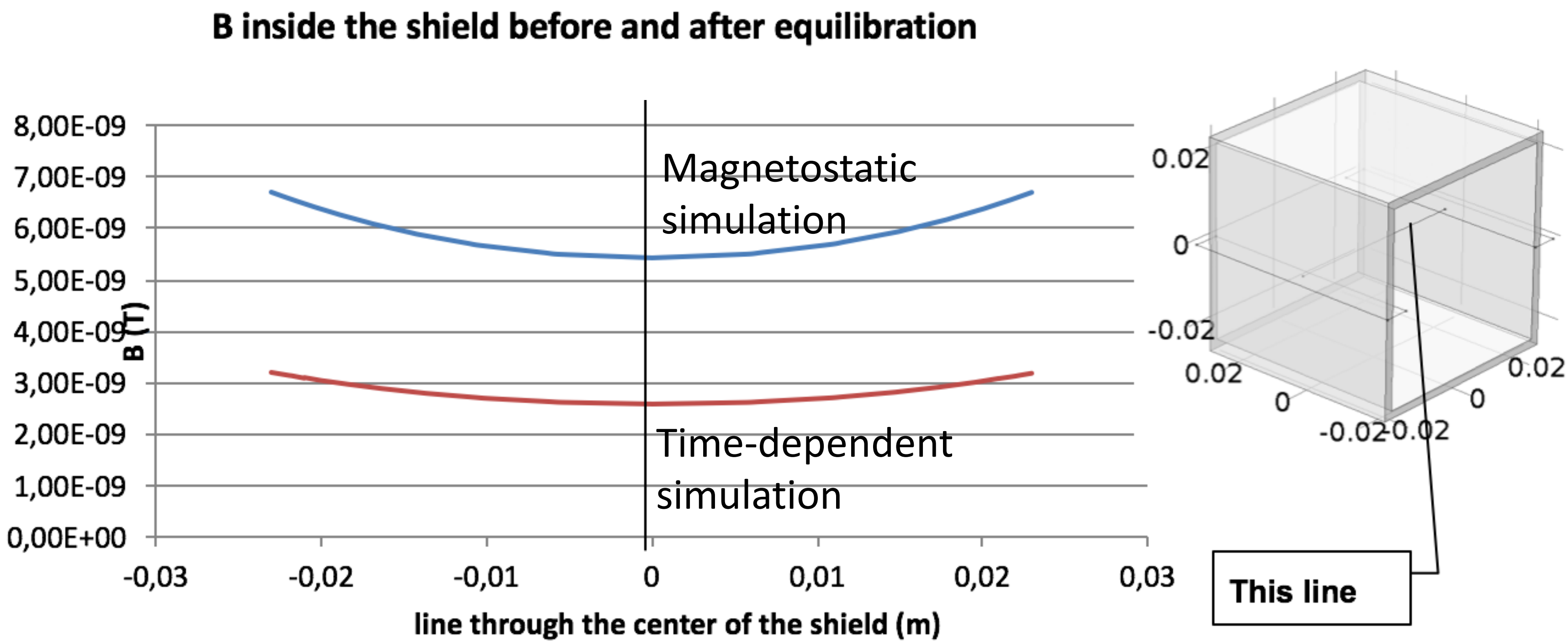




Joint activity of FM, TUM, PTB, HIT, IBS

... Implications (examples)

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

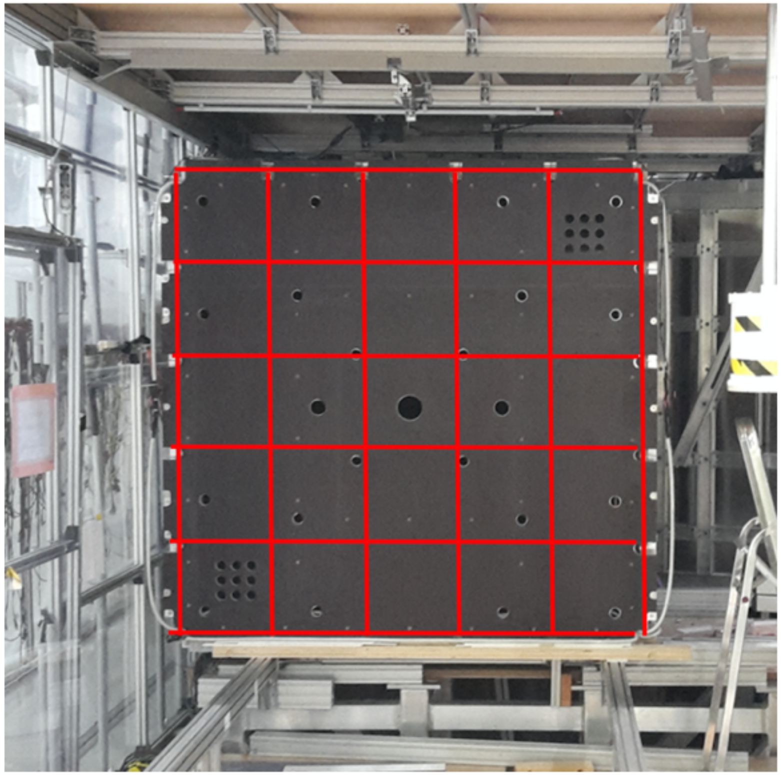


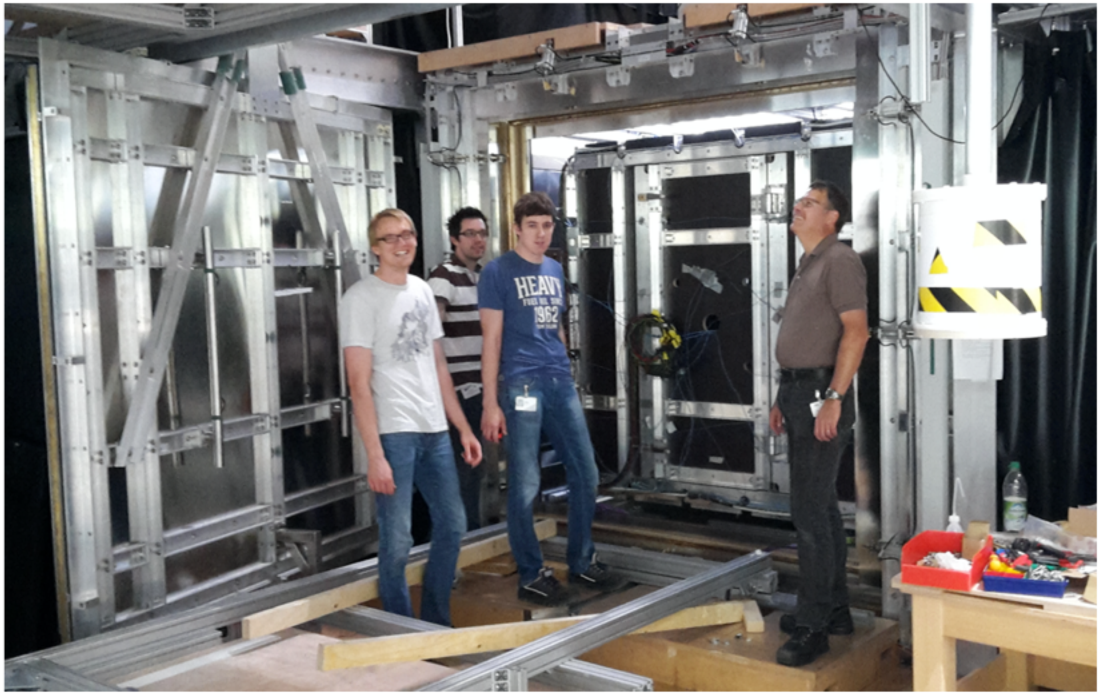
(External field: 1 μT)

Z. Sun (HIT), in collaboration with TUM

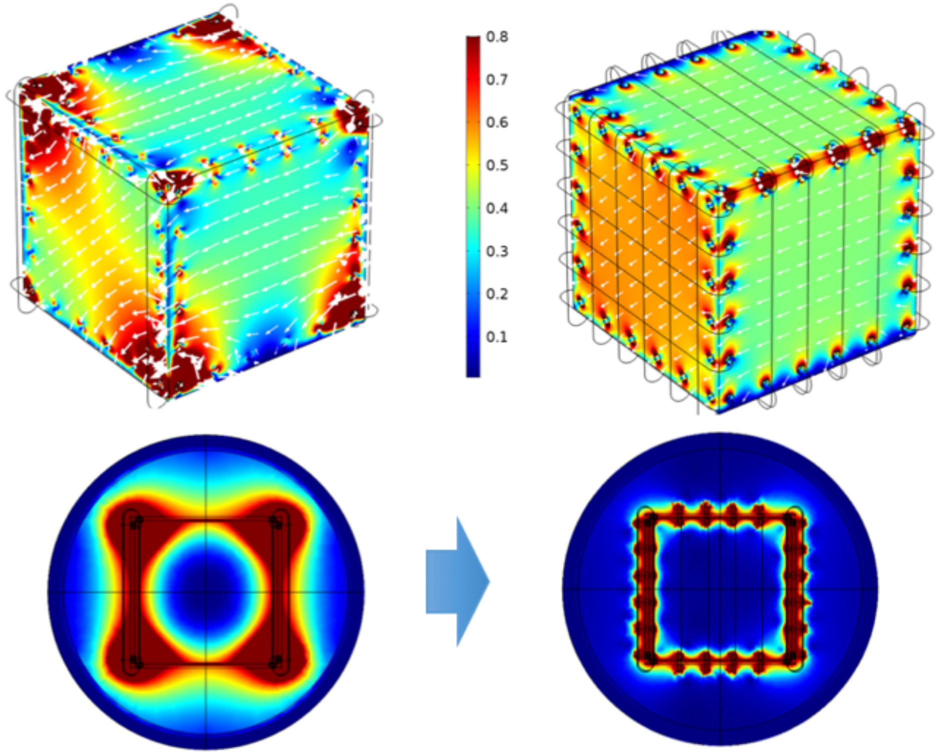
A magnetic shield with new design

- New wall design
- 2 mm thick, 1 shell
- L-shaped, (**NEW) distributed equilibration coils**
- Installed temporarily inside outer TUM EDM shield for characterization





New: distributed equilibration coils

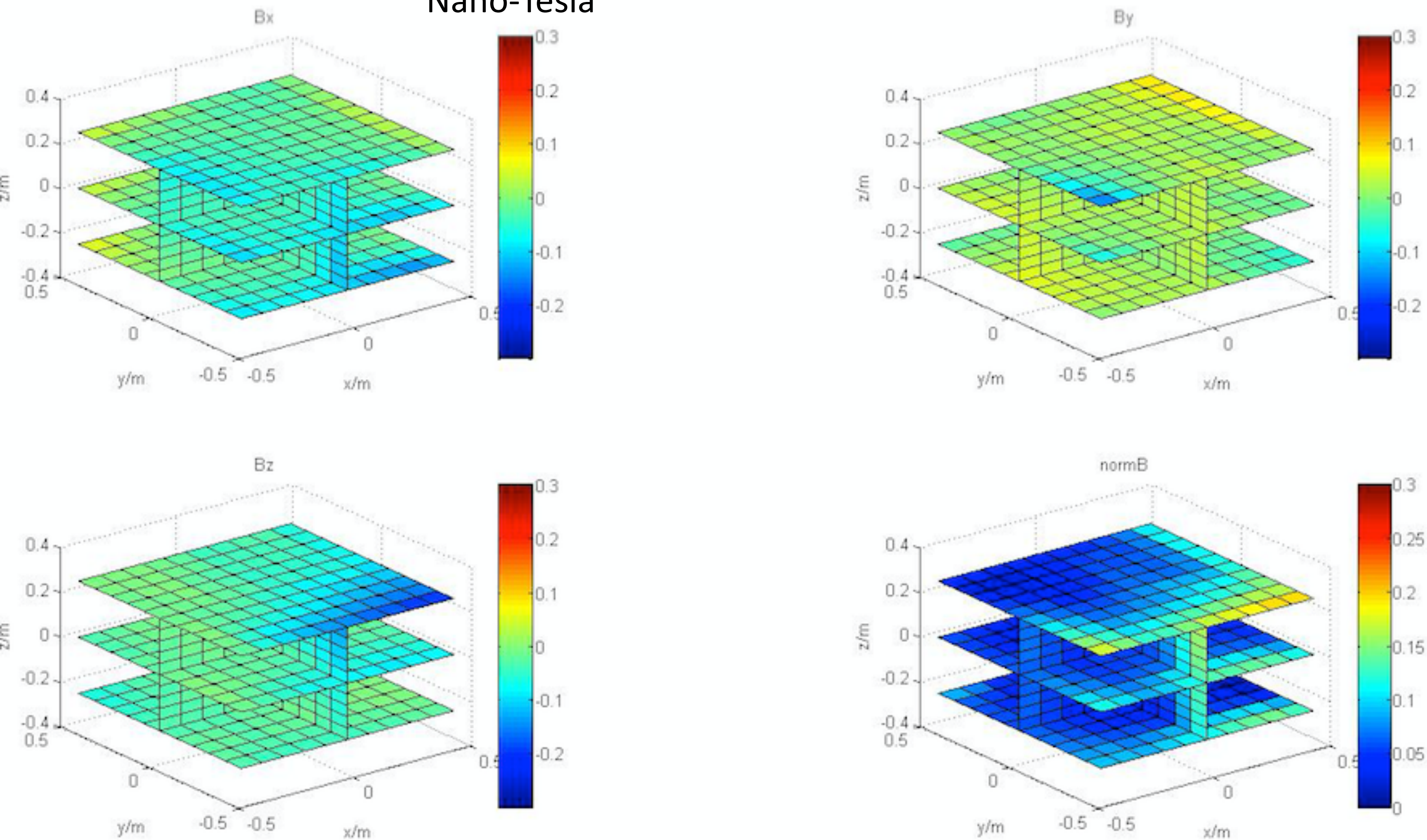


- Idea: keep “mistakes’ close to material (similar to pEDM octagon prototype)
- Used in several new experiments and installations (e.g. at Harbin Inst. of Techn., also e.g. in atomic fountains, at ISS, and for a new PRIMORDIAL MAGNETIC FIELD experiment
- Best results: < 25 pT in 1 m^3 measured at TUM with PTB and HIT (8/2016)

Figures: Z. Sun

Residual field of new design – a typical map

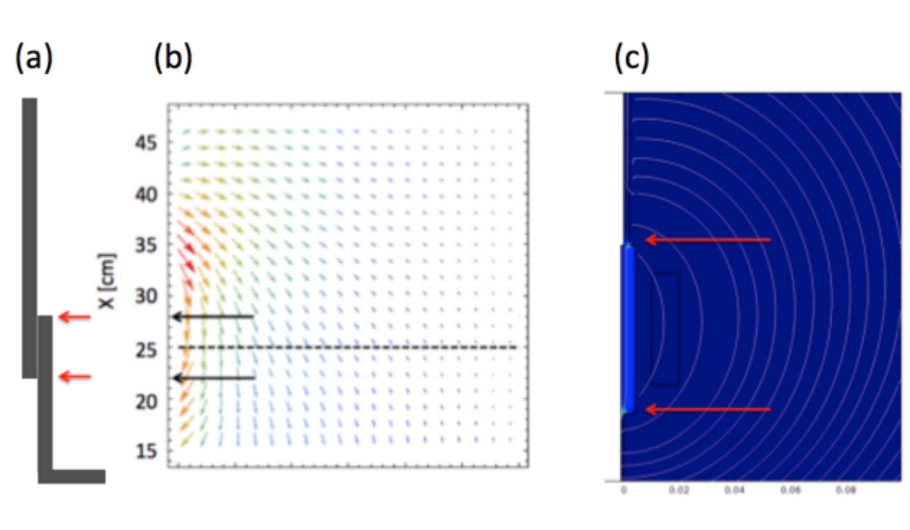
Nano-Tesla



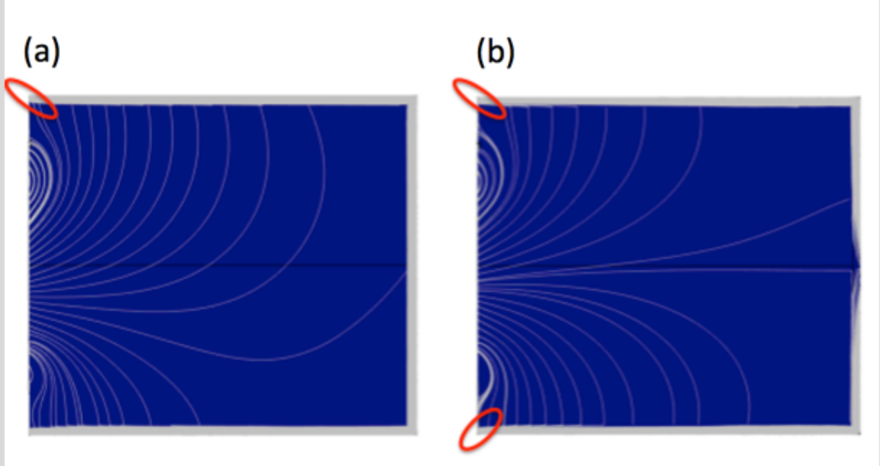
A simple trick for residual field modeling

Applying DC bias-currents in equilibration coils produces similar field pattern as imperfect equilibration:

Example 1: door overlap



Example 2: arrangement of degaussing coils

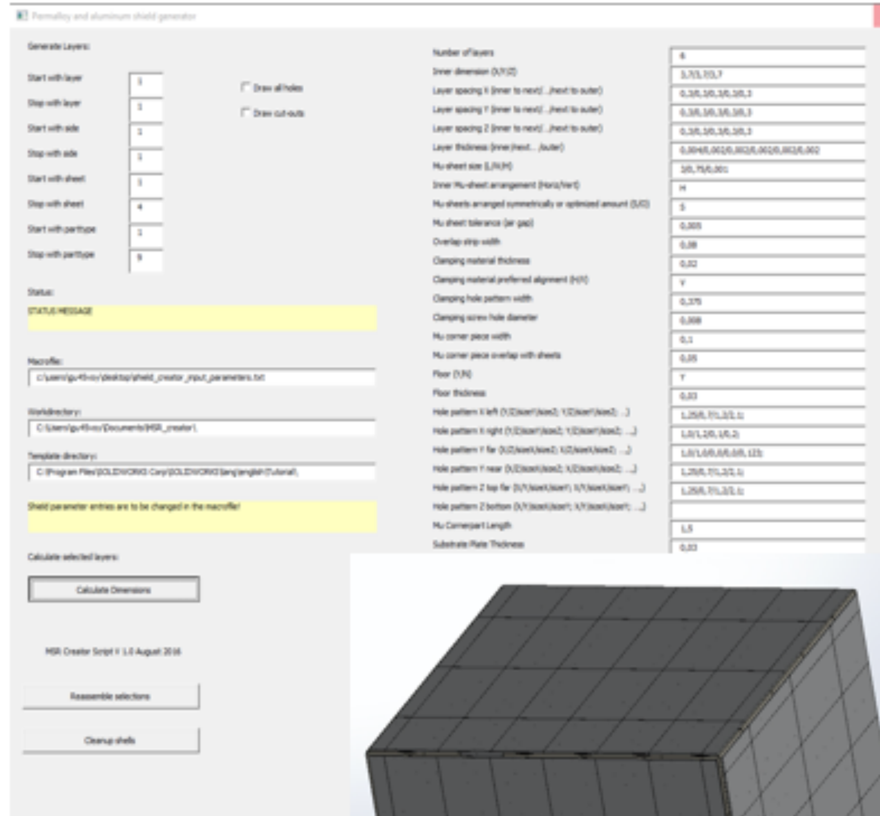


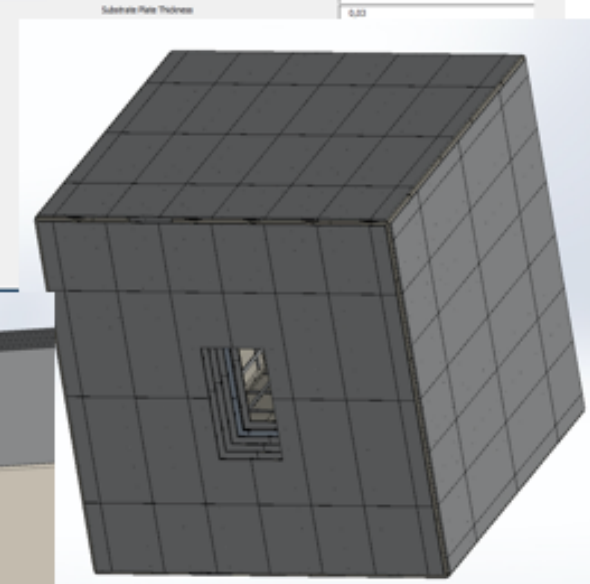
Side note: MSR creator script
(free and open source)

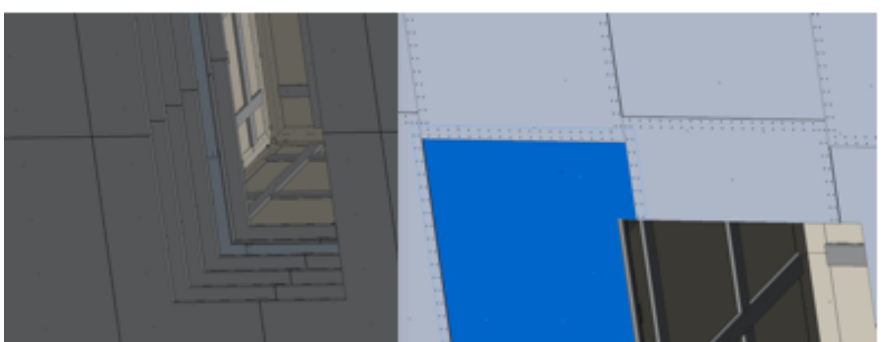
Magnetic shields contain a logical structure.
Why design this manually?

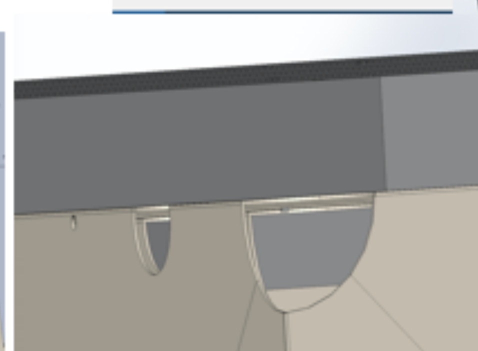
Inputs:
Number of Permalloy shields,
Dimensions and holes,
RF shield position,
Substrates for Permalloy etc.

Output:
Full Solidworks 3D model of shields
with all parts in details (screw holes, tolerances, materials)



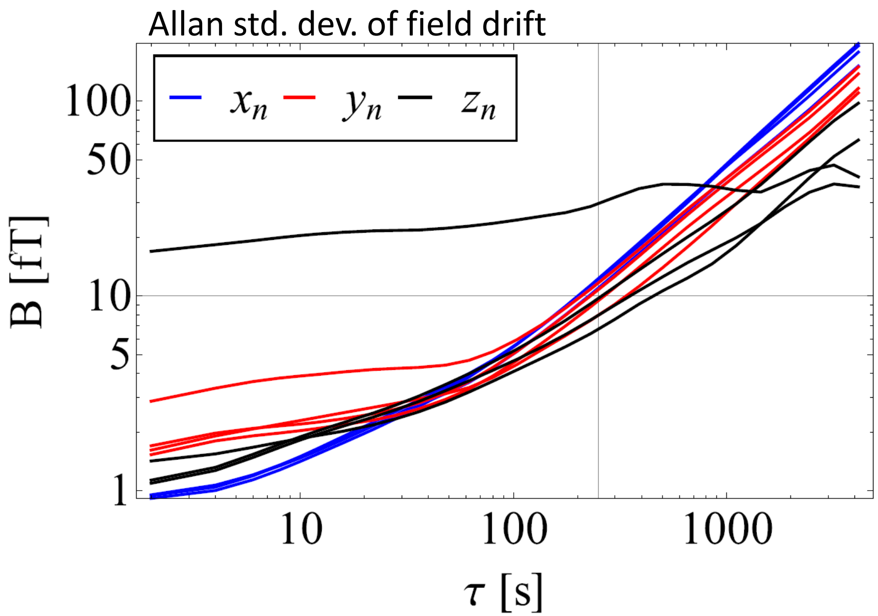


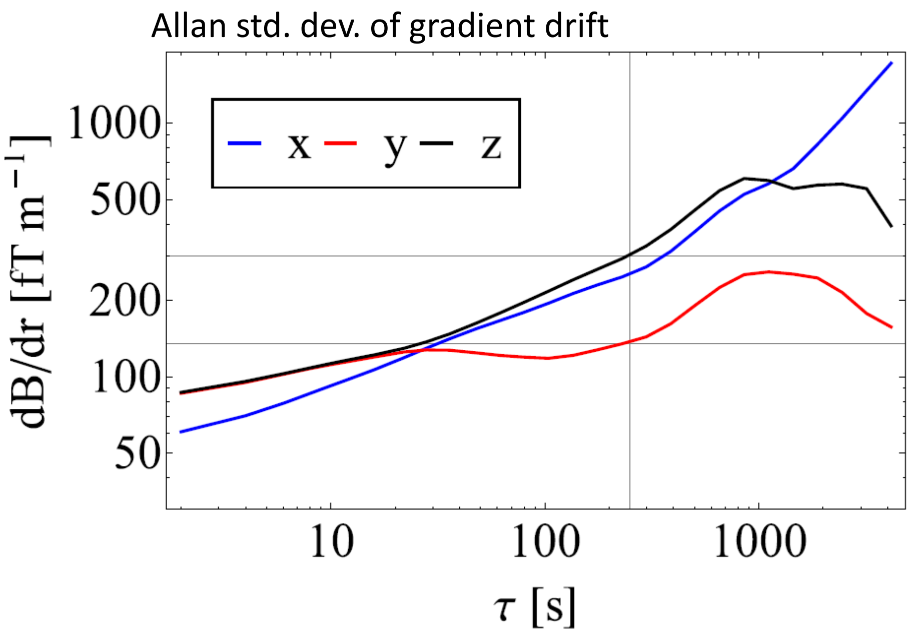




Field and gradient drifts

SQUID measurements inside cuboid magnetic shields
(inner cylinder NOT used: factor 6 lowered performance in plots!)



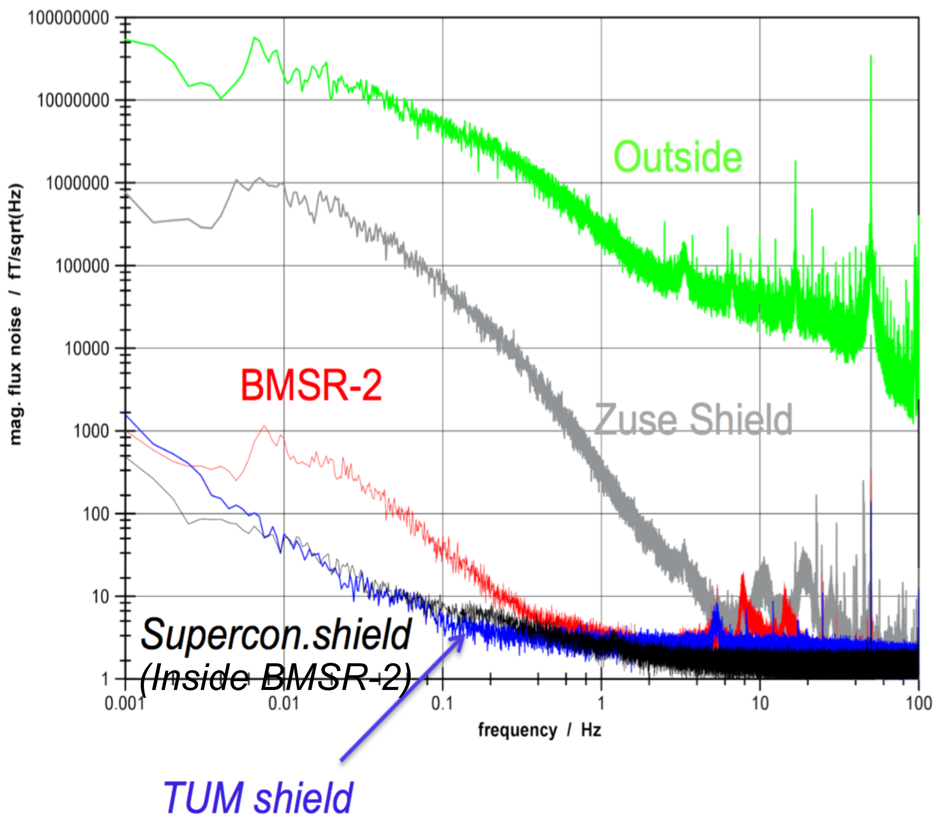


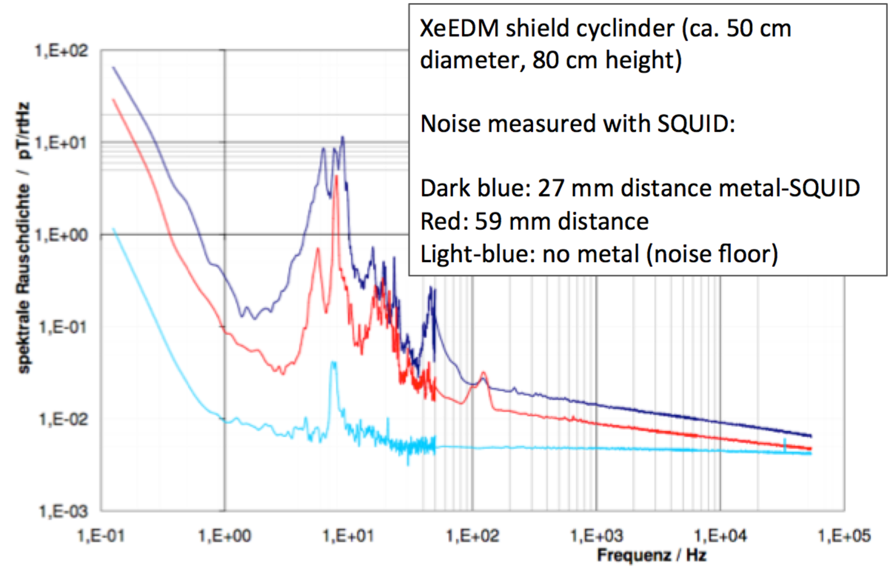
Example: 10^{-28} ecm in nEDM ~ few fT goal for unmeasured drifts
(Measurement issue: drift-noise compromise!)

Example: double cell nEDM: 10 cm typical CM-separation: < 10 fT drift

Noise and drifts

Comparison of SQUID measurements inside magnetic shields -
superconducting shield and mu-metal comparison:



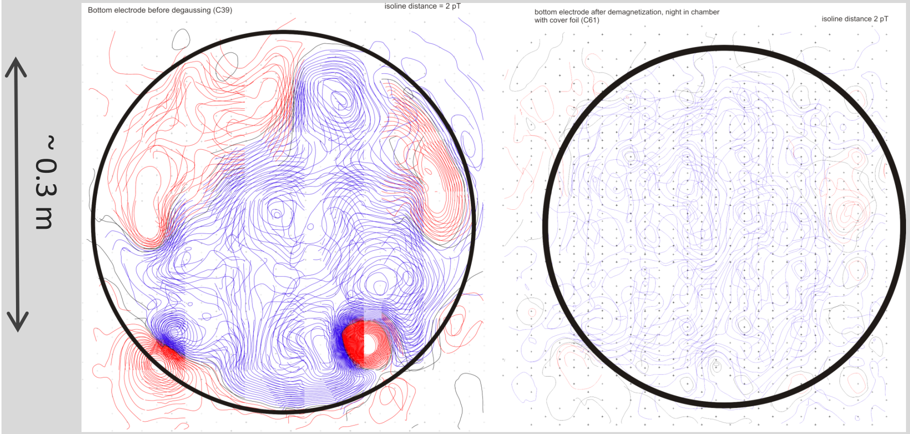


... Everything placed inside shield is a potential problem!

(Measured by PTB, baseline limited by meas. instruments)

Problems to keep in mind also for pEDM

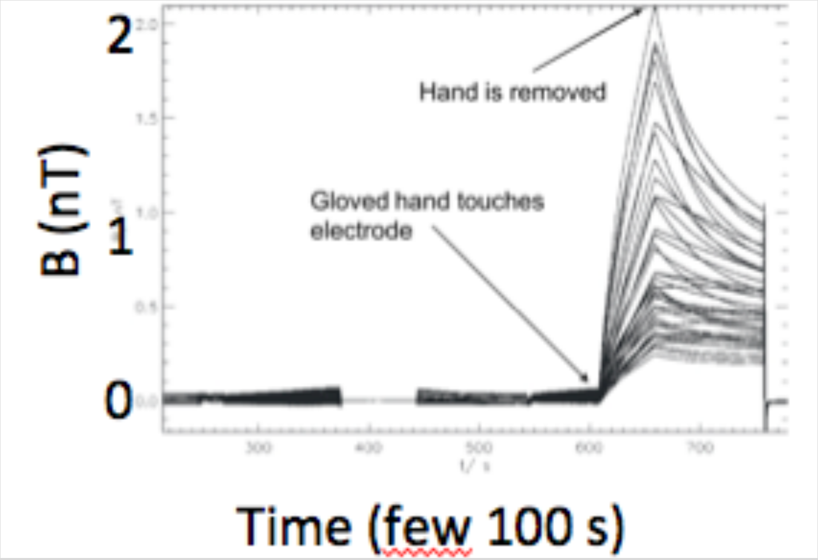
SQUID measurements of Sussex- EDM electrodes @ PTB Berlin



> 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

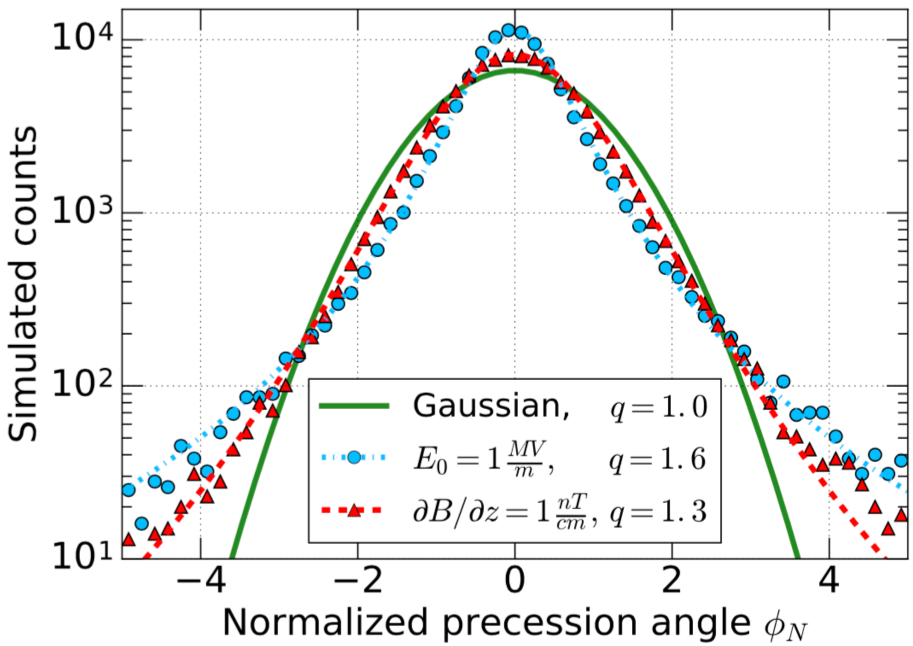


Next generation...

What is *really* happening in next-generation experiments?

E.g.

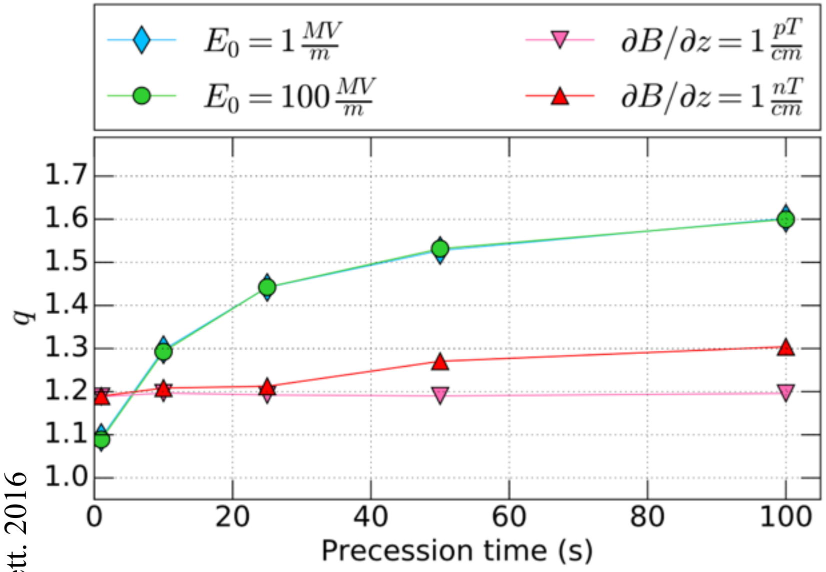
- Tsallis-distributions of particle spins
- Distributions can also have higher moments: possible identification of origin of false effects
- Could also show up elsewhere?
- Skewness -> would lead to wrong estimation of a frequency shift?



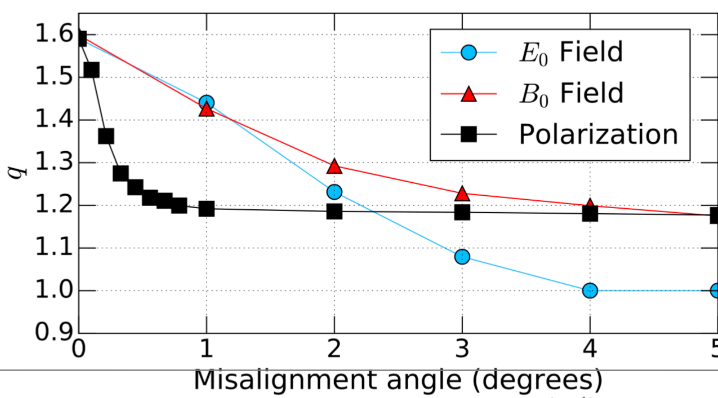
M. Bales et al., Eur. Phys. Lett. 2016

Next generation...

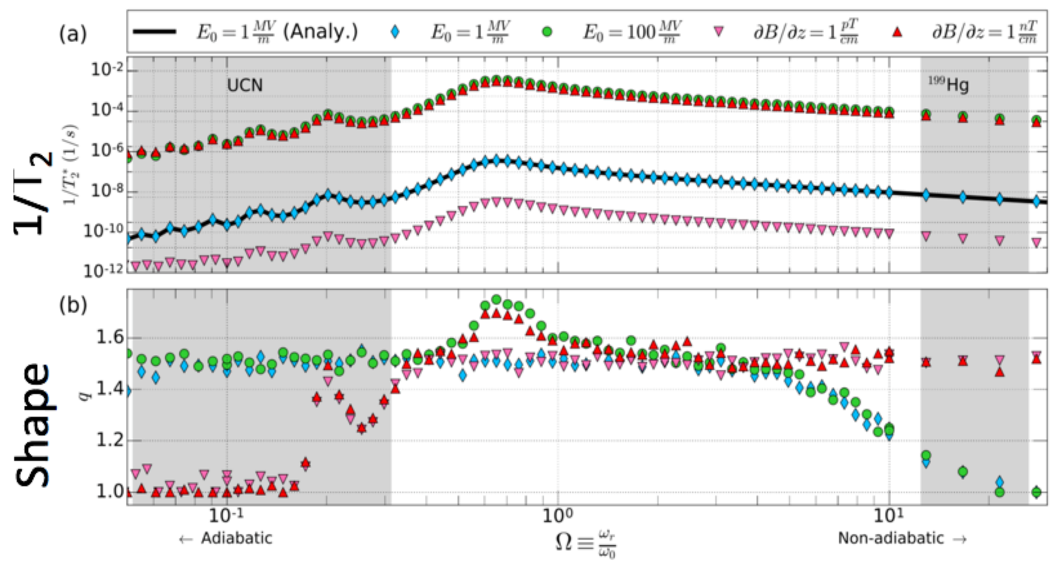
Build-up of non-gaussian shape over time:



Effect of misalignment:



Different for different polarized species due to adiabaticity:



Adiabatic regime | Non-adiabatic

M. Bales et al., Eur. Phys. Lett. 2016

Summary

- Improvements of techniques compared to EDM shields in 2016
- Very small residual fields are possible with fast equilibration
- Johnson noise of MSRs ~ 100 aT/rt(Hz)
- Thermal currents in metallic parts will likely dominate (e.g. in electrodes!)
- High (passive) stability possible
- Gradient requirements for EDM measurements realistic
- 'Yet unknown' systematics may require even better magnetic shielding…