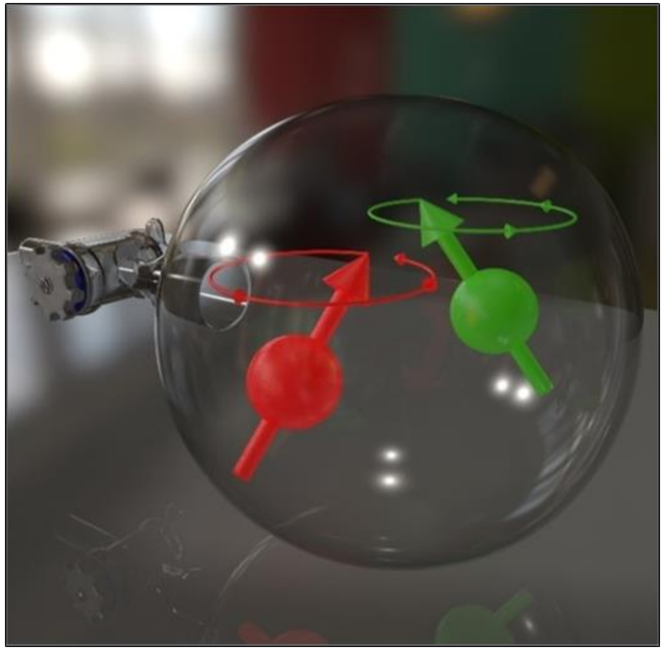
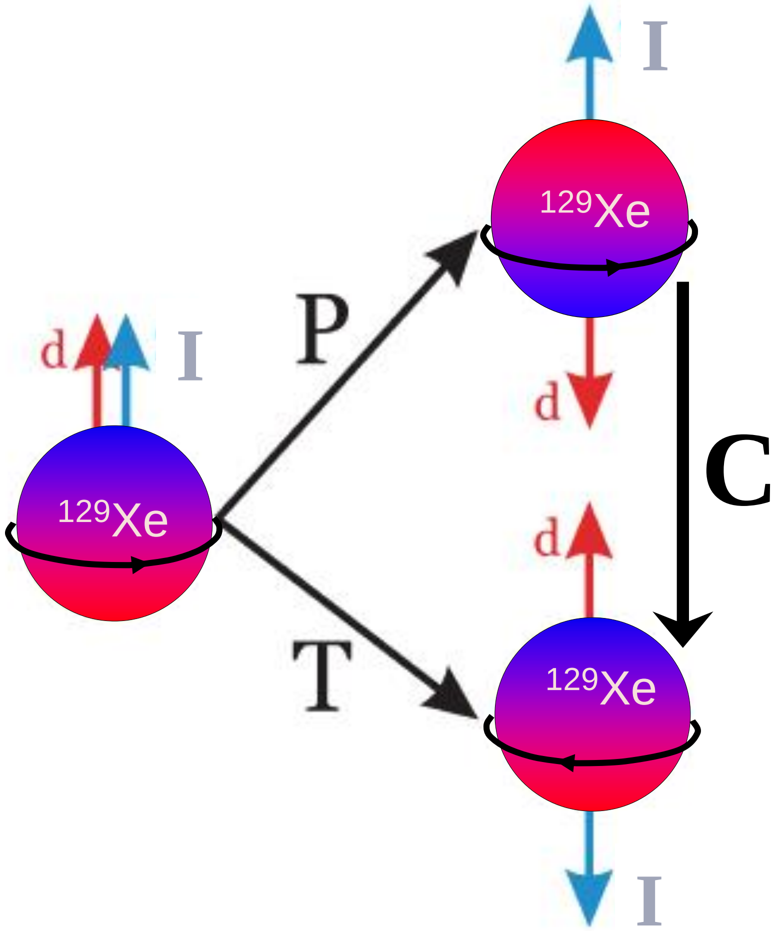
"Xenon is the best atom"
Measurement of the atomic EDM of ^{129}Xe



HeXe-Collaboration

Mainz
Jülich
Heidelberg

Ulrich Schmidt
Physikalisches Institut
Uni Heidelberg



Outline

- The ^{129}Xe-^{3}He-Comagnetometer
- Setup of the ^{129}Xe atomic EDM at Jülich (MIXed-collaboration)
- Results of ^{129}Xe atomic EDM measurements at Jülich

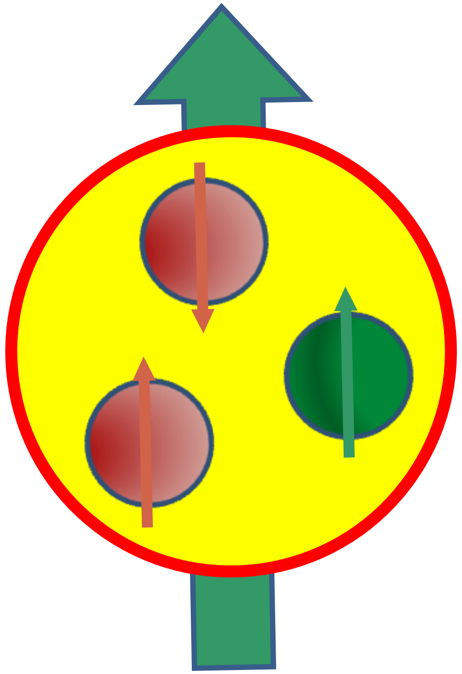
Status: Setup at Heidelberg

- The MSR (Magnetically shielded room)
- Outlook

^{3}He-^{129}Xe-Comagnetometer

Nuclear spin properties:

"First order" nuclear structure:
Both nuclei have one unpaired neutron, which accounts for the nuclear spin. All other nucleons are paired with antiparallel spins $\rightarrow \quad J = \frac{1}{2}$



$$\mu_n = -1.913\mu_N$$

$$\mu_{^3He} = -2.1276\mu_N$$

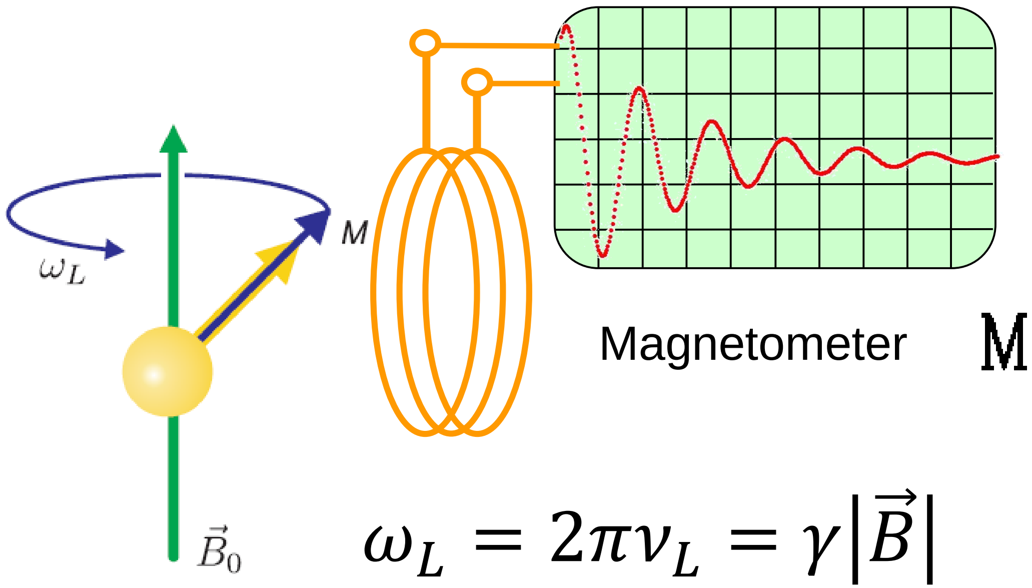
$$\mu_{^{129}Xe} = -0.7779\mu_N$$

^{3}He polarization
Optical pumping of metastable ^{3}He*-atoms (MEOP)

^{3}He and ^{129}Xe polarization
Spin exchange with optically pumped Rb-vapour (SEOP)

Free induction decay

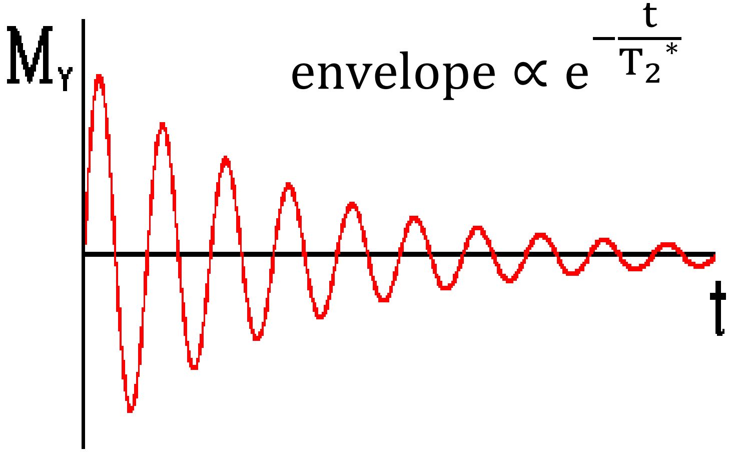
Polarized nuclear spins generate a macroscopic magnetic moment which precesses around a static B-field B_0



$$\omega_L = 2\pi\nu_L = \gamma\left|\vec{B}\right|$$

(G. D. Cates, et al., Phys. Rev. A 37, 2877)

Example:
Nuclear **M**agnetic **R**esonance

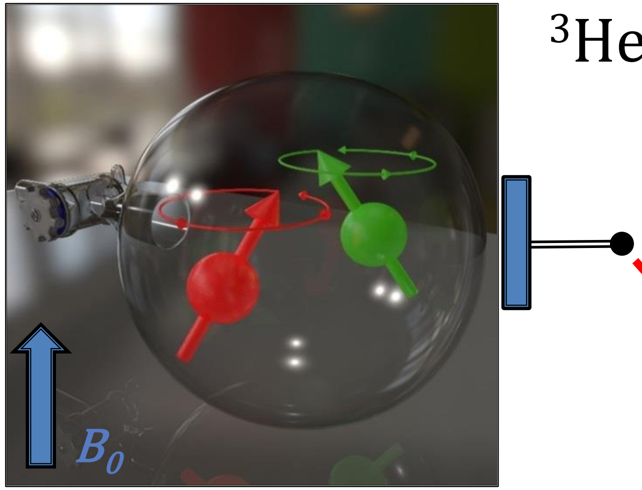


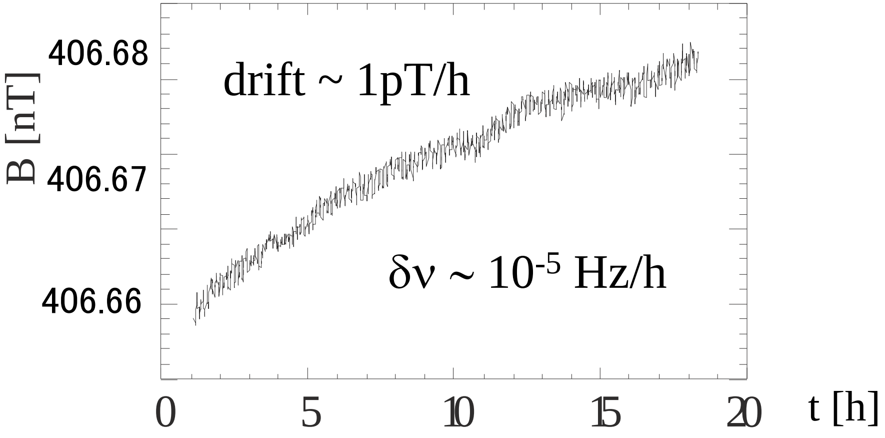
$$\text{envelope} \propto e^{-\frac{t}{T_2{}^*}}$$

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{1}{T_{2,\text{field}}}$$

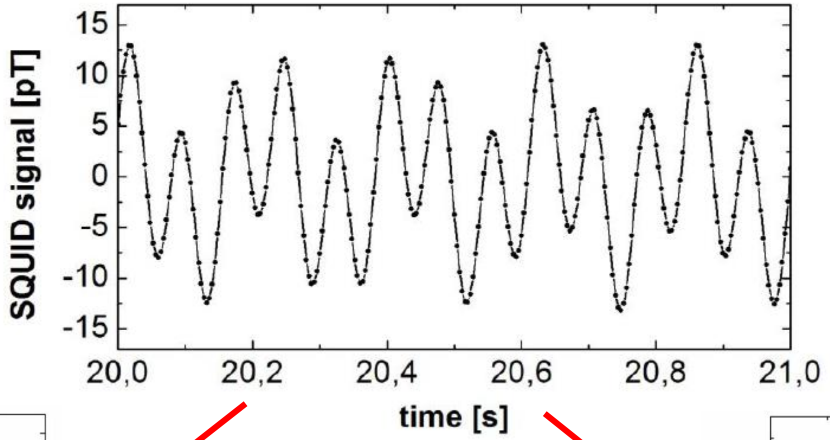
$$\frac{1}{T_{2,\text{field}}} \approx \frac{4R^4\gamma^2}{175D}\left(\left|\vec{\nabla}B_{1,z}\right|^2 + \left|\vec{\nabla}B_{1,y}\right|^2 + 2\left|\vec{\nabla}B_{1,x}\right|^2\right) \propto R^4 \cdot p \cdot \left|\vec{\nabla}B\right|^2$$

$^{3}He^{129}Xe$-Comagnetometer

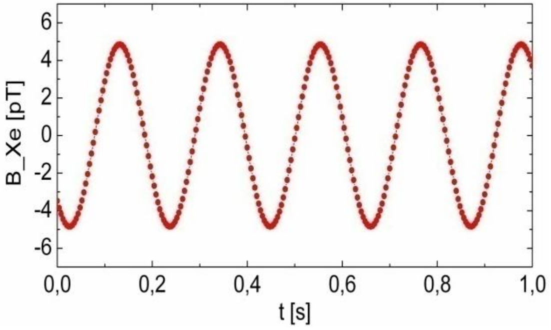




$$\omega_L = 2\pi\nu_L = \gamma\left|\vec{B}\right|$$

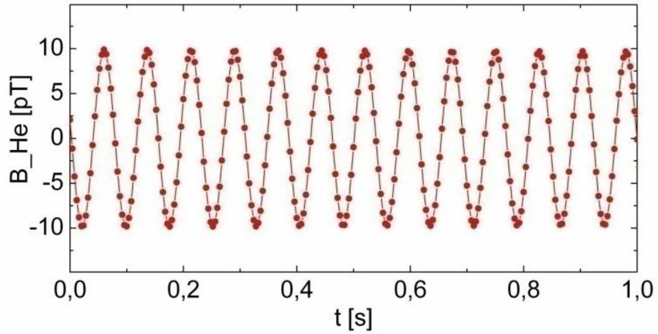


^{129}Xe **(4,7 Hz)**

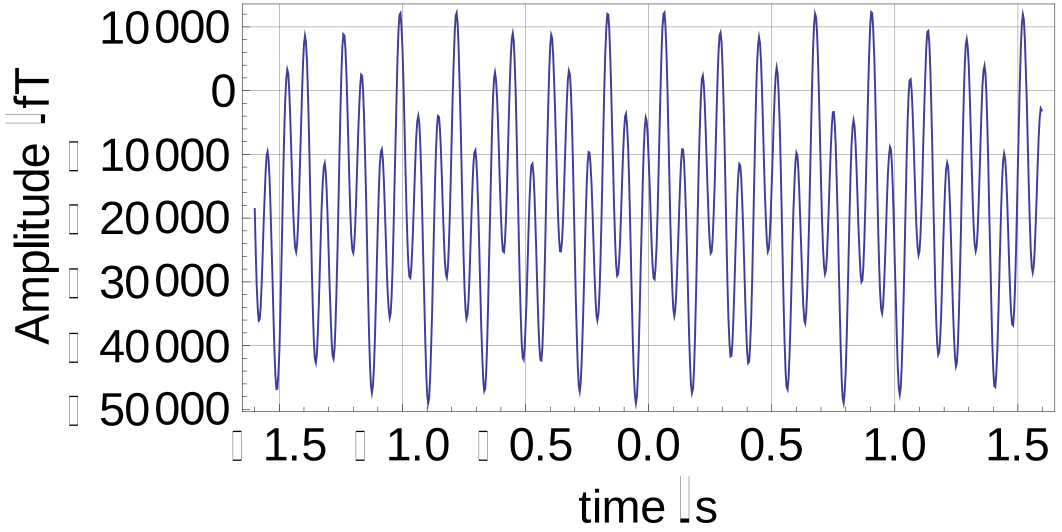


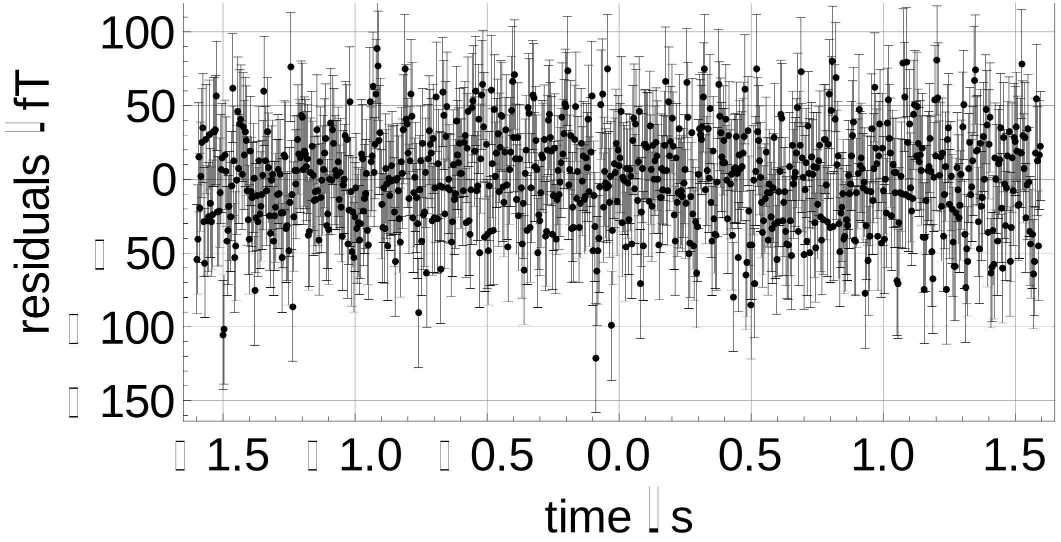
$$\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe} = \; const.$$

^{3}He **(13 Hz)**



$$B_S(t) = c_{He} \cdot \cos(\omega_{He} t) + s_{He} \cdot \sin(\omega_{He} t) + c_{Xe} \cdot \cos(\omega_{Xe} t) + s_{Xe} \cdot \sin(\omega_{Xe} t) + c_{lin} \cdot t + c_{const}$$

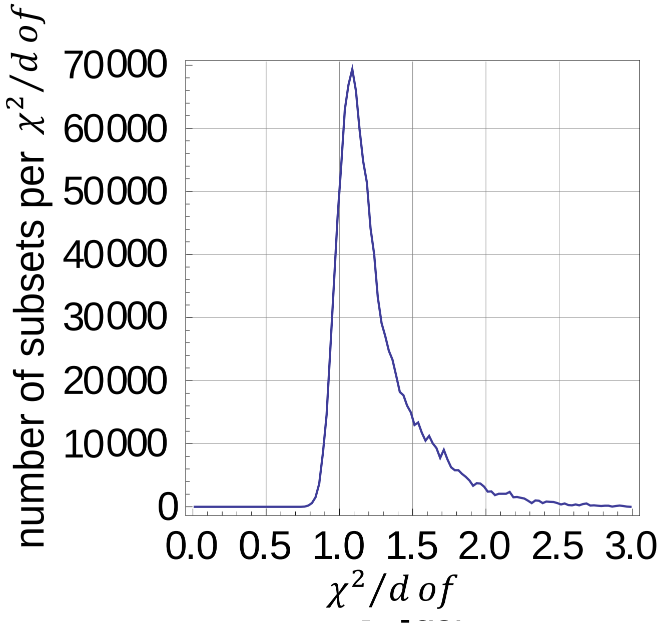




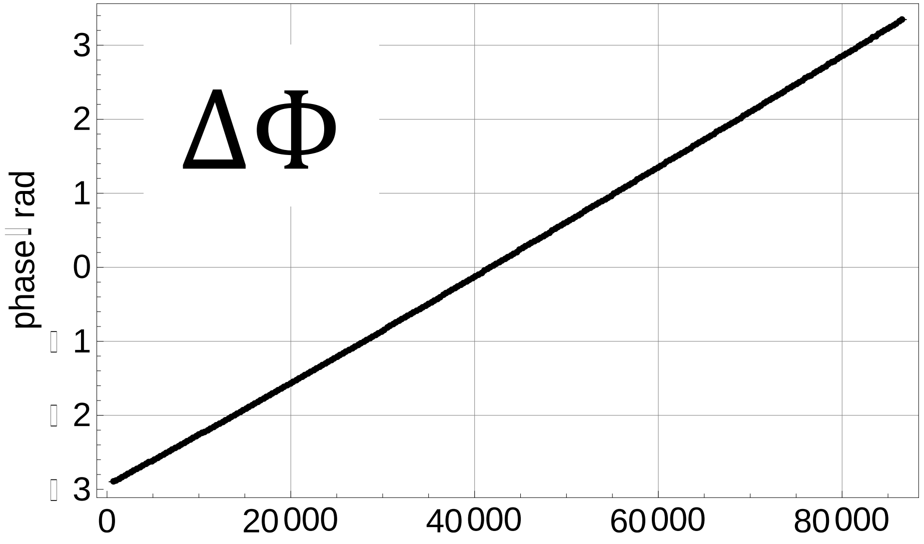
Fitting subset

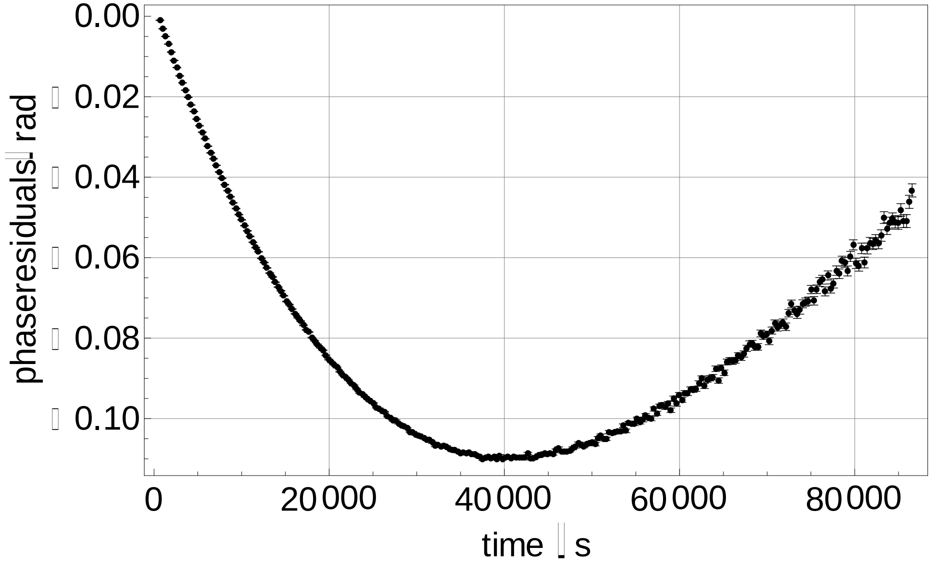
subset left:

χ^2/dof = 1.03



Subtraction of deterministic phase shifts





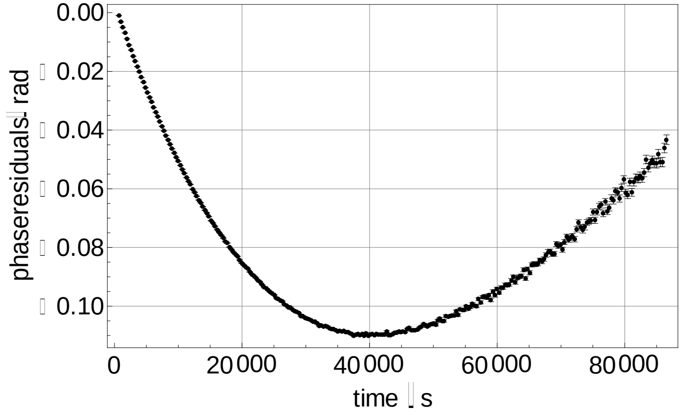
$$\Phi_{He} = 2\pi \cdot 12\text{Hz} \cdot 1\text{day}$$
$$= 6.5 \cdot 10^6$$

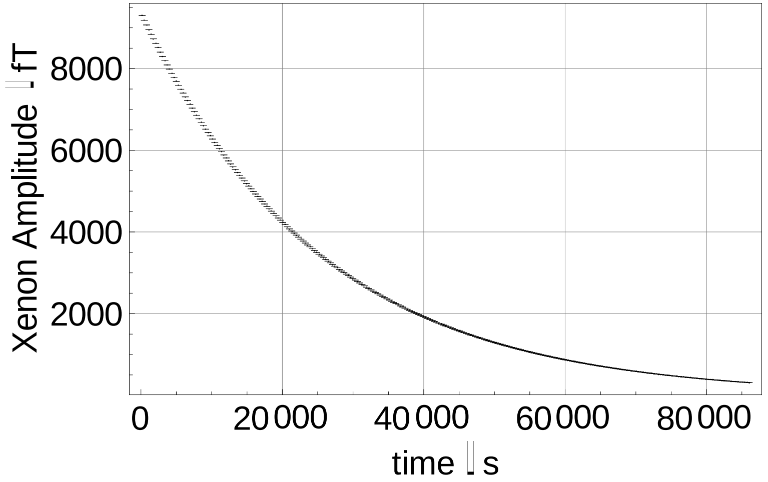
$$\Delta\Phi = \Phi_{He} - \gamma_{He}/\gamma_{Xe}\Phi_{Xe}$$

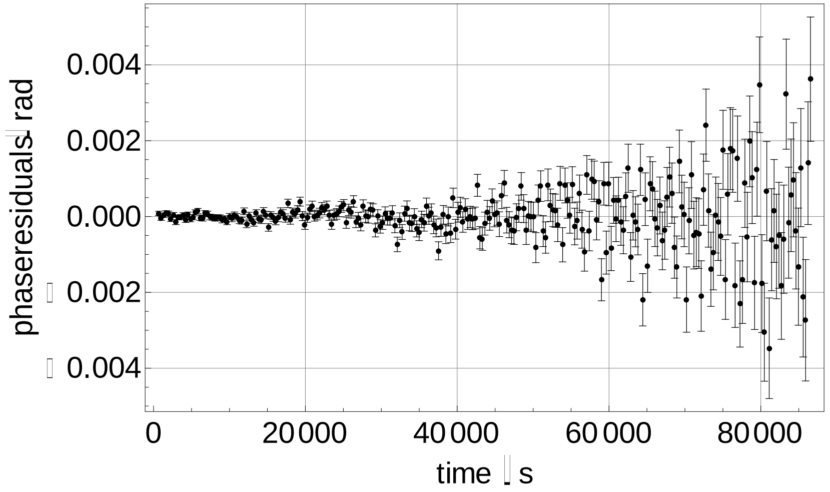
$$\Delta\Phi = c + a_{lin} \cdot t$$

a_{lin}: earth rotation and chemical shift

Subtraction of deterministic phase shifts







$$\Delta\Phi = c + a_{lin} \cdot t$$
$$+ a_{He} \cdot e^{-t/T^*_{2,He}} + a_{Xe} \cdot e^{-t/T^*_{2,Xe}}$$
$$+ b_{He} \cdot e^{-2t/(T^*_{2,He})} + b_{Xe} \cdot e^{-2t/(T^*_{2,Xe})}$$
$$+ \Phi(\mathrm{t})_{\mathrm{spin-coupling}}$$

a: generalized Ramsey-Bloch-Siegert-Shift $\propto$ Magnetisation

b: Bloch-Siegert-Shift $\propto$Magnetisation^2 of other spin species

The detection of the free precession of co-located $^{3}He/^{129}Xe$ sample spins can be used as ultra-sensitive probe for

non-magnetic spin interactions of type:

$$V_{non-magn.} = \vec{a} \cdot \vec{\sigma}$$

- Search for a Lorentz violating sidereal modulation of the Larmor frequency

$$V(r)/\hbar = \langle \tilde{b} \rangle \, \hat{\varepsilon} \cdot \vec{\sigma} \, / \hbar$$

- Search for spin-dependent short-range interactions

$$V(r)/\hbar = c\vec{\sigma} \cdot \hat{n}/\hbar$$

- Search for EDM of Xenon

$$V(r)/\hbar = -|d_n| \vec{\sigma} \cdot \vec{E}/\hbar$$

…

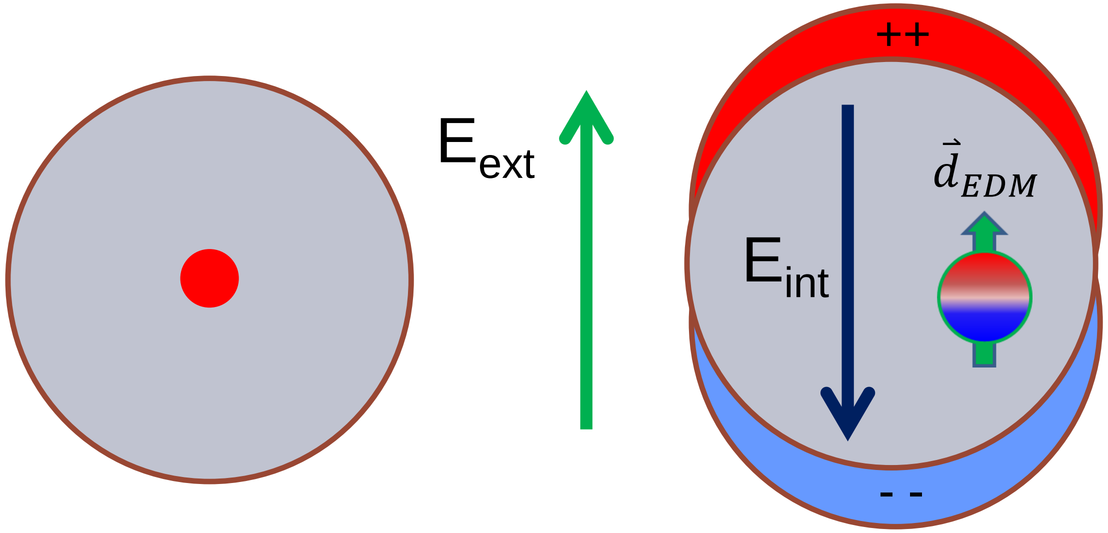
Observable:

$$\Delta\omega = \omega_{L,He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \omega_{L,Xe} \neq 0$$

Atomic EDM's

$$E_{eff} = E_{ext} + E_{int} = \varepsilon \cdot E_{ext} = 0$$

→ Talk of Herlik Wibowo



$$\Delta E_{EDM} = -\vec{d}_{atom} \cdot \vec{E}_{ext}$$
$$= -\vec{d}_{EDM} \cdot \varepsilon \cdot \vec{E}_{ext}$$

Schiff's screening theorem (L.I.Schiff *PR **132** 2194,1963)*:
System of non-relativistic charged point particles that interact electrostatically can not have an EDM

Finite size violation of Schiff screening

Diamagnetic EDMs – „Schiff suppression: ε "

For a finite nucleus, the charge and EDM have different spatial distributions

<u>S- Schiff moment</u>: $\vec{S} = S\frac{\vec{I}}{I} = \frac{1}{10}\left[\int e\rho(\vec{r})\vec{r}r^2d^3r - \frac{5}{3Z}\vec{d}\int\rho(\vec{r})r^2d^3r\right]$

Schiff moment is dominant CP-odd N-N interaction for large atoms

$$d_A = k_A \cdot 10^{-17} \cdot \left[\frac{S}{e\,fm^3}\right] e\,cm \quad (k_{Xe} \sim 0.38)$$

$$S = S\left(\bar{g}_{\pi NN}^{(i)}, d_n, d_p, \ldots\right) \quad \text{(low energy parameters)}$$

- $d_A \sim 10\,Z^2(R_N/R_A)^2 d_{nuc} \sim O\,(10^{-3})\,d_{nuc}$ $\quad d_A = \varepsilon \cdot d_{nuc}$
- Nuclear deformation can enhance heavy atom EDMs (e.g., 225Ra, 223Rn)

Parameter	^{199}Hg	Best alternate limit
d_e / (e ·cm)	3.0×10^{-27}	ThO:8.6×10^{-29}
d_n / (e ·cm)	1.6×10^{-26}	n: 2.9×10^{-26}
d_p / (e ·cm)	2.0×10^{-25}	TlF: 5.4×10^{-23}
θ_{QCD}	8.5×10^{-11}	n: 2.4×10^{-10}
C_S	1.3×10^{-8}	Tl:2.4×10^{-7}
C_T	1.5×10^{-10}	TlF:4.5×10^{-7}
C_{PS}	1.2×10^{-7}	TiF: 3×10^{-4}
η	8.0×10^{-5}	Xe: 5×10^{-2}

$$d\left(^{199}\,\mathrm{Hg}\right) \leq 7.4 \cdot 10^{-30}\mathrm{e}\cdot\mathrm{cm}$$

(95% CL)

Reduced Limit on the Permanent Electric Dipole Moment of ^{199}Hg
B. Graner, Y. Chen, E. G. Lindahl, and B. R. Heckel
arXiv:1601.04339v2 [physics.atom-ph] 17 Aug 2017

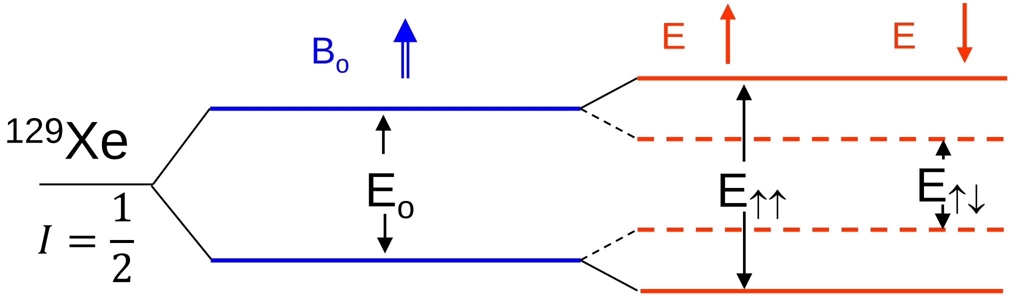
$$d\left(^{199}\,\mathrm{Hg}\right) = 10^{-2}d_e + \left(2.0\times10^{-20}C_T + 5.9\times10^{-22}C_S + 6\times10^{-23}C_{PS} + 3.9\times10^{-25}\eta\right)\mathrm{e}\cdot\mathrm{cm}$$

$$d\left(^{129}\,\mathrm{Xe}\right) = 10^{-3}d_e + \left(5.2\times10^{-21}C_T + 5.6\times10^{-23}C_S + 1.2\times10^{-23}C_{PS} + 6.7\times10^{-26}\eta\right)\mathrm{e}\cdot\mathrm{cm}$$

$$d\left(^{129}\,\mathrm{Xe}\right) \leq 3.3 \cdot 10^{-27}\mathrm{e}\cdot\mathrm{cm}$$

6× less sensitive to CP violating interactions

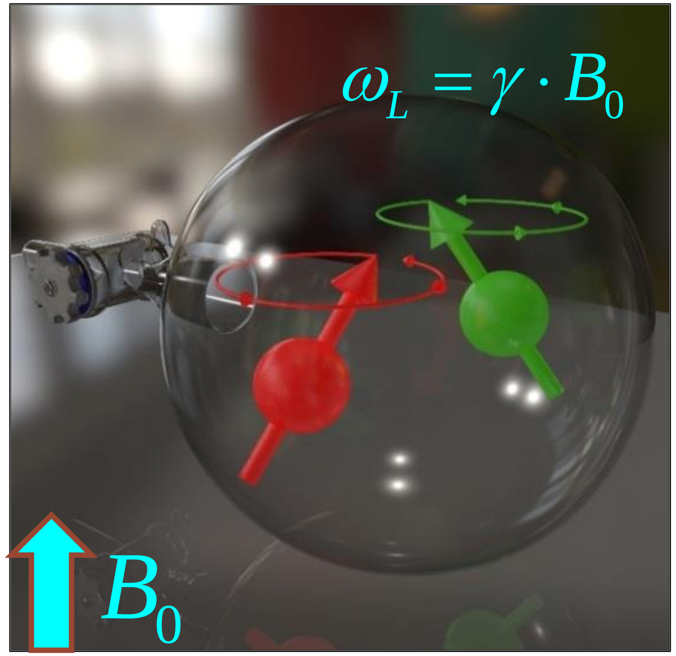
^{129}Xe electric dipole moment



$$\hbar \cdot \Delta\omega_{EDM} = (\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow}) = 4 \cdot E \cdot |d_{Xe}|$$

Zeeman: $\mu B_0 \approx 10^{-13}$ eV $d_{Xe} \cdot E \approx 10^{-25}$ eV

Comagnetometry to get rid of magnetic field drifts



Observable:

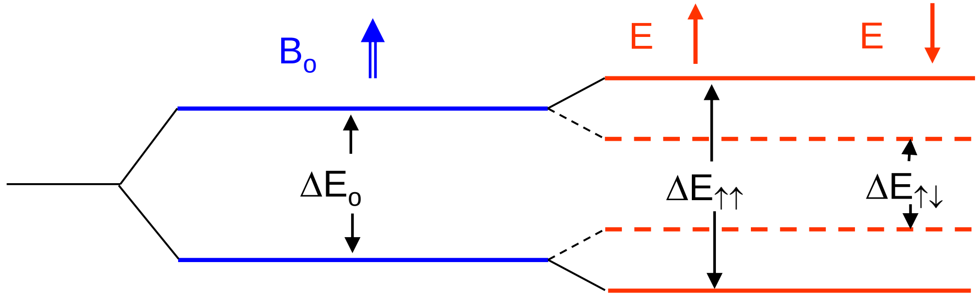
weighted frequency (phase) difference

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

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

$$\delta\omega_{EDM} = \Delta\omega_{\uparrow\uparrow} - \Delta\omega_{\uparrow\downarrow} = 4 \cdot E \cdot d_{Xe}/\hbar$$

Measurement sensitivity: ^{129}Xe electric dipole moment



$$h \cdot \Delta\nu = h \cdot (\Delta\upsilon_{\uparrow\uparrow} - \Delta\upsilon_{\uparrow\downarrow}) = 4 \cdot E \cdot |d_{Xe}|$$

$$4 \cdot 10^{-15}\mathrm{eVs} \times 1\mathrm{pHz} =$$

$$4 \times 1 \cdot 10^{3}\,\frac{\mathrm{V}}{\mathrm{cm}} \times 1 \cdot 10^{-30}\mathrm{e\ cm}$$

The **C**ramer-**R**ao **L**ower **B**ound (CRLB) sets the lower limit on the variance

$$\sigma_f^2 \geq \frac{12}{(2\pi)^2 \cdot (SNR)^2 \cdot f_{BW} \cdot T^3} \times C\ (T_2^*)$$

Correction for T_2-relaxation

$$\sigma_f \propto \left[\begin{matrix}\text{Fourier} \\ \text{width}\end{matrix} \propto \frac{1}{T}\right] \times \frac{1}{[\#\text{datapoints} \propto \mathrm{T}]^{\frac{1}{2}}} \propto \frac{1}{T^{\frac{3}{2}}}$$

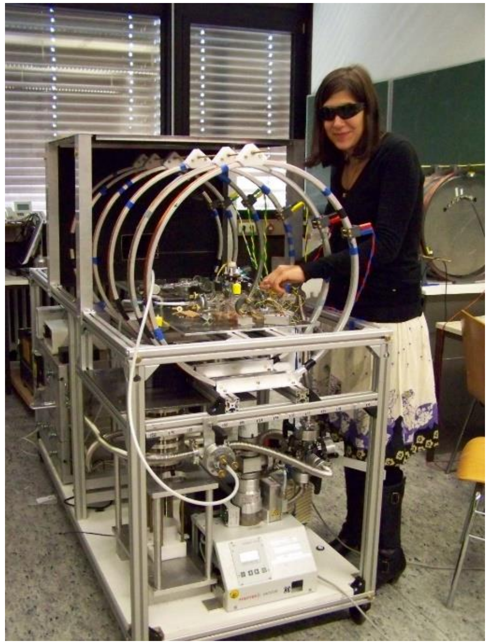
$$\sigma_\phi \propto 1/\sqrt{T}$$

example: SNR = 10000:1 , f_{BW} = 1 Hz , T= 1 day $\Rightarrow \sqrt{\sigma_f^2} \approx 1$ pHz

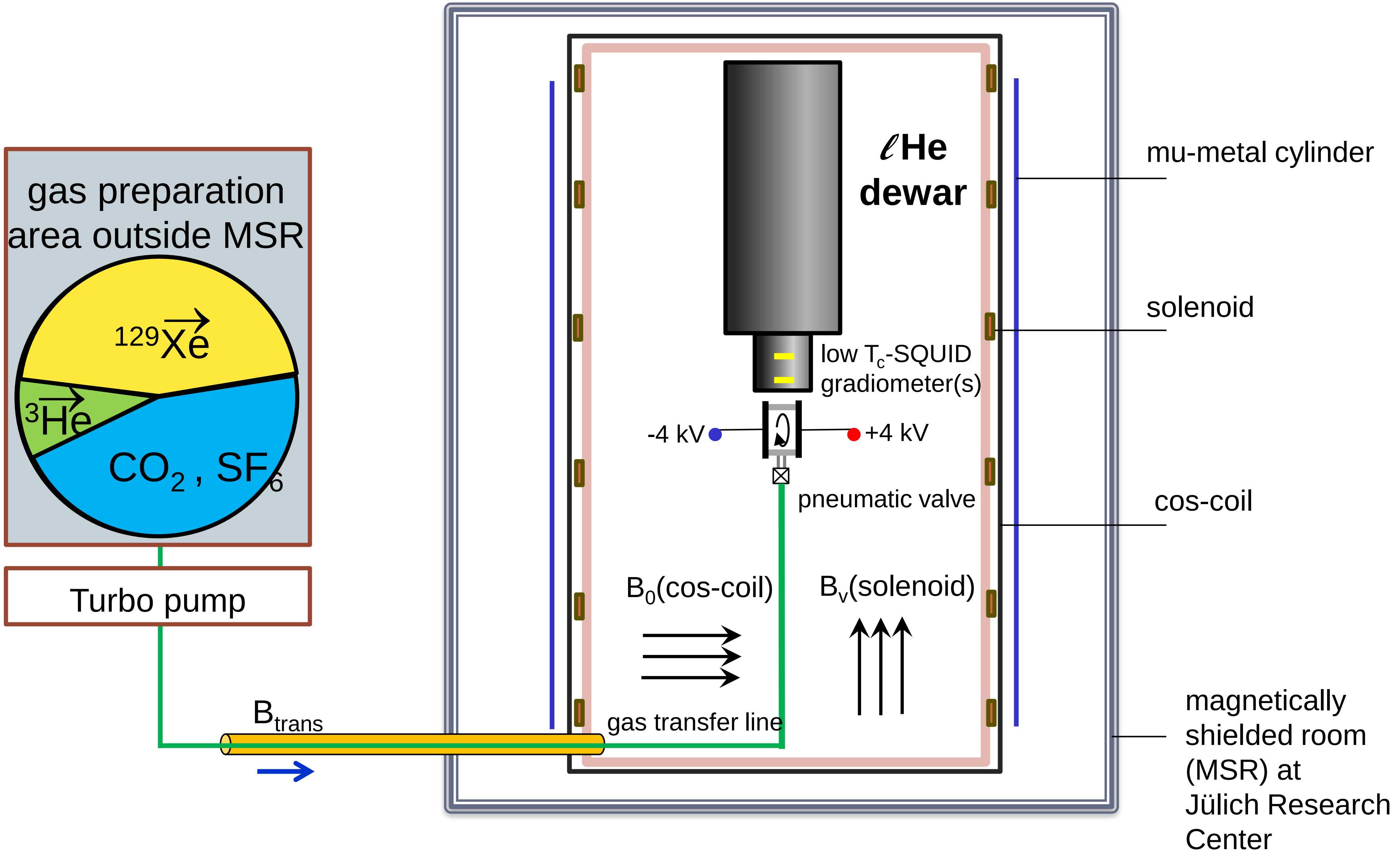
MIXed

Measurement and Investigation of the Xenon-129 electric dipole moment

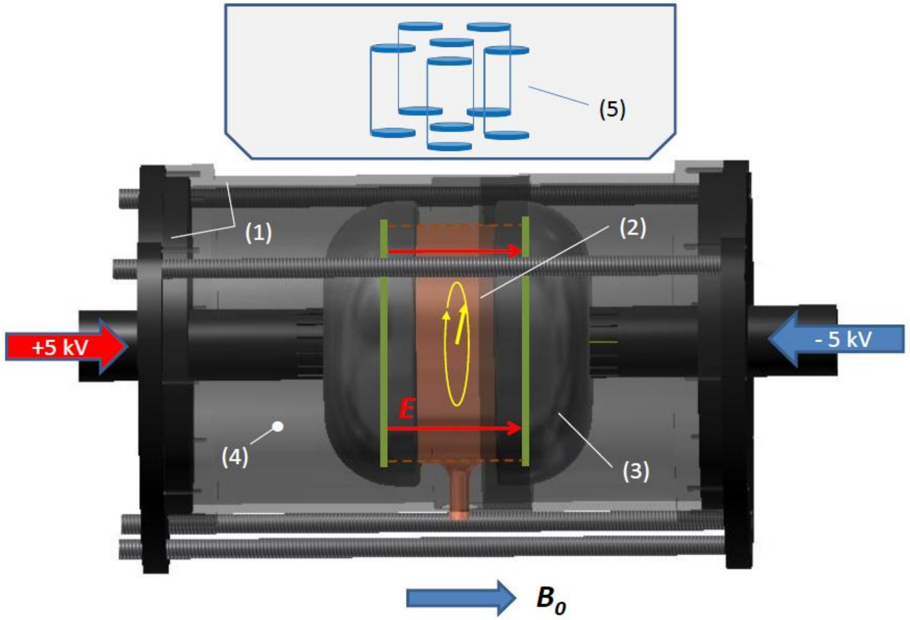
^{129}Xe EDM Setup at the magnetically shielded room at Forschungszentrum Jülich



Experimental Setup: **Overview**



Scheme inner setup of the ^{129}Xe-EDM experiment



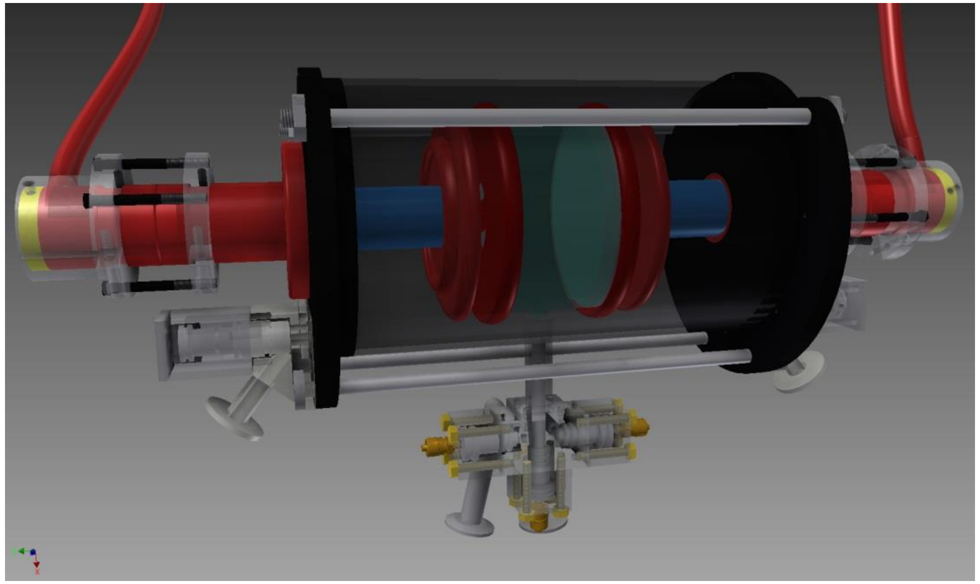
(1) Conductive Plastic housing

(2) Glass cell with silicon lids

(3) High voltage electrodes with cabling

(4) Filled with SF_6

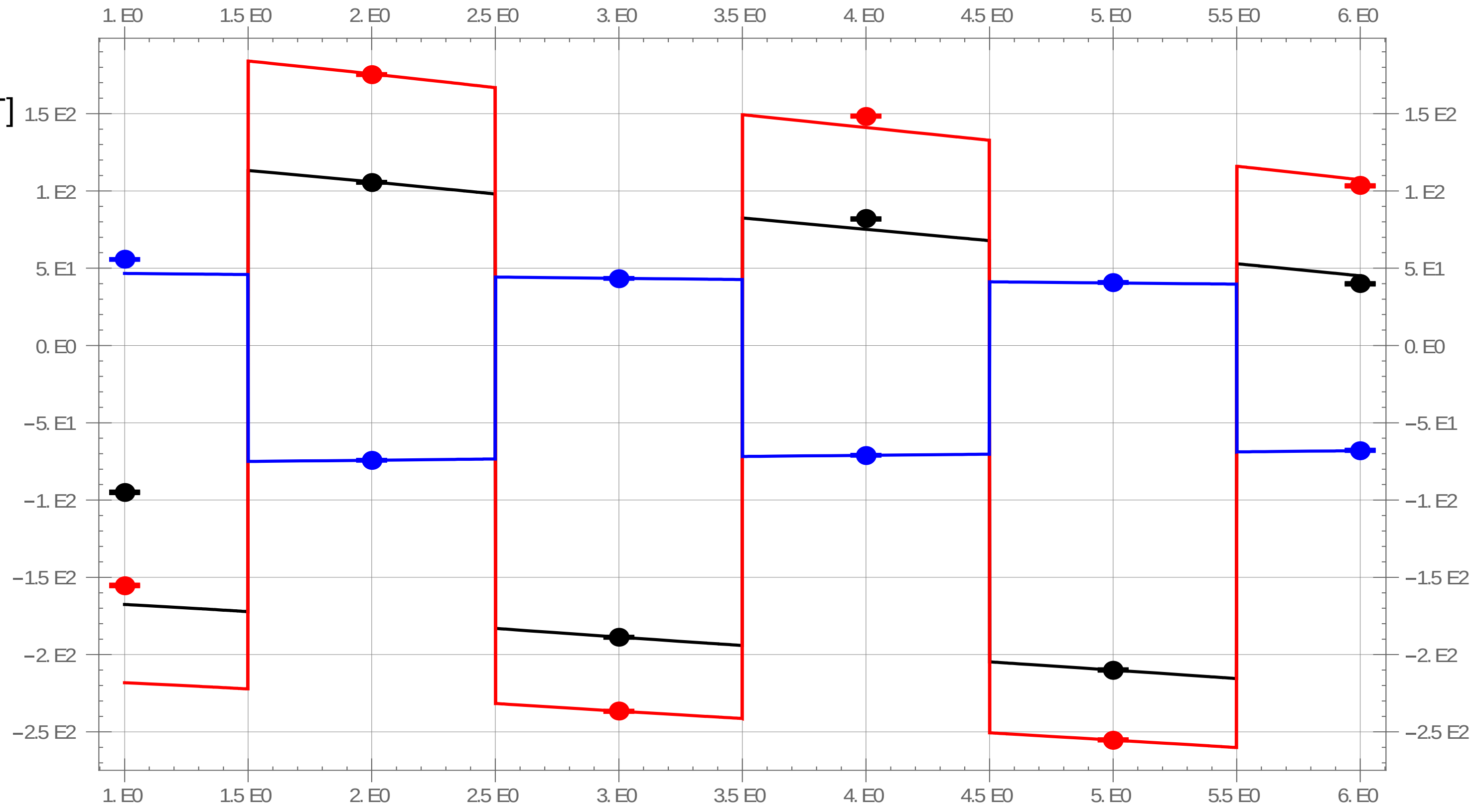
(5) Cryostat made of carbon fiber, inside special low temperature SQUID Gradiometers



$$\left(\frac{\Delta\omega_{Larmor}}{\gamma}\right)$$

He,Xe

Co-magnetometer equivalent

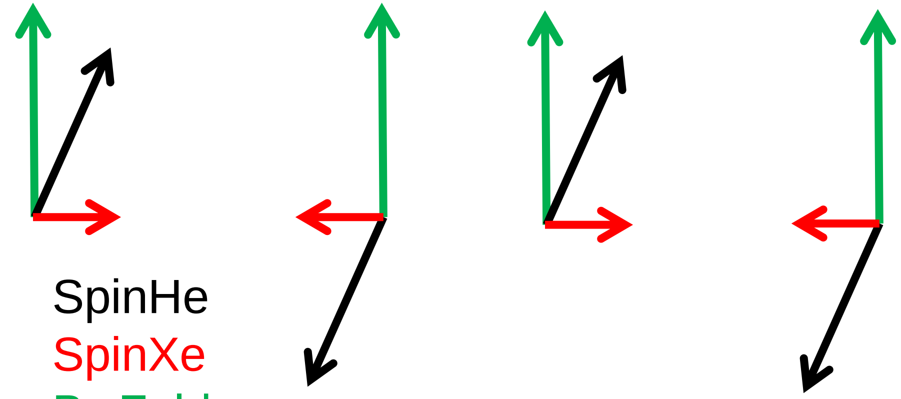


time

cylindrical cell

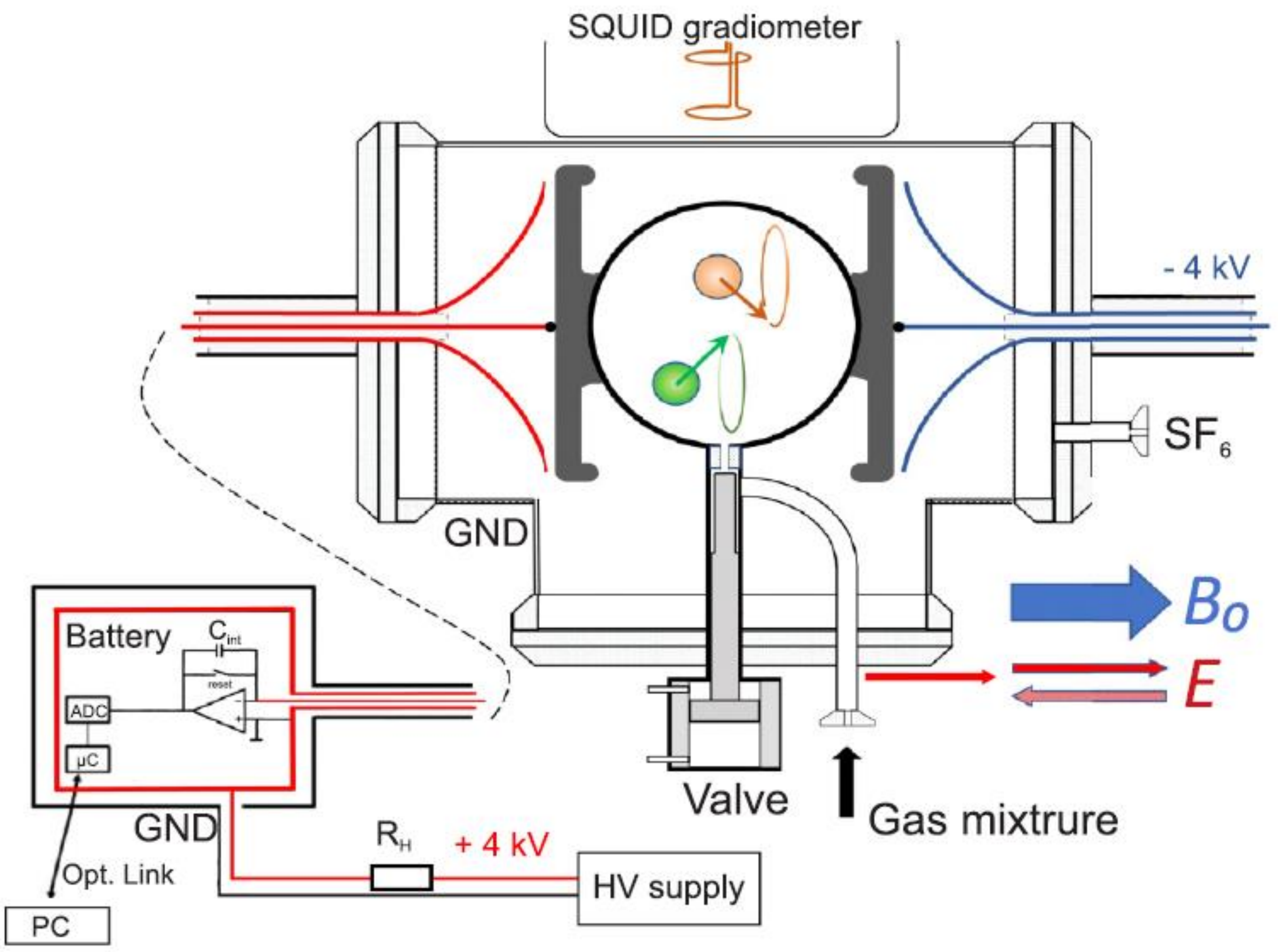
"Demagnetisation" fields

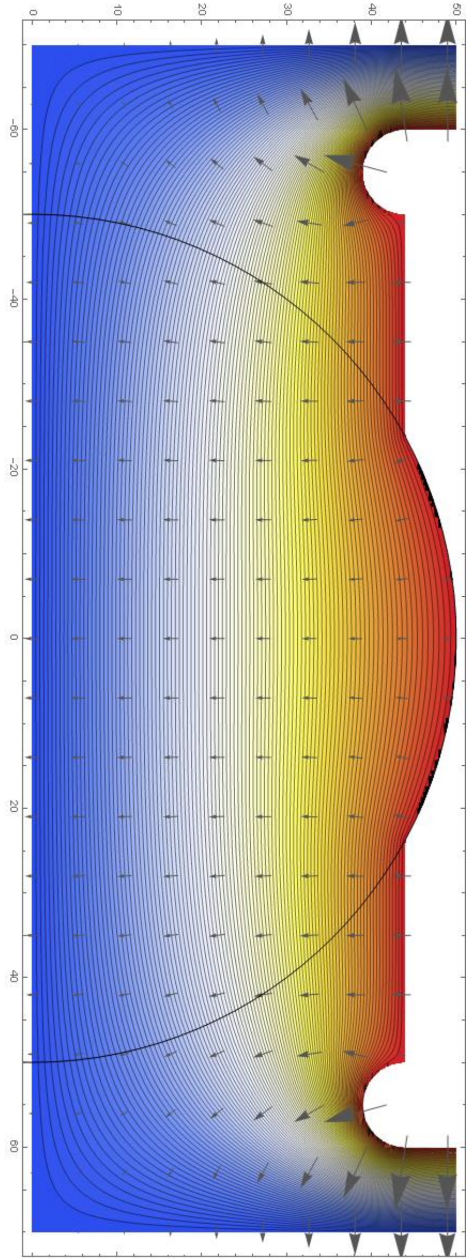
Used numerical codes to calculate these fields



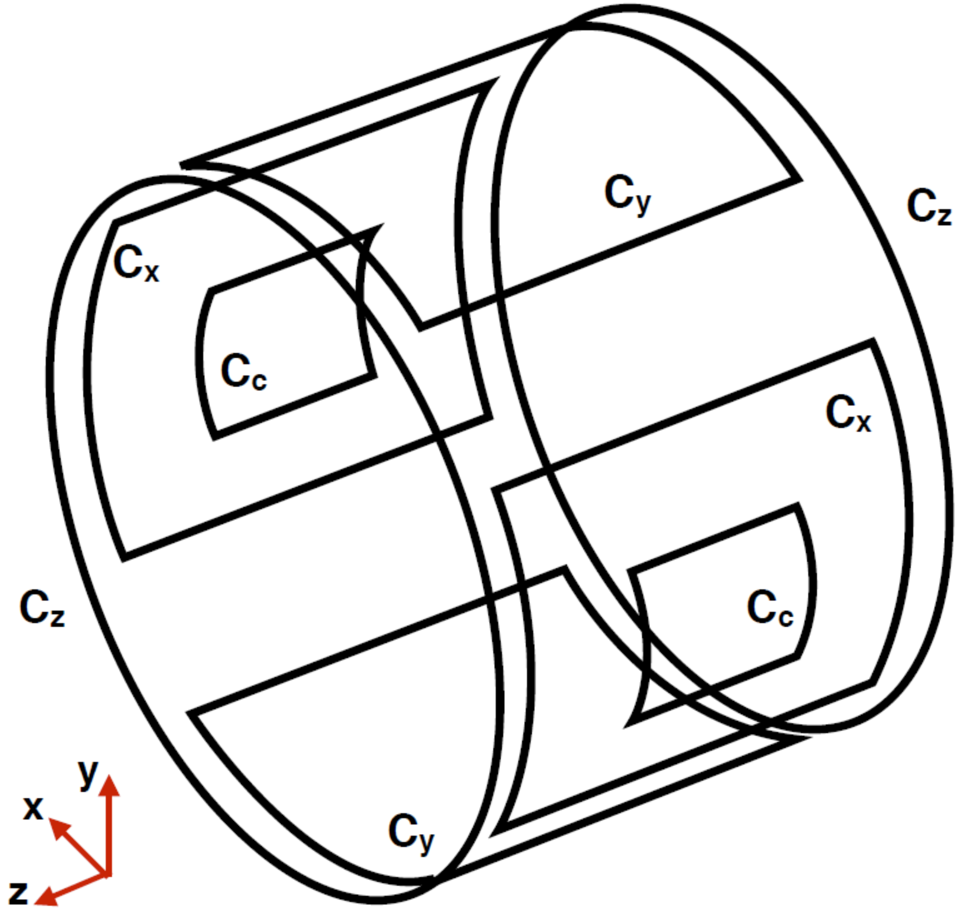
SpinHe
SpinXe
B_0-Feld

→ spherical cell


SQUID gradiometer
- 4 kV
SF6
GND
Battery
Cint
reset
ADC
μC
GND
Opt. Link
PC
RH
+ 4 kV
HV supply
Valve
Gas mixtrure
Bo
E



Additional coils for gradient compensation



Four current sources:
- Resolution: 16 bit
- Range: -5 ... +5 mA

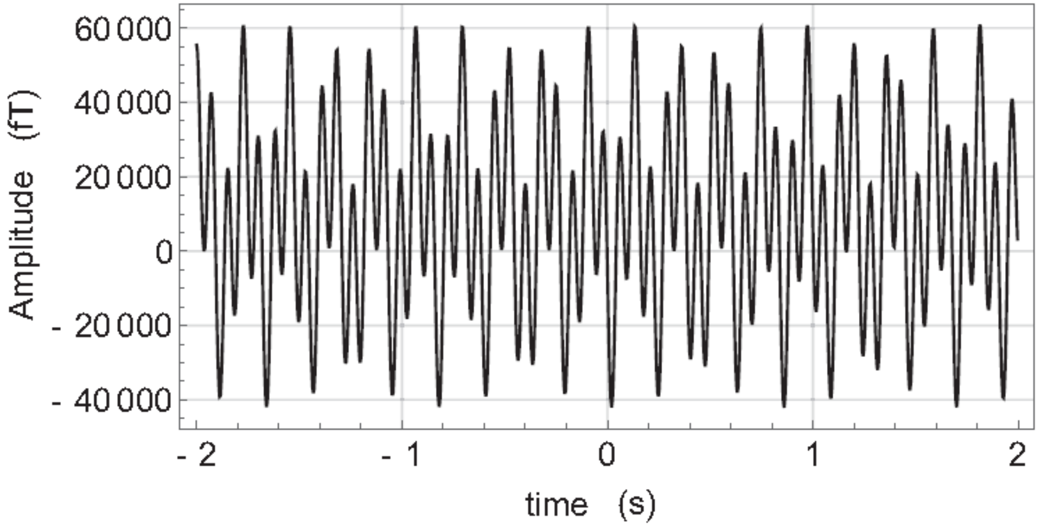
Results of automatic gradient compensation
(Downhill-simplex algorithm)

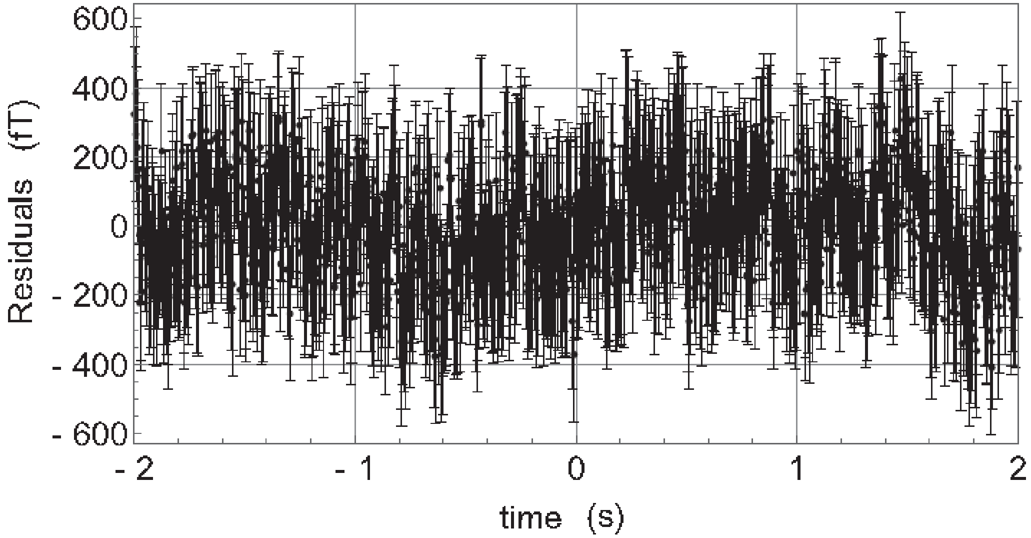
Example: Spherical cell (diameter 10 cm) filled with 30 mbar of polarized ^3He

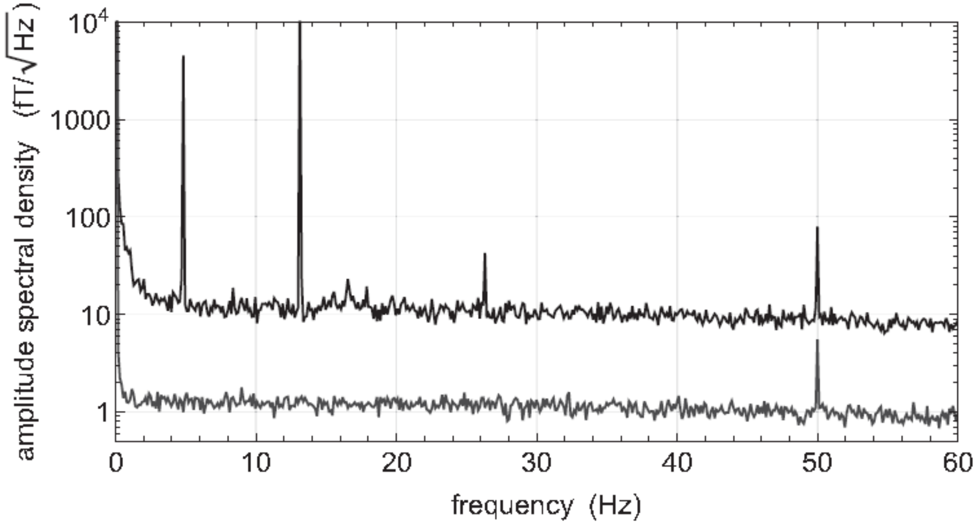
T_2^* measurement time: 10 minutes, total measurement time: 4 hours

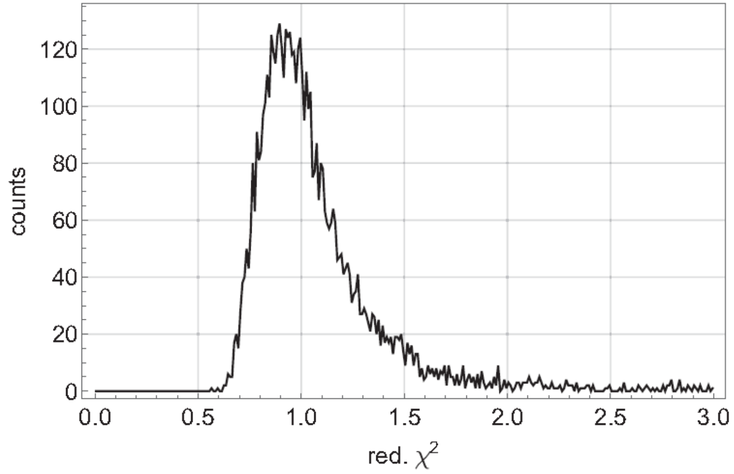
Iteration	**C_x / mA**	**C_y / mA**	**C_z / mA**	**C_c / mA**	**Spin coherence time T_2^* / s**	effective Gradients
start	0	0	0	0	7499	50 pT/cm
0	0	0.15	0	0	9758	
1	0.11	0.11	-0.30	0.11	14750	
3	0.30	0.30	-0.34	0.01	26590	
5	0.33	0.30	-0.60	0.02	35120	
13	0.30	0.40	-0.67	0.18	37686	< 10 pT/cm

$$B_S(t) = c_{He} \cdot \cos(\omega_{He} t) + s_{He} \cdot \sin(\omega_{He} t) + c_{Xe} \cdot \cos(\omega_{Xe} t) + s_{Xe} \cdot \sin(\omega_{Xe} t) + c_{lin} \cdot t + c_{const}$$

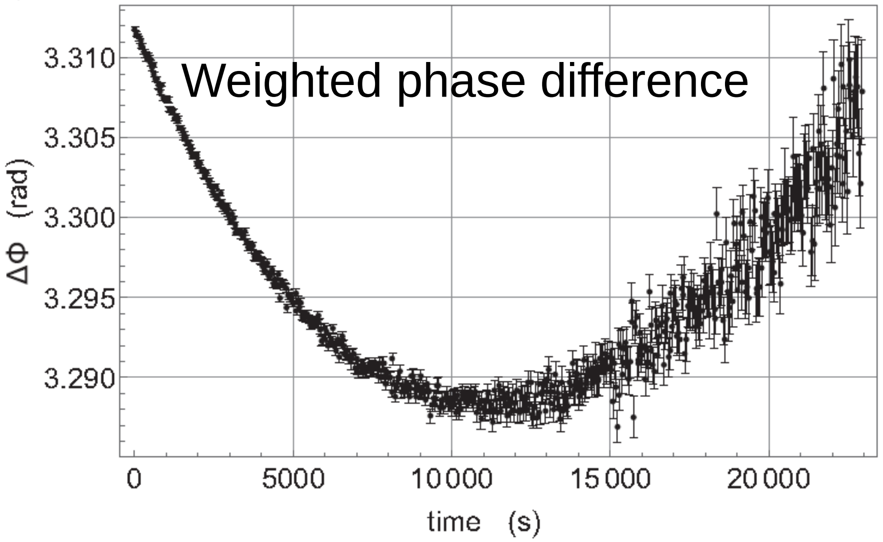


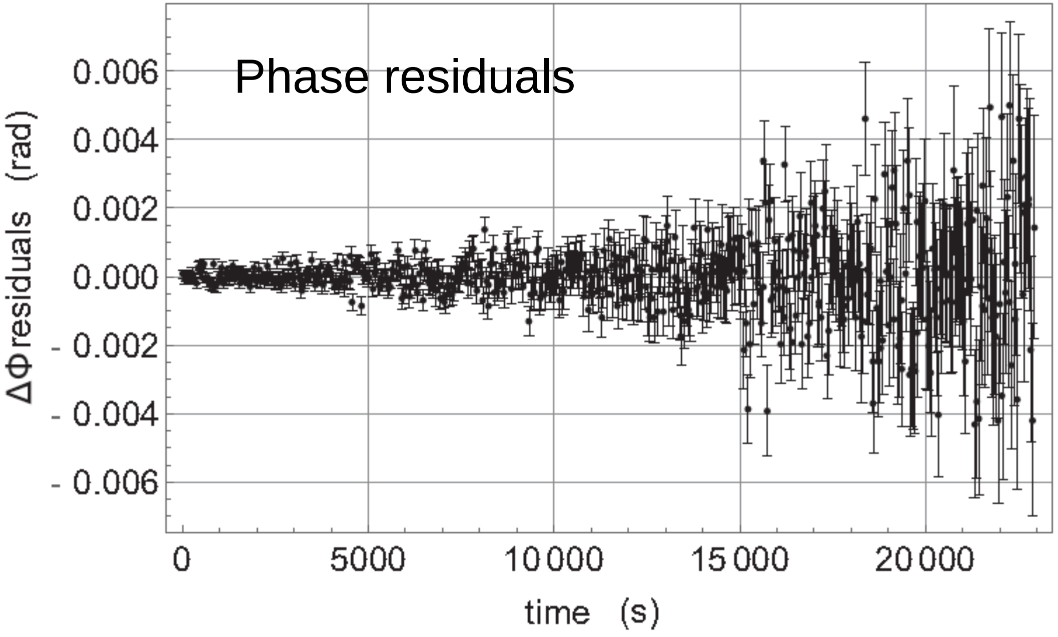


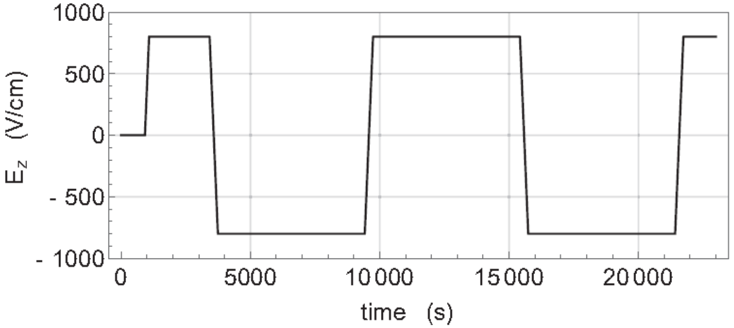


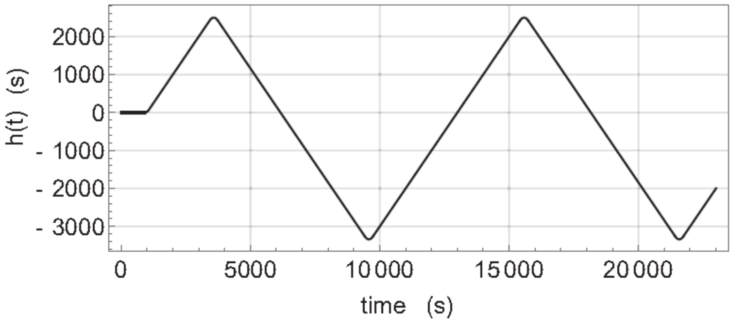


Data evaluation: Final Fit



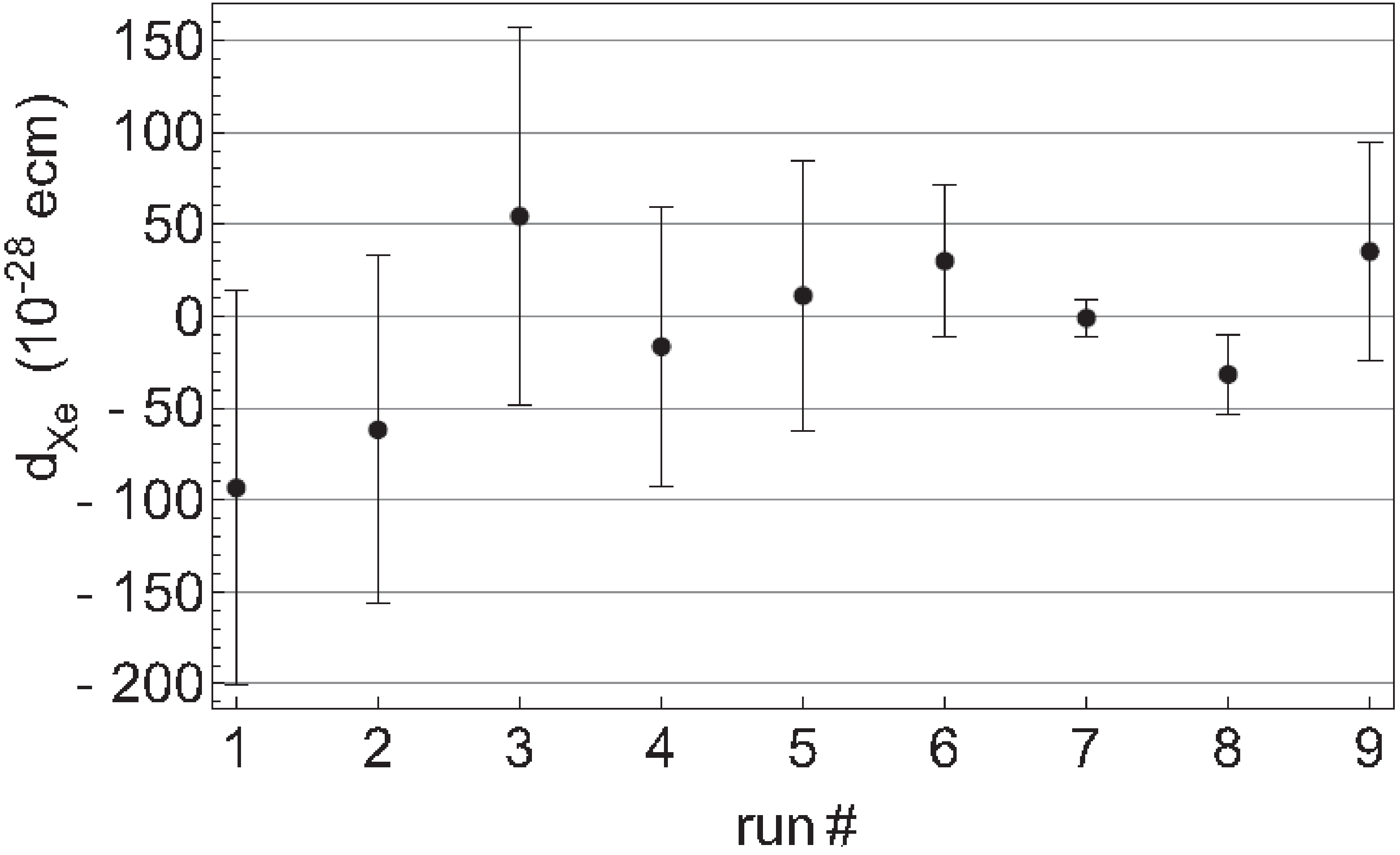






$$\Delta\Phi = c + a_{lin} \cdot t + a_{He} \cdot e^{-\frac{t}{T_2^{He}}} + a_{Xe} \cdot e^{-\frac{t}{T_2^{Xe}}} + b_{He} \cdot e^{-\frac{2t}{T_2^{He}}} + b_{Xe} \cdot e^{-\frac{2t}{T_2^{Xe}}} + g \cdot h(t, T_a)$$

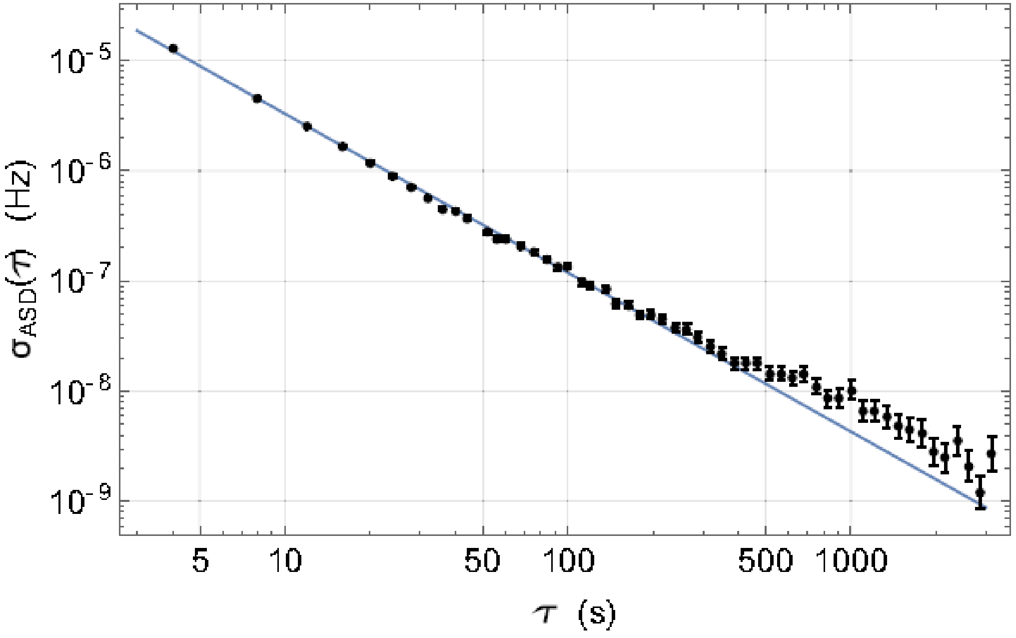
$$\Phi_{EDM}(t) = \frac{2d_{Xe}}{\hbar} E_z \cdot h(t, T_a) = g \cdot h(t, T_a)$$



$$d_{Xe} = (-4.7 \pm 6.4) \cdot 10^{-28} \mathrm{e} \cdot \mathrm{cm} \Rightarrow |d_{Xe}| < 1.5 \cdot 10^{-27} \mathrm{e} \cdot \mathrm{cm}$$

F. Allmendinger et al. Phys Rev A **100**, 022505 (2019) DOI: 10.1103/PhysRevA.100.022505

Allan standard deviation of the residual frequency noise

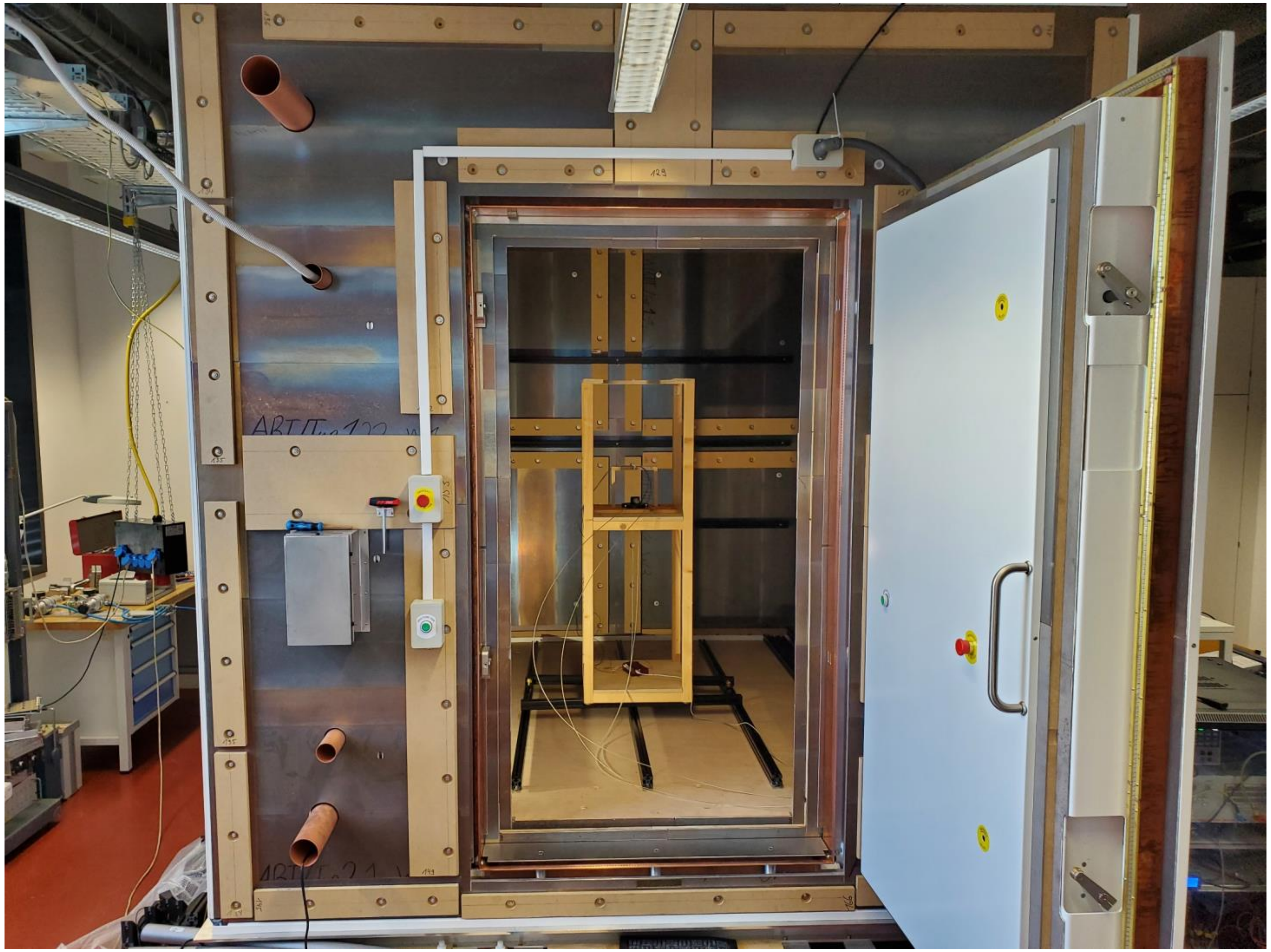


Summary of systematic false EDM effects

Effect		Value/e cm
Gravitational shift	d_{grav}	8.5×10^{-33}
Relax. rate shift	d_{T2}	8.5×10^{-30}
Motional magn. field		
Linear	d_m	5.8×10^{-31}
Quadratic	d_{m2}	7.6×10^{-37}
Geometric	d_{geom}	1.7×10^{-31}
Total (quadrature sum)		8.5×10^{-30}

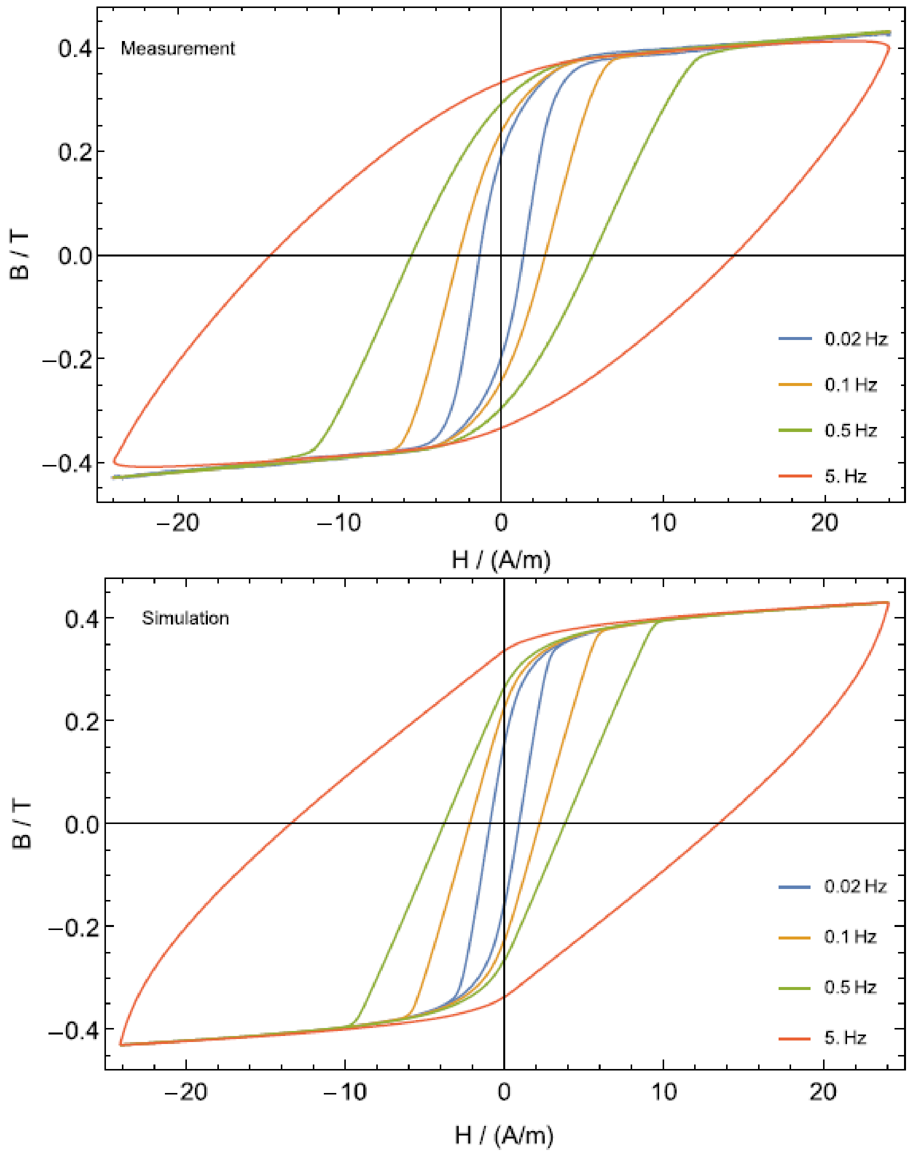
Setup of the next generation ^{129}Xe-EDM experiments at Heidelberg

Allmendinger et al. Rev. Sci. Instrum. **94**, 115105 (2023); doi: 10.1063/5.0167663

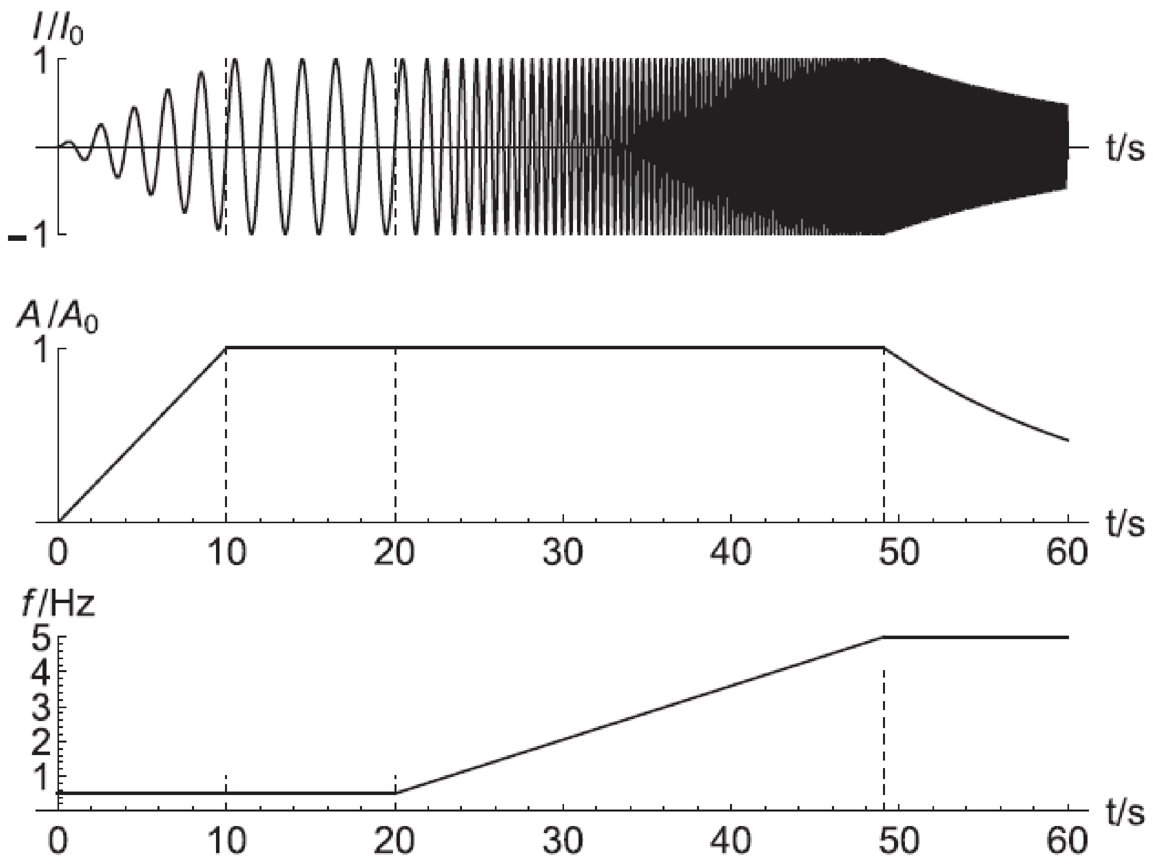


New magnetically shielded room (MSR)
Maunufacturer: Vakuum Schmelz Hanau
Size outer Dim: Cube 3x3x3m
3 Layer μ-metal shielding 3mm thick
1 Layer EMS:
cooper plated Aluminum 10mm thick
Special construction for have a rigid frame of nonmagnetic wood-epoxy item profile inside.

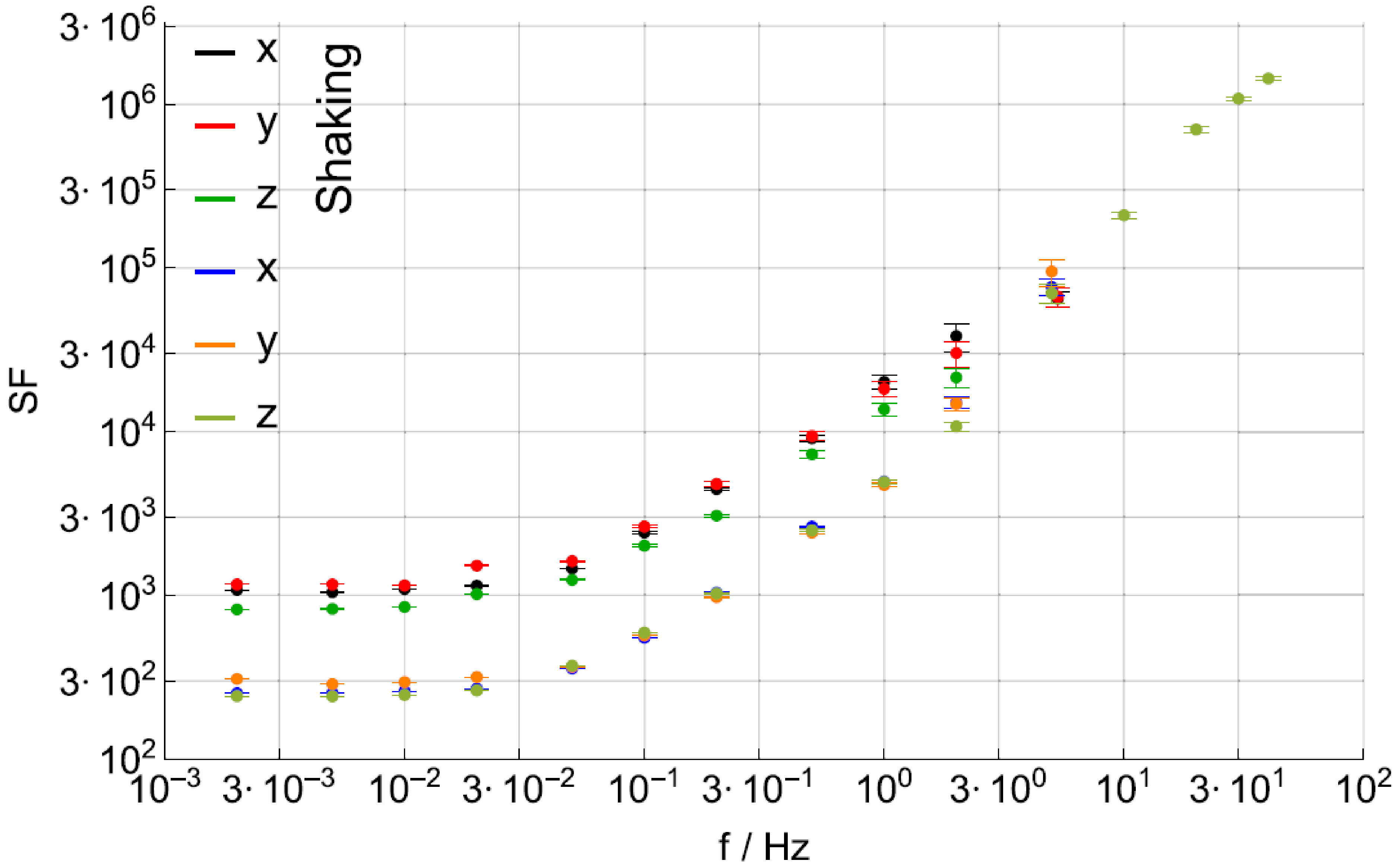
Hysteresis of the µ-metal



Degaussing scheme



Shielding factor with and without low frequency shaking



New Xe-polarizer in operation:

$$P = 37 \mp 3\%$$

Ongoing tasks toward an new EDM-measurement:

- Conductive coting tests for the new EDM-cell
- Design of the new EDM-cell
- Gas recycling and purification
- Getting the He-Polarizer into operation