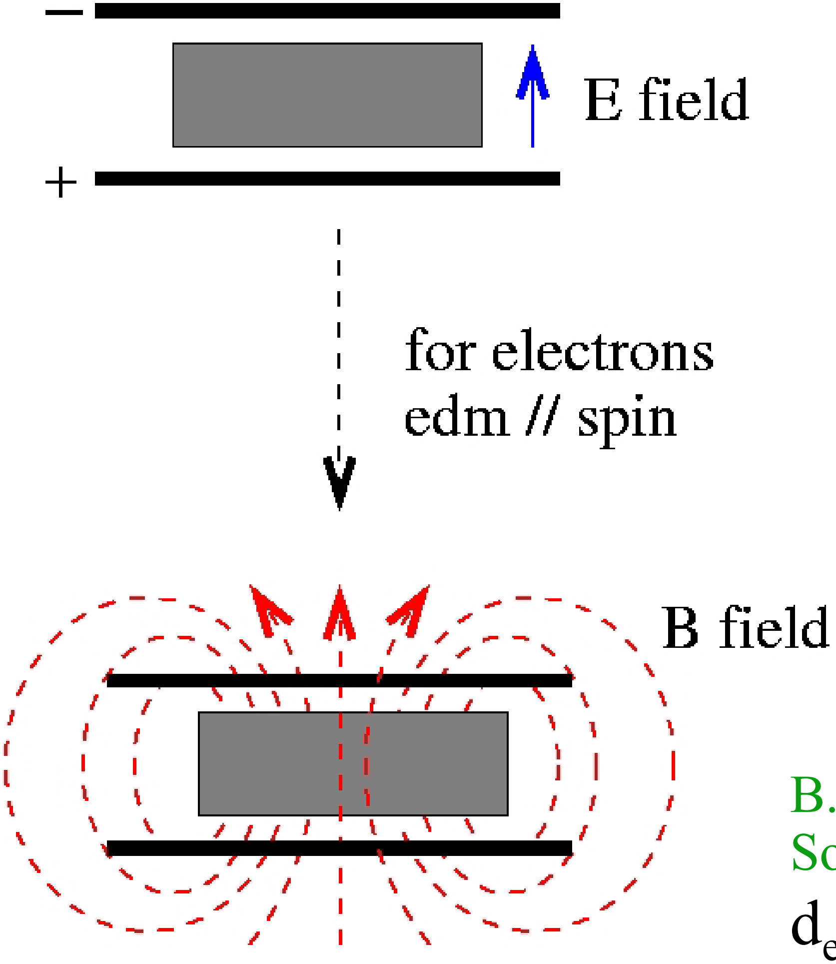
A Search for a Permanent Electric Dipole Moment of the Electron in a Solid State System

EDM & CP violation workshop
Seattle, March 19, 2007

Chen-Yu Liu, Indiana University at Bloomington

S. K. Lamoreaux, J. Gomez, J. Boissevain,
M. Espy, A. Matlachov
Los Alamos National Laboratory

Shapiro’s proposal -- using a solid state system to measure eEDM



Usp. Fiz. Nauk., **95** 145 (1968)

B.V. Vasil’ev and E.V. Kolycheva,
Sov. Phys. JETP, **47** [2] 243 (1978)

$d_e = (0.81 \pm 1.16) \times 10^{-22}$ e-cm

Features of solid state eEDM experiment

Pros:

- High number density of bare electrons ~ $10^{22}/cm^3$.

PbO Cell	**Tl Beam:**
$N = nV \sim 10^{16}$	$N = nV \sim 10^{8}$

- Electrons are confined in solid ⇒ No motional field effect. $B_{motional} = v \times E$
- Solid state sample:
  - Large magnetic response.

Cons:

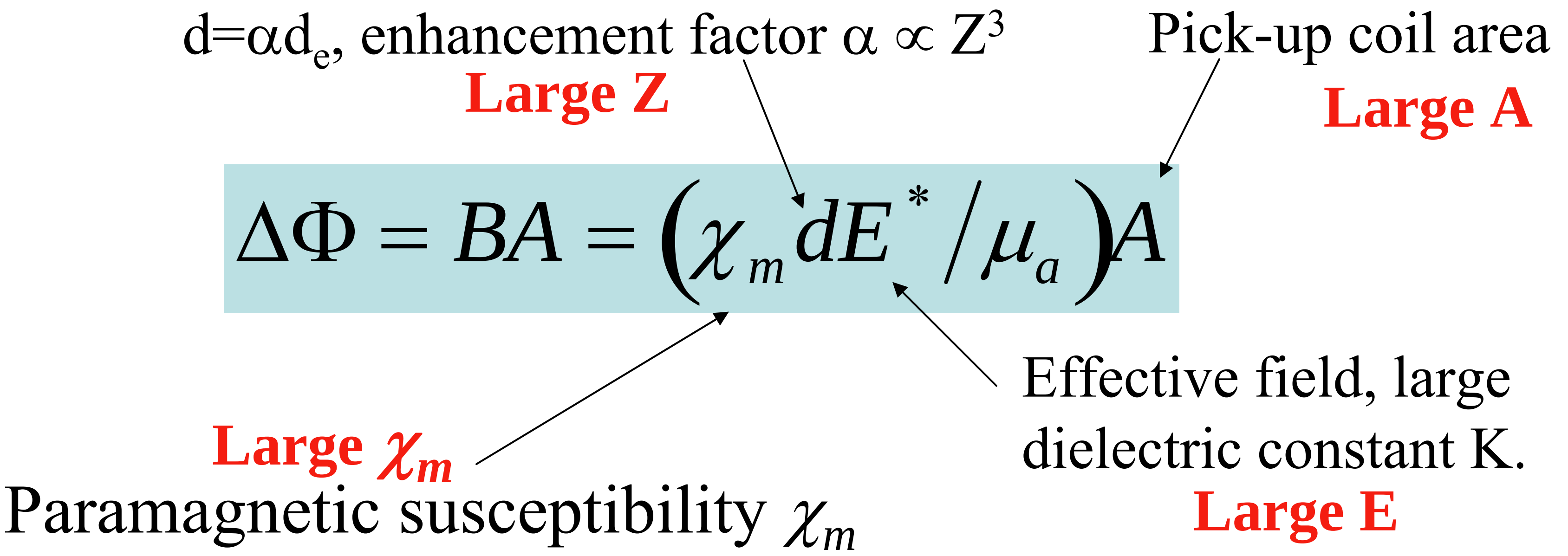
- Solid state sample:
  - High dielectric strength.
- Concerns
  - Parasitic, hysteresis solid state effects might limit the sensitivity to the EDM signals .

What are required to have Macroscopic T Nonconservation?

- W, Bialek, J. Moody, F. Wilczeck, Phys. Rev. Lett. 56, 1623 (1986)
- Proposed “EuS” near its Curie point
- Requirements:
  - System can be found in which intrinsic EDM’s are not screen out at the atomic level.
  - Chemical bonding does not obliterate the atomic EDM.
  - An external electric field will actually be felt by atoms in the interior of the sample.
  - The T-nonconserving effects which we seek to observe cannot be mimicked by effects associated with broken inversion symmetry in the crystal.

Figure of Merit

- Sensitive magnetometers
  - Superconducting Quantum Interference Device (SQUID).
  - Atomic cell (non-linear Faraday effect).
- Measure induced magnetic flux:



d=αd$_e$, enhancement factor $\alpha \propto Z^3$

Large Z

Pick-up coil area

Large A

$$\Delta\Phi = BA = \left(\chi_m dE^* / \mu_a\right)A$$

Large χ_m

Paramagnetic susceptibility χ_m

Effective field, large dielectric constant K.

Large E

A paramagnetic insulating sample

S. Lamoreaux, Phys. Rev. A (2002)

New experiment

Gadolinium Gallium Garnet ($Gd_3Ga_5O_{12}$) polycryostal

- Gd^{3+} in GGG
  - –$4f^7 5d^0 6s^0$ (**7 unpaired electrons**).
  - –Atomic enhancement factor = -4.9±1.6.

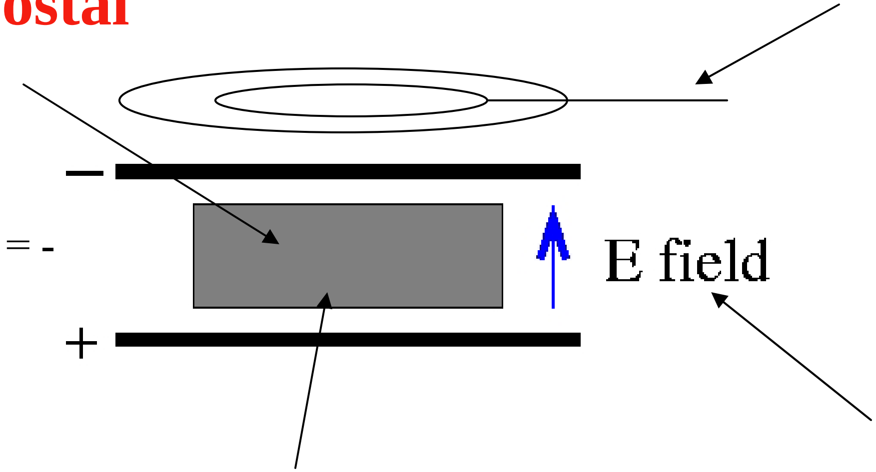
–Langevin paramagnet.

–Dielectric constant ~ 12 (or 30).

–Low electrical conductivity and high dielectric strength

- Volume resistivity = 10^{16} Ω-cm.
- Dielectric strength = 10 MV/cm (amorphous sample).

–Cubic lattice.



Better SQUID design

Higher E field: 10kV/cm

Large Sample size: 100 cm^3

Lower Temperature: 50mK

EDM Enhancement Factor

of electrons in Gd^{3+} in garnet crystal

- Buhmann, Dzuba, Sushkov, Phys. Rev. A 66, 042109 (2002).
- Dzuba, Shushkov, Johnson, Safronava, Phys. Rev. A 66, 032105 (2002).
- Kuenzi, Sushkov, Dzuba, Cadogan, Phys. Rev. A 66, 032111 (2002).
- Mukhamedjanov, Dzuba, Sushkov, Phys. Rev. A 68, 042103 (2003).

$$d_a = K_{atom} K_{CF} d_e$$

$$\Rightarrow -2.2 \times 9.5 d_e = -20.9 d_e$$

$$\Delta\varepsilon = -20.9 d_e E^{\text{int}} = \frac{-20.9}{30} d_e E^{ext}$$

$$\Rightarrow 0.7 d_e E^{ext}$$

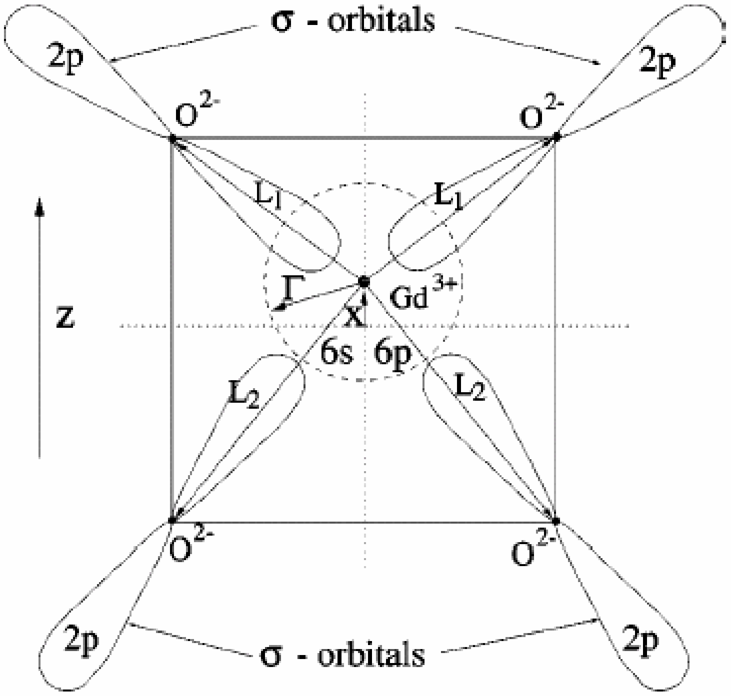


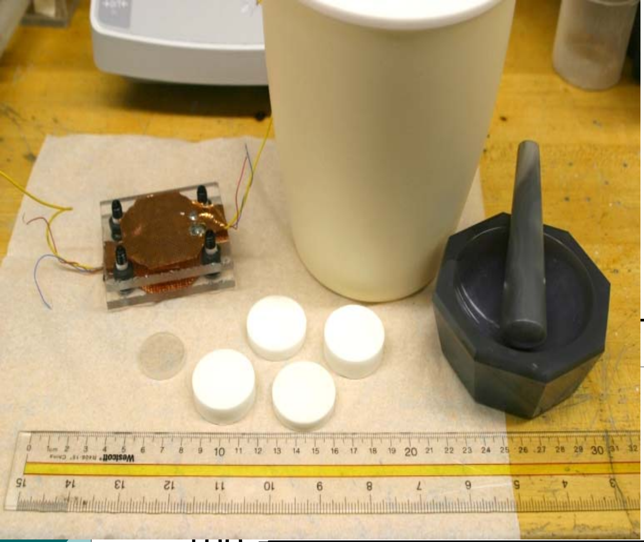
FIG. 3. A schematic two-dimensional picture for penetration of $2p_\sigma$ orbitals of O^{2-} inside the shifted Gd^{3+}.

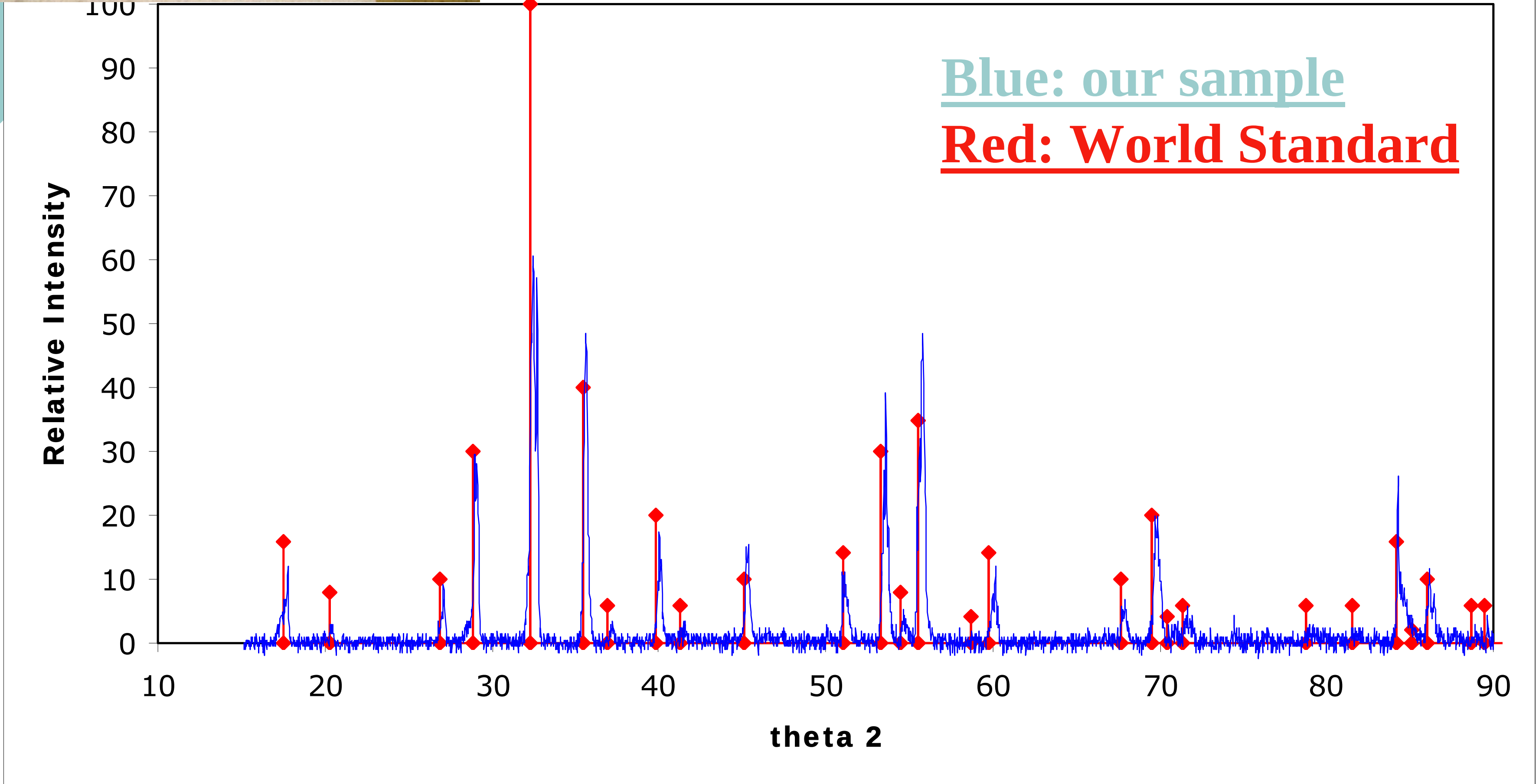
A simple estimate of EDM Sensitivity

- EDM signal: $\Phi_p = 17\mu\Phi_0$ per 10^{-27}e-cm.
  - with 10kV/cm, T=10mK, A=100 cm^2 around GGG
- SQUID noise: $\Delta\Phi_{sq} = 0.2\mu\Phi_0/\sqrt{t}$ (research quality)
- Flux transfer = $\Phi_{sq}/\Phi_p = \sqrt{(L_{sq}L_i)}/(L_p+L_i) = 8\times10^{-3}$.
  - L_{squid}= 0.2 nH.
  - $L_{pick\text{-}up}$= 700 nH. (gradiometer)
  - L_{input}= 500 nH.

- $d_e = \Delta\Phi_{sq}/\Phi_{sq} = (0.2\mu\Phi_0/\sqrt{t})/(8\times10^{-3} \times \Phi_p) \times10^{-27}$e-cm.
  - $d_e = 1.47\times10^{-27}/\sqrt{t}$ e-cm
- In 10 days of averaging, $d_e \sim 10^{-30}$ e-cm.

J. Valdez and K. Sickafus, LANL

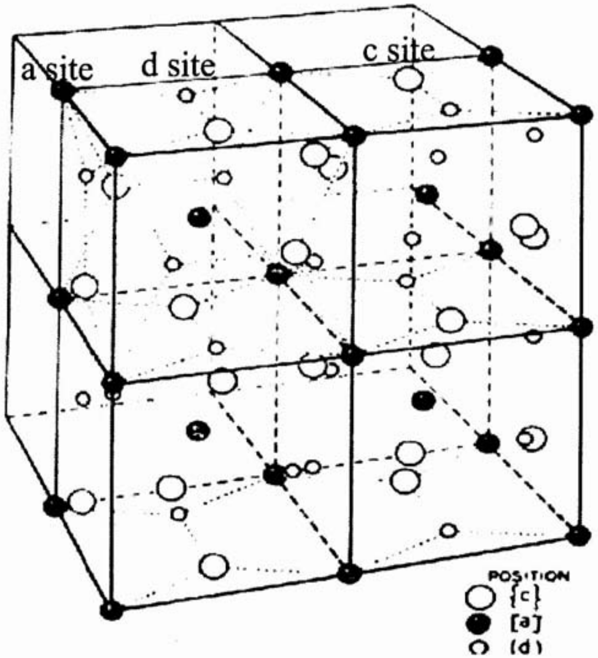



GGG X-ray Diffraction

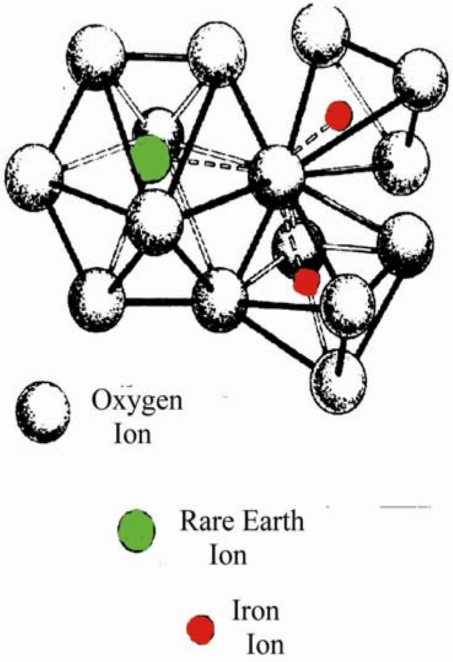
Blue: our sample

Red: World Standard

Garnet Crystalline Structure



The unit cell of GdIG. The cell contains 16 Fe^{3+} ions at octahedral sites (a), 24 Fe^{3+} ions at tetrahedral sites (d), and 24 Gd^{3+} ions at dodecahedral sites (c). The oxygen ions are not shown.



- Garnet Structure: $\{\overset{\uparrow}{A_3}\}[\overset{\downarrow}{B_2}](\overset{\uparrow}{C_3})O_{12}$
  - –A {dodecahedron}: M^{3+}
    - •Ca, Mn, Fe, R (La,..Gd,..Lu)
  - –B [octahedron],C (tetrahedron):
    - •Fe, Ga, …

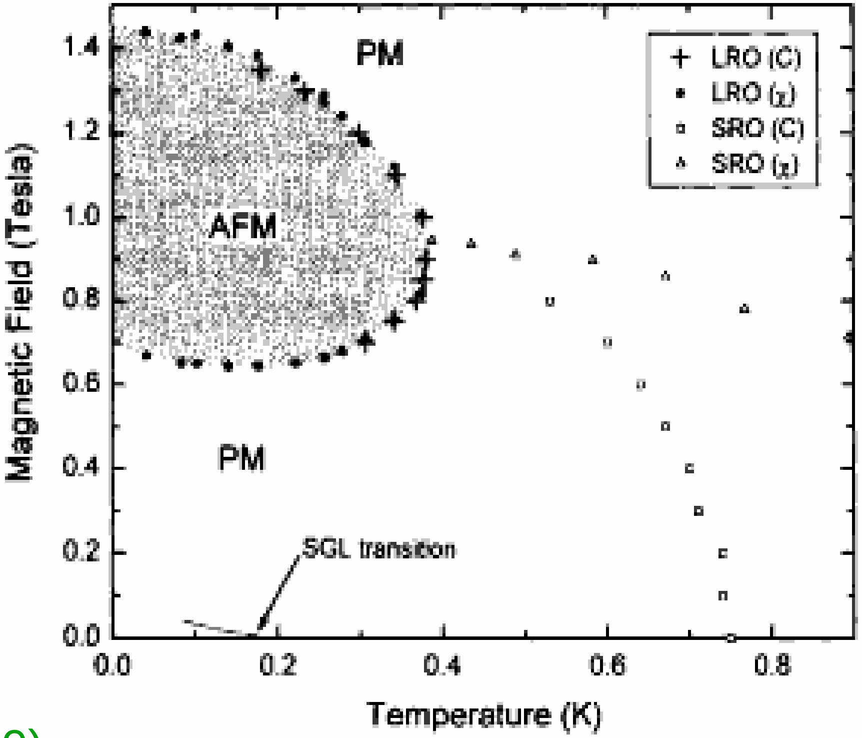
Magnetic Properties of GGG (**$Gd_3Ga_5O_{12}$**)

P.Schiffer, et al. PRL **73**, 2500 (1994)

○ Anti-Ferromagnetic (AF) interaction on a triangular lattice

⇒ Geometrically frustrated AF magnet:

⇒ Spin glass transition at 0.4K (Limit of temperature).



S. R. Dunsiger, et al. PRL **85**, 3504 (2000)

- spin dynamics using muon spin relaxation

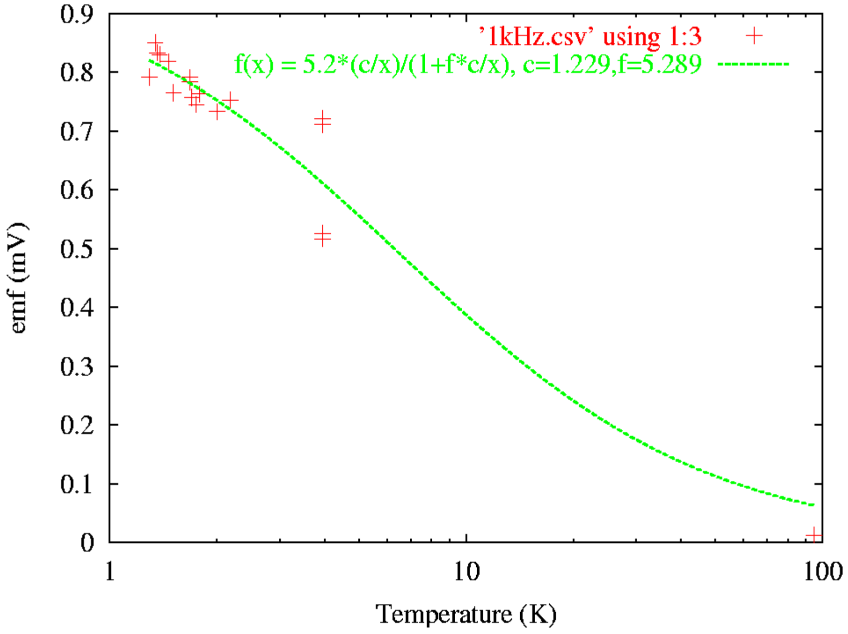
  “ The system is close to ordering but remains slowly fluctuating, at least down to 25 mK”.

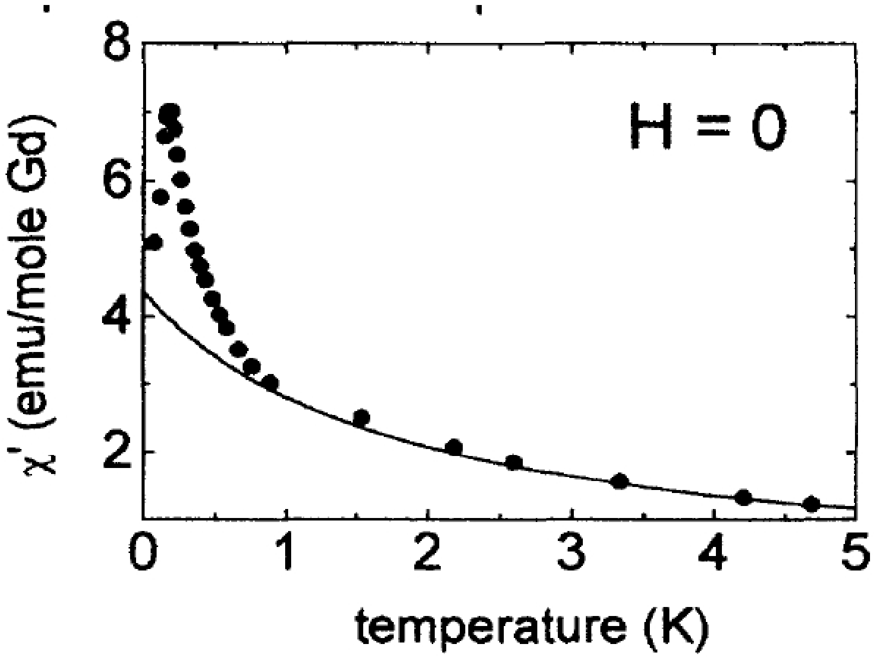
(Spin Glass Transition happens at a much lower T)

Possible solution: spin dilution Gd(Y)GG

Susceptibility χ_m Measurements

Traditional AC field method





- Paramagnetic susceptibility

$$\chi_m = \frac{C}{T} \qquad C = \frac{N\mu_b^2}{3k_B} = 1.29$$

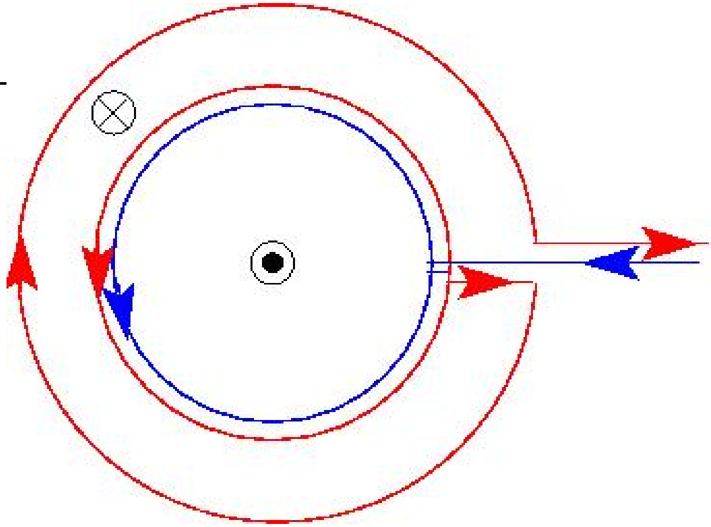
$$N^{Gd^{3+}} = 1.03\times10^{22}/cm^3$$

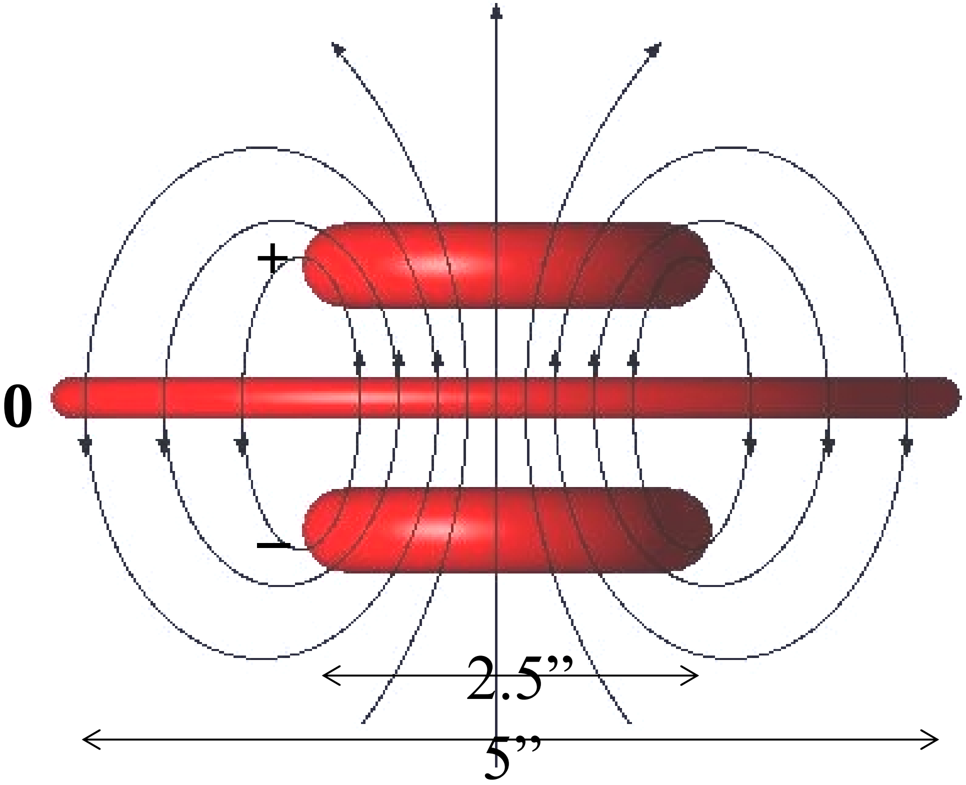
- P. Schiffer at. al., Phys. Rev. Lett, 74, 2379 (1995).

The measured suscepbtibility is as large as expected.

Electrodes and Magnetic flux pick-up coils (planar gradiometer)

- Common mode rejection of external uniform B field and fluctuations.
- Enhancement of sample flux pick-up.

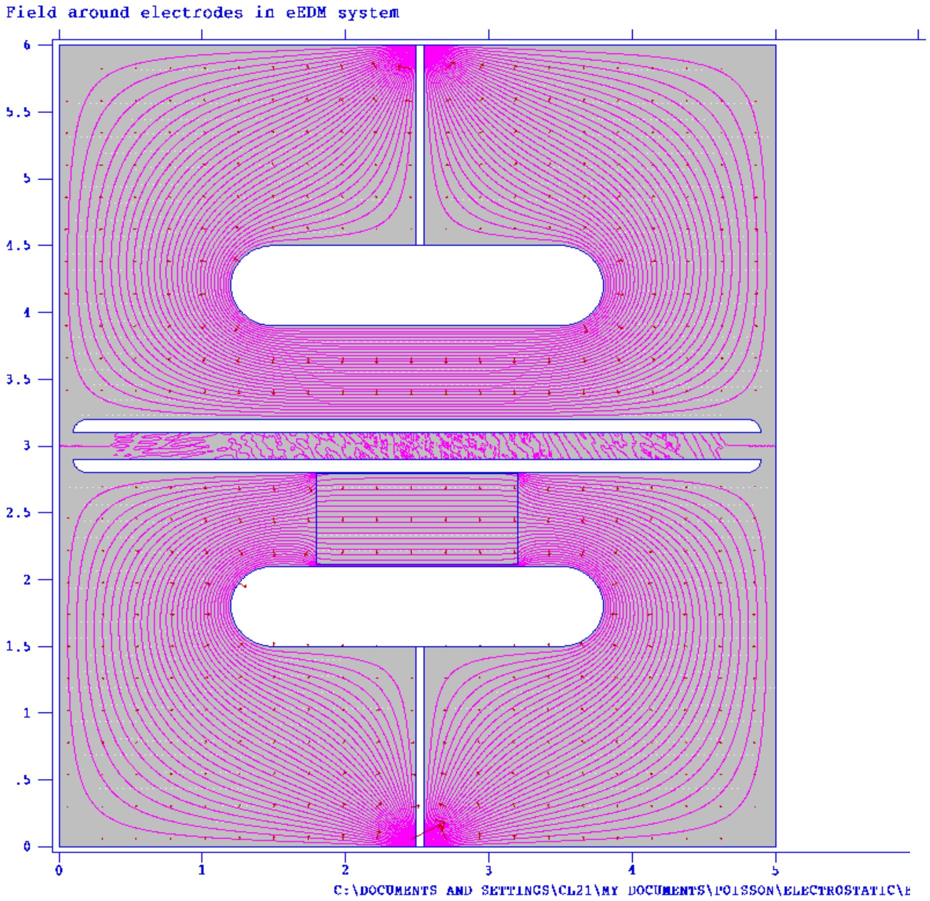


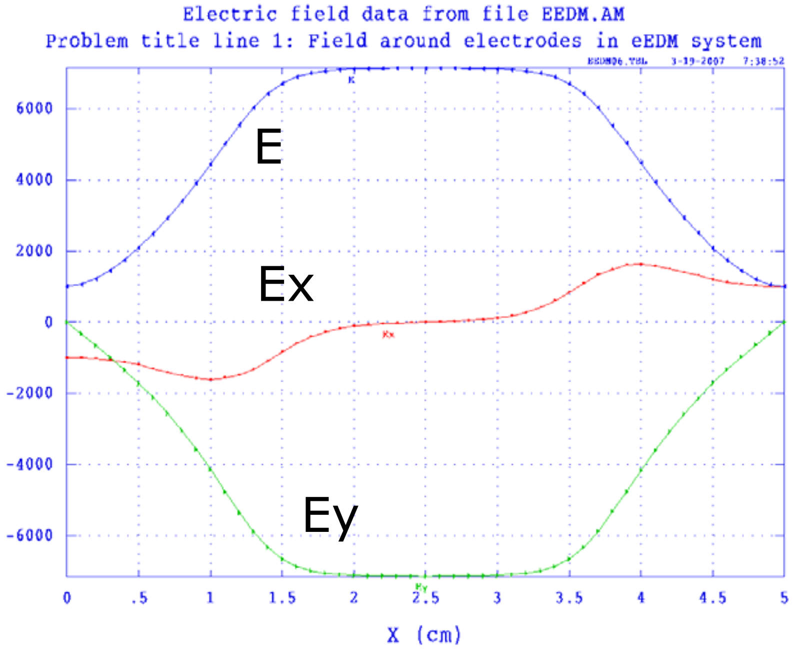


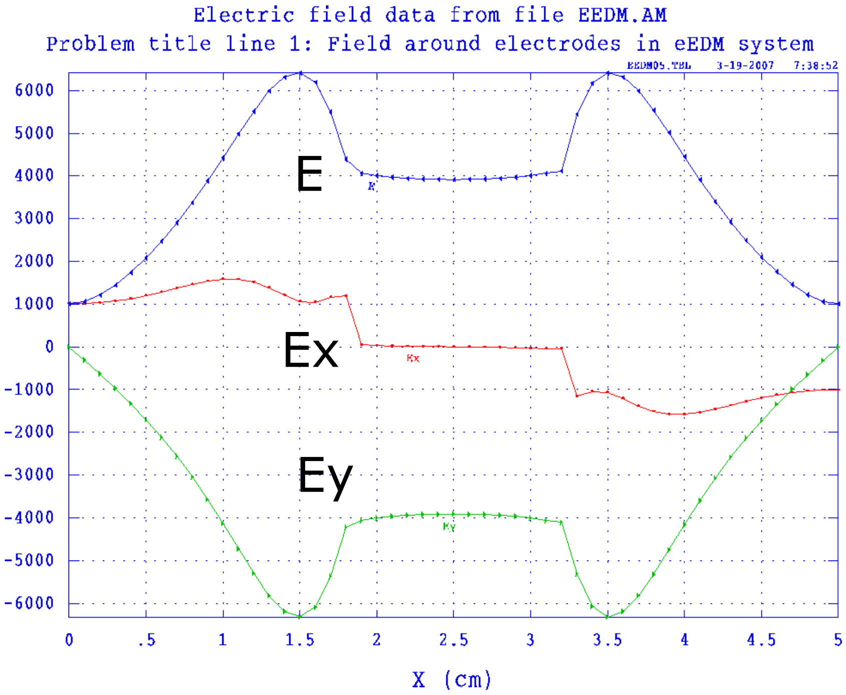
R_1=2cm
R_2=2cm
$R_3=\sqrt{(R_1^2+R_2^2)}$=3.42cm
L_G=700nH for 10μm dia. wire
=500nH for 100μm dia. Wire
(Nb superconducting wire)

CMRR = 238
⇒ 0.4% area mismatch

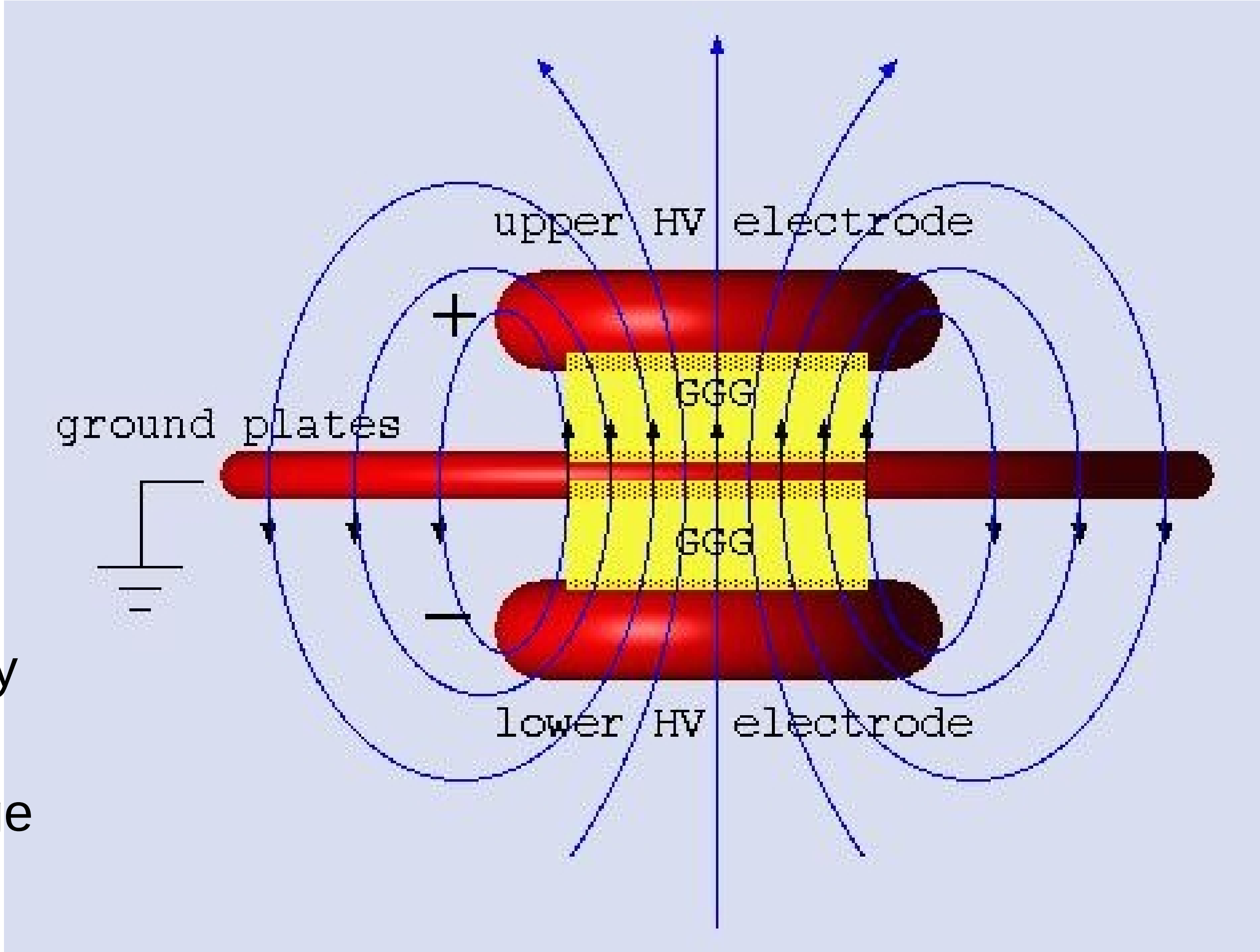
E Field


Field around electrodes in eEDM system
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
.5
0
0
1
2
3
4
5
C:\DOCUMENTS AND SETTINGS\CL21\MY DOCUMENTS\POISSON\ELECTROSTATIC\E


Electric field data from file EEDM.AM
Problem title line 1: Field around electrodes in eEDM system
EEDM06.TBL 3-19-2007 7:38:52
6000
4000
2000
0
-2000
-4000
-6000
E
Ex
Ey
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
X (cm)


Electric field data from file EEDM.AM
Problem title line 1: Field around electrodes in eEDM system
EEDM05.TBL 3-19-2007 7:38:52
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
E
Ex
Ey
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
X (cm)

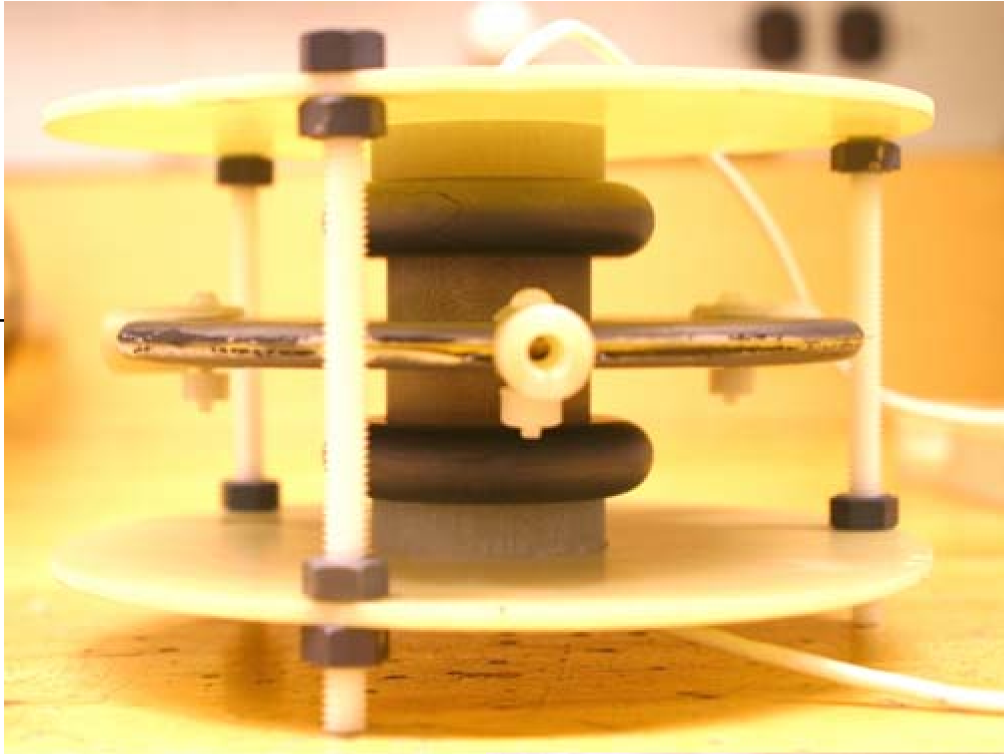
eEDM Measurement Sequence

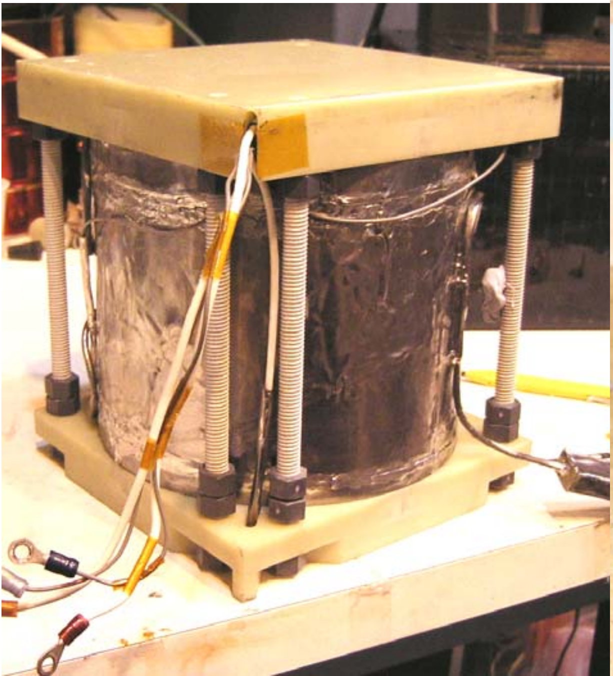


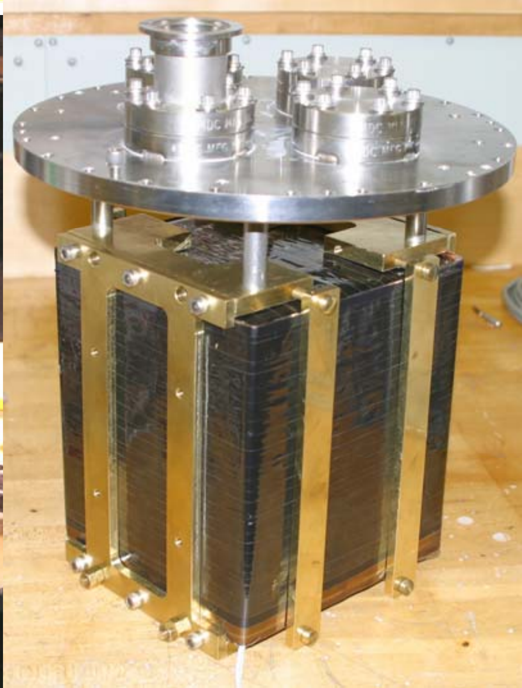
- Reverse HV polarity
- monitor sample for magnetization change

Instrumentation

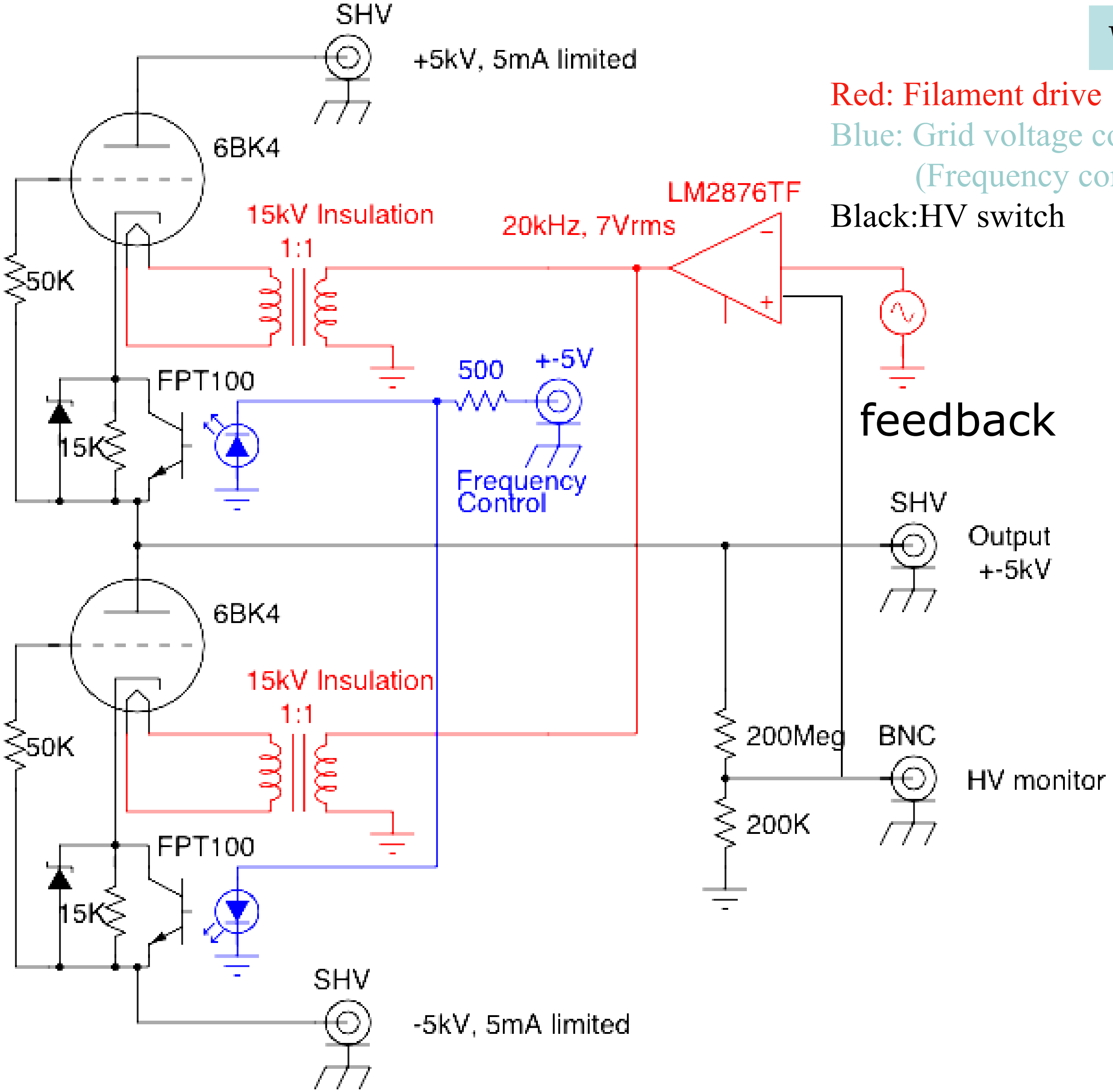
- High Voltage Electrodes: **Macor** coated with **graphite.**
- Magnetic Shield:
  - Superconducting **Pb** foils (2 layers)
    - S factor > 10^9
  - High μ **Metglas** alloy ribbons in cryostat.
    - S factor ~ 100
  - An additional cylinder of "**Conetic**" sheet outside the cryostat.
    - S factor ~ 10
- The whole assembly is immersed in **L-He bath**, and will be cooled by a dilution refrigerator. (3.5mW at 120mK)



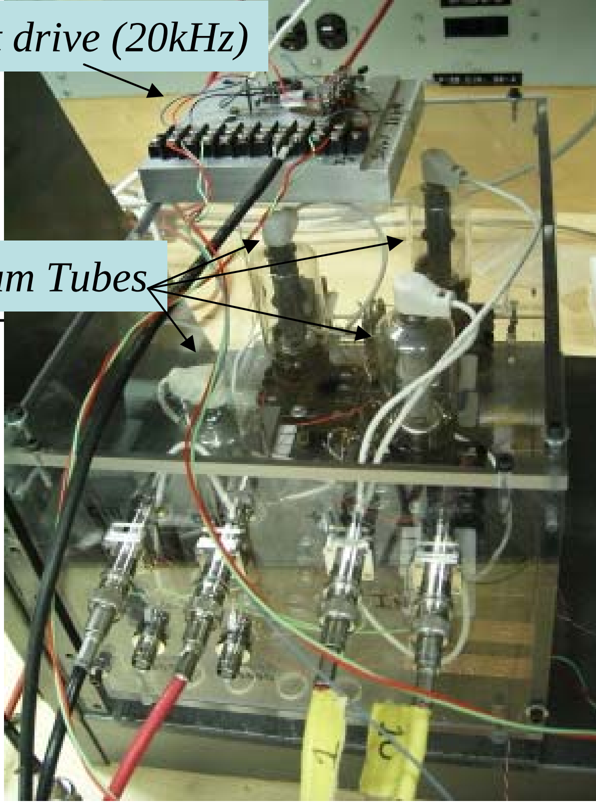




E Field Modulation -- High Voltage Polarity Switch



Red: Filament drive
Blue: Grid voltage control
(Frequency control)
Black:HV switch



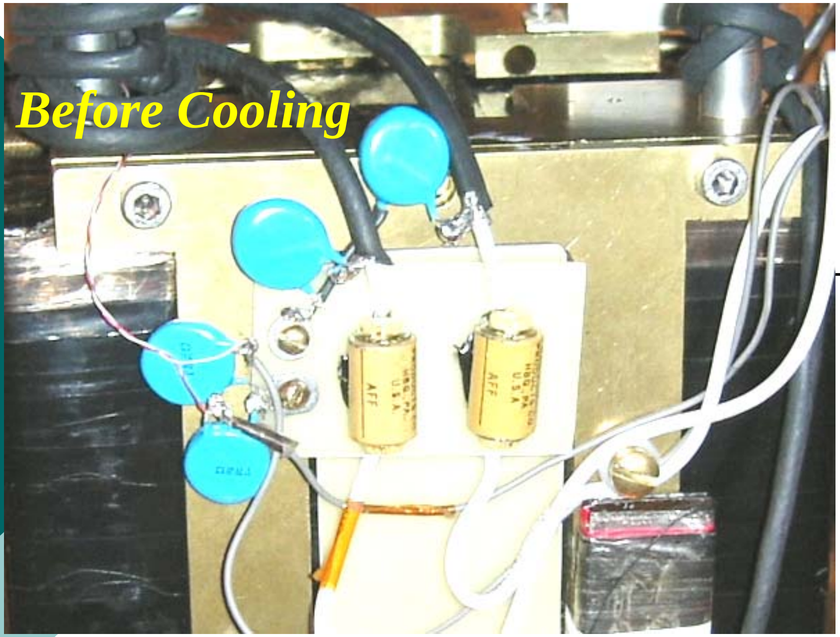
Filament drive (20kHz)

Vacuum Tubes

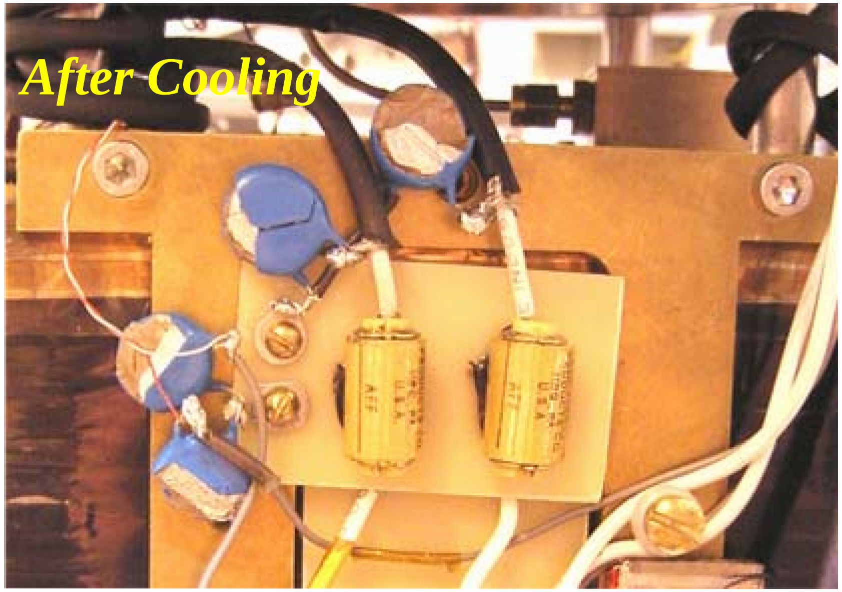
- Power Supply: PS350
  - 5kV, 25W, 15ppm ripple
- Field reversal rate:1~10Hz.
- Use vacuum tubes (triode) to handle the high voltage.
- Turn the two tubes on/off alternatively by driving the grid-cathode voltages to the cut-off voltage.

Capacitors between HV shield to the chamber ground, ground plans to the chamber ground.

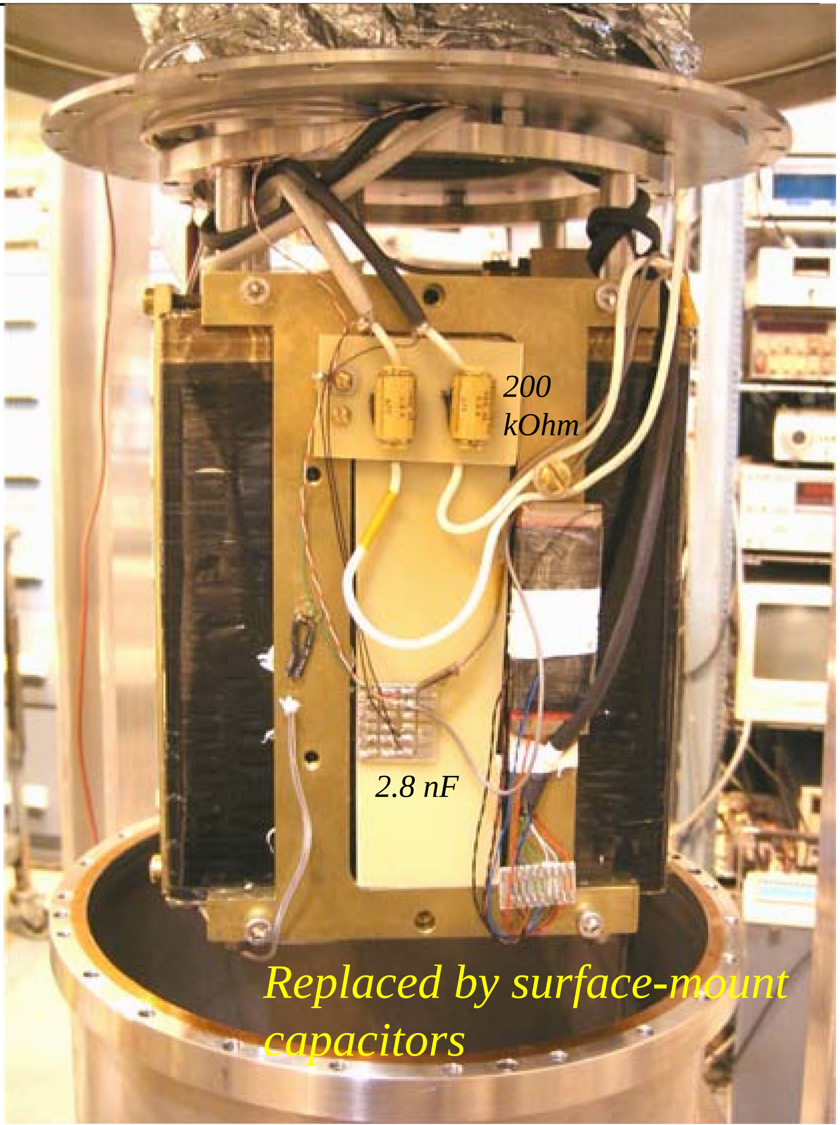
Alleviate the micro-sparks in HV cables from going into the electrodes



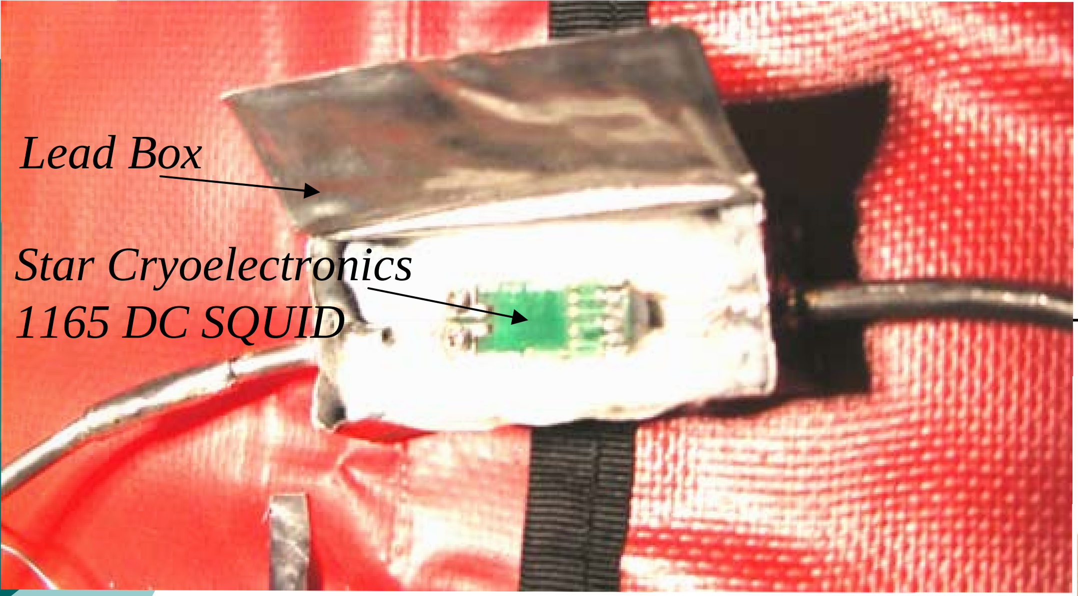
Before Cooling



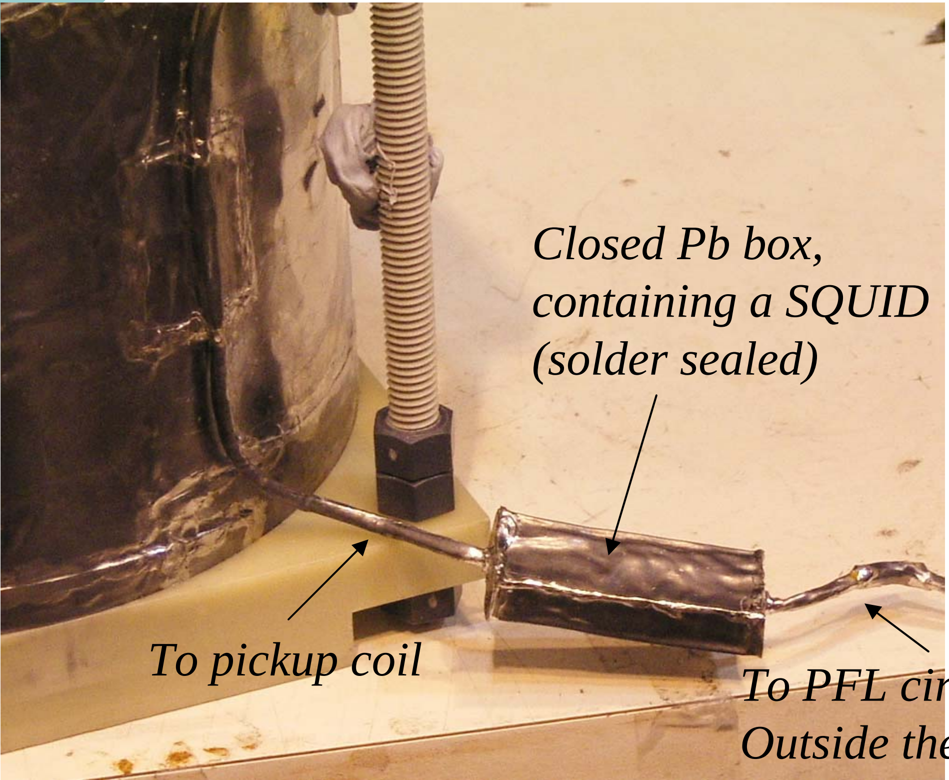
After Cooling

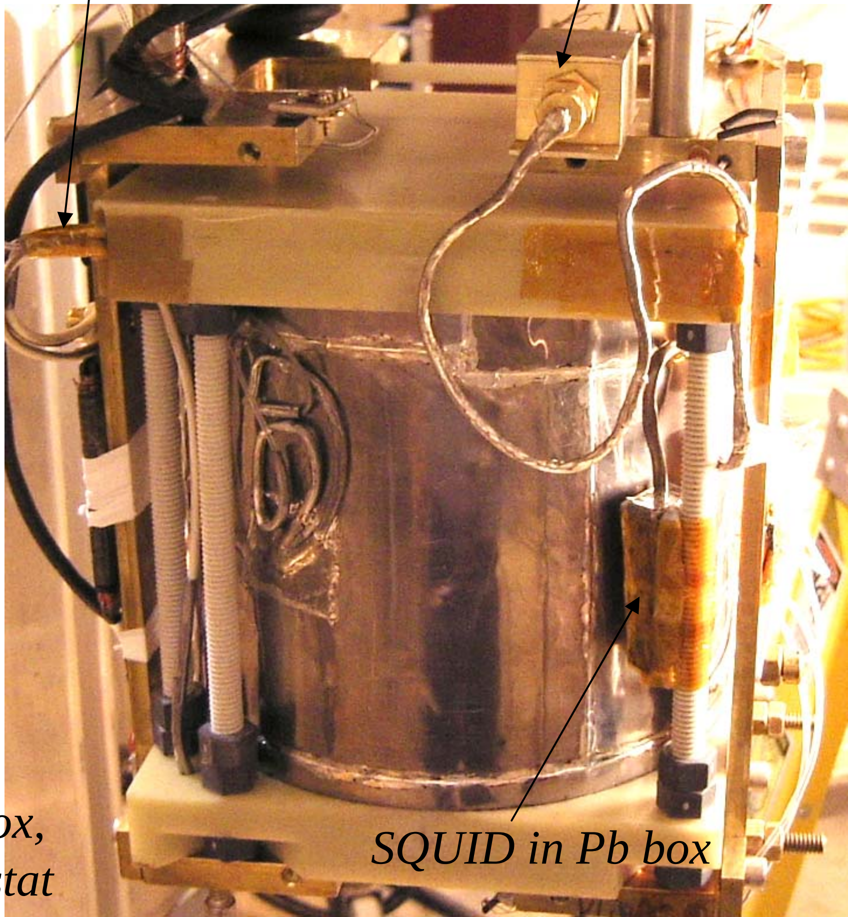


Replaced by surface-mount capacitors



- Star Cryoelectronics 1165 SQUID:
  - Fails after a few thermal cycles.
  - Current lock mode built-in
- Quantum Design DC SQUID, Model 50:
  - Very sturdy
  - Flux lock mode

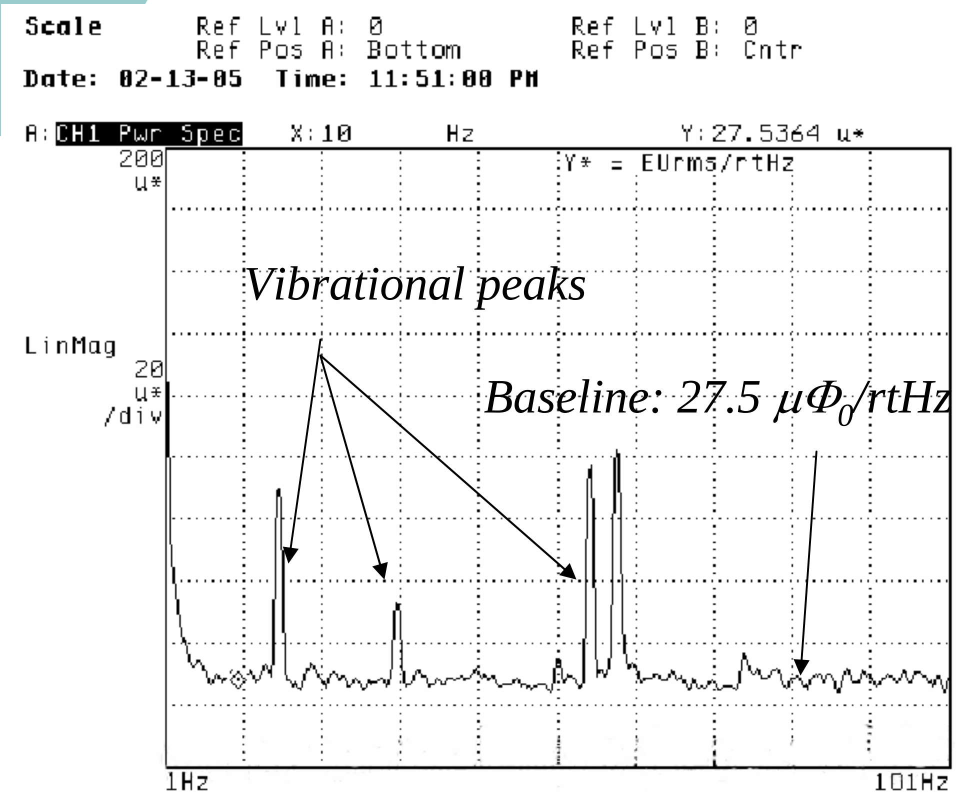




SQUID Noise Spectrum

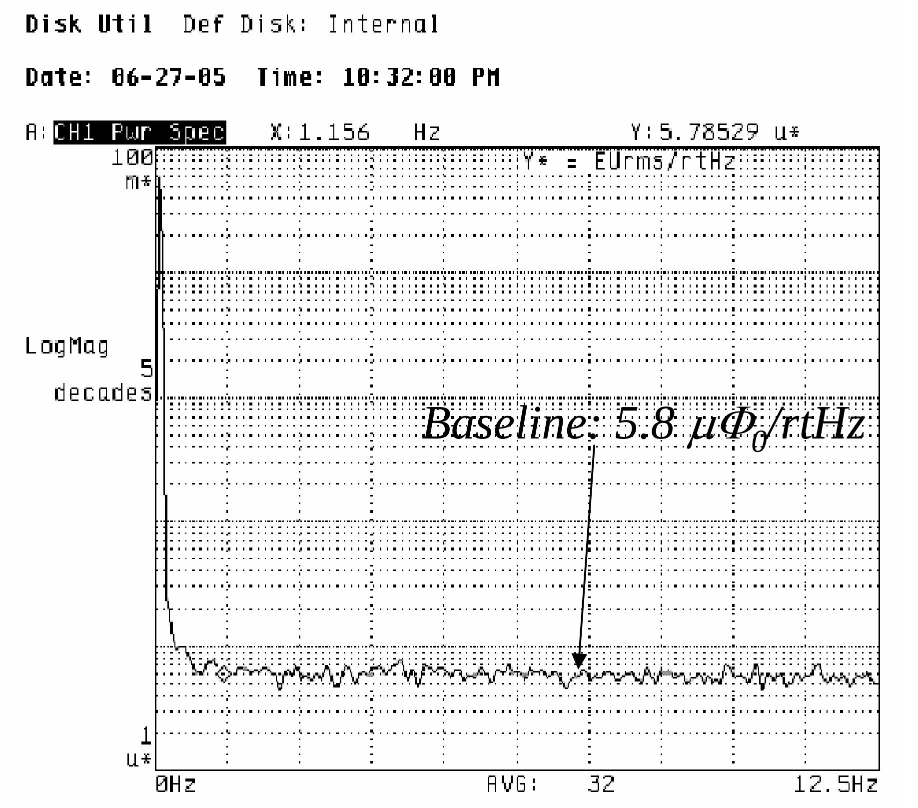
- One layer of Pb superconducting foil

- 2 layers of Pb superconducting foil
- Background ~ Intrinsic SQUID noise
- 1/f corner of SQUID noise < 1Hz



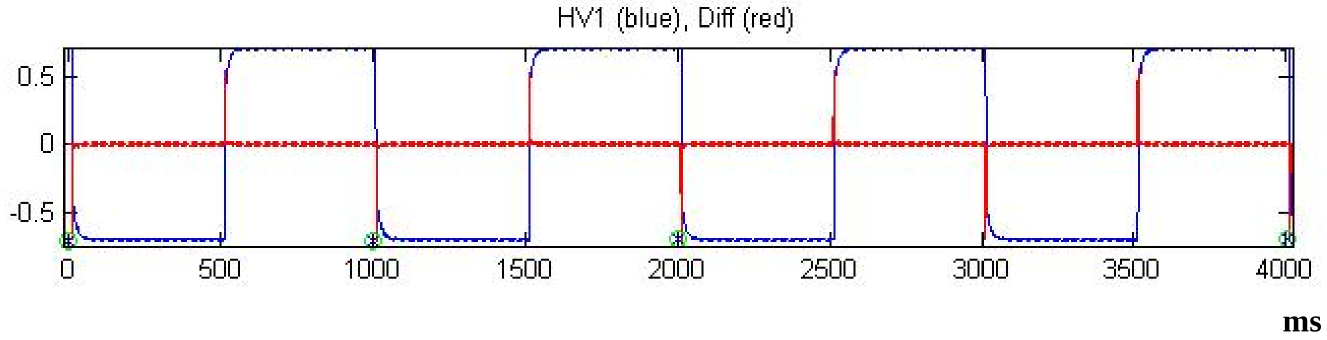
Vibrational peaks

Baseline: 27.5 $\mu\Phi_0$/rtHz

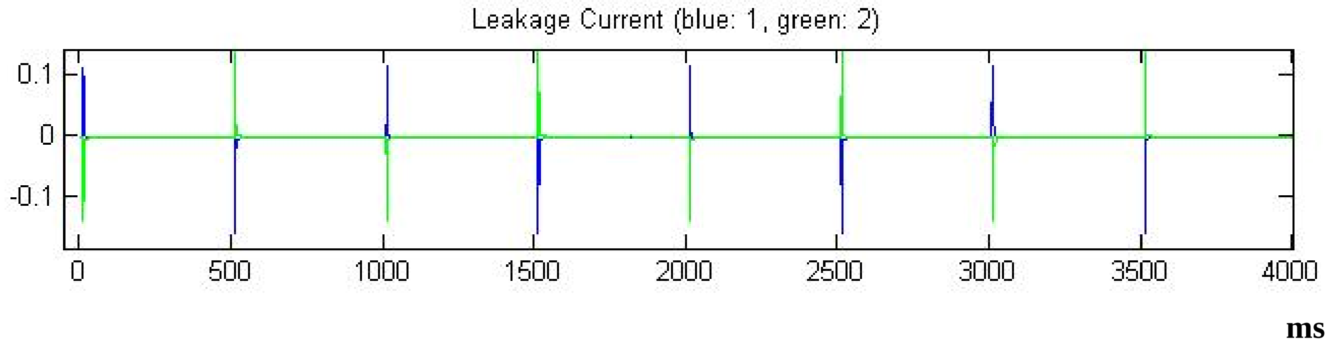


Baseline: 5.8 $\mu\Phi_0$/rtHz

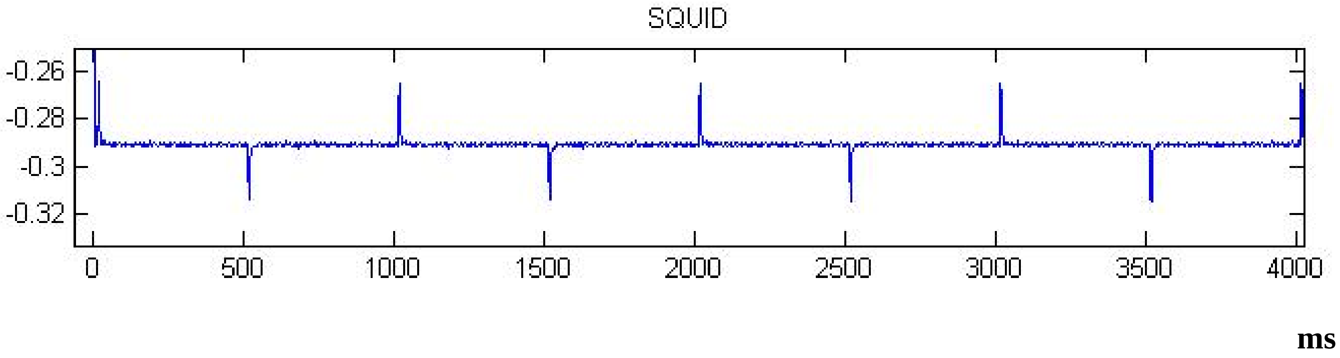
HV
monitor



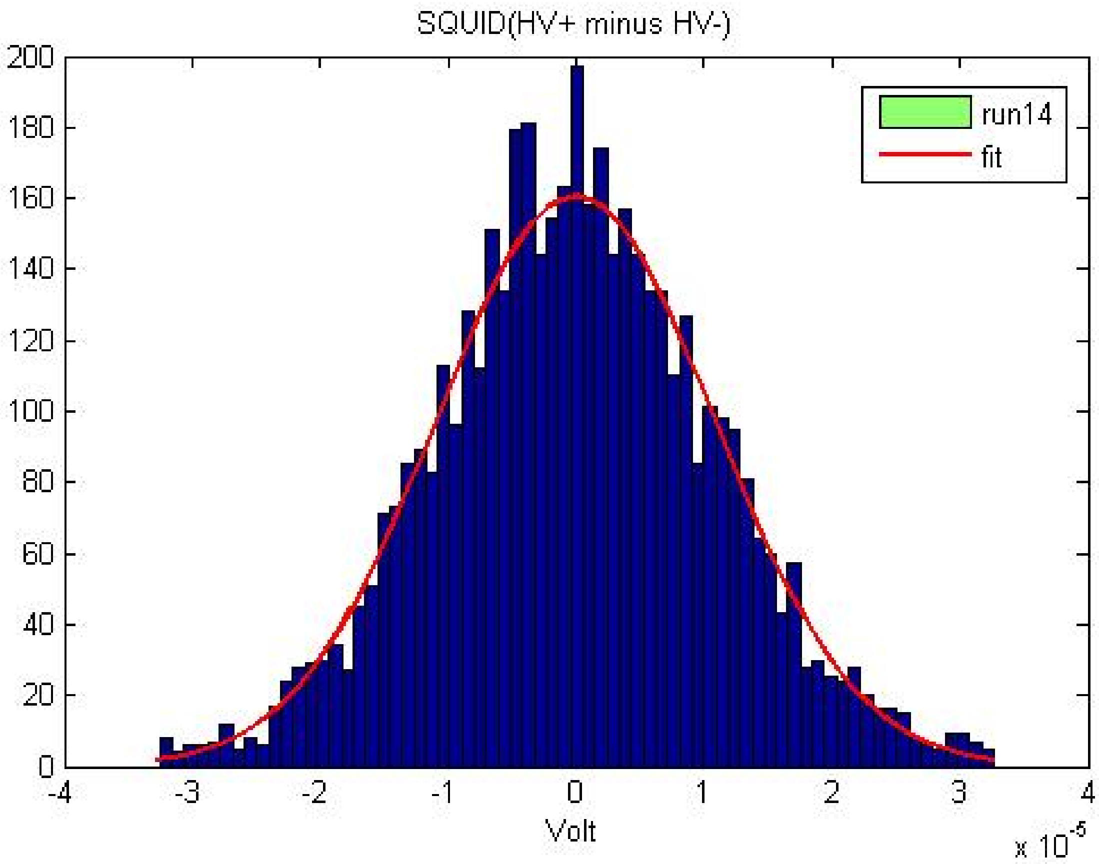
Current
In the ground
plate



SQUID
signal



eEDM Limit



May 2005
4K, 2.8kVpp, 1.13Hz, 50 minutes

SQUID signal:
(-2.68+-5.5)e-7 V
(-0.66 +- 2.8)e-7 V (drift corrected)

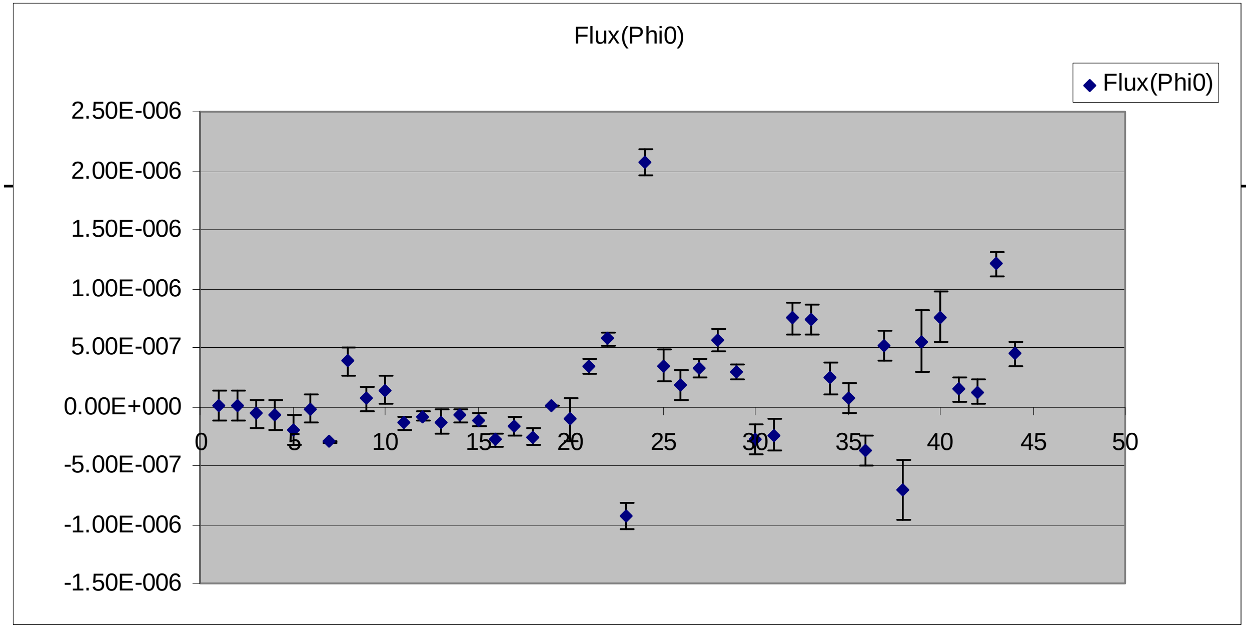
Current measured in ground planes:
(-4.6 +- 0.1)e-10 A (cross talk)

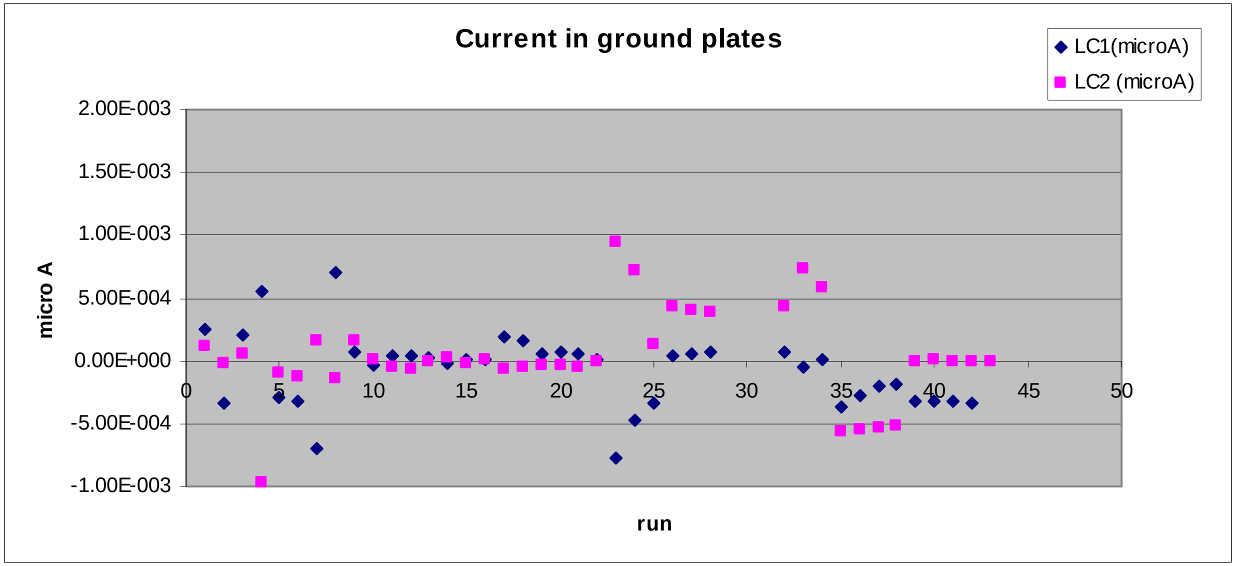
$d_e=(1.46 \pm 6.16) \times 10^{-24}$ e-cm

Vasil'ev and Kolycheva, Sov. Phys. JETP, **47** [2] 243 (1978)
$d_e=(0.81 \pm 1.16)\times 10^{-22}$ e-cm

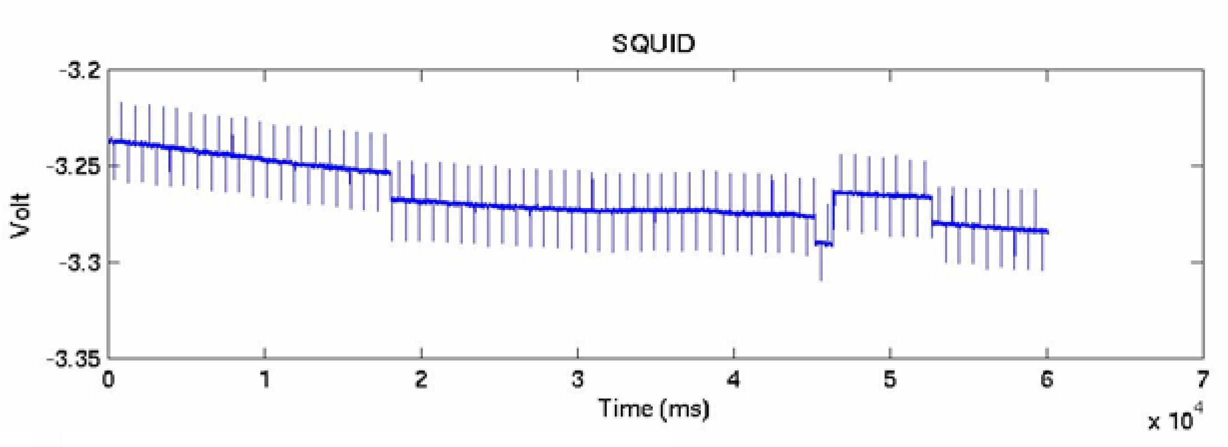
Most Run in Oct. 2006
Accumulated EDM:
$(1.7 \pm 5.2) \times 10^{-23}$ e-cm

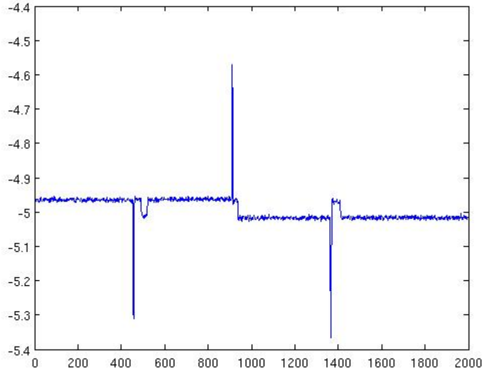
December 2005

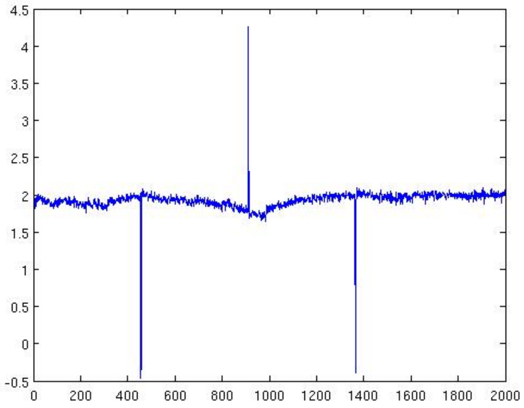


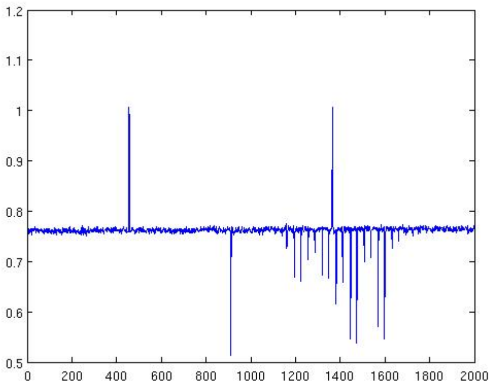


Instabilities in SQUID sensor output









- Adding current bypass capacitors to the ground greatly reduce the high frequency spark signals into the SQUID.
- Stability of the SQUID feedback circuit.
  - A larger RC constant of the FB circuit makes the SQUID operation less susceptible to frequent HV polarity switches.

Leakage Current

- Flux = (-7.43 ± 2.2) $\mu\Phi_0$
  - Field = (1.28 × 10^{-14} gauss)/0.008 = 1600 f-gauss
- 10fA, a quarter turn gives 1 f-guass
- I= 16 pA (to account for the field)

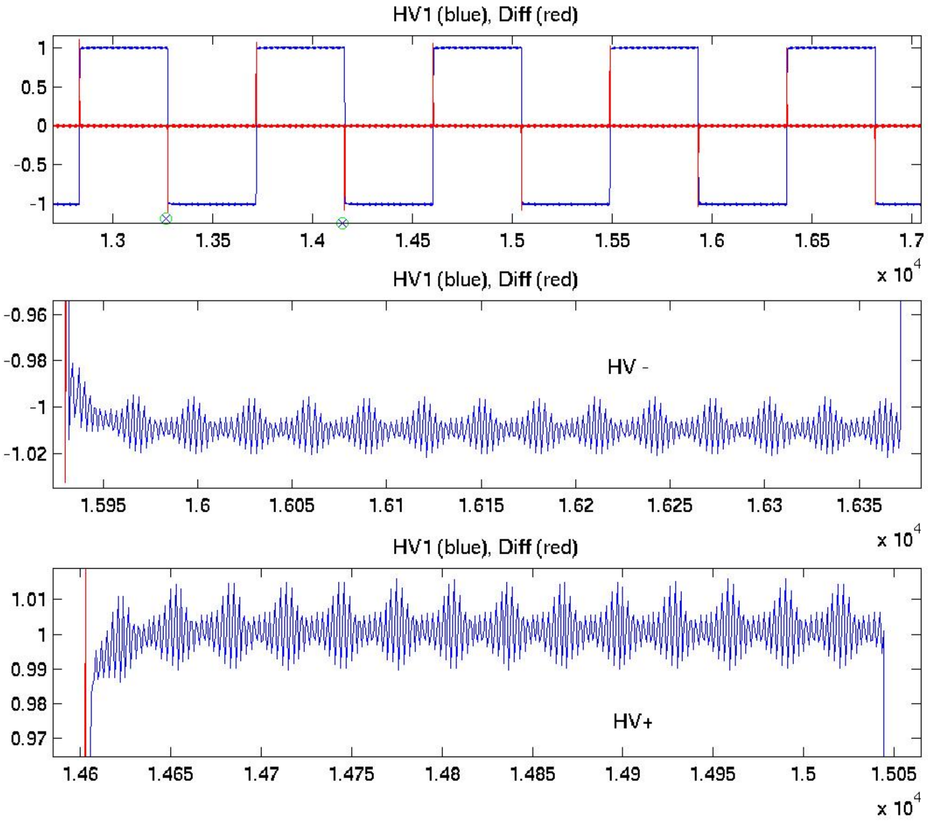
- $I_{volume}=V/R_{volume}$
  - $1kV/(10^{16}\Omega cm*1cm/12cm^2) = 1.2$ pA
  - Resistivity should be larger at low T

HV supply drift

Sampled at 1kHz

Measured Ripples:
10mV/1V=1%
Beat ~ 30 Hz
Vacuum tube filament drive: 20kHz

HV supplies spec:
(PS350, 5kV, 25W)
Ripple: 15ppm

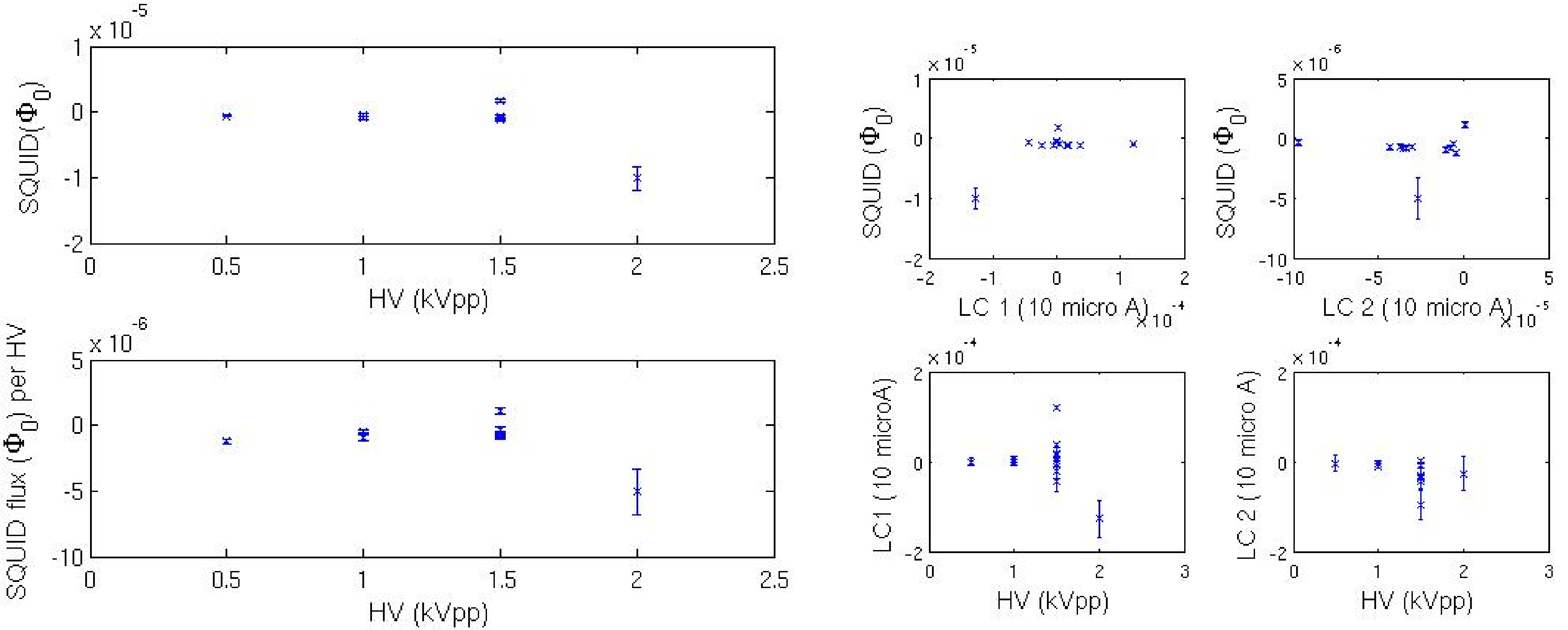


$$I = C\frac{dV}{dt} \xrightarrow[\text{I<10fA}]{\text{C=28pF}} \frac{dV}{dt} < 3.6\times 10^{-4} V/s = 0.36\,ppm/s$$

Improve the feedback cirtuit

Some Observations

- Current monitor is contaminated by the channel crosstalk due to HV monitors.
  - LC < 10^{-10} A
- Correlation between flux and HV is not conclusive.
- SQUID flux measurement seems to be affected by the data filtering (need further investigations).



Other Systematic Effects

- Displacement current at field reversals.
  - Generate large field (helps to check SQUID functionality).
  - This effect is both spatially and temporally orthogonal to the true signal.
  - Magnetize materials around ???
  - Modulate the reversal frequency (or ramping time) to measure this artifact
    - the induced magnetic field is proportional to the frequency, but the electric field is not.

Solid State Effects

- T-violating EDM effect: Magnetization of the sample in response to an electric field (in the absence of an external magnetic field)

- Possible crystal effects:
  - An interaction energy linear in the magnetization could arise if
    - The material itself spontaneously breaks T invariance: choose a sample without magnetic order.
  - “dirt effect” due to residual magnetic fields: $\mu_e S \cdot (T \cdot E) \cdot H$
    - related to the electric-field-dependent *g*-value shits in magnetic-resonance experiments.

$$\mu_e |T| |H| << d_e$$

  - Tensor T vanishes in inversion-symmetric crystal structure.
    - Point defects and substitutional impurities could pair up to restore inversion symmetry.
    - Defect concentration of 1:10^9 should impose no problem.

W, Bialek,
J. Moody,
F. Wilczeck,
Phys. Rev.
Lett. 56, 1623
(1986)

Conclusions

- **The current setup** is sensitive to eEDM signal ~ 10^{-23} e-cm using a hour of data.

- **The prototype system** cooled to 40 mK and 2 days of data averaging should have an eEDM sensitivity of 10^{-27} e-cm.
  - Keep on understanding the non-zero background.
    - Eliminate channel crosstalks
    - Stabilize operations of SQUID (improved RF shields)
    - Implement multiple SQUID sensors
    - Stabilize HV supply
    - Couple to a DR

- Further improvements (towards 10^{-30} e-cm):
  - Scale up the prototype system
  - Spin dilution: Gd(Y)GG
  - employ better magnetometers