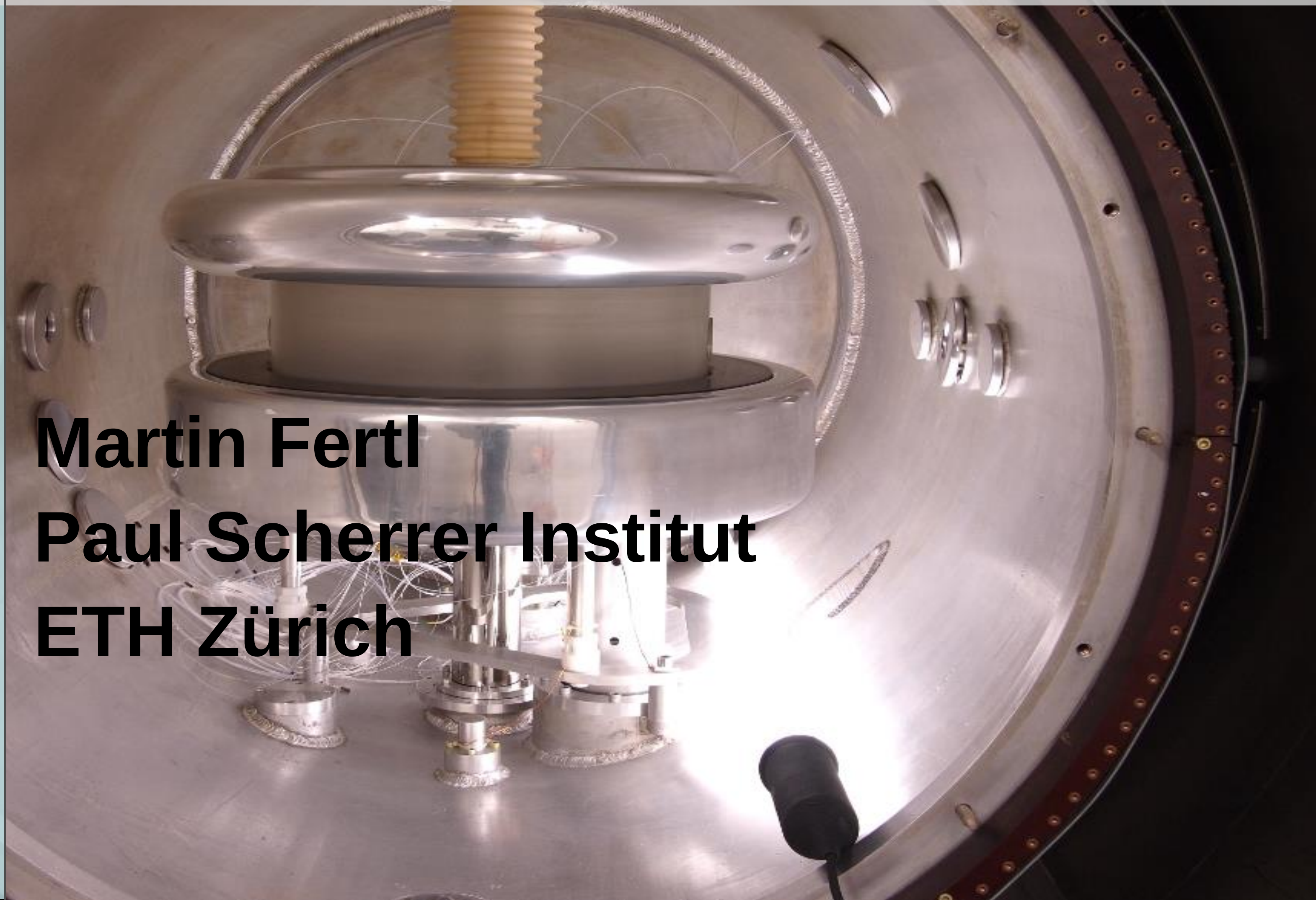
A UV laser system for the Hg co-magnetometer in the nEDM experiment at PSI



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Sursee, 24.06.2013

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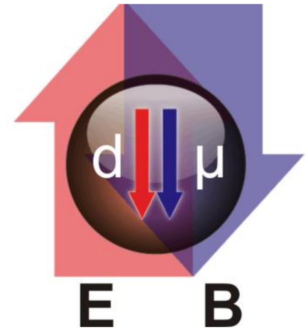
Outline

1. Short introduction to nEDM experiment
2. The Hg co-magnetometer and the new UV laser: first results
3. New possibilities opened up by the UV laser system

EDMs and symmetries

T →



$$H_0 = -\left(-d\,\frac{\vec{\sigma}}{|\vec{\sigma}|}\cdot\vec{E} + \mu\,\frac{\vec{\sigma}}{|\vec{\sigma}|}\cdot\vec{B}\right) \qquad H_{\mathrm{T}} = -\left(-d\,\frac{(-\vec{\sigma})}{|(-\vec{\sigma})|}\cdot\vec{E} + \mu\,\frac{(-\vec{\sigma})}{|(-\vec{\sigma})|}\cdot\left(-\vec{B}\right)\right) \neq H_0$$

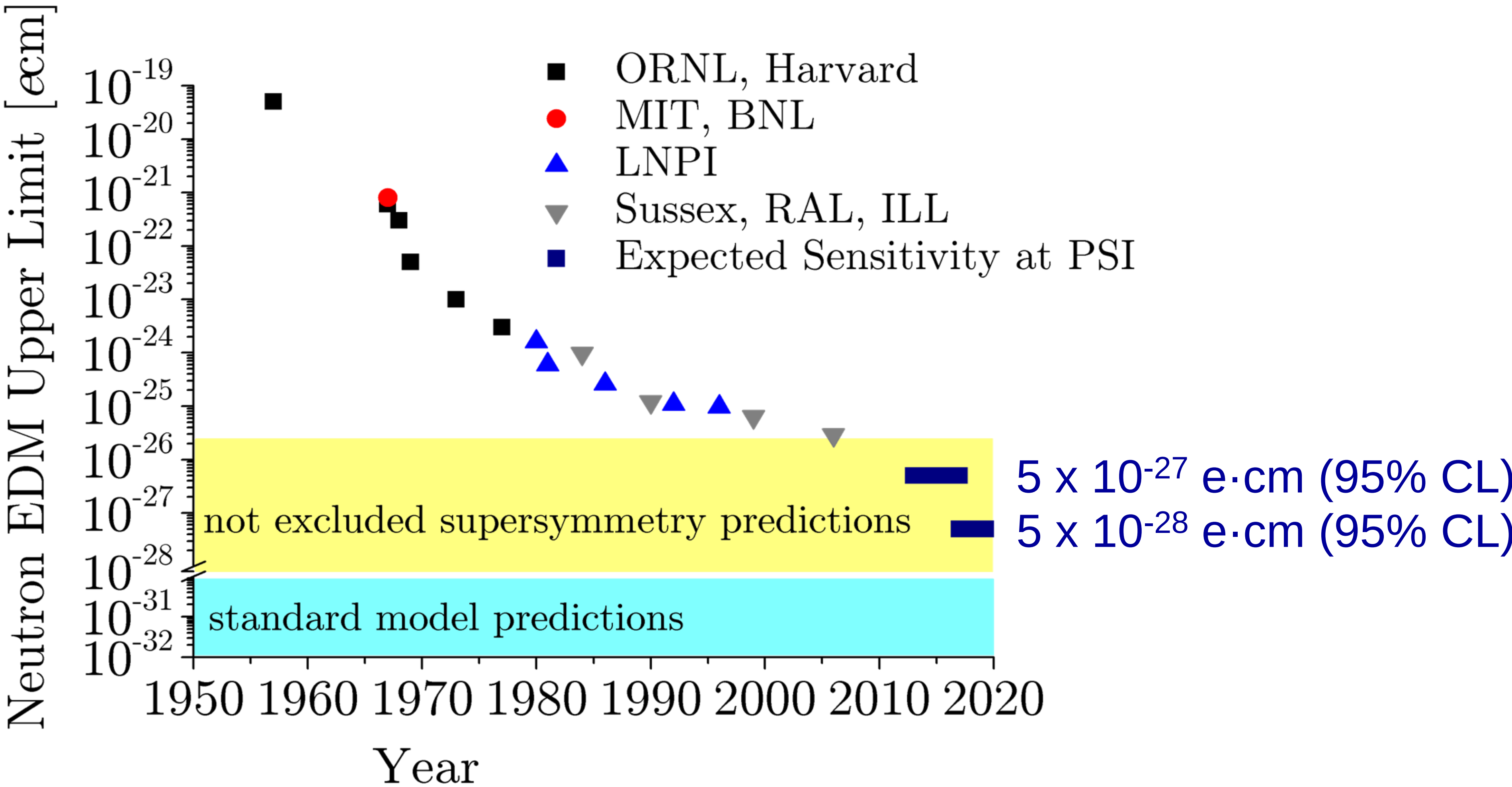
T violation, assuming CPT conservation, also CP violation.
(Purcell and Ramsey, Phys. Rev. 78, 807 (1950))

The strong CP problem: 1 CP violating dimension 4 operator in QCD

$$\mathcal{L}^{\mathrm{QCD}}_{\mathrm{dim}=4} = \frac{g_{\mathrm{s}}^2}{32\pi^2}\bar{\theta}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} \qquad d_{\mathrm{n}} \approx \bar{\theta}_{\mathrm{QCD}} \times 10^{-16}\mathrm{e\cdot cm}$$

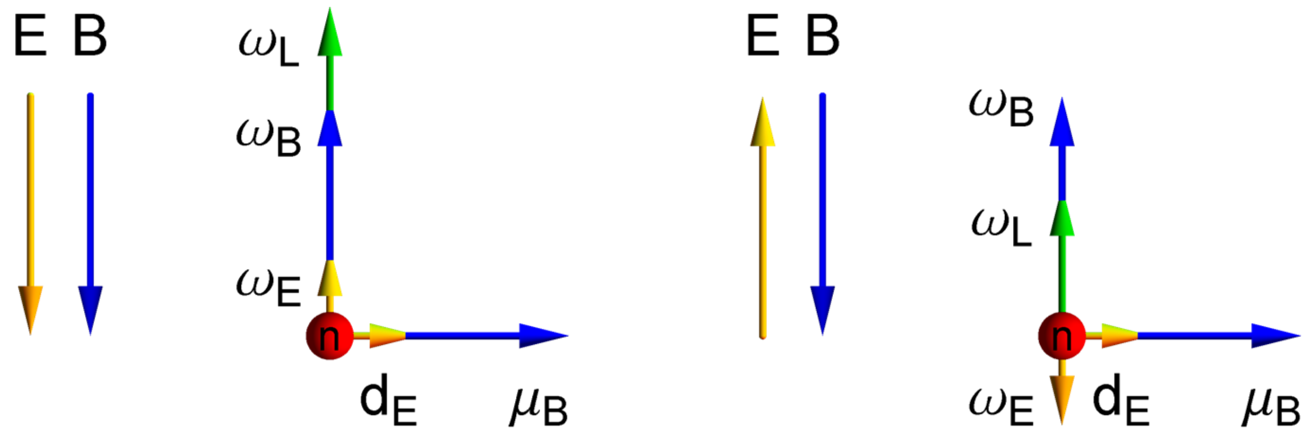
But: $d_{\mathrm{n}} \leq 2.9\times 10^{-26}\mathrm{e}\cdot\mathrm{cm}\,(90\%\mathrm{CL}) \rightarrow \bar{\theta}_{\mathrm{QCD}} \approx 10^{-10}$

History of nEDM



nEDM measurement

Goal: detect $\Delta\omega_L$ correlated to the relative B and E field direction

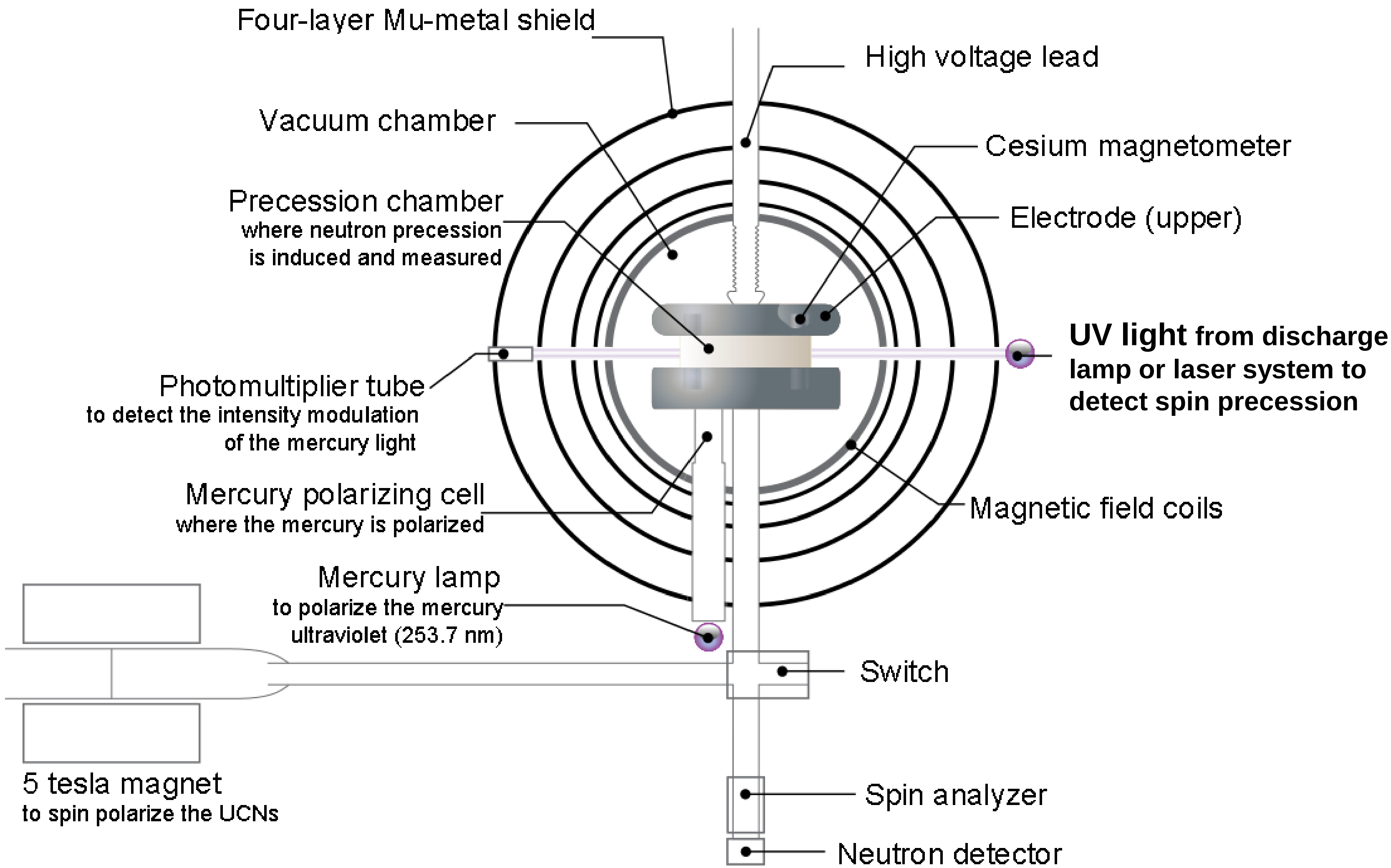


major source of systematic effects

extract nEDM from: $$d_{\mathrm{n}} = \frac{\hbar\Delta\omega - \mu_{\mathrm{n}}\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}{2\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right)}$$

$$B_0 \approx 1\,\mu\mathrm{T} \Longrightarrow \omega_{\mathrm{L,n}} \approx 2\pi \times 30\,\mathrm{Hz}$$
$$E \approx 12\,\frac{\mathrm{kV}}{\mathrm{cm}},\, d_{\mathrm{n}} \leq 3 \times 10^{-26}\mathrm{e} \cdot \mathrm{cm} \Longrightarrow \Delta\omega_{\mathrm{L,n}} \approx 2\pi \times 9\,\mathrm{nHz}$$

nEDM apparatus



surrounding field compensation

nEDM sensitivity

From $d_\mathrm{n} = \frac{\hbar\Delta\omega - \mu_\mathrm{n}\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}{2\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right)} \Rightarrow d_\mathrm{n} = \frac{\hbar\Delta\omega}{4E}$

if $2\mu_\mathrm{n}\left(B_{\uparrow\downarrow} - B_{\uparrow\uparrow}\right) \ll \hbar\Delta\omega = 4Ed_\mathrm{n} \rightarrow \sigma\left(\Delta B\right) \ll \frac{2E\sigma\left(d_\mathrm{n}\right)}{\mu_\mathrm{n}}$

$$\sigma\left(d_\mathrm{n}\right) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

- α Visibility of resonance (0.75)
- E Electric field strength (12 kV/cm)
- T Time of free precession (150s)
- N Number of neutrons (350000)

For nEDM@PSI as planned per run:

$$\sigma\left(d_\mathrm{n}\right) = \frac{\hbar}{2\alpha ET\sqrt{N}} = 4\cdot 10^{-25} ecm$$

→ σ(ΔB)=100 fT per cycle (nEDM)
→ σ(ΔB)=10 fT per cycle (n2EDM)

Systematic effects

Effect	class (d/i)	Shift and σ 10^{-27} e · cm RAL/Sx/ILL	Shift and σ 2012 10^{-27} e · cm
Leakage currents	d	0.0±0.1	0.00±0.04
$v \times E$			
- First order	d	0.0±1.0	0.00±0.54
- Second order	d	0.00±0.02	0.00±0.00
Electric forces	d	0.0±0.4	0.00±0.00
AC fields	d	0.00±0.01	0.00±0.00
Uncompensated B drifts	d	0.0±2.4	-0.46±0.36
^{199}Hg atom edm	i	-0.40±0.30	0.02±0.06
^{199}Hg light shifts	i	3.50±0.82	0.00±0.27
Geometric phase effect			
- Dipole fields	i	-5.60±6.32	0.00±0.00
- Quadrupole difference	i	-1.30±2.00	5.59±9.02
Total		-3.80±7.19	5.13±9.08

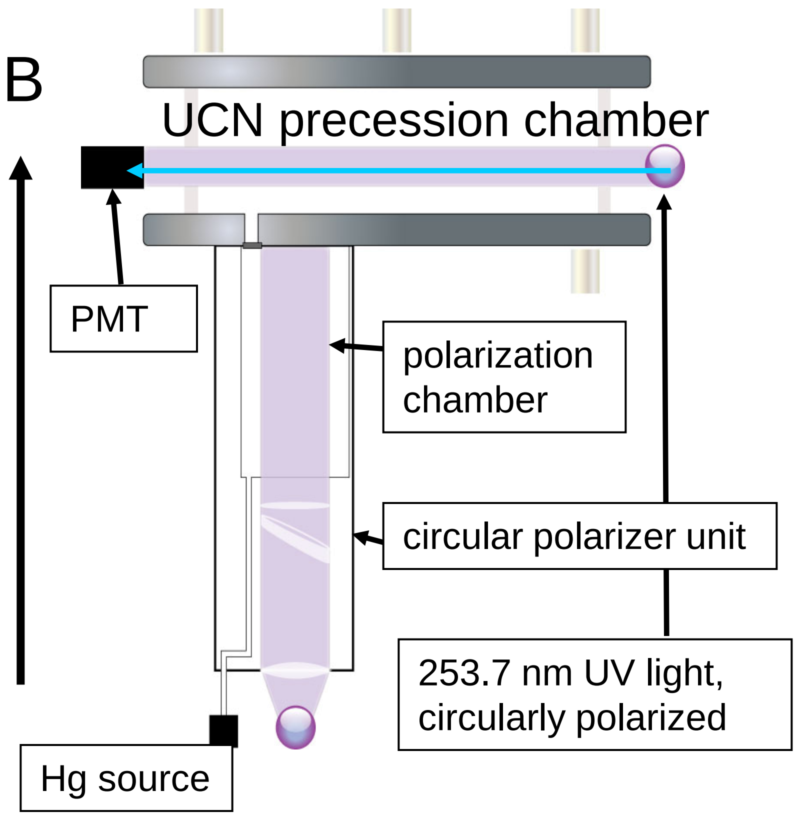
d: direct effect on UCN
i: indirect effect

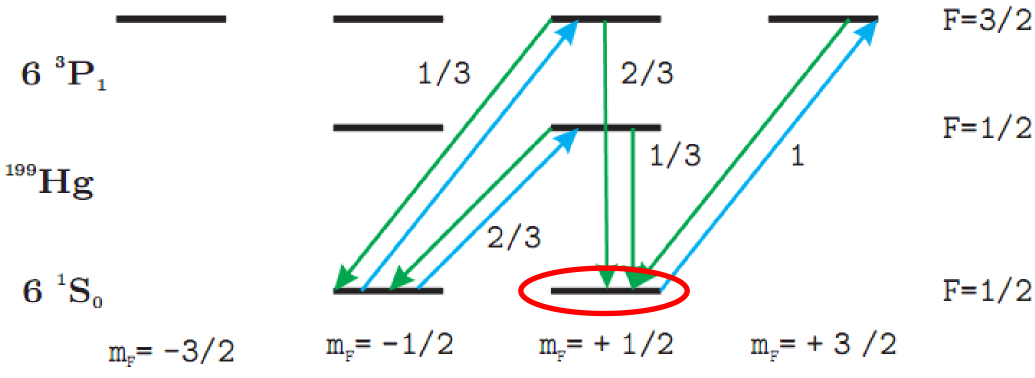
→ major systematic effects are related to the Hg co-magnetometer

→ one is directly related to the light source

Optical pumping of ^{199}Hg

Goal: Measure residual magnetic field drifts via optically detected nuclear magnetic resonance



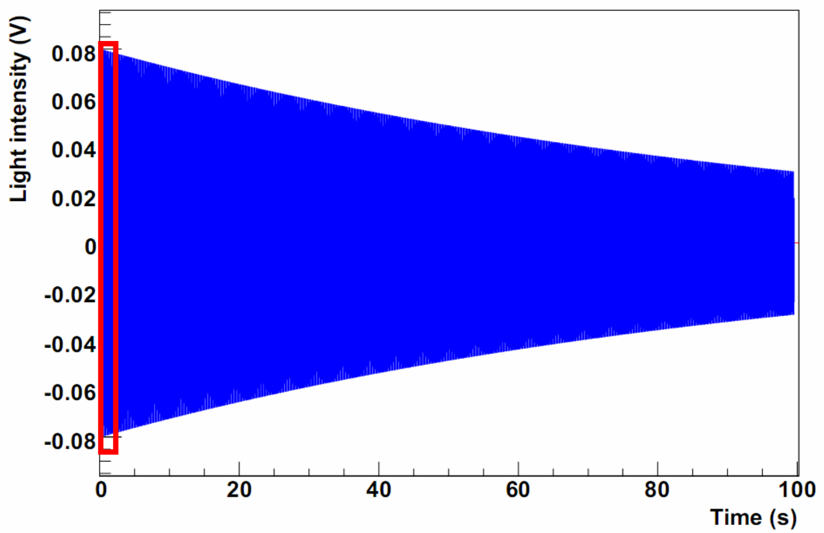


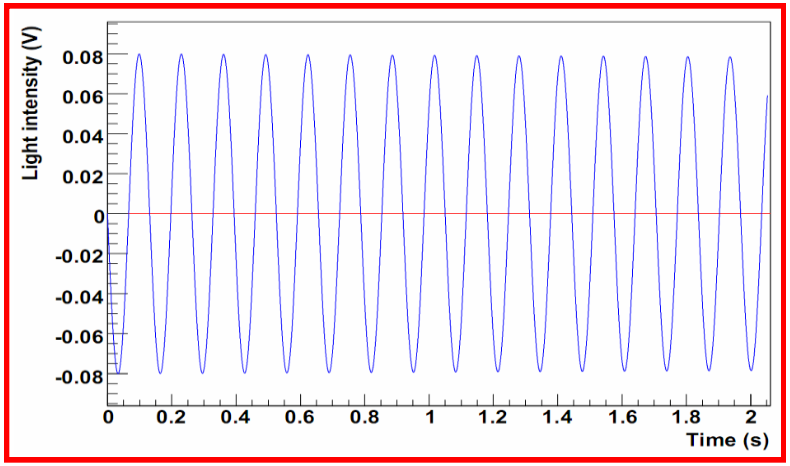
Spin polarize by optical pumping

Absorption cross section depends on the relative orientation of photon and atom angular momentum

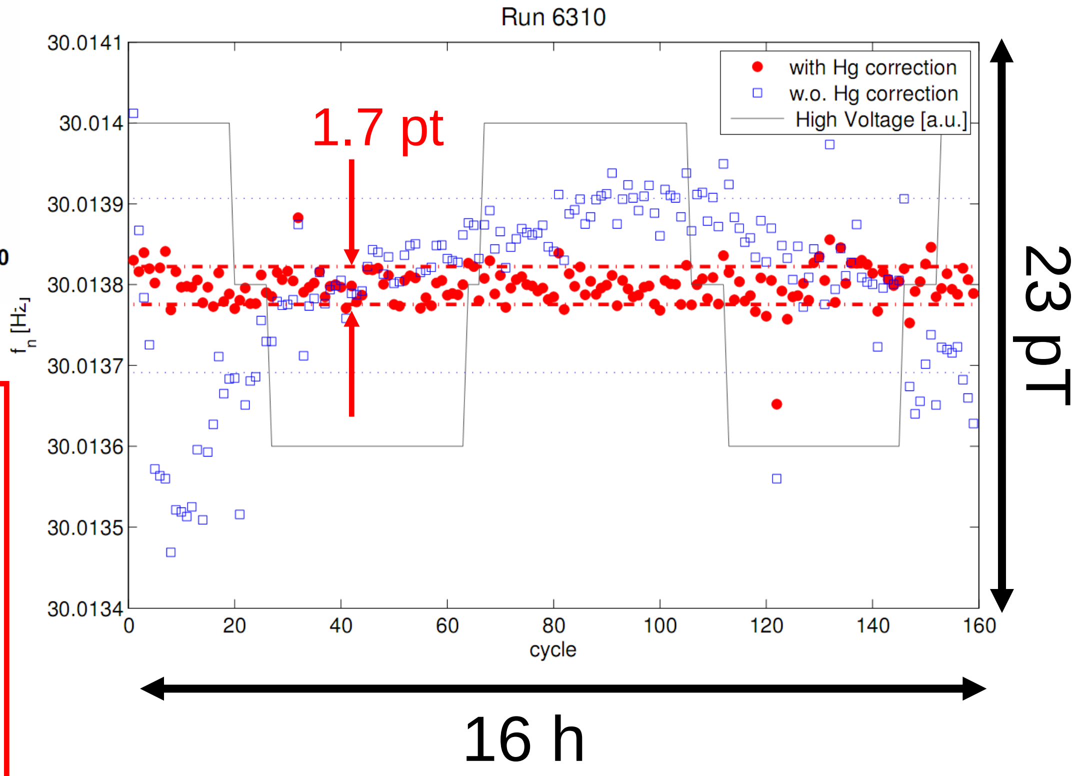
Transmission modulation of circularly polarized light beam perpendicular to main magnetic field after π/2 flip

Hg co-magnetometer





Extract B field from Larmor frequency and correct UCN frequency (lamp data)

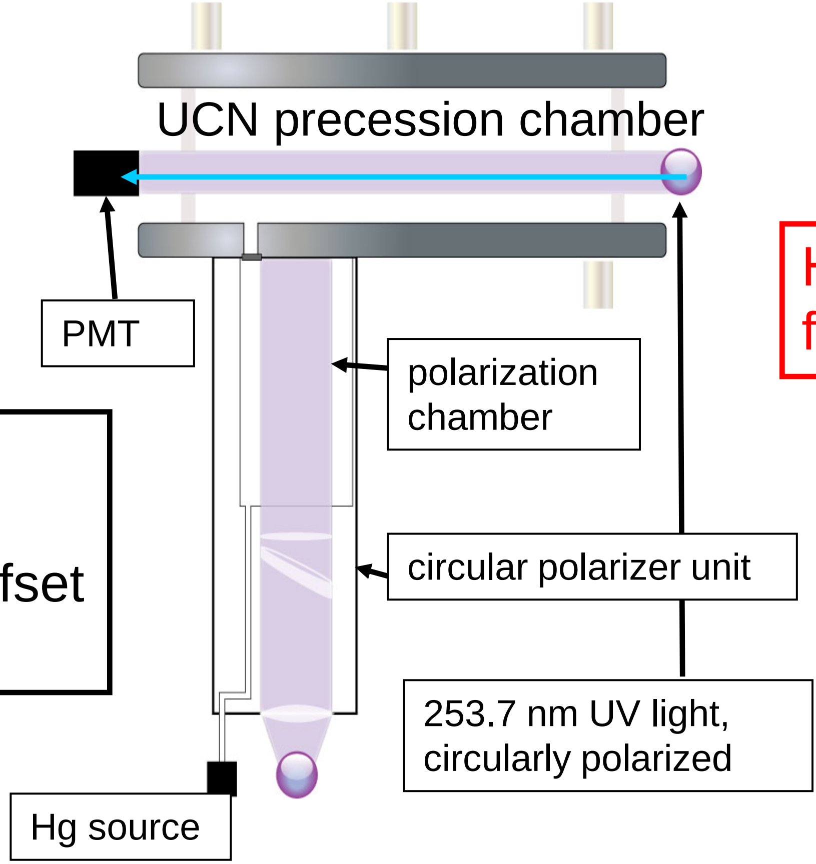


Hg co-magnetometer

Goal: Measure residual magnetic field drifts via optically detected nuclear magnetic resonance (ODMR) with ^{199}Hg atoms

Same volume as UCN!

Same volume average as UCN?
- Center of mass offset
- Adiabaticity



Hg specific "magnetic" field effects

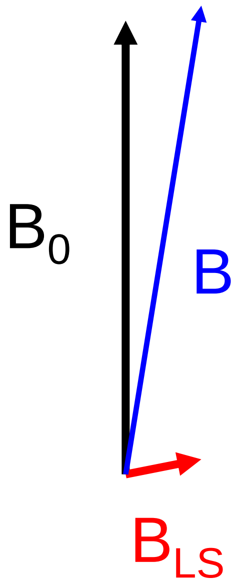
Vector light shift in ^{199}Hg

Atomic energy levels are influenced by the interaction with light

Spin dependent part can be by modeled as effective magnetic field
(which only alters the Larmor frequency of the Hg atoms, not of the UCN)

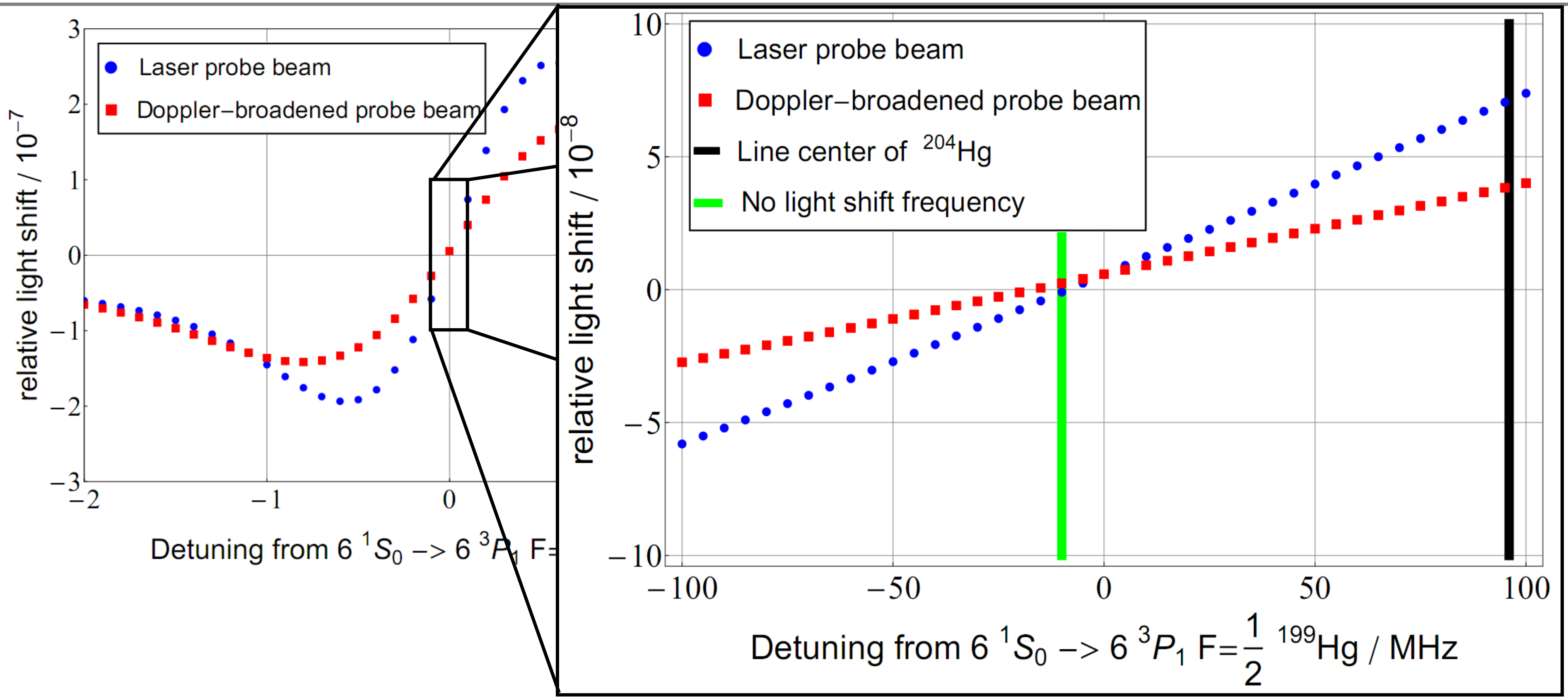
Effective magnetic field depends on:

- Light intensity
- Light polarization
- Light frequency
- Light beam alignment



All four parameters have to be under control for reliable calculations.

Vector light shift in ^{199}Hg



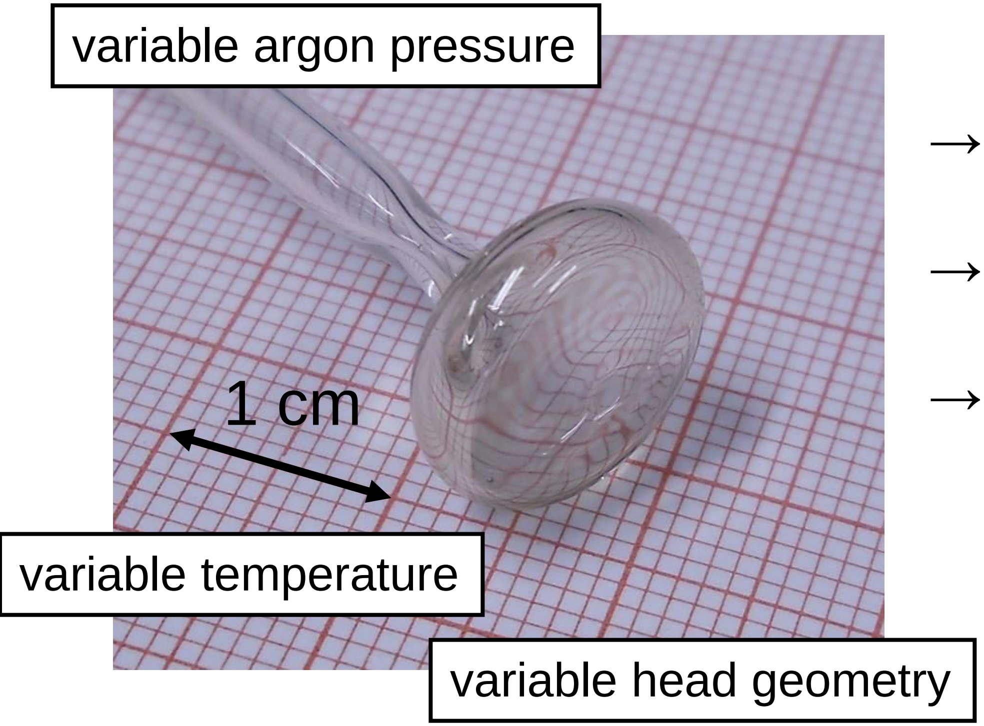
Calculation for 5 µW UV circular polarized light in UCN chamber, 5 mm diameter, 1 mrad misalignment to the main magnetic field for a laser (~1 MHz) and a Doppler broadened (~1 GHz) readout light (W. Happer, B.S. Mathur, Phys. Rev. 163, 12 (1967))

→ residual effect on resonance is ~ 6 ppb (6 fT) → good enough for n2EDM

Hg discharge bulbs

current UV light sources: ^{204}Hg (90%) discharge lamps

advantage: easy to run, emission line overlaps ^{199}Hg F=1/2
disadvantage: many details unknown and prone to changes, possible vector light shifts, self-absorption

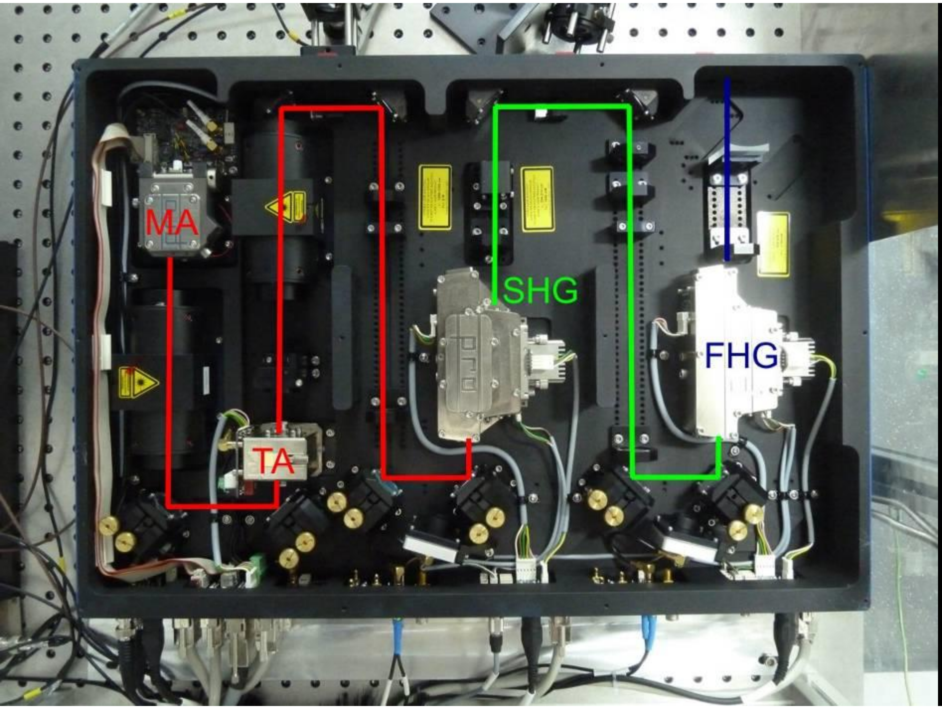


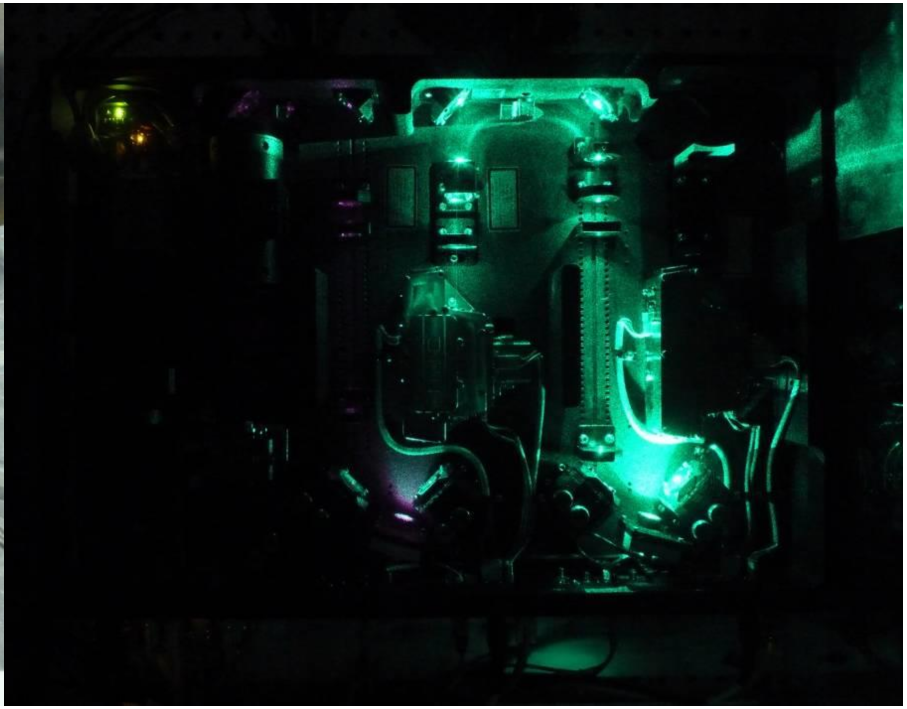
→ large uncertainty on the output frequency spectrum
→ affects estimates of systematic effects

→ well controllable light source important

UV FHG system

Fourth harmonic generator (IR→VIS→UV)
Toptica TA FHG installed in a test lab (20 mW @ 254 nm)
50 m away from the nEDM setup

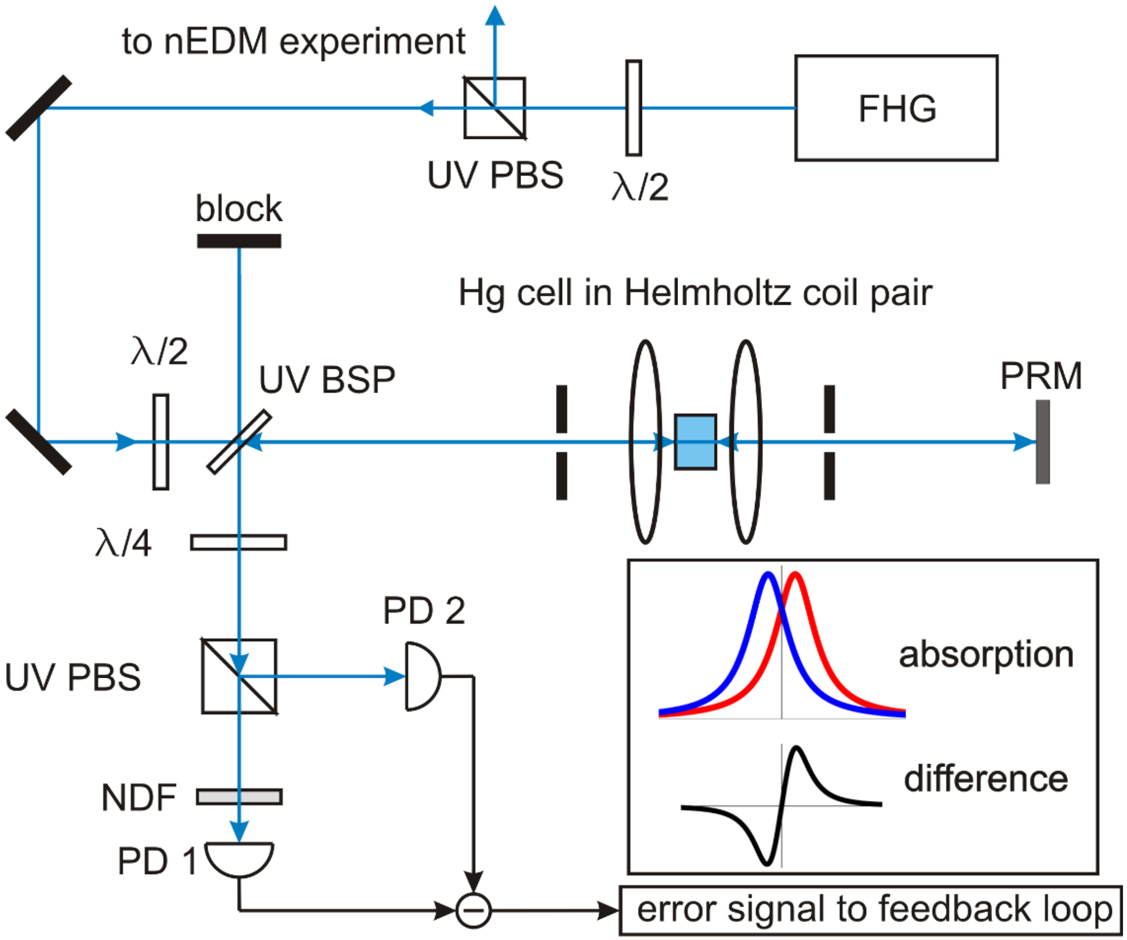




MHz accuracy lock necessary to suppress vector light shift

SD-DAVLL

Frequency stabilization by **S**ub-**D**oppler **D**ichroic **A**tomic **V**apor **L**aser **L**ock scheme (SD-DAVLL)

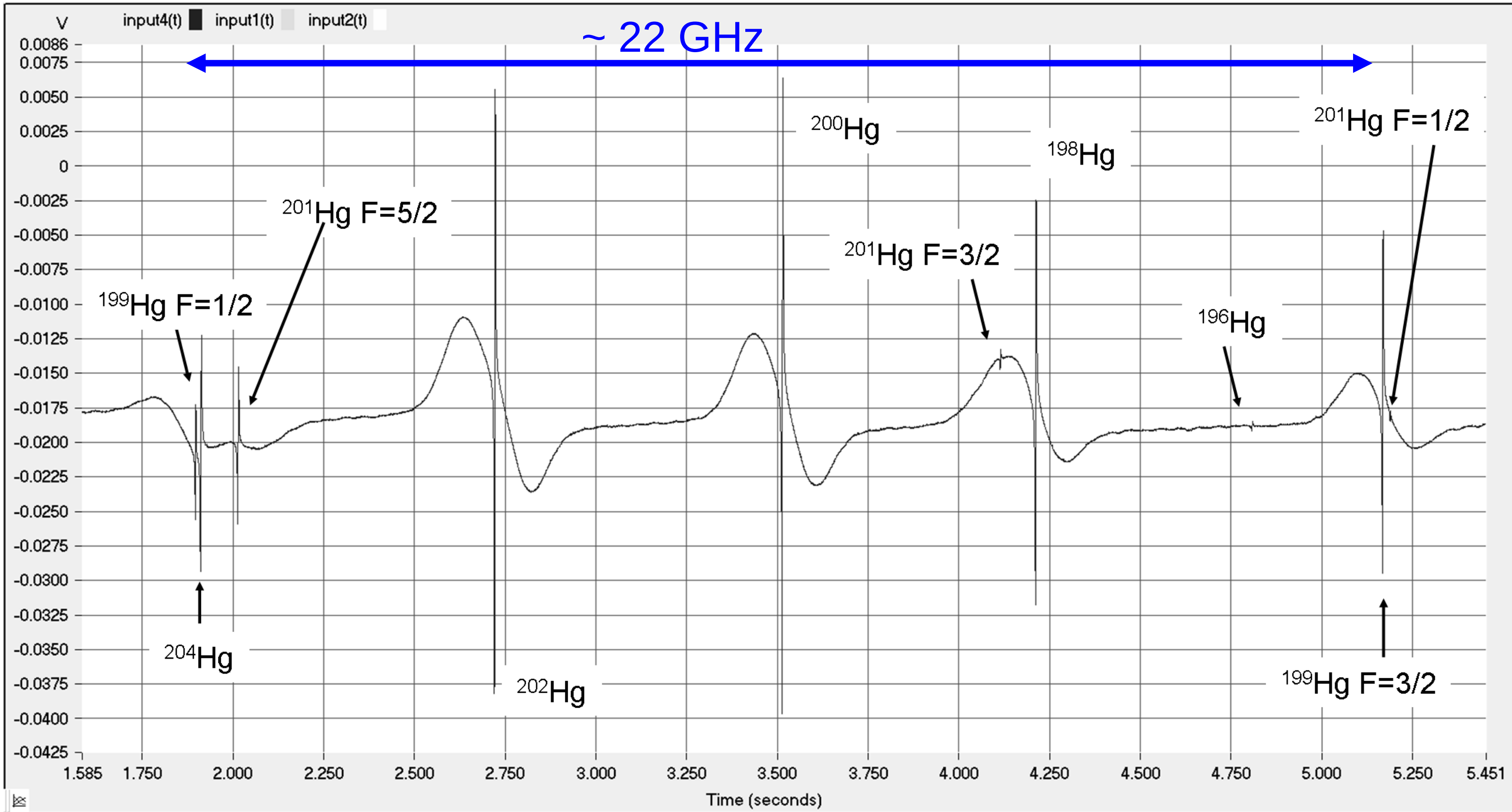


Dichroism induced by an external magnetic field

advantages:

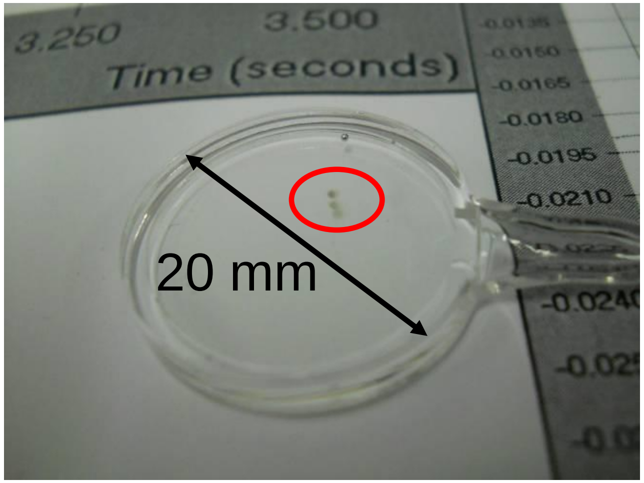
- 1st order independence of magnetic field changes
- modulation free

SD-DAVLL spectrum I



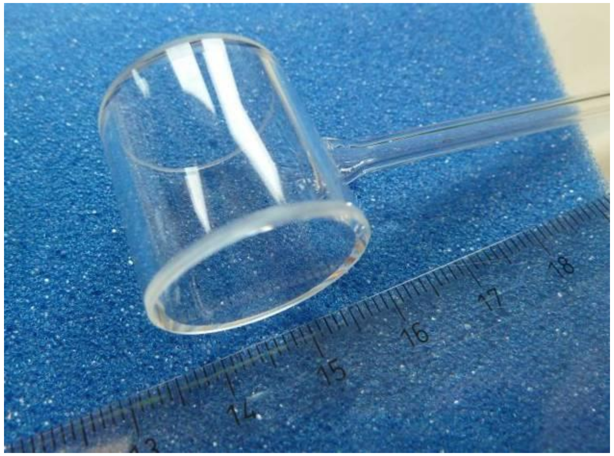
Hg 195	Hg 196	Hg 197	Hg 198	Hg 199	Hg 200	Hg 201	Hg 202	Hg 203	Hg 204	Hg 205
9,5 h	0,15	64,1 h	9,97	16,87	23,10	13,18	29,86	46,59 d	6,87	5,2 m

Hg spectroscopy cells



Commercial prefilled spectroscopy cells degraded within hours/days

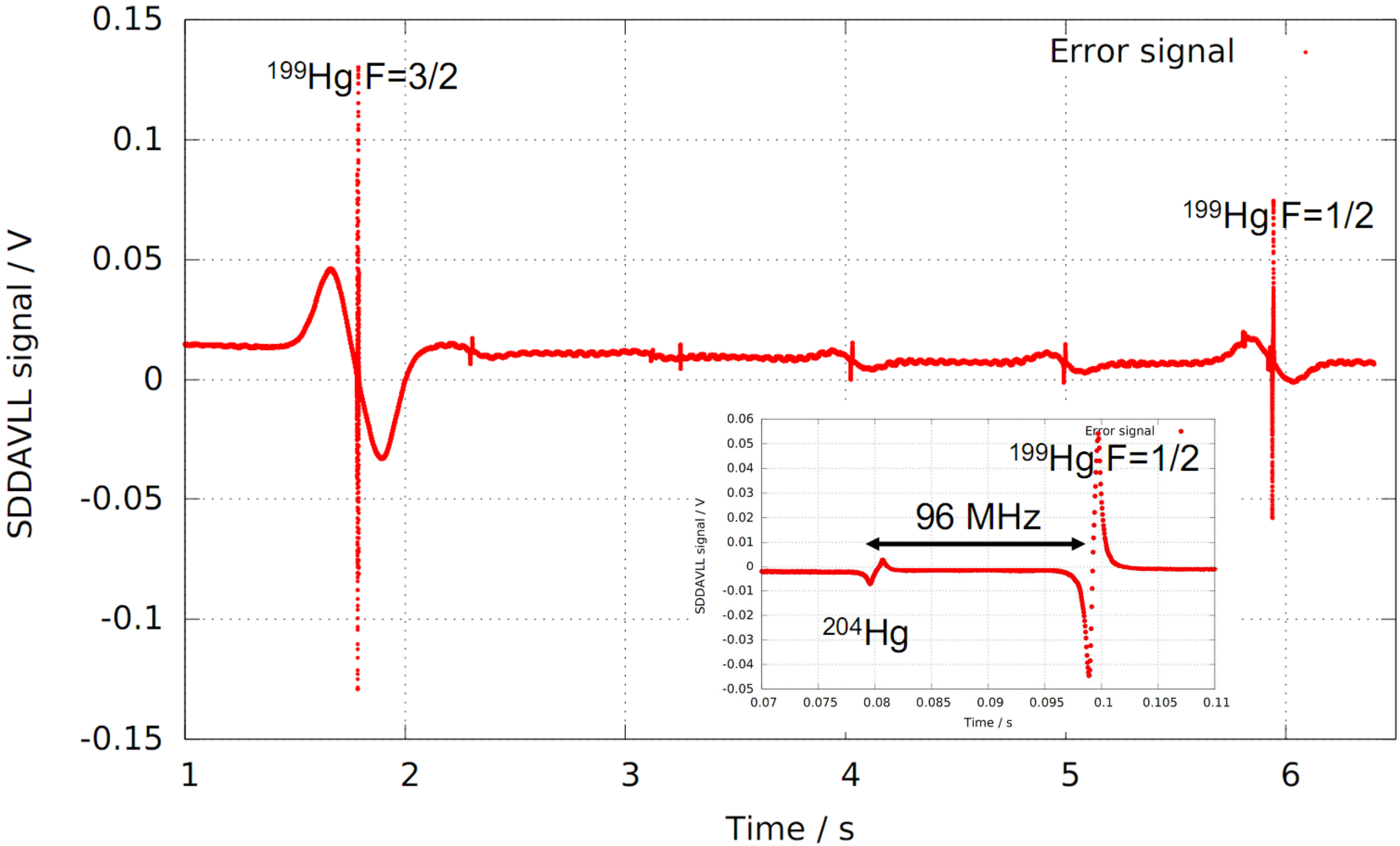
→ recover by heating, not convenient



Fill long quartz cells with enriched ^{199}Hg ourselves

→ no darkening even after months of operation

SD-DAVLL spectrum II

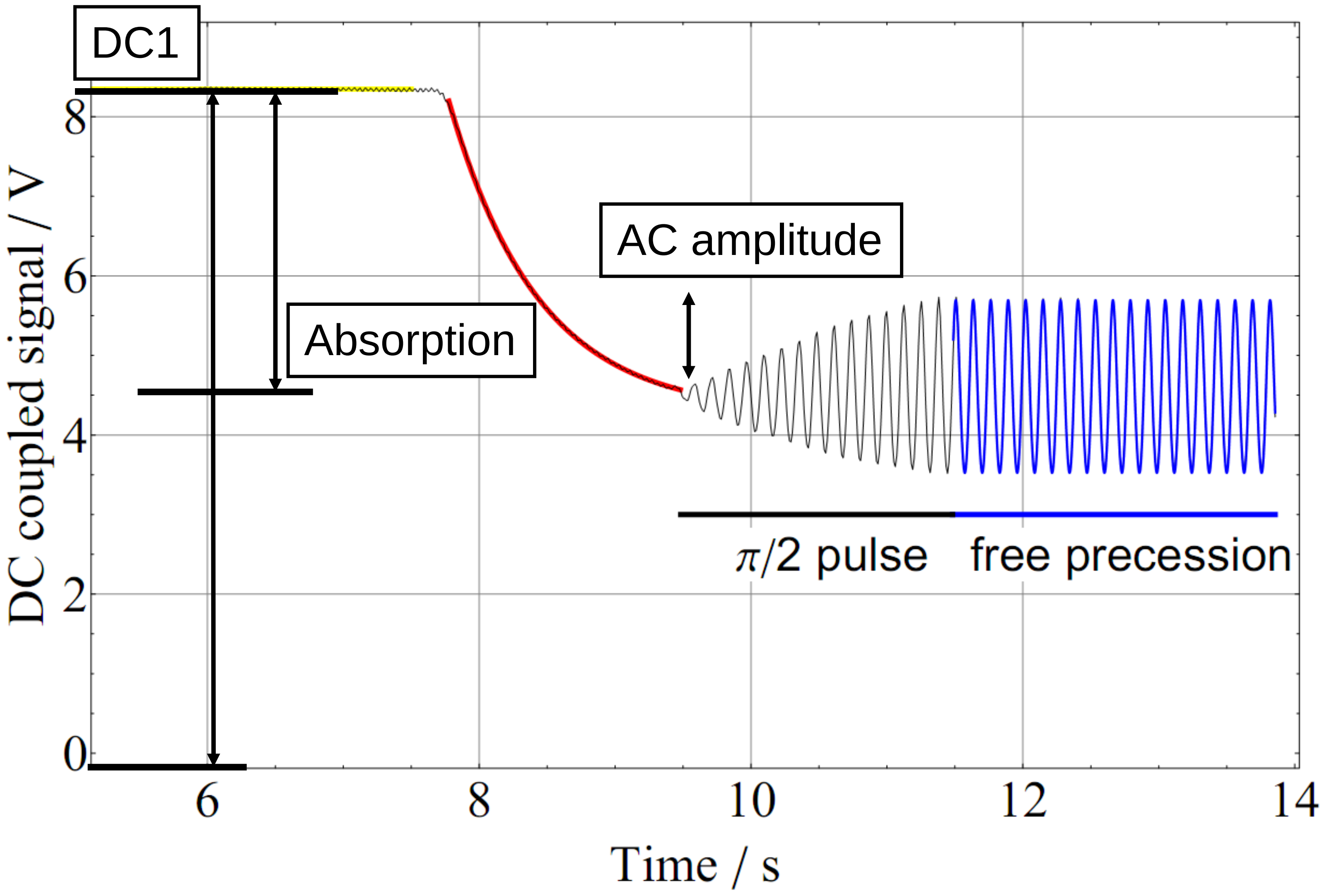


UV laser in nEDM

Jan 2013: first UV laser light in the nEDM setup

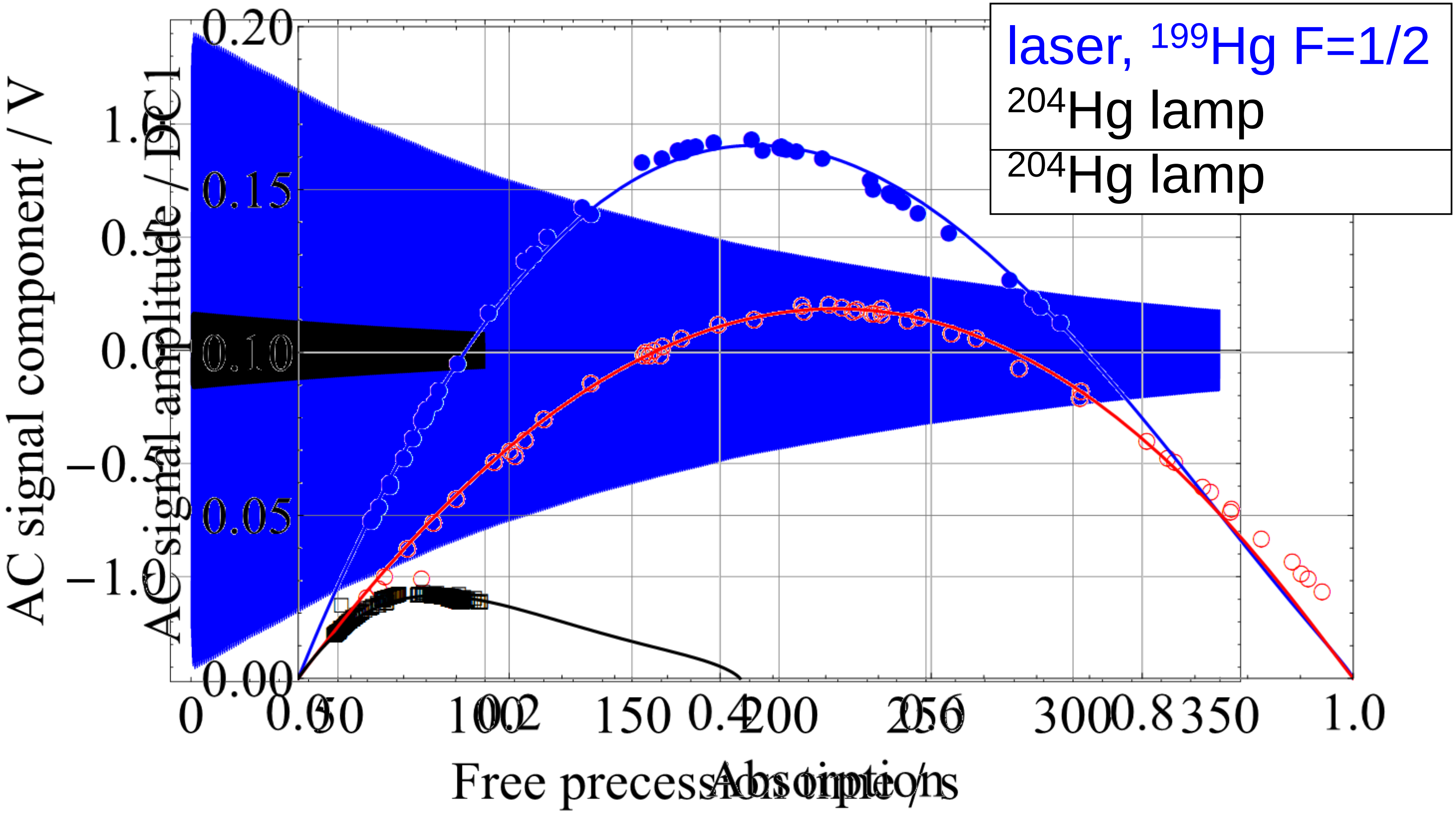
→ transport UV over 50 m multimode fiber to the experiment

Hg co-magnetometer



UV laser: First results

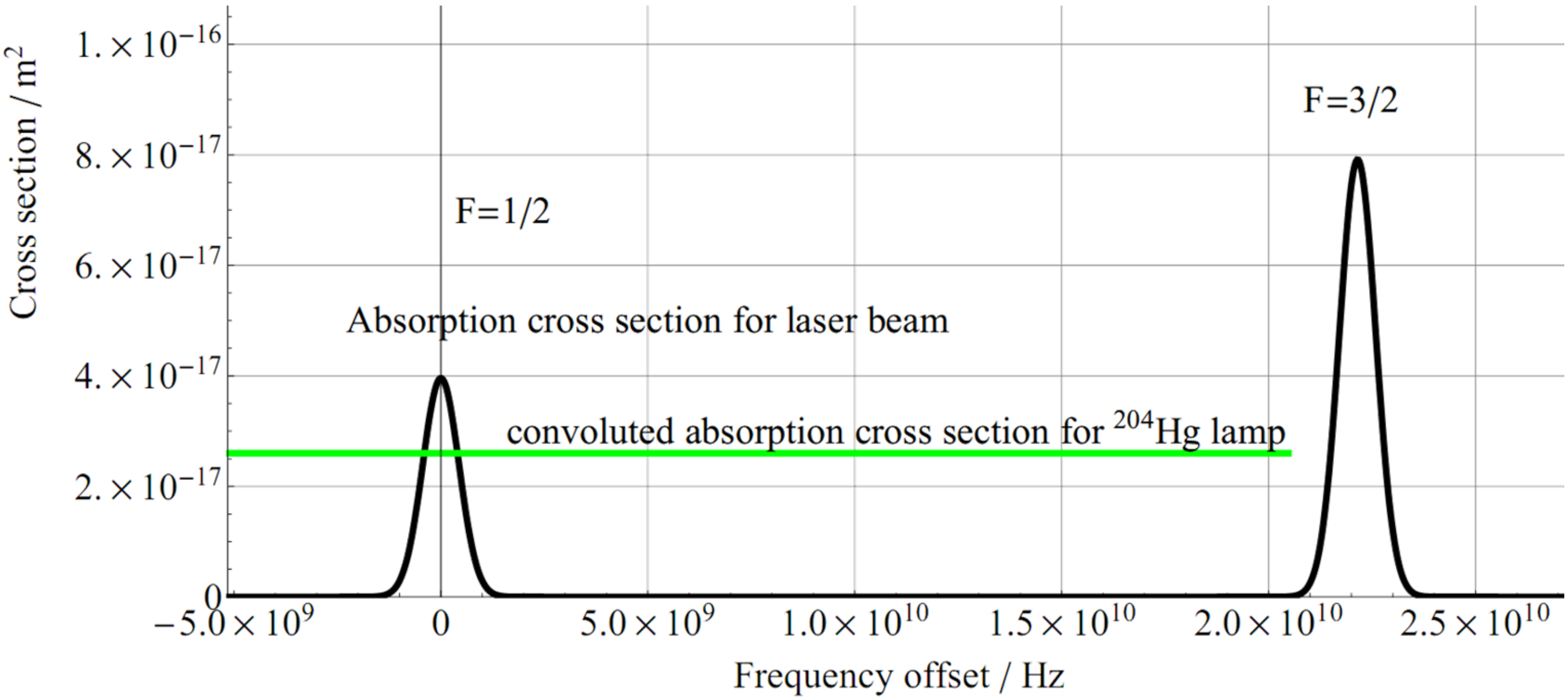
Result: six fold increase of normalized amplitude



Improvement 1

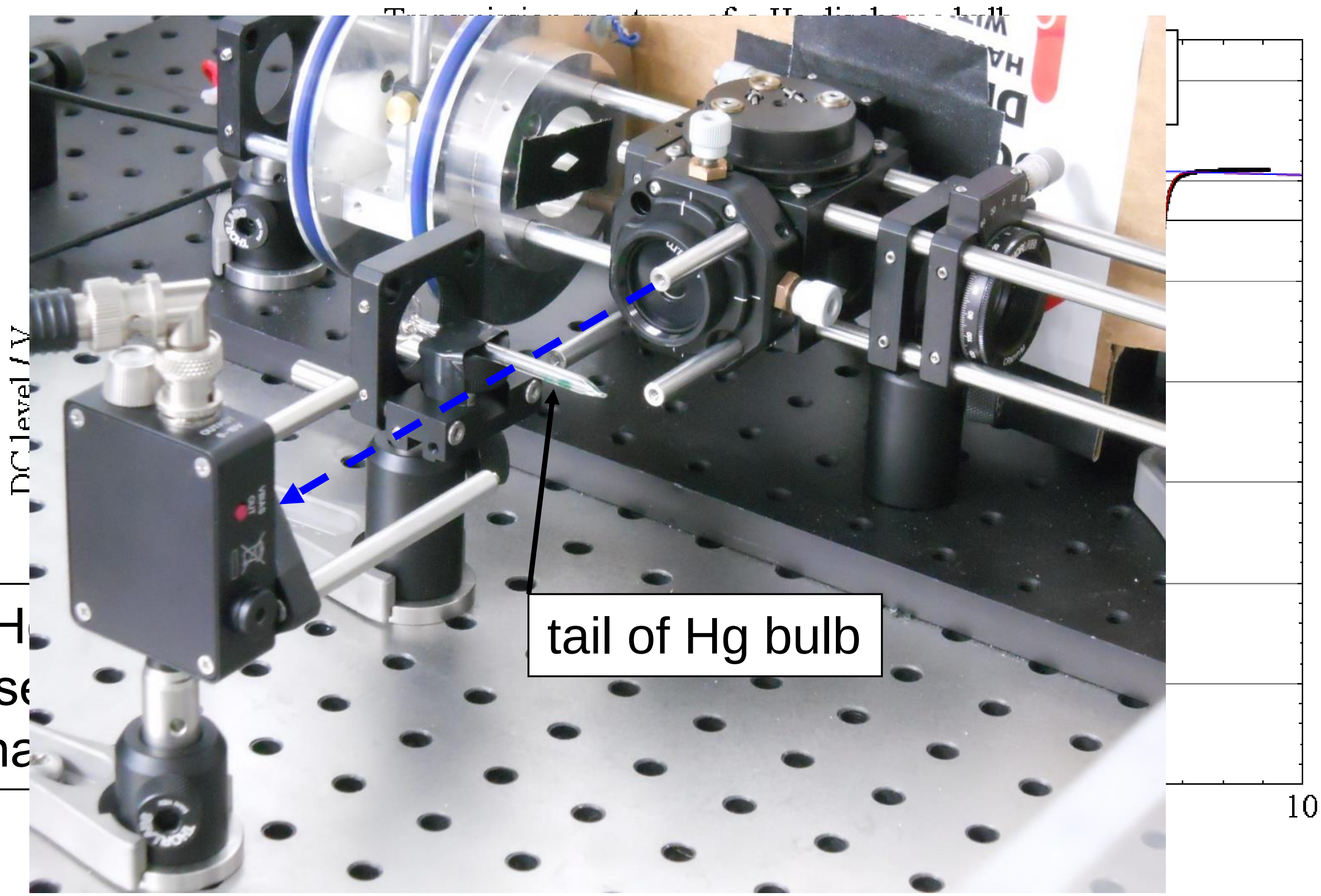
Observed increase in signal amplitude is a combination of several effects

1) no Doppler-broadening of readout beam (factor 1.5)



Improvement 2

2) Isotopic composition of the ^{204}Hg lamp

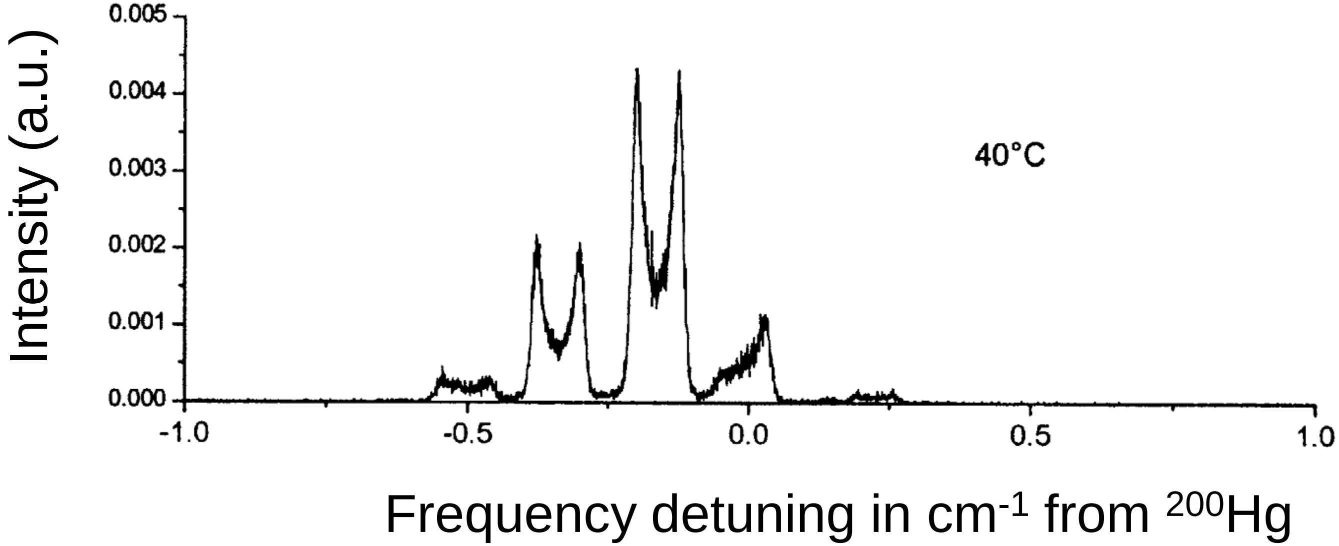


~ 90% ^{204}H
→ strong se
→ more tha

Improvement 3

3) Deformation of ^{204}Hg emission line due to self-absorption

→ reduction of effective absorption cross section,

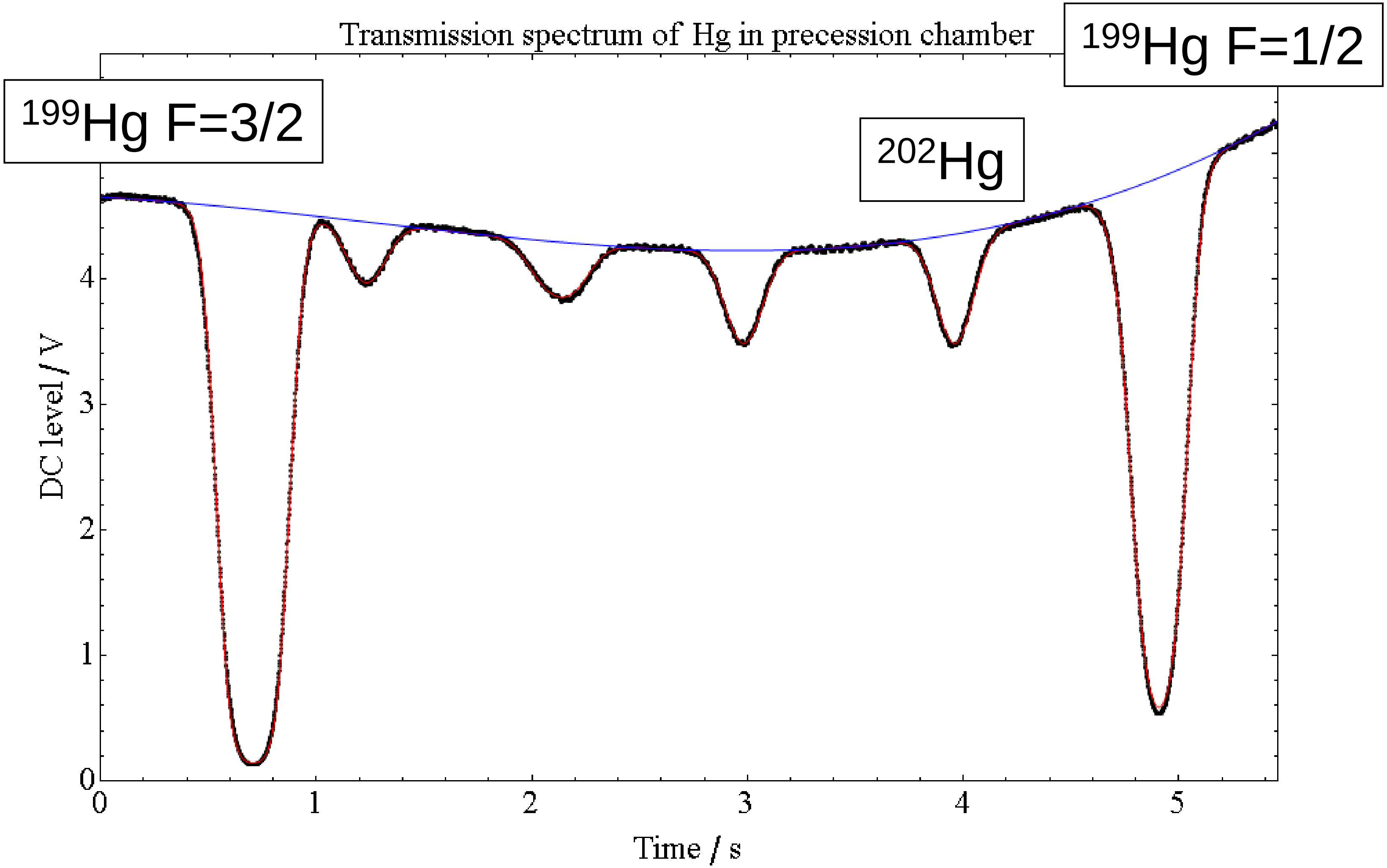


A Monte-Carlo simulation of Hg-Ar discharge lamps with natural isotopic composition (M. Baeva and D. Reiter, Plasma Chemistry and Plasma Processing, Vol. 23, No. 2, June 2003 (2003))

→ we run the Hg bulbs also at 40°C

Improvement 4

4) Isotopic composition of the enriched ^{199}Hg



Improvements summary

The six fold gain in normalized amplitude modulation can be explained by the combination of four factors.

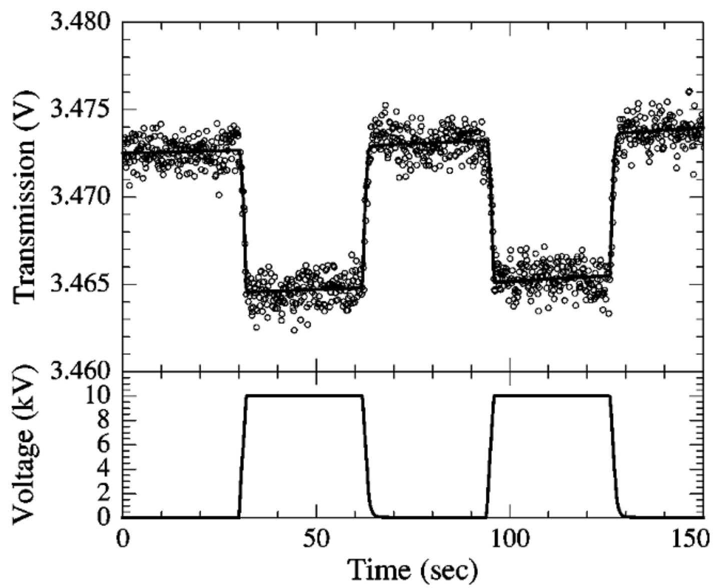
Signal/Noise was improved by a factor of 2-3 with active power stabilization in this first experiment

→ noise pickup on the 50 m of fiber

→ bring the laser closer to the nEDM

New possibilities

In-situ measurement of E field via quadratic Stark shift (Romalis et al.)



Recent improvements of UV single mode (!) fibers may allow stable light distribution on timescale of weeks

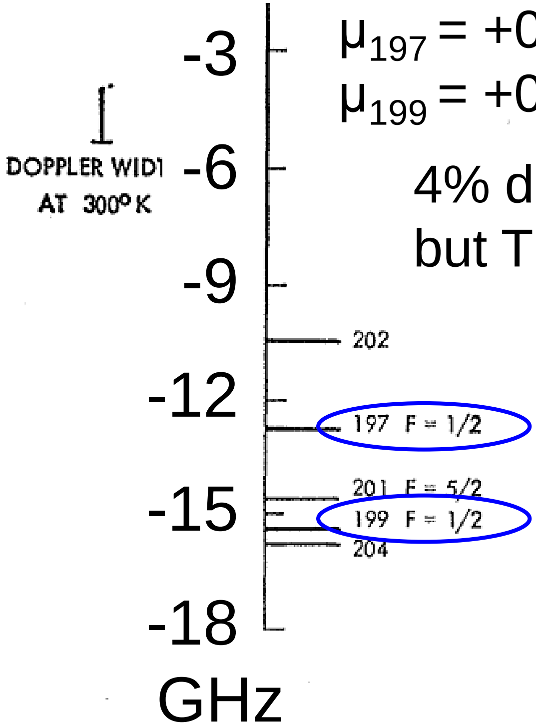
^{197}Hg co-magnetometer ?

$\mu_{197} = +0.5273744$

$\mu_{199} = +0.5058855$

4% different,

but $T_{1/2,197}$ = 64 h



Conclusions

- Setup a frequency stabilized UV laser system for nEDM
- Factor six increase of modulation signal demonstrated

- Superior control of vector light shift effect

- Many new possibilities not in reach with the lamps used so far (e.g. E-field measurement, maybe different isotope).

Thanks to…

- the current and former members of the UCN group at PSI,
  the workshop staff at PSI
- the nEDM collaboration
- the members of the Precision Physics at Low Energy group at ETHZ