The Search for Electric Dipole Moment (EDM) of $^{199}\mathrm{Hg}$ and its Application for the LANL Neutron EDM experiment

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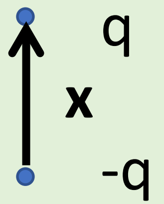
Collaboration: neutron Electric Dipole Moment experiment at Los Alamos National Laboratory (nEDM@LANL)

Outline

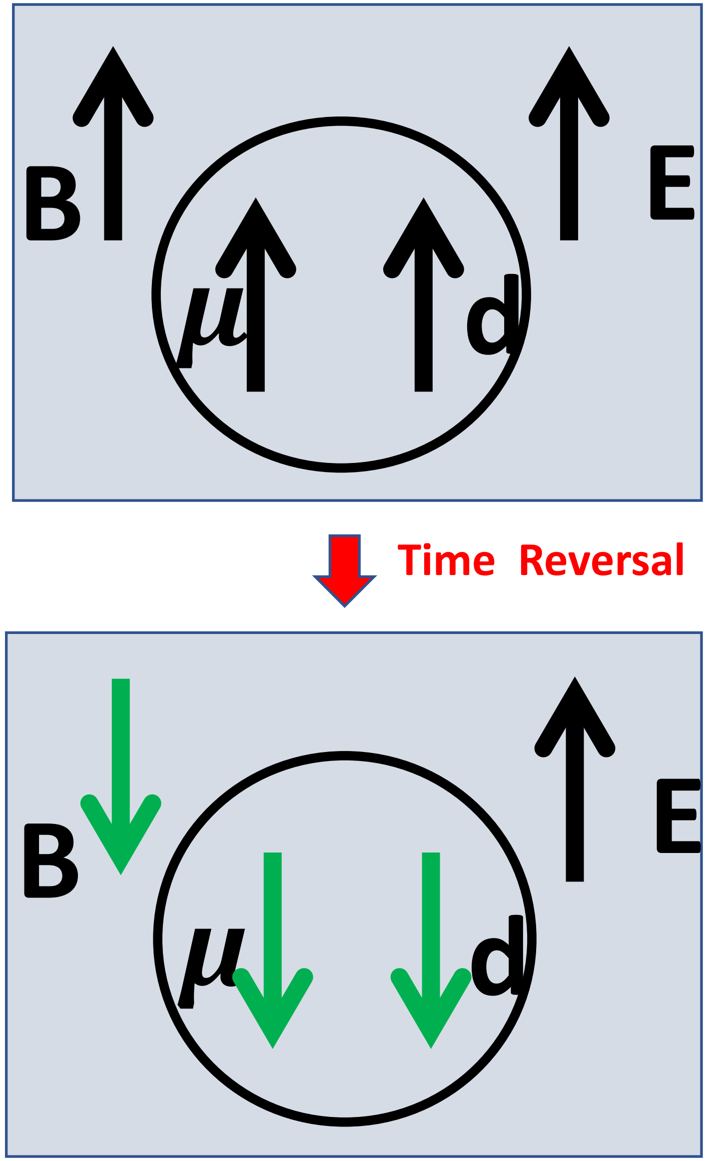
- Hg-199 EDM
  - EDM definition and Hg-199 EDM
  - Measurement techniques
  - Experiment setup
  - Data analysis
  - The dominant systematics
- Hg-199 as co-magnetometer in nEDM experiment
  - Solve the limiting factor but does create new systematics error
- Hg-199 magnetometry systems in nEDM@LANL
  - Two Hg systems and Cs cells
- Study on coating vs Hg coherence time

Electric Dipole Moment

$\mathbf{d} = qx$



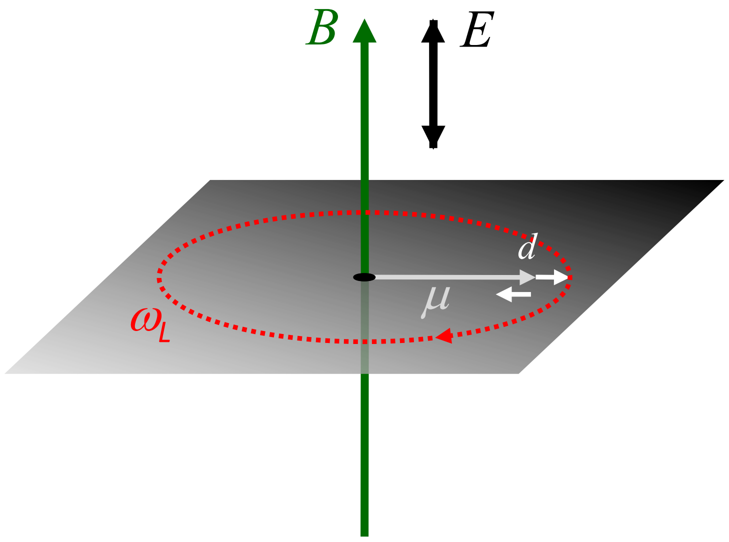
$$H = -\boldsymbol{\mu} \cdot \boldsymbol{B} - \boldsymbol{d} \cdot \boldsymbol{E}$$



- $\mathbf{d} = q \cdot \boldsymbol{x}$ for two point charges, with +q and –q, separated by distance x.[e· cm]
- CPT theorem: Under CPT transformation, all physical phenomena (Hamiltonian) is conserved(C: charge conjugation; P: parity; T:time)
- Hg EDM is induced by Schiff moment.
  - Schiff theorem says the nuclei could be completely screened by electrons if nuclei was point-like and nonrelativistic.
- Test time reversal symmetry by flipping the E

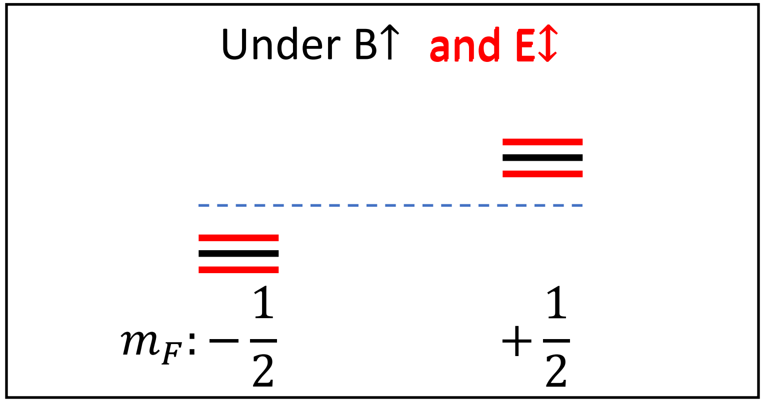
Measuring an EDMs via Larmor Precession

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



$$\omega_1 = \frac{2\vec{\mu} \cdot \vec{B} + 2\vec{d} \cdot \vec{E}}{\hbar} \qquad \left(\frac{\mathrm{B} \cdot \mathrm{E}}{\|\mathrm{B} \cdot \mathrm{E}\|} = 1\right)$$

$$\omega_2 = \frac{2\vec{\mu} \cdot \vec{B} - 2\vec{d} \cdot \vec{E}}{\hbar} \qquad \left(\frac{\mathrm{B} \cdot \mathrm{E}}{\|\mathrm{B} \cdot \mathrm{E}\|} = -1\right)$$

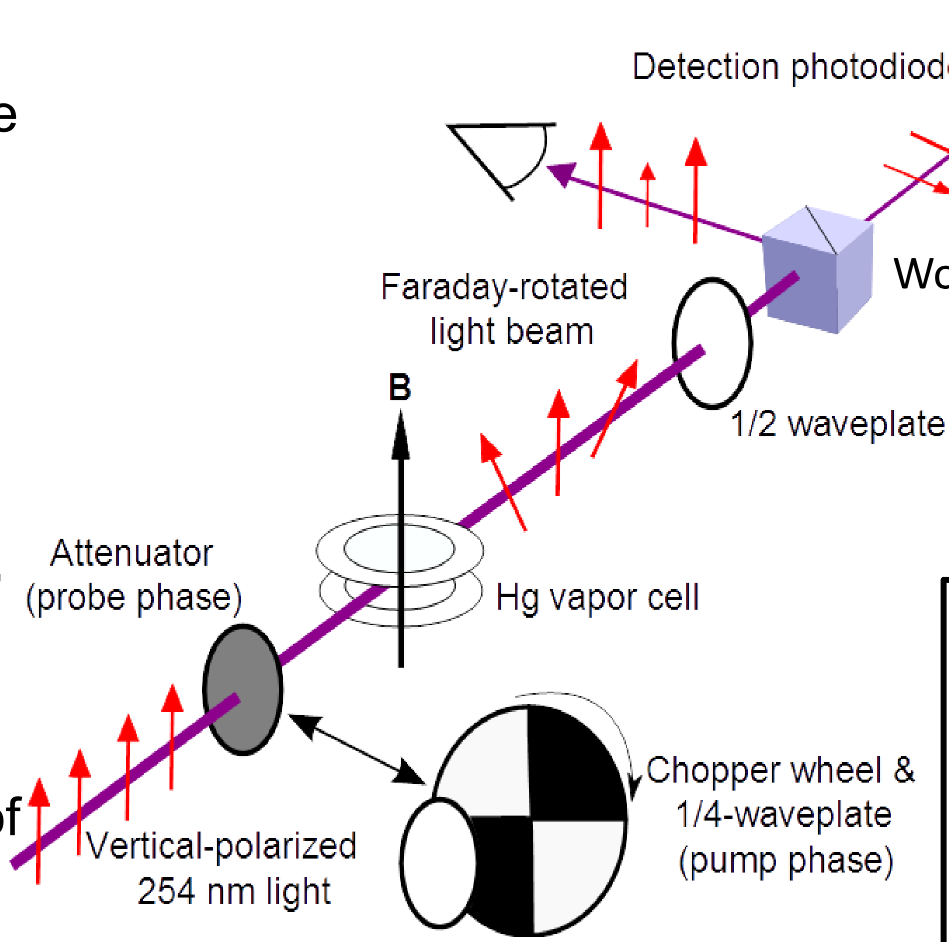


$$\omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

$\approx nHz$

Faraday Rotation Detection

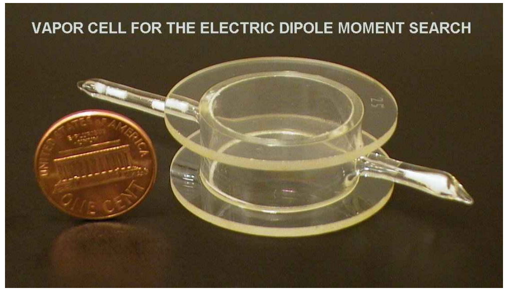
- Atomic polarization changes the index of refraction for σ_+ and σ_- light
- Incoming linearly polarized probe light is rotated
- Rotation angle oscillates at the Larmor frequency
- A polarizing beam splitter separates the beam into vertical, horizontal components
- Intensity of 2 orthogonal polarization states oscillate out of phase



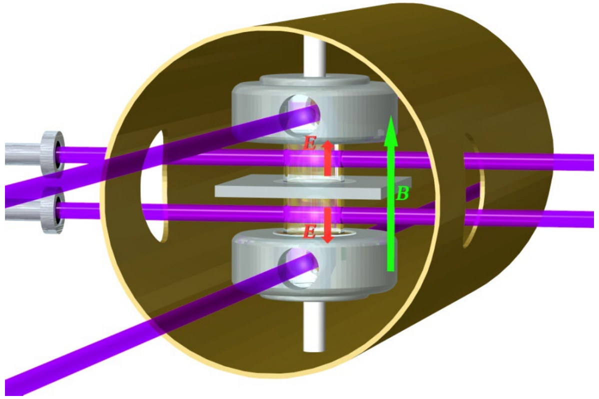
One pump-probe cycle

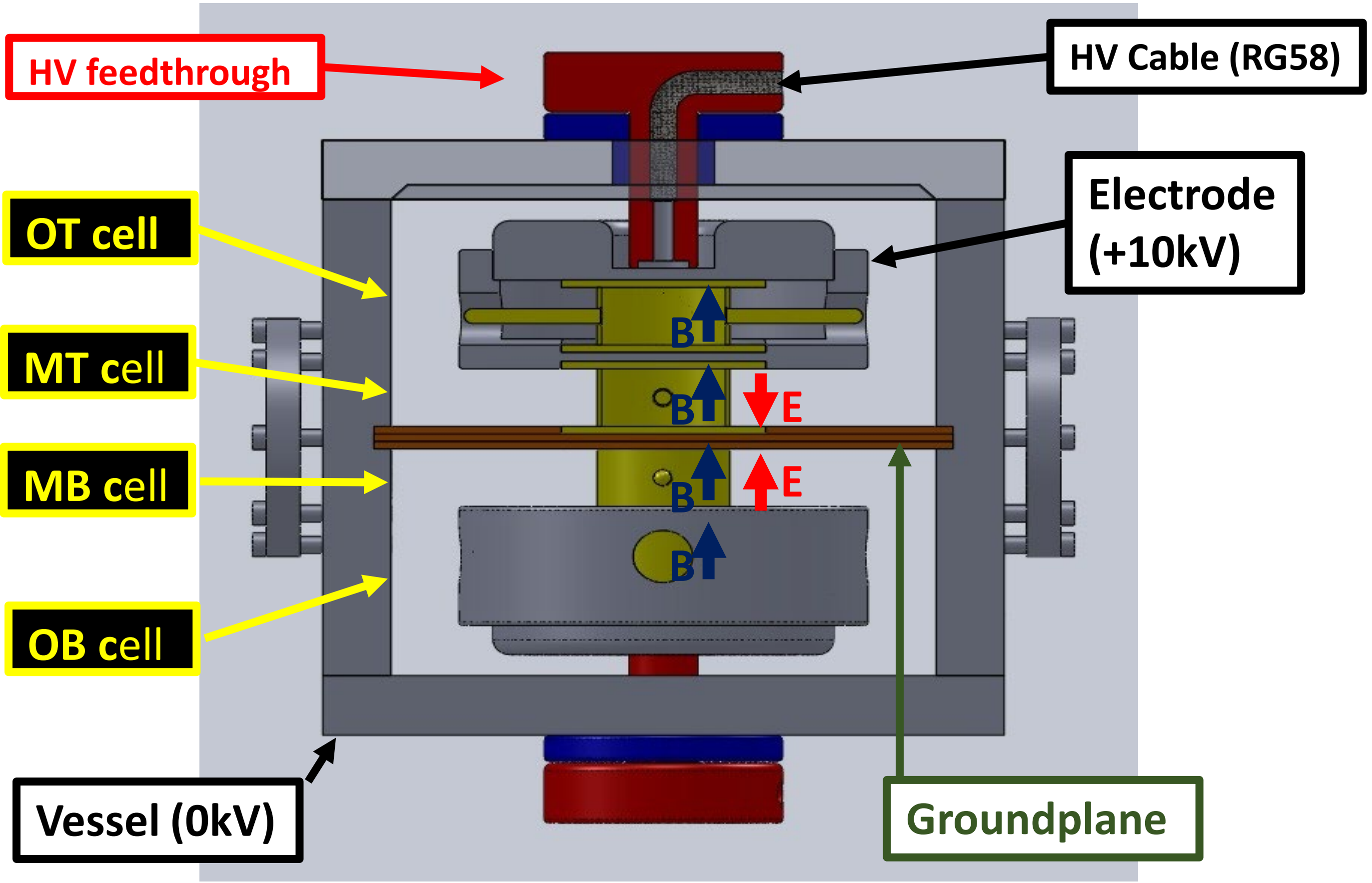
1. Pump with circular light with a chopper
2. Remove chopper and ¼-waveplate, change laser wavelength
3. Probe with linear light

Hg-199 Vapor Cell



Seattle's Hg EDM Experiment

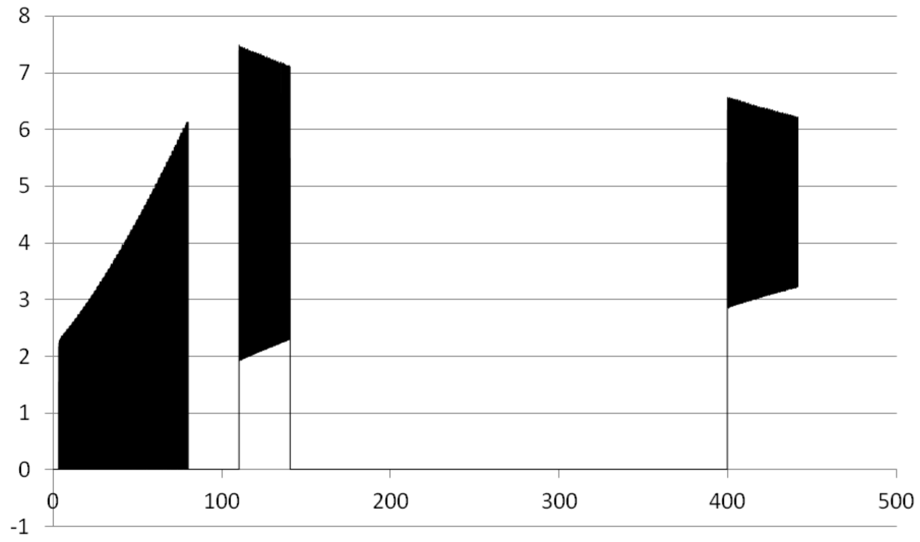




- A stack of four Hg vapor cells
- The fused-silica plate defines the ground
- The outer two cells sit inside of HV electrodes and serve as magnetometers.
- The vessel sits inside the three-layer mu-metal shields.

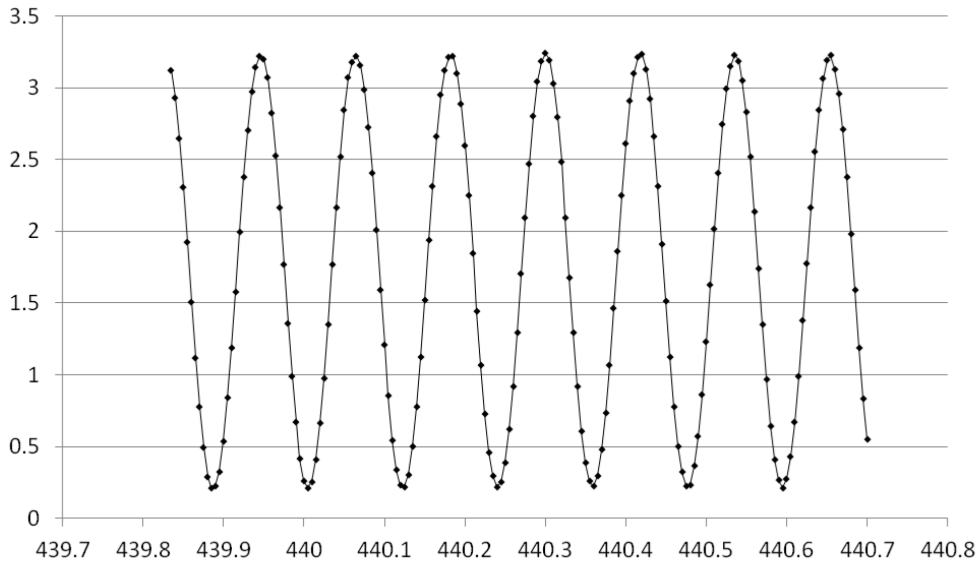
Phase Difference Analysis

^{199}Hg EDM raw data (run 16030, 5/29/2013)



Photodiode signal (V) vs. time (seconds)

^{199}Hg EDM run 16030 data excerpt (-3.0V offset)



Photodiode signal (V) vs. time (seconds)

- Instead of fitting a single long sample for **ω**, we can apply the Ramsey method: fit 2 samples for Δφ with light off in between for time Δt

- Freq. difference $(\omega_{MT} - \omega_{MB}) = \dfrac{\Delta\,\varphi_{MT-MB}(t_f) - \Delta\varphi_{MT-MB}(t_i)}{t_f - t_i}$

- $\mathbf{d}_{Hg}$ signal = $\Delta_{HV}[(\omega_{MT} - \omega_{MB}) - 1/3(\omega_{OT} - \omega_{OB})]$ EDM combo

Typical One Overnight Run

HV sequence: + - + -

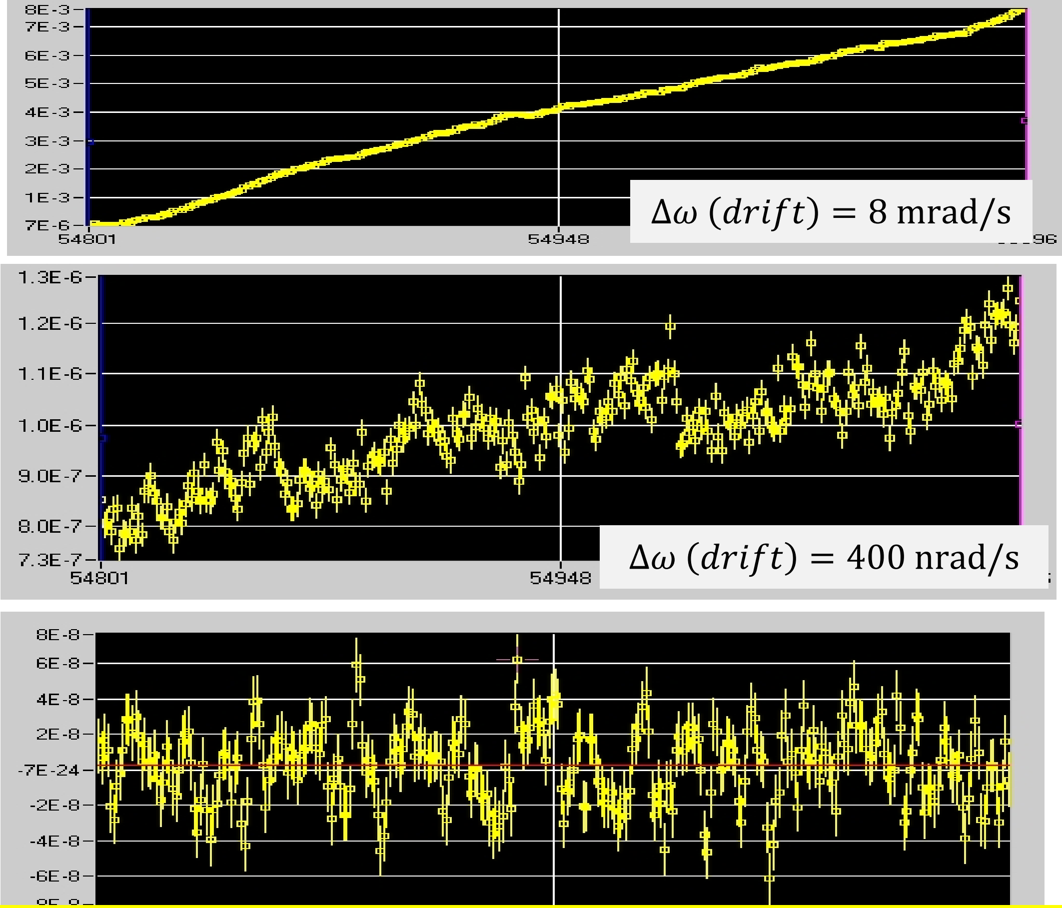
Avg. ω

4 Cell EDM Combo

MT–MB–1/3 (OT–OB)

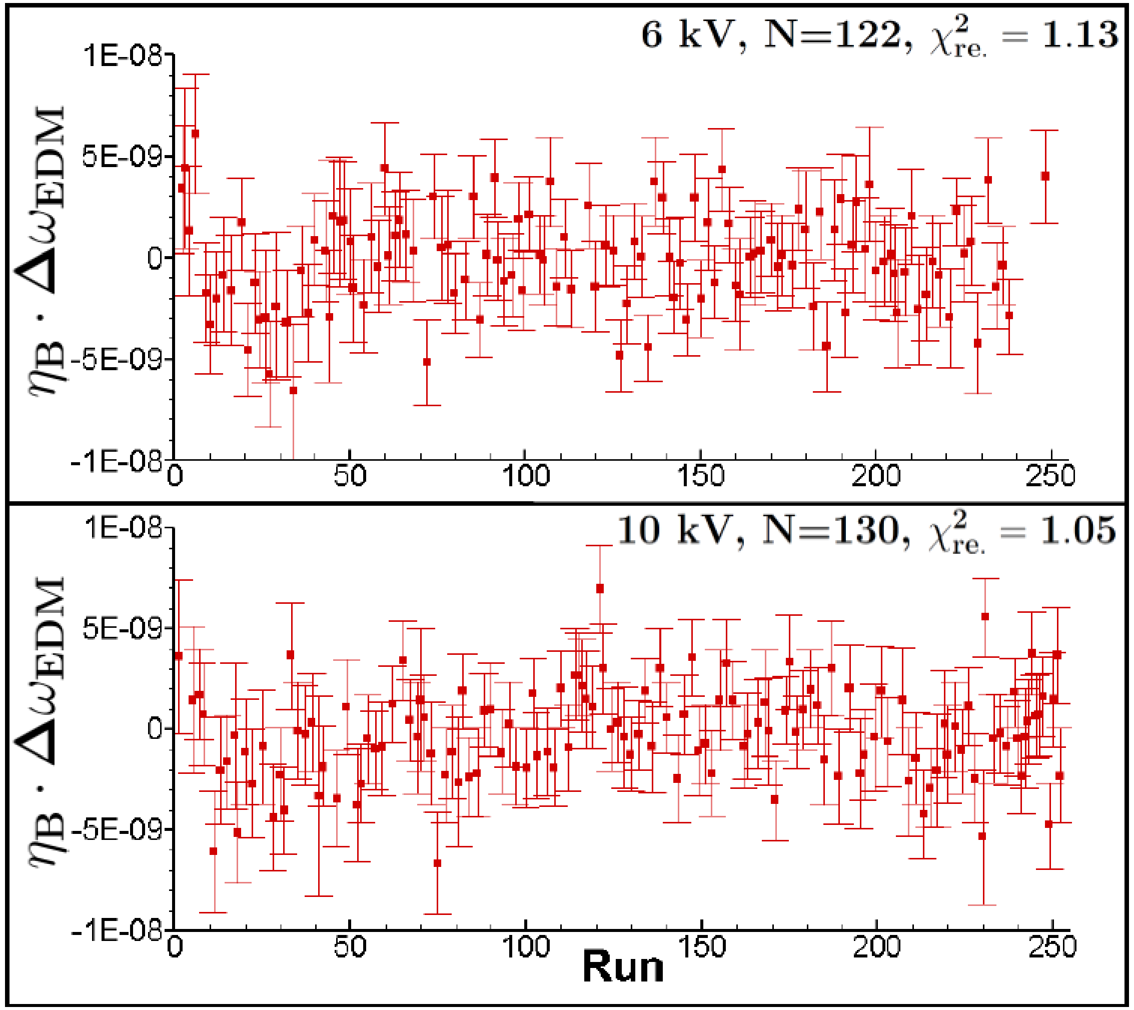
HV Corr. (EDM signal)

$$(-1)^n \frac{\Delta\omega_n - 2\Delta\omega_{n+1} + \Delta\omega_{n+2}}{4}$$



$\sigma^{\Delta\omega}{}_{stat} = 2.0 \times 10^{-9}$ Hz $\rightarrow \sigma^{d}{}_{stat} = 3.28 \times 10^{-29}$ e cm, $\chi^2 = 2.17$

Statistical Performance



- 2009 EDM paper had statistical sensitivity of

  6.43 $*10^{-10}$ s^{-1}

- New data set has an avg. daily error bar 2.0 $*10^{-9}$ s^{-1}

- 252 runs remain after cuts

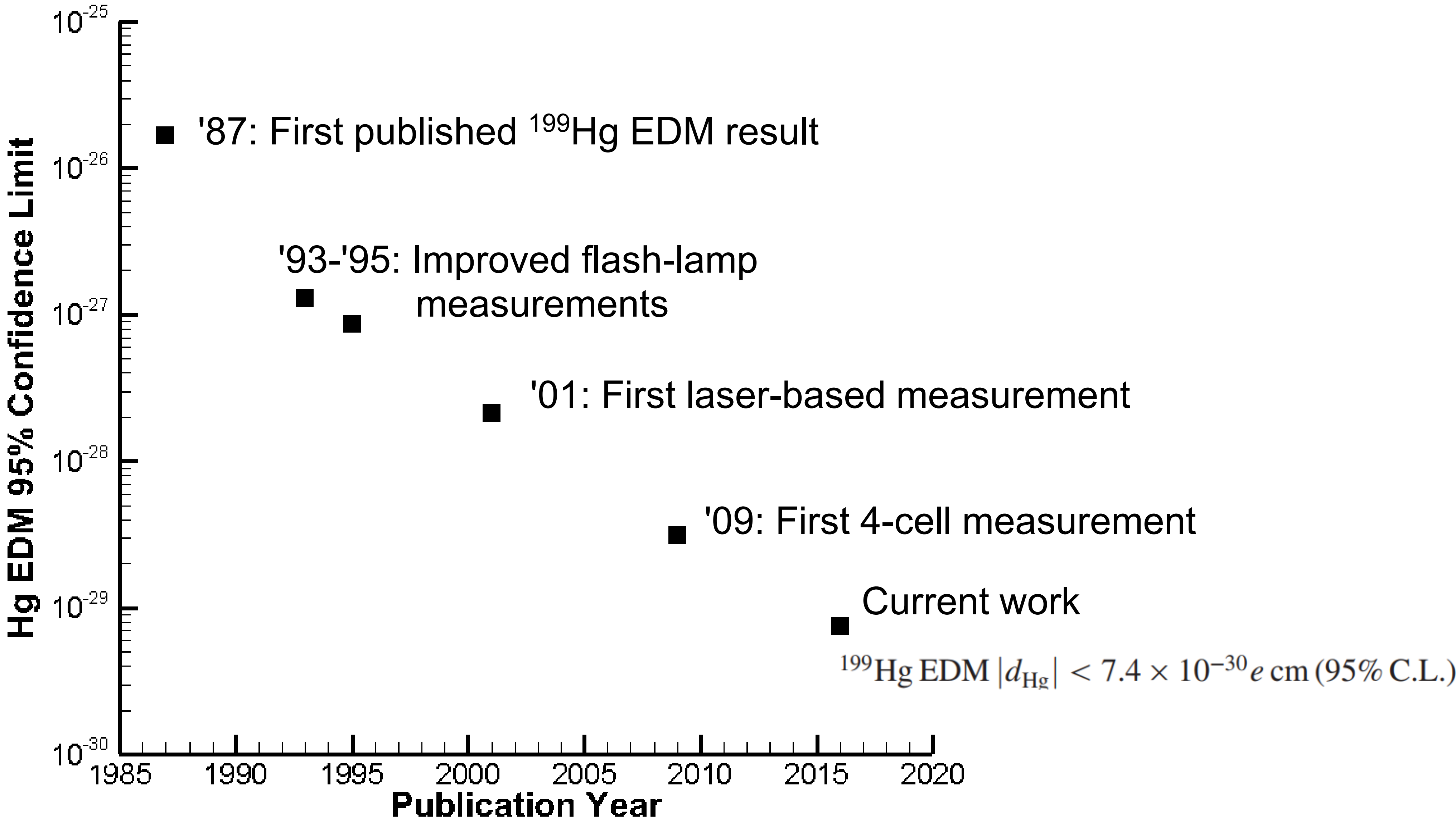
- New EDM data set has a stat. error of 1.45 $*10^{-10}$ s^{-1}

Systematic Error Budget at Hg-199 EDM experiment

Source	Error($10^{-31} e \cdot cm$)
Axial Cell Motion	12.62
Leakage Currents	5.02
Radial Cell Motion	3.36
E^2 Effects	3.04
Parameter Correlations	2.33
$\mathbf{v} \times \mathbf{E}/c$	2.29
Charging Currents	1.83
Geometric Phase	0.06
Quadratic Sum	**14.8**
(Statistical Error	27.5)

New Systematic:
Cell Motion -
88% of Total Error

Hg EDM Limits vs. Time



Hg-199 as the co-magnetometer in nEDM experiment

$$\omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

↓

$$\frac{4d_nE}{\hbar} = \langle\omega_{Hg}\rangle(R_+ - R_-)$$

ELSEVIER
Nuclear Instruments and Methods in Physics Research A 404 (1998) 381–393
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Performance of an atomic mercury magnetometer in the neutron EDM experiment

K. Green[a], P.G. Harris[a,*,1], P. Iaydjiev[a,2], D.J.R. May[b], J.M. Pendlebury[b], K.F. Smith[b], M. van der Grinten[b], P. Geltenbort[c], S. Ivanov[d]

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Received 15 September 1997

$$R_{\pm} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right|\left(1 \underbrace{\pm \delta_{\mathrm{EDM}} \pm \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{Q}}}_{\text{E-field}} \underbrace{+\delta_{\mathrm{G}} + \delta_{\mathrm{T}}}_{\text{B-field}} \underbrace{+ \delta_{\mathrm{E}} + \delta_{\mathrm{LS}} + \delta_{\mathrm{I}} + \delta_{\mathrm{P}} + \delta_{AC}}_{\text{Secondary effects}}\right)$$

*P. Schmidt-Wellenburg. The latest episode in the quest for an electric dipole moment of the neutron and the future endeavor at PSI. FRIB EDM workshop. (2019)

Hg-199 is not perfect!

1998 ILL

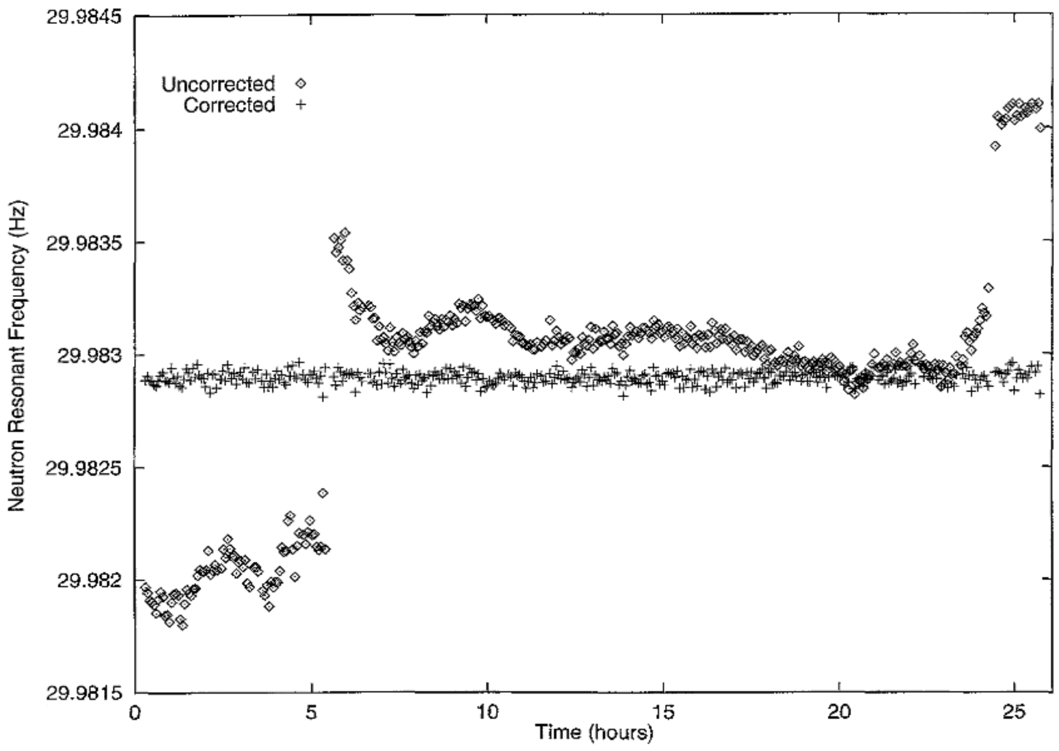


Fig. 8. Neutron resonant frequency, measured over the same 26-hour period, before and after correction of the effect of the drifting magnetic field by normalisation to the measurements of the mercury magnetometer.

2020 PSI

TABLE I. Summary of systematic effects in 10^{-28} e.cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below that are considered separately.

Effect	Shift	Error
Error on $\langle z \rangle$	...	7
Higher-order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
→ Hg EDM [8]	−0.1	0.1
Local dipole fields	...	4
$v \times E$ UCN net motion	...	2
Quadratic $v \times E$	...	0.1
Uncompensated G drift	...	7.5
→ Mercury light shift	...	0.4
→ Inc. scattering ^{199}Hg	...	7
TOTAL	69	18

Geometric phase

Green, K., et al. "Performance of an atomic mercury magnetometer in the neutron EDM experiment." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 404.2-3 (1998): 381-393.

Abel, Christopher, et al. "Measurement of the permanent electric dipole moment of the neutron." *Physical Review Letters* 124.8 (2020): 081803.

Laser path in Hg Magnetometry in LANL nEDM

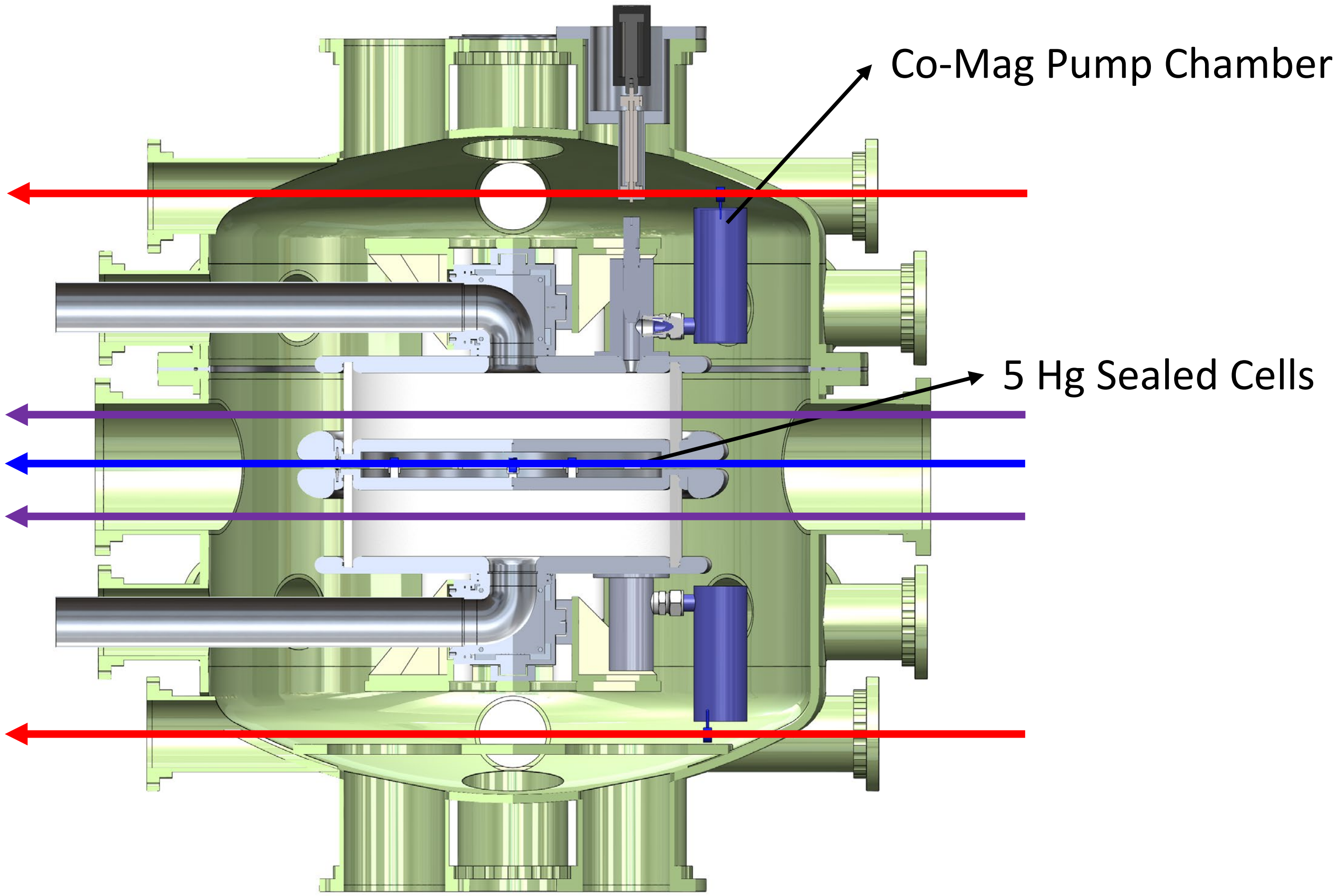
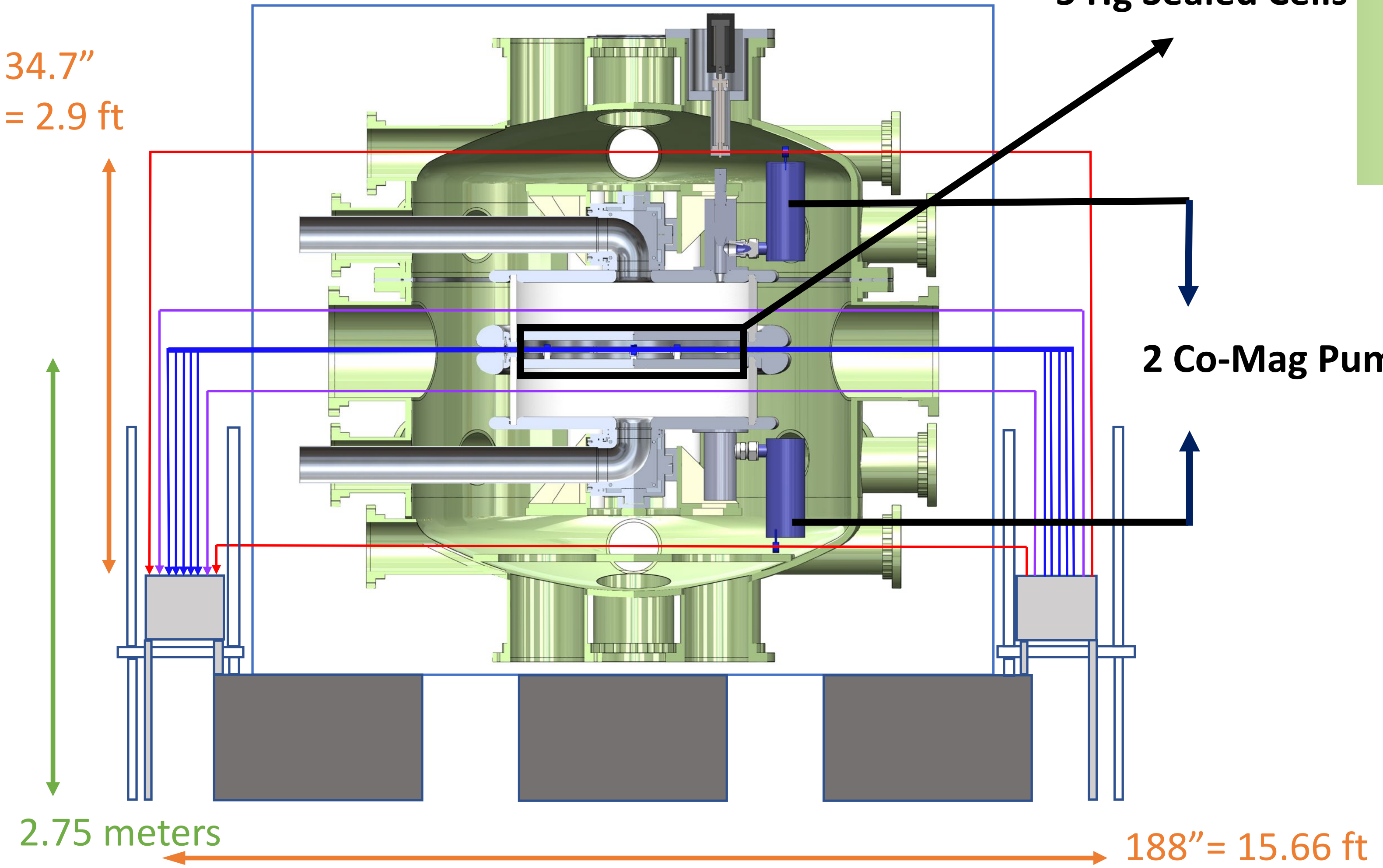
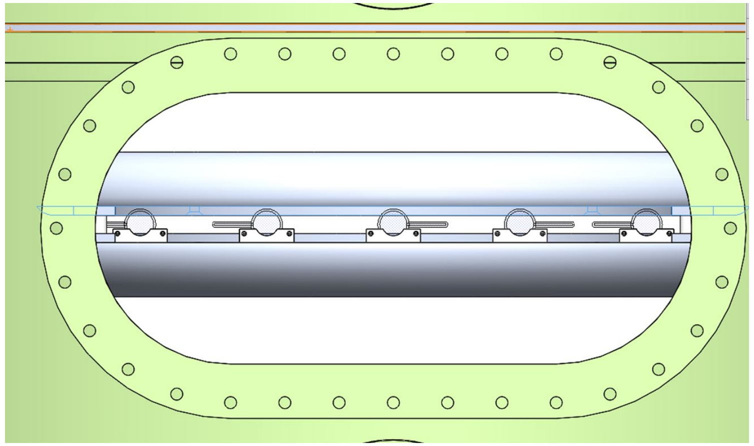


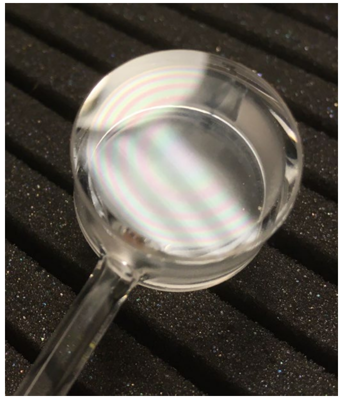
Image by Chris O'Shaughnessy

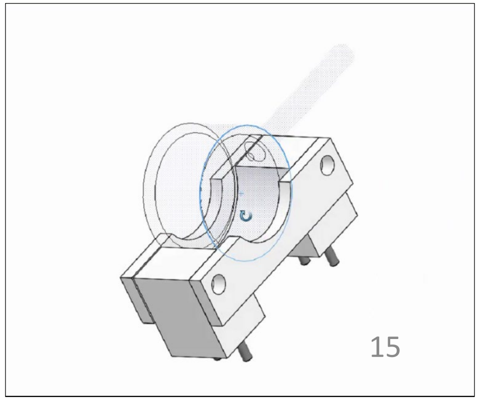
Hg-199 as co-magnetometer and magnetometers

- Optics design and test
- Hg sealed cell fabrication
    - Wall coating study
- Beam H = 3”; Optics table to the work platform = 28.25”; work platform to the floor = 30”



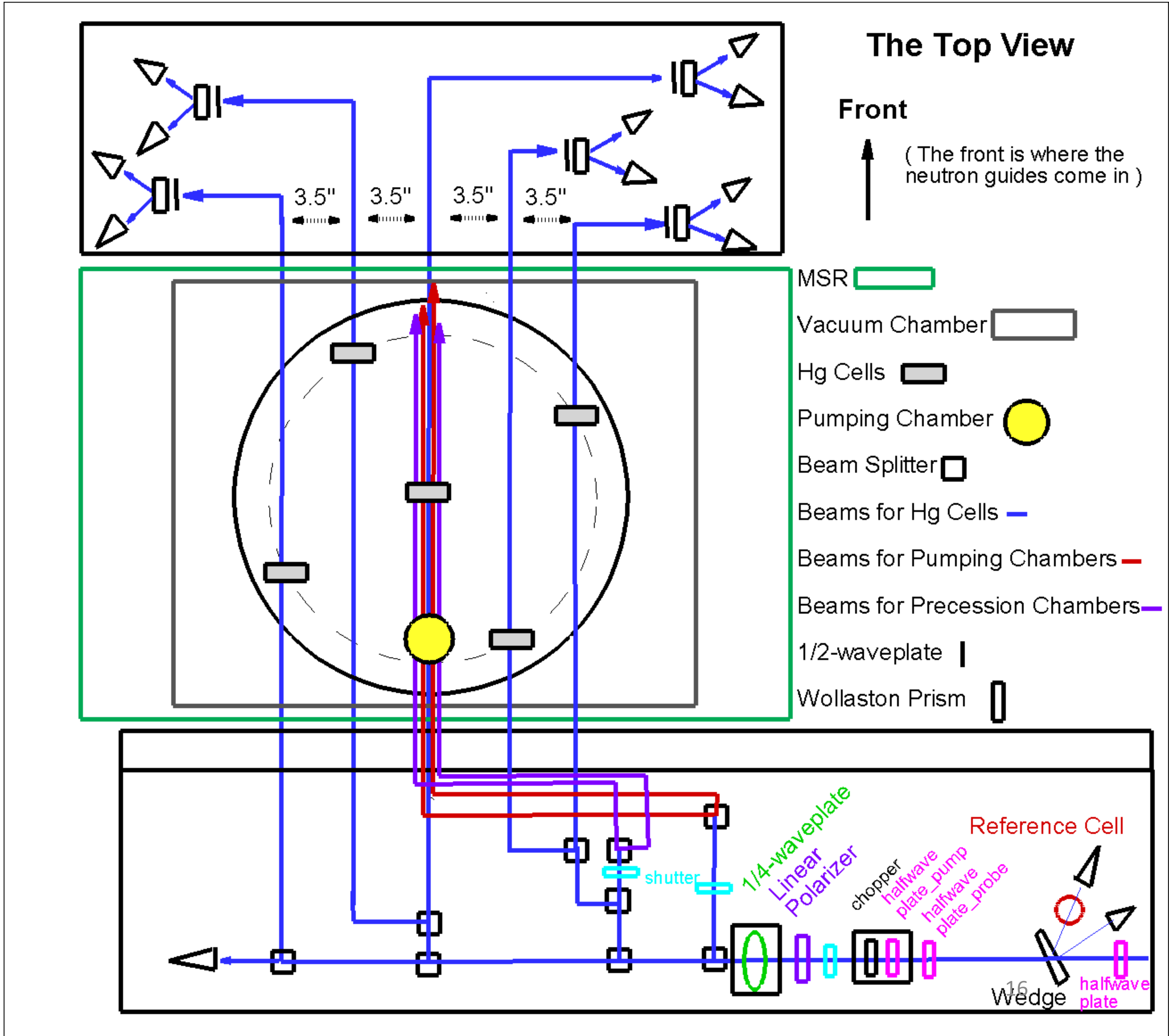






Status

- Optics setup for nEDM@LANL
- The Larmor precession frequency is detected by the Faraday rotation of the laser polarization.
- Lock the laser frequency during the pump and probe phases with a Hg reference cell.
  - Frequency locking circuit design and fabrication
- Hg cell fabrication with various coatings

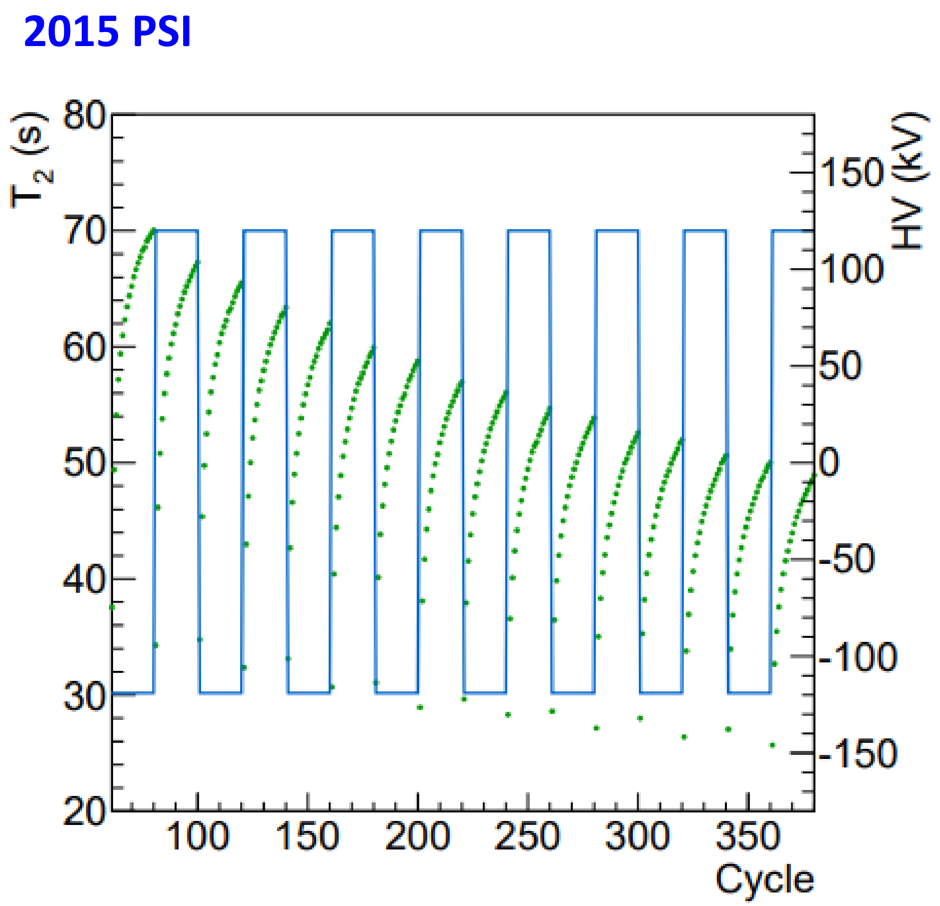


	Reference cell	HV external Hg mag cell	Hg polarizing chamber	Hg in precession chamber
Number	1	5	2	2
Wall coating	None	Dotriacontane	TBD	TBD
Size	Cylinder: ID = 19 mm H=10mm	Cylinder: ID = 19 mm H = 10 mm	Cylinder: ID = 90 mm H = 203.2 mm (8”)	Cylinder: ID = 482.6 mm (19”) H = 95.25 mm (3.75”)
Optical Length	10 mm	10 mm	10 mm	482.6 mm
Hg number density [atoms/cc]	5.4×10^{13}@ 23°C	5.4×10^{13}@ 23°C	4×10^{11}	3×10^{10}
Buffer gas	100 torr He	5 torr CO	None	None
Pressure Shift	57 MHz	-12.4 MHz	None	None
Pressure Broadening	787 MHz	47.35 MHz	None	None
Zero vector light shift (- is to the red)		-10 MHz	-10 MHz	-10 MHz
Challenge	**A decent error signal at λ_{pump} and λ_{probe}**	**Photon re-emission**	**Photon re-emission**	**Laser has a long vertical travel**

Magnetic shielding room at LANL nEDM experiment

Magnetic shielding room and non-magnetic vacuum chamber

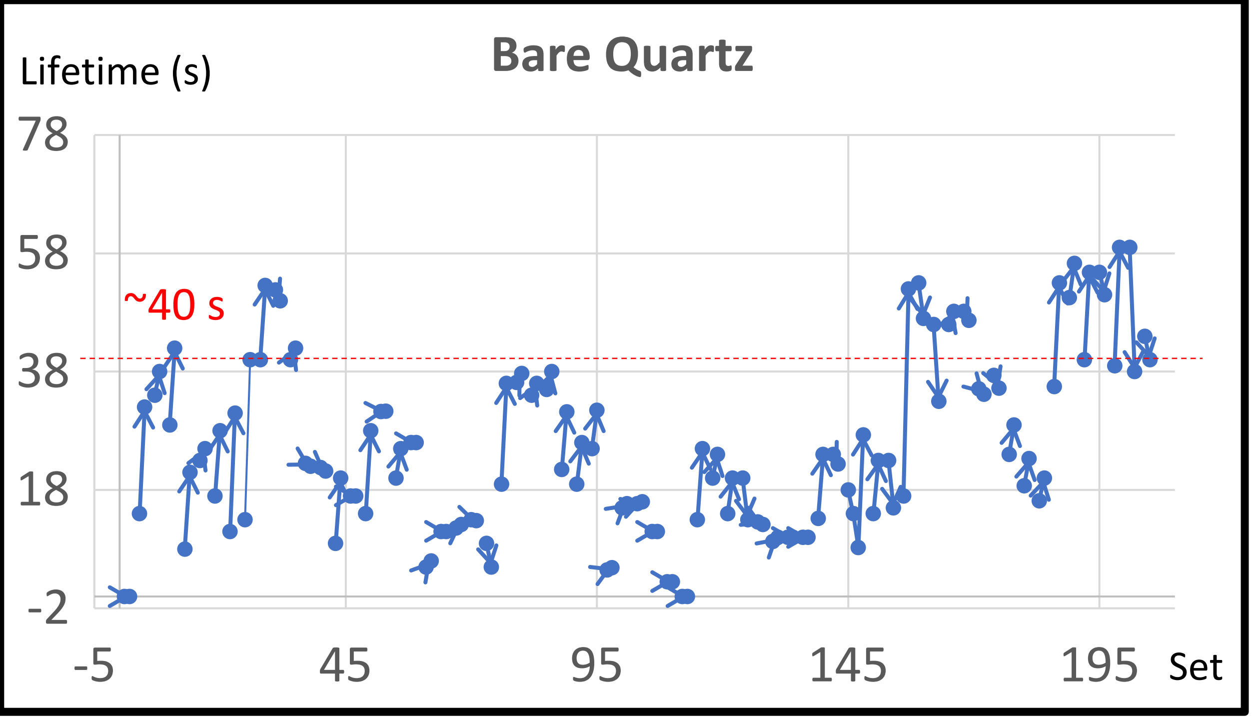
Coherence time drops when HV is reversed at PSI

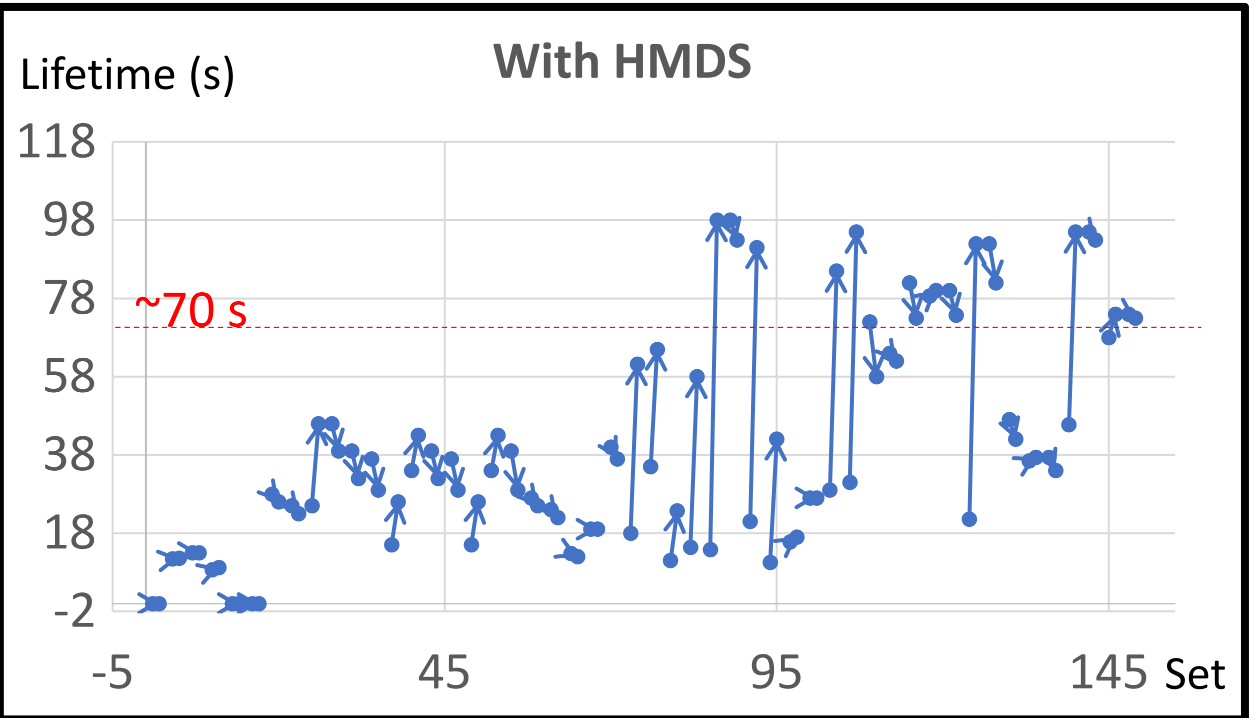


- An effect to be considered.
- The HV reversal is creating new relaxation sites for Hg on the chamber wall (most likely near the negative electrode)?
- Hg might not uniformly average the volume within the precession chamber? Averaging different for 2 HV polarities?
- This potential systematics error is very difficult to quantify.

Afach, Sam, et al. "Measurement of a false electric dipole moment signal from 199Hg atoms exposed to an inhomogeneous magnetic field." *The European Physical Journal D* 69.10 (2015): 1-7.

Brent Graner. *Reduced Limit on the Permanent Electric Dipole Moment of 199Hg*. PhD thesis, University of Washington, 2017.



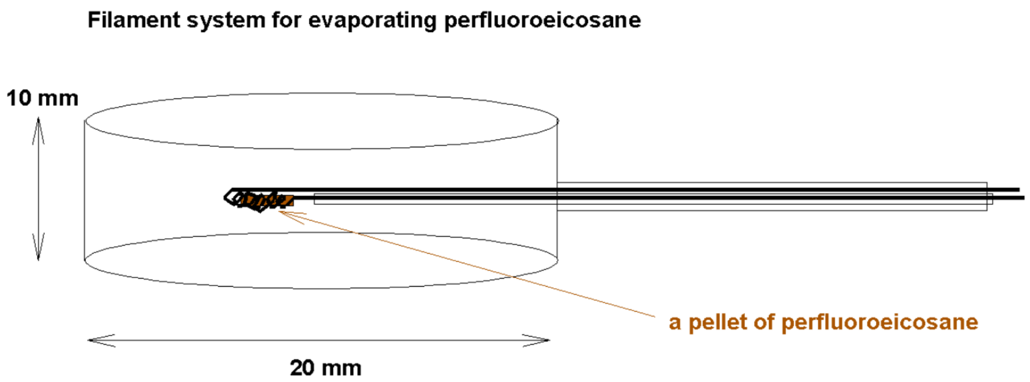


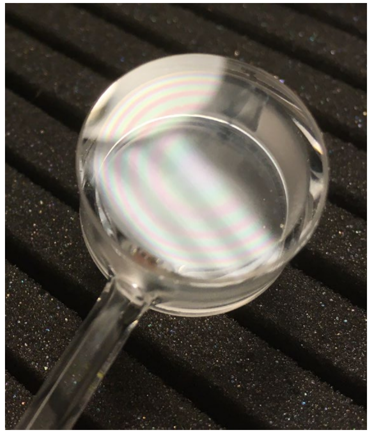
Lifetime Measurement

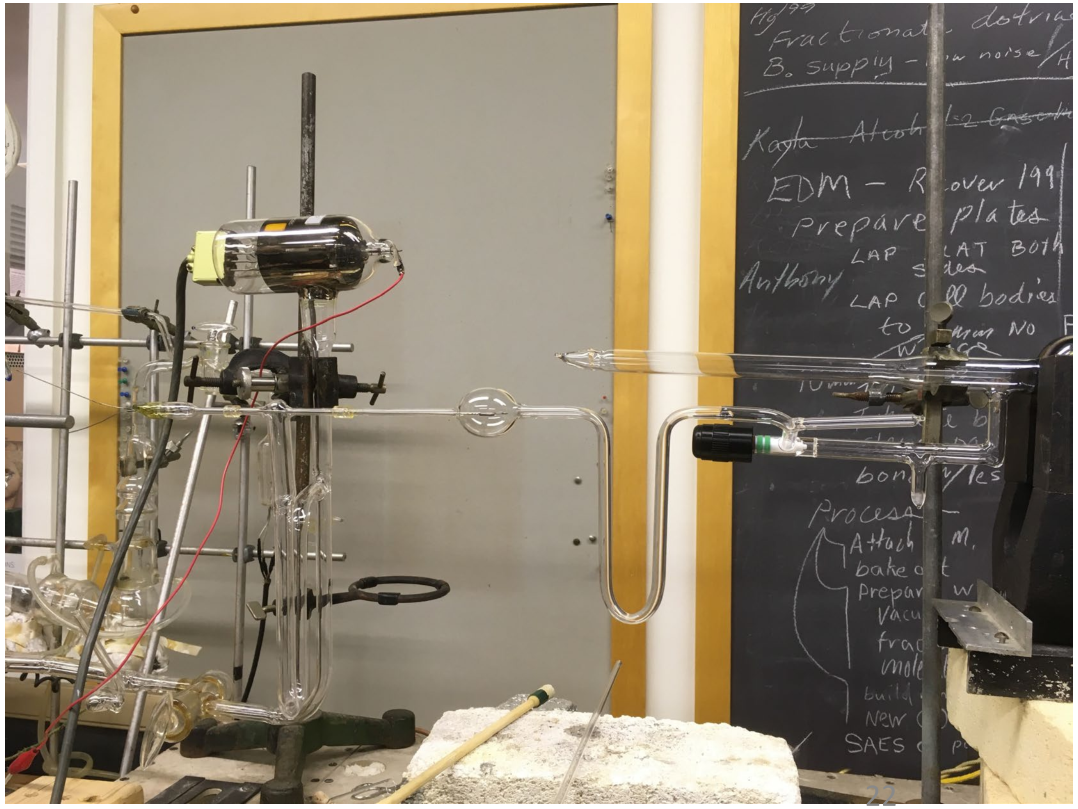
- Experiment with the pre-coating: hexamethyldisilizane (HMDS)
- Bare Quartz is without HMDS and another is with HMDS.
- How much work goes in after sealing off the cell from the vacuum manifold.
- Parameters:
  - The wax and its distribution
  - Excess of Hg
  - Contamination
- Stabilized at 40 s and 70 s.

Coating with Perfluoroeicosane (C20F42)

- Commonly used wax is dotriacontane (C32H66) paraffin.
- Eliminate the atomic Hydrogen from Paraffin wax. Replaced with fluorine.
- Two challenges:
  - Evaporating the wax inside a small cell.
  - Form an uniform layer of coating with a control







Summary

- Hg EDM experiment updates
  - an additional shielding, better care on the returning fields, and the degaussing scheme
- Development on Hg magnetometry systems for nEDM at LANL
  - Reference cell
  - Test with various wall coatings
- Next steps:
  - research on Hg-199 interacting with various coating and surfaces.
  - Prototype Hg co-mag system

The collaboration of nEDM@LANL

- Los Alamos National Laboratory
    - Takeyasu Ito
    - Christopher O'Shaughnessy
    - Steven Clayton
    - Taufique Hassan
    - Pinghan Chu
- Indiana University
    - Joshua Long
    - Gerard Visser
    - Mark Luxnat
    - Yi Chen
    - Douglas Wong
- University of Illinois Urbana-Champaign
    - Chen-Yu Liu
- University of Kentucky
    - Bradley Plaster
    - Jared Brewington
- University of Michigan
    - Tim Chupp
- California Institute of Technology
    - Christopher Swank
- East Tennessee State University
    - Robert Pattie
- Tennessee Tech University
    - Adam Holley

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