A new measurement of the permanent electric dipole moment of 129-Xe

using

3-He comagnetometry

and

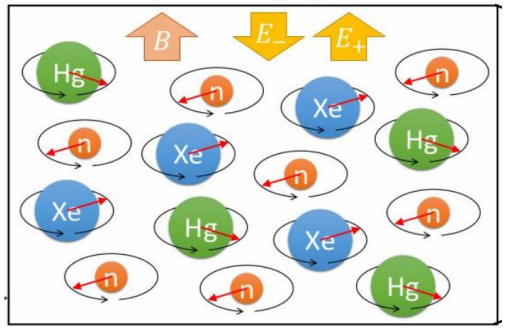
SQUID detection

E. Babcock[5], M. Burghoff[2], T. Chupp[3], S. Degenkolb[7], I. Fan[2], P. Fierlinger[1], W. Kilian[2], S. Knappe-Grueneberg[2], F. Kuchler[6], J. Meinel[1], N. Sachdeva[3], Z. Salhi[5], A. Schnabel[2], F. Seifert[2], J. Singh[4], S. Stuiber[1], W. Terrano[1], L. Trahms[2], J. Voigt[2]

[1]Excellence Cluster Universe, Technische Universitaet Muenchen, Garching
[2]Physikalisch-Technische Bundesanstalt, Berlin
[3]University of Michigan, Ann Arbor
[4]Michigan State University, East Lansing and NSCL
[5]Juelich Center for Neutron Science, Jülich
[6]TRIUMF, Vancouver
[7]ILL, Grenoble

Funded by DFG FA 1456/1-1 and TR 408/12-1

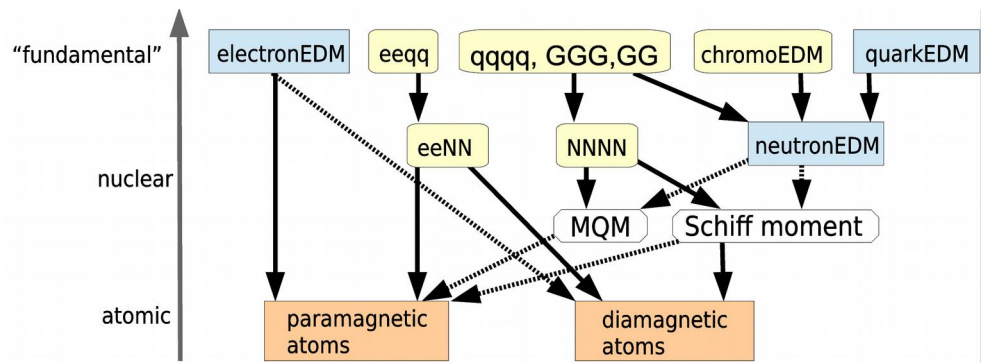
- ^{129}Xe as potential additional comagnetometer in neutron EDM search
  Masuda et al., Phys. Lett. A 376, 1347 (2012)
  - comagnetometer frequency $\omega_i^{\uparrow\uparrow} = \gamma_i B_0 - \underbrace{\frac{1}{4c^2}\gamma_i^2 R^2 \frac{\partial B_{0z}}{\partial z}|E|}_{\text{shift due to geometric phase effect}}$
  - measurement of $d_n \lesssim 1 \times 10^{-27}\ e\text{cm}$ requires $d_{Xe} \lesssim 10^{-28}\ e\text{cm}$



- Additional improved limit on the EDM of ^{129}Xe can tighten constraints in global analysis (vs sole-source analysis)

e.g. diamagnetic atom

$$d_{atom} = \kappa_S \underbrace{S(\bar{g}_\pi^{(0)}, \bar{g}_\pi^{(1)}, d_n)}_{\text{nuclear Schiff moment}} + k_T C_T + \text{H.O.}$$



Each limit is based on the assumption that it is the sole contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

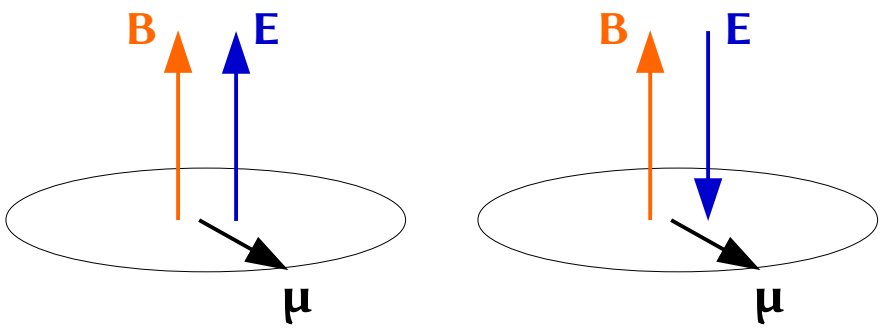
Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{Hg}/(1.9\ \text{fm}^2)$	$1.6 \times 10^{-26}\ e\,\text{cm}$	[21]

Graner, PRL **116**, 161601 (2016)

Schiff, Phys. Rev. **132**, 2194 (1963)
Chupp et al, Phys. Rev. C 91, 035502 (2015)
Chupp et al, Rev. Mod. Phys. 91, 015001 (2019)

Spin-polarized sample ⟶ spin precession in ultra-low magnetic (1 μT) and high electric fields (~ 10 kV/cm)

Hamiltonian for angular momentum F $\mathcal{H} = -(\mu\vec{B} + d\vec{E})\vec{F}/F$



Look for frequency difference between measurements with parallel and antiparallel magnetic and electric fields

e.g. polarized sample of F = S = ½

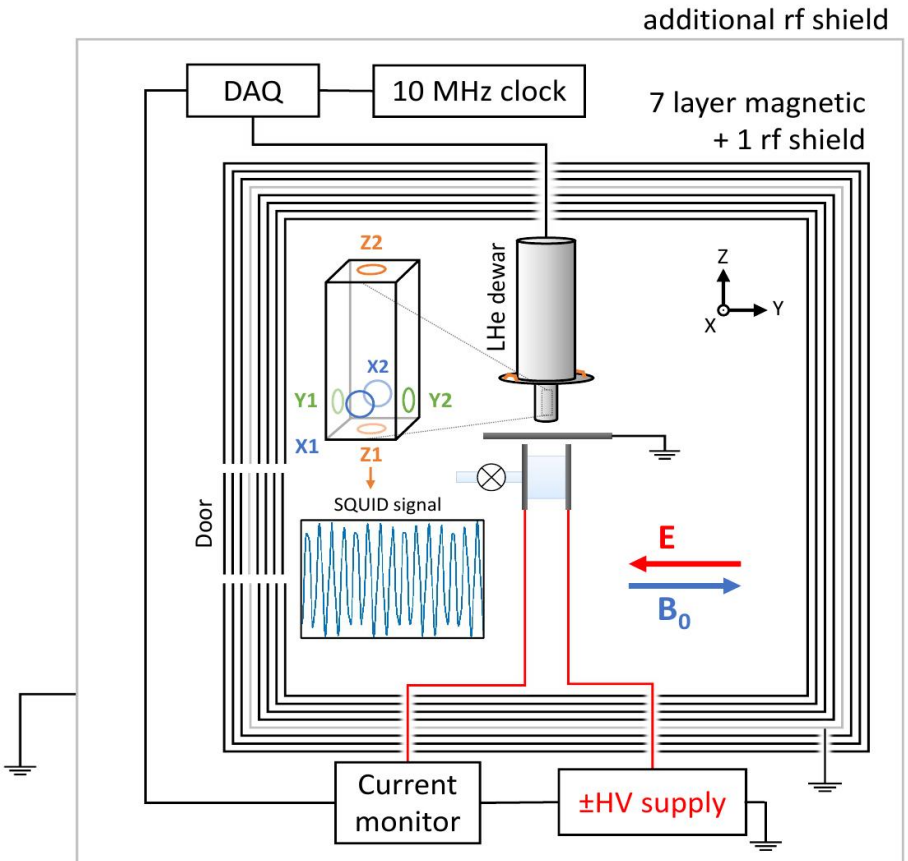
$$\Delta\omega = \omega^{\uparrow\uparrow} - \omega^{\uparrow\downarrow} = \frac{4d|E|}{\hbar} + \gamma\delta B$$

Illustration of technical challenges in determination of magnetic field (in particular when correlated to electric field):

$$d \approx 10^{-27}\,\mathrm{ecm} \Longleftrightarrow \sigma_\nu \approx 10\,\mathrm{nHz} \Longleftrightarrow \delta B \approx 0.1\,\mathrm{fT}$$

- high-quality magnetically controlled environment
  (low gradients, low magnetic background, magnetic field cont
- high-pressure (0.5-1.0 bar) mixture of ^{3}He : ^{129}Xe : N_2
  (typically 70-85% : 10-20% : 5-10%)
- simultaneous spin-polarization of ^{3}He and ^{129}Xe
- detection of spin precession using SQUID sensors:
  noise level < 10 fT/sqrt(Hz)
- comagnetometer correction $\omega_{co} = \omega_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}}\omega_{He}$
  (Schiff moment ~Z^2)
- newly developed measurement cells with silicon electrodes (2 mm thick, 1-10 Ωcm)

Sensitivity reach of d_{Xe} ~ 10^{-29} ecm



Magnetically shielded room @TUM

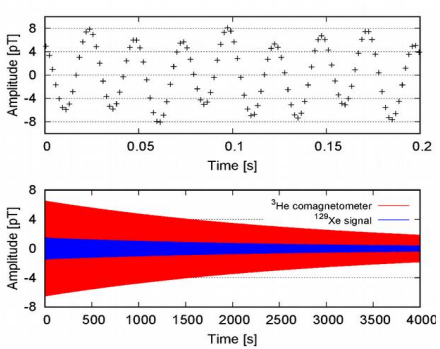
|B| < 1 nT (10 μG) |δB| < 0.3 nT/m (3 μG/m)

SF: 300 below 0.1 Hz 10^5 above 10 Hz

- techniques developed in test runs 2014-2016
- moved to ILL for neutron EDM search

Altarev et al, Rev. Sci. Instr. 85, 075106 (2014)

FK et al, Hyperfine Interact 237, 95 (2016)



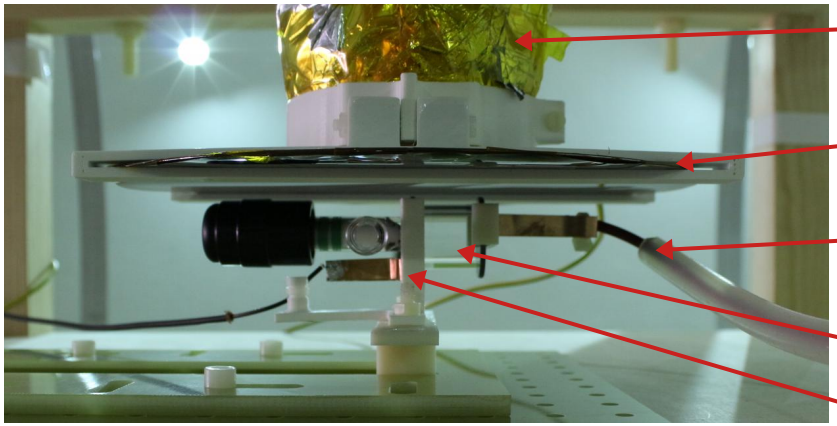
BMSR-II @PTB

|B| < 0.8 nT (8 μG) |δB| < 0.4 nT/m (4 μG/m)

SF: 75000 below 0.1 Hz 10^8 above 6 Hz

- EDM runs started in 2017
- low RF noise, stable environment, manpower on-site

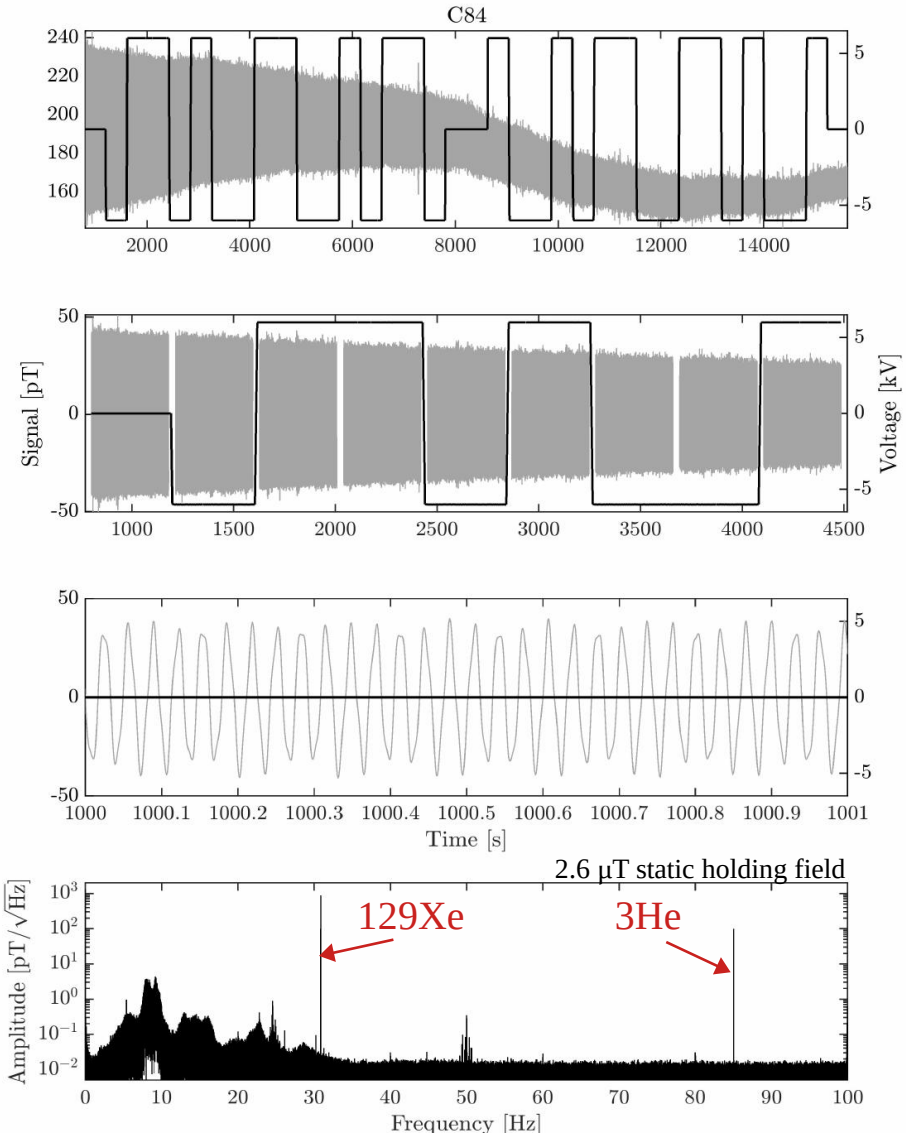
Bork et al, Proc. Biomag 2000, 970 (2000)



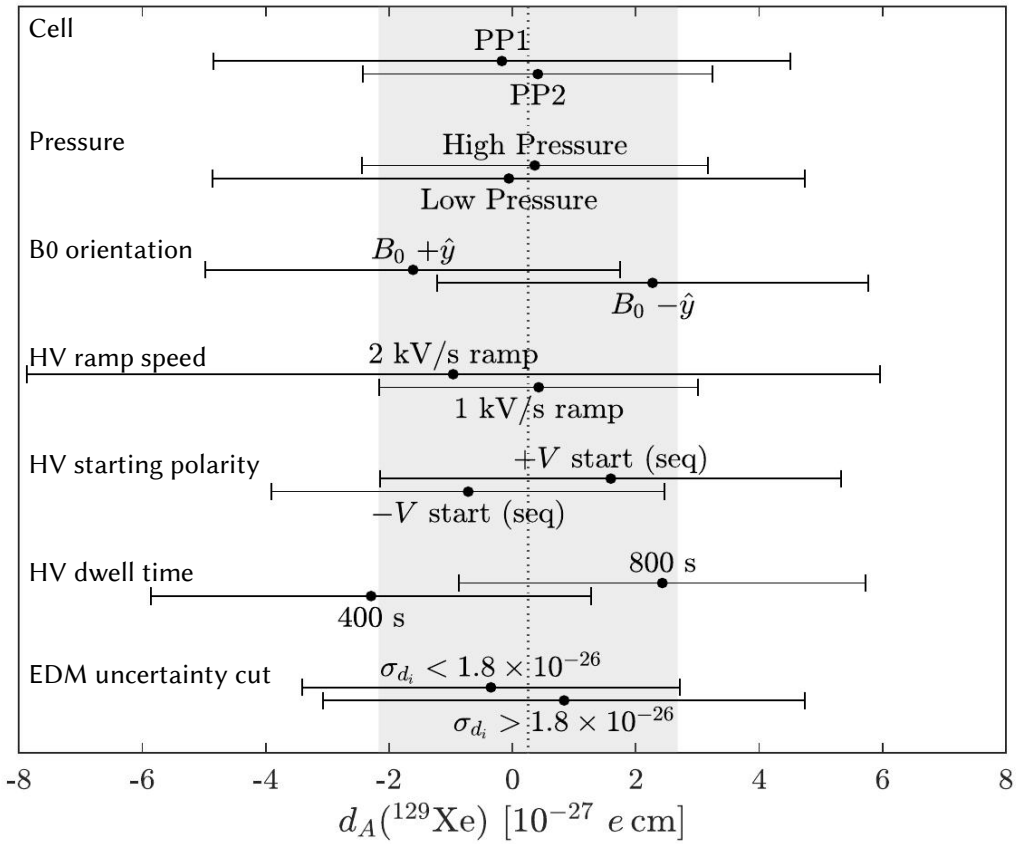
- π/2 spin-flip pulse resonant with ^{3}He and ^{129}Xe
- HV up to +/-6 kV (2.7-3.2 kV/cm)
- T_2^* ~ 3700-8000s for both species

2017 campaign of four weeks:

- one week of EDM runs ⟶ total of 16 runs, ea ~15000 s
- 120 EDM measurements under different conditions
- data was blinded with randomized frequency offset and un-blinded after cuts and systematics corrections



Comparing EDM results grouped by parameters varied during EDM measurements:

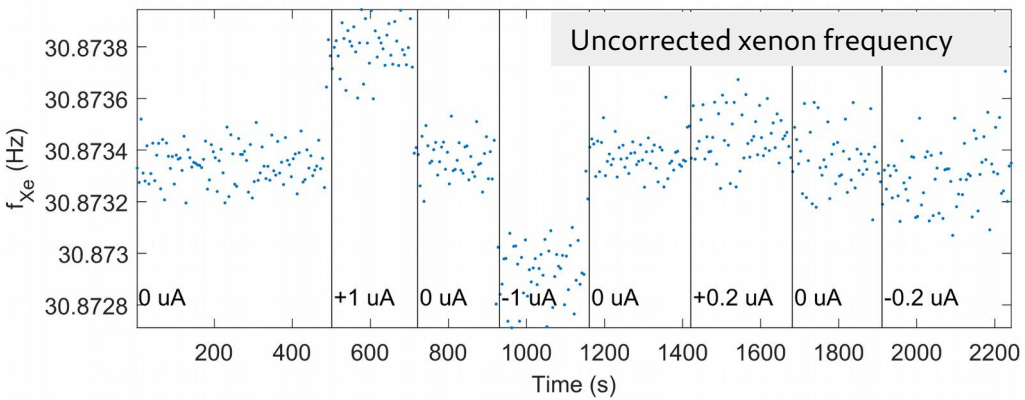


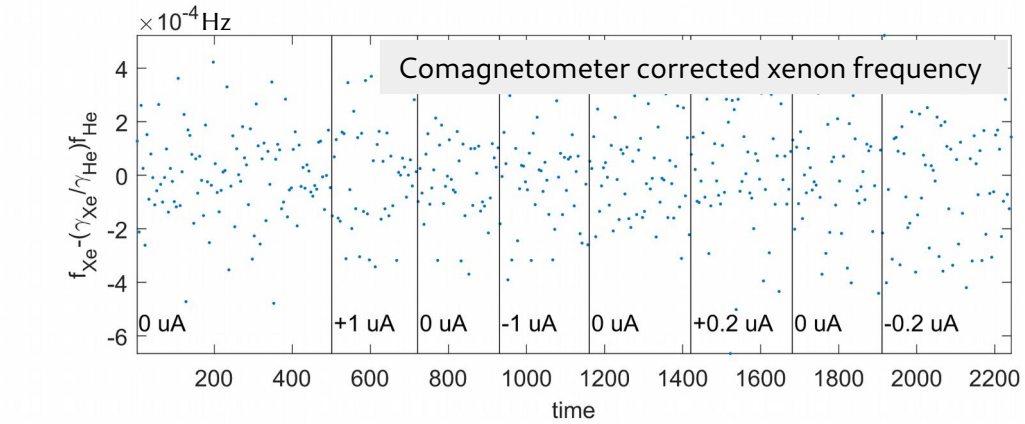
Determining systematics:

- dependence of ω_{co} on amplified effects of:
  - leakage currents
  - charging currents
  - magnetic field gradients
  - cell motion
- scaled by monitored HV correlations

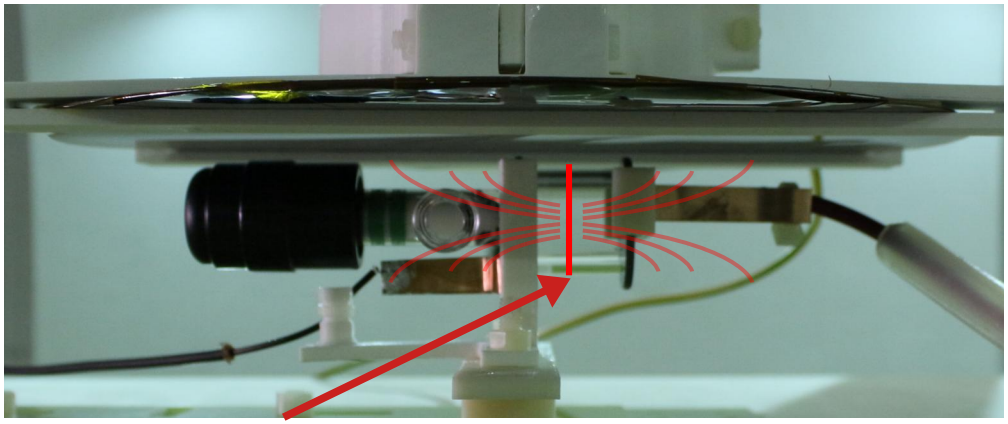
Source	**Sys. Error** (e cm)
Leakage current	1.2×10^{-28}
Charging currents	1.7×10^{-29}
$\vec{E}$-correlated cell motion (rotation)	4.2×10^{-29}
$\vec{E}$-correlated cell motion (translation)	2.6×10^{-28}
Comagnetometer drift	6.6×10^{-28}
$\lvert\vec{E}\rvert^2$ effects	1.2×10^{-29}
$\lvert\vec{E}\rvert$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

Sachdeva et al, arXiv:1902.02864 [physics.atom-ph]



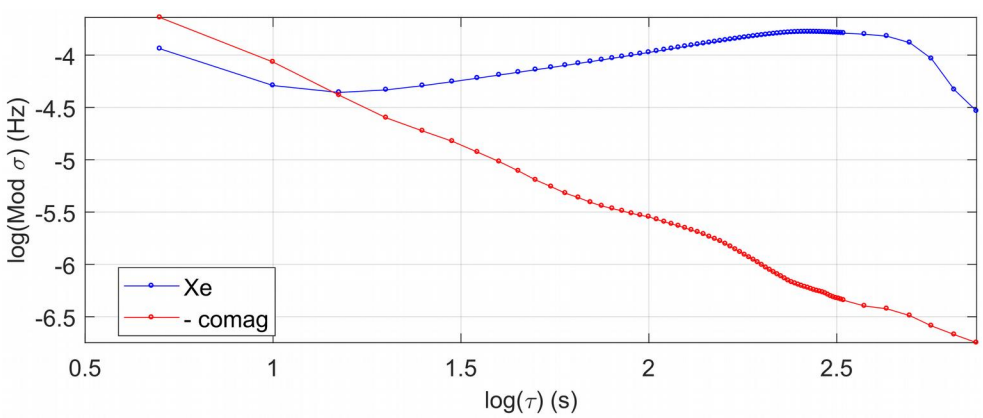


1 µA generated ~5 µHz shift for corrected xenon frequency
⟶ leakage current of 100 pA, eg. 0.5 nHz shift



Wire loop to generate
fake magnetic field

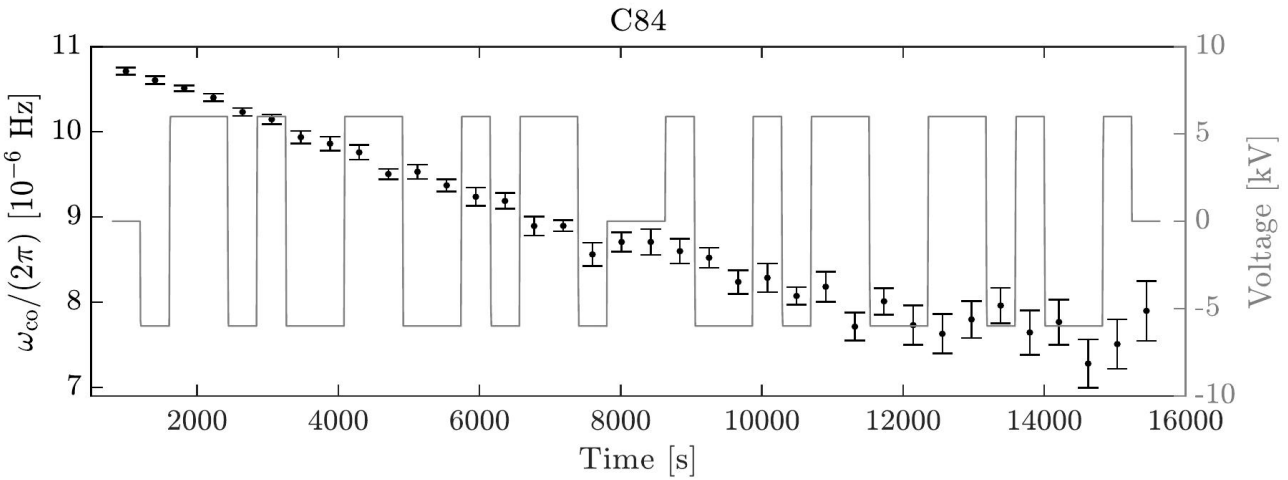
Allan deviation of uncorrected and corrected xenon frequency
^{3}He: 2 pT/7000s – ^{129}Xe: 14 pT/4000s

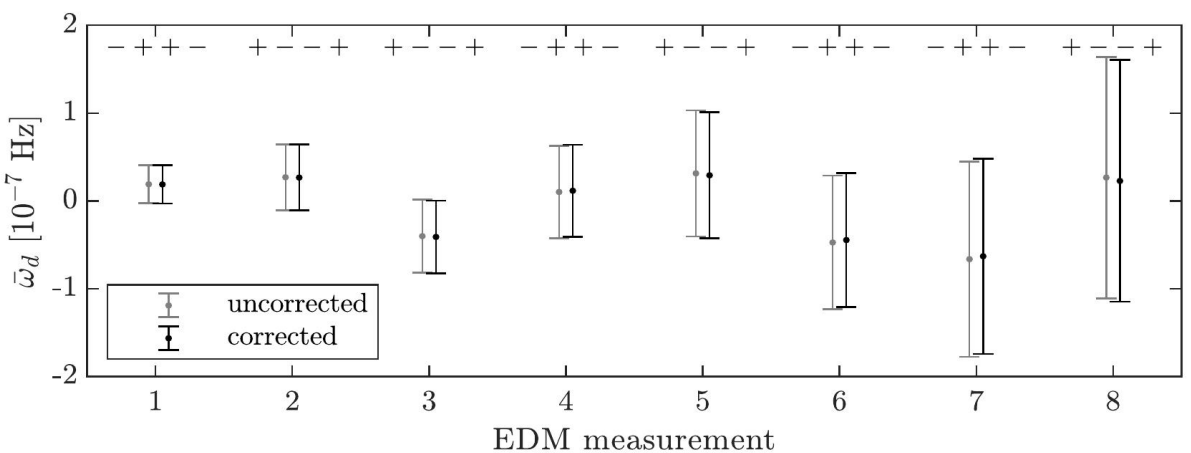


- Drift in corrected frequency

$$\omega_{\mathrm{co}} = \omega_{\mathrm{Xe}} - \frac{\gamma_{\mathrm{Xe}}}{\gamma_{\mathrm{He}}}\omega_{\mathrm{He}}$$

- False EDM from frequency shift between segments with opposite E.B
- Internal longitudinal magnetization identified as source during tests at TUM
- Observed drift (of order 1 µT/run) parametrized by polynomial of up to 4th order, but predominantly linear
- EDM measurements with E-field pattern (+--+, -++-) to cancel linear drift
- Applied correction for higher order drift → used to determine systematic error
- Checked for consistency with 8- and 16-segment pattern





Terrano et al, arXiv:1805:11119, accepted in PRA
Sachdeva et al, arXiv:1902.02864 [physics.atom-ph]

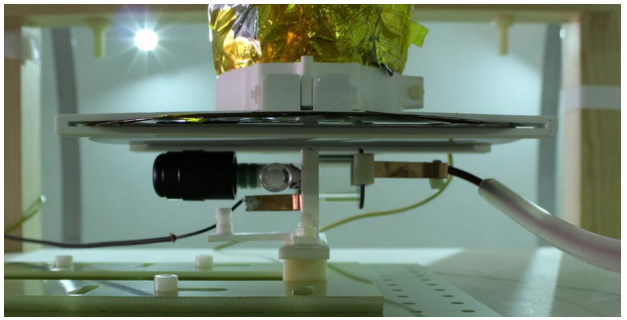
EDM run at PTB during four weeks in **2017**:

- 120 EDM measurements (one week)
- Result of the 2017 data analysis:

$d_A(129Xe) = 0.26 +/- 2.33_{stat} +/- 0.72_{sys} \times 10^{-28}$ ecm

$|d_A(129Xe)| < 4.81 \times 10^{-27}$ ecm (95% C.L.)

- Improves last limit by factor of 1.4



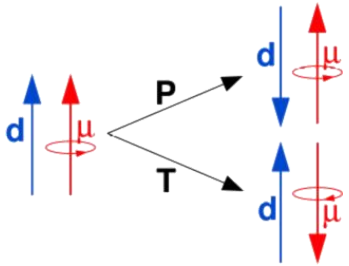
Future plans

- Analysis of 2018 EDM run
- Next runs:
  - Systematics improvements
    - optimized cell geometry & accurate spin flips ($\delta < 1°$)
    - leakage current measurement
    - cell motion measurements
  - Statistics improvements
    - improve SNR (^{3}He polarization, reduced noise dewar)
    - longer measurement time
    - circulating gas system

Improving result by factor 15 makes ^{129}Xe a feasible comagnetometer species for the TUCAN EDM experiment aiming at $d_n \sim 10^{-27}$ ecm

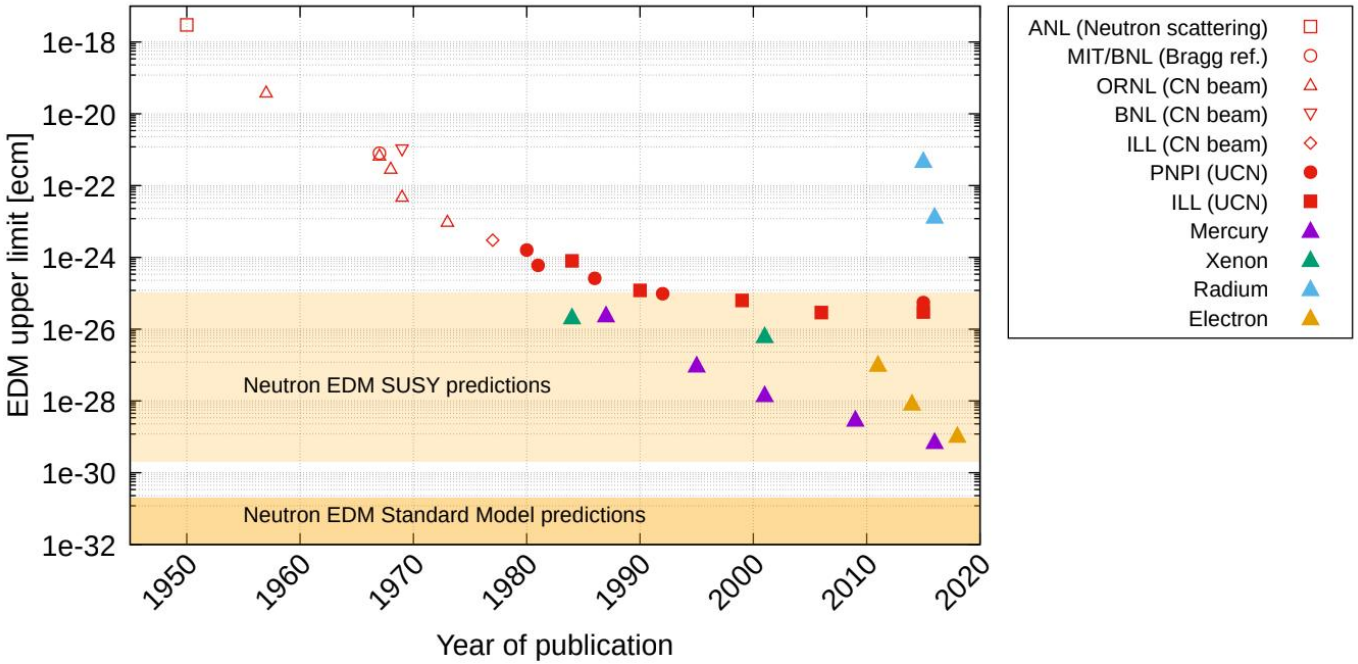
Sachdeva et al, arXiv:1902.02864 [physics.atom-ph]

non-zero EDM violates T and CP symmetries ⟶ baryon asymmetry

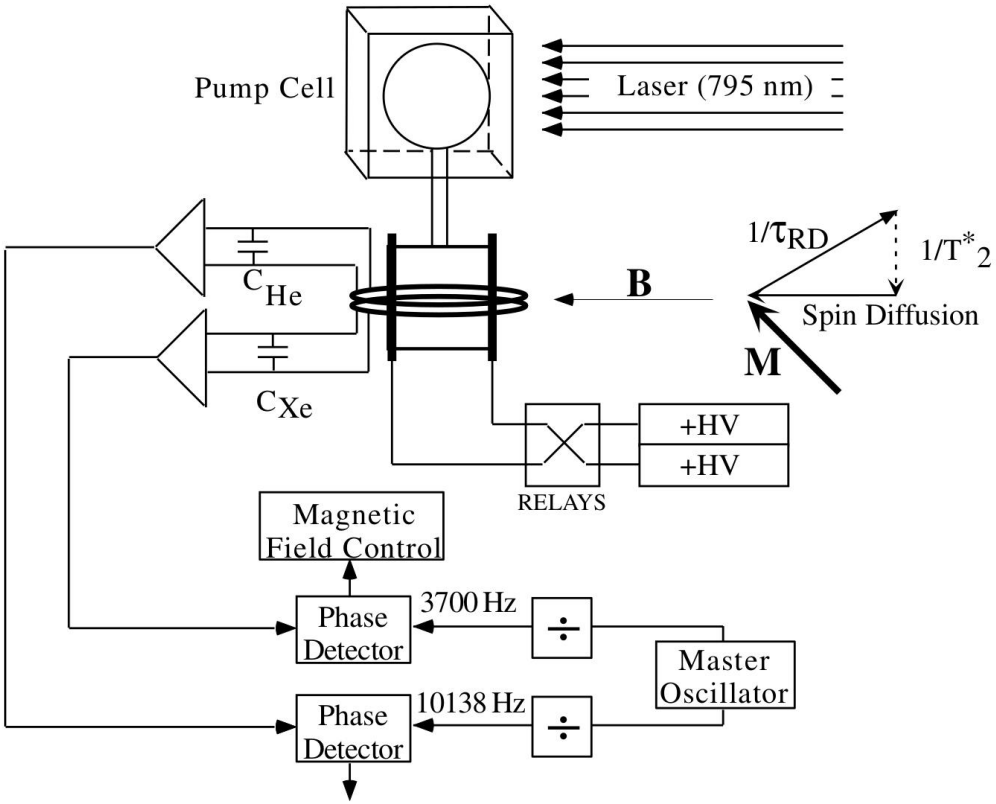


EDMs are a sensitive direct probe of new physics!

EDM "zero-results" put strong constrains on new physics models



	Neutron	^{199}Hg	^{129}Xe	^{225}Ra
	90% CL	95% CL	95% CL	95% CL
Exp. upper limit [*ecm*]	2.9×10^{-26}	7.4×10^{-30}	6.6×10^{-27}	1.4×10^{-24}
SM pred. [*ecm*]	~ 10^{-31} - 10^{-32}	~ 10^{-34}	~ 10^{-34}	
References Exp.	Baker, PRL **97**, 131801 (2006)	Graner, PRL **116**, 161601 (2016)	Rosenberry, PRL **86**, 22 (2001)	Bishof, Phys. Rev. C **94**, 025501 (2016)
References Pred.	Ellis, Nucl.Instr.Meth. A **284**, 33 (1989)	Donoghue, Phys.Lett. B **196**, 196 (1987)	Shushkov, Sov. Phys. JETP **60**, 873 (1984)	



Rosenberry et al, PRL 86, 22 (2001)

Result $d_{Xe} < 6.6 \times 10^{-27}$ ecm

3He-129Xe spin-maser

- Continuous diffusion of polarized gas into EDM cell
- Resonant pickup coils generate torque on magnetization
- Long observation times
- Electronics stability limitations

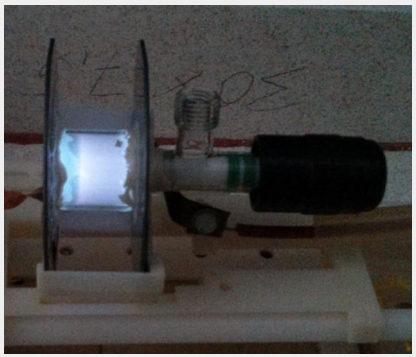
Ongoing efforts

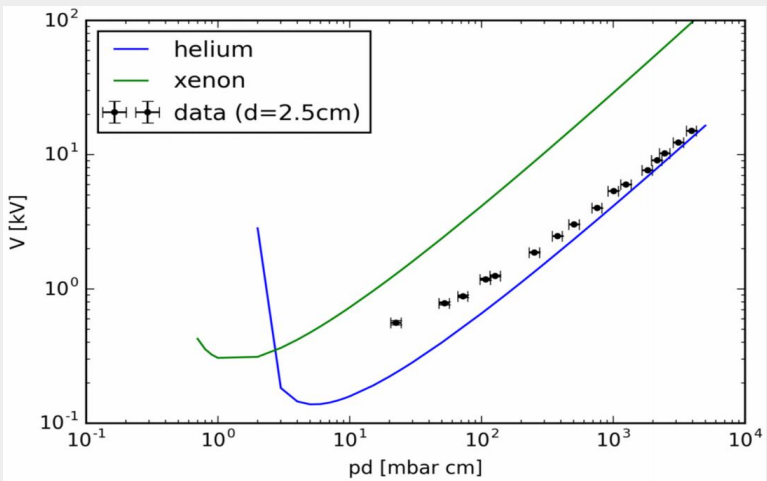
- Improved spin-maser with optical readout (Japan)
- MIXed collaboration
- HeXeEDM

MIXed
Measurement and Investigation of the Xenon-129 electric dipole moment

First EDM cells

- 1” GE180 cylinders with bonded/glued silicon electrodes (3” diameter)
- High-voltage breakdown tests



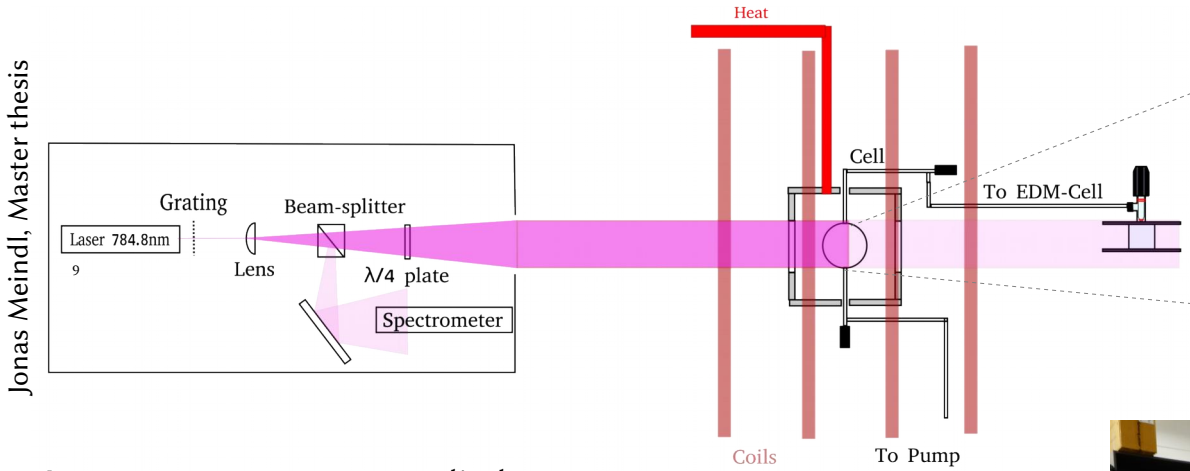


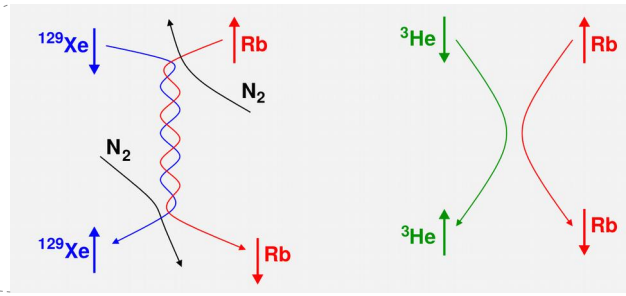
Eva Kraegeloh, Master thesis

New series of EDM cells

- Pyrex cylinders with bonded silicon electrodes (30mm diameter)
- made in Juelich glass shop
- high-field (mT) T1 ~ 6000 s/17400 s
- “PP2”: T2* ~ 6000-9000s
- (Xe and He, 1 muT, high pressure)

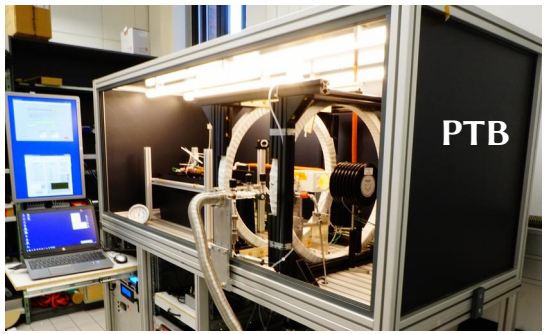
Simultaneous spin-exchange optical pumping of ^{3}He and ^{129}Xe

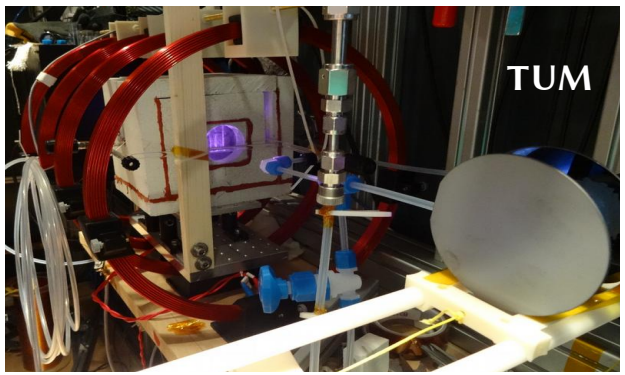


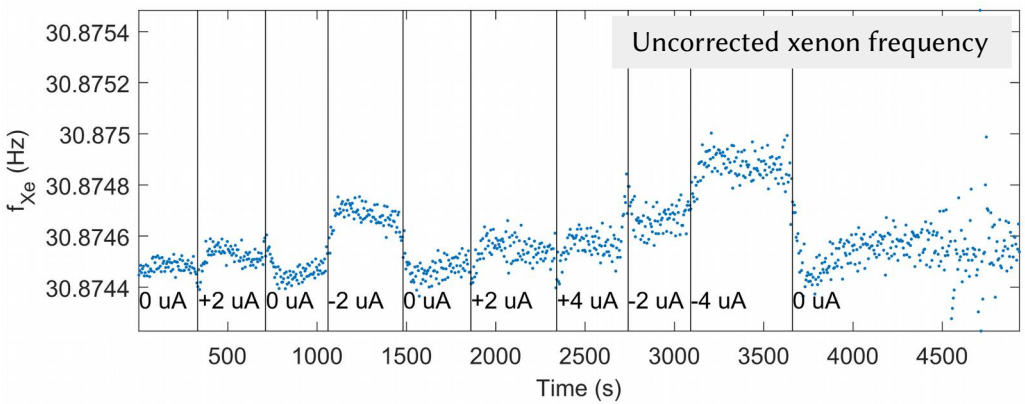


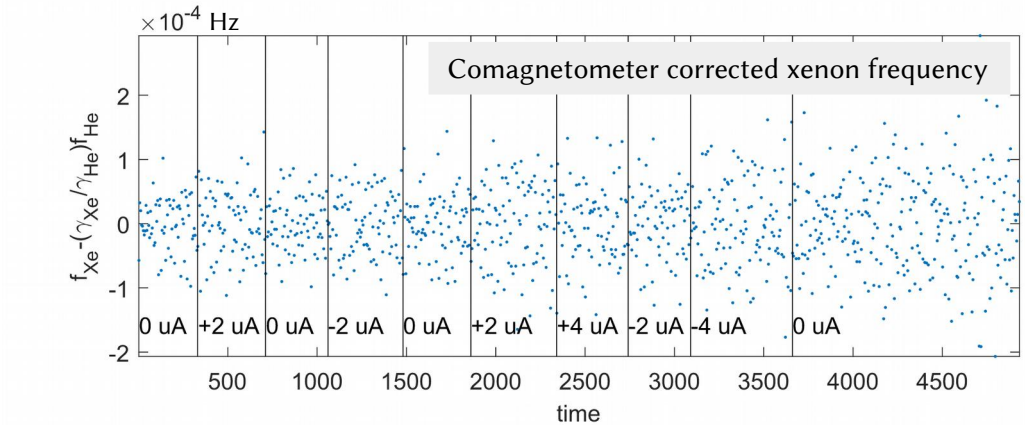
Walker et al, Rev. Mod. Phys. 69, 629 (1997)
Gentile et al, Rev. Mod. Phys. 89, 045004 (2017)

- Laser: 100 W diode array
  794.8 nm (water-cooled)
  width ~0.4 nm (narrowed by VBG)
- Holding field: B_0 ~ 3 mT
- Oven: >140 °C for ^{3}He (~ hrs)
  ~80 °C for ^{129}Xe (~min)
- OP cells: GE180 sealed bulbs
  GE180 with two Pyrex valves (TUM)
  Pyrex with one valve (PTB)
- Polarizer location: back of the MSR (TUM)
  one floor below the BMSR-II (PTB)
- Polarization: 9-12% ^{129}Xe; 0.1-0.2% ^{3}He (PTB)
  (EDM cell with 0.5-1.0 bar)

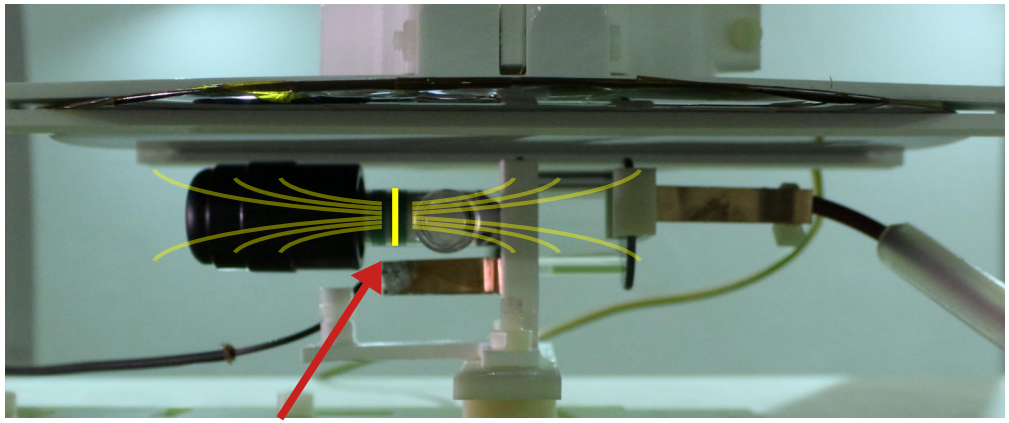






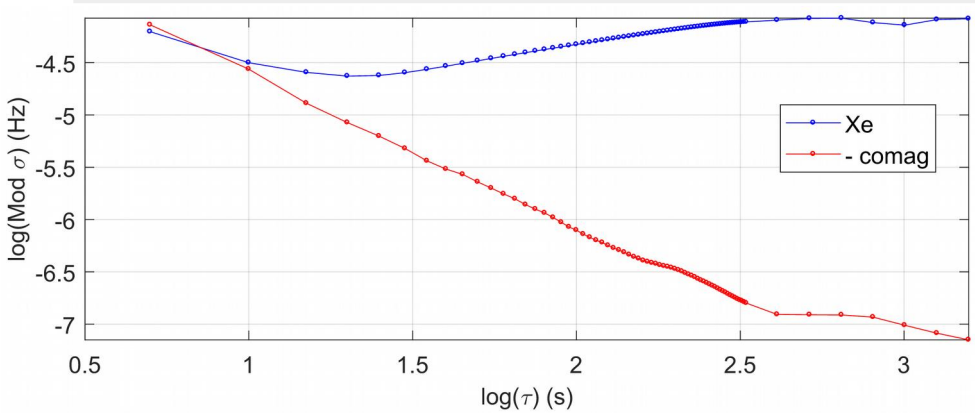


Observed hysteresis most likely due to magnetizing the stem/valve on EDM cell



Wire loop to generate fake magnetic field due to magnetic dipole nearby

Allan deviation of uncorrected and corrected xenon frequency
3He: 2 pT/7000s – 129Xe: 8 pT/4000s



Run	Cell	p [mbar]	$\hat{\mathbf{B}}_0$	$T^*_{2,\mathrm{Xe}}$ [s]	$T^*_{2,\mathrm{He}}$ [s]	r_{HV} [V/s]	t_{HV} [s]	Seq.	N_{tot}	$\lvert B_0\rvert$ [μT]
C82	PP2	960	$\hat{y}$	6593	6106	1000	400	A	36	2.622
C83	PP2	420	$\hat{y}$	7583	7132	1000	400	B	36	2.622
C84	PP2	976	$\hat{y}$	6929	6420	1000	400	B	36	2.622
C85	PP2	420	$\hat{y}$	7927	7462	1000	400	A	36	2.621
C86	PP1	950	$\hat{y}$	3727	5875	1000	400	A	36	2.621
C89	PP1	443	$\hat{y}$	3798	6488	1000	400	A	36	2.621
C91	PP1	1160	$\hat{y}$	4000	6557	2000	400	B	36	2.621
C92	PP1	510	$\hat{y}$	4040	7052	2000	800	B	18	2.621
C93	PP2	975	$\hat{y}$	7245	6807	1000	800	A	35	2.621
C02	PP2	970	$\hat{y}$	5344	4867	1000	800	B	36	2.621
C08	PP2	910	$-\hat{y}$	5366	4985	1000	400	A	36	2.630
C10	PP1	1020	$-\hat{y}$	3705	5783	1000	400	B	36	2.630
C12	PP2	450	$-\hat{y}$	8579	8082	1000	400	B	36	2.630
C13	PP2	950	$-\hat{y}$	7835	7301	1000	800	A	18	2.630
C14	PP2	456	$-\hat{y}$	7697	7281	1000	400	B	36	2.630
C15	PP1	560	$-\hat{y}$	3858	6650	1000	400	A	36	2.630