Precise Measurements and Shimming of Magnetic Field Gradients in the Low Field Regime

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for the MIXed collaboration

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Measurement and Investigation of the Xenon-129 electric dipole moment

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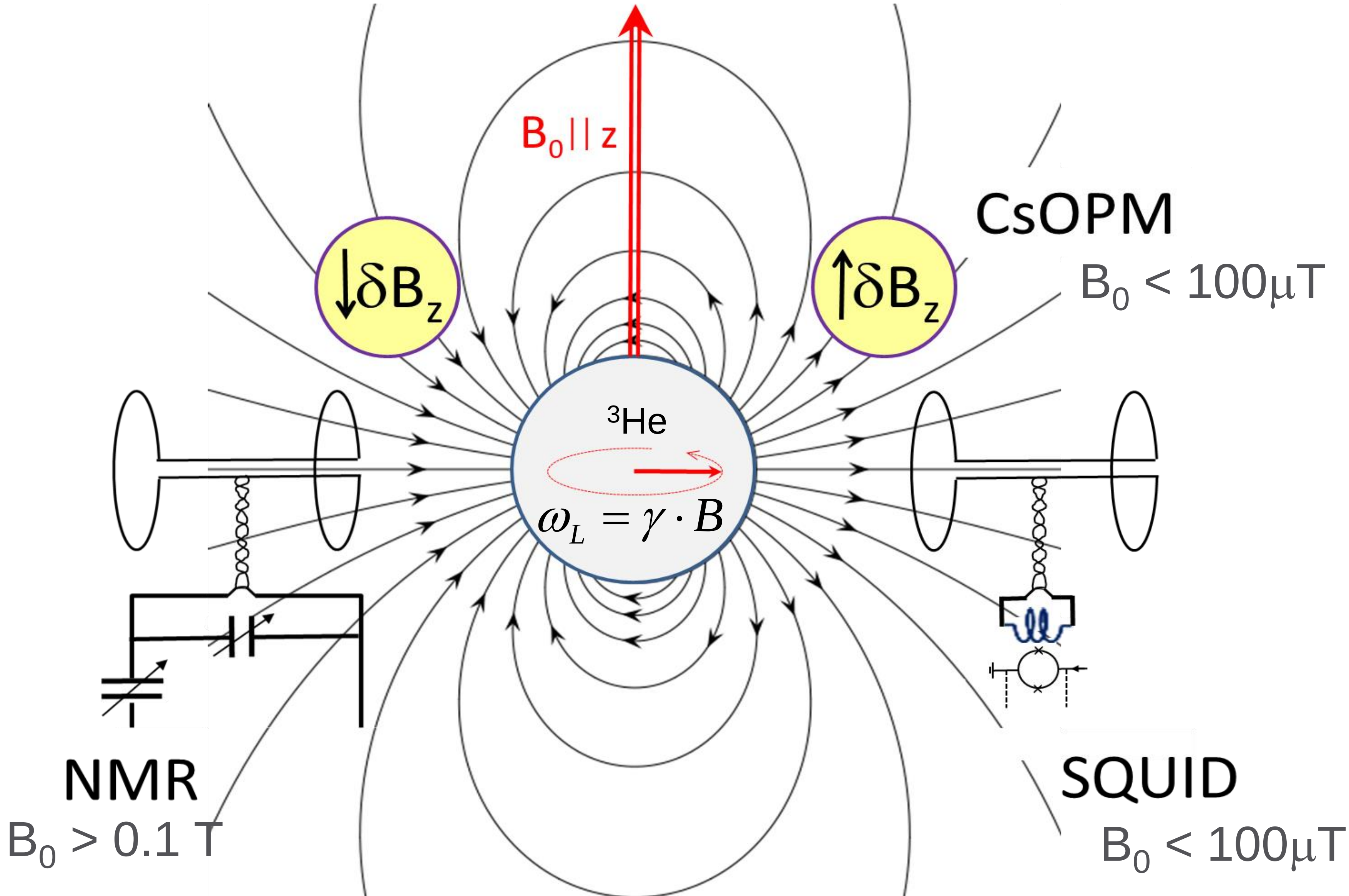
Motivation

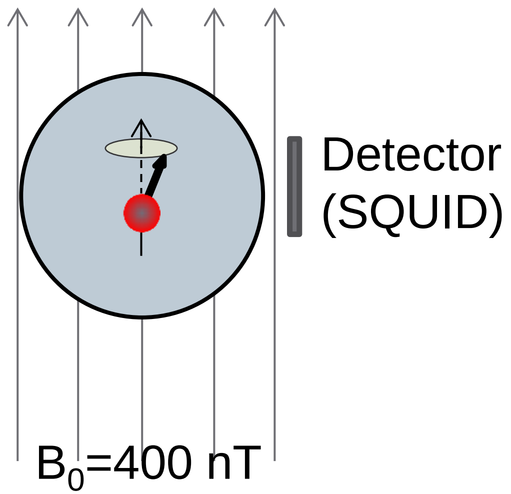
Characterization and compensation of magnetic field gradients is useful in many types of experiments:

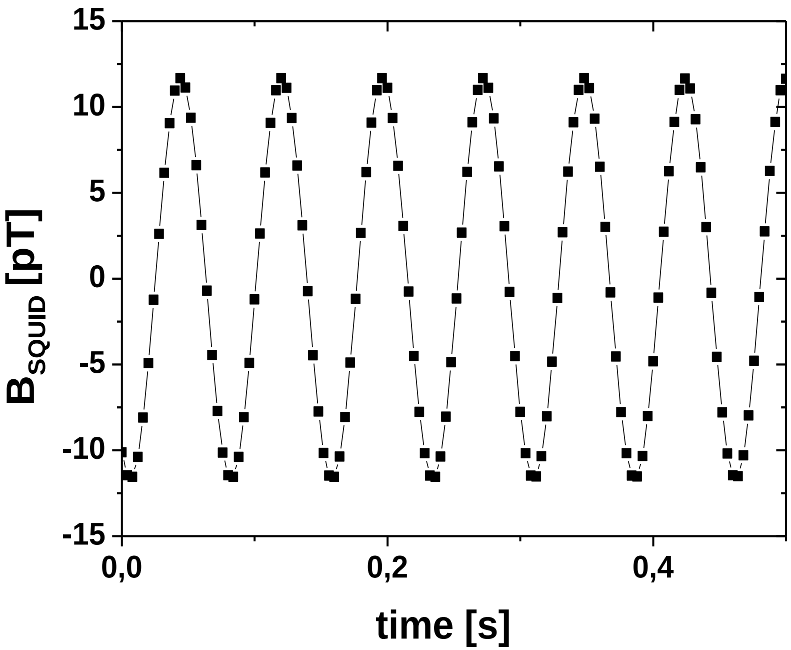
- Fundamental physics
  - Measurement of Electric Dipole Moments (EDMs), e.g. Neutron or ^{129}Xe EDM
    - Resolution is partially limited by gradients
    - Systematic effects (false EDMs) due to gradients
- Applied physics
  - MR Imaging
  - MR Spectroscopy

Detection of free spin precession



Magnetometry with fT accuracy

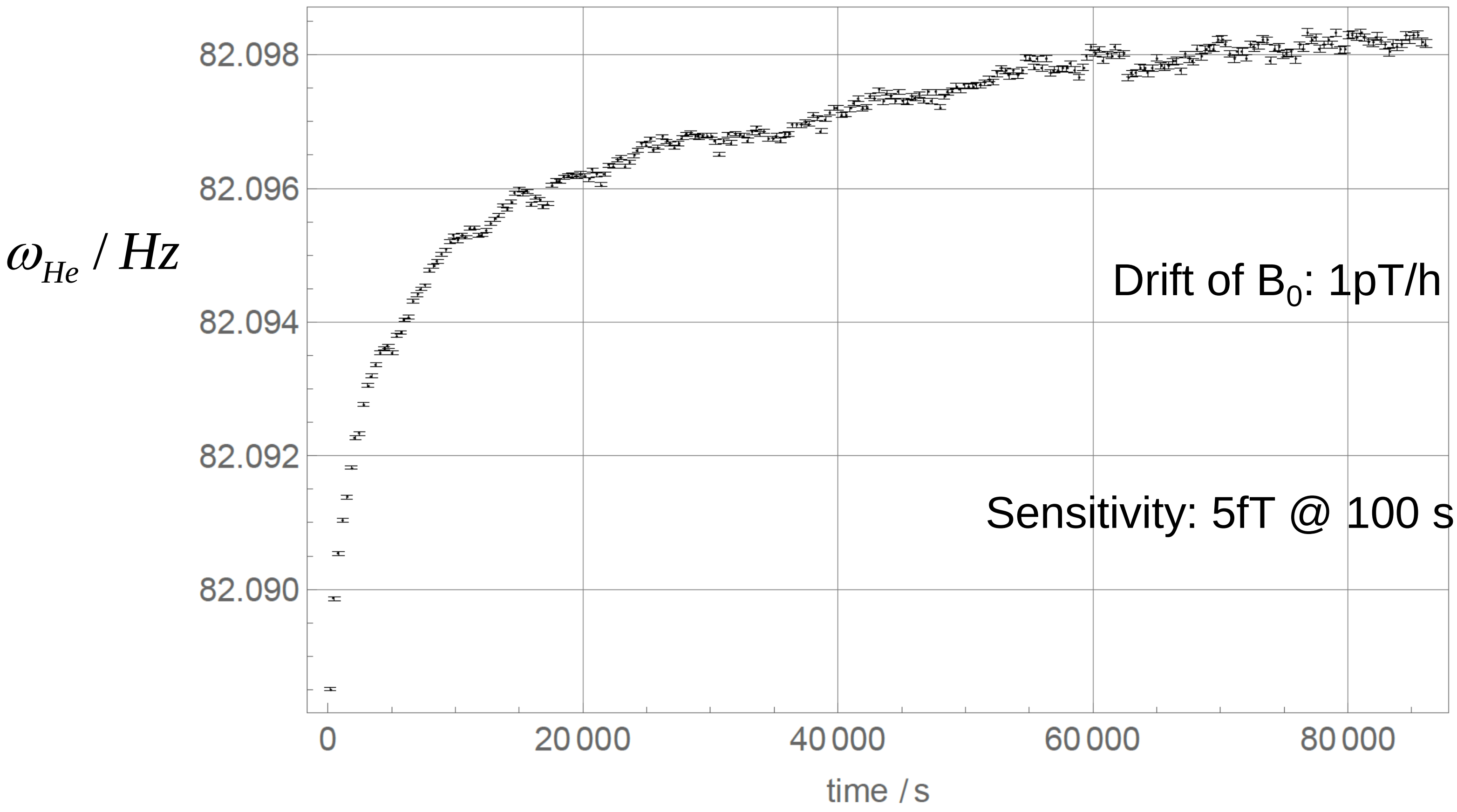




1) Monitoring of B_0: $$\omega_L = \gamma \cdot B_0$$

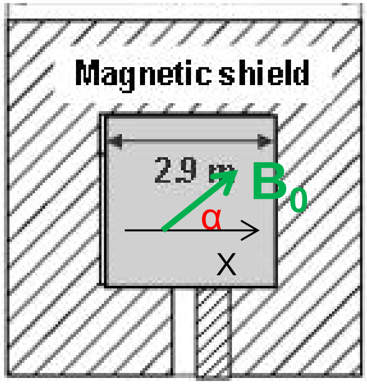
2) Monitoring of Gradients: $$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{4R^4\gamma^2}{175D}\left(\left|\vec{\nabla}B_{1,y}\right|^2 + \left|\vec{\nabla}B_{1,z}\right|^2 + 2\left|\vec{\nabla}B_{1,x}\right|^2\right)$$

1) Monitoring of B_0 over one day

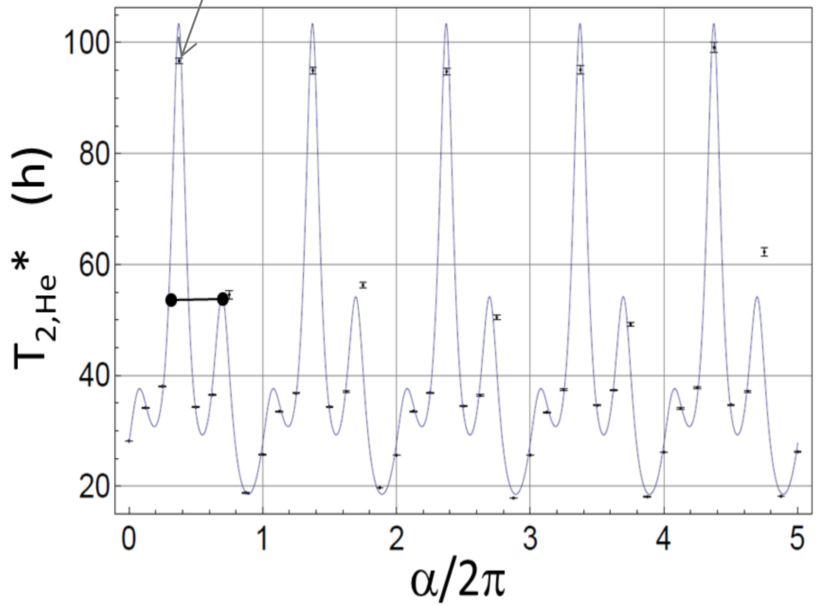


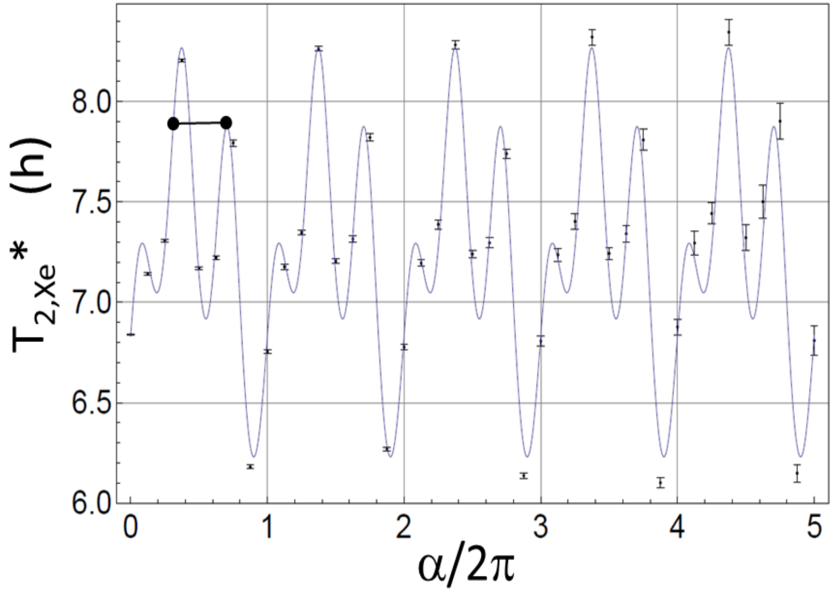
2) Sensitivity on field gradients

Setup at PTB Berlin



Gradients < 7 pT/cm





Gradient optimization for EDM experiments

- EDM resolution is determined by frequency resolution

$$d = \frac{h\,\Delta\omega}{2\pi\; 4E}$$

- Frequency resolution is determined by coherent measurement time, and thus spin coherence time

$$\sigma_f^2 \geq \frac{12}{(2\pi)^2 \left(A/\rho_\alpha\right)^2 T^3} C.$$

- Spin coherence time is (partially) determined by magnetic field gradients

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{4R^4\gamma^2}{175D} \left(\left|\vec{\nabla} B_{1,y}\right|^2 + \left|\vec{\nabla} B_{1,z}\right|^2 + 2\left|\vec{\nabla} B_{1,x}\right|^2 \right)$$

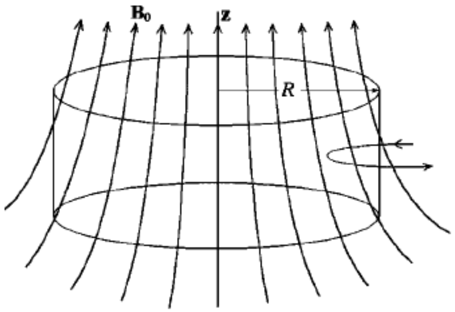
Systematic error: geometric phase

Motional (transverse) field

$$B_v = \frac{1}{c^2} E \times v$$

\+

Magnetic transverse field



- Frequency shift correlated with electric field
- False EDM for Mercury (fast regime of GPE)

$$d_{\mathrm{Hg}}^{\mathrm{False}} = \frac{\hbar \gamma_{\mathrm{Hg}}^2}{32 c^2} D^2 \frac{\partial B}{\partial z}$$

Pendlebury et al,
PRA **70** 032102 (2004)

- False neutron EDM when using Hg comagnetometer

$$d_{\mathrm{n}}^{\mathrm{False}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}} d_{\mathrm{Hg}}^{\mathrm{False}}$$

Indirect systematic effect

Setup & Principle of Measurement

Setup placed inside a
2 layer magnetically shielded room
at FZ Jülich

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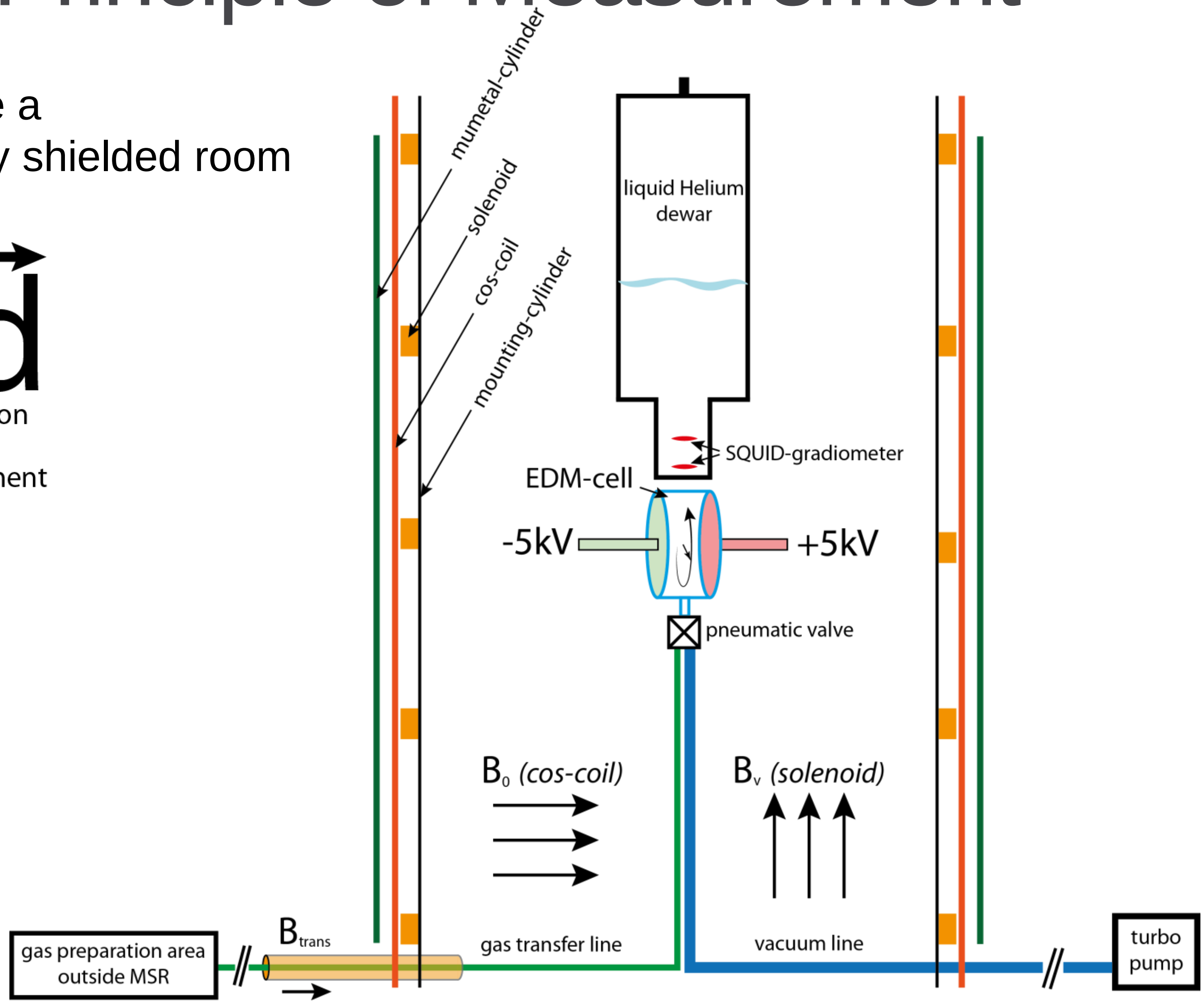
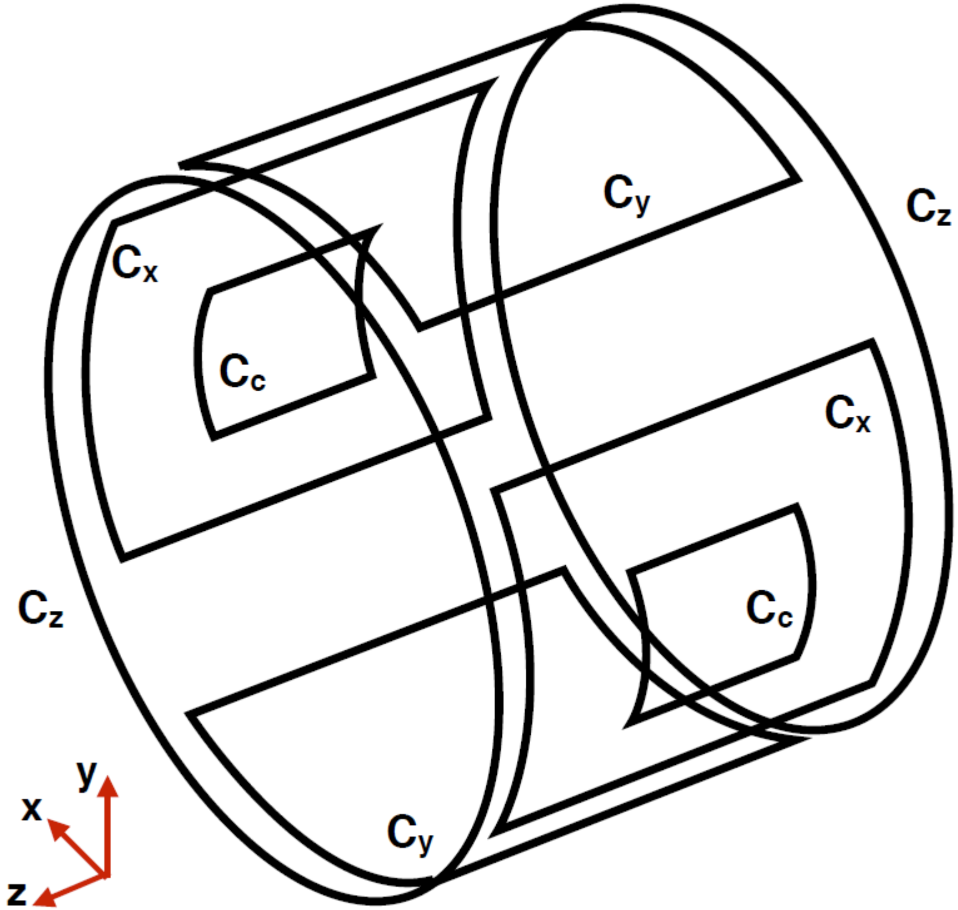


Setup & Principle of Measurement
Additional coils for gradient optimization



Four current sources:

- 16bit resolution
- Range: -5 ... +5 mA

Procedure for gradient optimization: Use T_2* to measure gradients!

- Measure T_2* for five initial settings of the 4-channel current source
- Repeatedly measure T_2* and choose new settings for the current source according to a downhill-simplex algorithm (Nelder-Mead)

➢ This procedure is fully automated
➢ No need to change the setup before or after the optimization, in-situ optimization!

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{4R^4\gamma^2}{175D}\left(\left|\vec{\nabla}B_{1,y}\right|^2 + \left|\vec{\nabla}B_{1,z}\right|^2 + 2\left|\vec{\nabla}B_{1,x}\right|^2\right)$$

Results of automatic gradient optimization

Example: Spherical cell (diameter 10 cm) filled with 30 mbar of polarized ^3He

T2* measurement time: 10 minutes

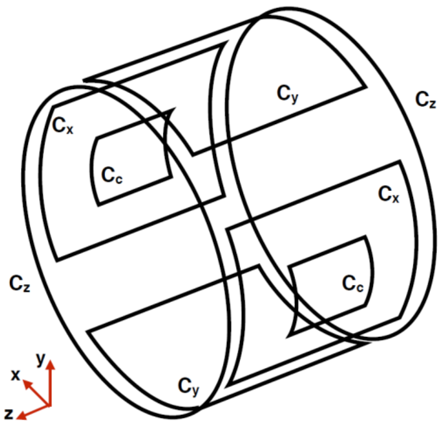
Total measurement time: 4 hours

Iteration	Ch A / mA	Ch B/ mA	Ch C / mA	Ch D / mA	T_2* / s
start	0	0	0	0	7499
0	0	0.15	0	0	9758
1	0.11	0.11	-0.30	0.11	14750
3	0.30	0.30	-0.34	0.01	26590
5	0.33	0.30	-0.60	0.02	35120
13	0.30	0.40	-0.67	0.18	37686

Results

	Ch A / mA	Ch B / mA	Ch C / mA	Ch D / mA	T_2^* / s	effective Gradients (RMS)
start	0	0	0	0	7499	50 pT/cm
end	0.30	0.40	-0.67	0.18	37686	< 10 pT/cm

$$\vec{\nabla} B_{0,x} = \begin{bmatrix} \left(\frac{\partial B_{0,x}}{\partial x}\right)_{res} + \left(\frac{\partial B_{0,x}}{\partial x}\right)_{grad} \\ \left(\frac{\partial B_{0,x}}{\partial y}\right)_{res} + \left(\frac{\partial B_{0,x}}{\partial y}\right)_{grad} \\ \left(\frac{\partial B_{0,x}}{\partial z}\right)_{res} + \left(\frac{\partial B_{0,x}}{\partial z}\right)_{grad} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$



Take currents at optimum to calculate individual gradient components at the starting point:
dominant contributions:

$$\frac{\partial B_{0,x}}{\partial x} = -24\text{pT/cm}$$

$$\frac{\partial B_{0,x}}{\partial z} = 35\text{pT/cm}$$

General gradient relaxation

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{4R^4\gamma^2}{175\ D}\left[a \cdot \left(\left|\vec{\nabla} B_{0,z}\right|^2 + \left|\vec{\nabla} B_{0,y}\right|^2\right) + 2\left|\vec{\nabla} B_{0,x}\right|^2\right]$$

(Cates et al.)

$$a = \frac{175\,D^2}{4R^4\gamma^2 B^2} \times \sum_{n=1} \frac{1}{\left(x_{1n}^2 - 2\right) \cdot \left(1 + D^2 x_{1n}^4 \left(\gamma \cdot B\right)^{-2} R^{-4}\right)}$$

$0 < a \leq 1$.

Sensitivity to different gradient components can be selected by adjusting the partial pressures, e.g.:

1 mbar He: a=0.94

1 mbar He, 2 mbar Xe, 10 mbar N_2: a=0.02

Summary

- Magnetometry using ^{3}He/SQUID (or ^{3}He/CsOPM):
  < 5 fT (or 50 fT) accuracy can be easliy reached during Ramsey cycle
- Measurement and compensation of magnetic field gradients is necessary in many types of experiments.
- gradients of order pT/cm can be measured with high accuracy
- We developed a method to measure and shim gradients in the pT/cm range by using T_2* measurements and shim coils.
- In-situ optimization, fully automated, no need to change the setup!
- T_2* is typically improved by a factor of 5, finally reaching several hours (for ^{3}He) in our experiment.

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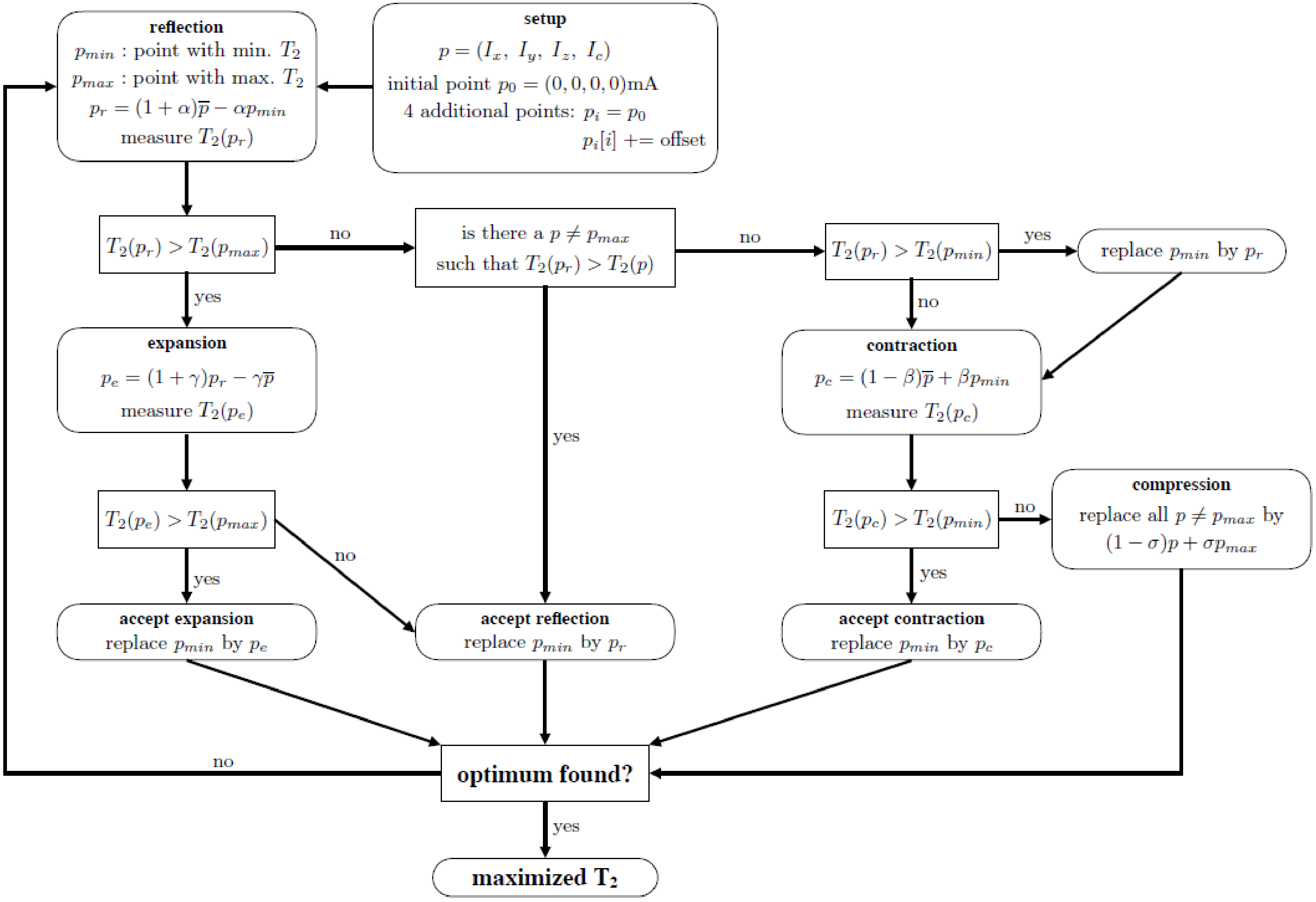
Downhill-simplex algorithm

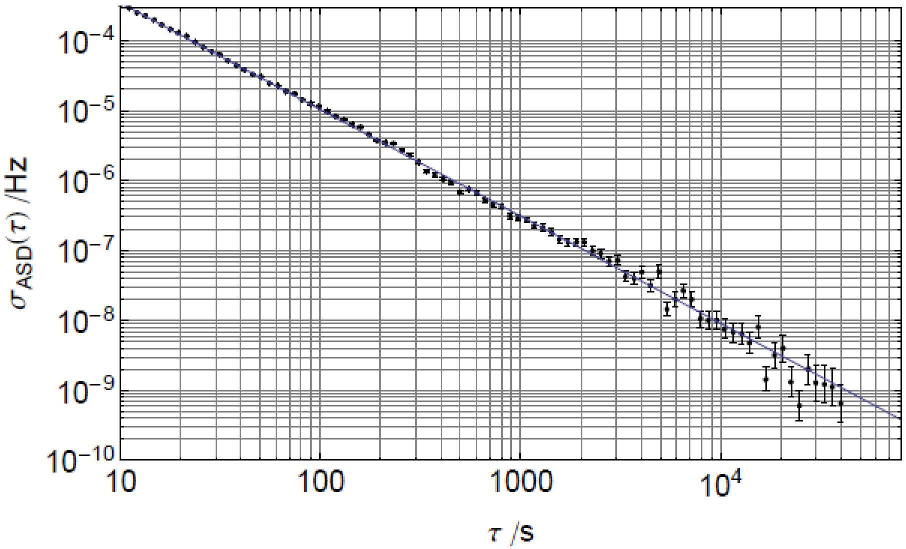


Magnetic Shielding

Requirements:

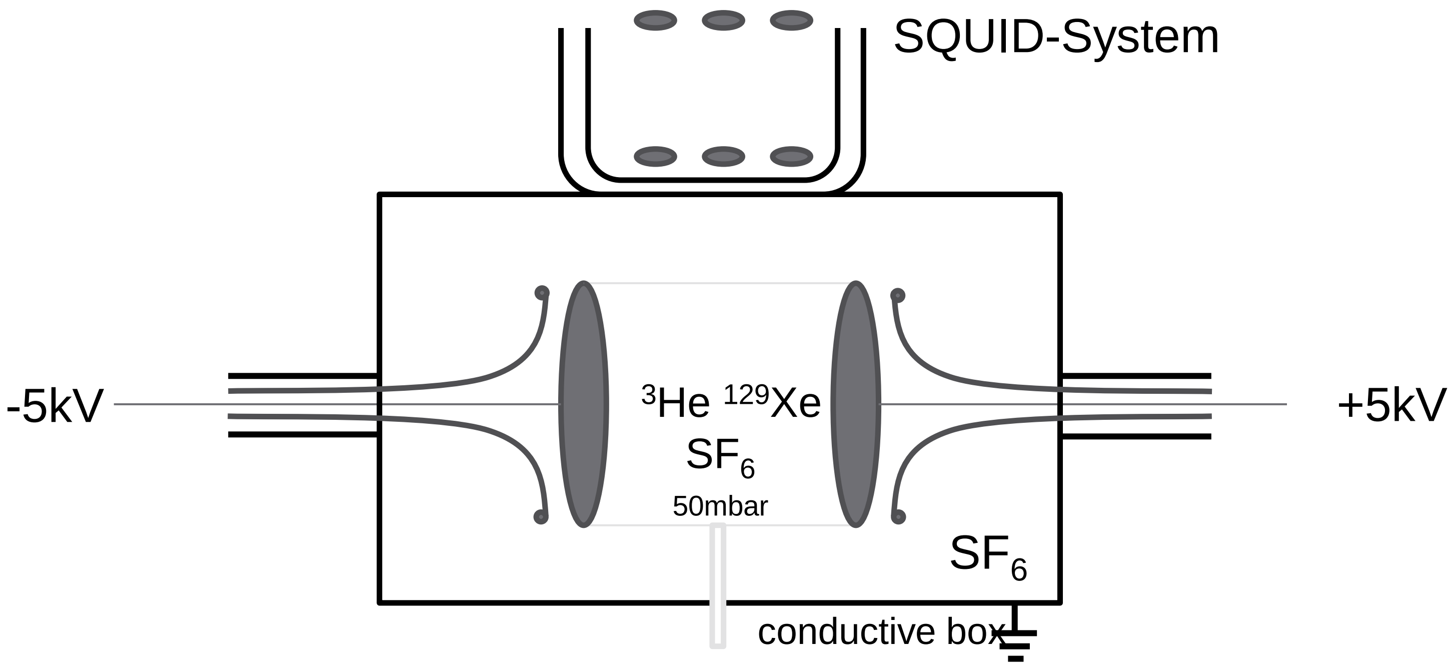
1. Low noise (about 5 fT/Sqrt(Hz) @ 10 Hz)
2. Low gradients (about 10 pT/cm)

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{4R^4\gamma^2}{175D}\left(\left|\vec{\nabla}B_{1,y}\right|^2 + \left|\vec{\nabla}B_{1,z}\right|^2 + 2\left|\vec{\nabla}B_{1,x}\right|^2\right)$$



$$\sigma_f^2 \geq \frac{12}{(2\pi)^2 \left(A/\rho_\alpha\right)^2 T^3} C.$$

Basic setup


SQUID-System
-5kV
+5kV
3He 129Xe
SF6
50mbar
SF6
conductive box