HeXe EDM – Motivation and Report

TUM
ESO
LMU
Excellence Cluster
Universe

PTB

MICHIGAN STATE
UNIVERSITY

JÜLICH
FORSCHUNGSZENTRUM

THE UNIVERSITY OF MICHIGAN
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1817

Collaboration - HeXeEDM

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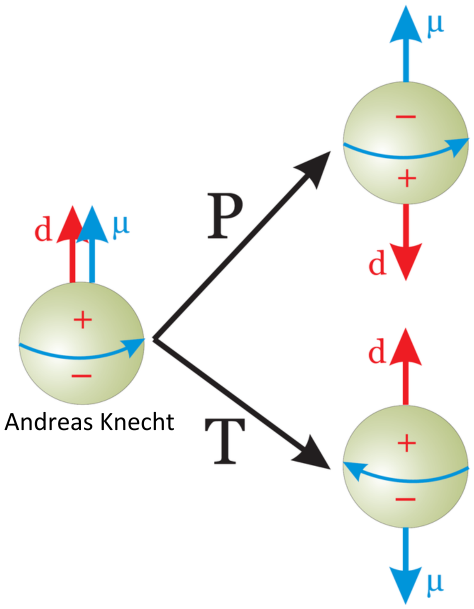
Motivations

1. $d_A(^{129}Xe)=(0.7\pm 3.3)x10\text{-}27$ e cm (2001!) We CAN do better.
2. Many sources of CP violation – don’t constrain individual EDMs
3. How we know ^{3}He EDM is << 10^{-28} e cm (^{199}Hg, ^{129}Xe)
4. nEDM comagnetometer – need $d_A(^{129}Xe)<10^{-27}$ e cm



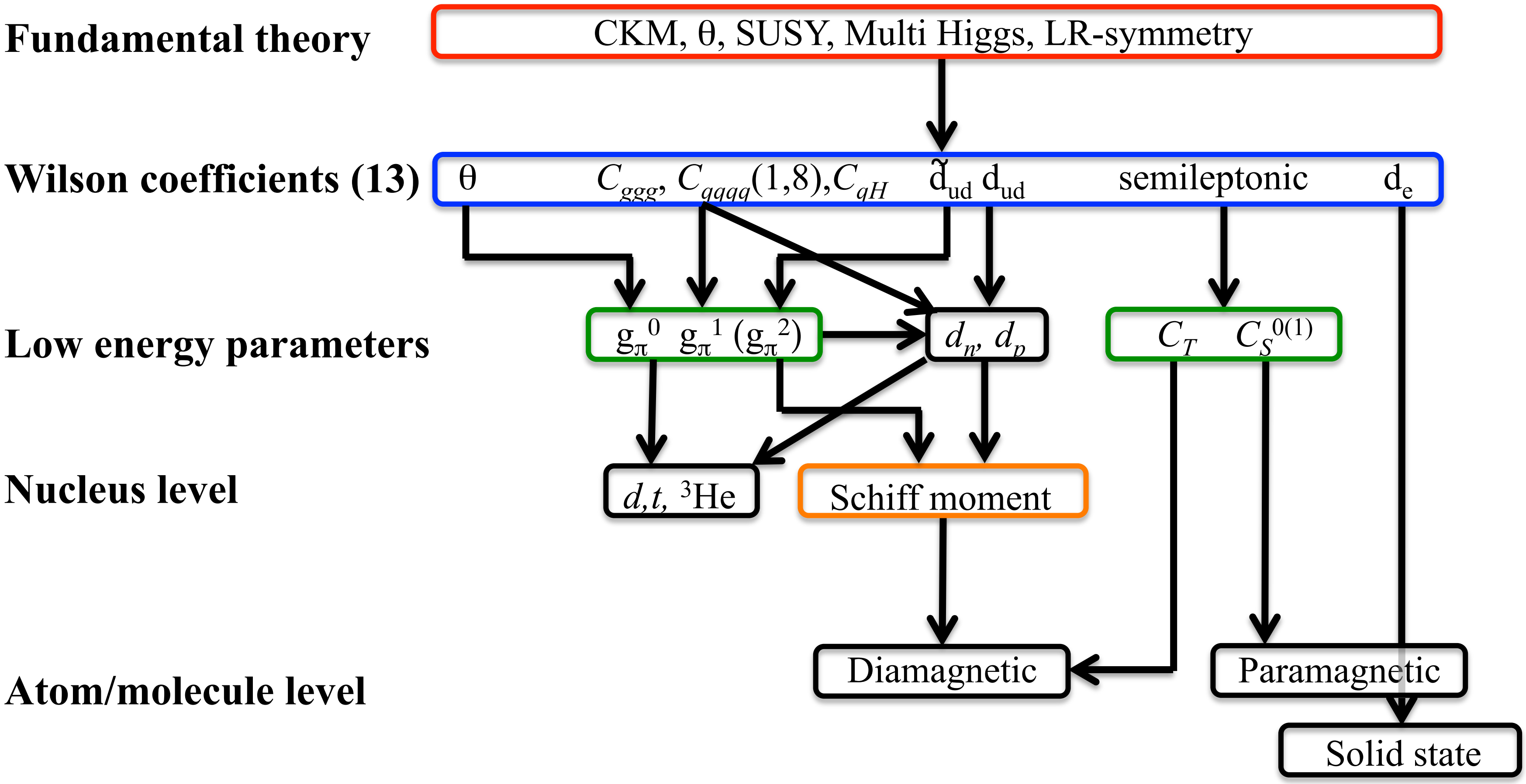
$$\vec{d} = \int \vec{r}(\rho_Q(\vec{r}) - \rho_m(\vec{r}))dV = d\vec{J}$$

Put this in *E* and *B* fields

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E} = \underbrace{-\mu\vec{J}\cdot\vec{B}}_{P_e T_e} - \underbrace{d\vec{J}\cdot\vec{E}}_{P_o T_o \,\to\, \cancel{CP}}$$

$\cancel{CP}$ Baryon Asymmetry ⟷ NEW PHYSICS (BSMP)

Atomic/Molecular EDMs arise from many sources



Fundamental theory CKM, θ, SUSY, Multi Higgs, LR-symmetry

Wilson coefficients (13) θ C_{ggg}, $C_{qqqq}(1,8)$, C_{qH} $\tilde{d}_{ud}$ d_{ud} semileptonic d_e

Low energy parameters g_π^0 g_π^1 (g_π^2) d_n, d_p C_T $C_S^{0(1)}$

Nucleus level d, t, ^{3}He Schiff moment

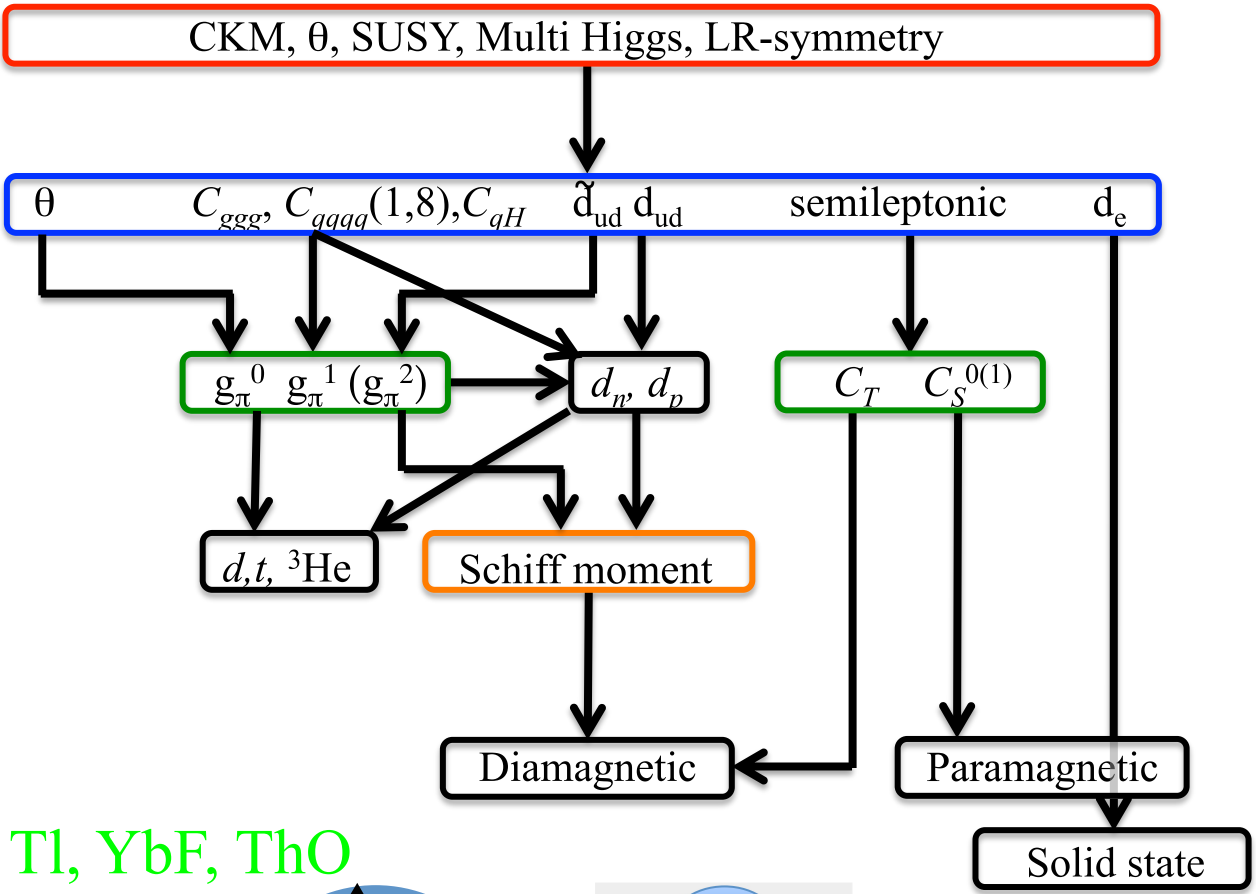
Atom/molecule level Diamagnetic Paramagnetic

Solid state

TC, Fierlinger, Ramsey Musolf, Singh arXiv 1710.02504

$$d_A = \eta_e d_e + \kappa_S S(\theta_{QCD}, g_\pi) + (k_T C_T + k_S C_S) + \text{h.o}$$

Atomic/Molecular EDMs arise from many sources



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$g_\pi^{\ 0}$ $g_\pi^{\ 1}$ ($g_\pi^{\ 2}$) d_n, d_p C_T $C_S^{\ 0(1)}$

Nucleus level

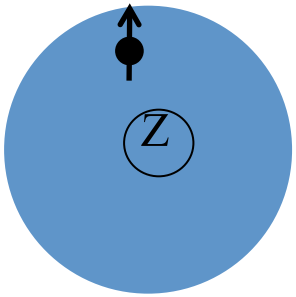
d,t, ^{3}He Schiff moment

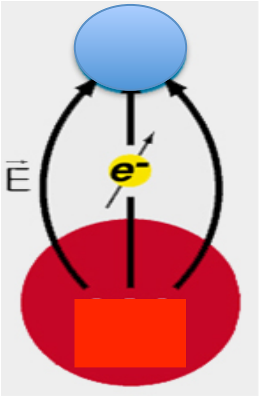
Atom/molecule level

Diamagnetic Paramagnetic Solid state

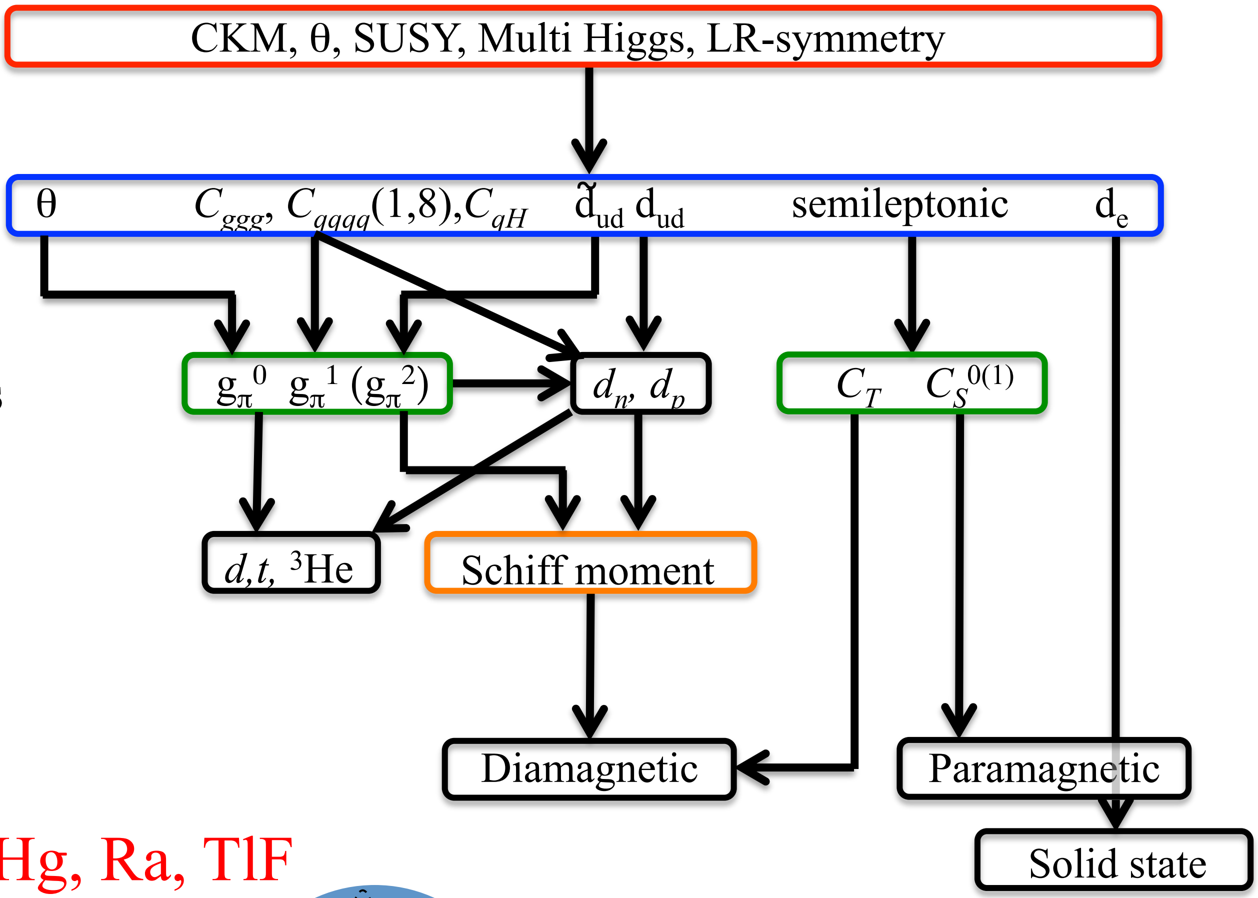
Paramagnetic : Cs, Tl, YbF, ThO

$$(\vec{L}\cdot\vec{S}\text{coupling})\,\vec{E}(\langle\vec{r}_e\rangle)\neq 0$$





Atomic/Molecular EDMs arise from many sources



Fundamental theory

CKM, θ, SUSY, Multi Higgs, LR-symmetry

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$g_\pi^{\ 0}$ $g_\pi^{\ 1}$ ($g_\pi^{\ 2}$) d_n, d_p C_T $C_S^{\ 0(1)}$

Nucleus level

d, t, ^{3}He Schiff moment

Atom/molecule level

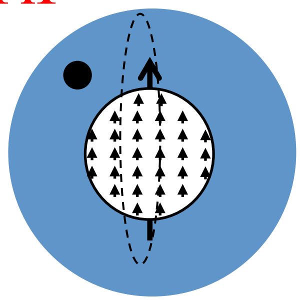
Diamagnetic Paramagnetic Solid state

Diamagnetic: Xe, Hg, Ra, TlF

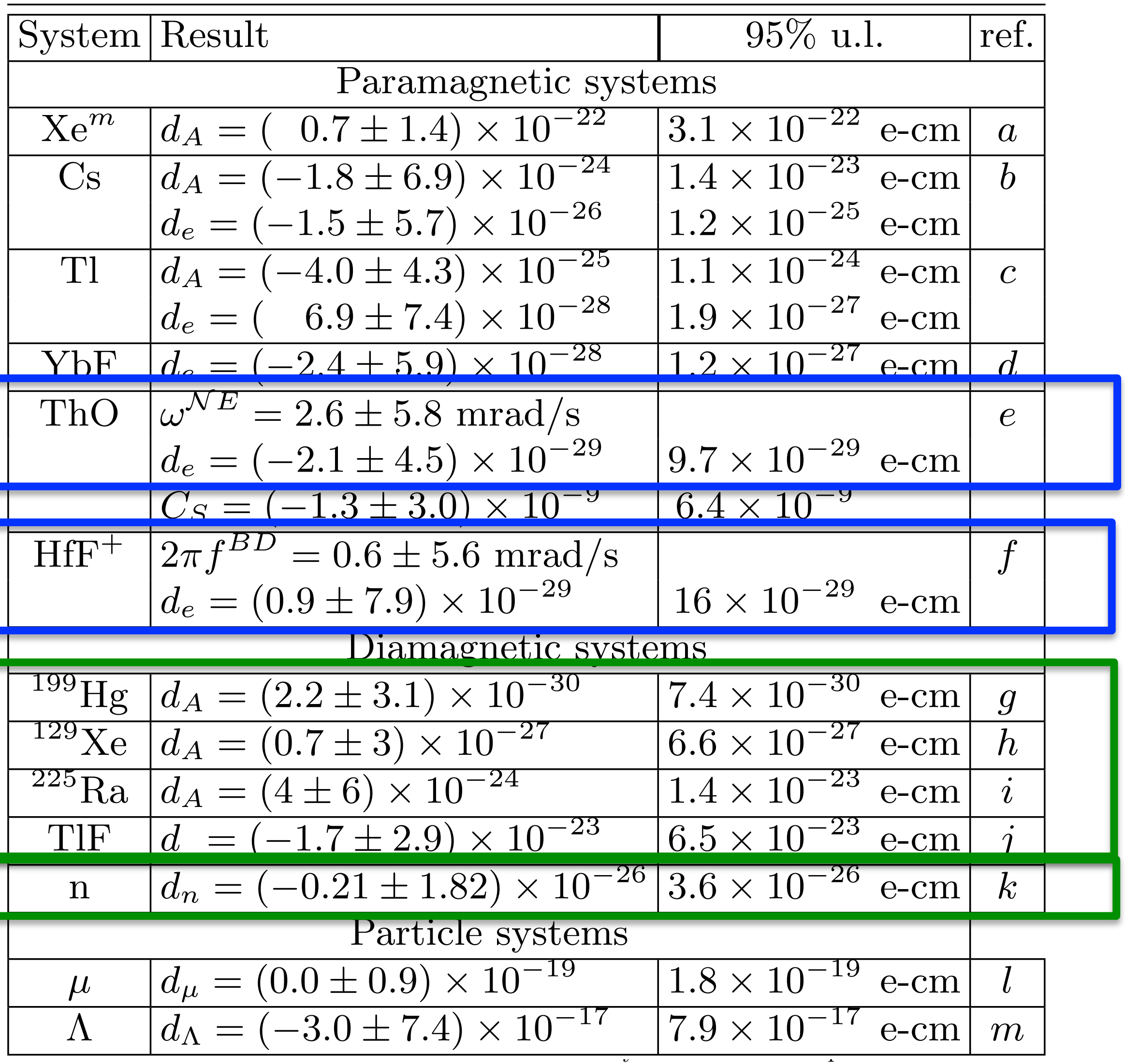
Schiff moment

$$\vec{S} = \frac{1}{10}\left\langle r^2 \vec{r}_p \right\rangle - \frac{1}{6} Z \left\langle r^2 \right\rangle \left\langle \vec{r}_p \right\rangle$$

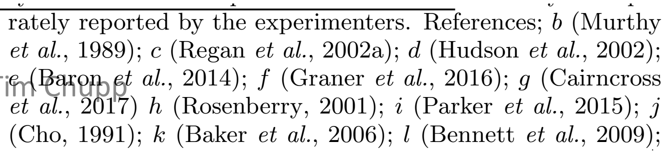
$$\vec{E} \propto \vec{J}$$



EDM results



System	Result	95% u.l.	ref.
	Paramagnetic systems		
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e-cm	a
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ $d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.4×10^{-23} e-cm 1.2×10^{-25} e-cm	b
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ $d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.1×10^{-24} e-cm 1.9×10^{-27} e-cm	c
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e-cm	d
ThO	$\omega^{\mathcal{N}E} = 2.6 \pm 5.8$ mrad/s $d_e = (-2.1 \pm 4.5) \times 10^{-29}$ $C_S = (-1.3 \pm 3.0) \times 10^{-9}$	 9.7×10^{-29} e-cm 6.4×10^{-9}	e
HfF^+	$2\pi f^{BD} = 0.6 \pm 5.6$ mrad/s $d_e = (0.9 \pm 7.9) \times 10^{-29}$	 16×10^{-29} e-cm	f
	Diamagnetic systems		
$^{199}\mathrm{Hg}$	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e-cm	g
$^{129}\mathrm{Xe}$	$d_A = (0.7 \pm 3) \times 10^{-27}$	6.6×10^{-27} e-cm	h
$^{225}\mathrm{Ra}$	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e-cm	i
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e-cm	j
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26} e-cm	k
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e-cm	l
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	7.9×10^{-17} e-cm	m



rately reported by the experimenters. References; b (Murthy *et al.*, 1989); c (Regan *et al.*, 2002a); d (Hudson *et al.*, 2002); e (Baron *et al.*, 2014); f (Graner *et al.*, 2016); g (Cairncross *et al.*, 2017) h (Rosenberry, 2001); i (Parker *et al.*, 2015); j (Cho, 1991); k (Baker *et al.*, 2006); l (Bennett *et al.*, 2009);

Sole-source analysis

Parameter	system	95% u.l.
d_e	ThO	9.2×10^{-29} e-cm
C_S	ThO	8.6×10^{-9}
C_T	^{199}Hg	3.6×10^{-10}
$\bar{g}_\pi^0$	^{199}Hg	3.8×10^{-12}
$\bar{g}_\pi^0$	neutron	2.2×10^{-12}
$\bar{g}_\pi^1$	^{199}Hg	3.8×10^{-13}
$\bar{g}_\pi^1$	TlF	4.1×10^{-10}
$\bar{g}_\pi^2$	^{199}Hg	2.6×10^{-11}
$\bar{d}_n^{sr}$	neutron	3.3×10^{-26} e-cm
$\bar{d}_p^{sr}$	TlF	8.7×10^{-23} e-cm
$\bar{d}_n^{sr}$	^{199}Hg	2.0×10^{-25} e-cm

Other parameters		
d_d	$\approx 3/4 d_n$	2.5×10^{-26} e-cm
$\bar{\theta}$	$\approx \bar{g}_\pi^0/(0.02)$	1.9×10^{-10}
$\tilde{d}_d - \tilde{d}_u$	$5 \times 10^{-15} \bar{g}_\pi^1$ e-cm	2×10^{-27} e-cm

Global analysis

Permanent Electric Dipole Moments of Atoms and Molecules

$$d_{\mathrm{A}} = k_{\mathrm{S}} S + \eta_{\mathrm{e}} d_{\mathrm{e}} + (k_{\mathrm{T}} C_{\mathrm{T}} + k_{\mathrm{S}} C_{\mathrm{S}} + k_{\mathrm{P}} C_{\mathrm{P}}). \tag{10}$$

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Tim: “Michael, how many EDM experiments do we need?”

Michael: “Only the one that discovers an EDM.”

Tim: “Oh – so now I know the one to work on!”

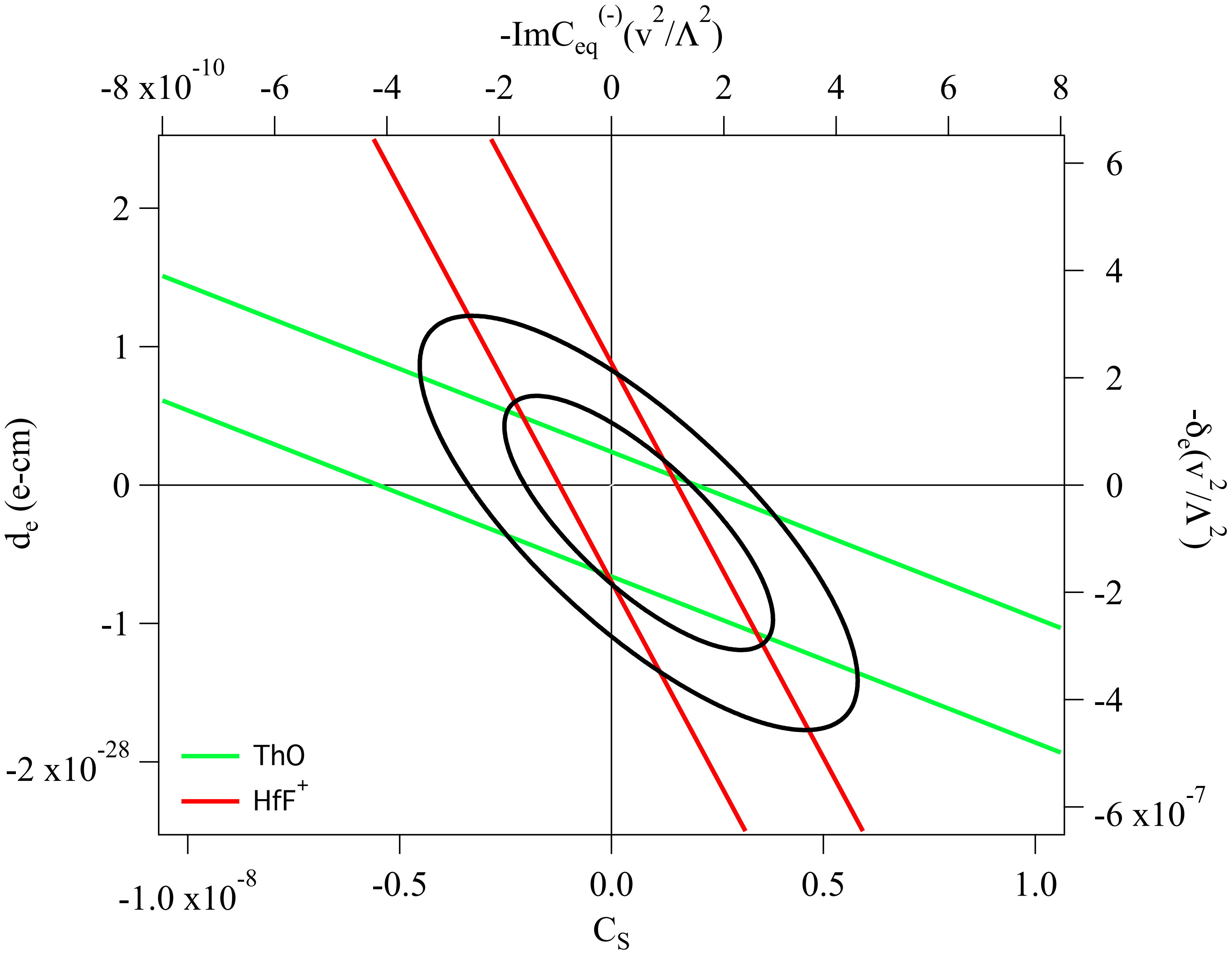
PHYSICAL REVIEW C **91**, 035502 (2015)

Electric dipole moments: A global analysis

TC, Fierlinger, Ramsey Musolf, Singh arXiv 1710.02504

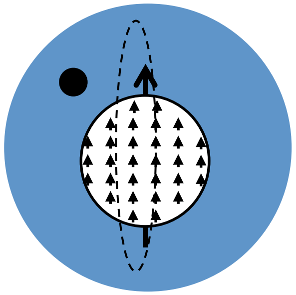
Global Analysis: Paramagnetic atoms isolate d_e, C_S

TC, Fierlinger, Ramsey-Musolf, Singh arXiv 1710.02504



Hadronic Systems

Currently: data from 5 experiments:



$\vec{E} \propto \vec{J}$

		d_0^{sr}	d_1^{sr}	C_T	g_π^0	g_π^1
Results	neutron	1	-1			
	Xe, Hg, TlF, Ra			x	x	x
Future	proton	1	+1			
	d, ^{3}H, ^{3}He				x	x

sr

$$d_n = \bar{d}_n^{\rm sr} - \frac{e g_A \bar{g}_\pi^{(0)}}{8\pi^2 F_\pi}\left\{\ln\frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2m_N} + \frac{\bar{g}_\pi^{(1)}}{4\bar{g}_\pi^{(0)}}(\kappa_1 - \kappa_0)\frac{m_\pi^2}{m_N^2}\ln\frac{m_\pi^2}{m_N^2}\right\}$$

$$d_A = \alpha_{C_T} C_T + \kappa_S(a_0\bar{g}_\pi^0 + a_1\bar{g}_\pi^1 + \cancel{a_2\bar{g}_\pi^2})$$

Global Analysis

Find χ^2 contours for 4-parameters

$$d = \alpha_{d_e} d_e + \alpha_{C_S} C_S + \alpha_{C_T} C_T + \alpha_{\bar{d}_n^{\rm sr}} \bar{d}_n^{\rm sr} + \alpha_{\bar{d}_p^{\rm sr}} \bar{d}_p^{\rm sr} + \alpha_{g_\pi^0} \bar{g}_\pi^0 + \alpha_{g_\pi^1} \bar{g}_\pi^1$$

$$d_i = \sum_i \alpha_{ij} C_j$$

System	$\partial d^{exp}/\partial d_e$	$\partial d^{exp}/\partial C_S$	$\partial d^{exp}/\partial C_T^{(0)}$	$\partial d^{exp}/\partial g_\pi^0$	$\partial d^{exp}/\partial g_\pi^1$	$\partial d^{exp}/\partial \bar{d}_n^{sr}$
neutron	0	0	0	1.5×10^{-14}	1.4×10^{-16}	1
^{129}Xe	-0.0008	-4.4×10^{-23} -4.4-(-5.6)	-6.1×10^{-21} -6.1-(-9.1)	-0.4×10^{-19} -23.4-(1.8)	-2.2×10^{-19} -19-(-1.1)	1.7×10^{-5} 1.7-2.4
^{199}Hg	-0.014 -0.014-0.012	-5.9×10^{-22}	3.0×10^{-20} 3.0-9.0	-11.8×10^{-18} -38-(-9.9)	0 $(-4.9$-$1.6) \times 10^{-17}$	-5.3×10^{-4} -7.7-(-5.2)
^{225}Ra			5.3×10^{-20}	1.7×10^{-15} 6.9-0.9	-6.9×10^{-15} -27.5-(-3.8)	$(-1.6$-$0) \times 10^{-3}$
TlF	81	2.9×10^{-18}	2.7×10^{-16}	1.9×10^{-14} 0.5-2	-1.6×10^{-13}	0.46 -0.5-0.5

$$\chi^2(\mathbf{C_j}) = \sum_i \frac{(d_i^{\rm exp} - d_i)^2}{\sigma^2_{d_i^{\rm exp}}}$$

TC, Fierlinger, Ramsey-Musolf, Singh arXiv 1710.02504

Global Analysis

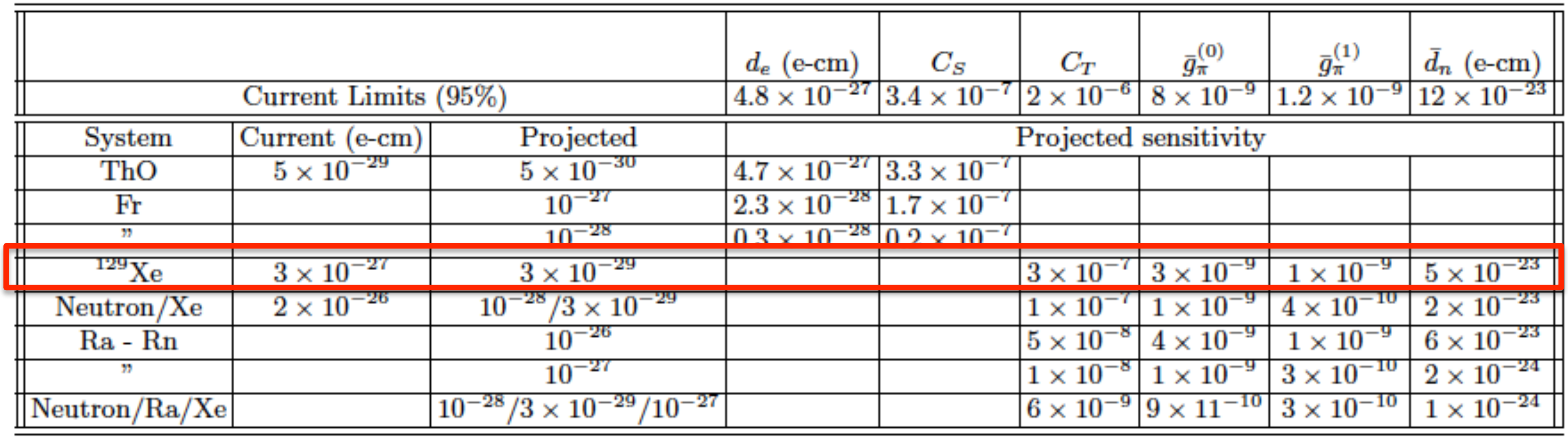
$$d_i = \sum_i \alpha_{ij} C_j$$

$$\begin{bmatrix} d_{Hg} \\ d_{Xe} \\ d_{TlF} \\ d_n \end{bmatrix} = \begin{bmatrix} -2.0\times10^{-20} & -3.8\times10^{-18} & 0 & 0 \\ 4.0\times10^{-21} & -2.9\times10^{-19} & -2.2\times10^{-19} & 0 \\ 1.1\times10^{-16} & 1.2\times10^{-14} & -1.6\times10^{-13} & 0 \\ 0 & 1.5\times10^{-14} & 1.4\times10^{-16} & 1 \end{bmatrix} \times \begin{bmatrix} C_T \\ \tilde{g}_\pi^0 \\ \tilde{g}_\pi^1 \\ d_n^{sr} \end{bmatrix}$$

$$\begin{bmatrix} C_T \\ \tilde{g}_\pi^0 \\ \tilde{g}_\pi^1 \\ d_n^{sr} \end{bmatrix} = \begin{bmatrix} -1.48\times10^{19} & 1.83\times10^{20} & -2.52\times10^{14} & 0 \\ -1.85\times10^{17} & -9.64\times10^{17} & 1.32\times10^{12} & 0 \\ -2.41\times10^{16} & 5.36\times10^{16} & -6.32\times10^{12} & 0 \\ 2.78\times10^{3} & 1.44\times10^{4} & -1.90\times10^{-2} & 1 \end{bmatrix} \times \begin{bmatrix} d_{Hg} \\ d_{Xe} \\ d_{TlF} \\ d_n \end{bmatrix}$$

TC, Fierlinger, Ramsey-Musolf, Singh arXiv 1710.02504

Impact and Discovery



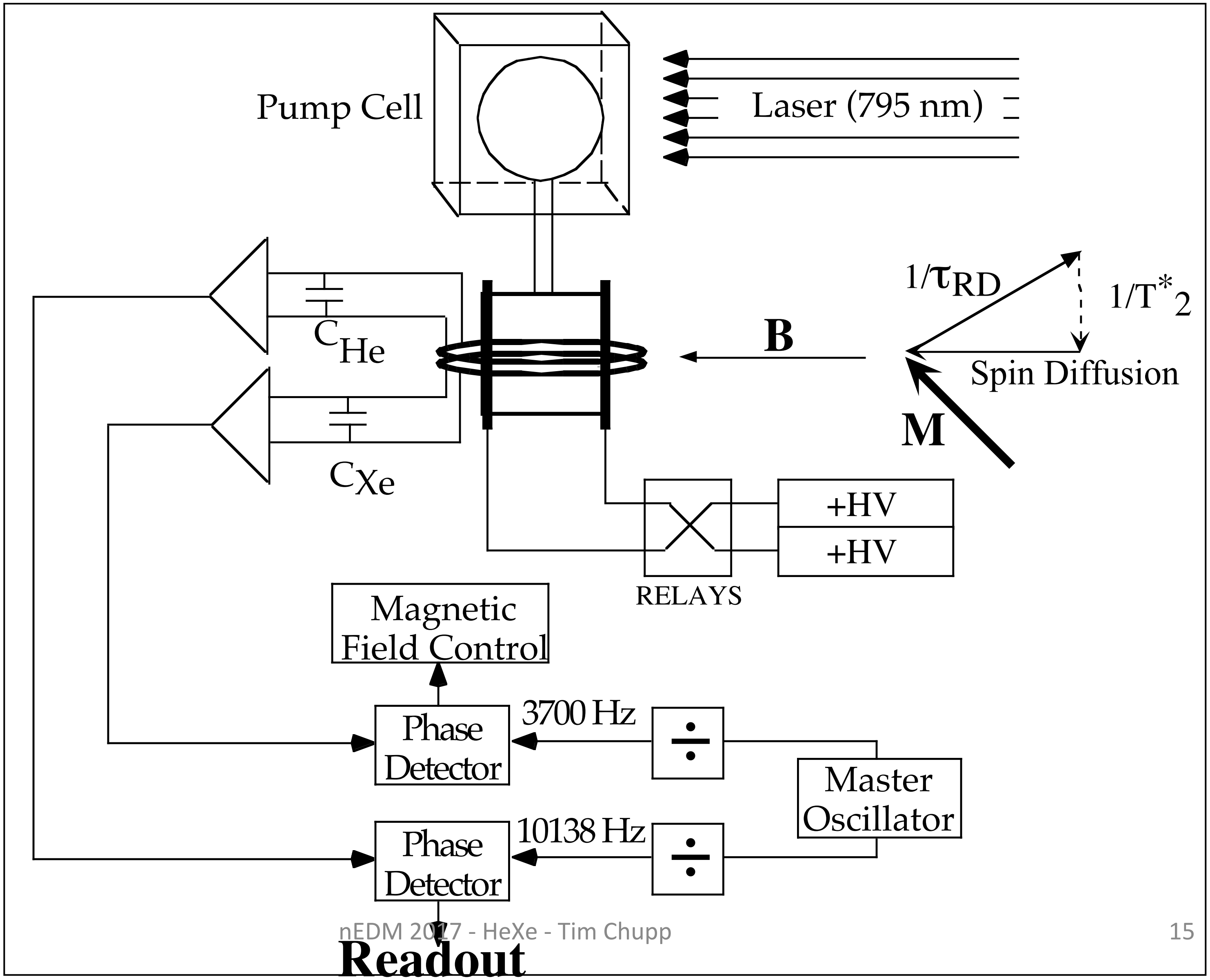
			d_e (e-cm)	C_S	C_T	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n$ (e-cm)
Current Limits (95%)			4.8×10^{-27}	3.4×10^{-7}	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	12×10^{-23}
System	Current (e-cm)	Projected	Projected sensitivity					
ThO	5×10^{-29}	5×10^{-30}	4.7×10^{-27}	3.3×10^{-7}				
Fr		10^{-27}	2.3×10^{-28}	1.7×10^{-7}				
"		10^{-28}	0.3×10^{-28}	0.2×10^{-7}				
^{129}Xe	3×10^{-27}	3×10^{-29}			3×10^{-7}	3×10^{-9}	1×10^{-9}	5×10^{-23}
Neutron/Xe	2×10^{-26}	$10^{-28}/3 \times 10^{-29}$			1×10^{-7}	1×10^{-9}	4×10^{-10}	2×10^{-23}
Ra - Rn		10^{-26}			5×10^{-8}	4×10^{-9}	1×10^{-9}	6×10^{-23}
"		10^{-27}			1×10^{-8}	1×10^{-9}	3×10^{-10}	2×10^{-24}
Neutron/Ra/Xe		$10^{-28}/3 \times 10^{-29}/10^{-27}$			6×10^{-9}	9×11^{-10}	3×10^{-10}	1×10^{-24}

Current ^{129}Xe efforts

- TRIUMF/nEDM
- Active maser: Tokyo
- MIXed (Mainz/Heidelberg/Juelich)
- HeXe (TUM, PTB, MSU, Umich)

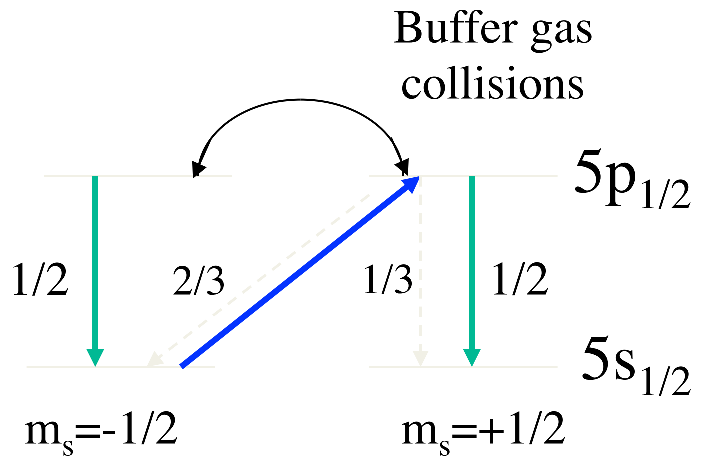
^{129}Xe Spin Exchange Pumped Zeeman Maser

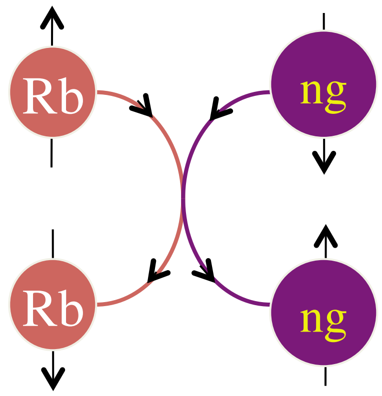
T. Chupp et al. PRL 72, p 2363 (1994) **R. Stoner et al. PRL 77, p 3971 (1996)** **D. Bear et al. PRA 57, p 5006 (1998)**



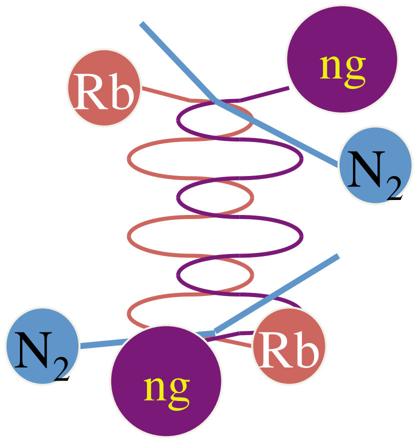
Spin-Exchange Optical Pumping

- Optically pump the Rb with circularly polarized laser light.
- Spin-exchange collisions transfer the polarization to the ^{3}He, ^{129}Xe, radon nuclei.





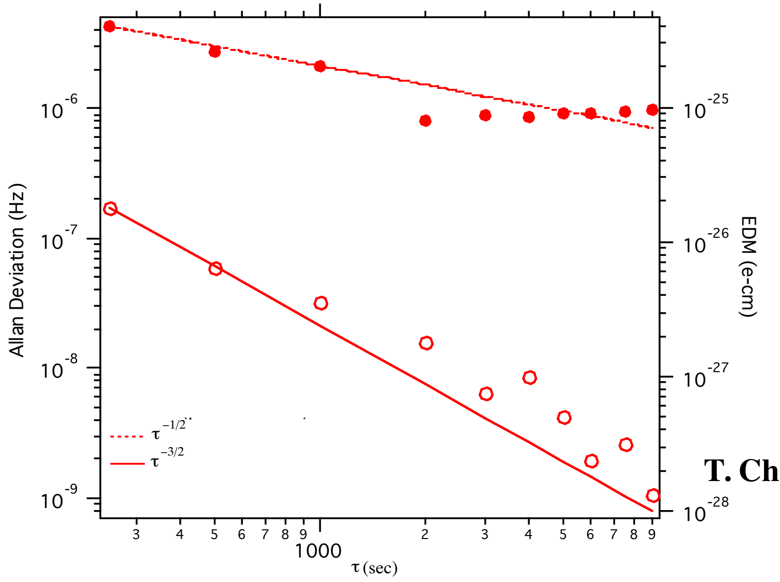
Binary Collision:
τ~10^{-12} sec.



van Der Waals Molecule

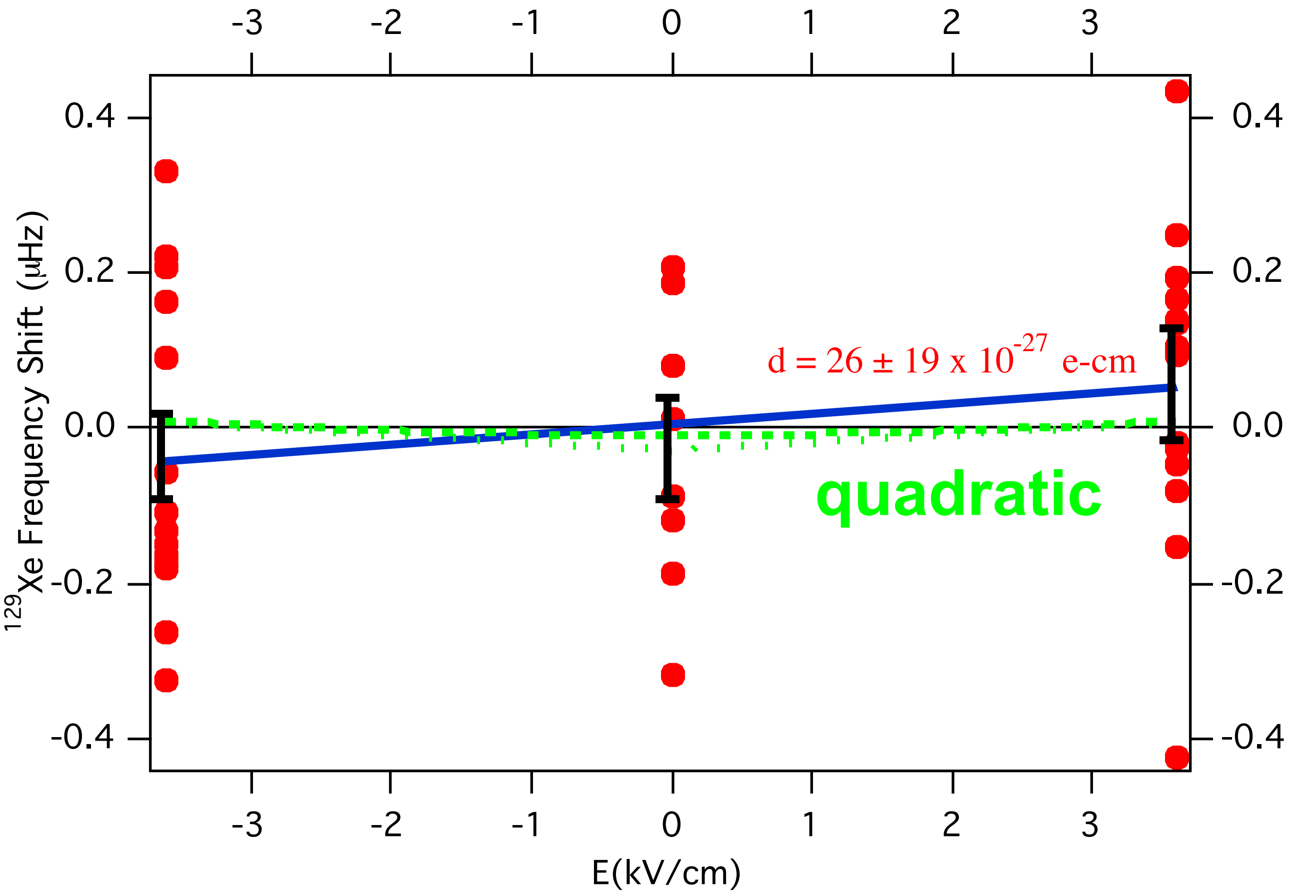
^{3}He Comagnetometer

- EDM ~ Z^2 for Schiff moment and C_T
- Polarized by spin exchange-optical pumping
- Monitor magnetic fields – due to leakage current
- Lock field to ^{129}Xe – change E – measure B with ^{3}He



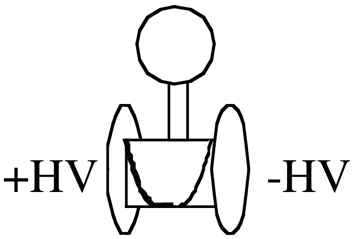
T. Chupp et al. PRL 72, p 2363 (1994)

EDM Run


-3
-2
-1
0
1
2
3
0.4
0.2
0.0
-0.2
-0.4
^{129}Xe Frequency Shift (μHz)
E(kV/cm)
d = 26 ± 19 x 10^{-27} e-cm
quadratic

False EDM Signals

Cell Leakage Currents
Two Species -- BUT not quite in the same place
CHECK: (1μA loop around cell) $d<1\times10^{-28}$ e-cm (20 pA)



E^2 Correlations (Polarizability; Noise)

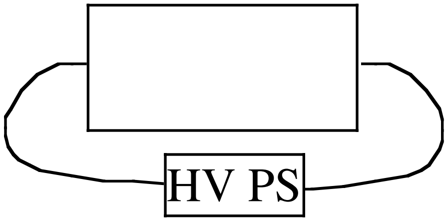
CHECK: $(d\nu/d(E^2) = (7\pm3)\times10^{-9}$ Hz/kV^2/cm^2

Reference Oscillators Disturbed by E, E2

CHECK: (clock test) $d<1\times10^{-28}$ e-cm

Charging Currents Magnetize Shields
PLL Control Loop Droop
Cavity Pulling Changes

CHECK: Zeros: $d<1\times10^{-26}$ e-cm (stat)



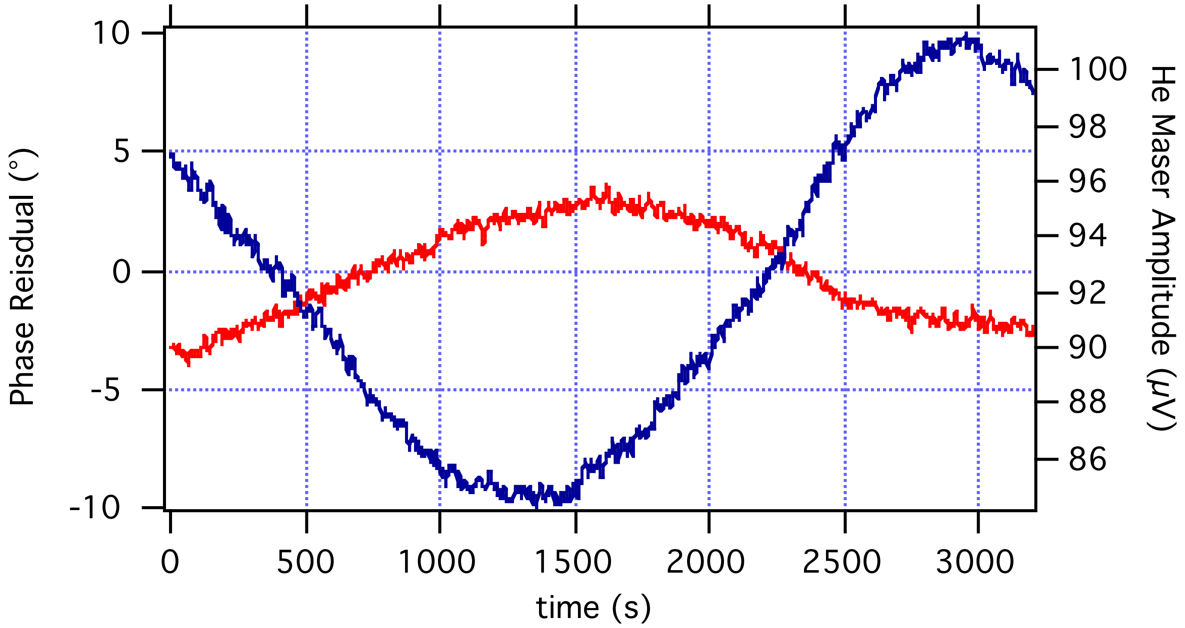
0 + - + - 0 - + - + 0 + - + - 0 - + - + ...

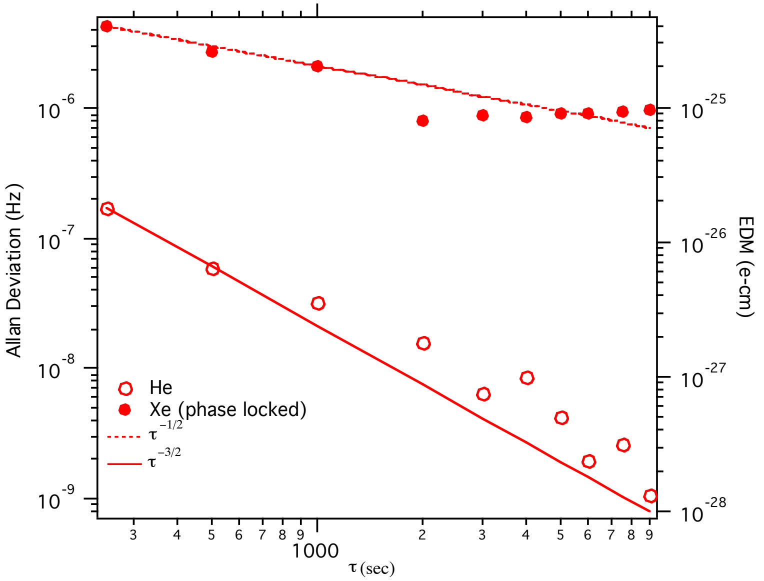
+ Memory?
- Memory?
+ Memory?

FLIP B

Much smaller than statistical error.

Magnetic Crosstalk

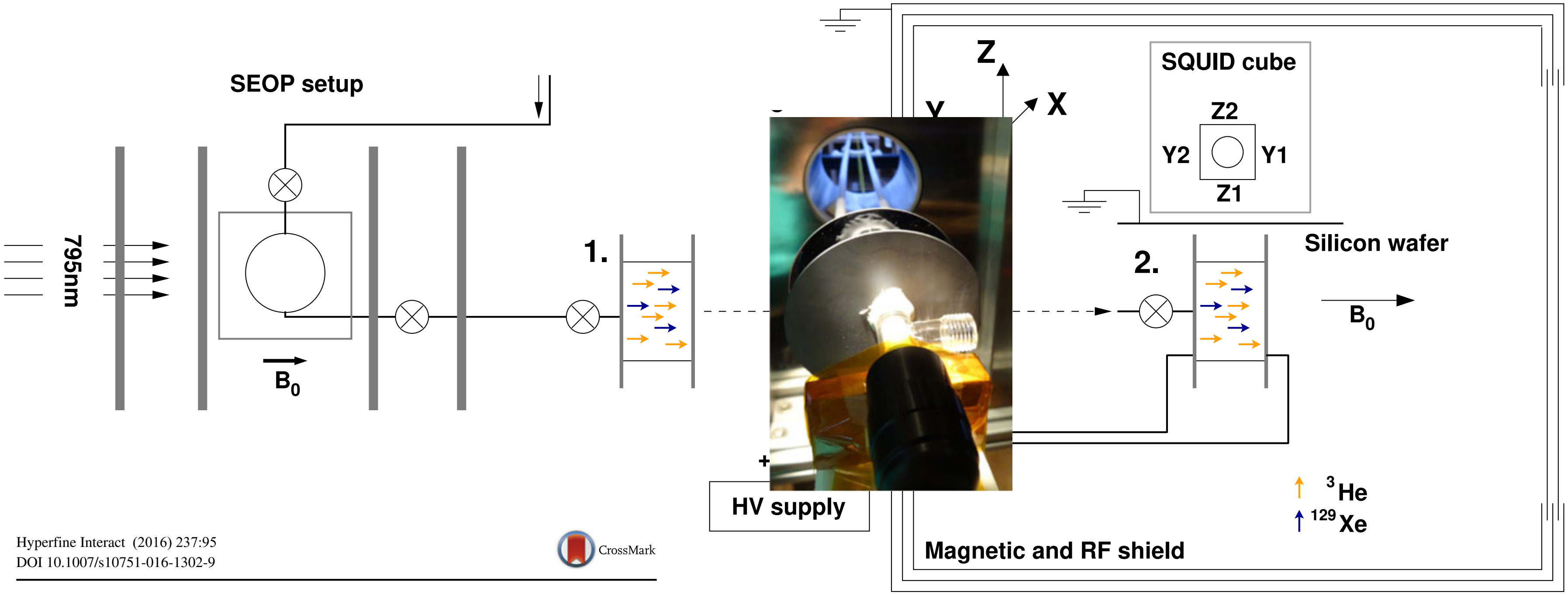


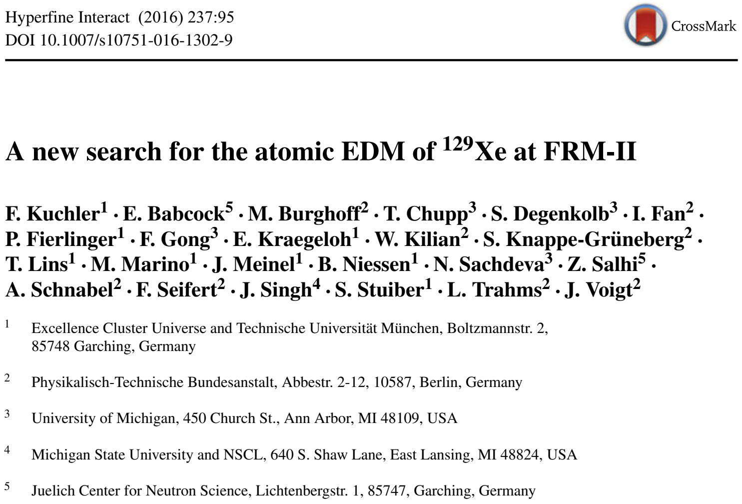


HeXeEDM

- High signal to noise SQUID detection
- Xe-129/He-3 co-magnetometer
- ~ nT remnant *B*-field
- ~ pT/cm gradients
- Stage-1 FRM-II/TUM 2-layer MSR
- Stage-2 PTB MSR2

HeXeEDM




Hyperfine Interact (2016) 237:95
DOI 10.1007/s10751-016-1302-9

CrossMark

A new search for the atomic EDM of ^{129}Xe at FRM-II

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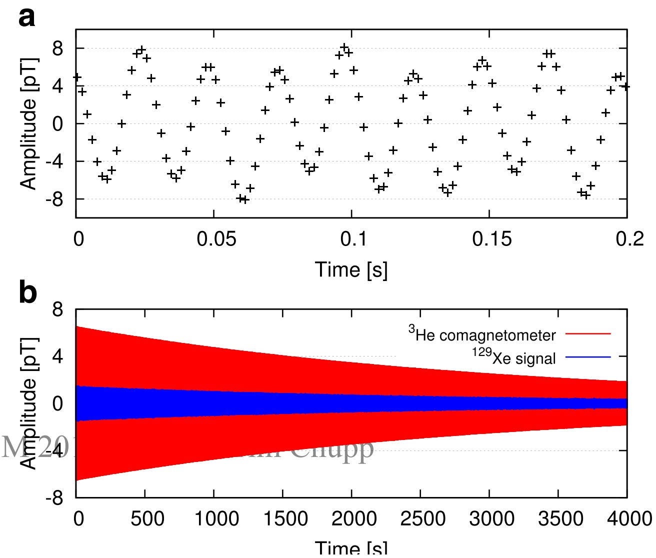
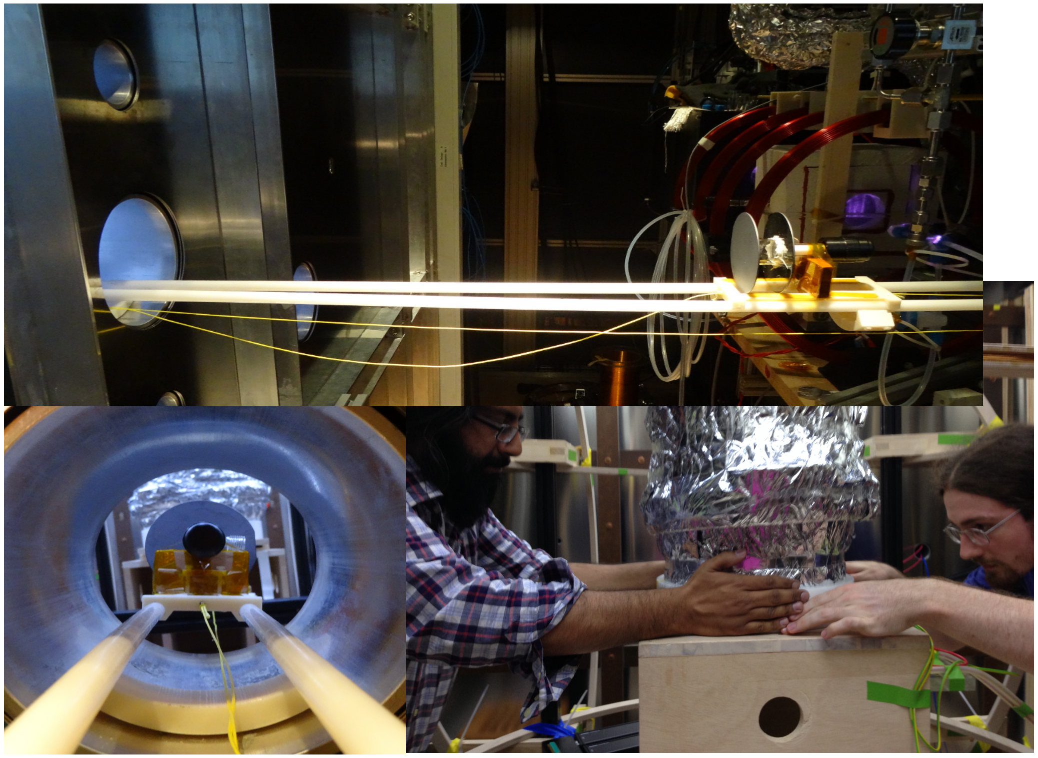


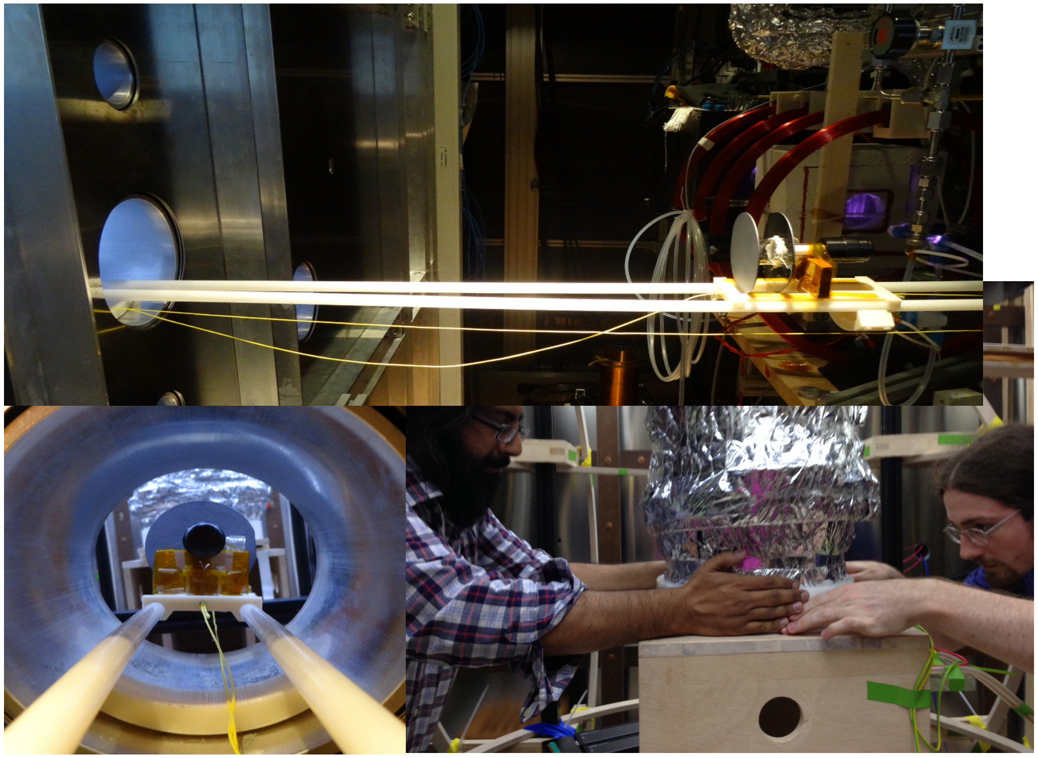
HeXeEDM



- ~ 2 weeks of "data" for Jonas and Natasha
- Systematic studies
  - Co-magnetometer leakage current cancellation
  - Hysteresis effects from dipole

Signal amplitude in shield

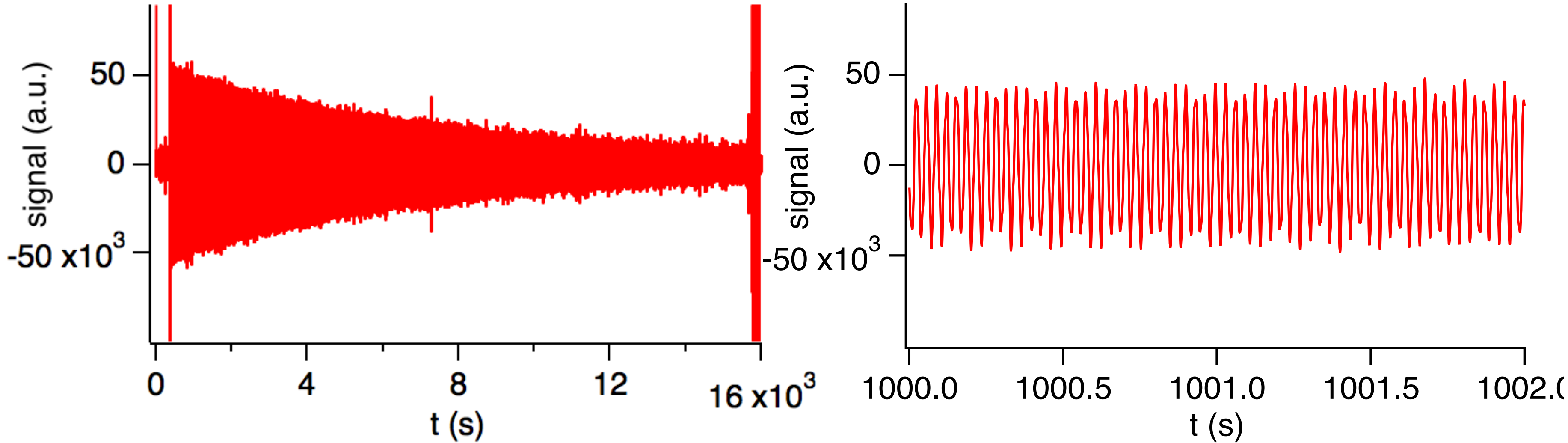
HeXeEDM

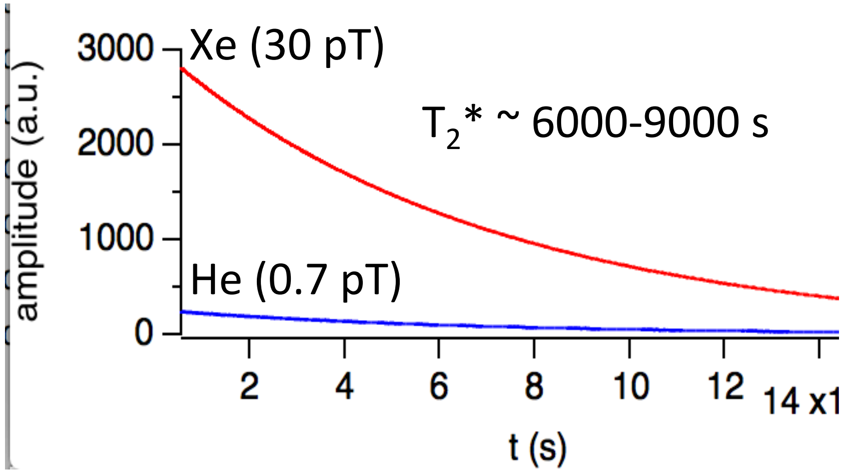


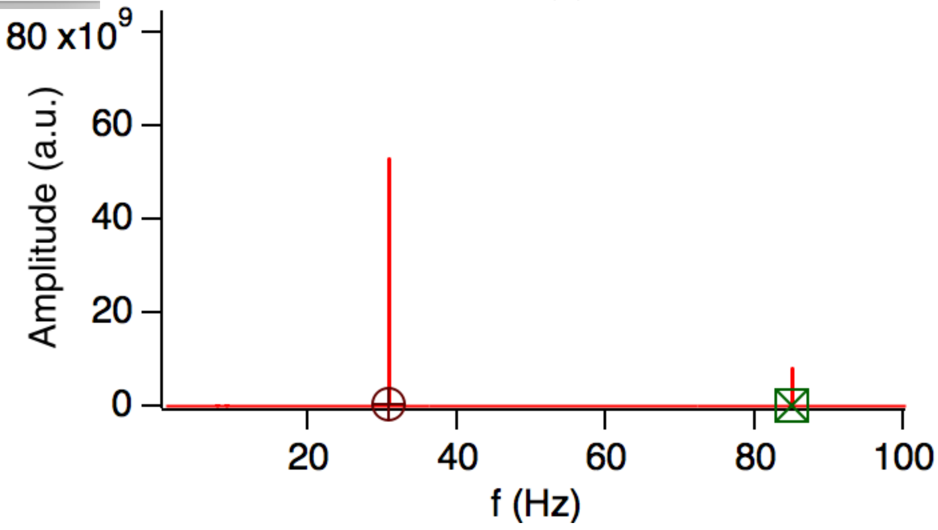
	^{129}Xe [pT]	^{3}He [pT]	
TUM 2016	13	44	less repeatable; laser drift
PTB 2017	25-40	5-7	pyrex pumping cell; "dirty" Rb?

Signal amplitude in shield

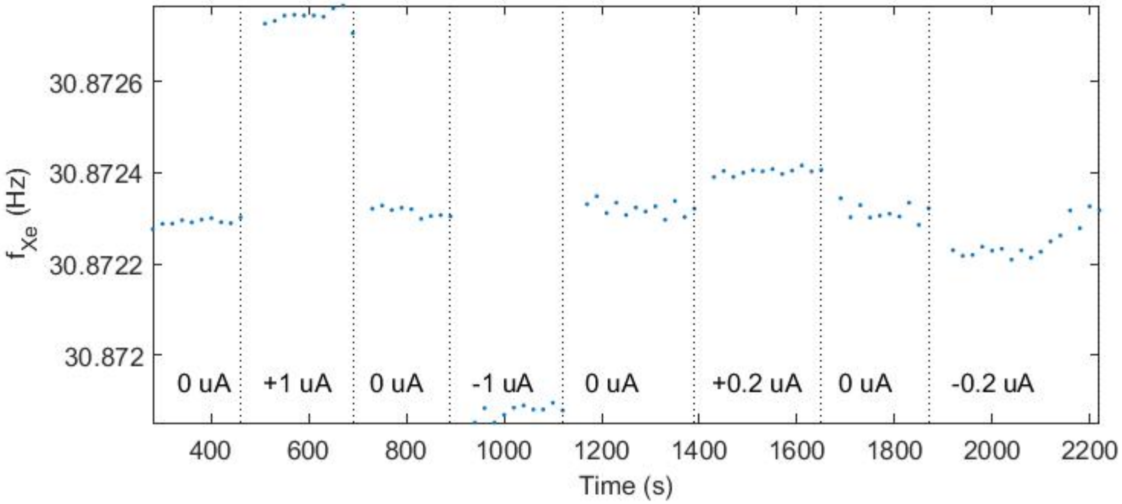
June 2017 PTB “test run”

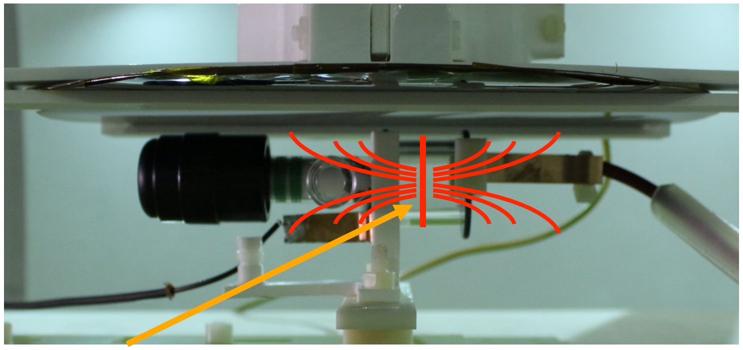




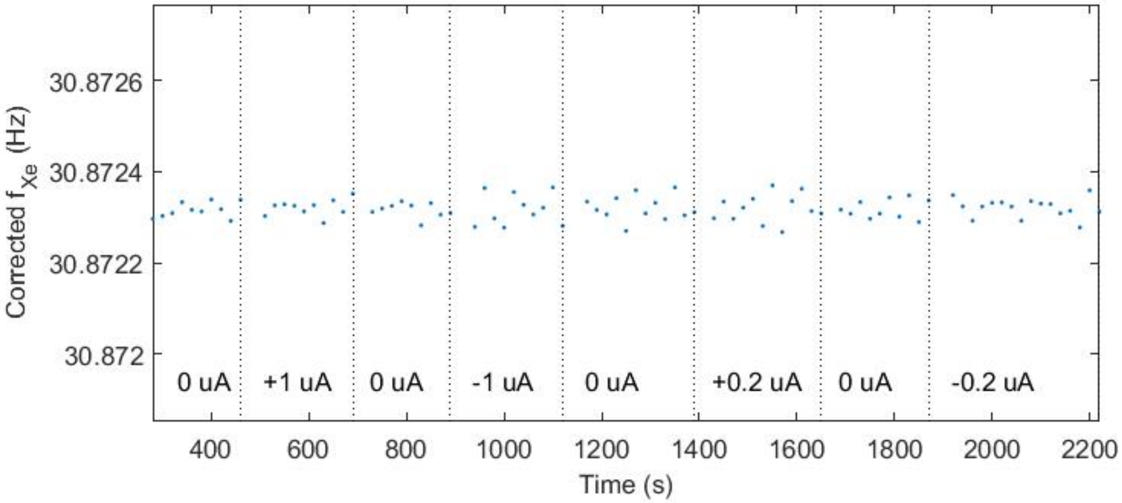


Leakage current test





Single loop – leakage current simulation

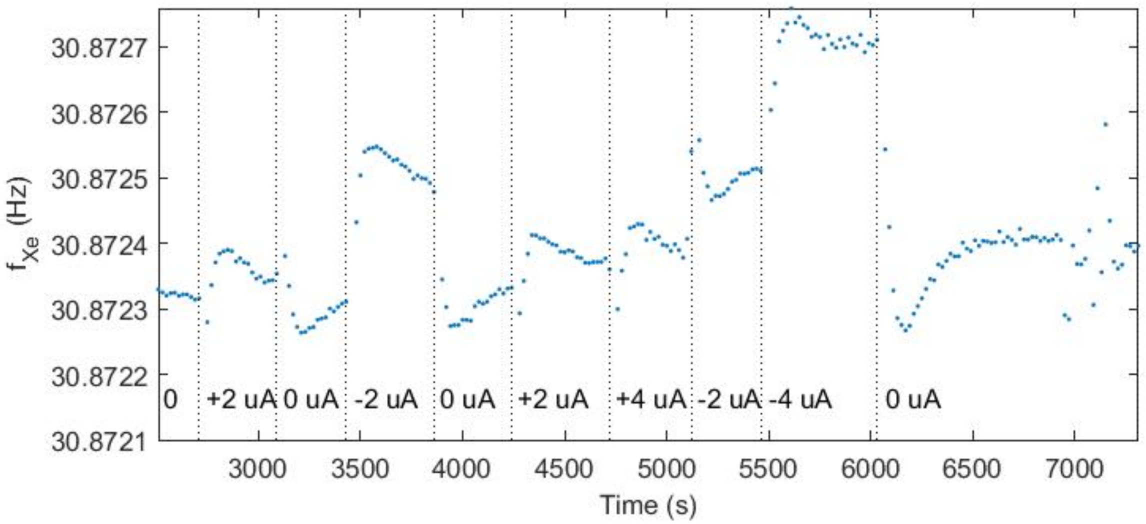


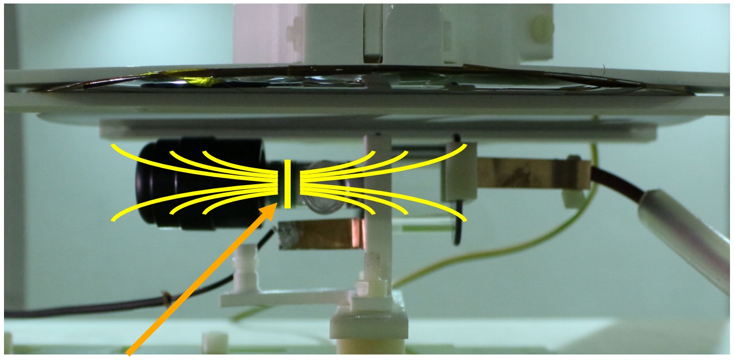
Shift < 5 μHz/μA

x20 pA

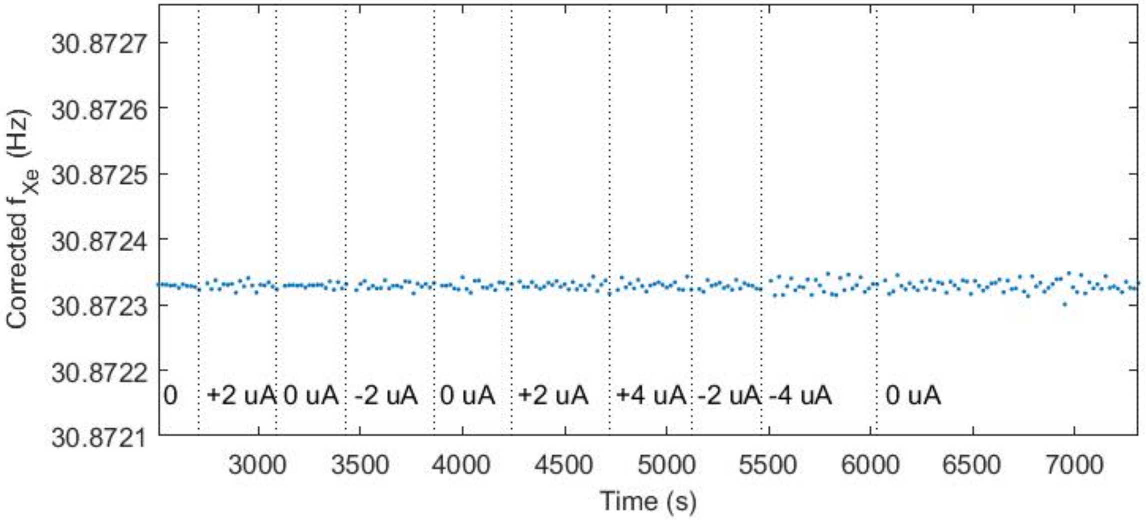
=0.1 nHz (u.l.)

Dipole/hysteresis test

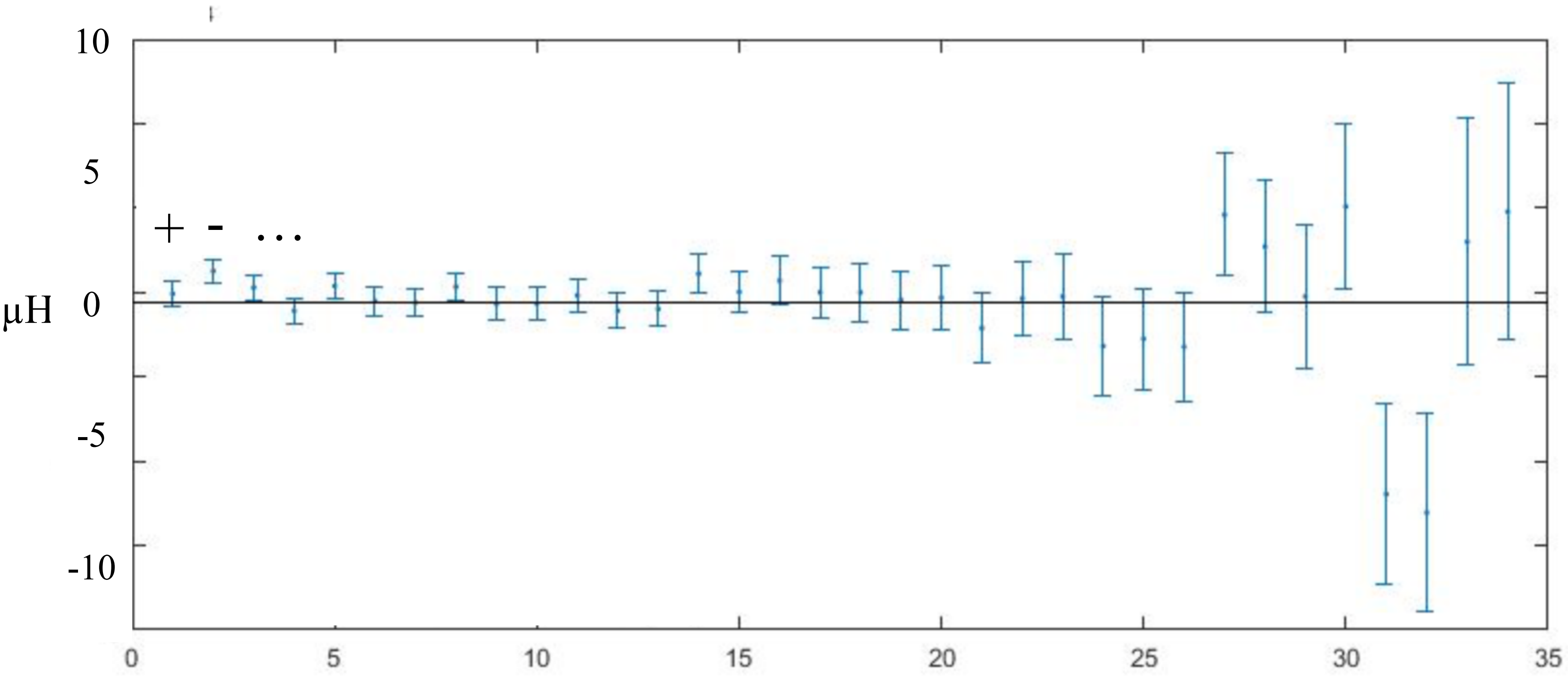


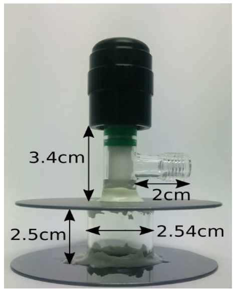


Loop



Blinded data run – 6 kV/400 s



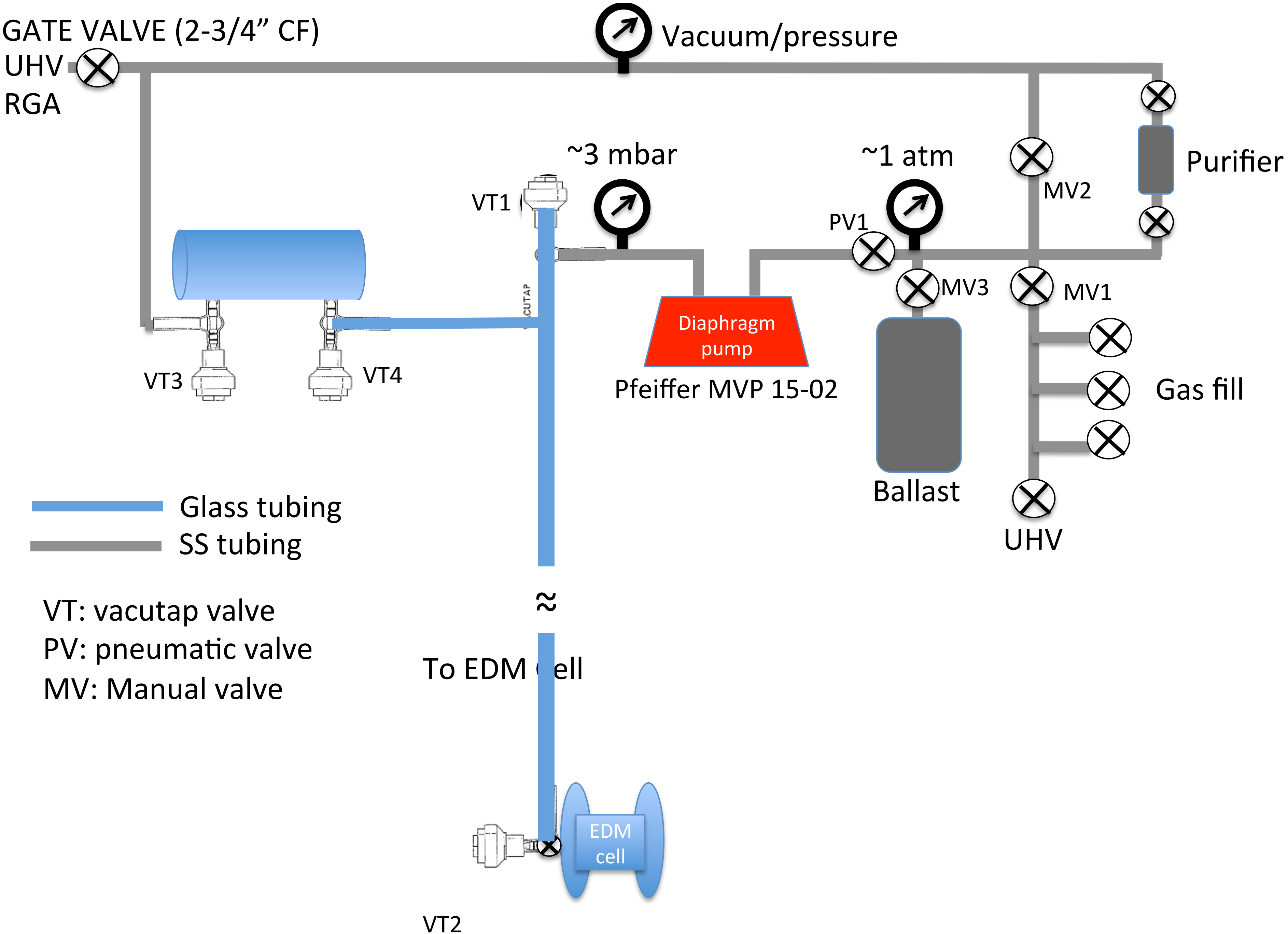


Reversals

E (~6 kV/2 cm)
B (1μT)
E-flip patterns
Cell orientationChange

Vary/monitor

Pressure/magnetization
"π/2" residual
I_{leak}
"HV Dwell"/ramp (kV/s)



Glass tubing

SS tubing

VT: vacutap valve

PV: pneumatic valve

MV: Manual valve

Summary

Global analysis sets limits on C_S, C_T, g_π^0, g_π^1…

Improving any “existing” system has discovery potential

^{129}Xe EDM NOT ruled out by ^{199}Hg/nEDM (amazing experiments) d_e

_ TUM/PTB 2016/**2017**:

- Systematic studies
- Blinded EDM data
- T_2^* of up to 9000 s in EDM cell
- ^{3}He signal limited
- Leakage currents < 20pA
- Blind EDM “analysis”/full systematics

PTB ~March 2018

- BMSR-II upgrade
  extra layer
- Improve ^{3}He polarization
  GE180 pumping cell
  Circulating-closed system
- Improved SQUID dewar (10x)
- Improve spin-flip pulse accuracy

	goal	2014 Run	2015 Run	2016 Run	2017 Run	2018 goal
SNR (1Hz BW)	10^4	150	1500	1800	**1000** (5000)	2500
E [kV/cm]	10	4	4	4	**2.4**	4
T_2^* [s]	200	90	2000	2500	**6000-9000**	> 8000

Thank You/Merci!

TUM
Peter Fierlinger
Florian Kuchler
Stefan Stuber
Mike Marino
Jonas Meinel

Julich FZ
Earl Babcock

PTB
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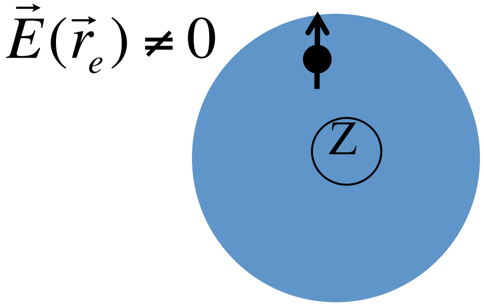
Issac Fan
Allard Schnabel
Sylvian Knappe
Martin Burghoff
Lutz Trahms

MSU
Jaideep Singh

UM
Natasha Sachdeva
Skyler Degenkolb (ILL)
Fei Gong
T.C.

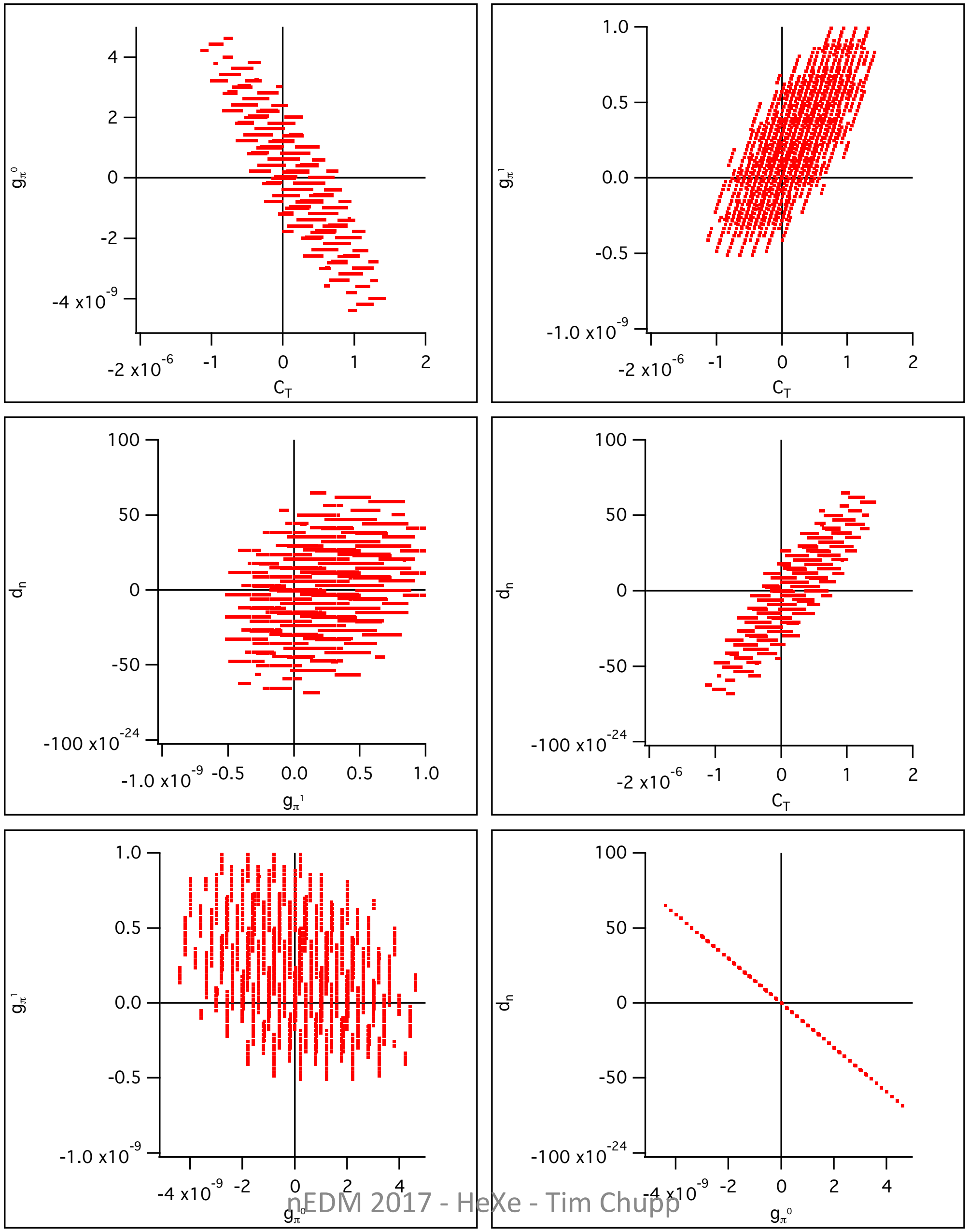
Thank you!

Paramagetic atoms/molecules isolate d_e, C_S

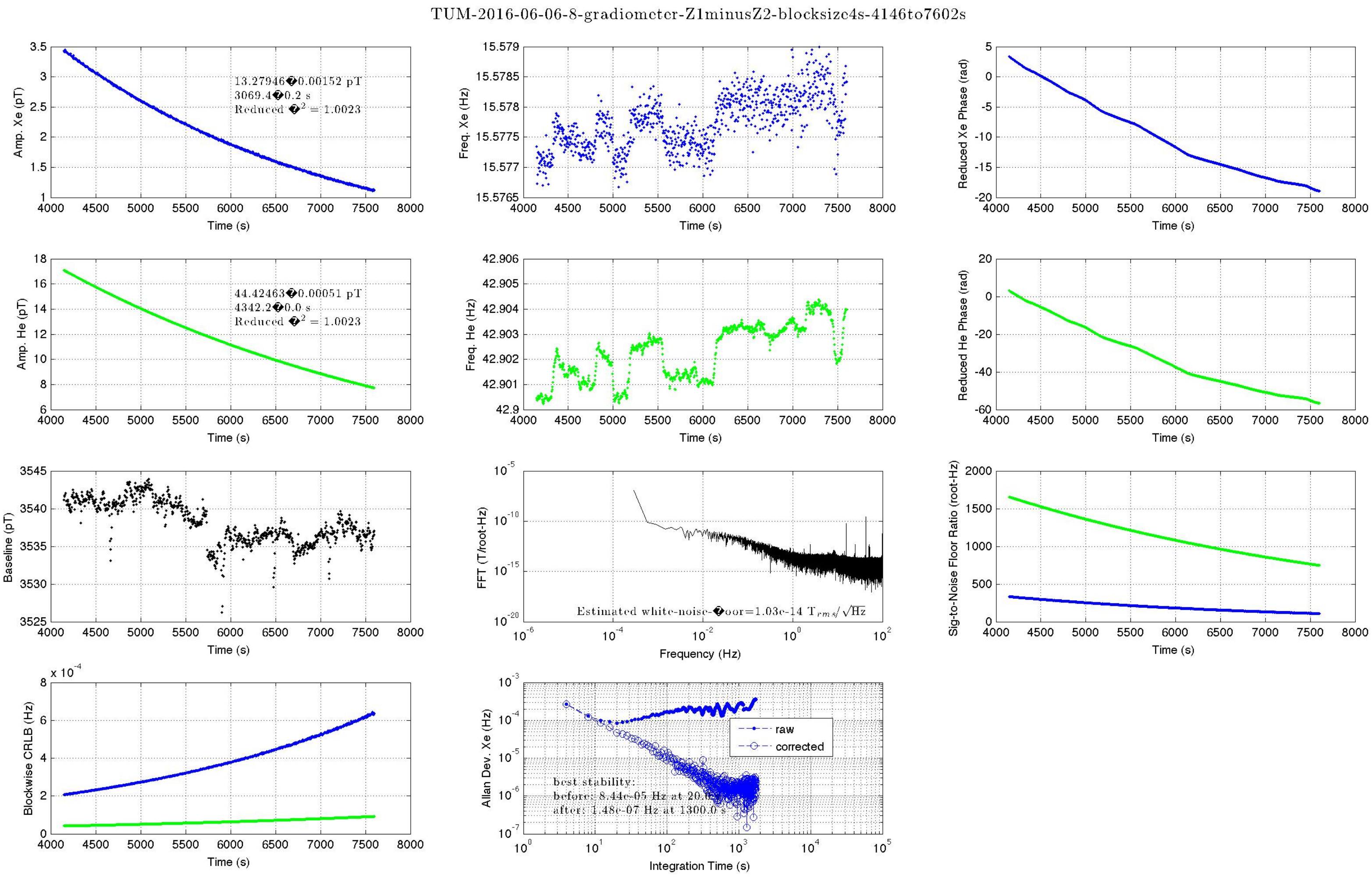


System	α_{d_e}	α_{C_S}	$\alpha_{C_S}/\alpha_{d_e}$ (e cm)
Cs	123 (100 – 138)	7.1×10^{-19} e cm (7.0 – 7.2)	5.8×10^{-21} $(0.6 - 0.7) \times 10^{-20}$
Tl	-573 $-(562 - 716)$	-7×10^{-18} e cm $-(5 - 9)$	1.2×10^{-20} $(1.1 - 1.2) \times 10^{-20}$
YbF	-1.1×10^{25} Hz/e cm -(0.9-1.2)	-9.2×10^{4} Hz -(92-132)	8.6×10^{-21} $(8.0 - 9.0) \times 10^{-21}$
ThO	-5.0×10^{25} Hz/e cm $-(4.0 - 5.0)$	-6.6×10^{5} Hz -(4.6-6.6)	1.3×10^{-20} $(1.2 - 1.3) \times 10^{-20}$

Global Analysis

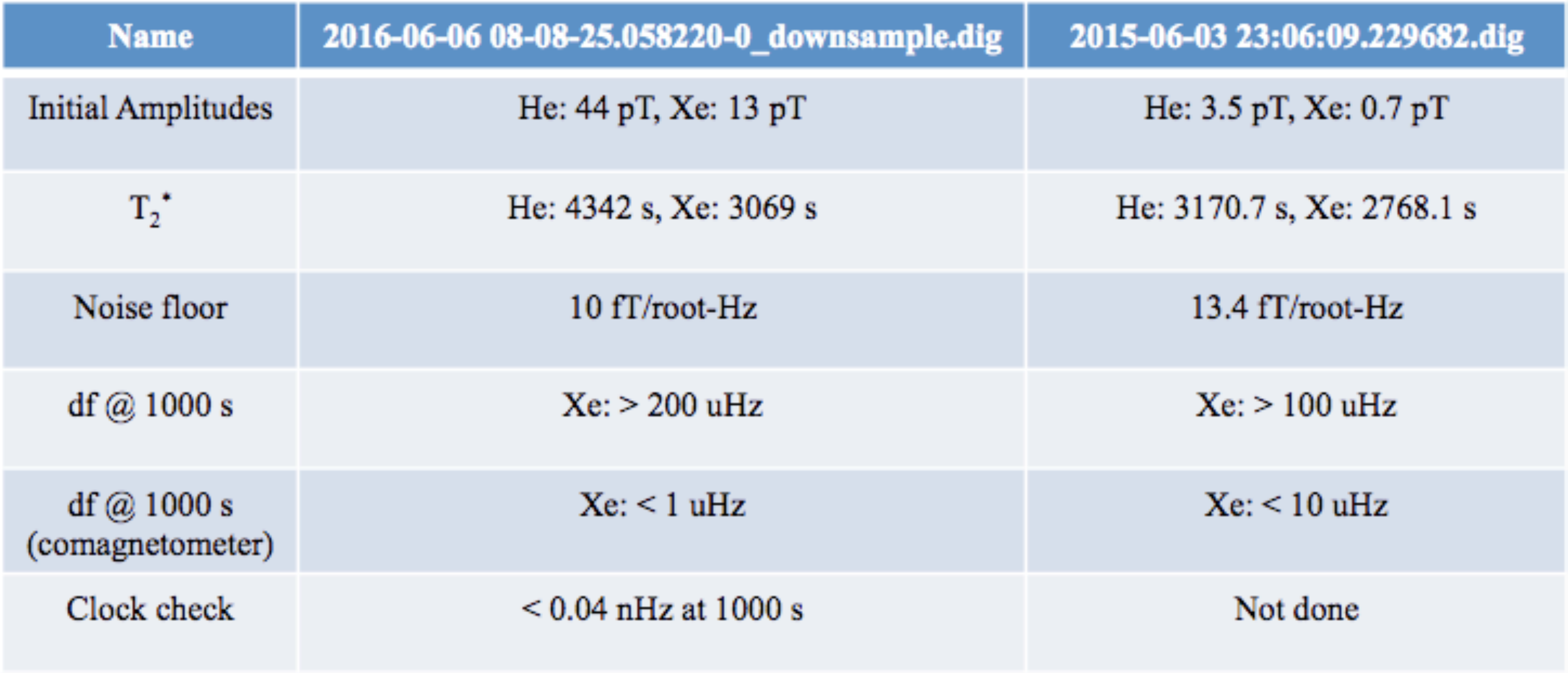


HeXeEDM



TUM-2016-06-06-8-gradiometer-Z1minusZ2-blocksize4s-4146to7602s
Amp. Xe (pT)
13.27946�0.00152 pT
3069.4�0.2 s
Reduced �² = 1.0023
Time (s)
Freq. Xe (Hz)
Time (s)
Reduced Xe Phase (rad)
Time (s)
Amp. He (pT)
44.42463�0.00051 pT
4342.2�0.0 s
Reduced �² = 1.0023
Time (s)
Freq. He (Hz)
Time (s)
Reduced He Phase (rad)
Time (s)
Baseline (pT)
Time (s)
FFT (T/root-Hz)
Estimated white-noise-�oor=1.03e-14 $T_{rms}/\sqrt{Hz}$
Frequency (Hz)
Sig-to-Noise Floor Ratio (root-Hz)
Time (s)
x 10⁻⁴
Blockwise CRLB (Hz)
Time (s)
Allan Dev. Xe (Hz)
raw
corrected
best stability:
before: 8.44e-05 Hz at 20.0 s
after: 1.48e-07 Hz at 1300.0 s
Integration Time (s)

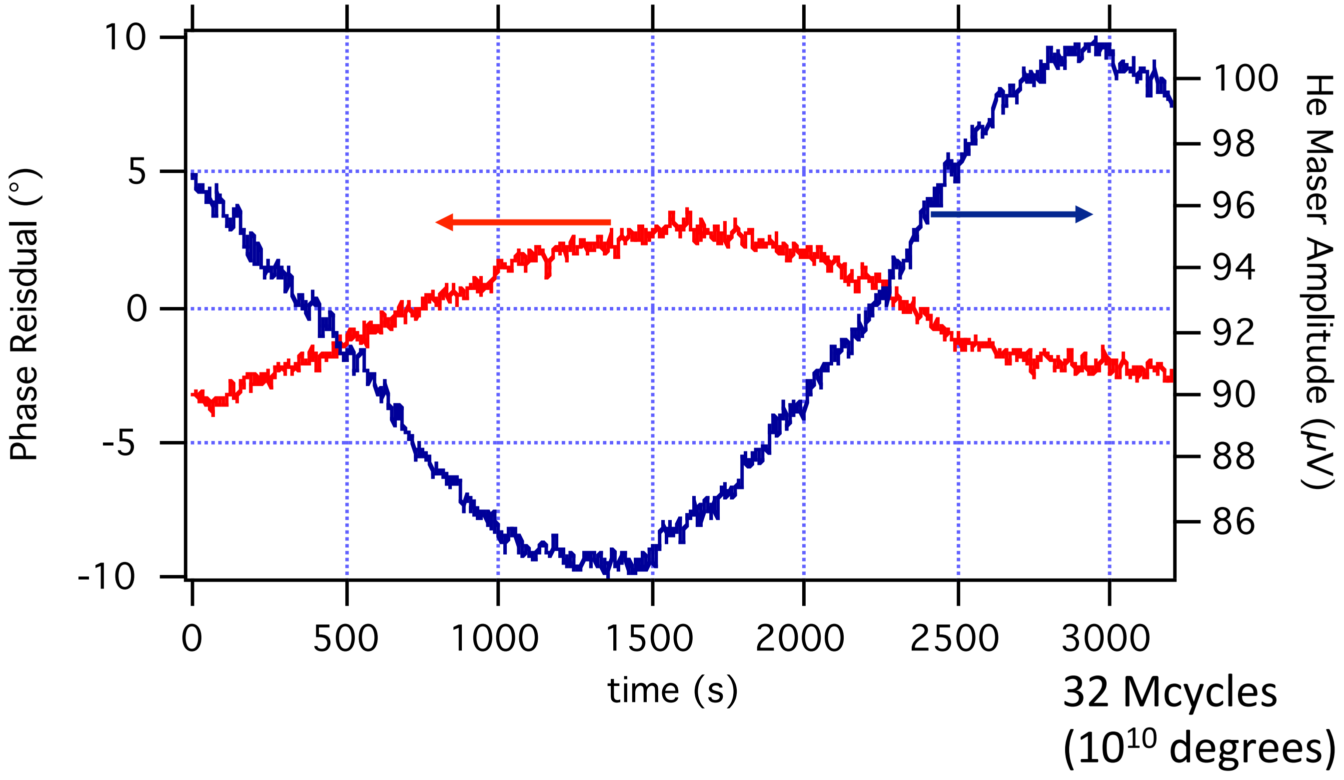
HeXeEDM 2015 vs 2016



Name	2016-06-06 08-08-25.058220-0_downsample.dig	2015-06-03 23:06:09.229682.dig
Initial Amplitudes	He: 44 pT, Xe: 13 pT	He: 3.5 pT, Xe: 0.7 pT
T_2^*	He: 4342 s, Xe: 3069 s	He: 3170.7 s, Xe: 2768.1 s
Noise floor	10 fT/root-Hz	13.4 fT/root-Hz
df @ 1000 s	Xe: > 200 uHz	Xe: > 100 uHz
df @ 1000 s (comagnetometer)	Xe: < 1 uHz	Xe: < 10 uHz
Clock check	< 0.04 nHz at 1000 s	Not done

Goal/expectation: $10^{-29/30}$ e-cm

Free Running (^{3}He) Maser Frequency Depends on Magnetization (M_z) (magnetic cross talk)



32 Mcycles
(10^{10} degrees)