Search for a Permanent Electric Dipole Moment of ^{199}Hg

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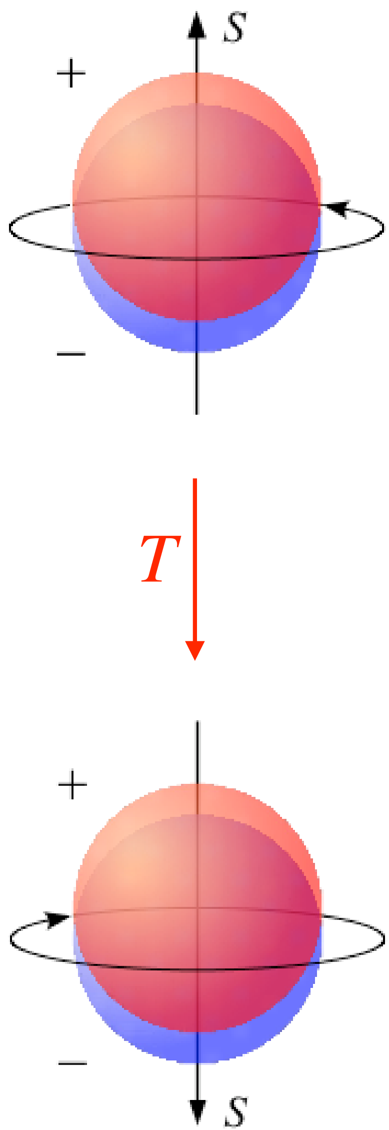
Outline

- Introduction
  - experimental EDM searches
  - UW Hg measurement
- 2-cell result from 2001
  - theoretical interpretation and implications
- 4-cell EDM measurement
  - apparatus changes
  - recent data and status

The Search for an EDM

A permanent EDM of a fundamental particle 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.

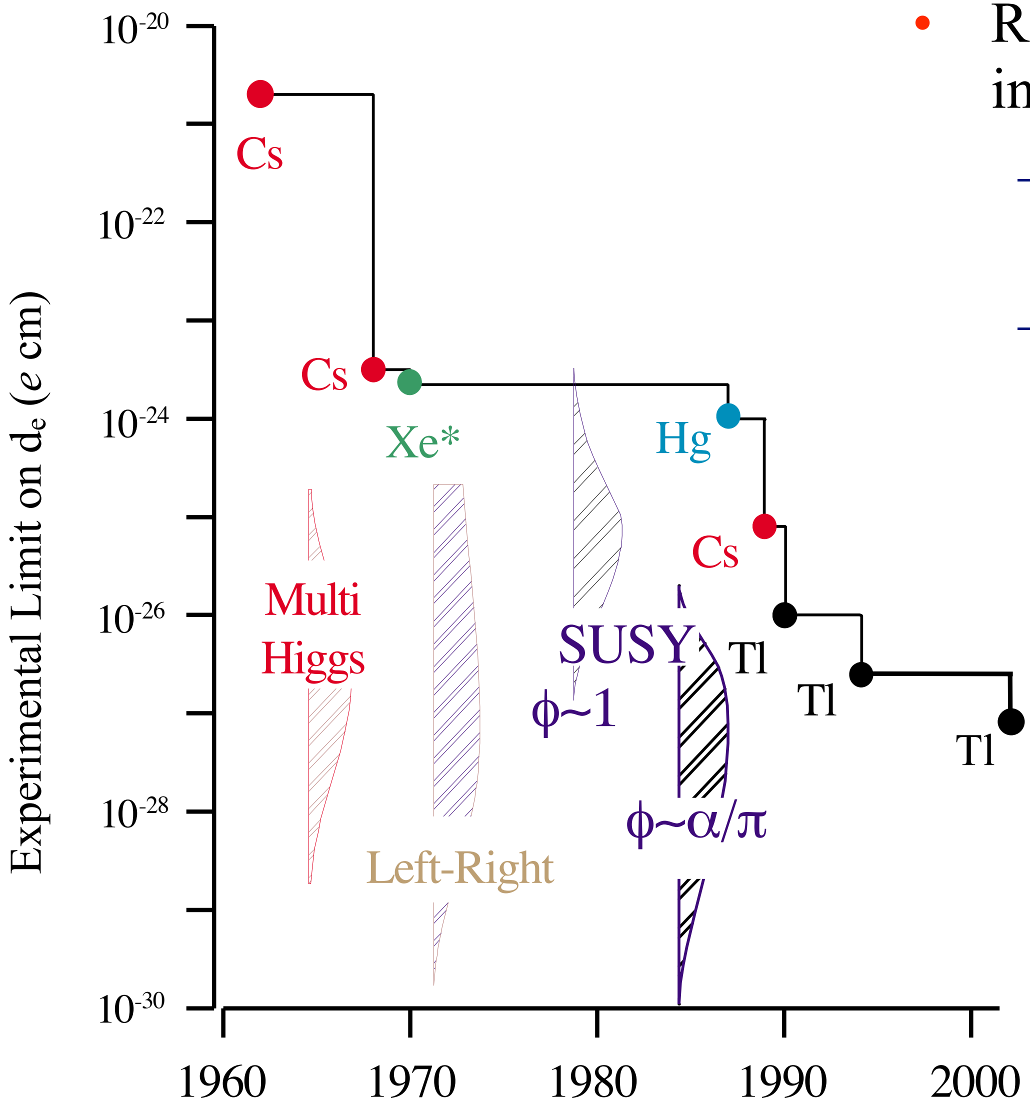
Search for an EDM of the neutron began over 50 years ago, so far no luck.

Crucial point 2:

Theories of physics beyond the Standard Model => EDMs large enough to see.

Therefore, keep on looking!

EDM searches: the electron



- Relativistic enhancement of the electron EDM in heavy paramagnetic atoms
  - sensitive to d_e through unpaired electron spin, scales as $Z^3\alpha$
  - best limit is from Thallium: $d_{\mathrm{Tl}} = -585\ d_e$

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

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

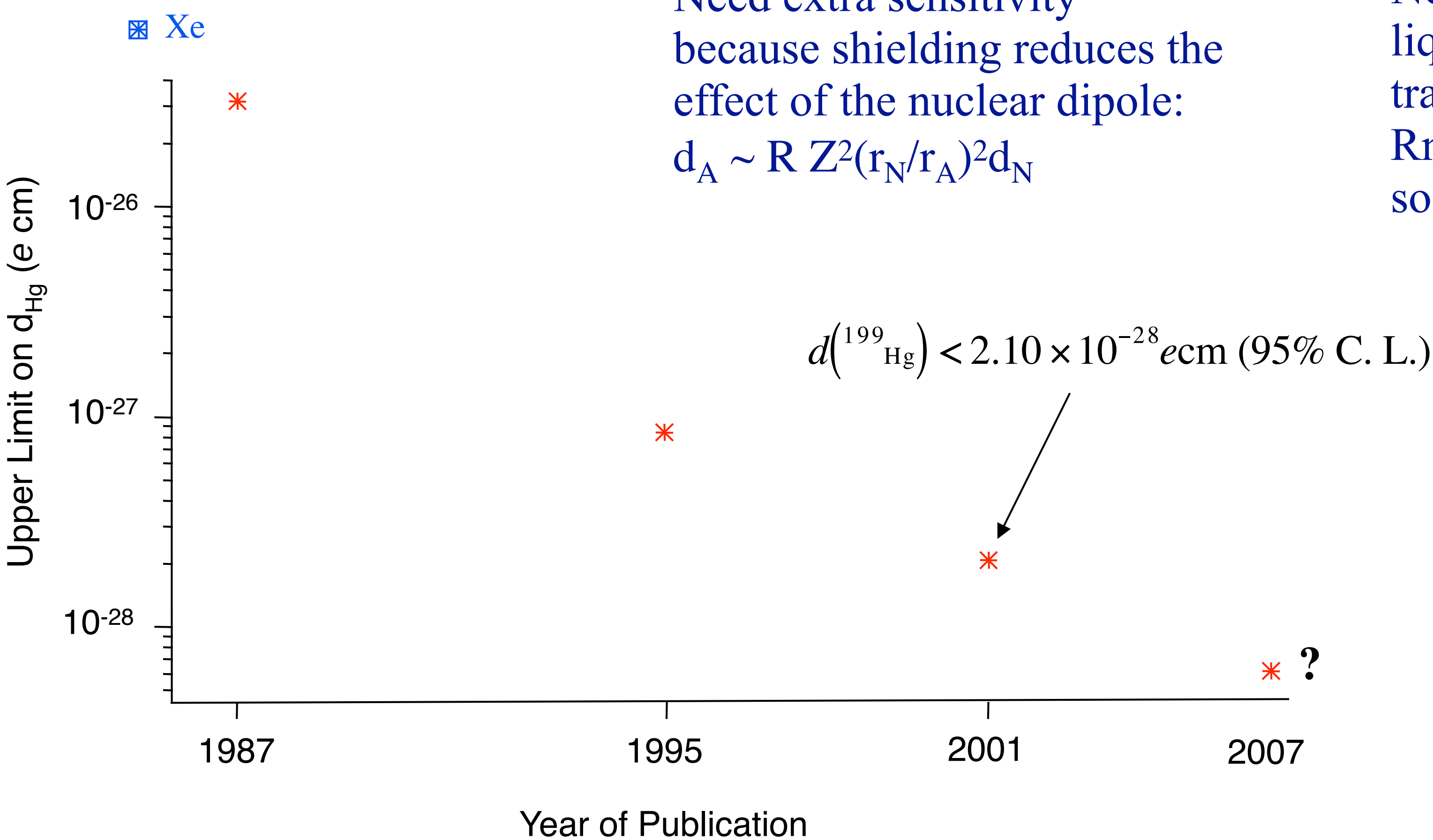
- Other approaches:
  - polar molecules
    - YbF (Imperial College)
    - PbO (Yale)
    - HfH^+ (JILA)
    - PbF (Oklahoma)
  - laser cooled Cs (Penn St., Texas)
  - solid state (Amherst, Indiana)

EDM searches: diamagnetic atoms (Seattle)

– Diamagnetic atoms ($^1S_0$ ground state) with finite nuclear spin (I) are sensitive to the EDM of nucleons and T-violating nucleon-nucleon forces

Need extra sensitivity because shielding reduces the effect of the nuclear dipole:
$d_A \sim R\, Z^2 (r_N/r_A)^2 d_N$

New approaches:
liquid Xe (Princeton)
trapped Ra (Argonne,KVI)
Rn (TRIUMF)
solid state (Berkeley)



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

From atomic EDM to fundamental physics

^{199}Hg atomic EDM:

↓ Atomic physics ↓

^{199}Hg Schiff moment:

↓ Nuclear physics ↓

CP-violating pion-nucleon coupling:

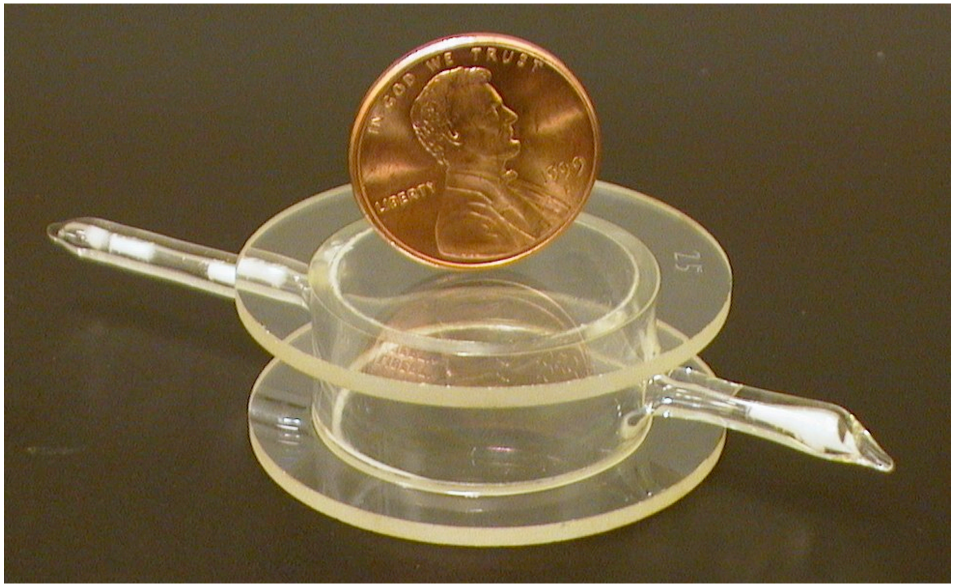
↓ QCD ↓

CP-violating QCD term, quark chromo-EDMs

↓ SUSY, etc... ↓

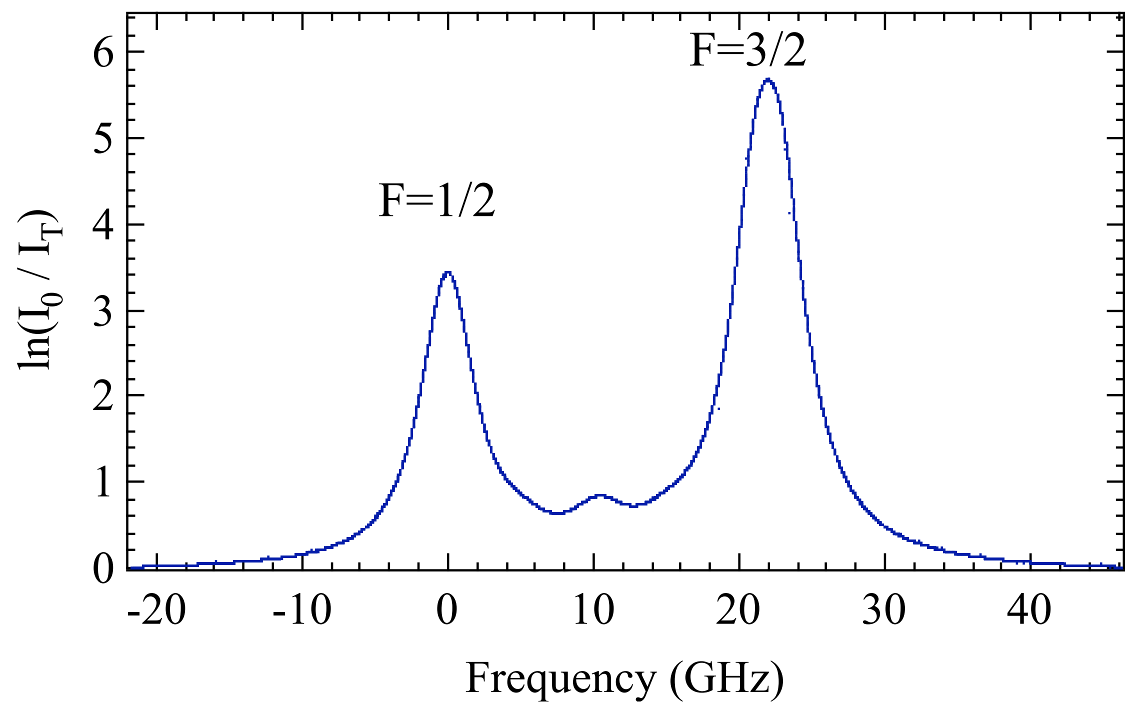
Model-dependent CP-violating parameters

^{199}Hg vapor cells

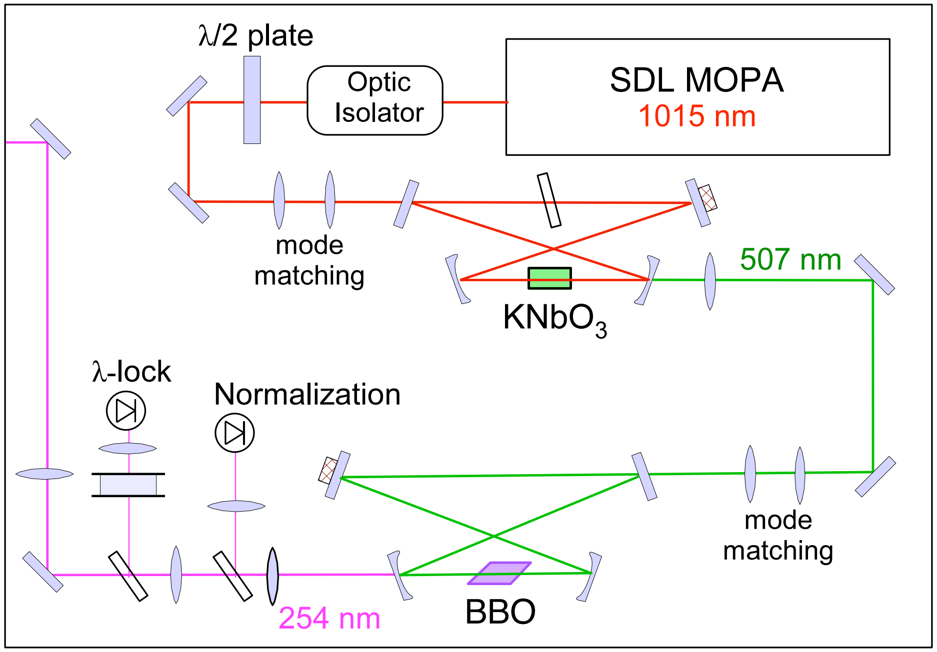


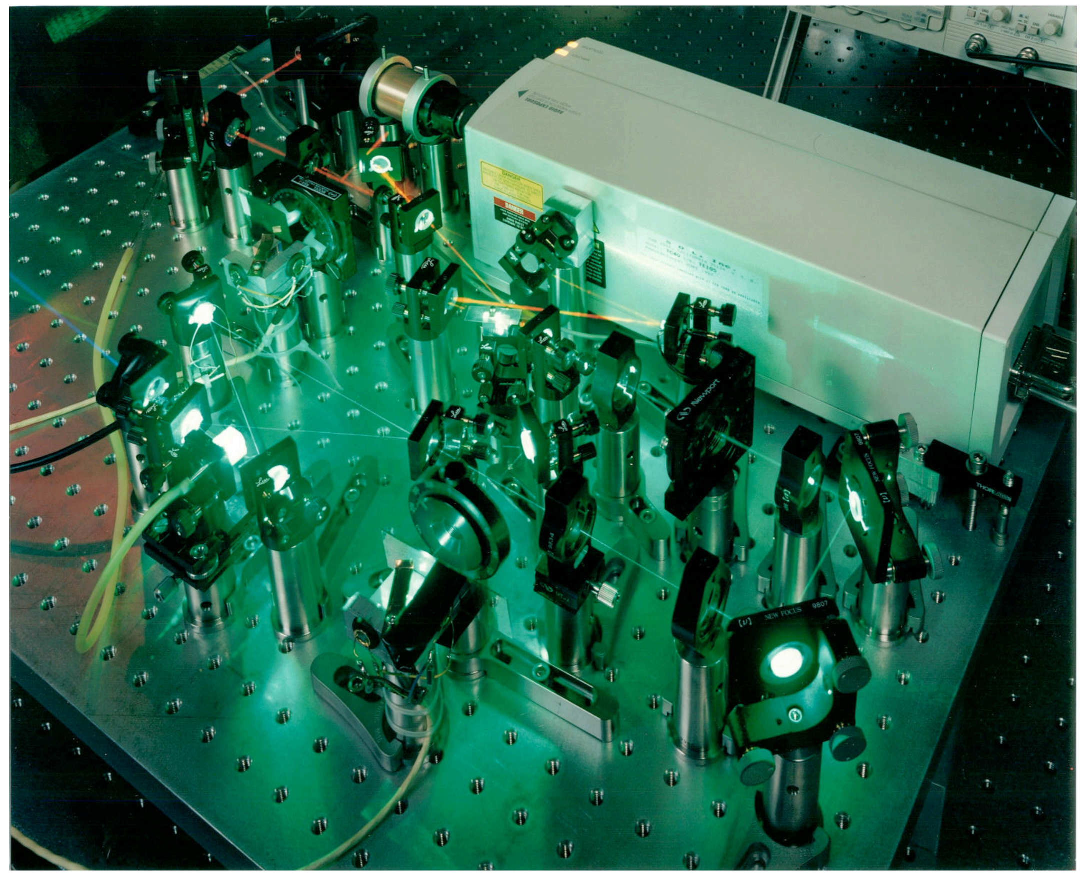
- Number of ^{199}Hg atoms: 10^{14}
- Leakage currents at 10 kV: 0.5 – 1 pA
- N_2 + CO buffer gas (500 Torr)
- Paraffin wall coating
- Spin relaxation time: 100 – 200 sec

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

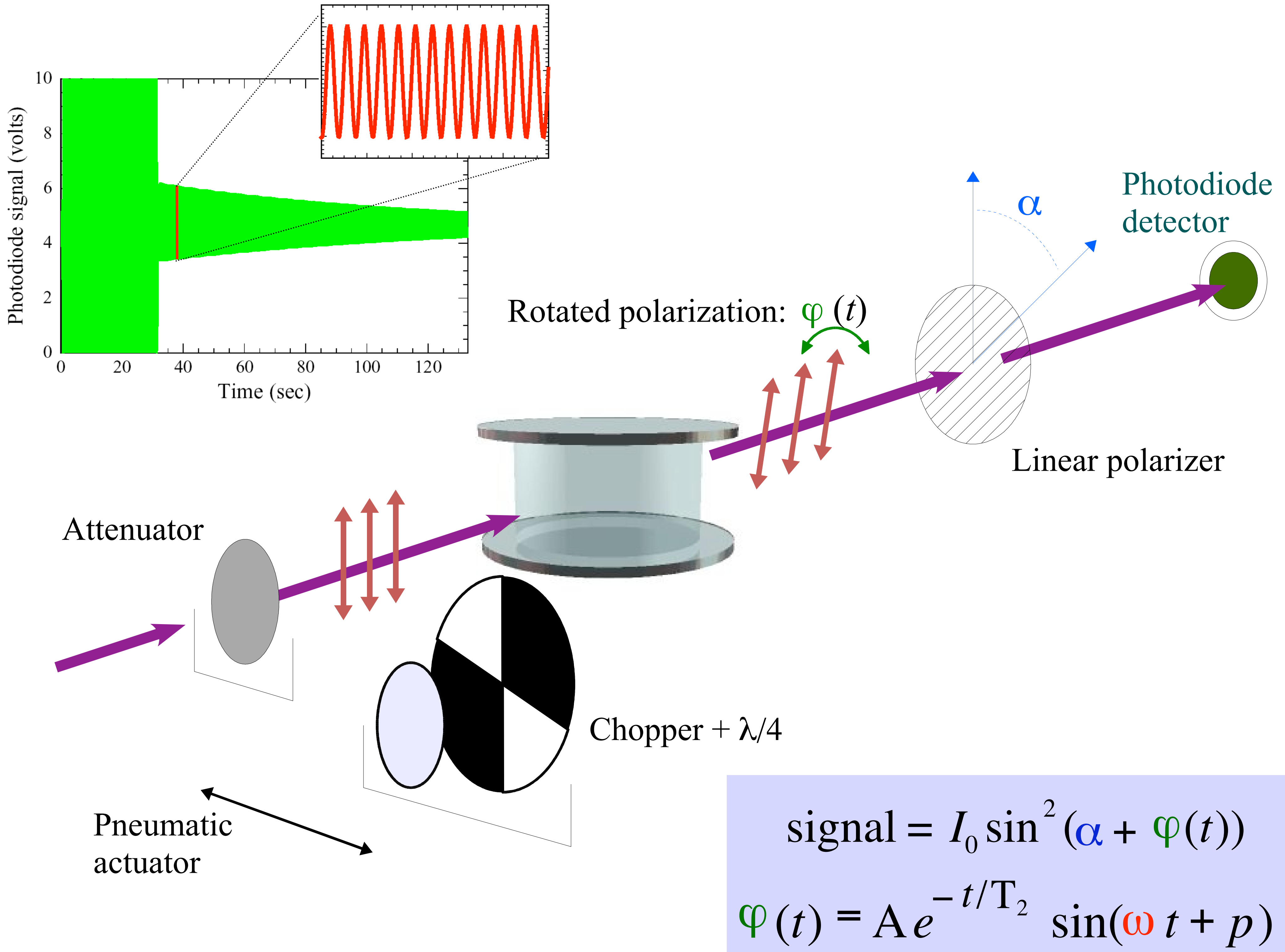


254 nm laser system

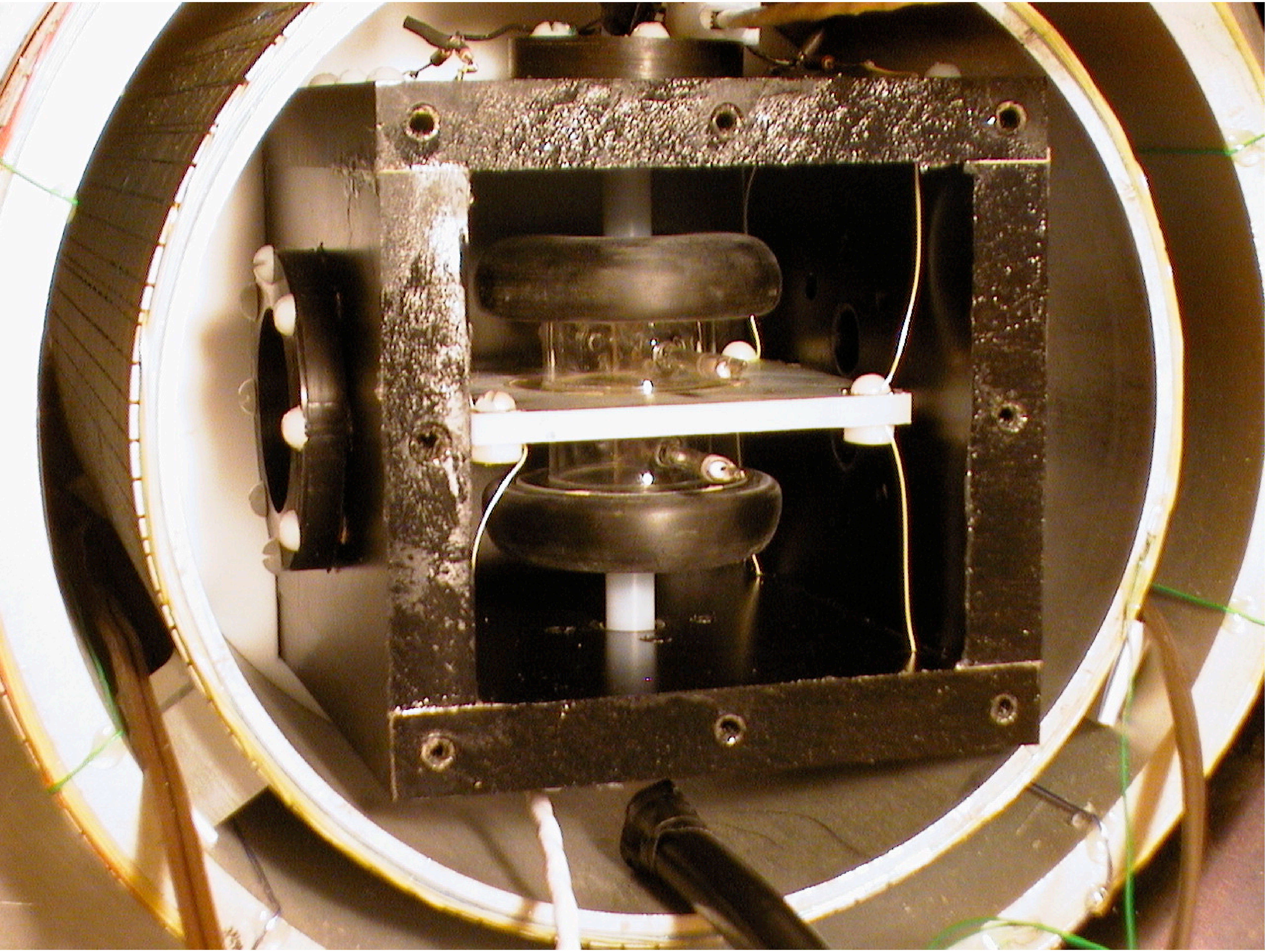




- SDL MOPA (Master Oscillator, Power Amplifier) Semiconductor laser: 500 mW at 1015 nm
- First doubling stage ($KNbO_3$): 130 mW at 507.4 nm
- Second doubling state (BBO): 6 mW at 253.7 nm



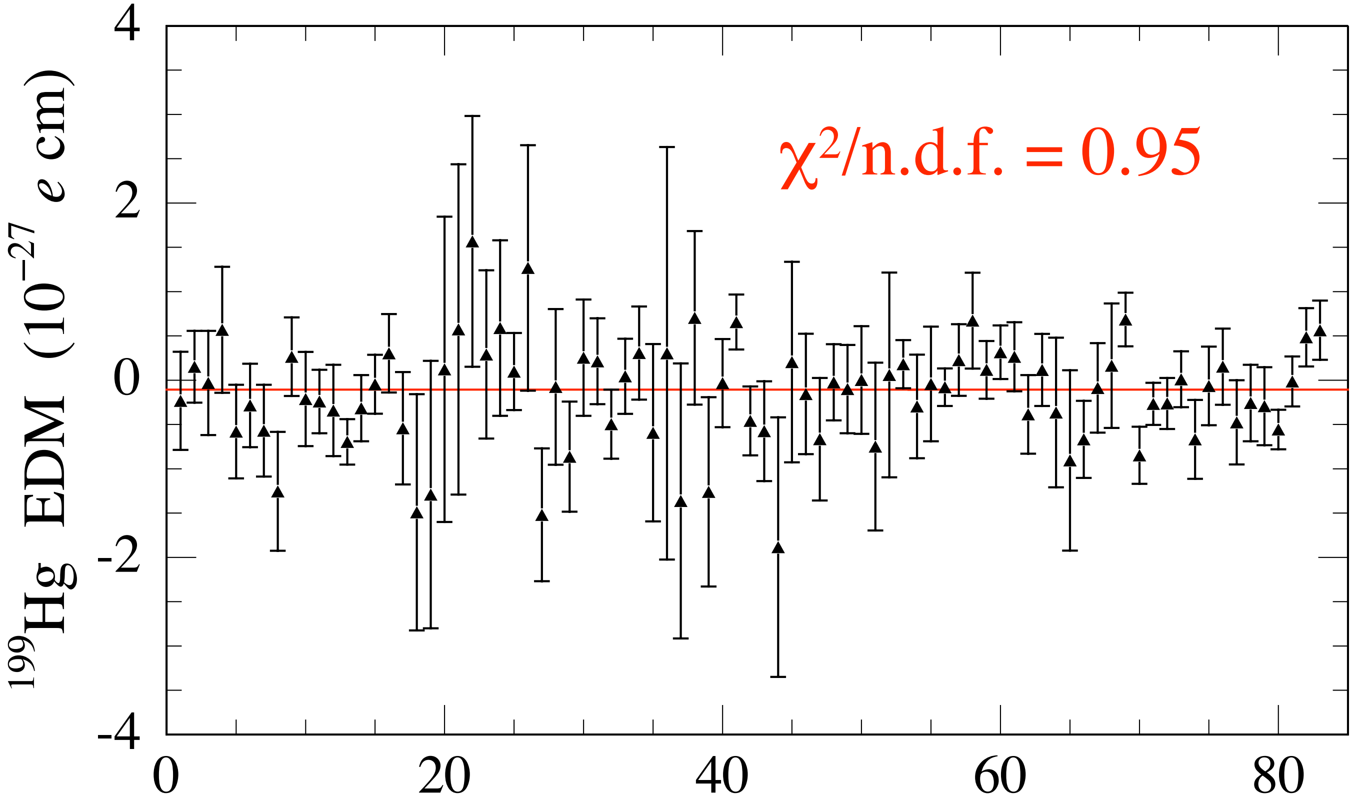
Photodiode signal (volts)
10
8
6
4
2
0
0
20
40
60
80
100
120
Time (sec)
Photodiode detector
α
Rotated polarization: φ (t)
Linear polarizer
Attenuator
Chopper + λ/4
Pneumatic actuator
$\text{signal} = I_0 \sin^2(\alpha + \varphi(t))$
$\varphi(t) = A e^{-t/T_2} \sin(\omega t + p)$



2001 result

60 days of data from Feb. to Aug. 2000

→ 40,000 electric field reversals



$d_{Hg} = -[1.06 \pm 0.49_{stat} \pm 0.40_{syst.}]\times10^{-28}\, e$ cm

$|d_{Hg}| < 2.1 \times 10^{-28}\, e$ cm at 95% C.L.

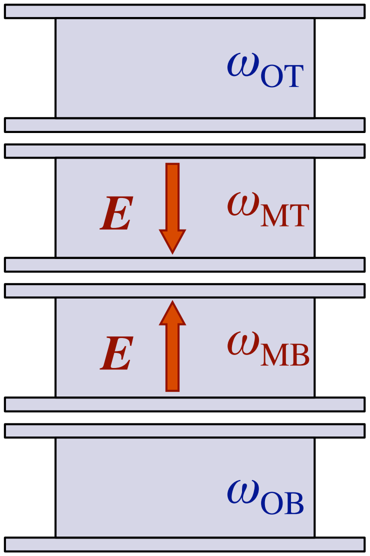
Frequency combinations

- Middle cell difference: $(\omega_{MT} - \omega_{MB})$
  - cancels common mode noise
  - equivalent to 2001 measurement

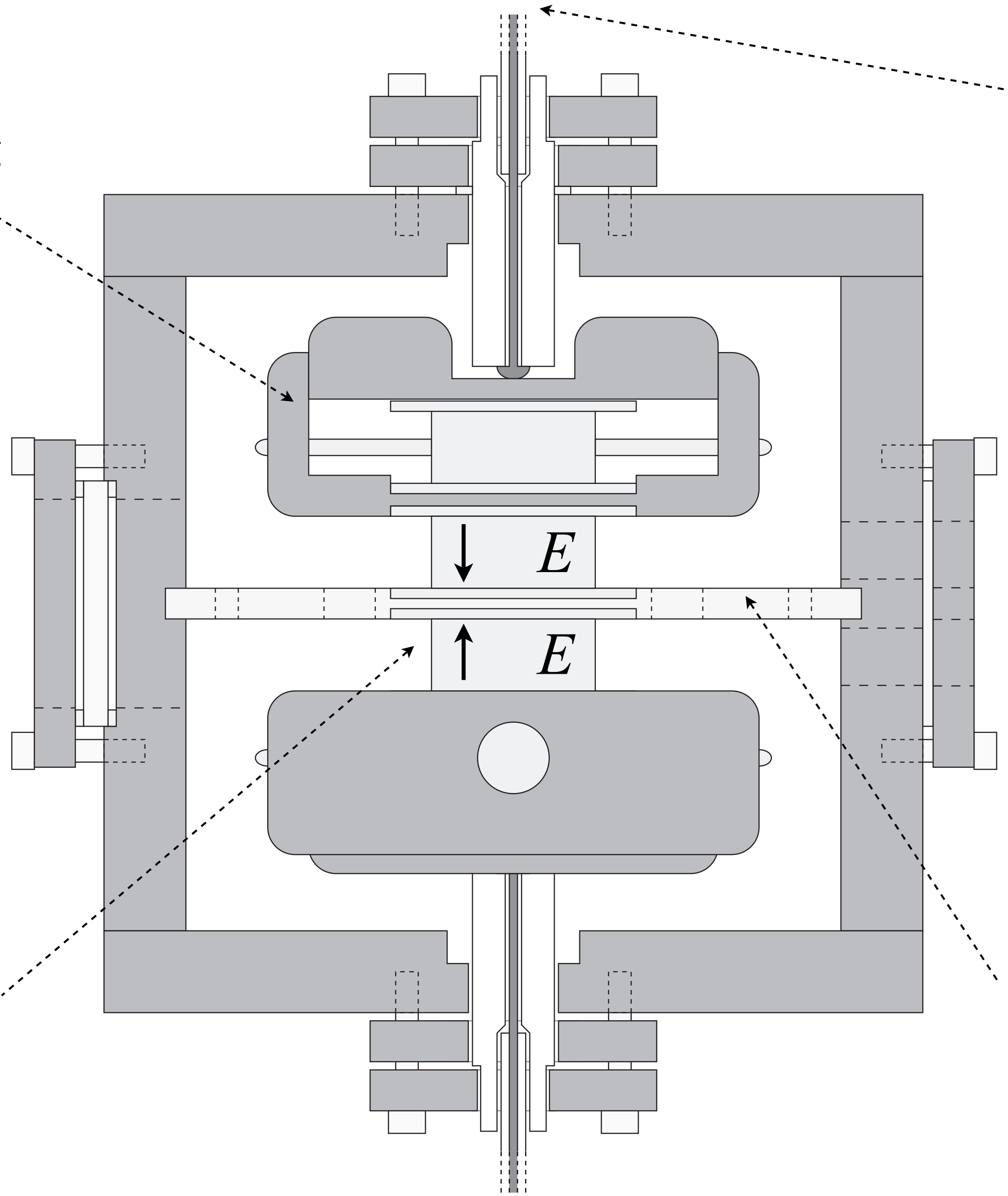
- Anti-symmetric combination
  (EDM combo): $(\omega_{MT} - \omega_{MB}) - \frac{1}{3}(\omega_{OT} - \omega_{OB})$
  - cancels up to 2nd order gradient noise
  - same EDM sensitivity as middle cell difference

- Symmetric combination
  (LeakTest combo): $(\omega_{MT} + \omega_{MB}) - (\omega_{OT} + \omega_{OB})$
  - cancels linear gradient noise
  - gives zero for a true EDM
  - sensitive to magnetic systematics

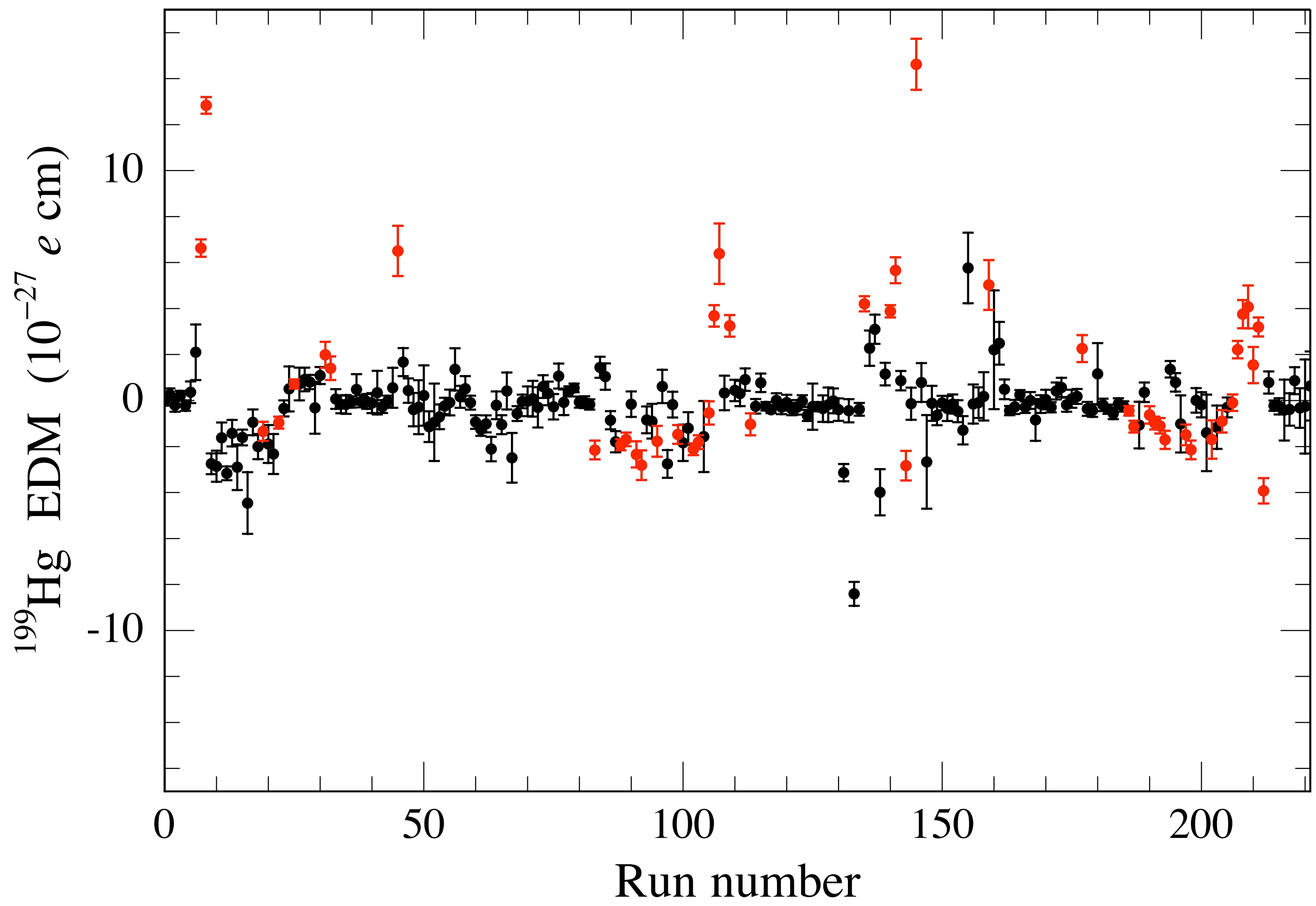
- Other combinations can also help reveal and localize spurious magnetic effects



4-cell vessel



4 cell data: 2002 – 2004



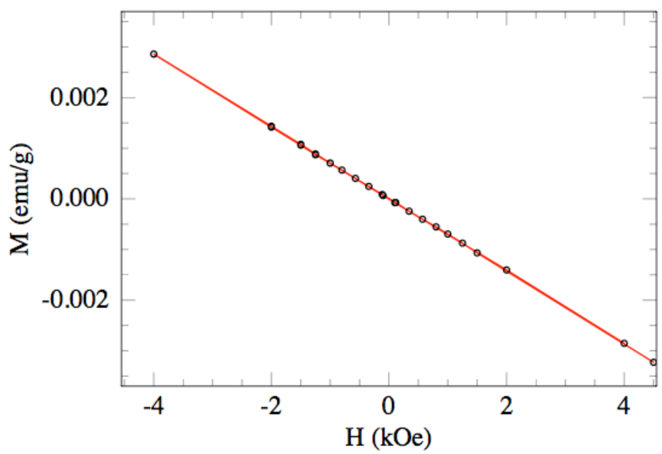
- 160 days of data with Electric field in 220 data runs.
- About 100 of these runs shows signs of a significant HV correlated frequency shift

False signal source?

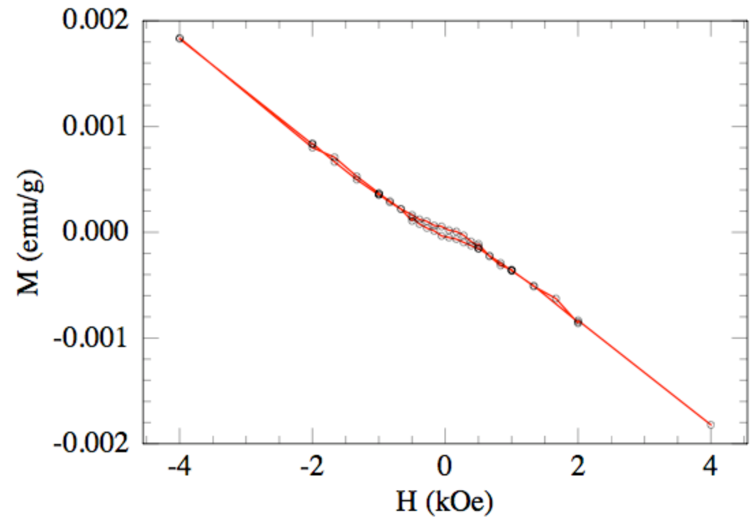
- Standard systematics - leakage currents, motional magnetic fields, etc...
- Electric field-induced motion in a magnetic field gradient.
- Electric field-induced beam steering coupled to a magnetic field gradient.
- Changes to vapor-cell buffer-gas composition?
- Effect introduced by new 4-cell vessel?
- Orientation of trace ferromagnetic material by HV discharges. Addressed by:
  - cleaning all components of the vessel with HCl to remove ferromagnetic surface material.
  - careful testing of all materials for trace ferromagnetic contamination.
  - improved surface quality of groundplane and HV electrodes

SQUID magnetometer materials testing

diamagnetic signal (Dow Corning 184 silicone)

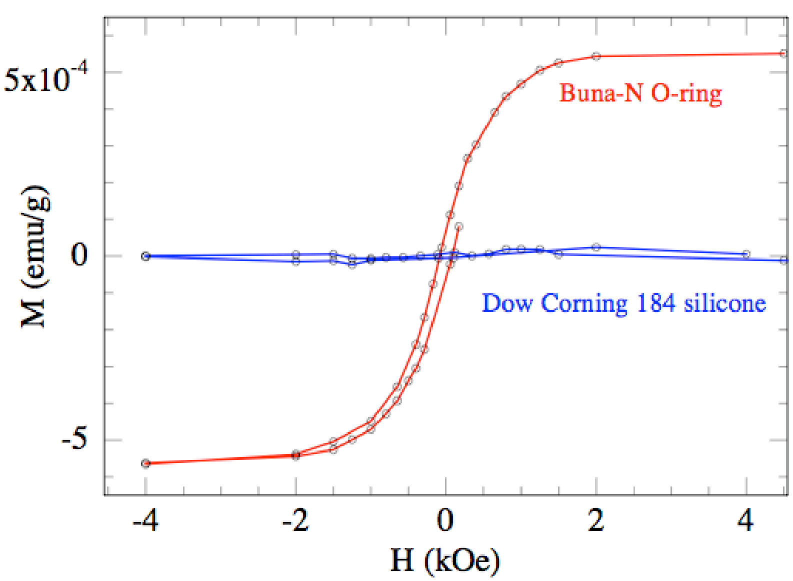


ferromagnetically contaminated signal (silver paint)

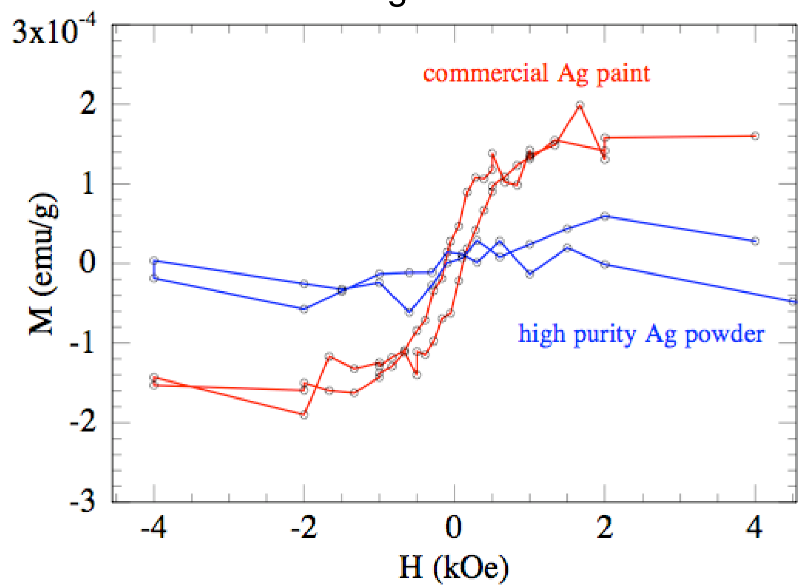


After linear background subtraction:

gasket material

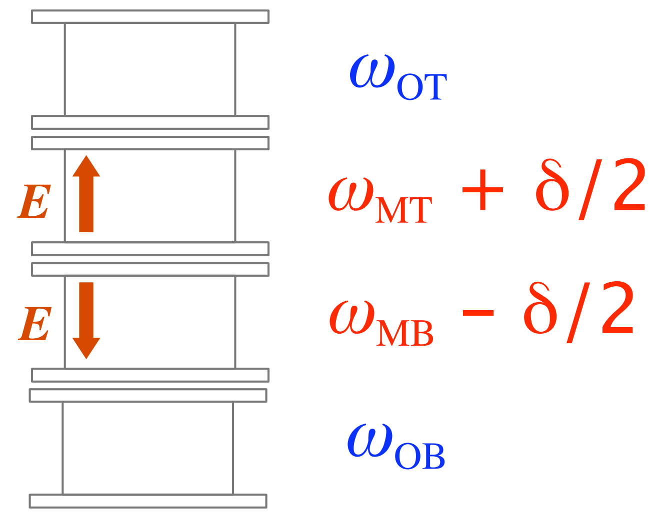


conductive coating



Blind analysis

- Initiated in March 2006 – a random offset, δ, was generated between $\pm 2 \times 10^{-28}$ *e* cm (our previous upper bound).
  - Range large enough to insure analysis is blind
  - Range small enough to reveal any large spurious signals that occurred previously



- Analysis program adds a HV correlated offset $\delta/2$ to the middle cell fitted frequencies.

- gives an EDM-like signal of size δ

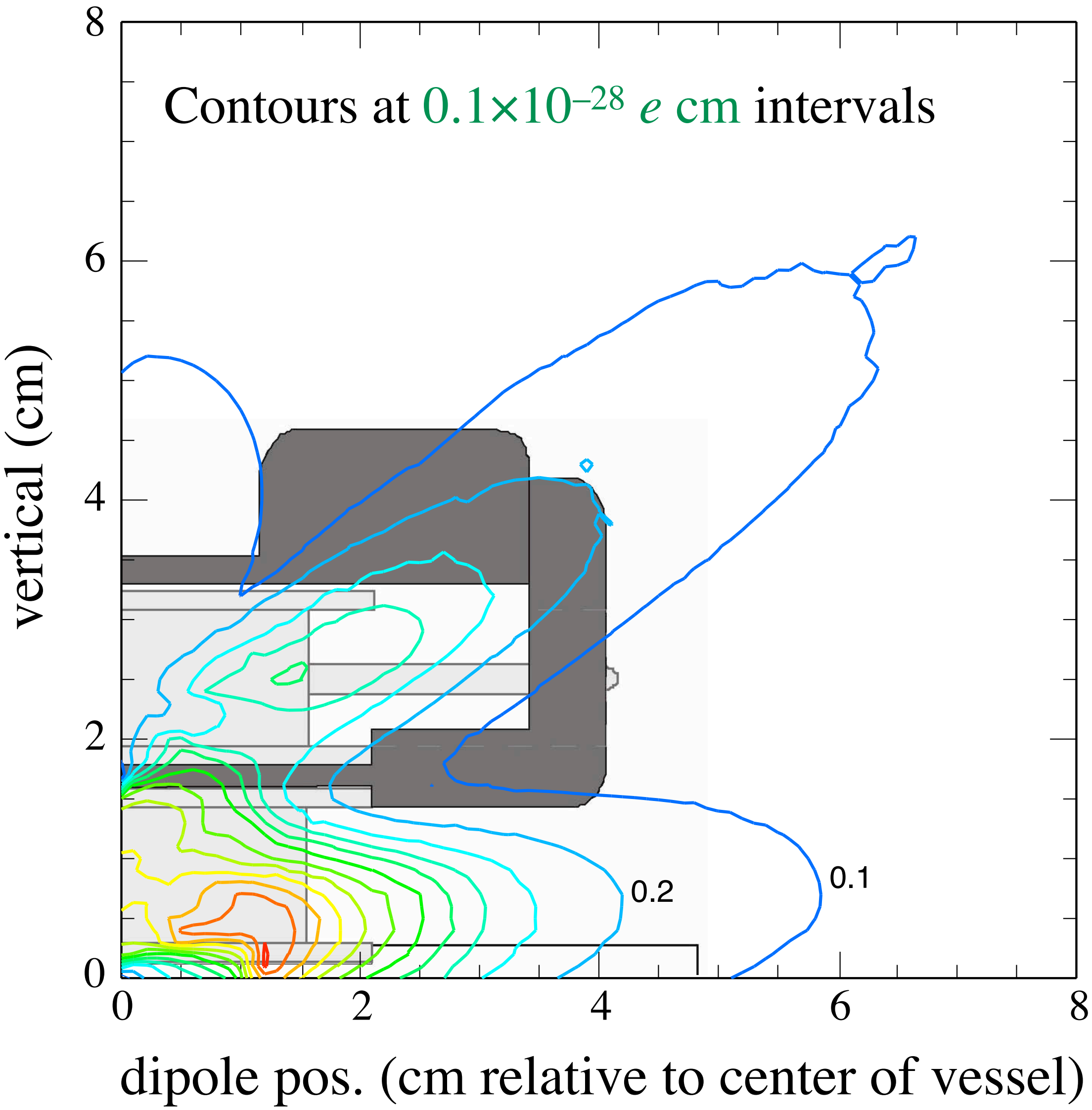
- Does not interfere with tests for systematic effects.

- And of course guards against human bias in decisions about making data cuts, etc.

Systematics

- Sources under control to below 1×10^{-29} *e* cm level
  - v x E effects - diffusion, thermal currents, etc.
  - HV correlated optical and laser beam effects
  - Stark interference (linear in E)
- Sources of greatest concern - HV correlated magnetic effects
  - Ferromagnetic contaminants
  - Leakage currents

Bounds on magnetic contaminant effects



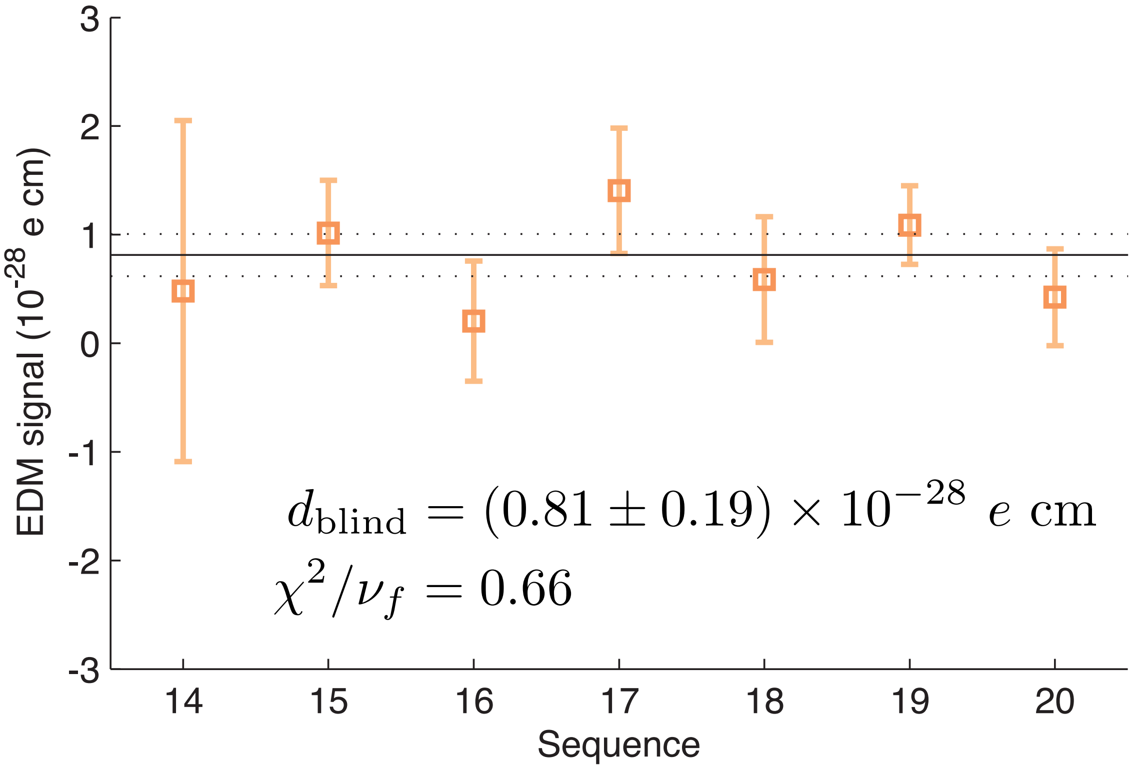
- Shown at left are upper bounds we could place on an EDM-like contribution
  - Assumes point magnetic dipole contaminant in various locations
  - based on projected sensitivity in all non-EDM frequency combinations **after 100 days of data**
- Adequate bounds except in materials in direct contact with the vapor cells (HV electrodes and groundplane).
- Can guard against contaminants in such locations by using
  - multiple sets of vapor cells and electrodes in different combinations
  - multiple versions of the groundplane.
- Similarly, can guard against leakage currents.

EDM data since November 2005

- data sequence ≡ 8 - 15 overnight data runs with a parameter reversal sequence, cell wall coatings regenerated and cell/electrode positions are swapped between sequences
- 20 sequences: blind since #6
- Result of non-blind data:
  - $d(^{199}\mathrm{Hg}) = [-5.4 \pm 4.1_{\mathrm{stat.}} \pm ??_{\mathrm{syst.}}] \times 10^{-29}\ e\ \mathrm{cm}$
  - Compare with 2001 result:

    $[-10.6 \pm 4.9_{\mathrm{stat.}} \pm 4.0_{\mathrm{syst.}}] \times 10^{-29}\ e\ \mathrm{cm}$
- Initial blind data: sequences 6 – 13 (March → August)
  - Statistical error: $\pm 2.4_{\mathrm{stat.}} \times 10^{-29}\ e\ \mathrm{cm}$
  - but, contaminated by HV-correlated currents in main field and gradient compensation coils
    - additional isolation measures have eliminated this effect
    - affected field coils produce mainly common mode and linear magnetic gradients → cancels in main EDM channel

EDM data since August 2006



- Blind data taken since HV-correlation of current sources eliminated has statistical error of about half that of the 2001 data.
- Signal consistent with size of blind offset: $d_{\rm offset} \leq 2 \times 10^{-28}\ e\,{\rm cm}$
- Initial data with 2nd groundplane is currently being taken

Status and summary

- Initial 4-cell data was contaminated by large HV-correlated magnetic fields
- After a protracted struggle, these correlations have been eliminated
- A blind ^{199}Hg EDM measurement is underway, data will continue at least until sensitivity of data with 2nd groundplane reaches $2.0 \times 10^{-29}\ e$ cm
- 4-cell ^{199}Hg measurement is on track to reach a new result in 2007 with:
  - $\sigma_{stat} = 1.5 \times 10^{-29}\ e$ cm
  - $\sigma_{syst} = 1.5 \times 10^{-29}\ e$ cm?
  - central value?