Precision measurements at low magnetic fields

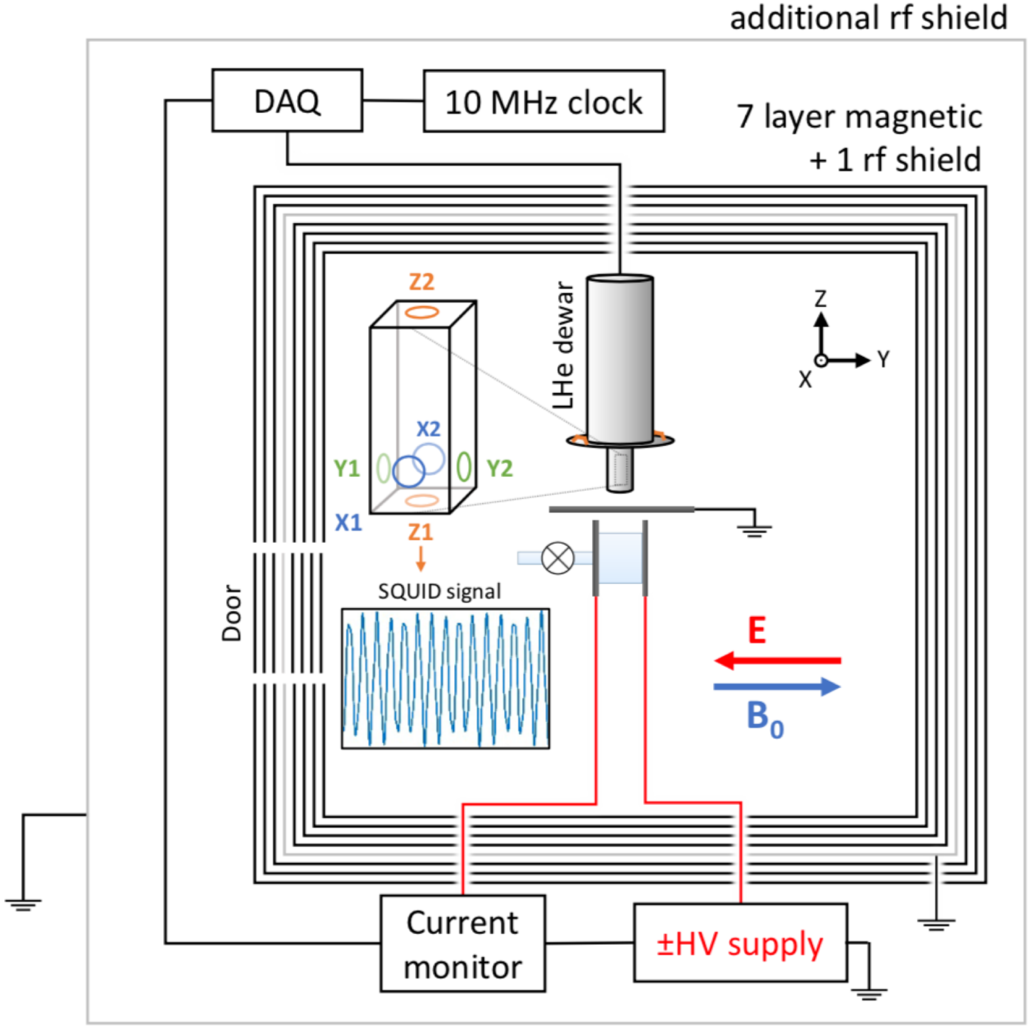
Peter Fierlinger
Technical University of Munich

Content

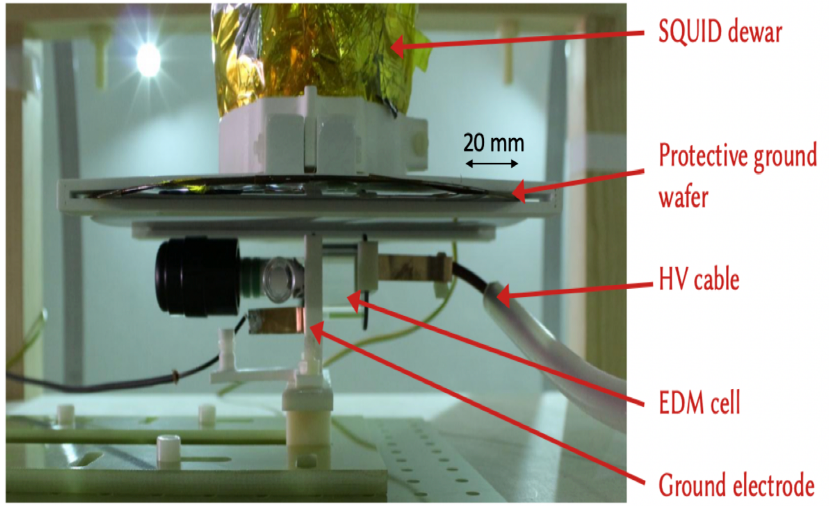
- Magnetic field control of (selected) fundamental experiments at low fields:
  - Co-magnetometer: 129-Xe EDM, storage ring
  - Multiple cells: neutron EDM
  - 4-pi magnetometry: ~ neutron EDM, new low-field lab
- Generating small magnetic fields (in free space)
- A new Cs atomic magnetometer
- Applications of technology

129-Xe EDM

SEOP-hyperpolarized 3-He / 129-Xe co-magnetometer

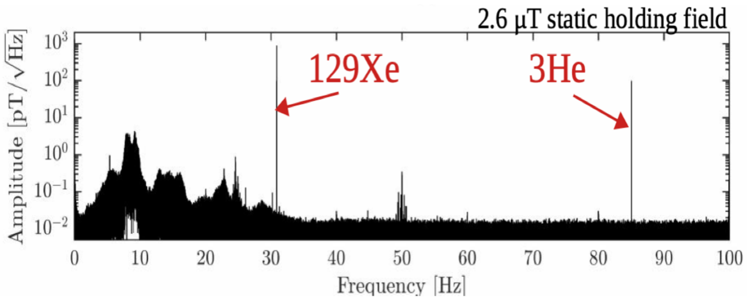


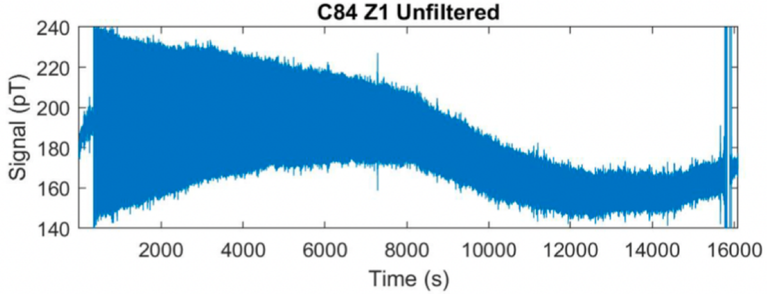
$$\sigma = \frac{\hbar}{2E}\delta\omega = \frac{\hbar}{2E}\frac{\epsilon}{\tau^{3/2}S\sqrt{N}}$$



129-Xe EDM

Raw data:





Systematic effects:

Source	Sys. Error (e cm)
Leakage current	1.2×10^{-28}
Charging currents	1.7×10^{-29}
$\vec{E}$-correlated cell motion (rotation)	4.2×10^{-29}
$\vec{E}$-correlated cell motion (translation)	2.6×10^{-28}
Comagnetometer drift	6.6×10^{-28}
$\|\vec{E}\|^2$ effects	1.2×10^{-29}
$\|\vec{E}\|$ uncertainty	2.6×10^{-29}
Geometric phase	$\leq 2 \times 10^{-31}$
Total	7.2×10^{-28}

Phys. Rev. Lett. 123, 143003 (2019)

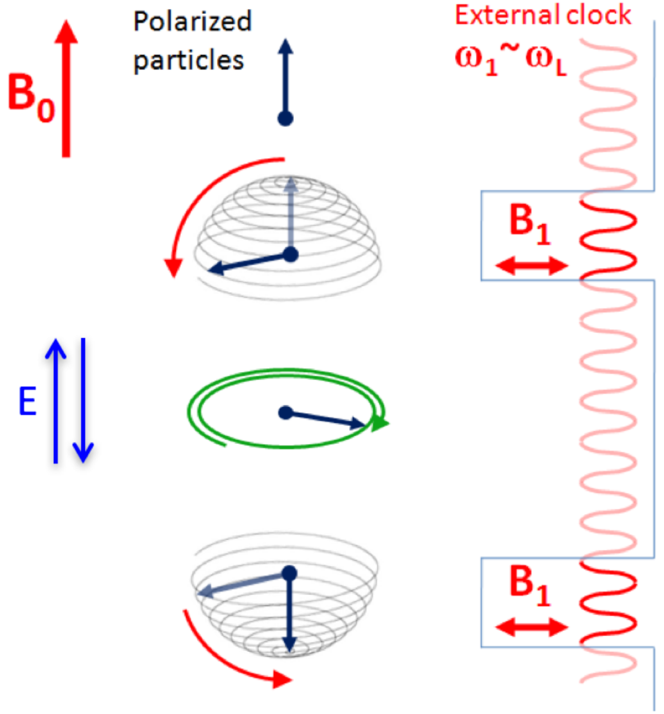
Result:

$$d_A(^{129}\mathrm{Xe}) = (0.26 \pm 2.33_{\mathrm{stat}} \pm 0.72_{\mathrm{syst}}) \times 10^{-27}\ e\,\mathrm{cm}$$

(10^{-24} eV energy resolution)

Stay tuned: next version currently being prepared…

Neutron EDM

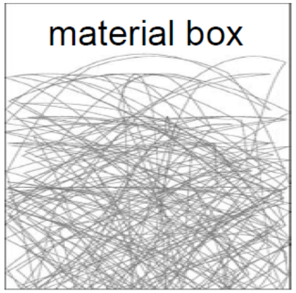


Statistical sensitivity:

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

“Typical” setup for ”next-gen” with 10^{-27} – 10^{-28} ecm sensitivity goal:

- Trapped ultra-cold neutrons

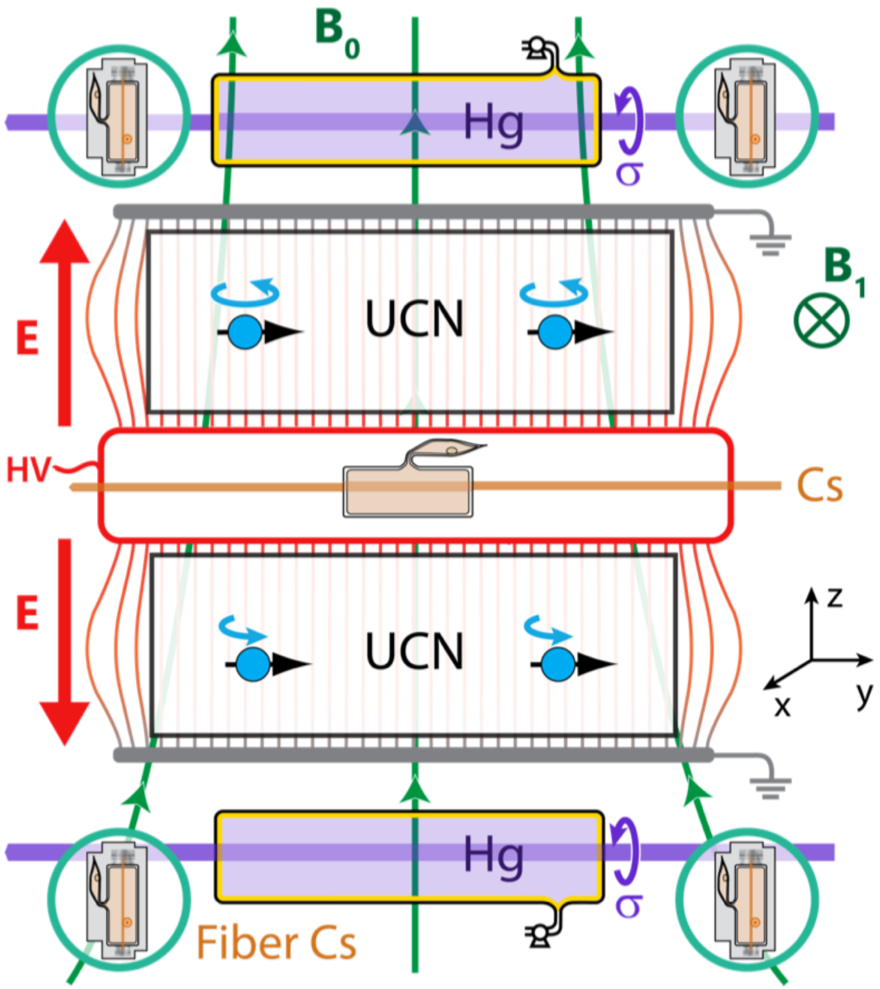


- Magnetometers: ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUIDs
- Direct B-field error ~ 1 fT over 250 s

$$d_{false:\Delta B} = \frac{2\mu\Delta B}{4E}$$

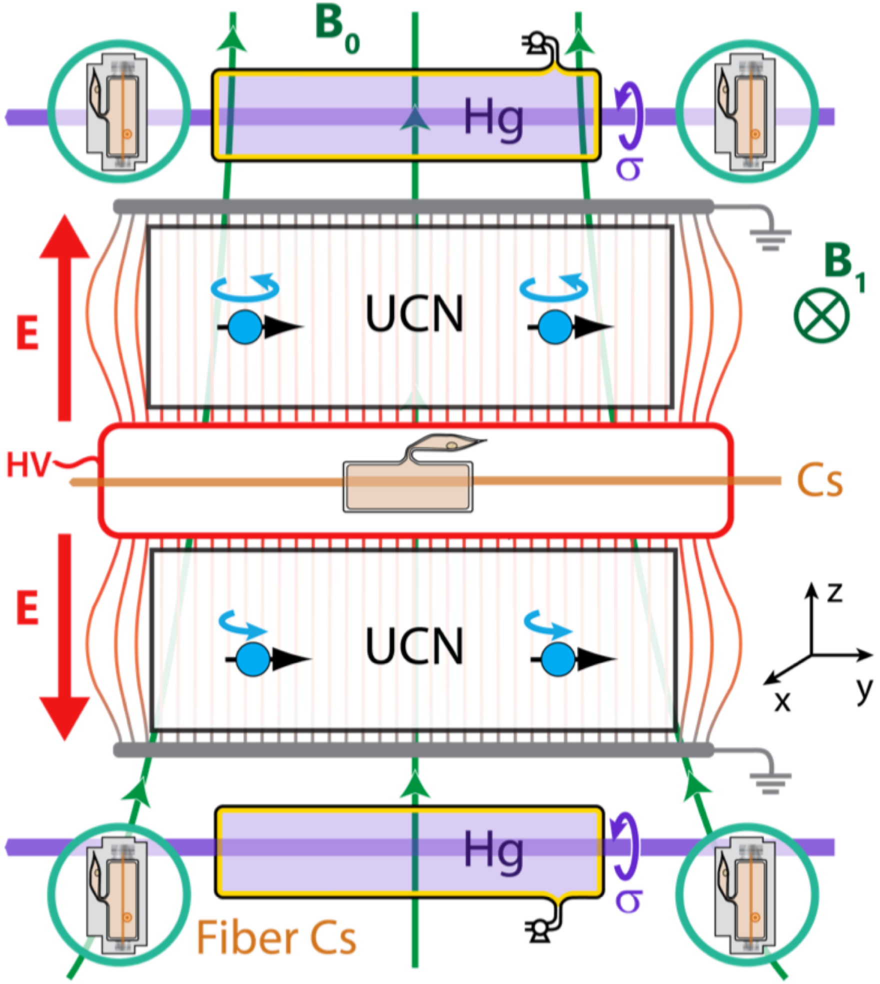
- Indirect (geometric phase) ~ Gradient ~ 0.1 nT/m

The PanEDM Experiment

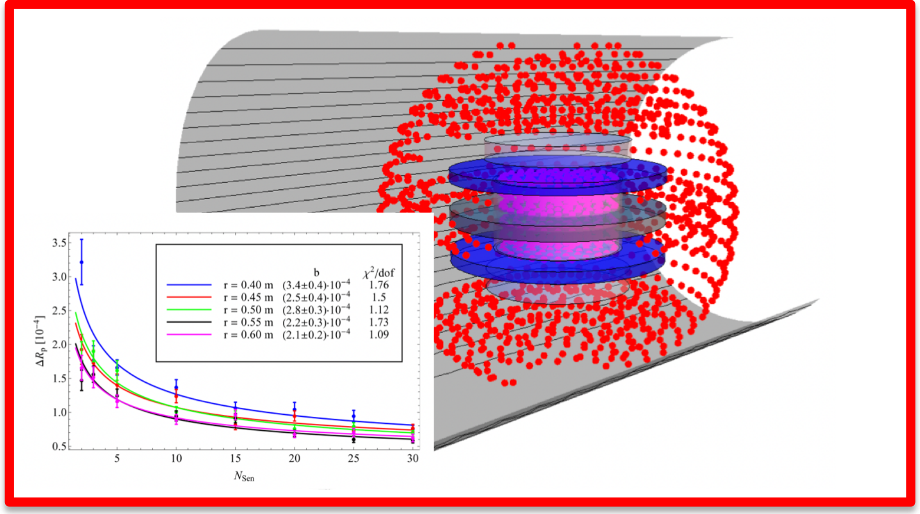


- Double chamber: Gradient drift with 5 fT/m in 250 s instead of B-field drifts
- Extreme shielding factor: 6.10^6 at 1 mHz
- < 100 pT residual field over whole volume
- Few x 10^{-4} relative homogeneity of 2 μT field
- EDM chambers as small as reasonably possible

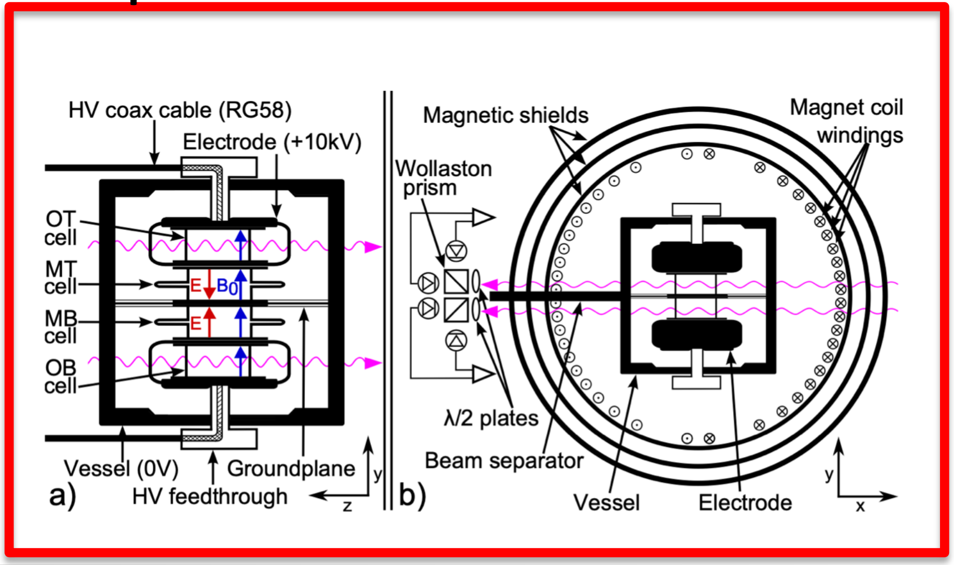
The PanEDM Experiment



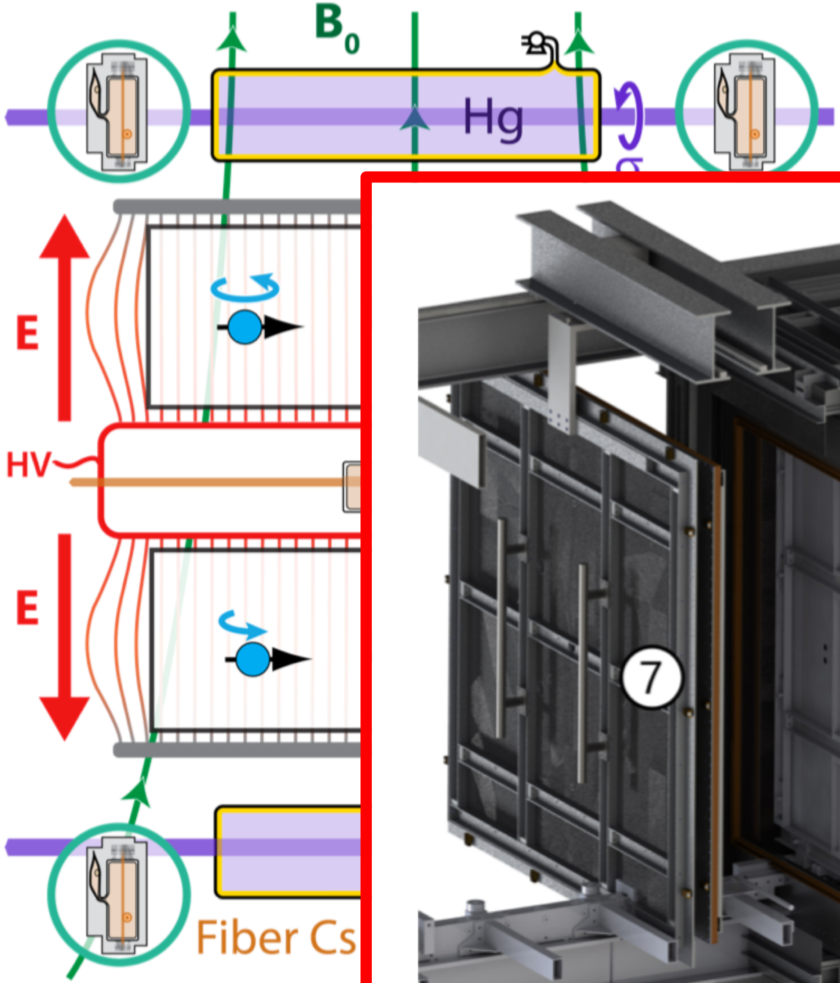
„Approximated“ 4-pi magnetometry

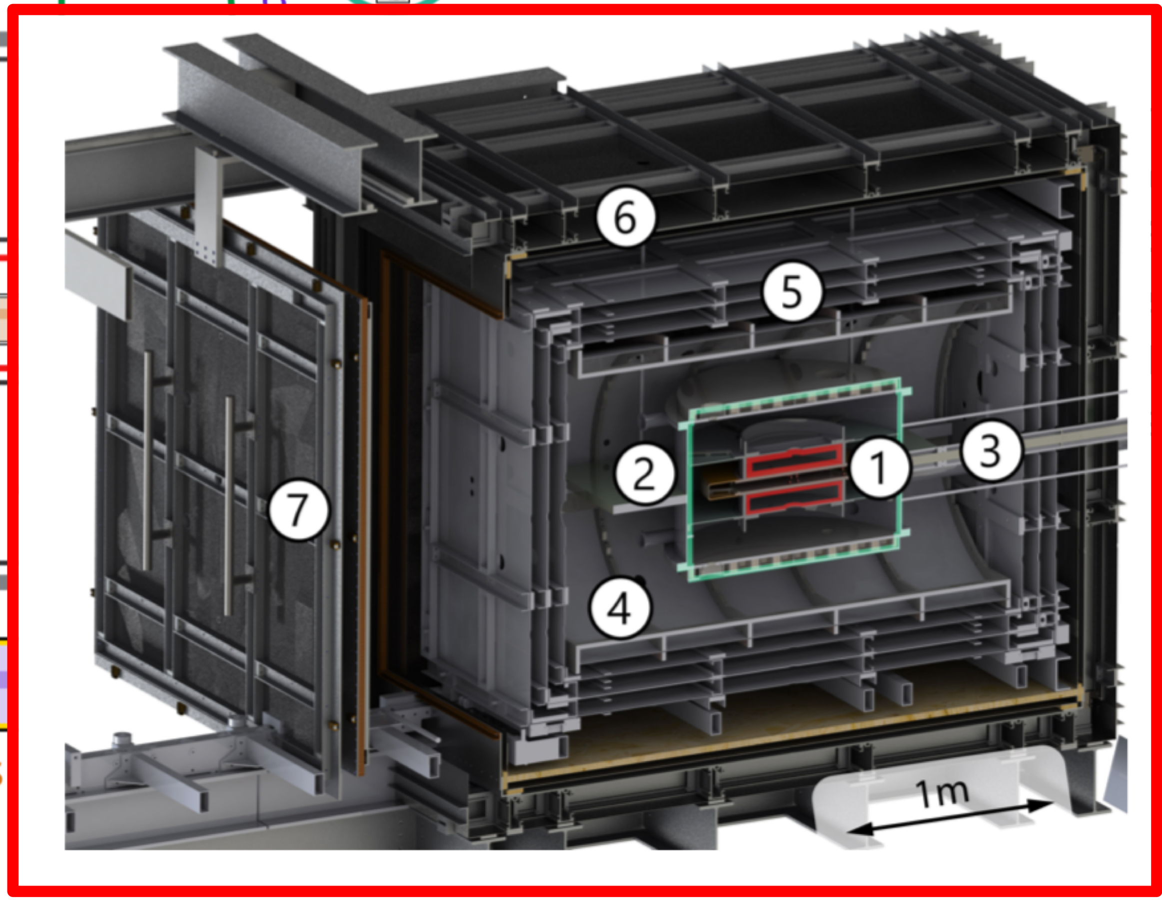


Multiple measurement cells



The PanEDM Experiment





drift with 5 fT/m
drifts
$.10^6$ at 1 mHz
whole volume
y of 2 μT field
reasonably

An ultra-light ALP search

Axion coupling to spins: $$\mathcal{L} = g_{a\psi\psi}\partial_\mu a\bar{\psi}\gamma^\mu\gamma_5\psi$$

The gradient of the axion field acts on spins:

$$\rightarrow H = -g_{aee}\nabla a \cdot \sigma \quad \Leftrightarrow \quad H = -\mu\nabla B \cdot \sigma$$

Observable as oscillating magnetic field:

$$\mu B_{eff} = g_{aee} a_o m_a \vec{v} cos(m_a t) = g_{aee}\sqrt{\rho_{DM}}\vec{v} cos(m_a t)$$

Natural scale ~ 10^{-20} T

A. Arvanitaki, A. Geraci, PRL 113 161801 (2014)

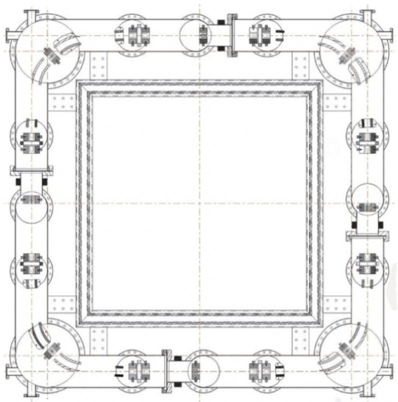
Experiment:

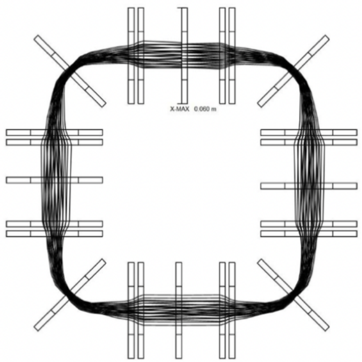
- Electrostatic storage ring for polarized ions with frozen spin
- Quasi a co-magnetometer, without low-frequency magnetic shielding, 36 kHz
- Versatile: electrostatic storage works for any ion
- DFSZ axion models couple to electrons -> demonstrator setup with electron spin

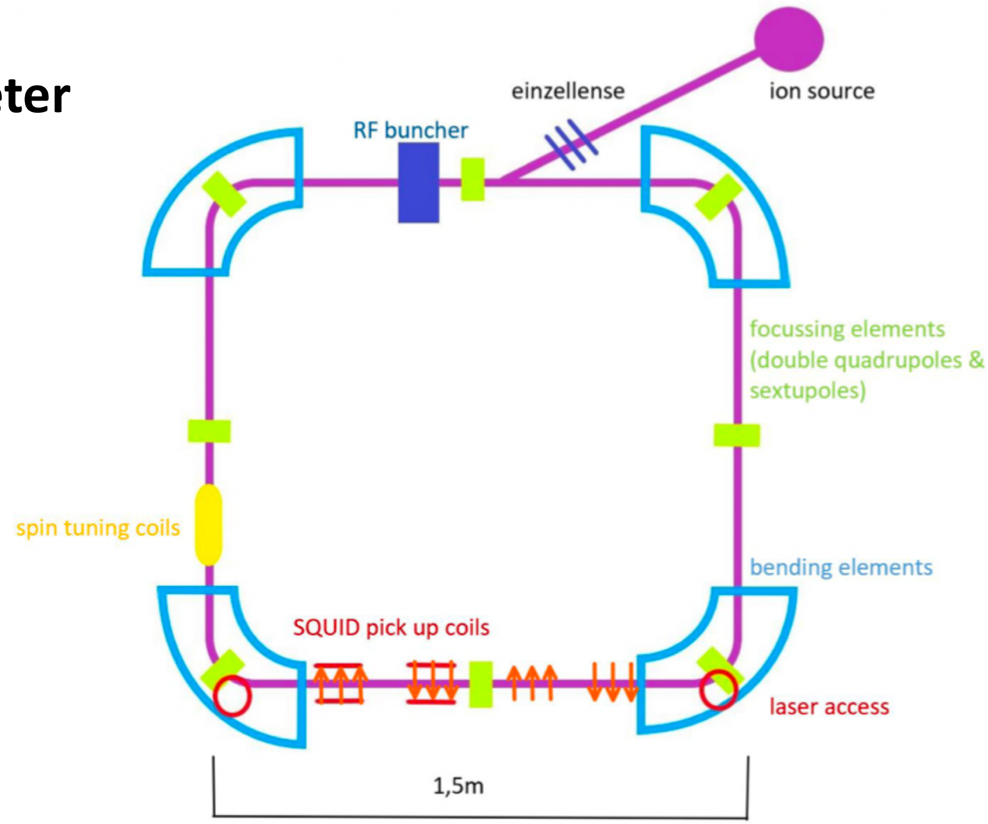
Poster by Chiara Brandenstein

Storage ring experiment

- Non-relativistic 30 keV ions in demonstrator setup with Ba+ (currently under construction), works for any ion or ionic moelcule
- **A sensitive differential magnetometer with ultimately 10^{-21} T resolution**, suitable for ALP or EDM searches







The „smallest“ and most stable magnetic fields with low noise

Residual field [pT]

Field homogeneity maps [pT]:

0.4 m (horizontal) × 1 m (vertical)

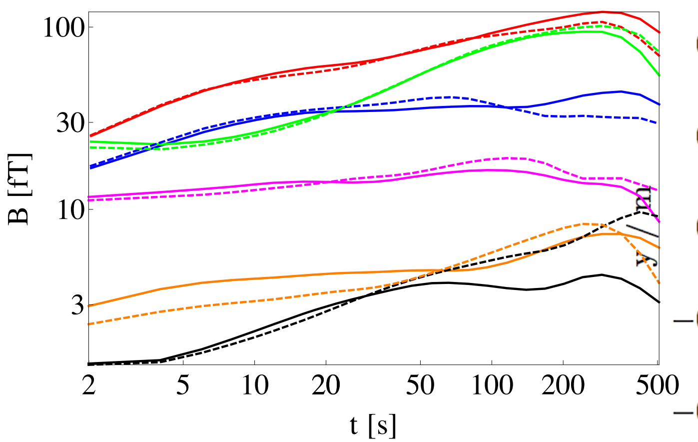
Bx in pT		
Xend-18	Xmitte0	Xend+18
8	50	88
11	59	80
29	80	85
18	48	91
19	51	91
12	43	97
-2	30	91

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!)

Stability [fT]

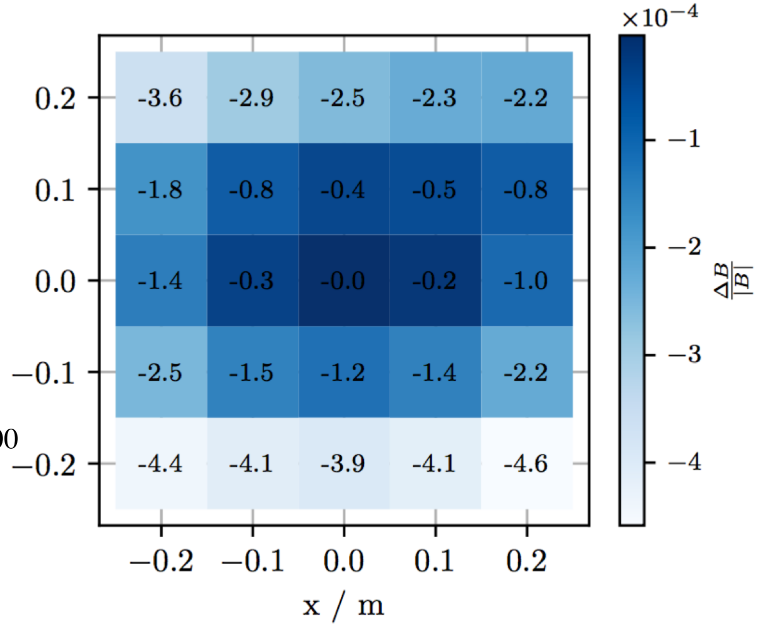


… Limited by SQUID

Damping factor:
0.01 Hz … 6.10^6
10 Hz > 10^8

(inside PanEDM experiment)

Applied B0 field



…Limited by sensor alignment

The „smallest“ and most stable magnetic fields with low noise

- Field conditions inside new shielded lab at Harbin Institute of Technology, China,
- Measured with Rb optical magnetometers

1 m × 1 m

Bx bottom (pT)		
38.4	27.0	15.6
7.8	3.8	-0.1
-22.9	-19.4	-15.9

By bottom (pT)		
27.0	20.4	13.9
-0.1	31.4	-2.3
-27.2	-22.9	-18.5

Bz bottom (pT)		
15.6	13.9	12.1
-8.0	-6.2	-4.5
-31.6	-26.4	-21.1

Bx center (pT)		
-1.9	-7.1	-12.4
-6.3	-7.1	-8.0
-10.6	-7.1	-3.6

By center (pT)		
7.7	0.3	-7.1
2.5	-1.9	-2.3
-2.8	-0.1	2.5

Bz center (pT)		
17.4	7.7	-1.9
11.2	7.3	3.4
5.1	6.9	8.6

Bx top (pT)		
14.9	9.7	4.4
7.9	-1.7	-11.3
0.9	-13.1	-27.1

By top (pT)		
19.3	12.3	5.3
8.8	-0.8	-8.7
-1.7	-12.2	-22.7

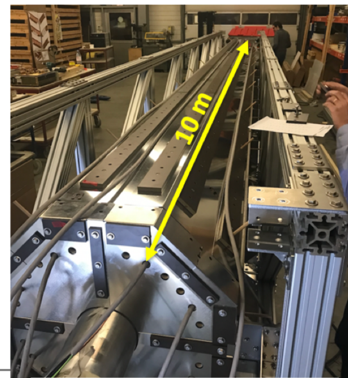
Bz top (pT)		
23.7	14.9	6.2
9.7	1.8	-6.1
-4.3	-11.3	-18.3

State of the art in 2010 ~ 2 nT

Experiments where the same technology is/will be applied (e.g.):

- n-nbar @ ESS
- Atomic fountains
- BECs (CARIOQA, BECCAL @ ISS)

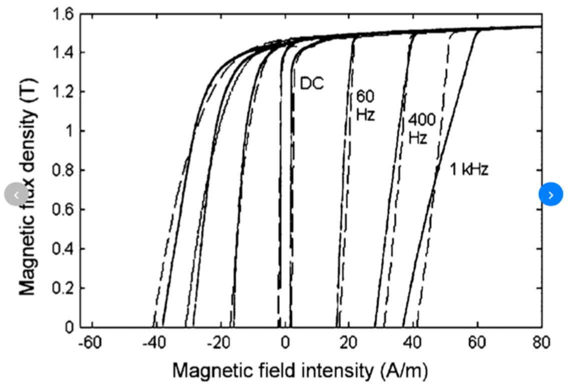
E.g. Atomic fountain at Univ. Hannover

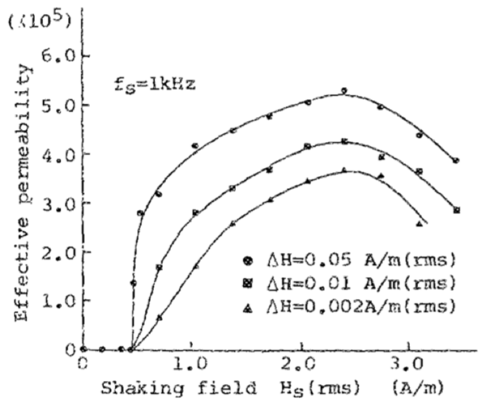


Rev. Sci. Instr. 91, 035117 (2020).

Magnetic domains and currents

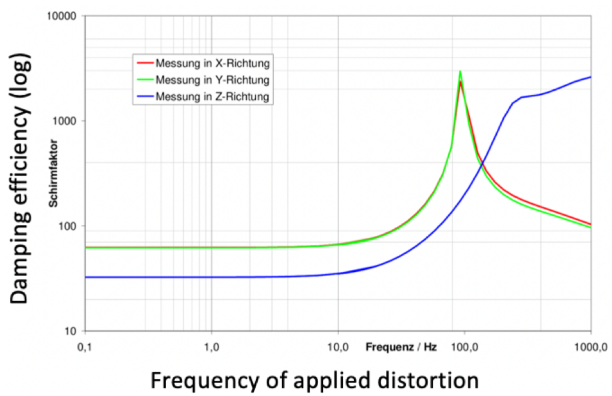
- Frequency and amplitude dependence, e.g. with Metglas

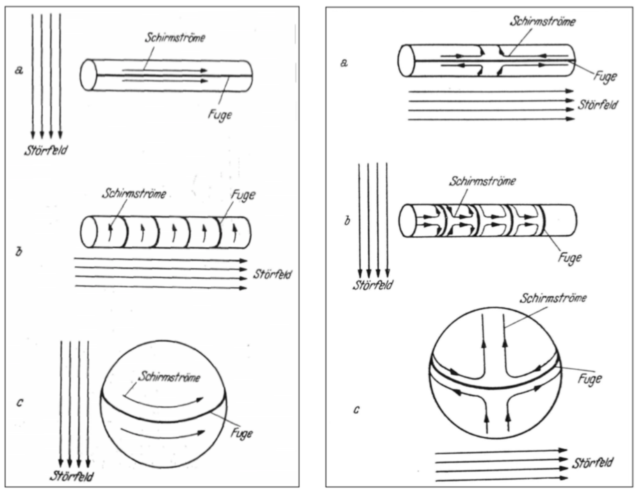




5697 J. Appl. Phys., Vol. 64, No. 10, 15 November 1988

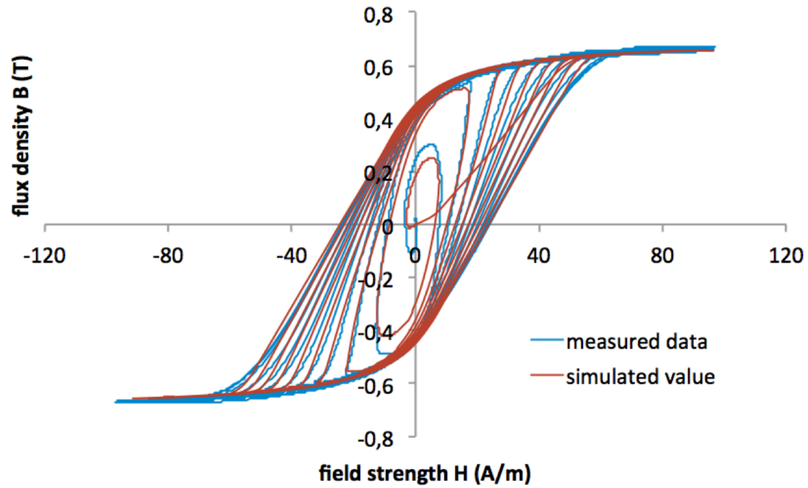
- Magnetic domains vs. currents





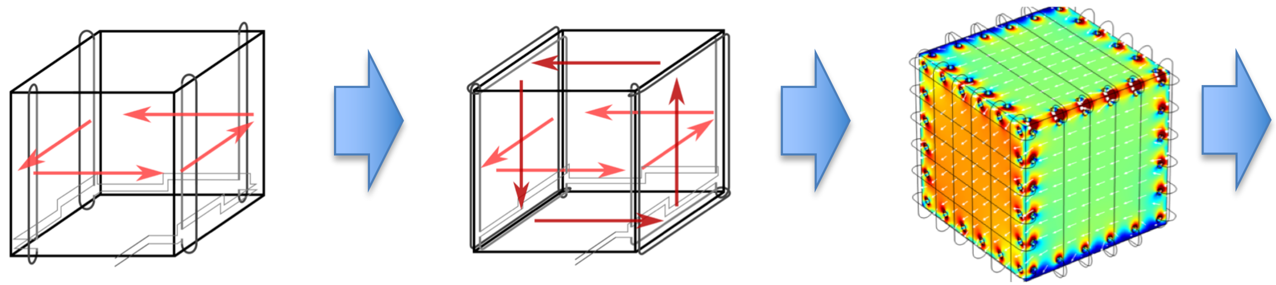
Equilibration

Quantitative agreement of simulation and experiment!

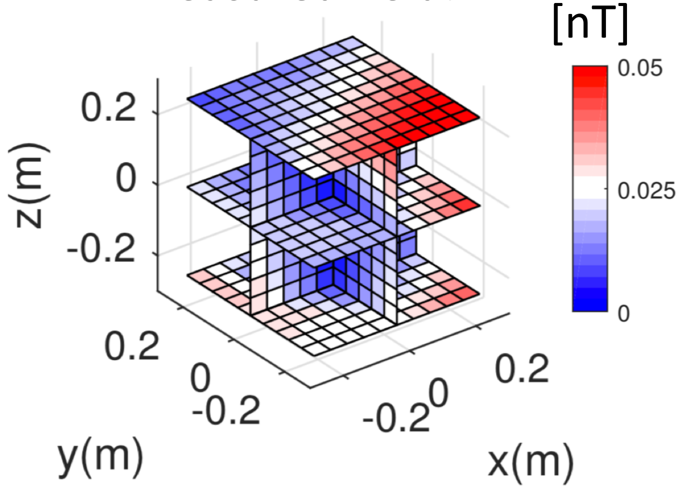


Modified Jiles-Atherton model:

- Interdomain coupling
- Domain wall density
- Saturation magnetization
- „Pinning" sites
- Presence of applied fields



Measured field:

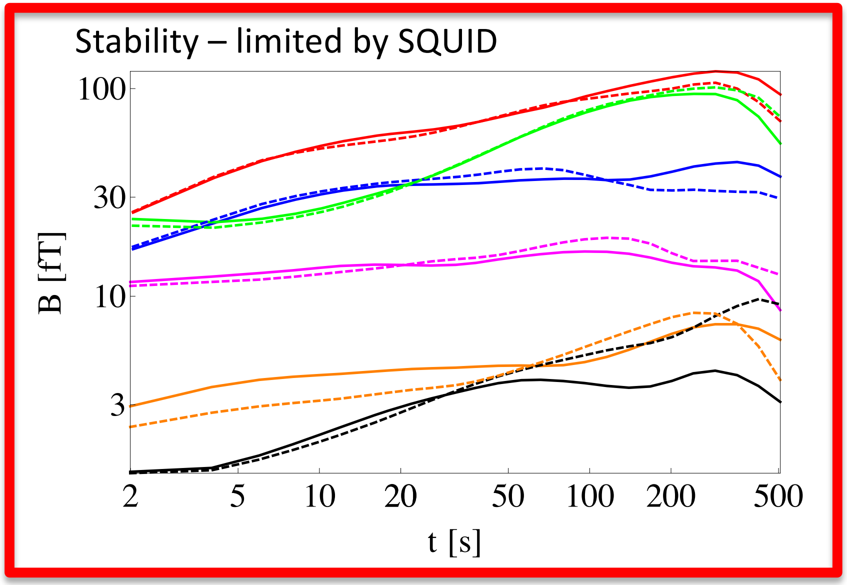


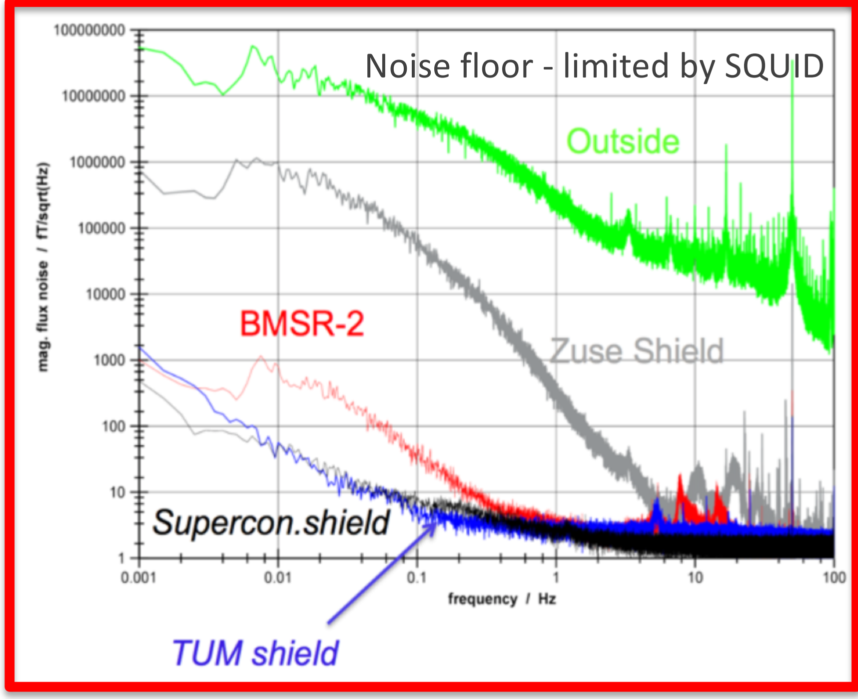
e.g.
Z. Sun et al., J. Appl. Phys. 119, 193902 (2016)
Z. Sun et al., IEEE Transactions on Industrial Electronics: 68 (2021), 6, 5385 - 5395

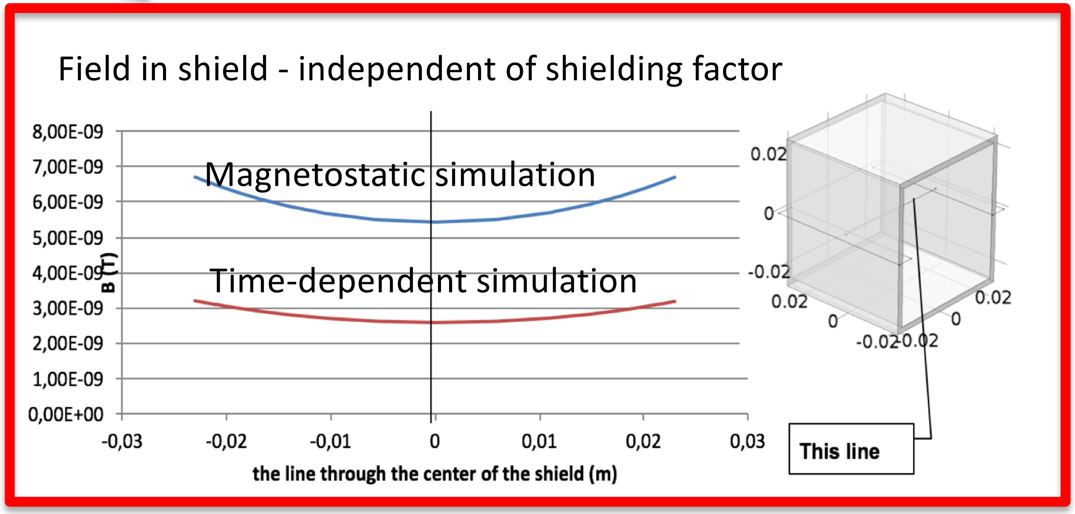
Equilibration

Consequences:

1) Stable conditions
2) Small fields
3) Small gradients







Noise

Where does noise come from?

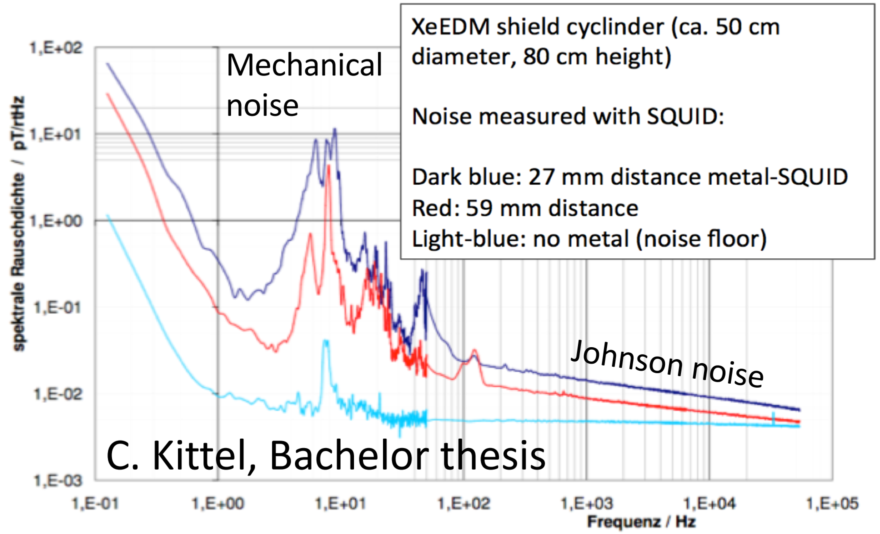
- Johnson noise

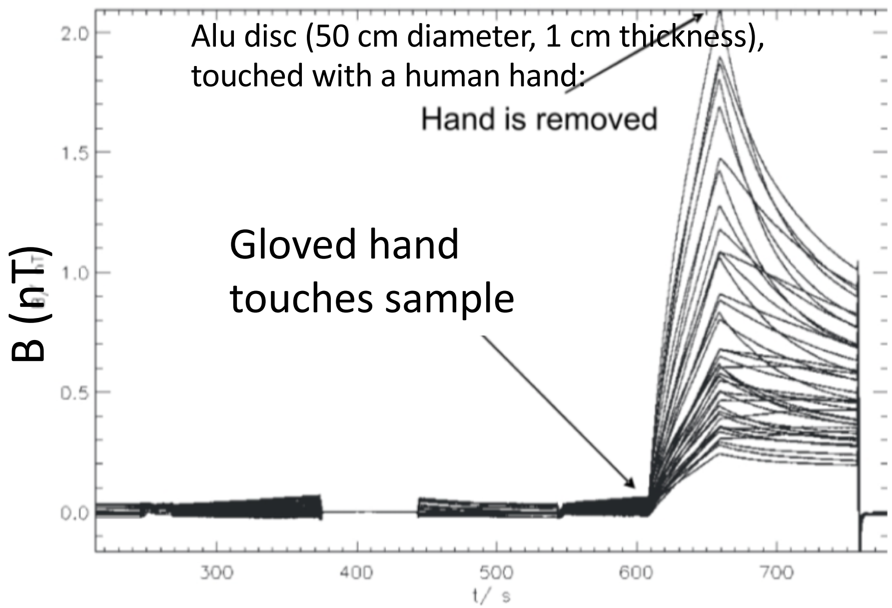
$$\delta I = \sqrt{4kT/R}$$

- Cut-off frequencies: skin-effect, self inductance, magnetic (inductive) cut-off

$$\delta B(f): f^{-1/2} \rightarrow f^{0} \rightarrow f^{-1/4} \rightarrow f^{-3/4}$$

- Thermal currents





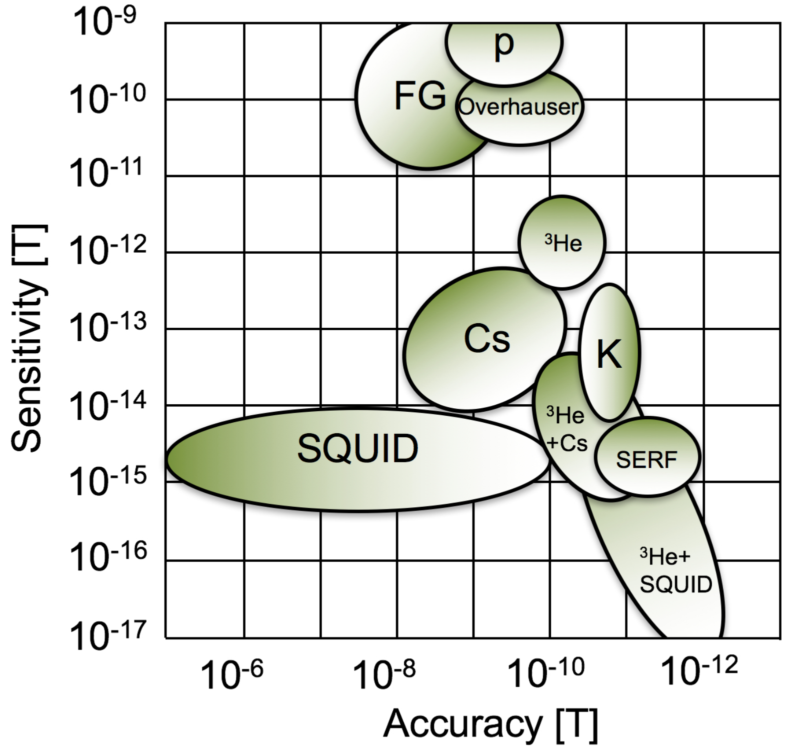
J. Appl. Phys. **103**, 084904 (2008)

Measuring magnetic fields

- Difference between accuracy and sensitivity
- Bandwidth:
  - Accuracy often comes with low bandwidth
  - Precision with low accuracy
- Sensor and field cannot be separated

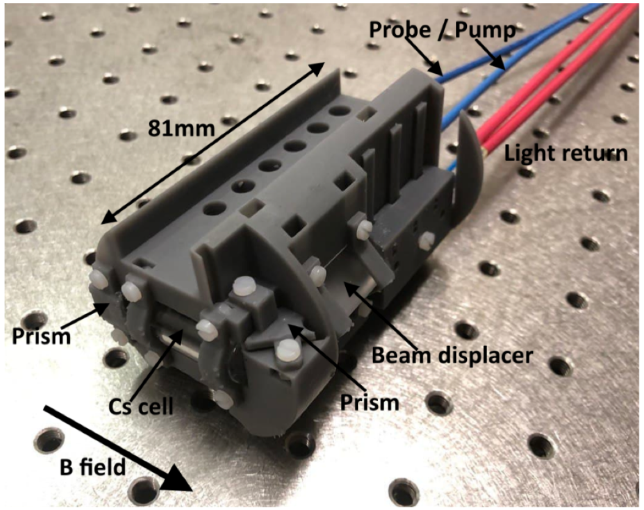
Best results typically obtained:

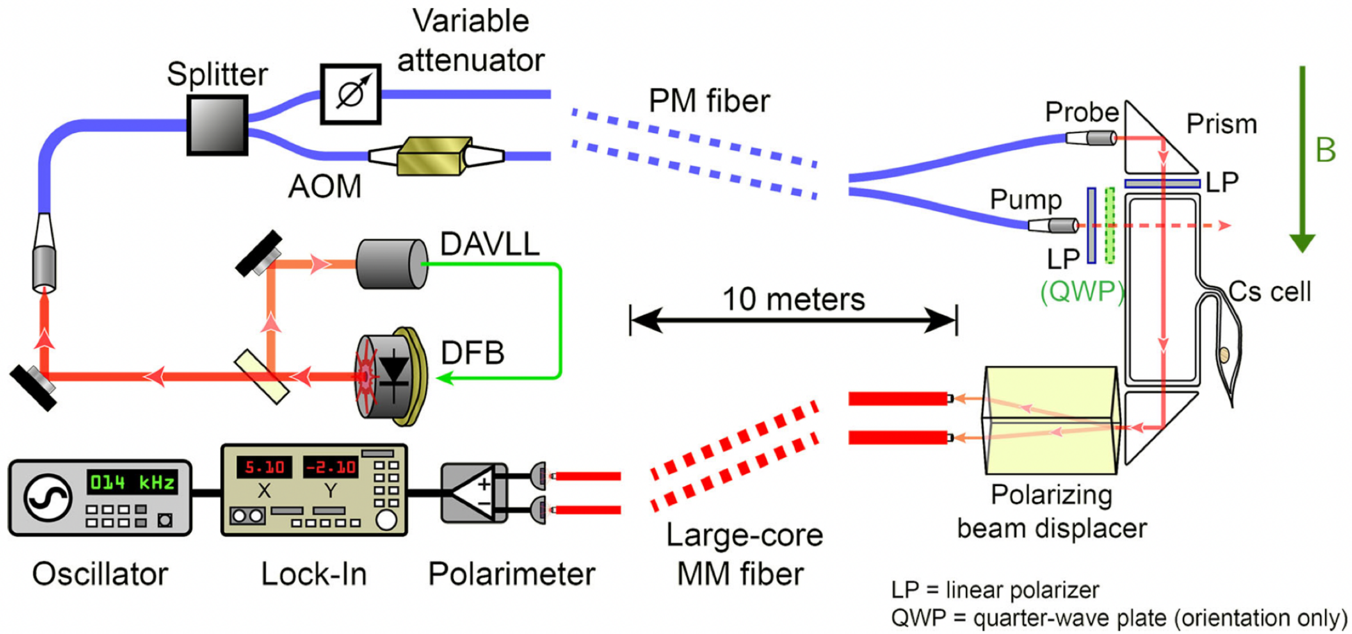
Polarized noble gas precession combined with high precision sensor



Example: Cs optical magnetometers

- Completely non-magnetic, 3D printed, room temperature
- Systematics very clean and well understood
- Operated as sensor array
- Insensitive to RF noise

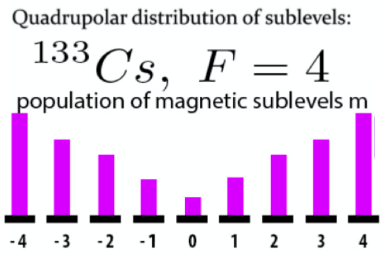


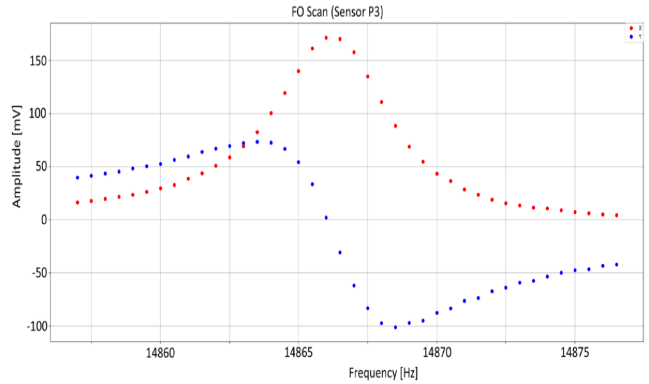


M. Rosner et al., Appl. Phys. Lett. **120**, 161102 (2022)

Cs optical magnetometers

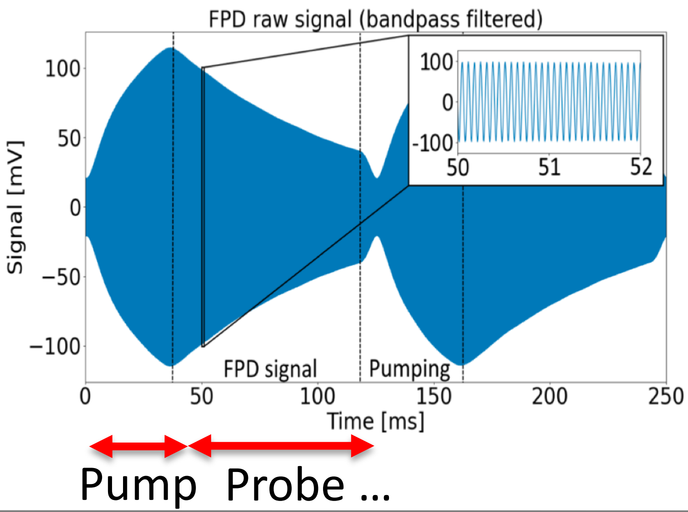
- Alignment pumping: no net polarization, just spin alignment

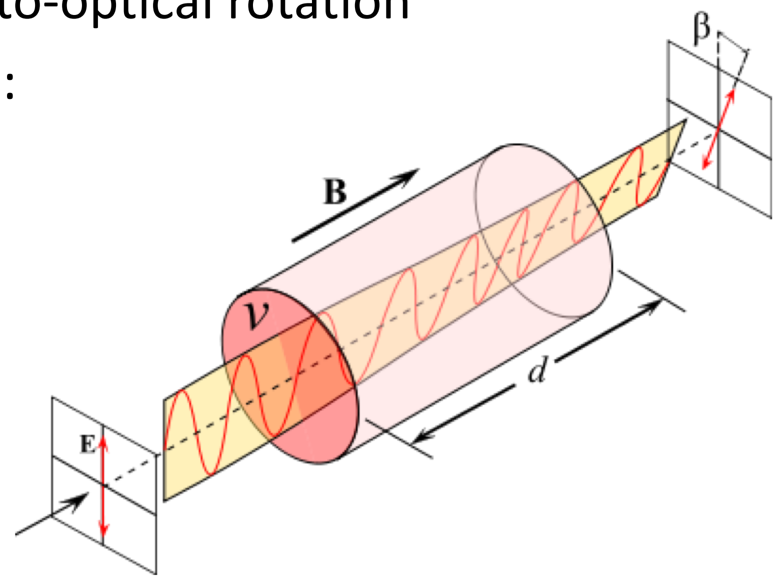




42 fT/sqrt(Hz) at ~ 0.1 s integration time

- Measurement principle: nonlinear magneto-optical rotation
- Operation optimized for small systematics:

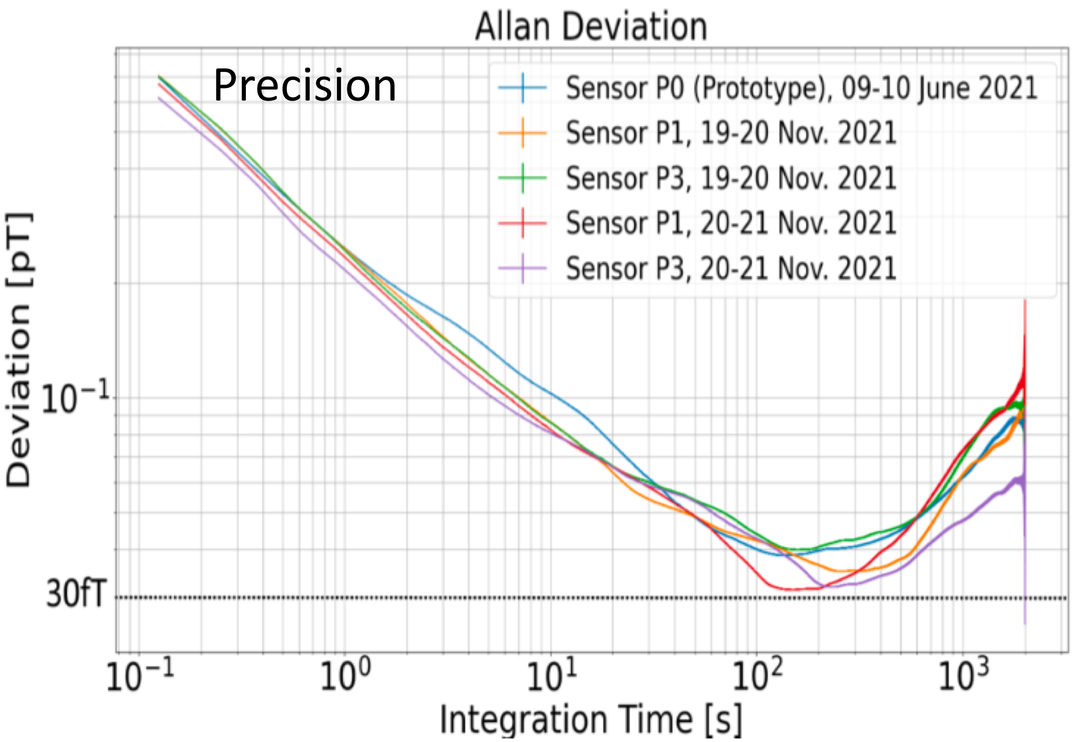


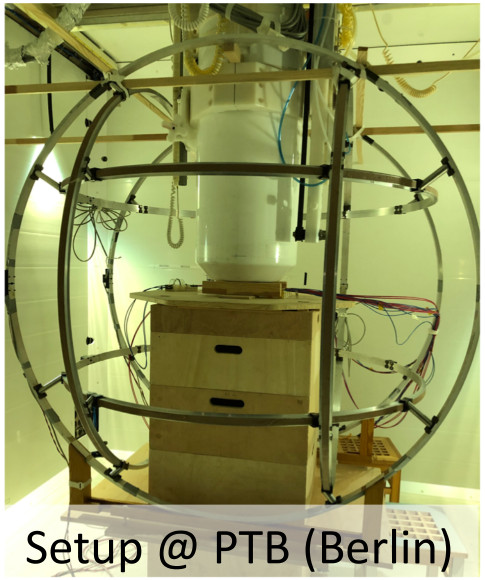


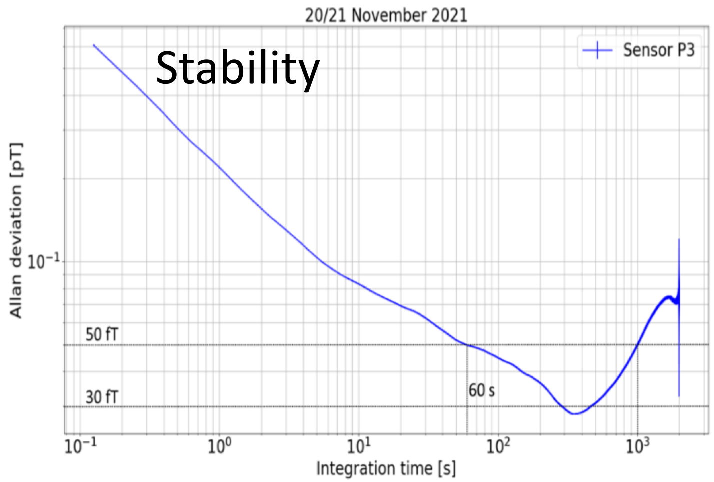
M. Rosner et al., Appl. Phys. Lett. **120**, 161102 (2022)

Cs optical magnetometers

- Photon count rate limited sensitivity – required for clean systematics
- Precision: 35 fT at ~ 250 s (typical Ramsey cycle)
- Stability: 25 fT at ~400 s integration
- Accuracy: few pT





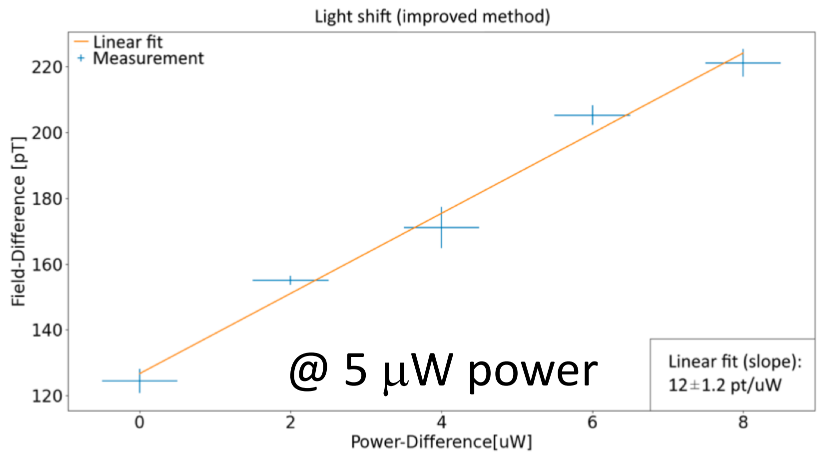


M. Rosner et al., Appl. Phys. Lett. **120**, 161102 (2022)

Cs optical magnetometers

Main systematic issue:

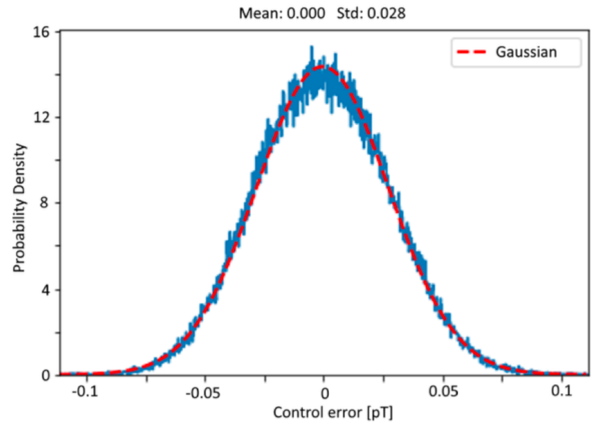
Light shift effect



Key features to make sensor work well:

- Polarizing optical fibers (Pump and Probe)
- Cleanup polarizers inside the sensor
- Polarization analysis directly after the cell
- Temperature stabilized DAVLL system
- Low-noise and drift-stable polarimeter board
- Free precession decay mode
- Active field stabilization (limit of performance) – field and sensor cannot be disentangled

Field stabilization @ PTB: at the limit



M. Rosner et al., Appl. Phys. Lett. **120**, 161102 (2022)

Comparison: the „best“ SQUID magnetometer @ PTB

- Extreme sensitivity of 160 fT/sqrt(Hz) at 40 Hz as gradiometer
- Fulfills a different tasks: no defined accuracy, high bandwidth, but > pT noise at 250 s integration time

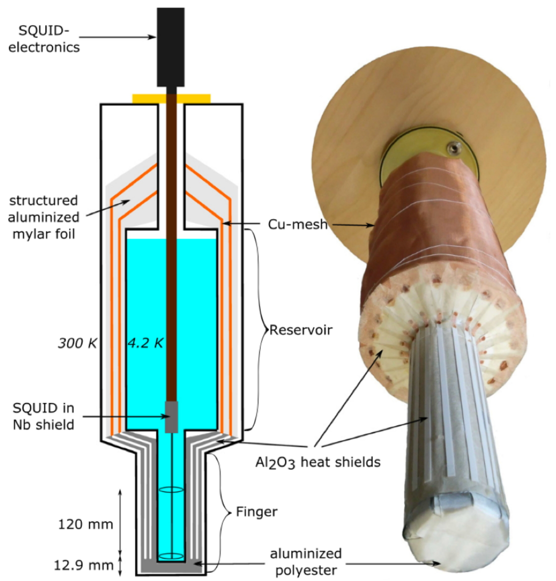


FIG. 1. Left: the schematic setup of LINOD2 in gradiometer configuration. Right: a view of one of the heat shields made from Al_2O_3 strips together with the copper mesh heat shield at the dewar reservoir. The outer shell has been removed.

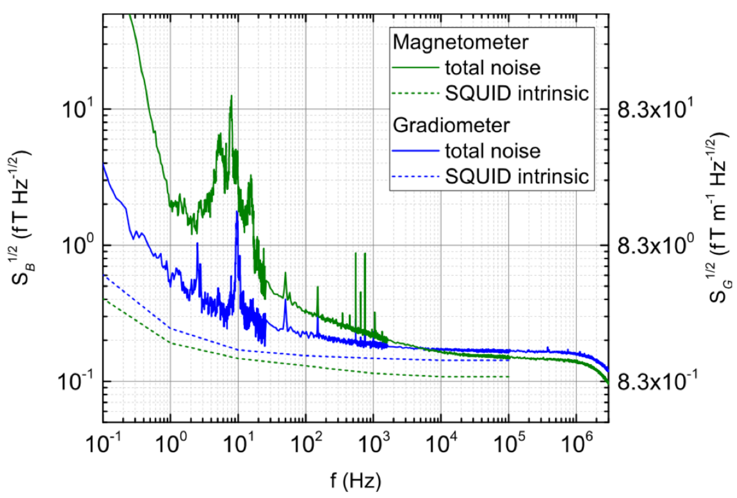
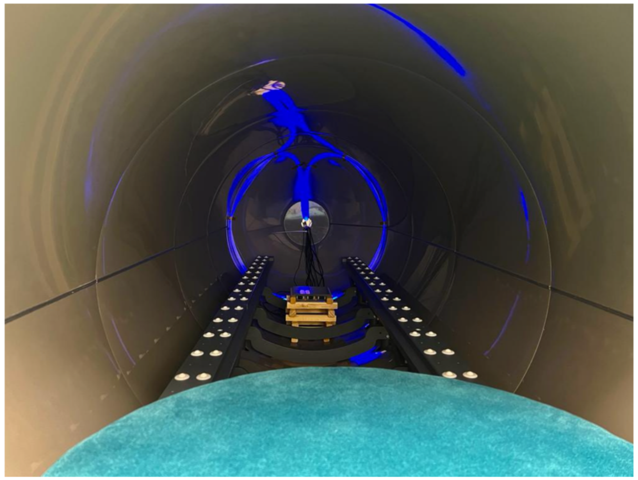


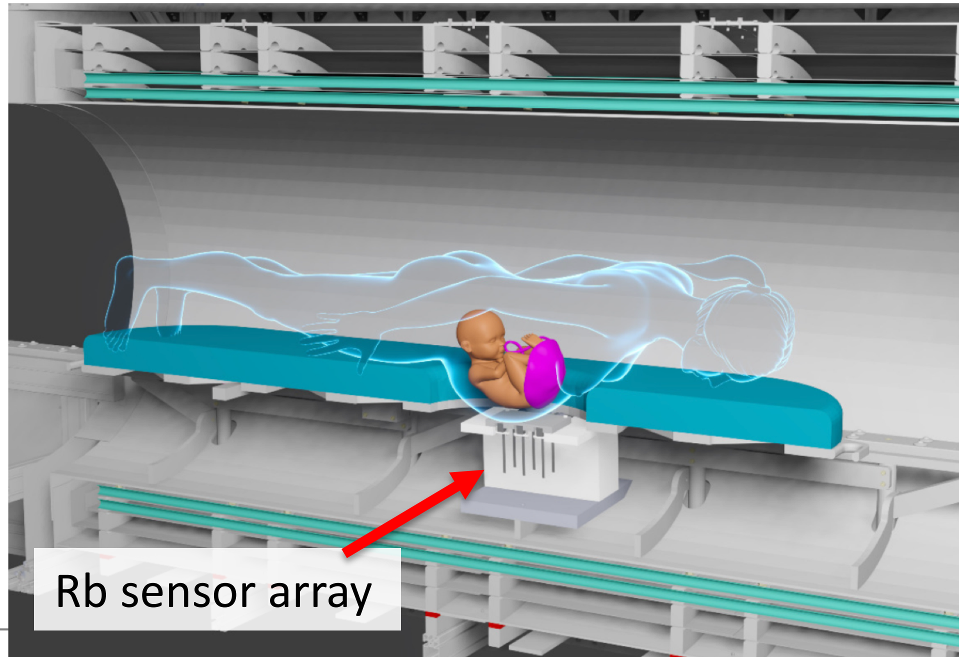
FIG. 2. Measured magnetic flux density noise $S_{B,m}^{1/2}$ for the two setups with 45 mm diameter pick-up coils: Magnetometer (solid green curve) and gradiometer (solid blue curve). The calculated intrinsic SQUID noise levels $S_{B,i}^{1/2}$ are given by the dotted curves. For the gradiometer, the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

J. Storm, Appl. Phys. Lett. 110, 072603 (2017)

Applications of sensors: Fetal Magnetocardiography (fMCG)

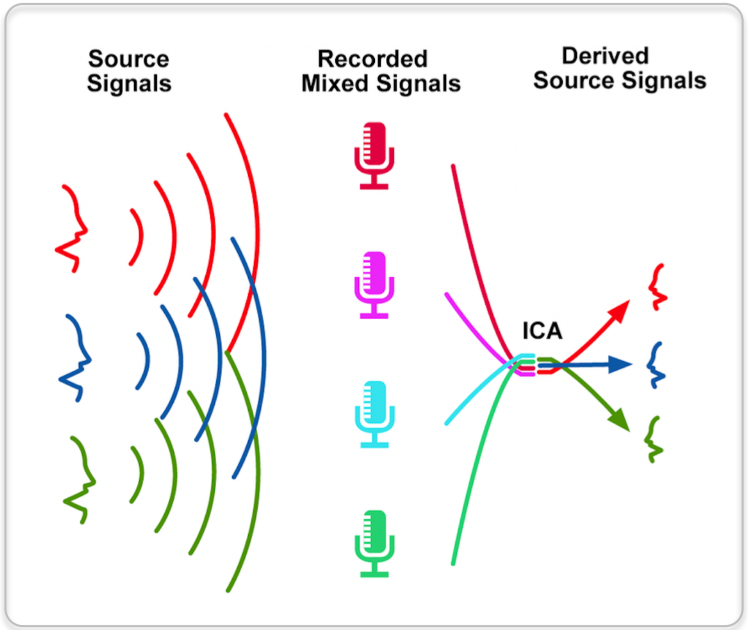
- Optically pumped alkali sensors are not RF sensitive (unlike SQUIDs), bandwidth 1-100 Hz
- Sensitive to medical conditions like the „long-QT“ problem, related to severe issues
- At TUM: collaboration with the Deutsches Herzzentrum, measurements with patients ongoing since Dec. 2021



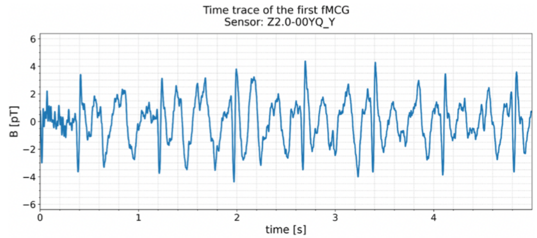


fMCG

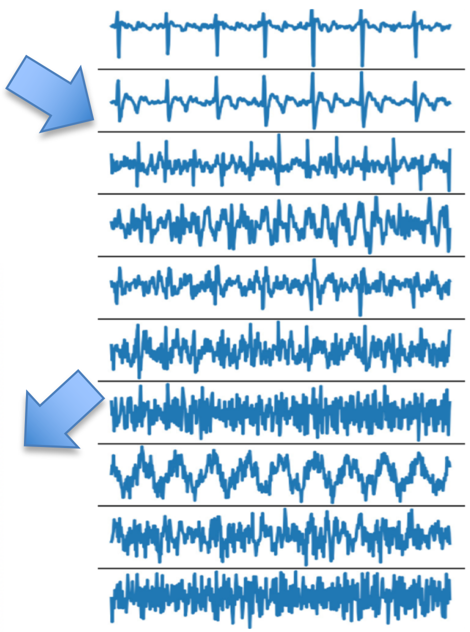
- Analysis using independent component analysis (ICA) – analogy: the cocktail party problem



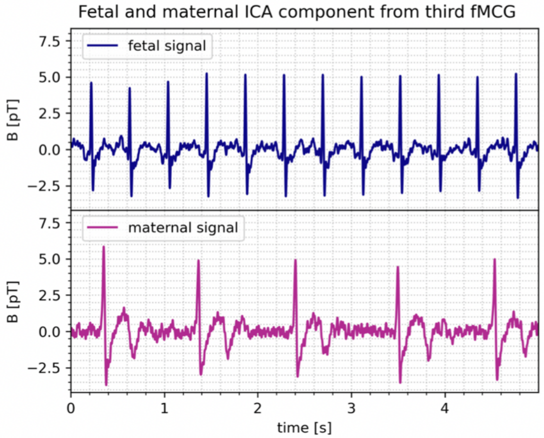
fMCG time trace data:



ICA…



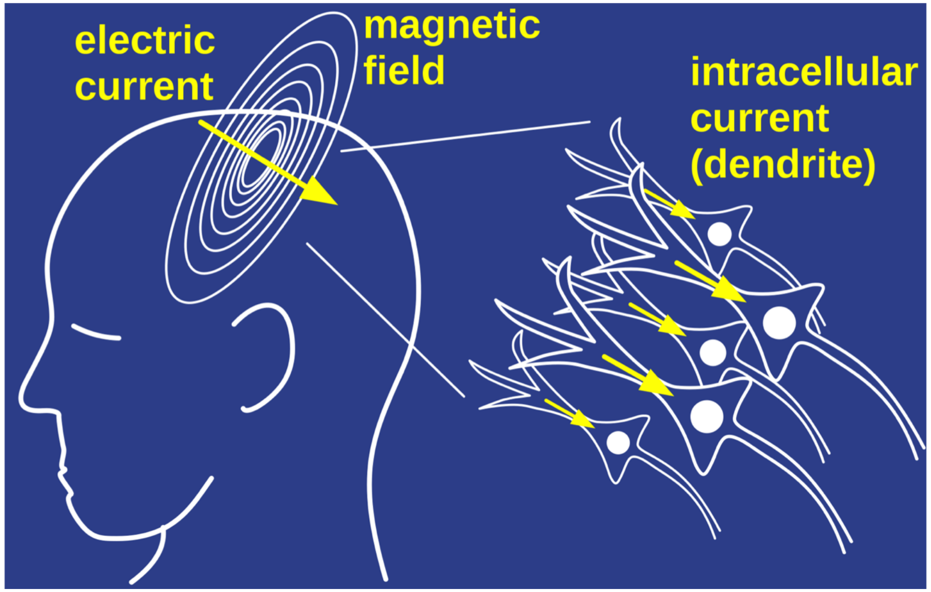
fMCG ICA result:



Technology transfer both ways:
ICA now used for signal improvement of 129-Xe measurements

Applications: Magnetoencephalography (MEG)

- Signal patterns are complicated (no simple dipoles) and at fT-level: machine learning methods combined with low-field techniques



The future: many pixels, machine learning methods for pattern recognition

MEG

Example:
- Altered gamma wave activity in mood & cognitive disorders (e.g. Alzheimer’s disease, epilepsy, schizophrenia

-DC signals related to motion control

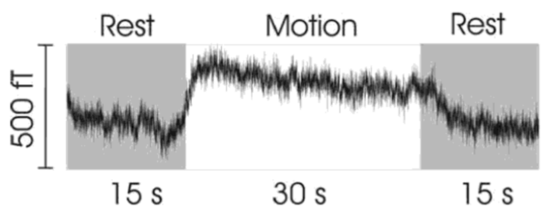
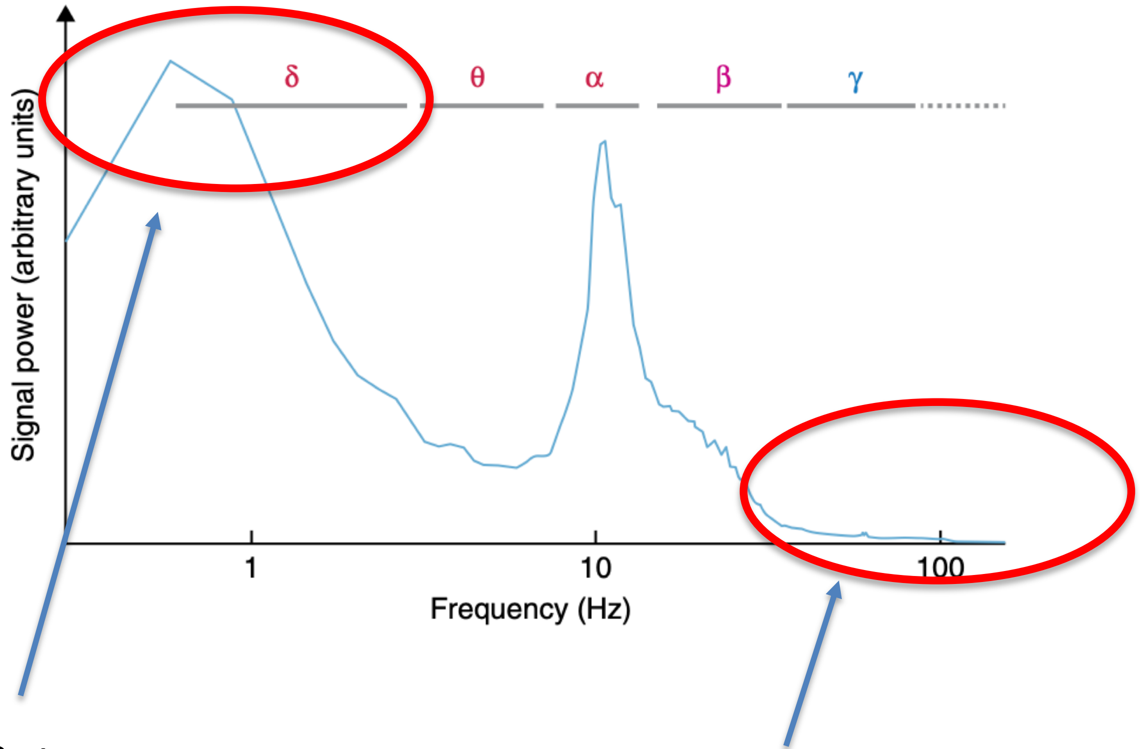


Figure 1: DC-MEG recording of a movement evoked brain response. After 15 seconds of rest, the volunteer started with a finger tapping paradigm over 30 seconds. A clear brain response with an amplitude step of about 300 fT can be seen. After stopping the finger movement, the signal returned to the resting level [6].



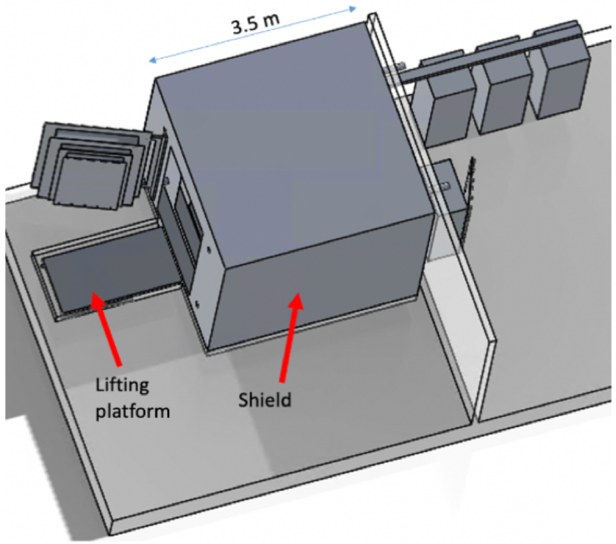
DC steps
In MEG hard to reach, due to limited stability of environment

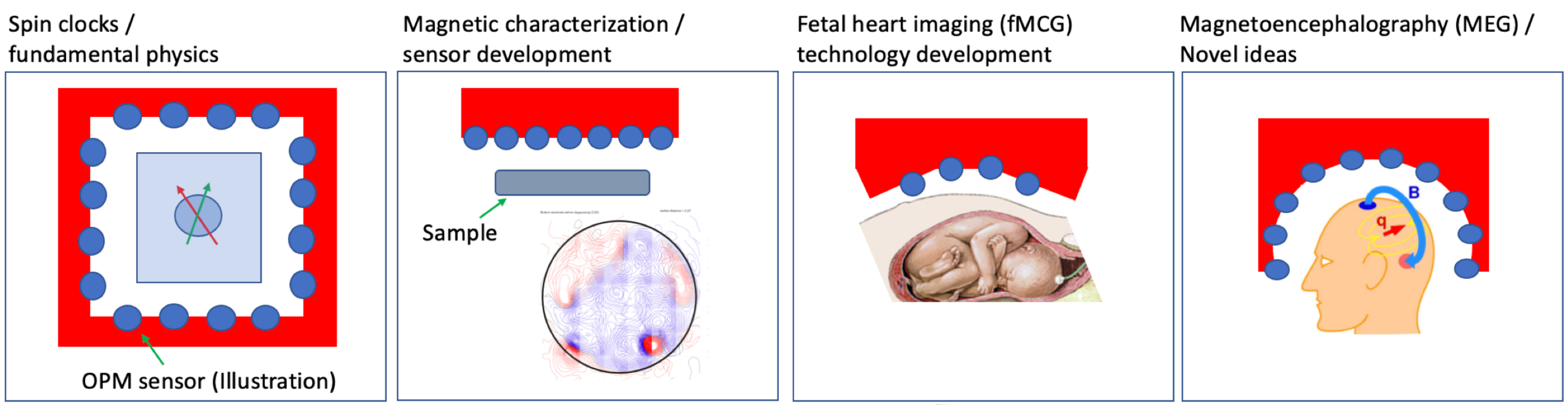
Low signal amplitude:
In MEG hard to reach, only in very strong shields

Next step: low magnetic field lab at TUM under construction!

A new facility using all recent experience:

- SF at mHz ~ 100.000
- Oder 1 pT residual field
- Below 1 fT noise
- Multi-channel field monitoring and characterization at fT-level in time and below pT in space
- Use for patients and fundamental research
- Ground work done, construction of shields and coils starting now





Side note: A new low-noise lab

- The lab: cubic wooden house without any metallic parts, additionally a measurement/operations house, to be built in summer 2023
- Site: near Tamsweg, at 1600 m altitude - no 50 Hz, no trucks, no cars, no trains, no hikers, geologically silent and extremely remote!

Science: (e.g.)

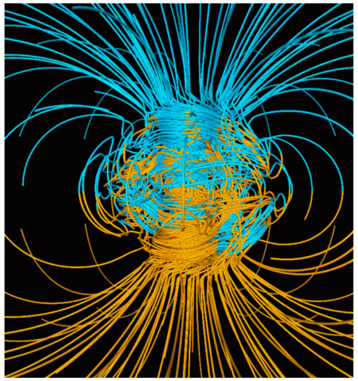
- Spin precession measurements without shielding, (e.g. Axion-electron coupling)

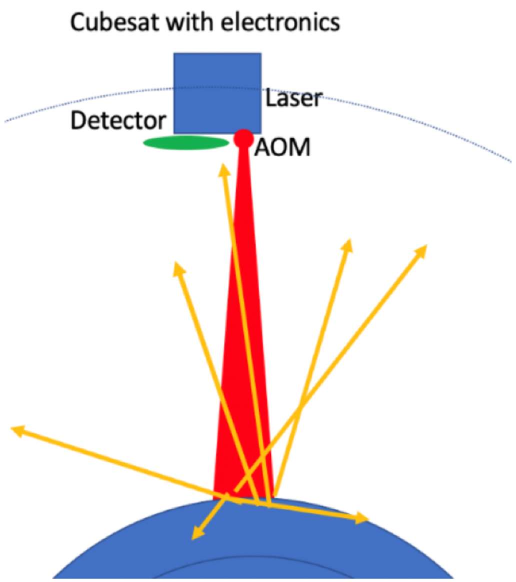
Technology:

- Extremely homogeneous B-fields
- Sensor calibration and alignment
- Sensor development e.g for MEG:
  - field and noise issues decoupled
- R&D for (satellite-based) mesospheric sodium magnetometry project

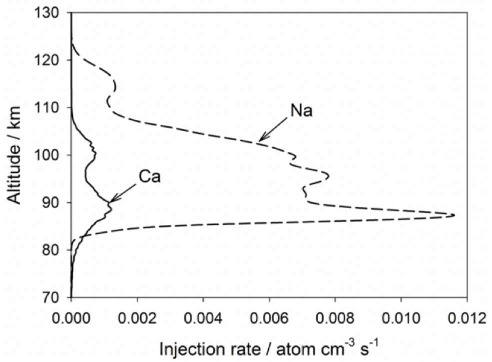
Side note:
Mesosphere Na magnetometer

- There is no full magnetic field map of the earth below satellite orbits – a problem for navigation





- Mesosphere (at 92 km height) offers a unique possibility: an optically thick Na layer!
- Cubesat at 450 km with a diode laser to probe Na Zeeman splitting
- Na lasers available from telescope guide stars



Summary

- Low field techniques are a connection between fundamental physics and applications
- ~ 30 fT level for stability and precision of atomic magnetometers over 100‘s of seconds
- Big advances in last decade: factor of 1000 reduction of residual fields, single-pT-level in reach!
  - Enables new quality of fundamental experiments
  - Allows access to new types of measurements e.g. for MEG
- New low-field lab at TUM under construction
- New low-noise lab being established