# Measurement of the $^{129}$Xe Electric Dipole Moment

Fabian Allmendinger

Phys. Rev. A **100** (2019). DOI: 10.1103/PhysRevA.100.022505

**Physikalisches Institut, Universität Heidelberg:**
F. Allmendinger, U. Schmidt, B. Brauneis, J. Tremmel

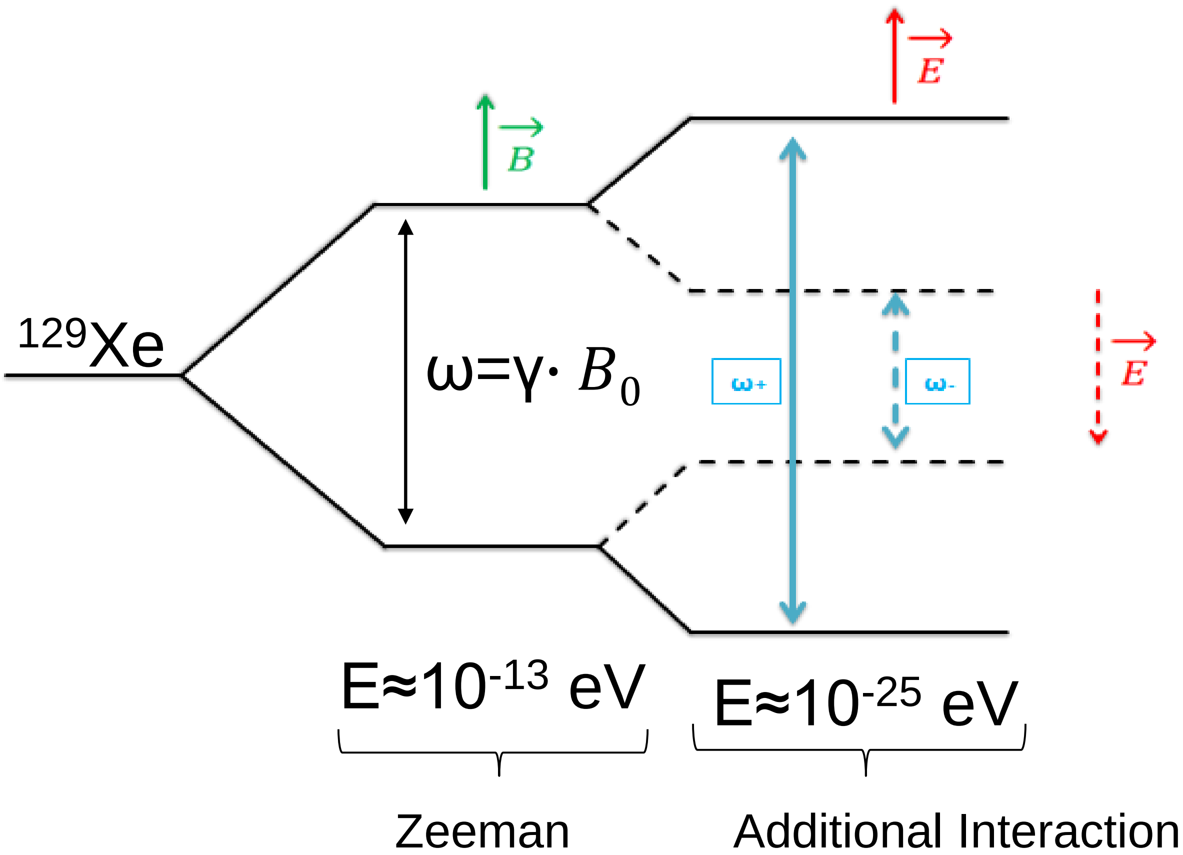
**Institut für Physik, Universität Mainz**
W. Heil, B. Niederländer, S. Karpuk, M. Repetto, S. Zimmer

**Forschungszentrum Jülich**
I. Engin, H.-J. Krause, A. Offenhäuser

# Principle of Measurement

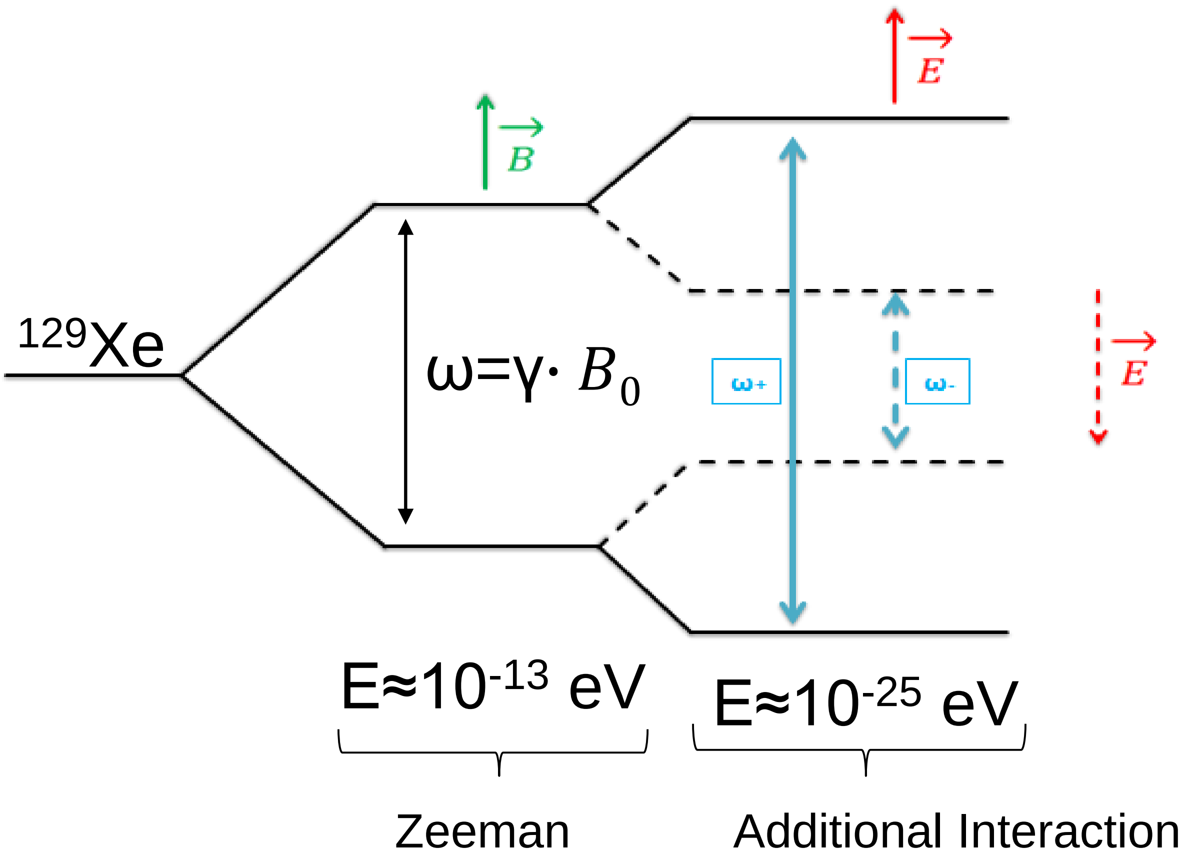
Method: free spin precession frequency measurements of gaseous, nuclear polarized $^{129}Xe$

$$H = -(\vec{\mu}\vec{B} + \vec{d}\vec{E})$$



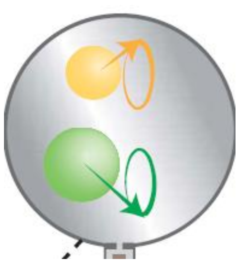
# Principle of Measurement

Use co-magnetometry, $^{129}$Xe and $^{3}$He, to become independent of drifts of the magnetic guiding field $B_0$




$$\Delta\omega = \omega_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}}\omega_{He}$$

$$\Delta\phi = \phi_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}}\phi_{He}$$



# EDM Sensitivity

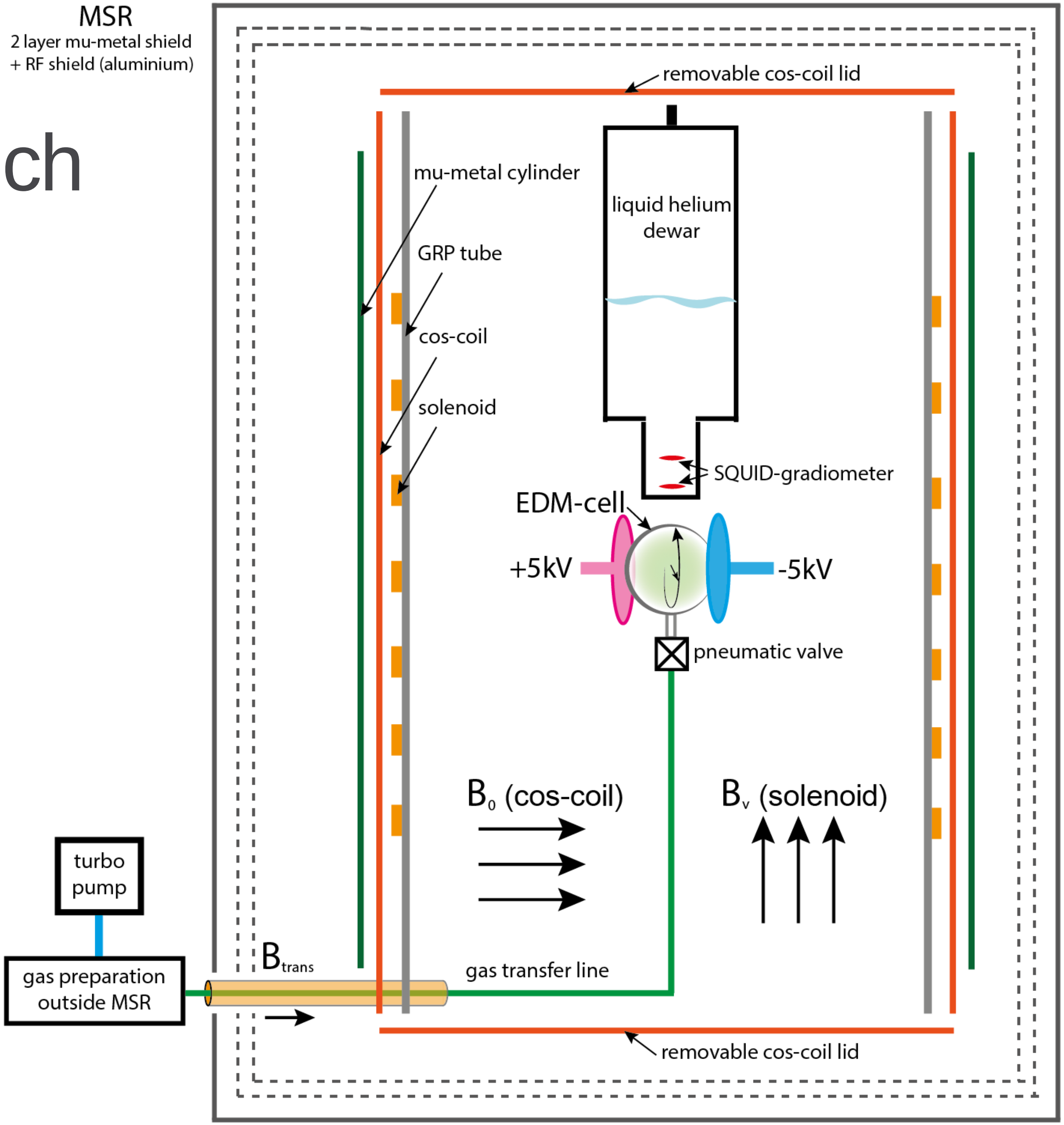
- EDM resolution

$$\sigma_d \sim \frac{1}{E_z} \cdot \frac{1}{SNR} \cdot \frac{1}{T^{3/2}}$$

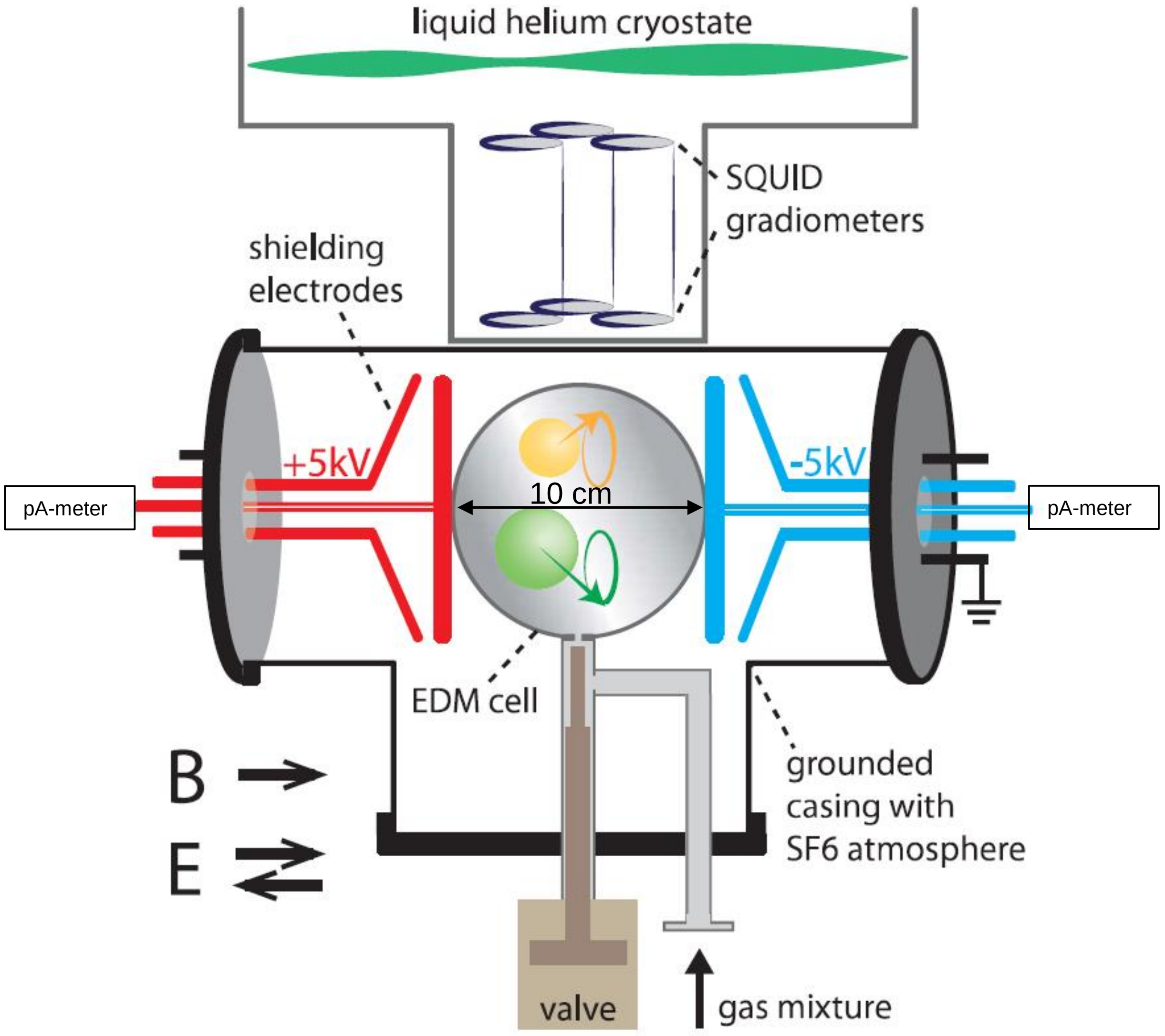
- $E_z$: electric field
- $SNR$ : signal to noise ratio
- $T$ : measurement time of coherent spin precession
- Spin coherence time is (partially) determined by magnetic field gradients

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

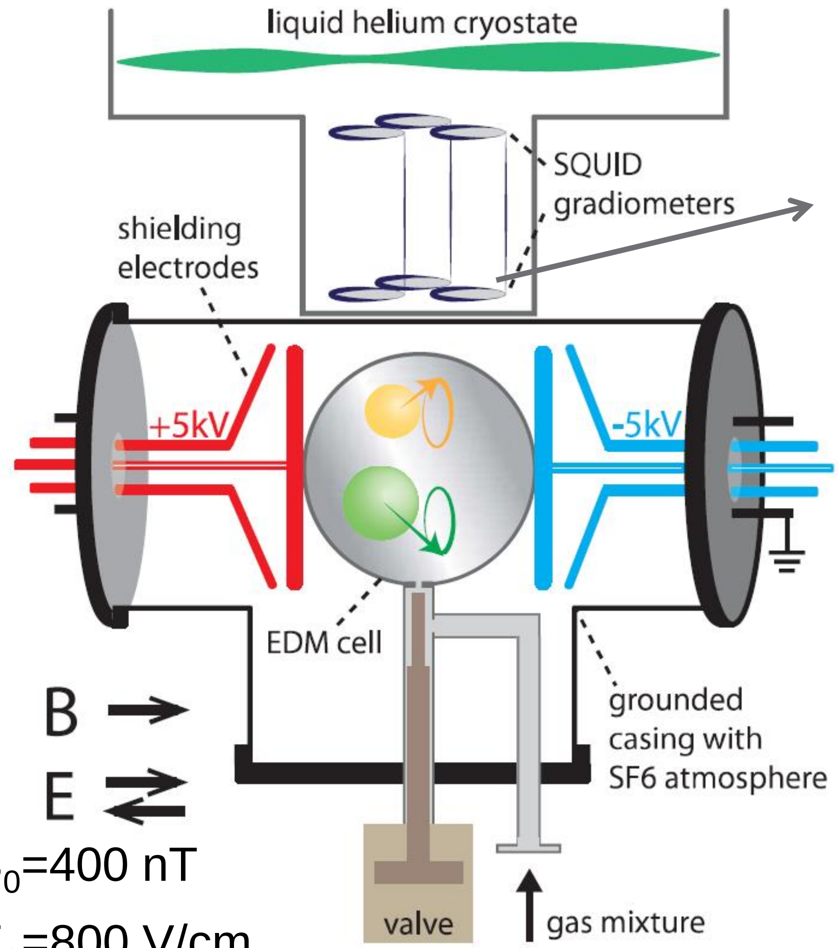
# Setup @ FZ Jülich



# Setup


liquid helium cryostate
SQUID gradiometers
shielding electrodes
+5kV
-5kV
10 cm
pA-meter
pA-meter
EDM cell
B
E
grounded casing with SF6 atmosphere
valve
gas mixture

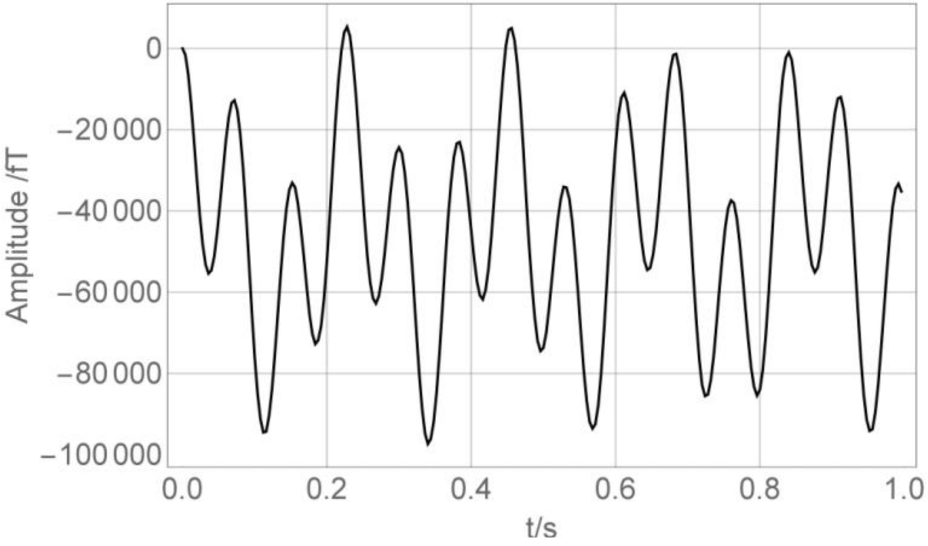
# Procedure of an EDM run

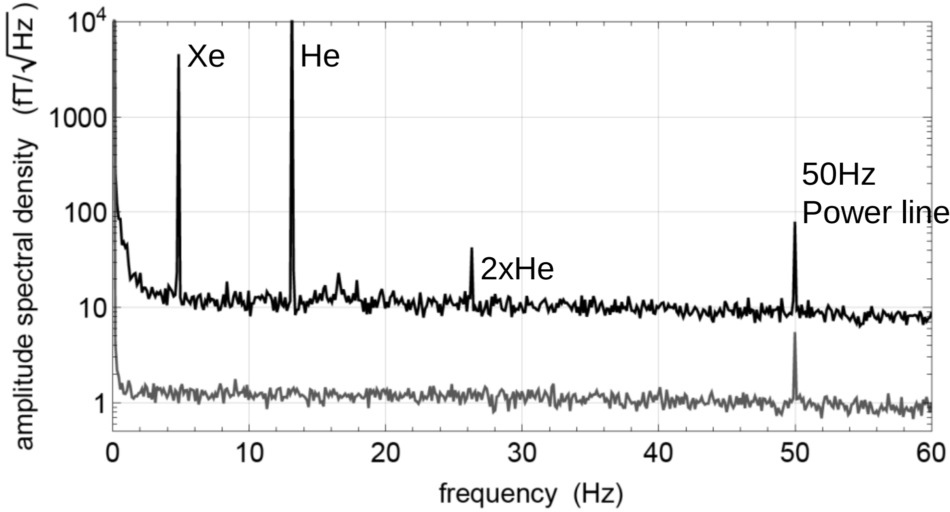



$B_0$=400 nT

$E_0$=800 V/cm,
periodically inverted

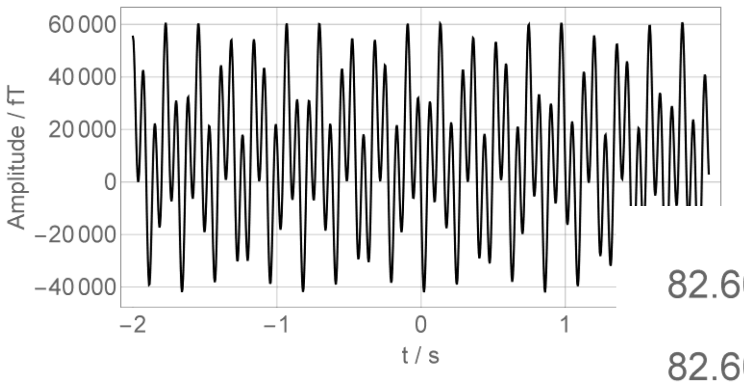
Recorded signal

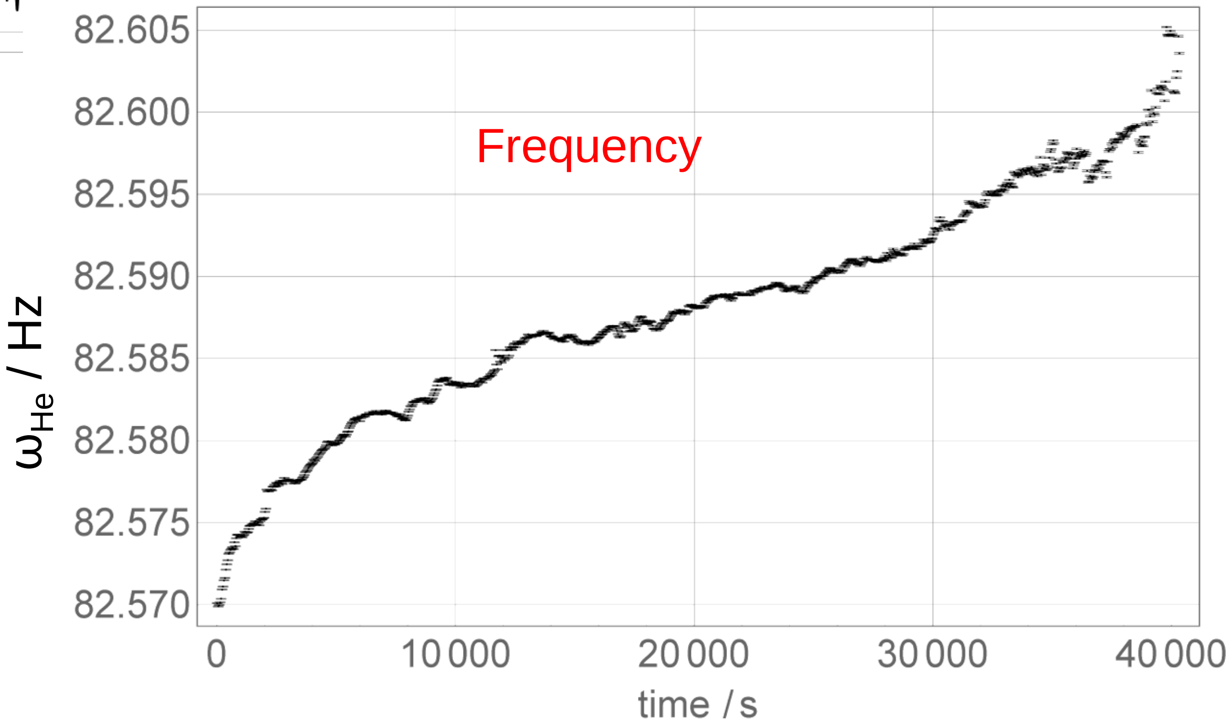


# Data evaluation

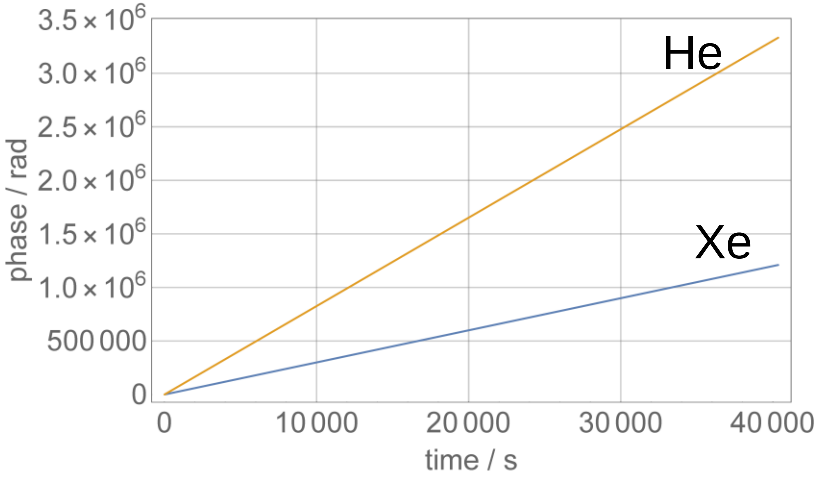
Fit to segments (4 s) to extract amplitudes, frequencies and phases



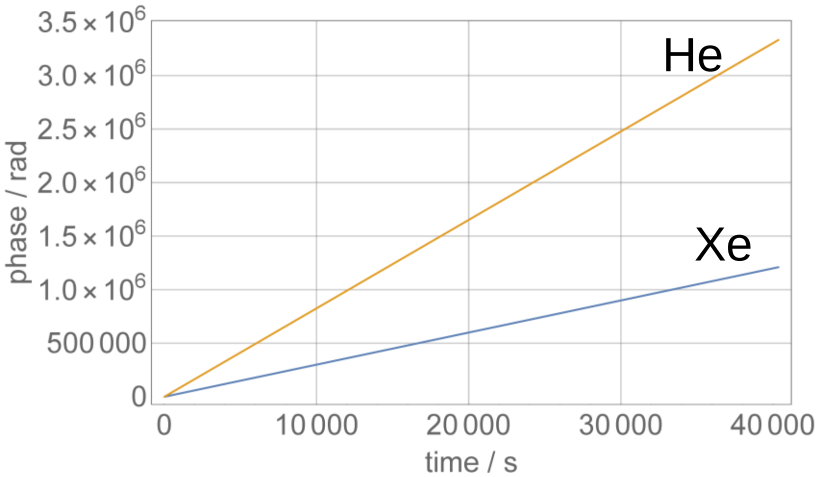
# Data evaluation

## 1. Step: Phases

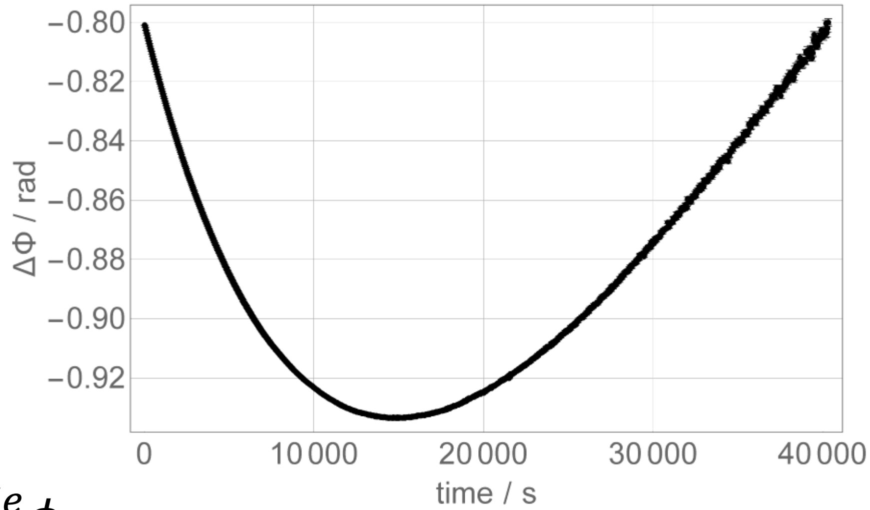


# Data evaluation

1. Step: Phases



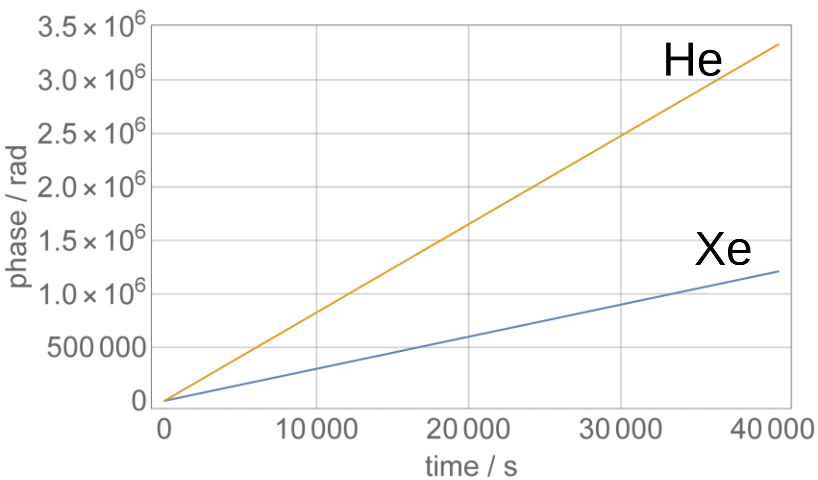

2. Step: Weighted phase difference



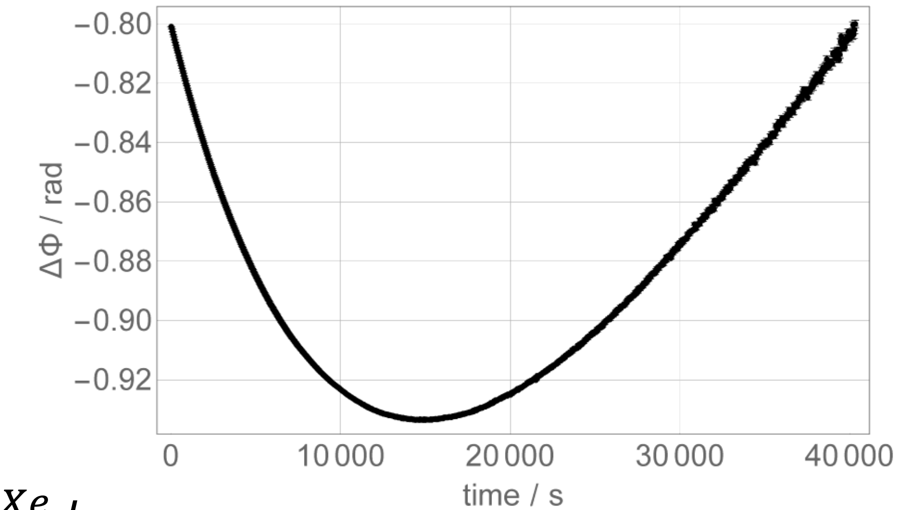

$$\Delta\phi = \phi_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}}\phi_{He}$$

# Data evaluation

1. Step: Phases




2. Step: Weighted phase difference

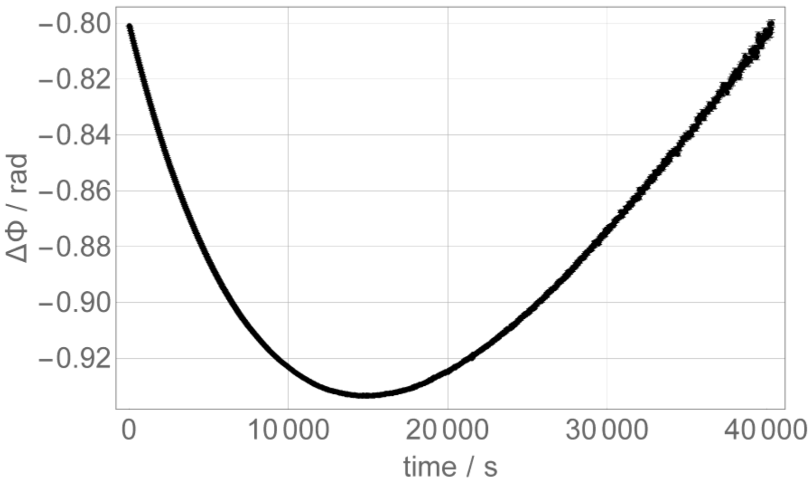



$$\Delta\phi = \phi_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}}\phi_{He}$$

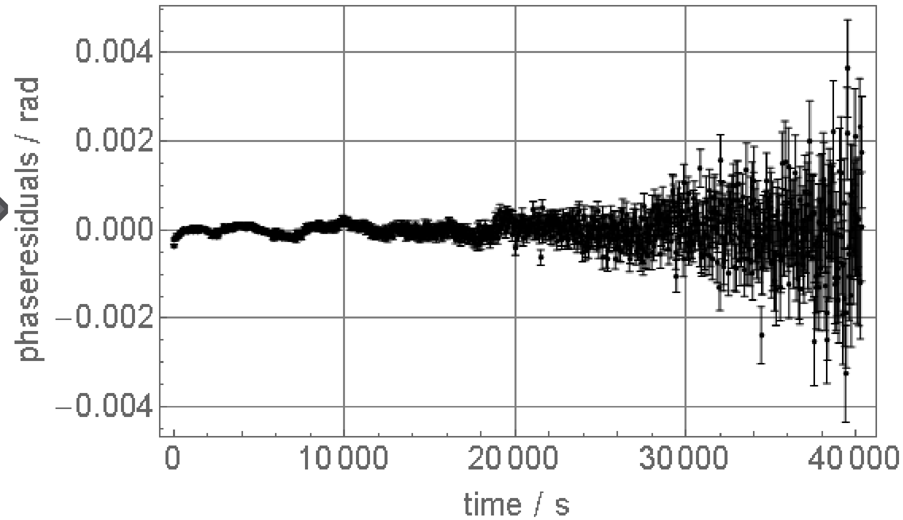
- Linear term
  - Chemical Shift
  - Earth rotation
- Four exponential terms
  - Ramsey-Bloch-Siegert shift

# Data evaluation:

## 3. Step: Fit to weighted phase difference to extract EDM



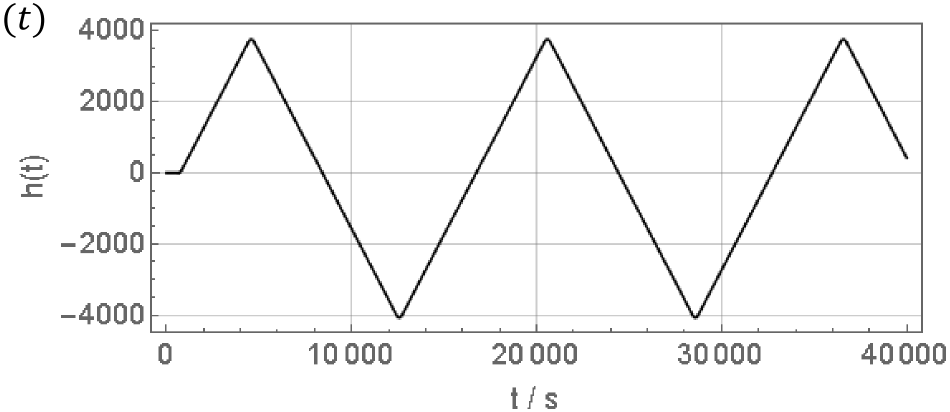

Weighted phase difference




Phase residuals

$$\Delta\phi(t) = a + b \cdot t + E_{He} \cdot \mathrm{Exp}\left[-\frac{t}{T_2{}^{He}}\right] + E_{Xe} \cdot \mathrm{Exp}\left[-\frac{t}{T_2{}^{Xe}}\right] + F_{He} \cdot \mathrm{Exp}\left[-\frac{2t}{T_2{}^{He}}\right] + F_{Xe} \cdot \mathrm{Exp}\left[-\frac{2t}{T_2{}^{Xe}}\right]$$

$$+ g \cdot h(t)$$

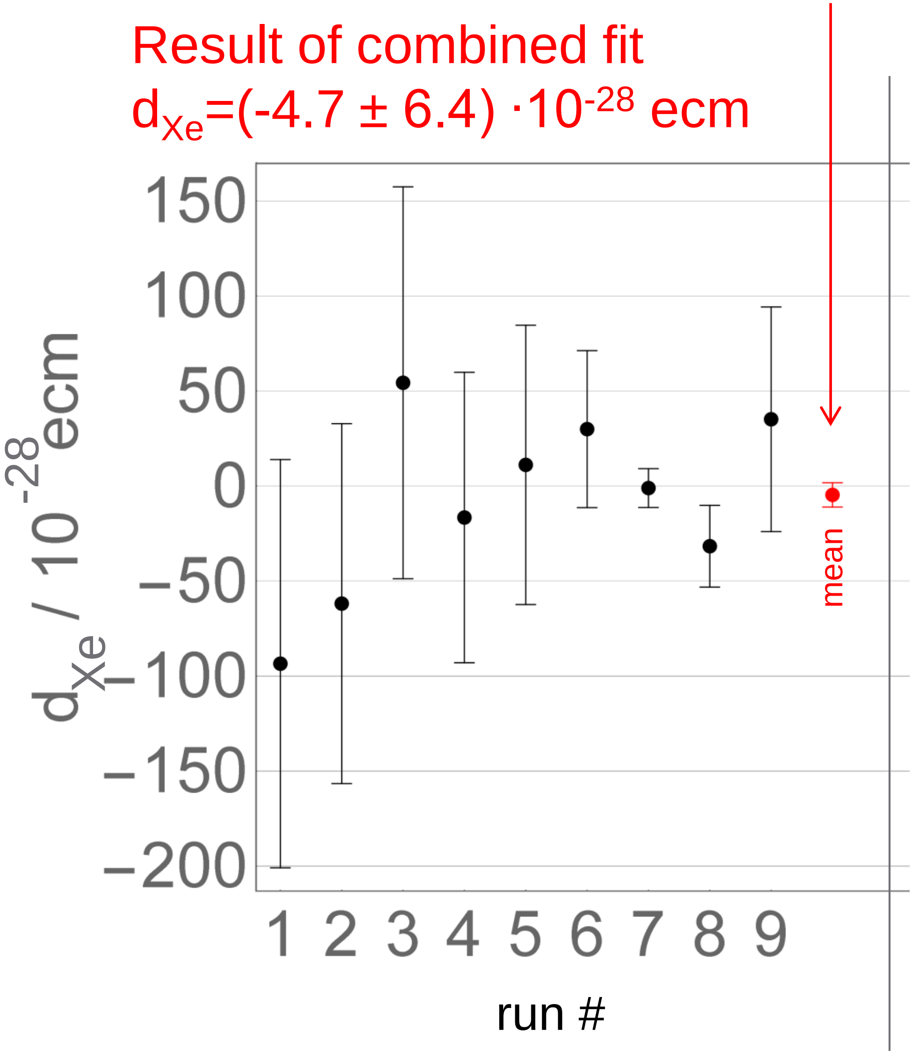



Correlation between fit parameters increases EDM error substantially!

# Xe-EDM results

Result of combined fit

$d_{Xe}$=(-4.7 ± 6.4) ·$10^{-28}$ ecm



# Xe-EDM results

Result of combined fit

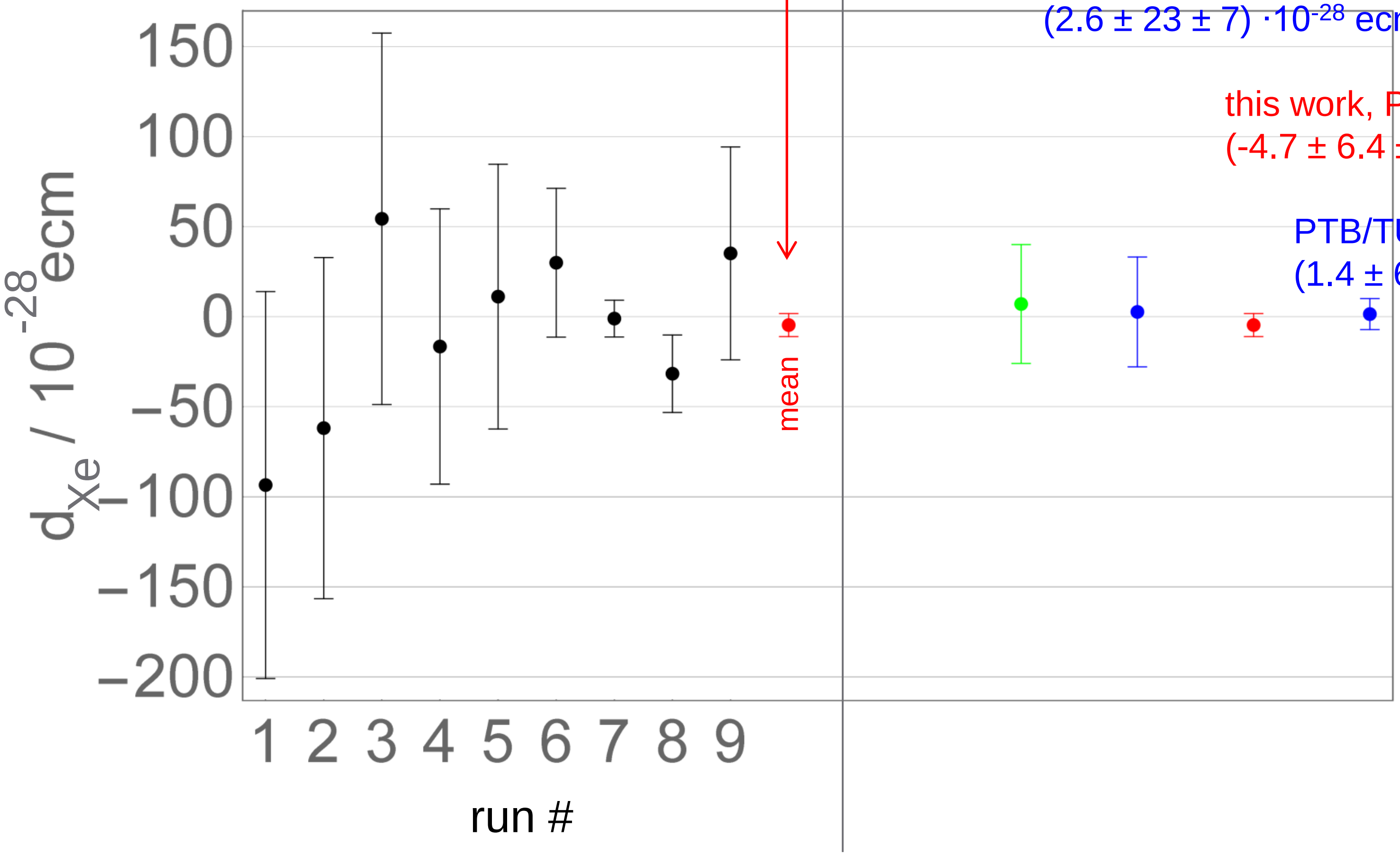
$d_{Xe}=(-4.7 \pm 6.4) \cdot 10^{-28}$ ecm

Rosenberry and Chupp, PRL 86 (2001):
$(7 \pm 33) \cdot 10^{-28}$ ecm

PTB/TUM, arXiv (Feb. 2019):
$(2.6 \pm 23 \pm 7) \cdot 10^{-28}$ ecm

this work, PRA 100 (Aug. 2019):
$(-4.7 \pm 6.4 \pm 0.1) \cdot 10^{-28}$ ecm

PTB/TUM, PRL 123 (Oct. 2019):
$(1.4 \pm 6.6 \pm 2.0) \cdot 10^{-28}$ ecm



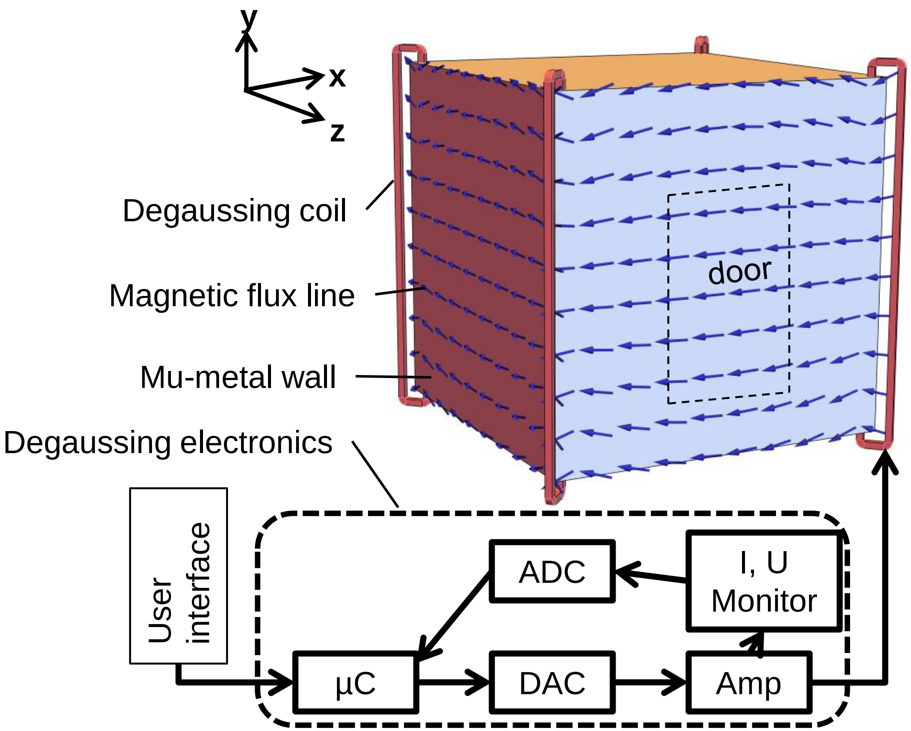
# New Setup @ PI Heidelberg

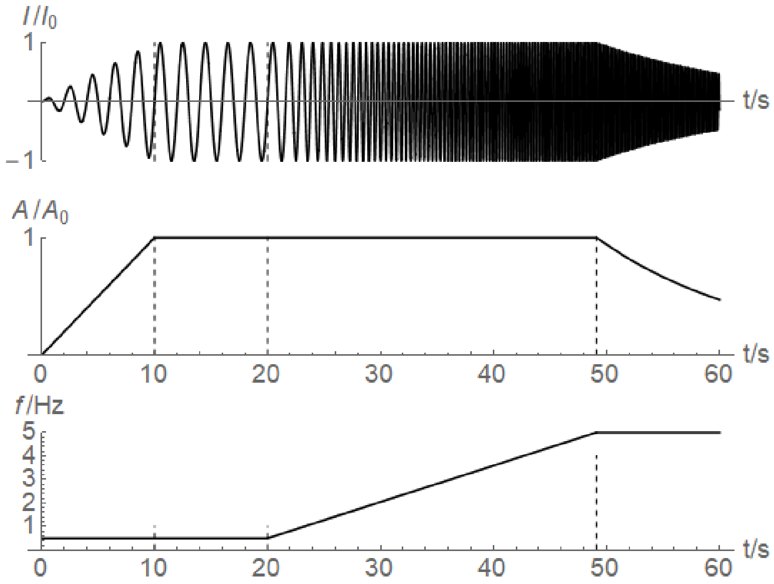
# New Setup @ PI Heidelberg

Magnetically Shielded Room (MSR):

- Build by Vacuumschmelze
- Outer dimensions: 3m x 3m x 3m
- 3 Mu-metal layers à 3mm
- 1 Eddy-current layer (HF shield)

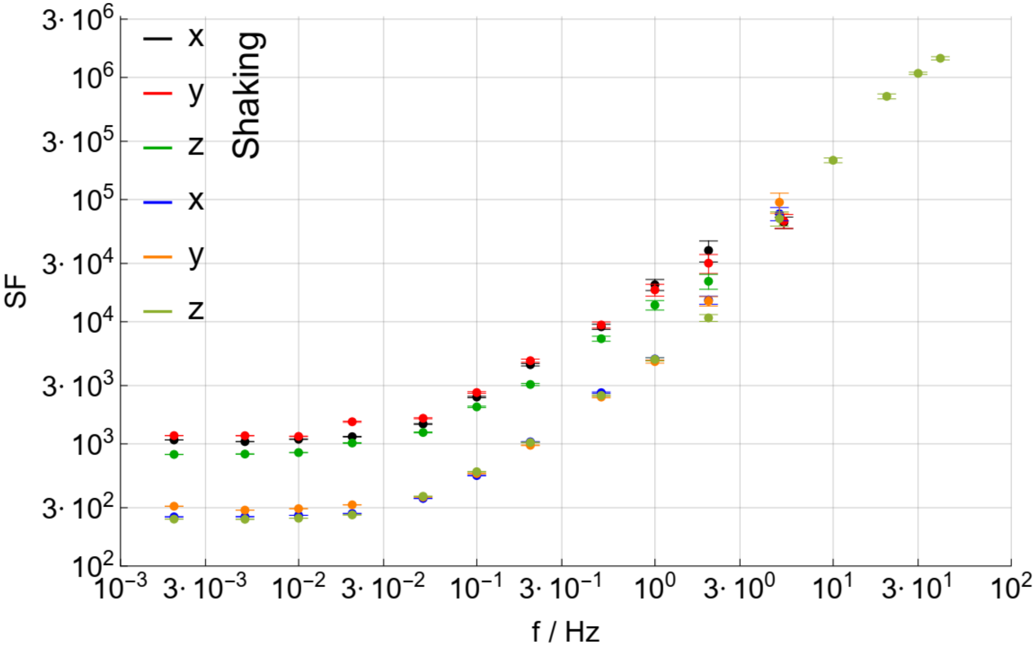
# Degaussing Procedure



# MSR performance

- Residual field < 1 nT
- Residual field homogeneity in central volume: gradients < 10pT/cm
- Shielding factor:




**Degaussing Procedure and Performance Enhancement by Low-Frequency Shaking of a 3-Layer Magnetically Shielded Room**
F. Allmendinger, B. Brauneis, W. Heil, U. Schmidt, Rev. Sci. Instrum. 94, 115105 (2023), DOI: 10.1063/5.0167663

# New Setup @ PI Heidelberg

Frame for coil system (main and gradient field)

Dewar with lTc-SQUIDs

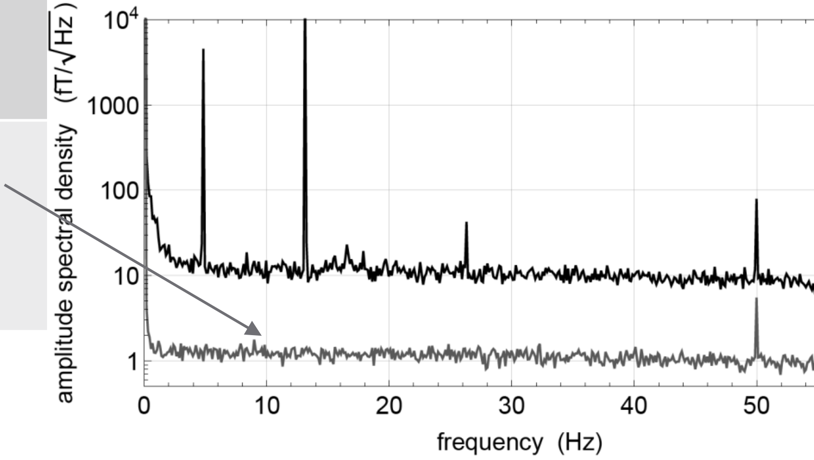
Mu-metal layers

HF shield

# Improvements (established methods)

$$\sigma_d \sim \frac{1}{E_z} \cdot \frac{1}{SNR} \cdot \frac{1}{T^{3/2}}$$

| Measure | Factor |
|---|---|
| Increase the electric field strength (now: E=800 V/cm) | 4 |
| Increase Xe and He pressure | 2 |
| Improve spin coherence time due to active gradient minimization | 2 |
| Reduced noise level inside new MSR | 10 |
| Combined: | 160 |

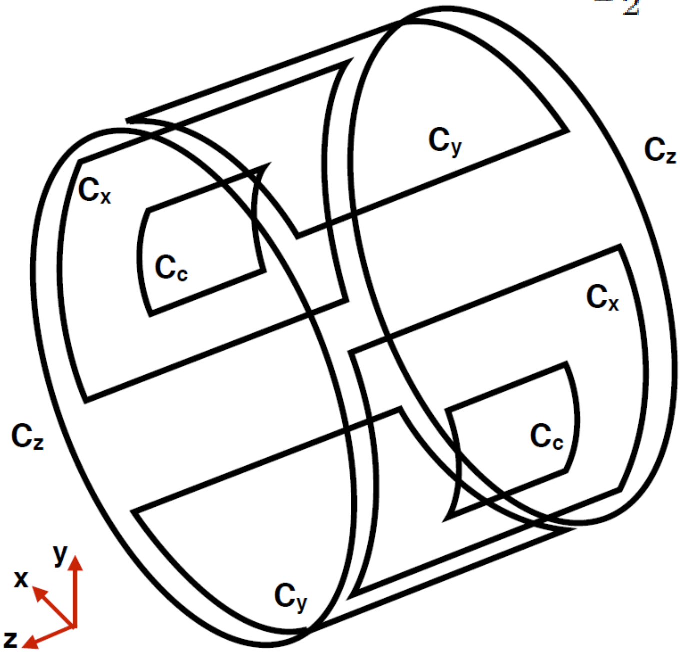



Expected EDM resolution: $1 \cdot 10^{-29}$ ecm
(statistical uncertainty)

# Additional coils for gradient compensation @ FZ Jülich

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

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




Four current sources:

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

# Results of automatic gradient compensation @ FZ Jülich

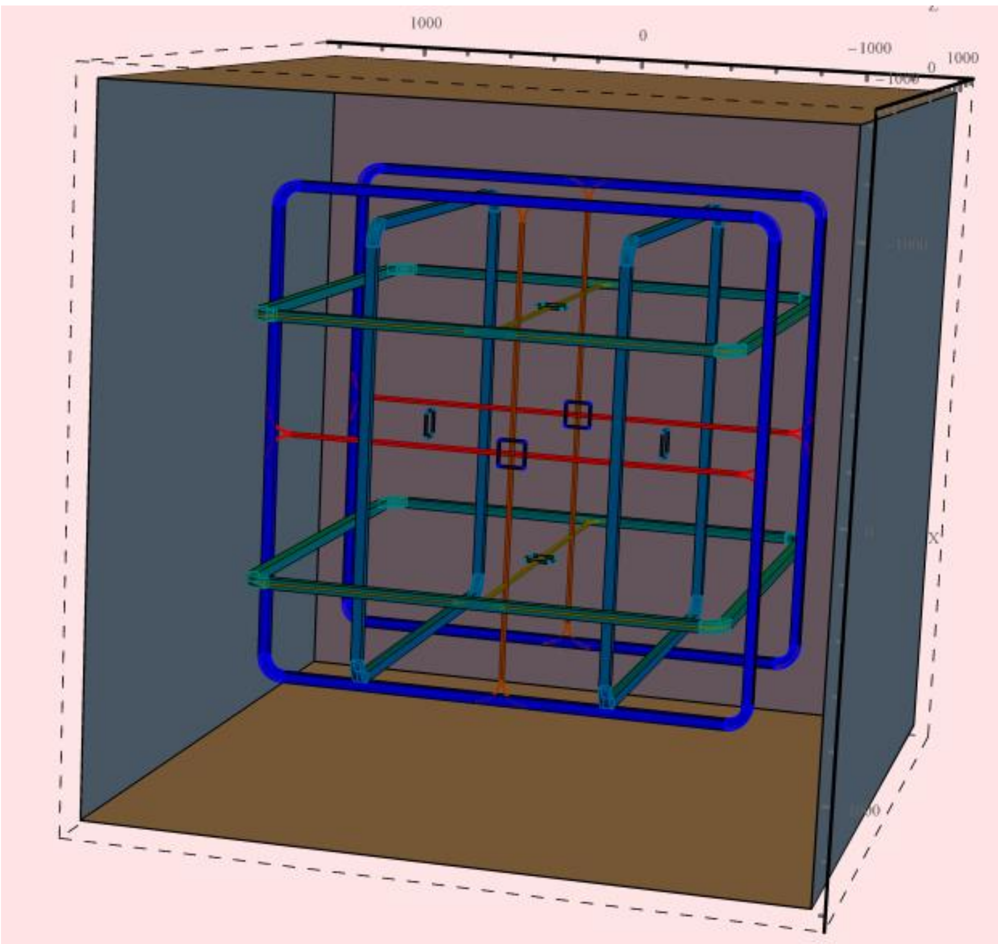
Example: Spherical cell (diameter 10 cm) filled with 30 mbar of polarized $^{3}He$

$T_2$* measurement time: 10 minutes

Total measurement time: 4 hours

| Iteration | $C_x$ / mA | $C_y$ / mA | $C_z$ / mA | $C_c$ / mA | Spin coherence time $T_2$* / s | effective Gradients |
|---|---|---|---|---|---|---|
| start | 0 | 0 | 0 | 0 | 7499 | 50 pT/cm |
| 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 | < 10 pT/cm |

# Additional coils for gradient compensation @ PI Heidelberg




Five gradient coils with current sources:

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

All five degrees of freedom of the linear gradient matrix

# Summary

- Measurement of the CP-violating Electric Dipole Moment of $^{129}Xe$ using comagnetometry (with $^{3}He$)
- Setup @ FZ Jülich
  - Result: $d=(-4.7 \pm 6.4) \cdot 10^{-28}$ ecm improves best $^{129}Xe$ EDM limit
  - **Measurement of the permanent electric dipole moment of the 129Xe atom,** F. Allmendinger, I. Engin, W. Heil, S. Karpuk, H.-J. Krause, B. Niederländer, A. Offenhäusser, M. Repetto, U. Schmidt, and S. Zimmer, Phys. Rev. A 100 (2019). DOI: 10.1103/PhysRevA.100.022505
- Setup @ Heidelberg
  - New MSR with improved performance
  - **Degaussing Procedure and Performance Enhancement by Low-Frequency Shaking of a 3-Layer Magnetically Shielded Room** F. Allmendinger, B. Brauneis, W. Heil, U. Schmidt, Rev. Sci. Instrum. 94, 115105 (2023), DOI: 10.1063/5.0167663
  - Two orders of magnitude can be gained by established methods

**Physikalisches Institut, Universität Heidelberg:**
F. Allmendinger, U. Schmidt,
B. Brauneis, J. Tremmel

**Institut für Physik, Universität Mainz**
W. Heil, B. Niederländer,
S. Karpuk, M. Repetto,
S. Zimmer

**Forschungszentrum Jülich**
I. Engin, H.-J. Krause,
A. Offenhäuser