New Limit on the Permanent Electric Dipole Moment of ^{199}Hg

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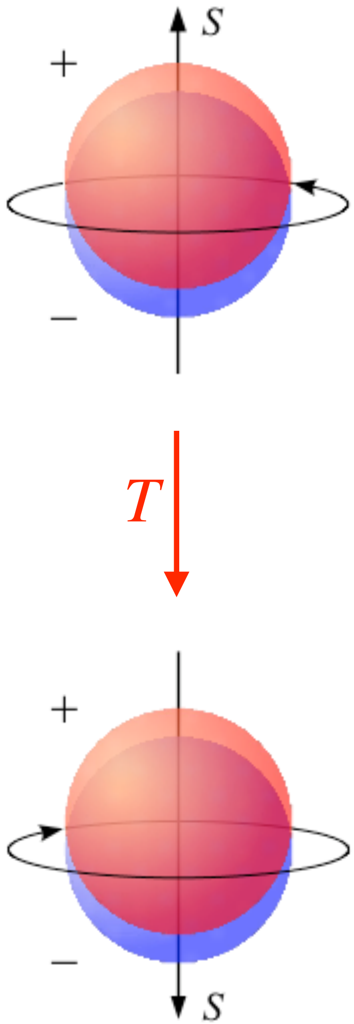
The Search for an EDM

A permanent EDM violates T :



Crucial point 1:

The Standard Model generates EDMs far too small to see.

Therefore, finding an EDM would be proof of new physics.

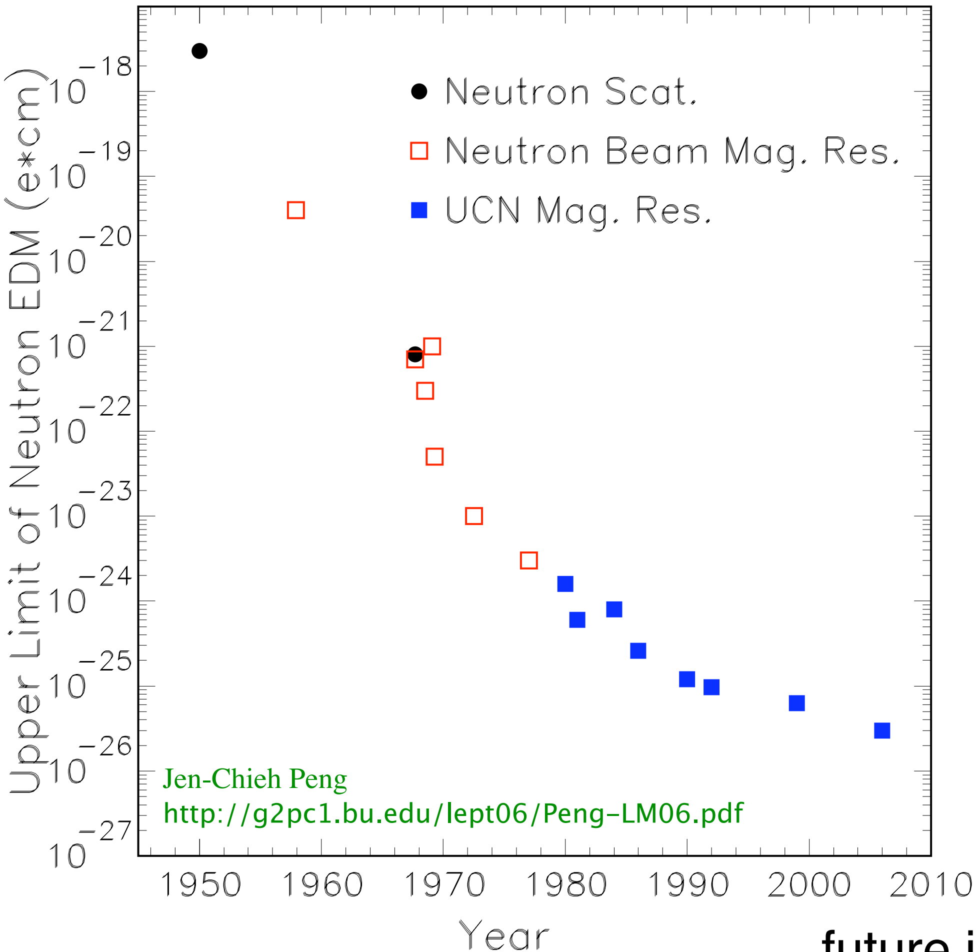
Search for an EDM of the neutron began over 50 years ago, so far no luck.

Crucial point 2:

Theories of physics beyond the Standard Model → EDMs large enough to see with current experiments.

Therefore, keep on looking!

EDM searches: the neutron



best limit:

$|d_n| < 3.0 \times 10^{-26}\ e\ \text{cm}$ (2006)

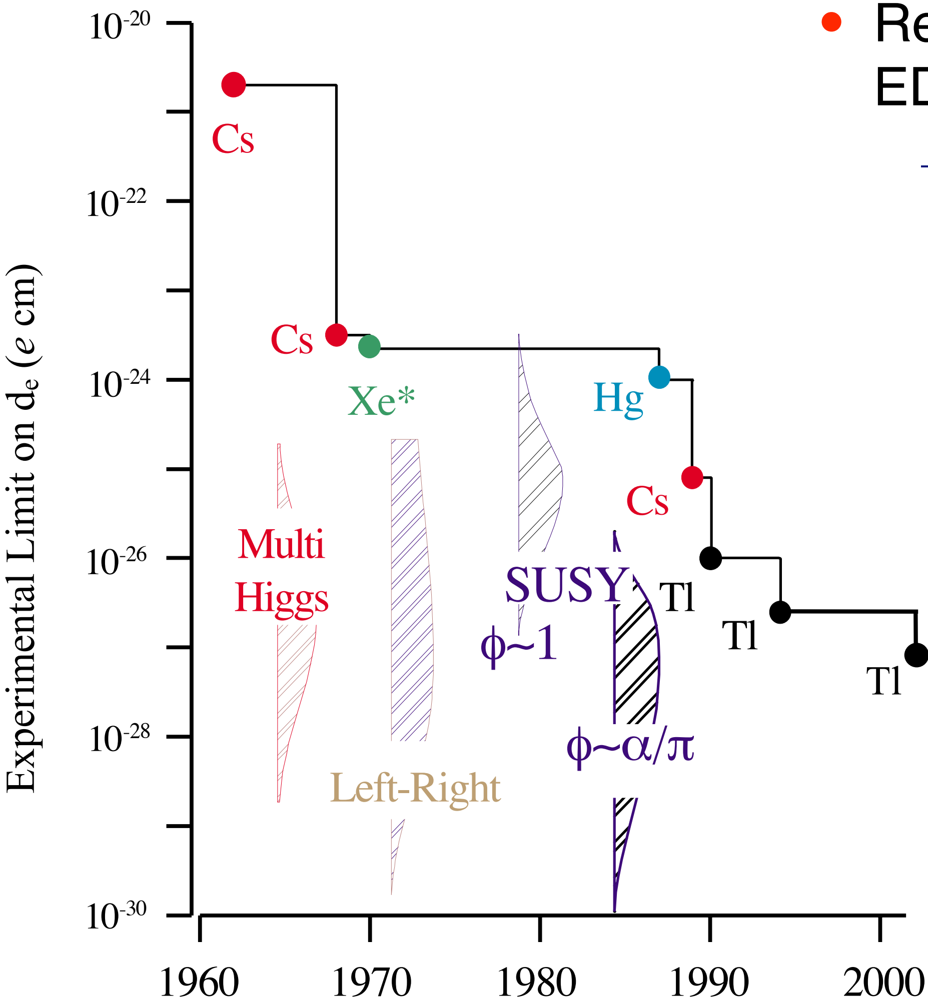
C. A. Baker *et al*, PRL **97**, 131801 (2006).

UCN + ^{199}Hg comagnetometer (Sussex/ILL)

future improvements:
continuation of UCN+199Hg (PSI)
neutrons in liquid He (SNS and ILL)

- Expected sensitivity ~ $10^{-28}\ e$ cm

EDM searches: the electron



- Relativistic enhancement of the electron EDM in heavy paramagnetic atoms
  - best limit is from Thallium:

$$d_{\mathrm{Tl}} = -585\, d_e$$

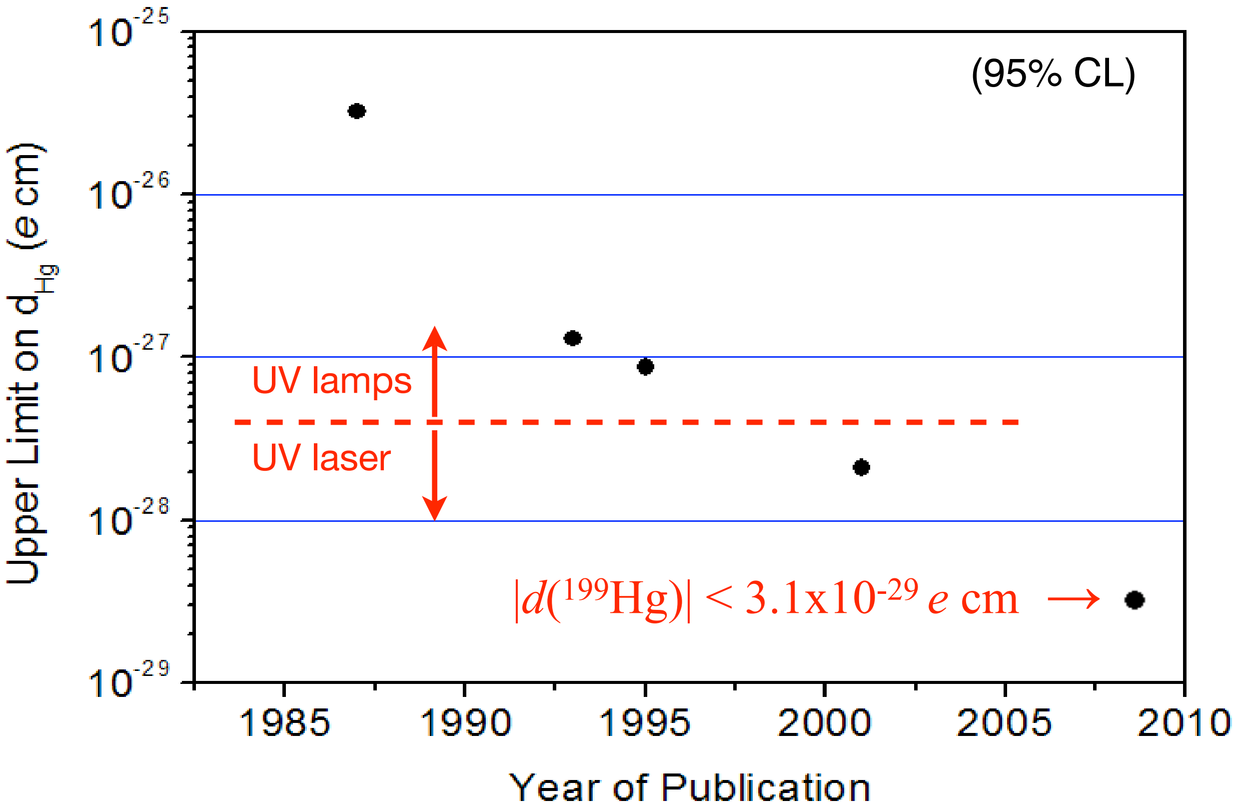
$$|d_e| < 1.6 \times 10^{-27}\ e\ \mathrm{cm}\ (2002)$$

B.C. Regan, E.D. Commins, C.J. Schmidt, and D. DeMille, PRL **88**, 071805 (2002).

- Other approaches:
  - polar molecules
    - YbF (Imperial College)
    - WC (Mich.), ThO (Harvard)
    - HfH^+ (JILA) ....
  - laser cooled Cs (Penn St., Texas)
  - solid state measurement? (Amherst, Yale)

EDM searches: diamagnetic atoms

– Diamagnetic atoms ($^1S_0$ ground state) with finite nuclear spin (I) are sensitive to the EDM of the nucleus



Shielding reduces the effect of the nuclear dipole:

$$d_{atom} \propto d_{nuc} \underbrace{\left[Z^2\left(\frac{r_n}{a_0}\right)^2\right]}_{\approx 10^{-3}}$$

other approaches:
liquid Xe (Princeton)
trapped Ra (Argonne,KVI)
Rn (Mich./TRIUMF)

S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab, and E.N. Fortson, PRL **59**, 2275 (1987).
J.P. Jacobs, W.M. Klipstein, S.K. Lamoreaux, B.R. Heckel, and E.N. Fortson, PRA **52**, 3521 (1995).
M.V. Romalis, W.C. Griffith, J.P. Jacobs, and E.N. Fortson, PRL **86**, 2505 (2001).
W.C. Griffith, M.D. Swallows, T.L. Loftus, M.V. Romalis, B.R. Heckel, and E.N. Fortson, PRL **102**, 101601 (2009).

From the ^{199}Hg EDM to fundamental physics

^{199}Hg Atomic EDM

↓ *Atomic Physics* ↓

^{199}Hg Schiff Moment

↓ *Nuclear Physics* ↓

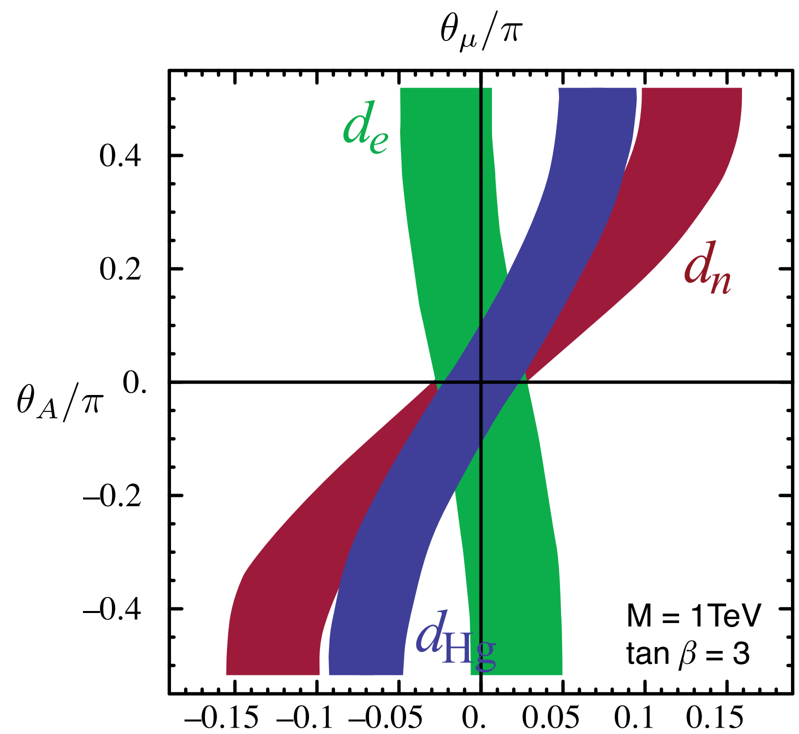
CP-Violating Pion-Nucleon Coupling

↓ *QCD* ↓

Quark Chromo-EDMs $\tilde{d}_q$

↓ *SUSY, etc …* ↓

Model-Dependent
CP-Violating Parameters



T. Falk, K. Olive, M. Pospelov, R. Roiban, Nucl. Phys. B560 3 (1999). Update A. Ritz (2009).

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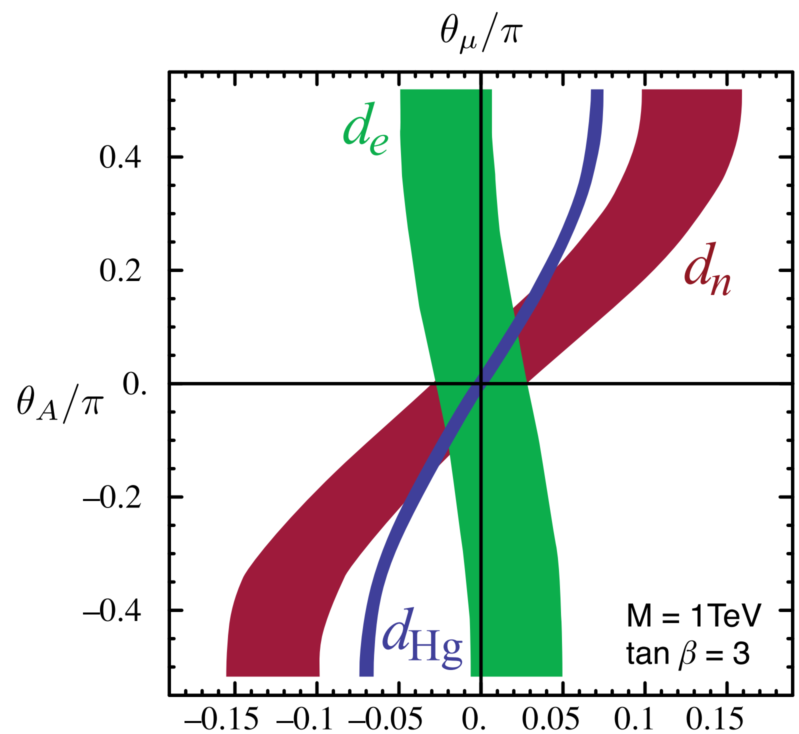

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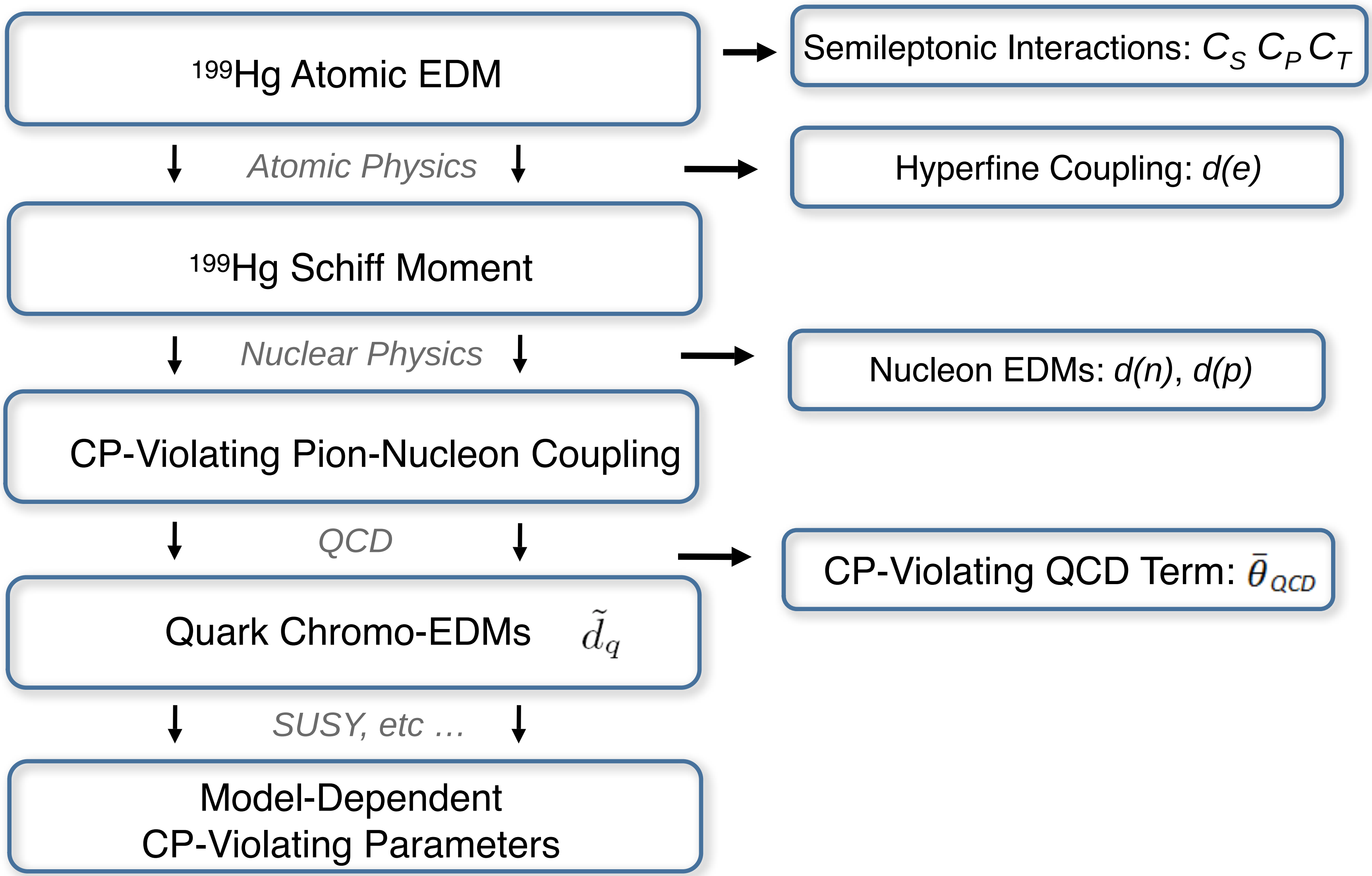
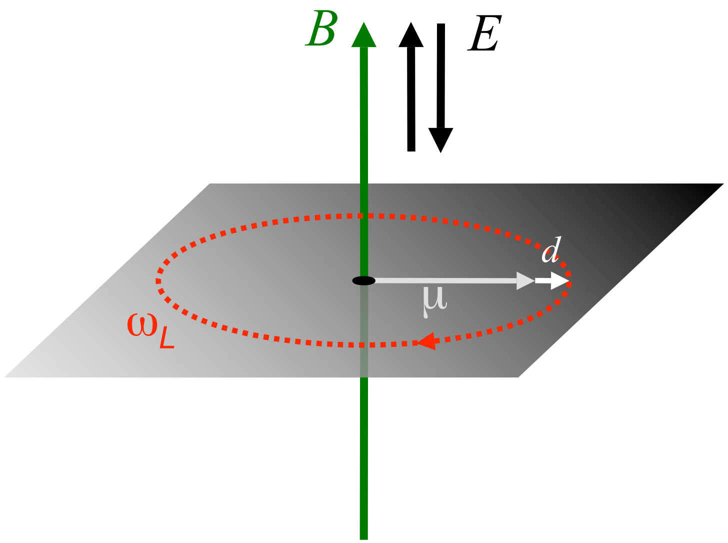


Measuring an EDM via Larmor precession

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

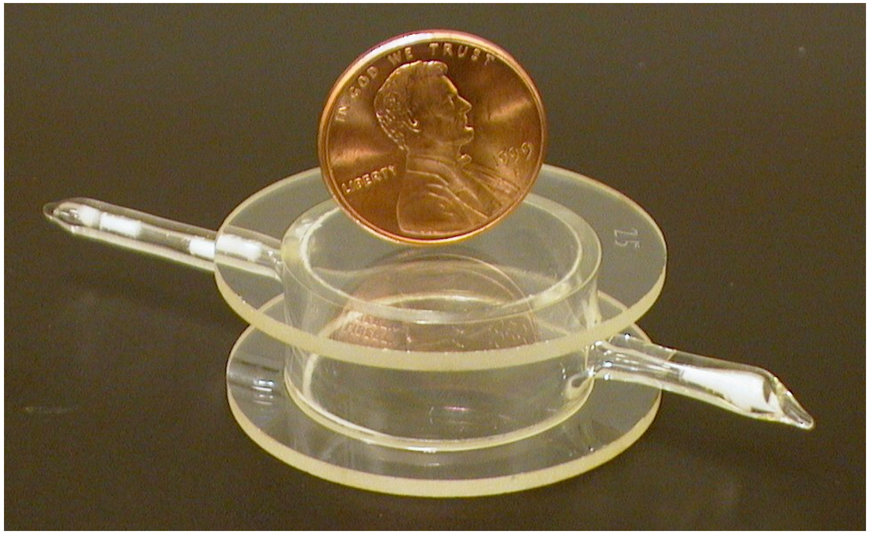


$$\omega_1 = \frac{2\vec{\mu} \cdot \vec{B} + 2\vec{d} \cdot \vec{E}}{\hbar}$$

$$\omega_2 = \frac{2\vec{\mu} \cdot \vec{B} - 2\vec{d} \cdot \vec{E}}{\hbar}$$

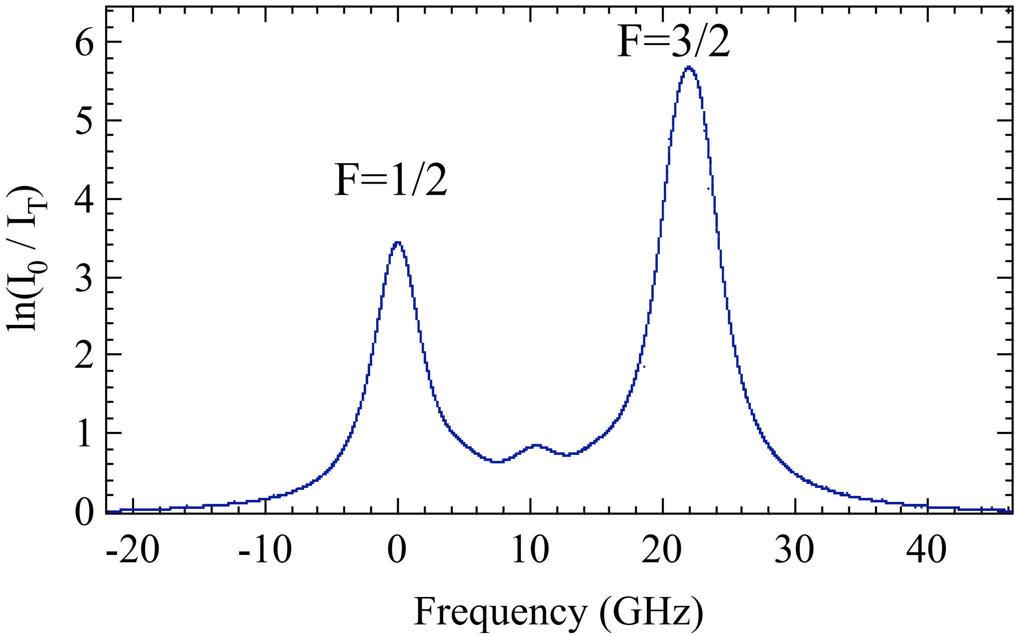
$$\Rightarrow \quad \omega_1 - \omega_2 = \frac{4\,d\,E}{\hbar}$$

^{199}Hg vapor cells



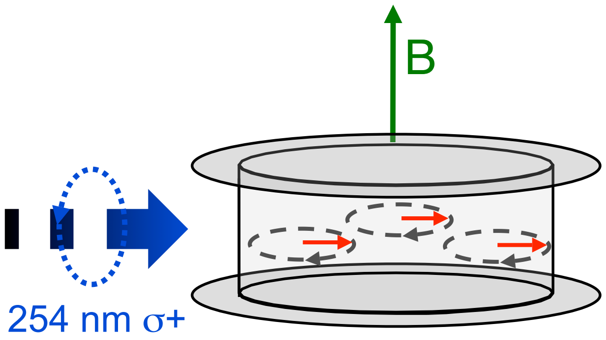
- Number of ^{199}Hg atoms: 10^{14}
- Leakage currents at 10 kV: < 1 pA
- CO buffer gas (500 Torr)
- Paraffin wall coating
- Spin coherence time: 100 – 200 sec

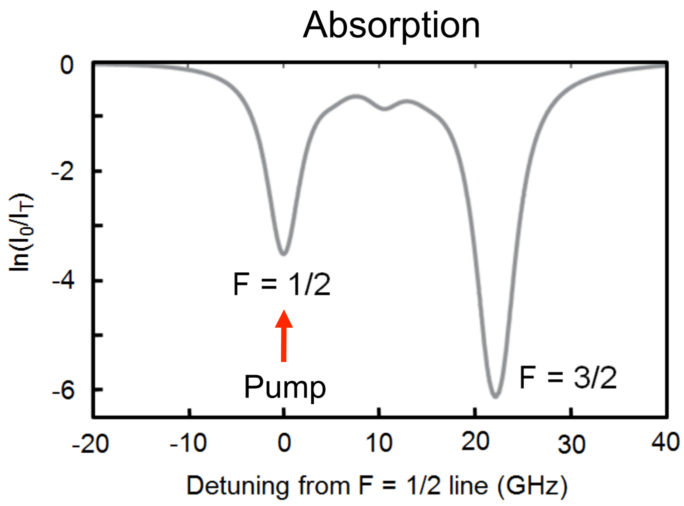
Absorption scan at 254 nm
$6^1S_0 \rightarrow 6^3P_1$



Spin precession measurement

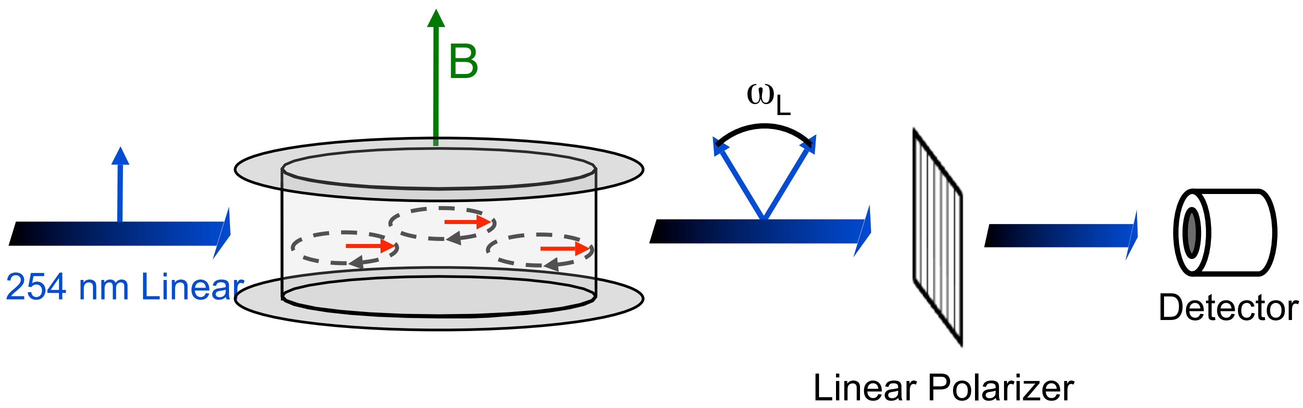
Transverse Optical Pumping

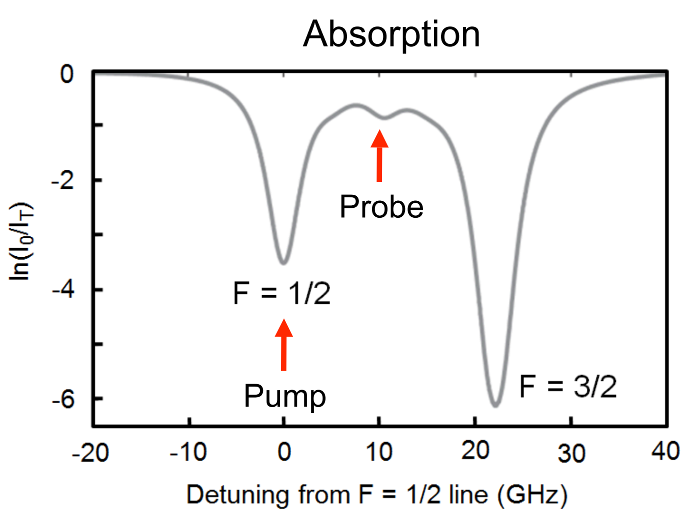


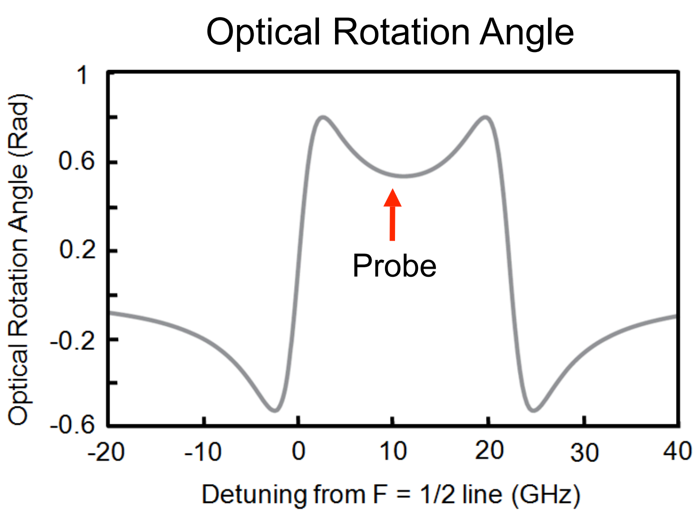


Spin precession measurement

Measure ω_L via Optical Rotation







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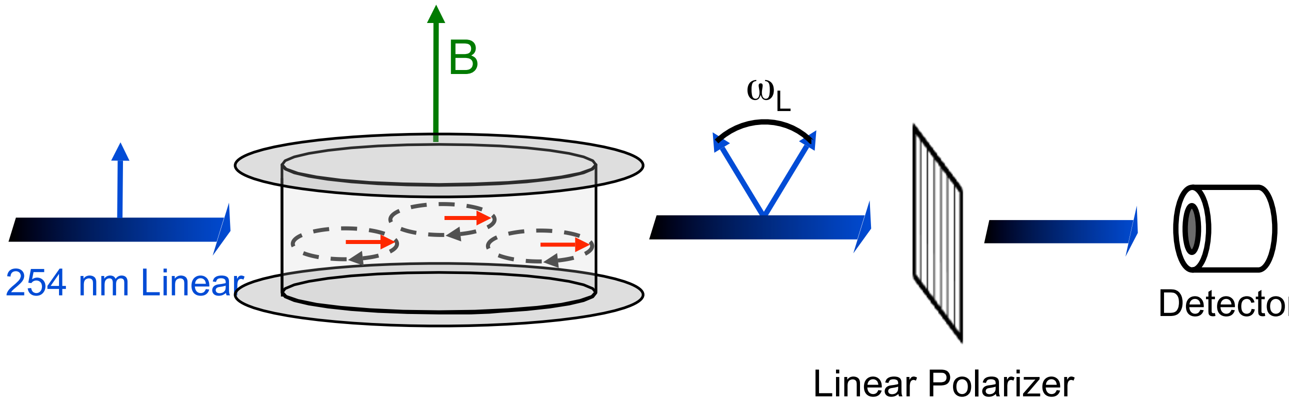
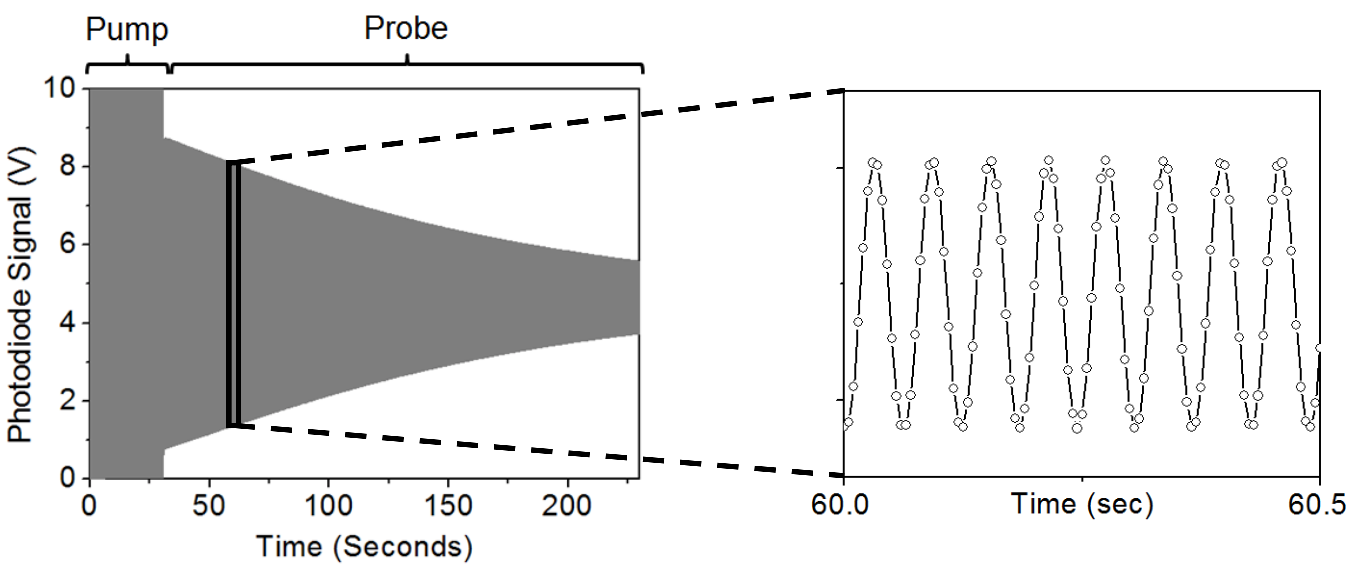
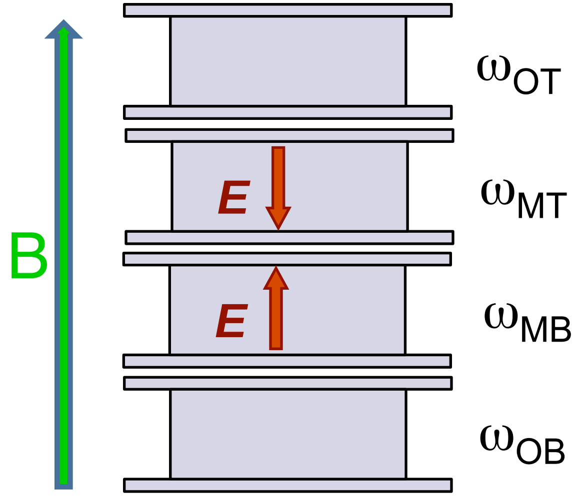
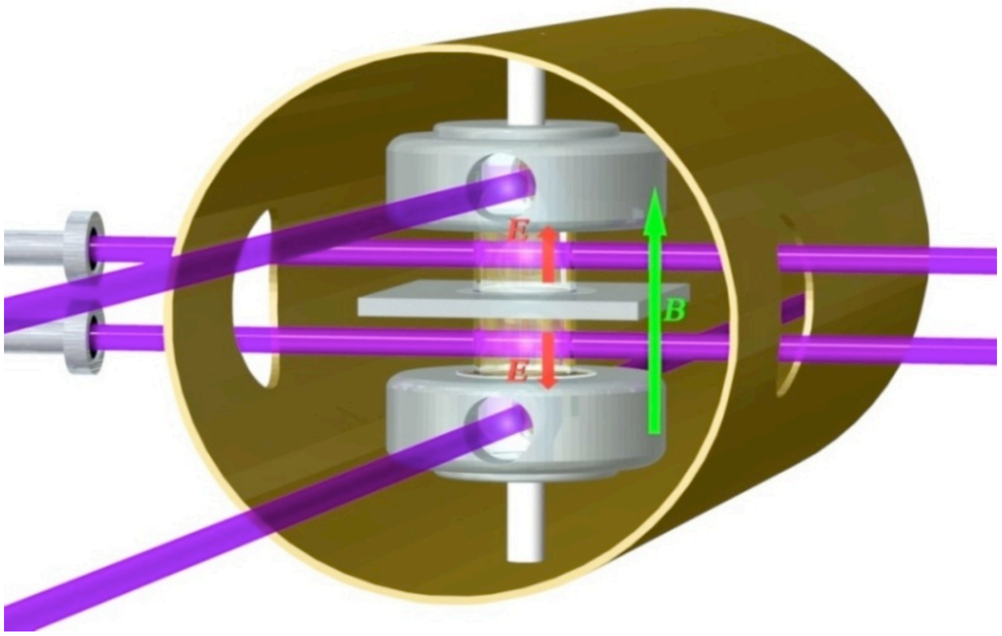




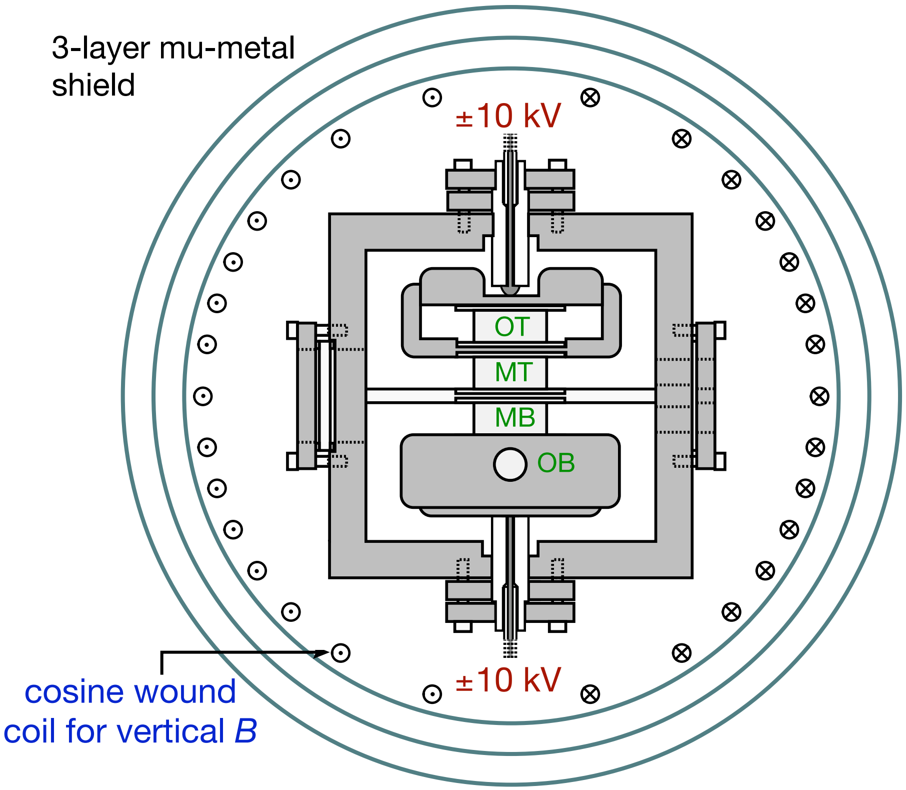
4-cell measurement

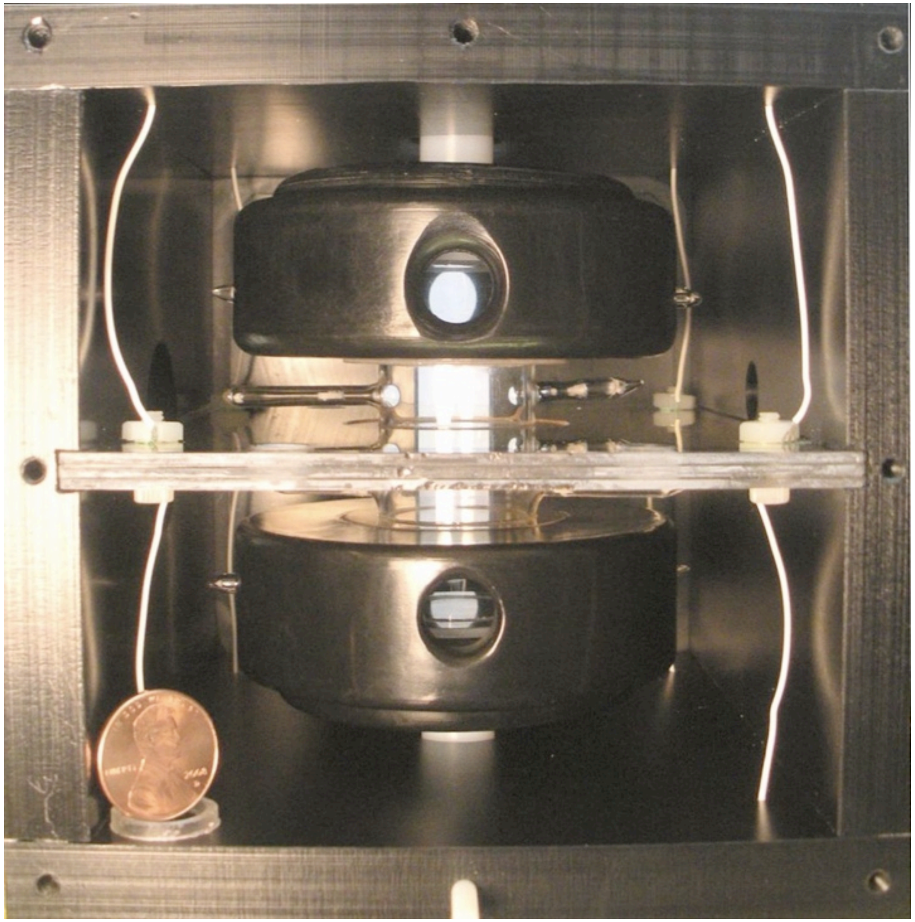




- outer cells at zero electric field – used to cancel magnetic gradient noise and check for magnetic systematics

Cell holding vessel



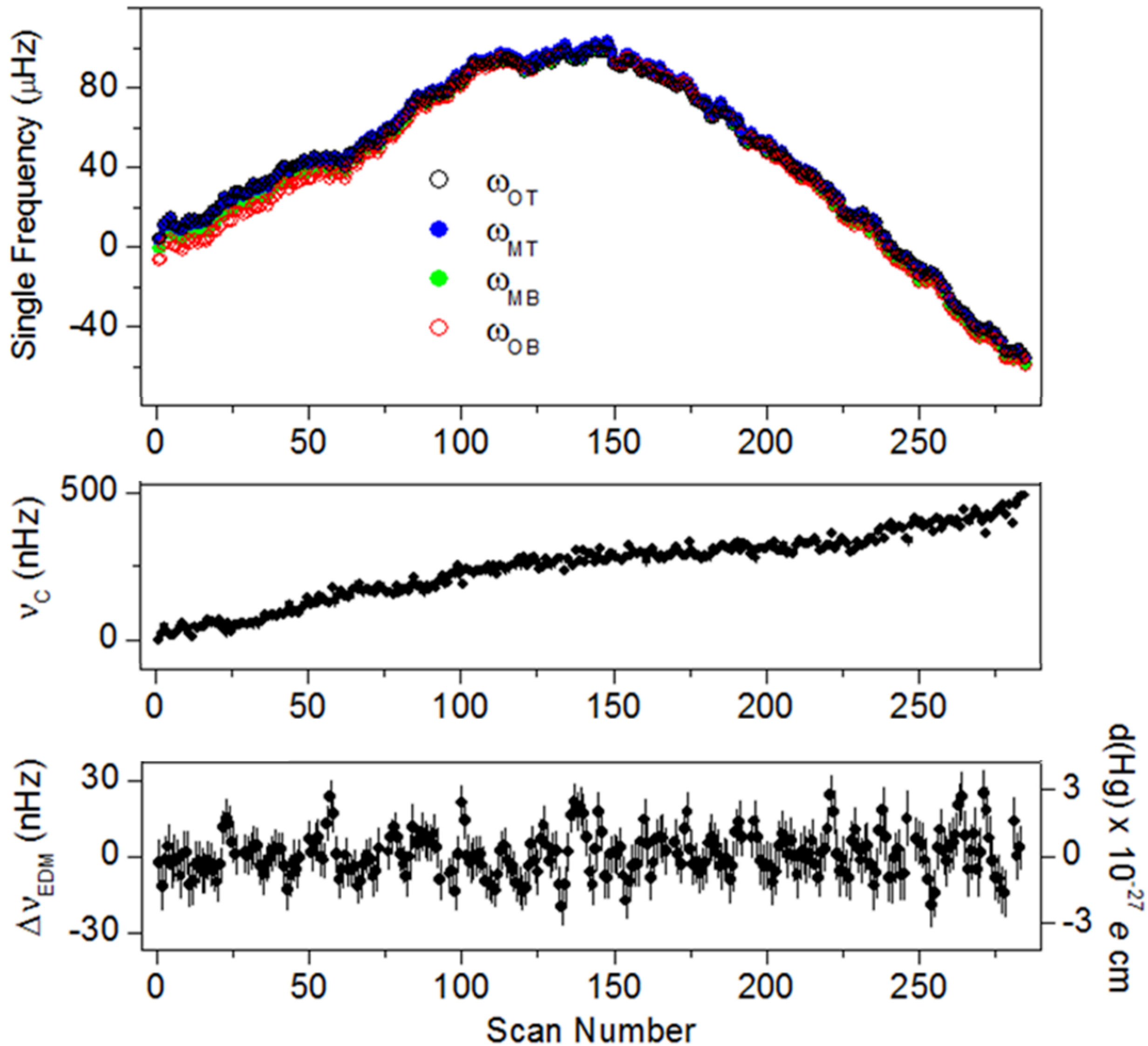


- Vessel and cell enclosing electrodes machined from electrically conductive, graphite filled polyethylene
- gold-coated fused silica groundplane between middle cells

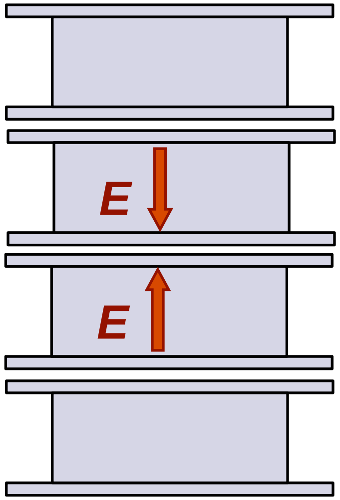
Typical 24 hour run

$$(\omega_{MT} - \omega_{MB}) - \frac{1}{3}(\omega_{OT} - \omega_{OB})$$

$$\frac{\omega_i - 2\omega_{i+1} + \omega_{i+2}}{4}$$



Blind analysis of HV correlated signals



ω_{OT}

$\omega_{MT} + \delta/2$

$\omega_{MB} - \delta/2$

ω_{OB}

Analysis program adds an unknown, HV-correlated, EDM-mimicking offset $\delta/2$ to the middle cell frequencies

Produced an EDM-like signal between

$\pm\, 2 \times 10^{-28}\ e\ \mathrm{cm}$

Masked the measured EDM

Revealed *only after* the data collection, data cuts, and error analysis were complete

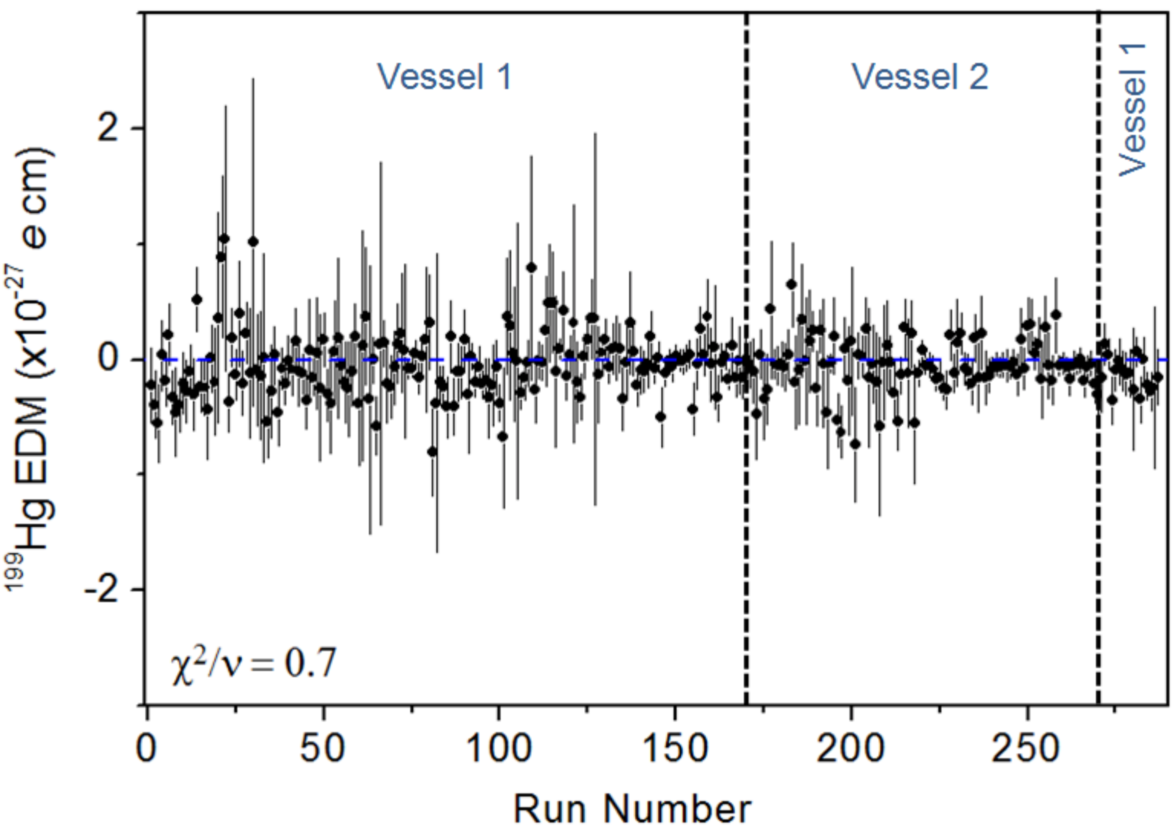
Measurement hierarchy

- **Scan:** Individual pump / probe cycle
- **Run:** Roughly 24 hours, several hundred scans (or HV reversals)
- **Sequence:** Self-contained collection of runs
  - 8-10 Dipole HV runs (+-+-+…), Equal number of B=F and B=R → EDM Data
  - 1 or more Quadrupole HV (+0-0+0-0 …) → Constrain E^2 Systematics
  - Several Dipole HV runs with tipped B-Field → Constrain $(\vec{v}\ x\ \vec{E})$ Systematics

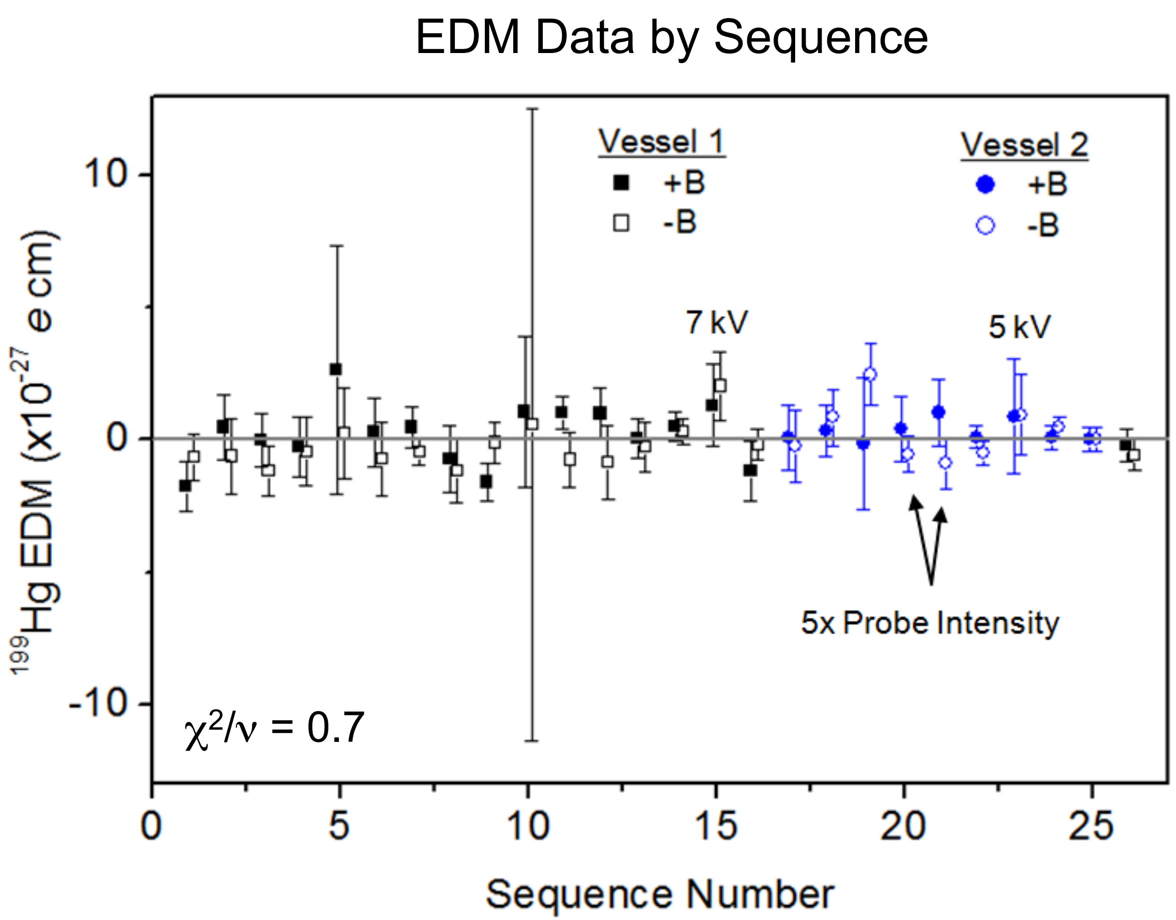
Complete Dataset: 332 runs (~ 98,000 HV Reversals)

Raw dataset

EDM Data by Run



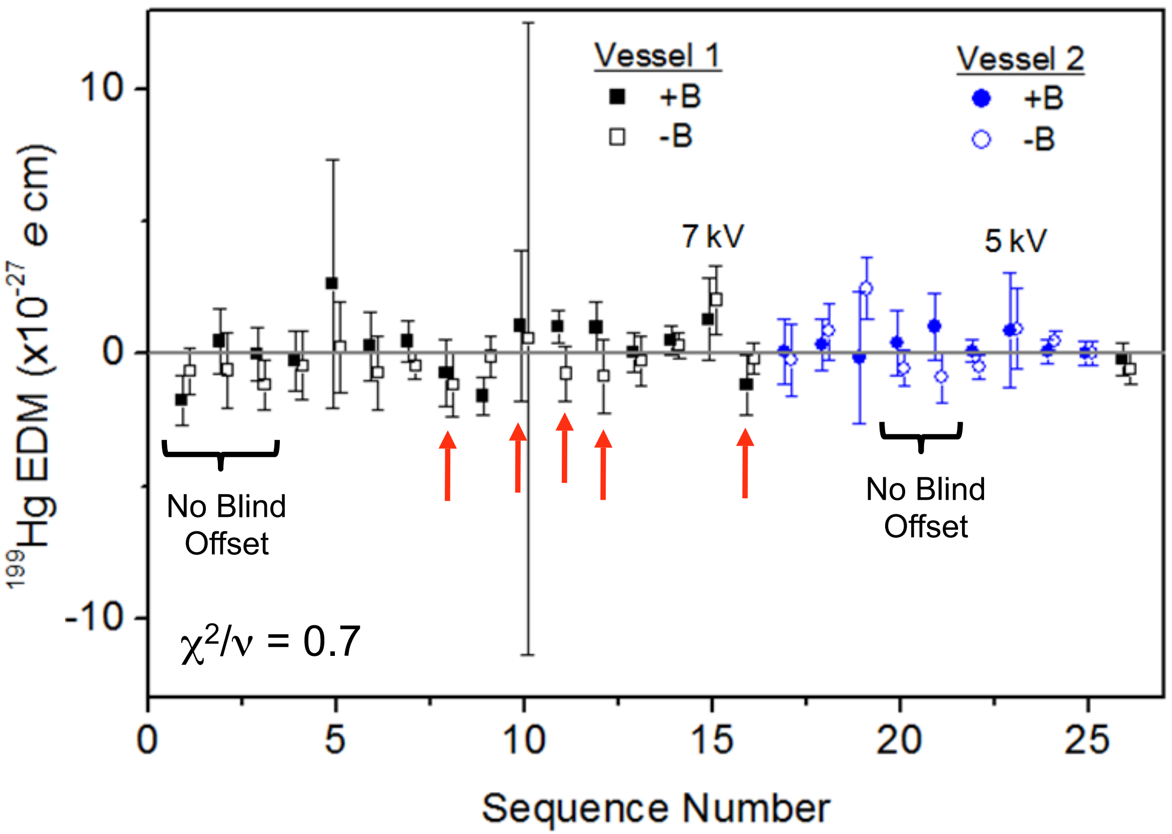
Raw dataset



EDM Data by Sequence
Vessel 1
+B
-B
Vessel 2
+B
-B
7 kV
5 kV
5x Probe Intensity
$\chi^2/\nu = 0.7$
^{199}Hg EDM (x10^{-27} e cm)
10
0
-10
0
5
10
15
20
25
Sequence Number

Raw dataset

EDM Data by Sequence



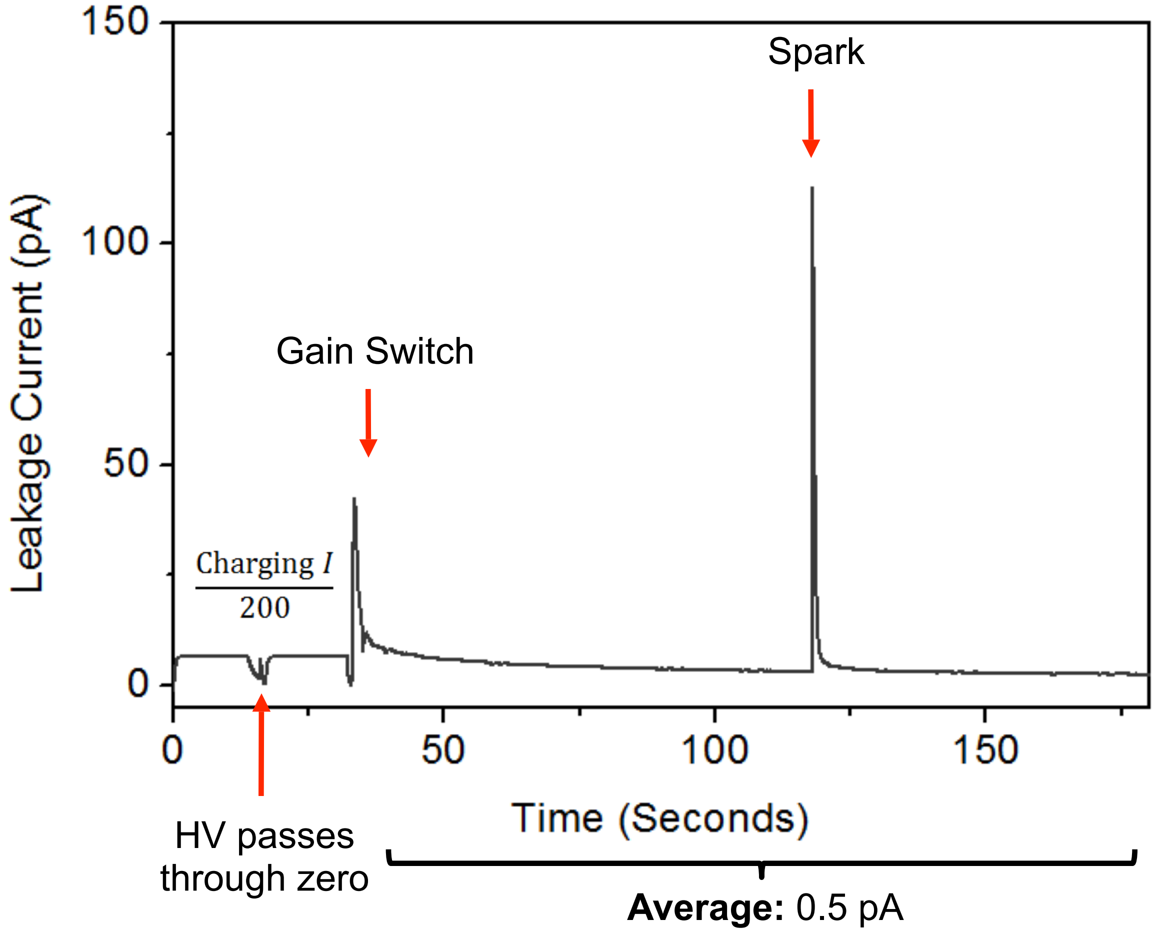
Excluded Sequences

No Blind Offset

Micro-Sparks

Spark correlations / cuts

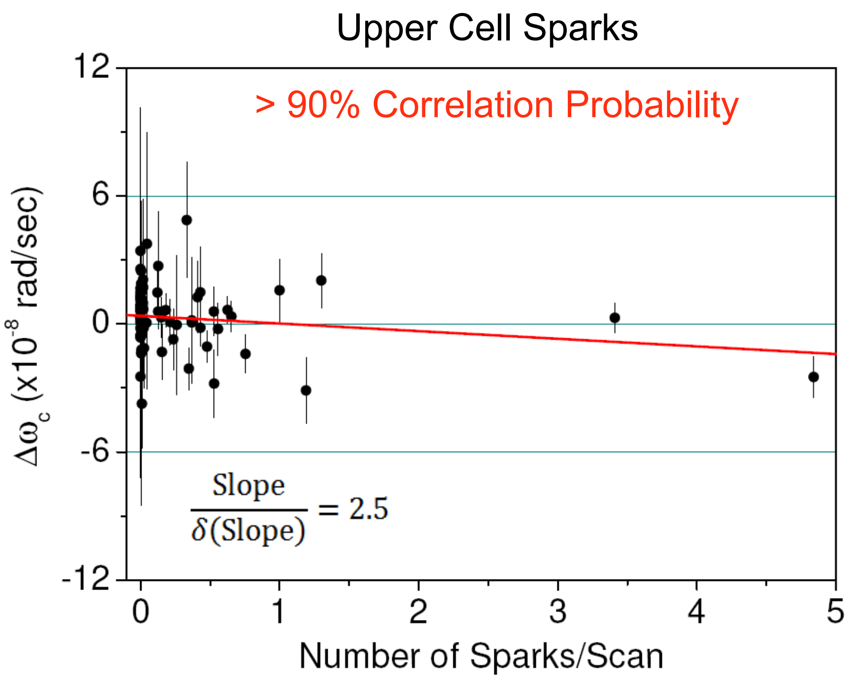
Current collected on the groundplane top-side:

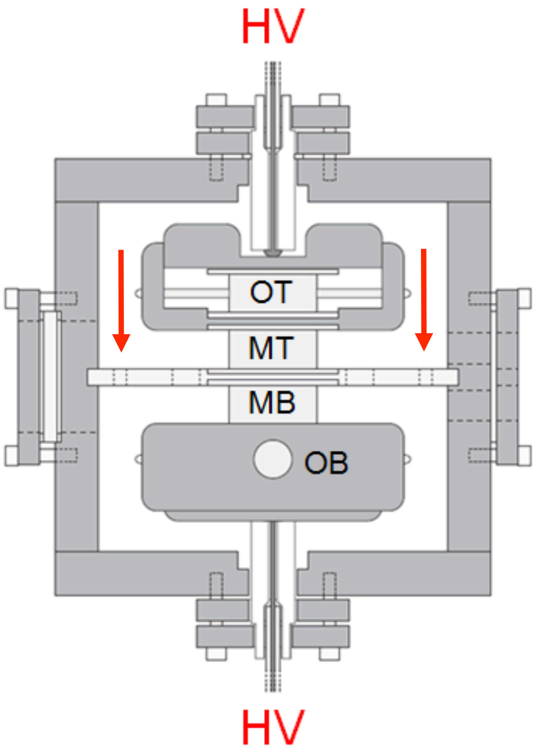


– Sparks occurred in sequences using periodically purged N_2 in vessel

– No sparks for periodically purged SF_6 or continuously flowed N_2

Spark correlations / cuts





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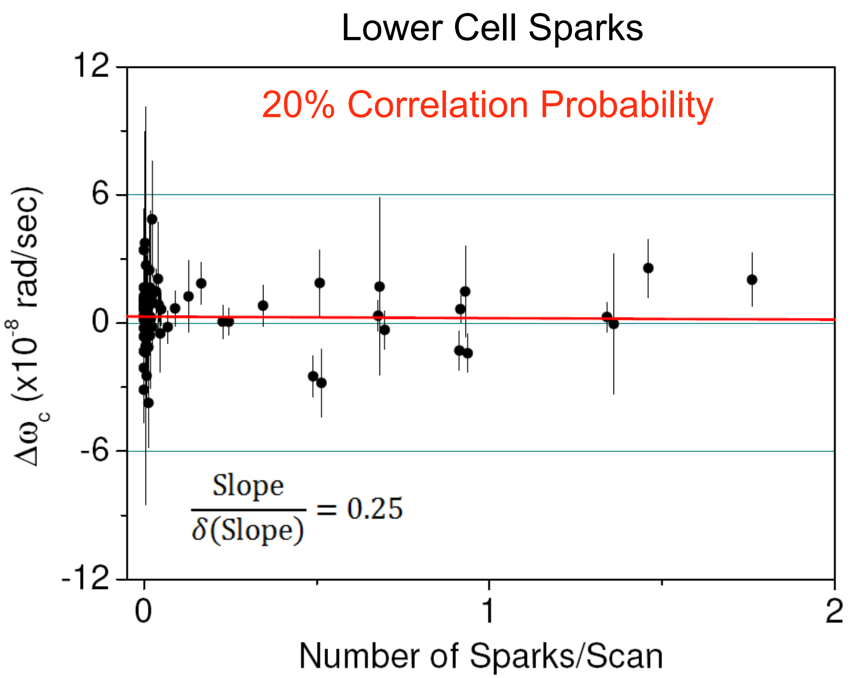

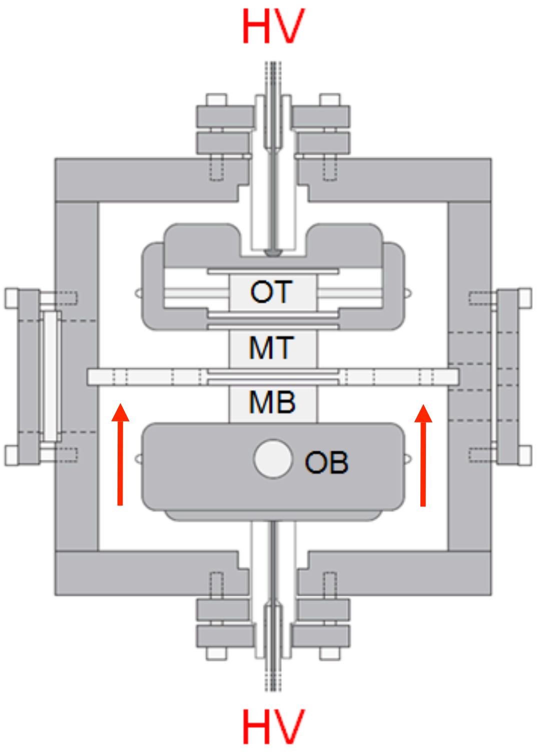

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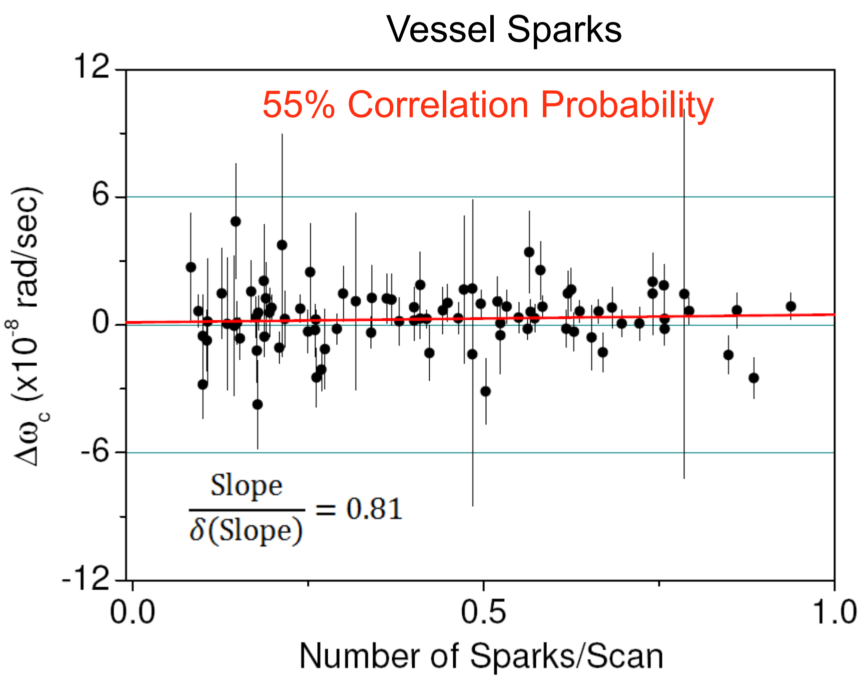
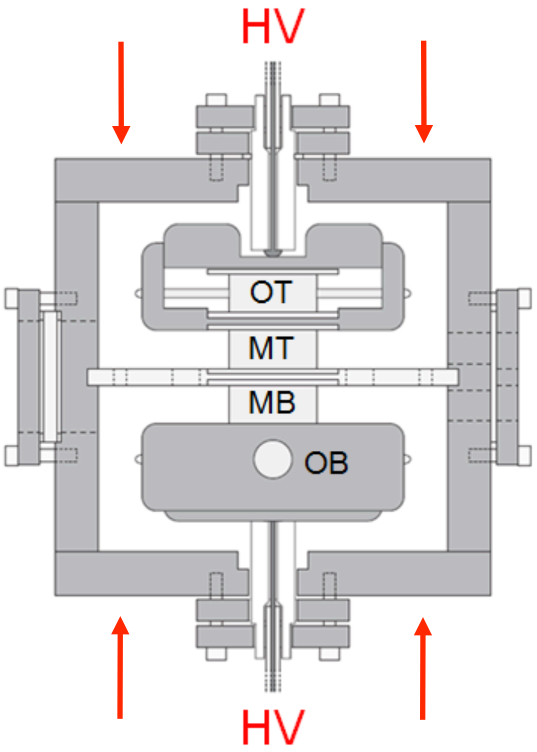




Spark correlations / cuts

Schemes for Data Cuts

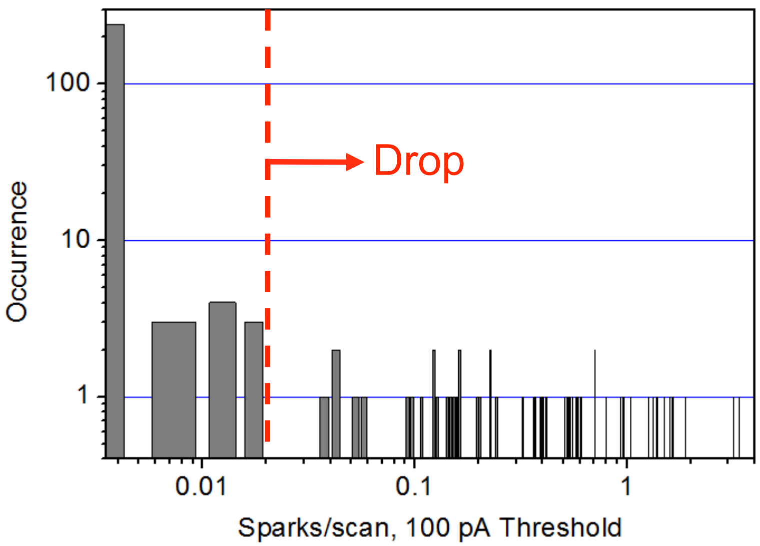
Eliminate any scan with sparks

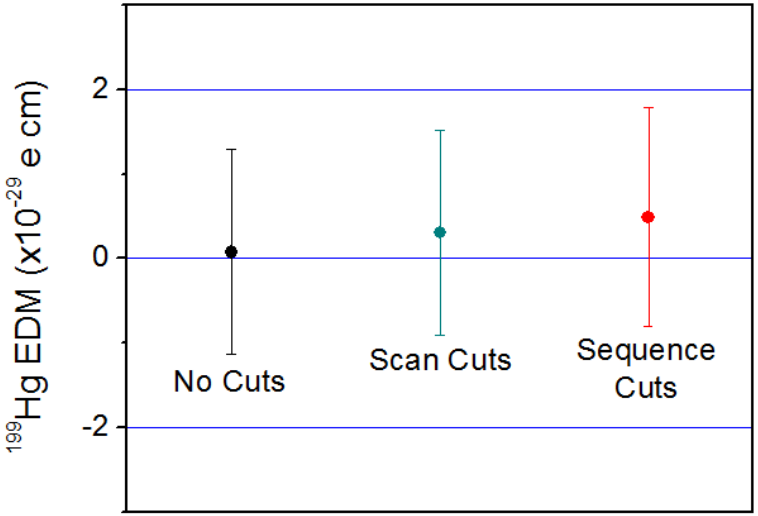
- Reconstruct the individual runs

Eliminate runs with sparks

- Drop sequences with incomplete B-Flips
- Equivalent to dropping all 5 sequences

Distribution of Sparks/Scan





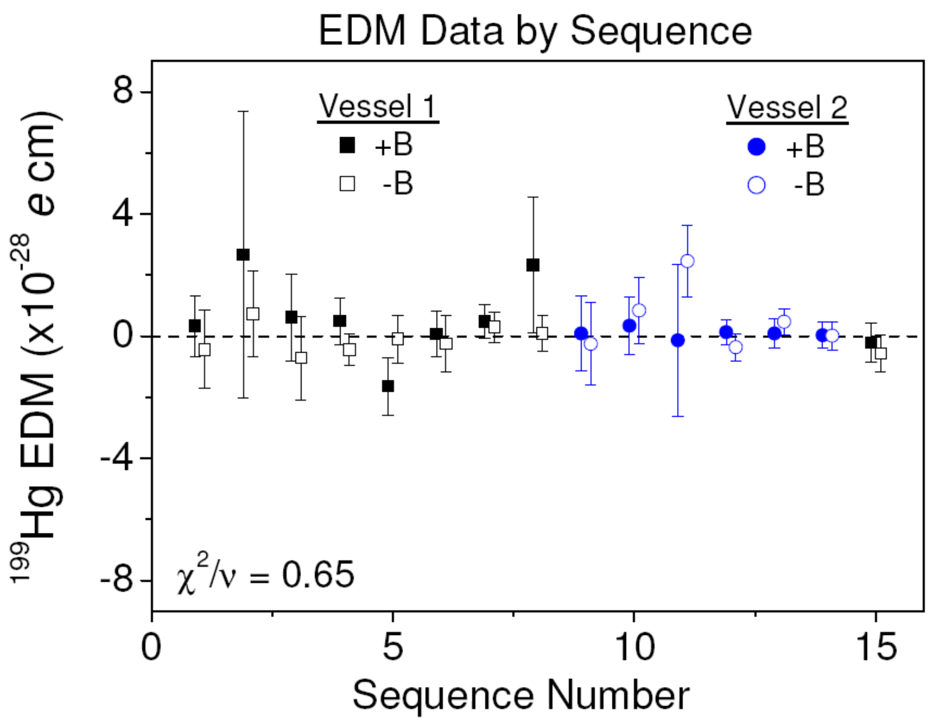
Agreement Between Spark Cut Central Values

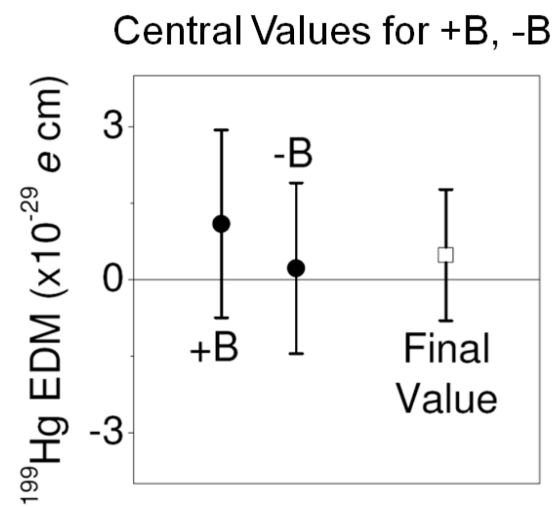
1.8×10^{-30} *e* cm

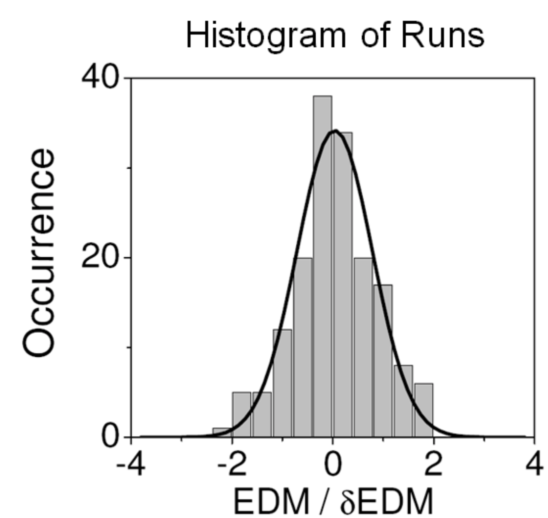
Shift Due to Spark Cuts

$< 4.2 \times 10^{-30}$ *e* cm

Final dataset







$$d(^{199}\text{Hg}) = (0.49 \pm 1.29_{\text{stat}})\text{x}10^{-29}\ e\ \text{cm}$$

0.1 nHz

Systematic checks and error budget

No Statistically Significant Dependence on:

- Vapor cells
- Electrodes
- Vessels

Systematic Error Budget

Source	Error (10^{-30} *e cm*)
Leakage Currents	4.53
Parameter Correlations	4.31
Spark Analysis	4.16
Stark Interference	1.09
E^2 Effects	0.62
Charging Currents	0.40
Convection	0.36
$(\vec{v} \times \vec{E})$ B-Fields	0.18
Berry's Phase	0.18
Quadrature Sum	**7.63**

99% of Total Error

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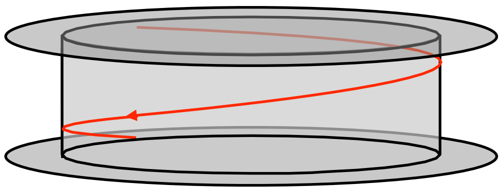
Leakage currents

Worst Case Scenario of Helical Current Flow



$$\delta(d_{Hg}) \approx 3.1 \times 10^{-29}\ (e\ \text{cm})/(\text{pA} - \text{Turn})$$

Average Single-Cell Current: 0.42 pA

Effective Current: √2(0.42 pA) = 0.59 pA

Maximum Helical Path (cell geometry): ½ Full Turn

Averaging Due to Cell Flips: Factor of 2

→ $4.5 \times 10^{-30}\ e$ cm

Parameter correlations

Parameters:

Larmor Precession Fits

- Single Cell
  - spin amplitudes
  - lifetimes
  - relative phases
  - frequency errors
  - background

Apparatus Sub-Sustems

- UV Laser System:
  - power
  - frequency
  - drive current
  - piezo control voltages
- External B-Fields:
  - 3-axis fluxgate magnetometer
- B-field coil currents:
  - Main coil and 3 shim coils

calculate
HV correlation &
correlation with $\Delta\omega_{EDM}$

→ 1-σ Limit from Product

↓

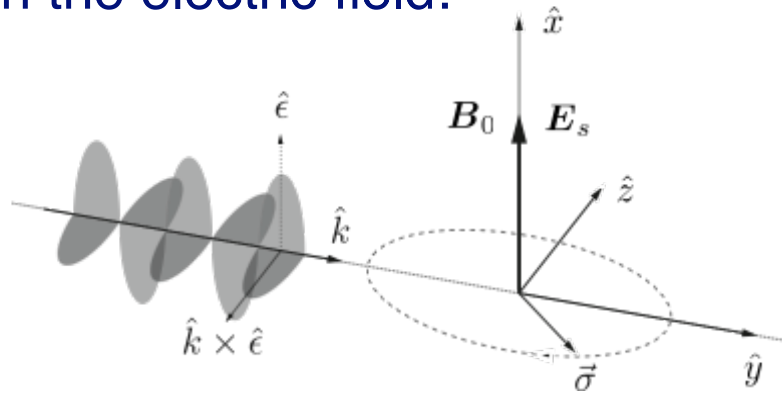
Quadrature Sum

4.3x10^{-30} e cm

Stark-induced interference

- Static electric field mixes *M*1 and *E*2 components into the $6^1S_0 \rightarrow 6^3P_1$ intercombination line
  - causes change in absorption linear in the electric field:

$$\frac{\delta\alpha}{\alpha} = (a_{E2} + a_{M1})(\hat{\epsilon} \cdot \vec{E}_s)(\hat{k} \times \hat{\epsilon}) \cdot \hat{\sigma}$$



- Our measurements currently give

$(a_{E2} + a_{M1}) = (0.39 \pm 0.32_{Stat}) \times 10^{-8}$ (kV/cm)$^{-1}$

$$\delta\omega_{SI} \approx 3.6 \times 10^{-31} \; (e\,\text{cm}/\text{degree})$$

misalignment of ε, $\boldsymbol{E_s}$, and $\boldsymbol{B_0}$ < ~3° over dataset

- Recent calculation: K. Beloy, V.A. Dzuba, and A. Derevianko, PRA 042503 (2009)

2009: $(a_{E2} + a_{M1}) = 0.80 \times 10^{-8}$ (kV/cm)$^{-1}$

Improved bounds on *CP*-violating parameters

$$d(^{199}\text{Hg}) = (0.49 \pm 1.29_{\text{stat}} \pm 0.76_{\text{sys}}) \times 10^{-29}\ e\ \text{cm}$$

$$|d(^{199}\text{Hg})| < 3.1 \times 10^{-29}\ e\ \text{cm (95\% CL)}$$

Parameter	^{199}Hg bound	Best other limit		
$\tilde{d}_q$(cm)	6×10^{-27}	n:	3×10^{-26}	Quark Chromo EDMs: 5x
d_p(e cm)	7.9×10^{-25}	TlF:	6×10^{-23}	Proton EDM: 76x
C_S	5.2×10^{-8}	Tl:	1.3×10^{-7}	Semi-Leptonic Interactions: C_S: 2.5x
C_P	5.1×10^{-7}	TlF:	3×10^{-4}	C_P: 590x
C_T	1.5×10^{-9}	TlF:	4.5×10^{-7}	C_T: 300x
$\bar{\theta}_{QCD}$	3×10^{-10}	n:	1×10^{-10}	QCD Phase
d_n(e cm)	5.8×10^{-26}	n:	2.9×10^{-26}	Neutron EDM
d_e(e cm)	3×10^{-27}	Tl:	1.6×10^{-27}	Electron EDM

For ^{199}Hg : $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$ while for n: $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$

Confidence Levels: ^{199}Hg (95%), n (90%), ^{205}Tl (90%), TlF (95%)

Summary

- still haven't found a non-zero EDM, but ...
- new 4-cell ^{199}Hg EDM measurement improves the upper bound by 7x
  - lowest EDM limit in any system
  - provides constraints on *CP*-violating nucleon-nucleon interactions, complementary to d_e and d_n.
- future plans: factor of 3-5 improvement
  - additional detectors for balanced-polarimeters
  - elimination of sparks
  - possible cell redesign for better light trans. and lower leakage currents
  - evaluate sensitivity of a "precession in the dark" measurement (reduces Stark interference syst.)