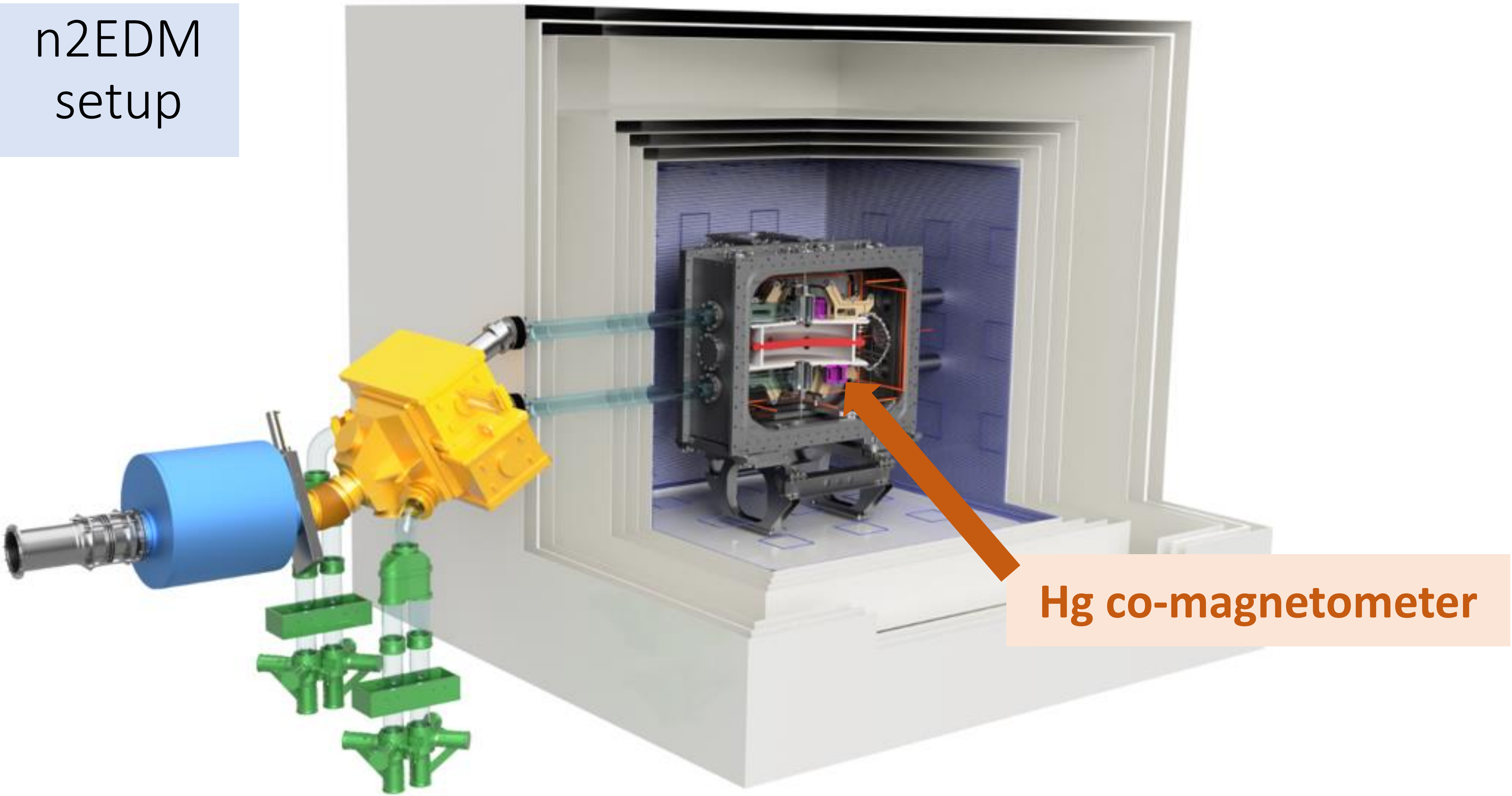
The ^{199}Hg co-magnetometer in the n2EDM experiment

Nov. 7. 2023, nEDM2023 workshop

Wenting Chen

on behalf of nEDM collaboration

n2EDM setup



Principle of the ^{199}Hg co-magnetometer

How do ^{199}Hg atoms join the n2EDM experiment

^{199}Hg atoms precess in the same field as neutrons:

$$f_{\mathrm{Hg}} = \left|\frac{\gamma_{\mathrm{Hg}}}{2\pi} B_0\right|$$

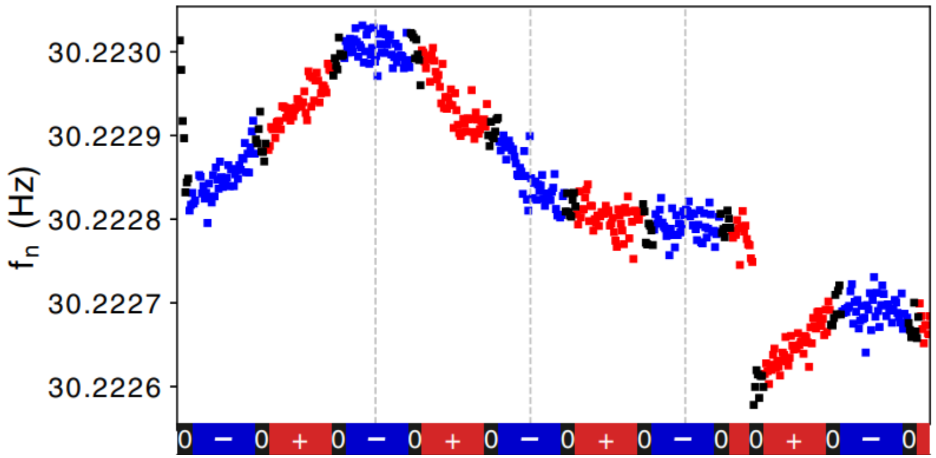
⇒ allows us to cancel the magnetic field drifts!

Use the ratio:

$$R_{\mp} = \frac{f_{\mathrm{n},\mp}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \mp \frac{|E|}{\pi\hbar f_{\mathrm{Hg}}} d_{\mathrm{n}}$$

Then extract

$$d_n = \frac{\pi\hbar \langle f_{\mathrm{Hg}} \rangle}{2|E|}(R_+ - R_-)$$



Neutron frequency as a function of cycle number

C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020).

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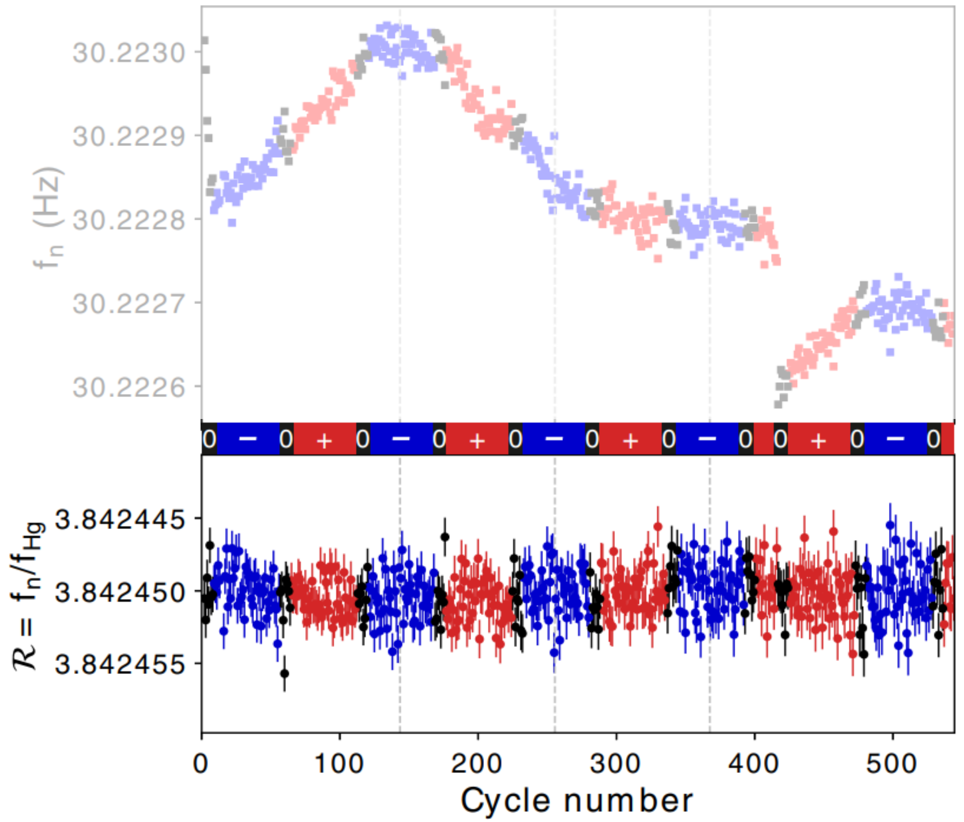
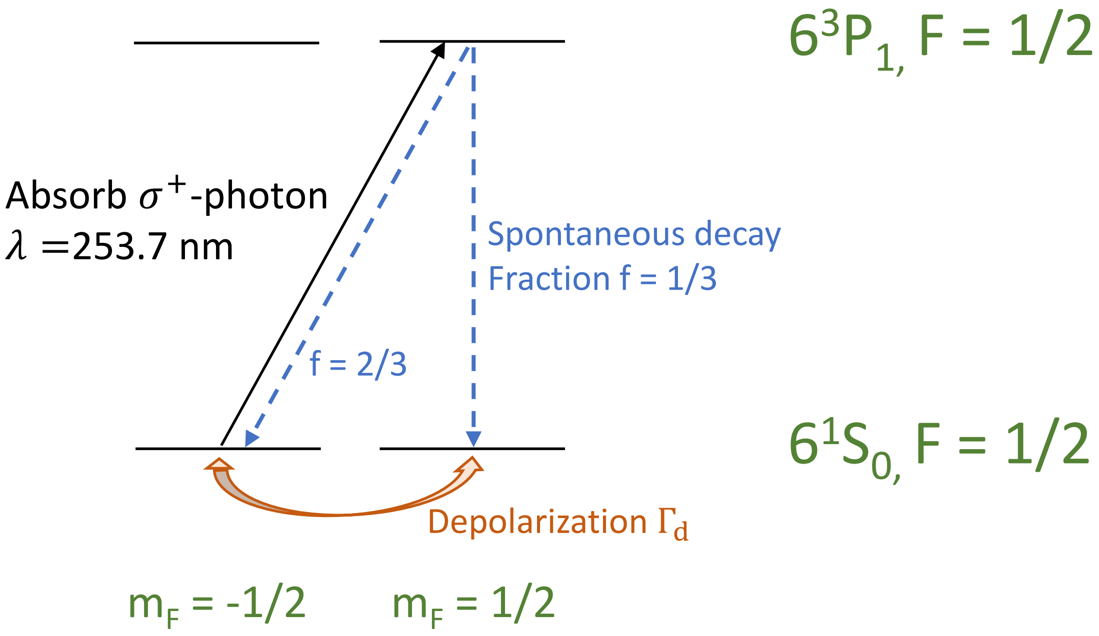


R ratio is nearly free from the magnetic field drifts.

C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020).

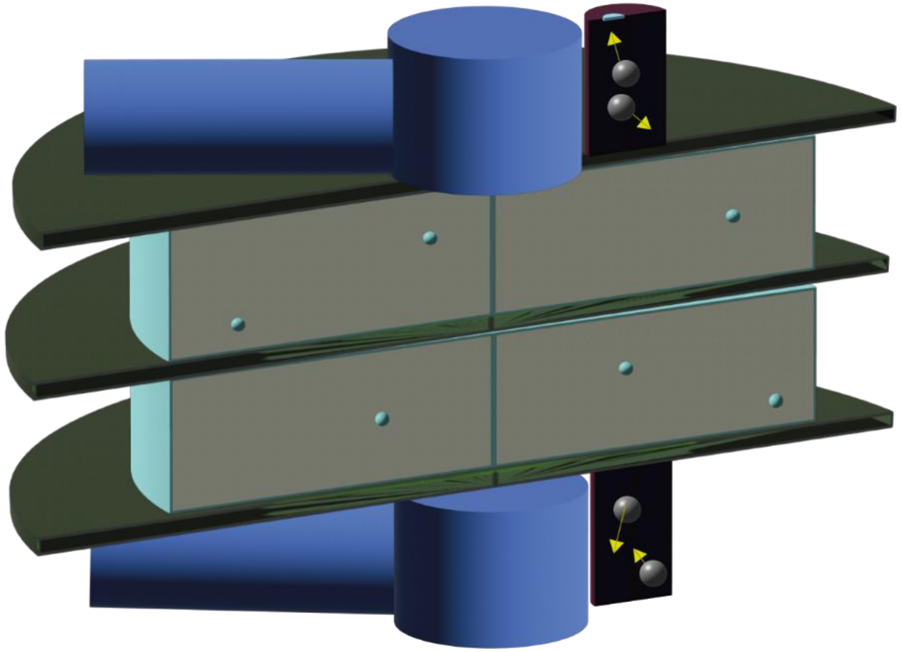
How do we extract $< f_{\mathrm{Hg}} >$?

Use UV laser to spin-polarize the ^{199}Hg atoms.



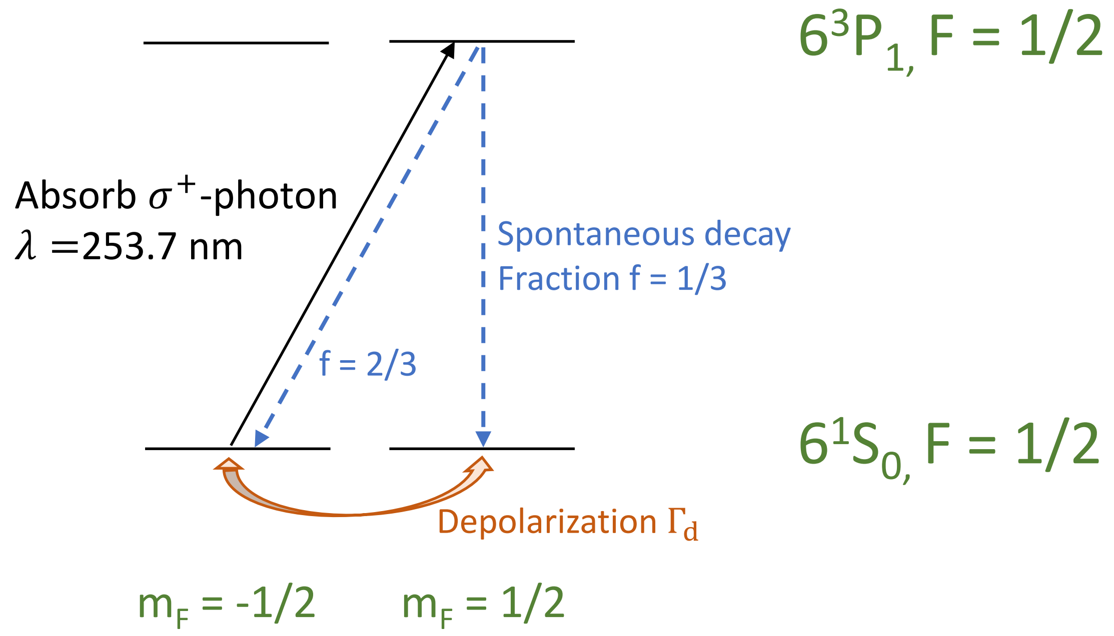
optical pumping of ^{199}Hg atoms

Hg atoms in the polarization chamber

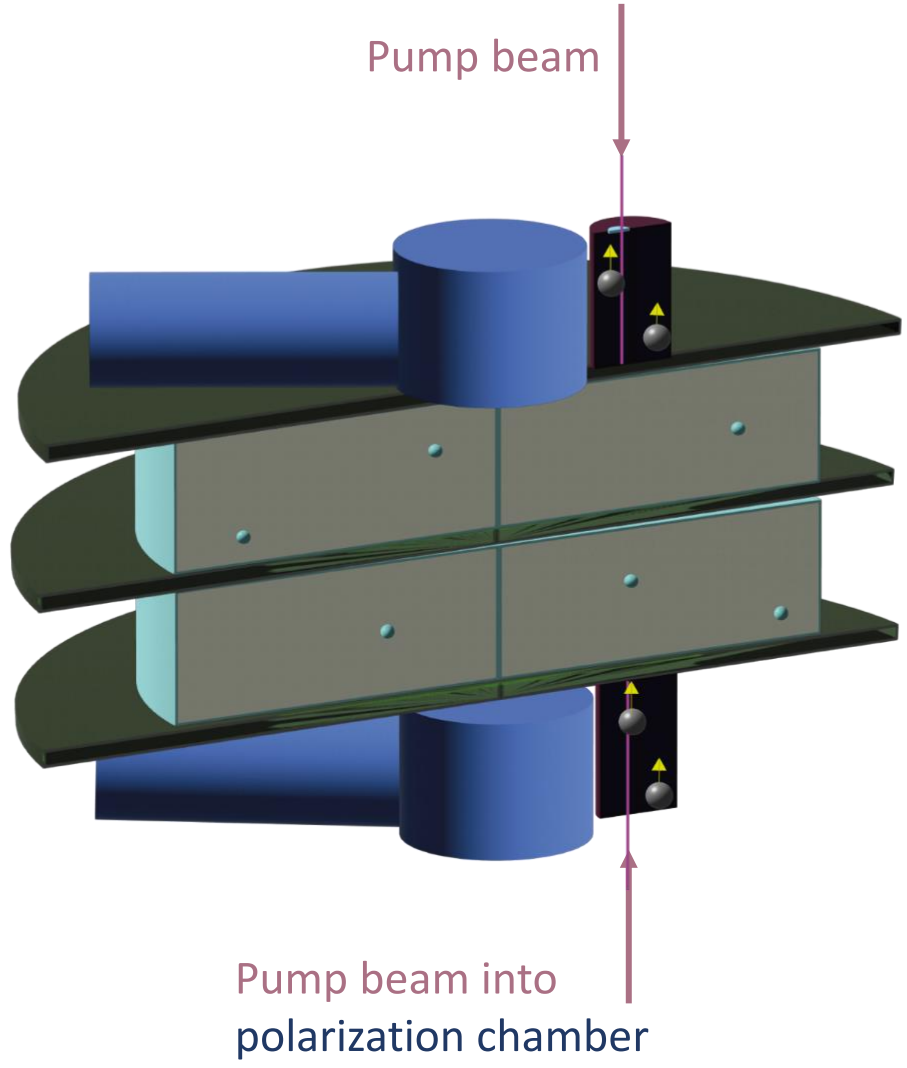


Extraction of f_{Hg} - optical pumping

Use UV laser to spin-polarize the ^{199}Hg atoms.



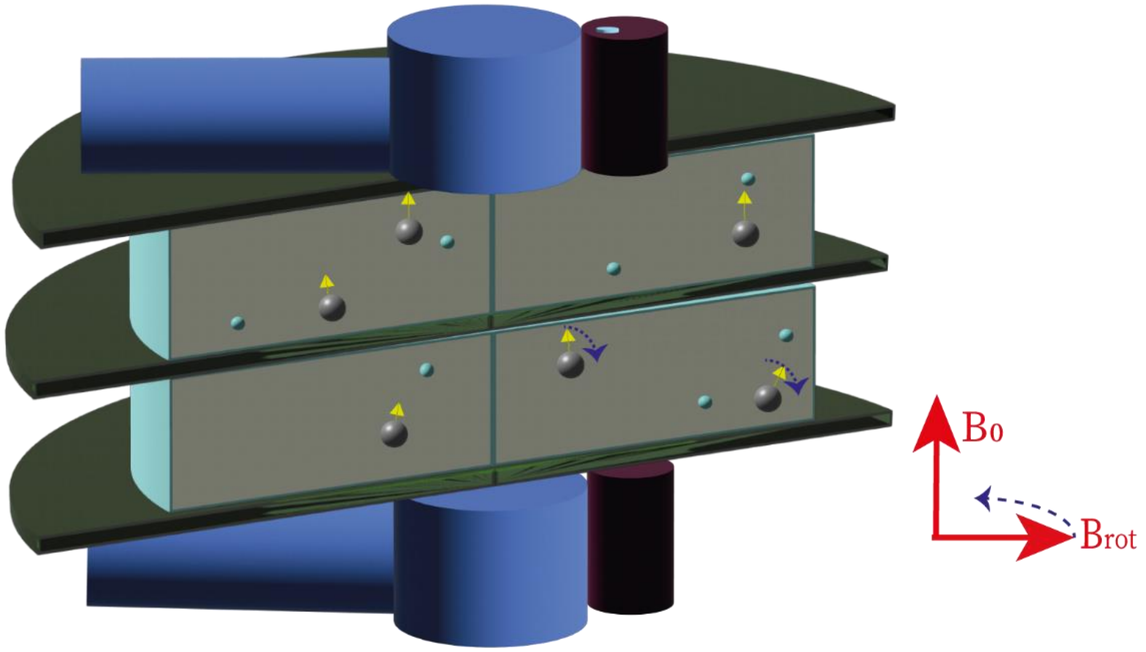
optical pumping of ^{199}Hg atoms



Extraction of f_{Hg} - Hg spin-flip

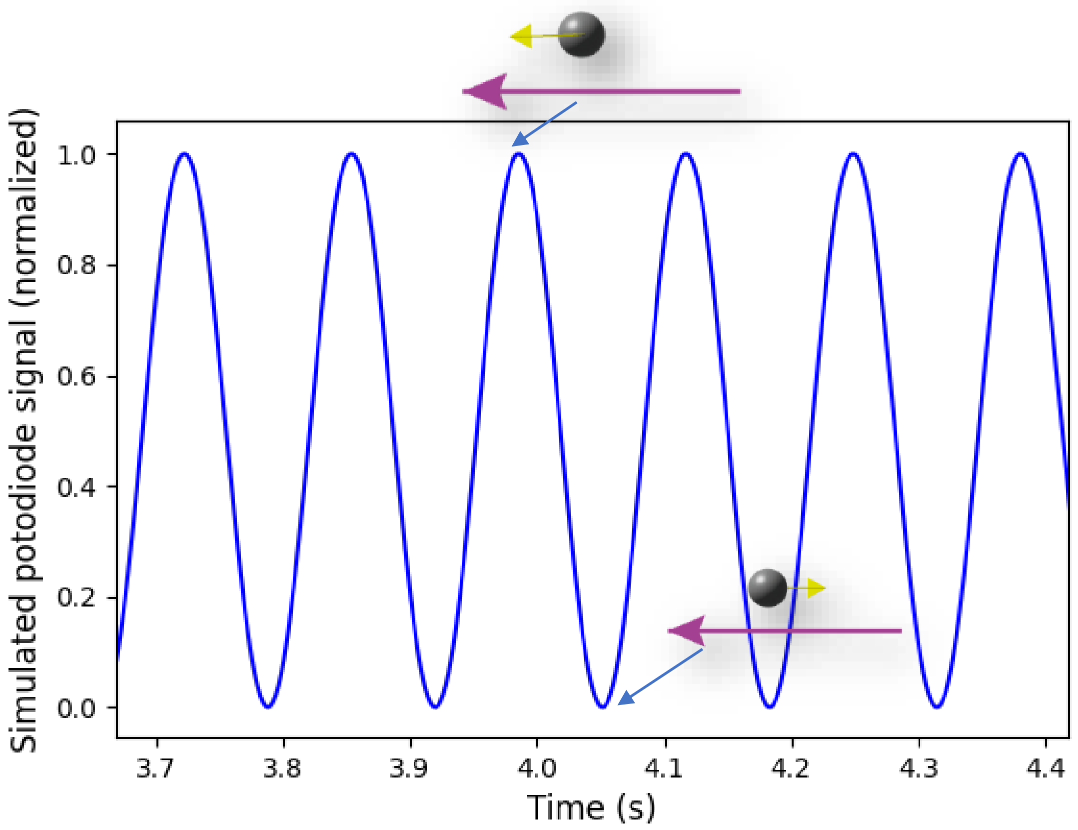
- Release the polarized atoms into precession chambers.

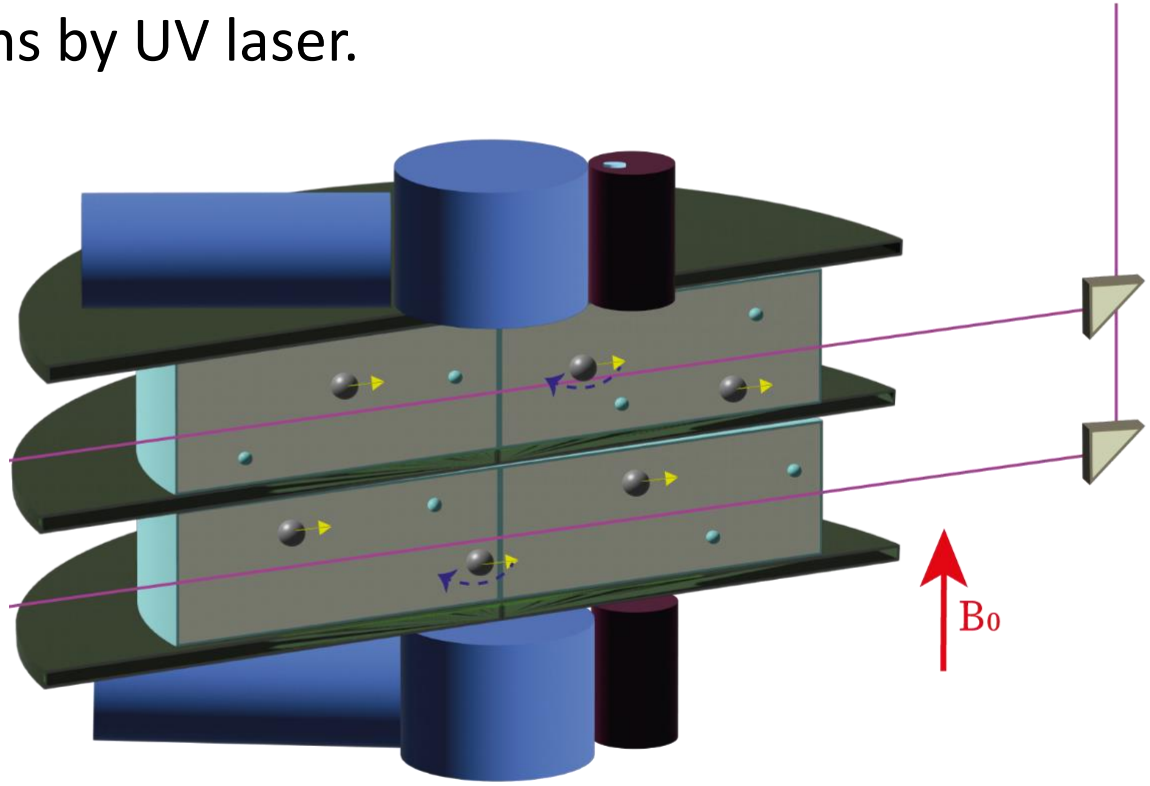
- Apply $\frac{\pi}{2}$ pulse to flip the ^{199}Hg spin by 90°.



Extraction of f_{Hg} - signal probing

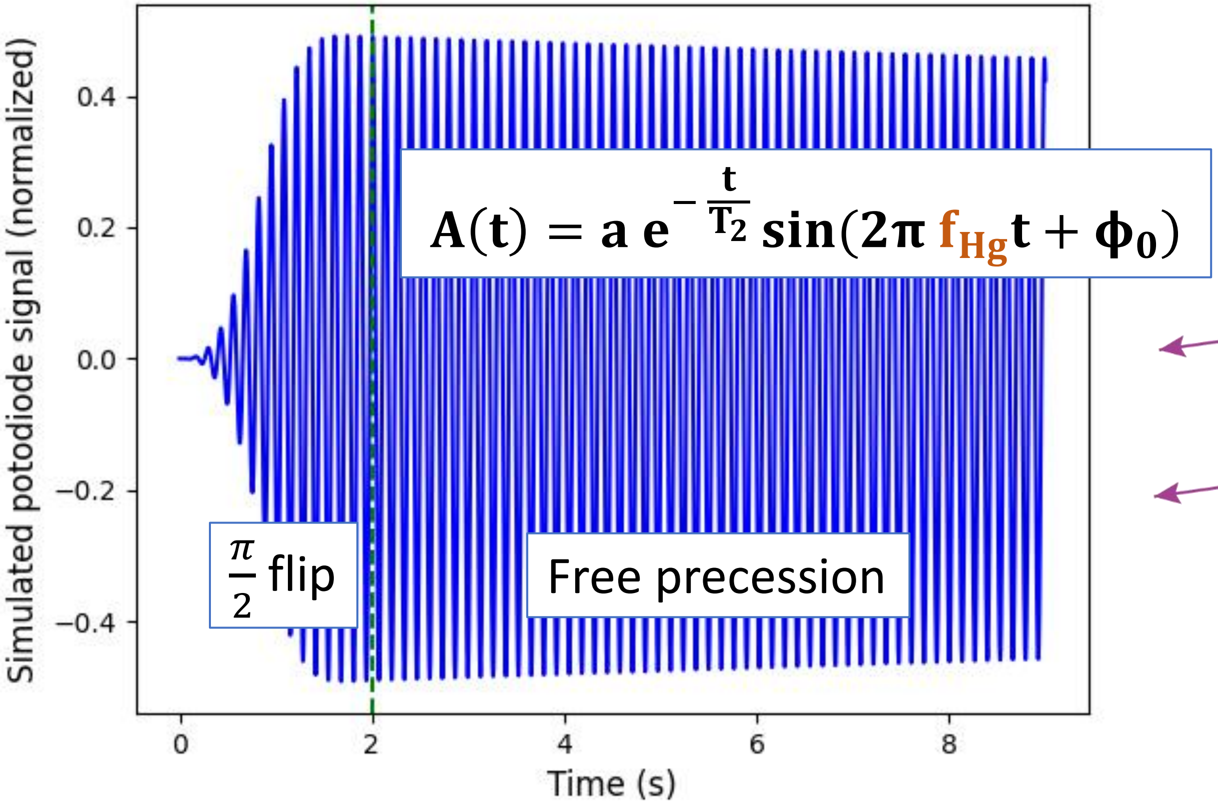
Probe the free precession signal of ^{199}Hg atoms by UV laser.

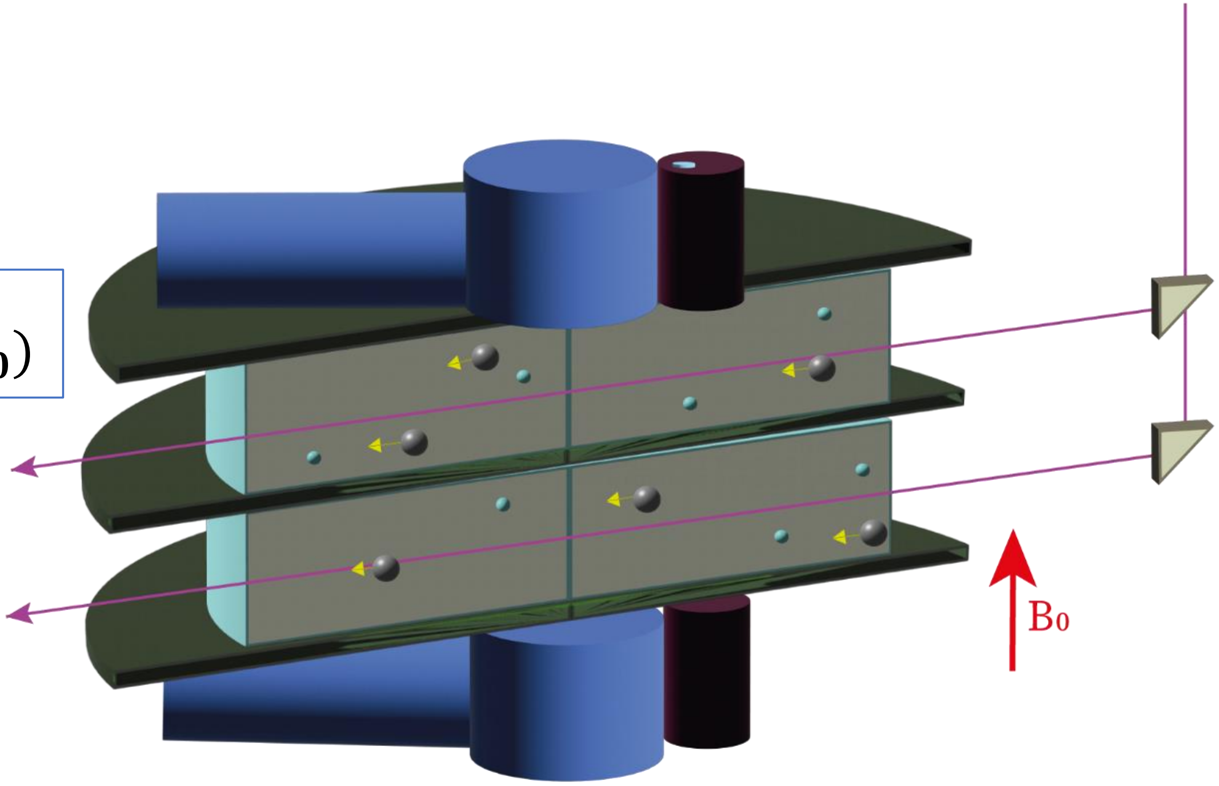




Extraction of f_{Hg} - data analysis

Analyze the free precession data

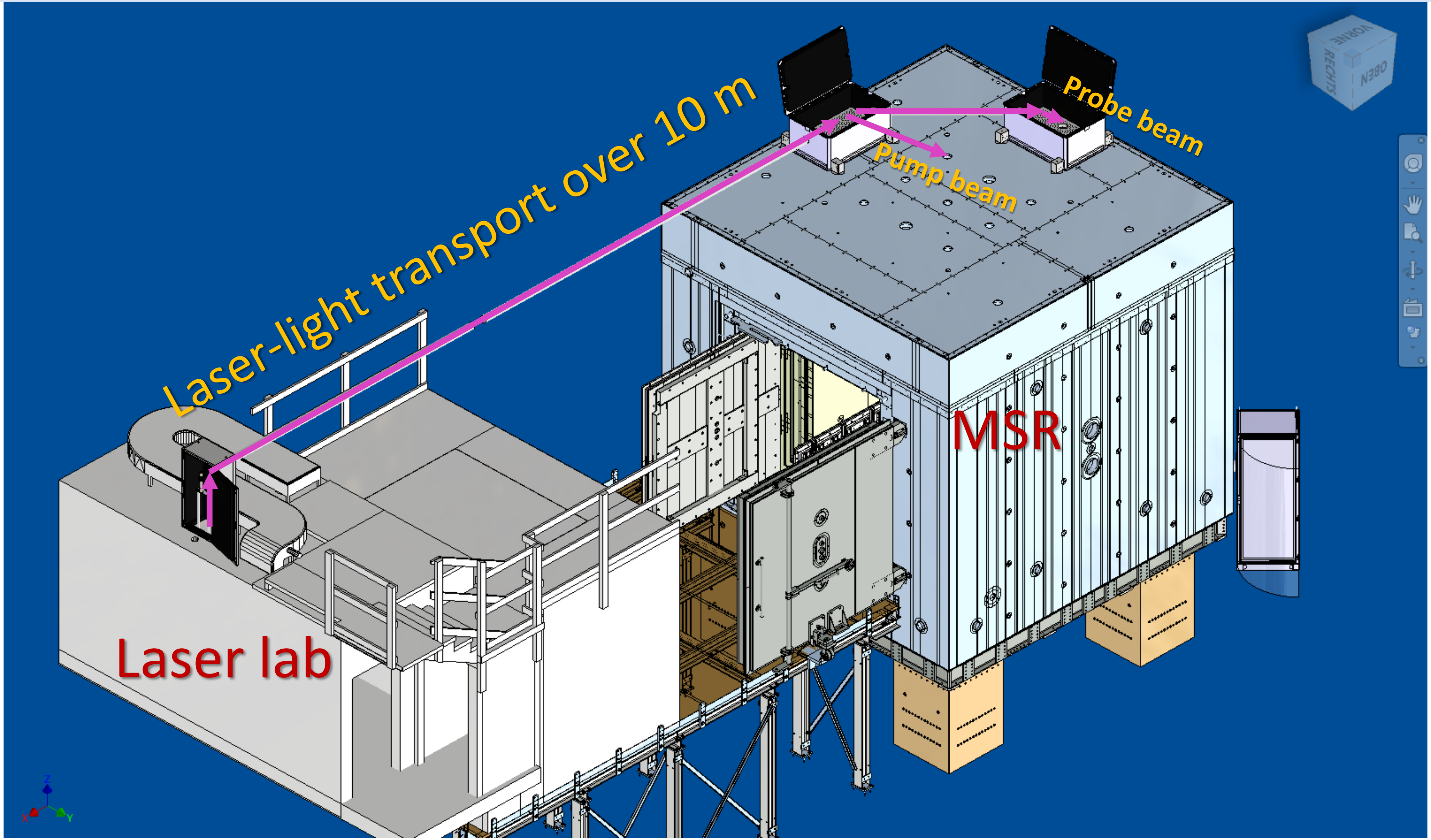




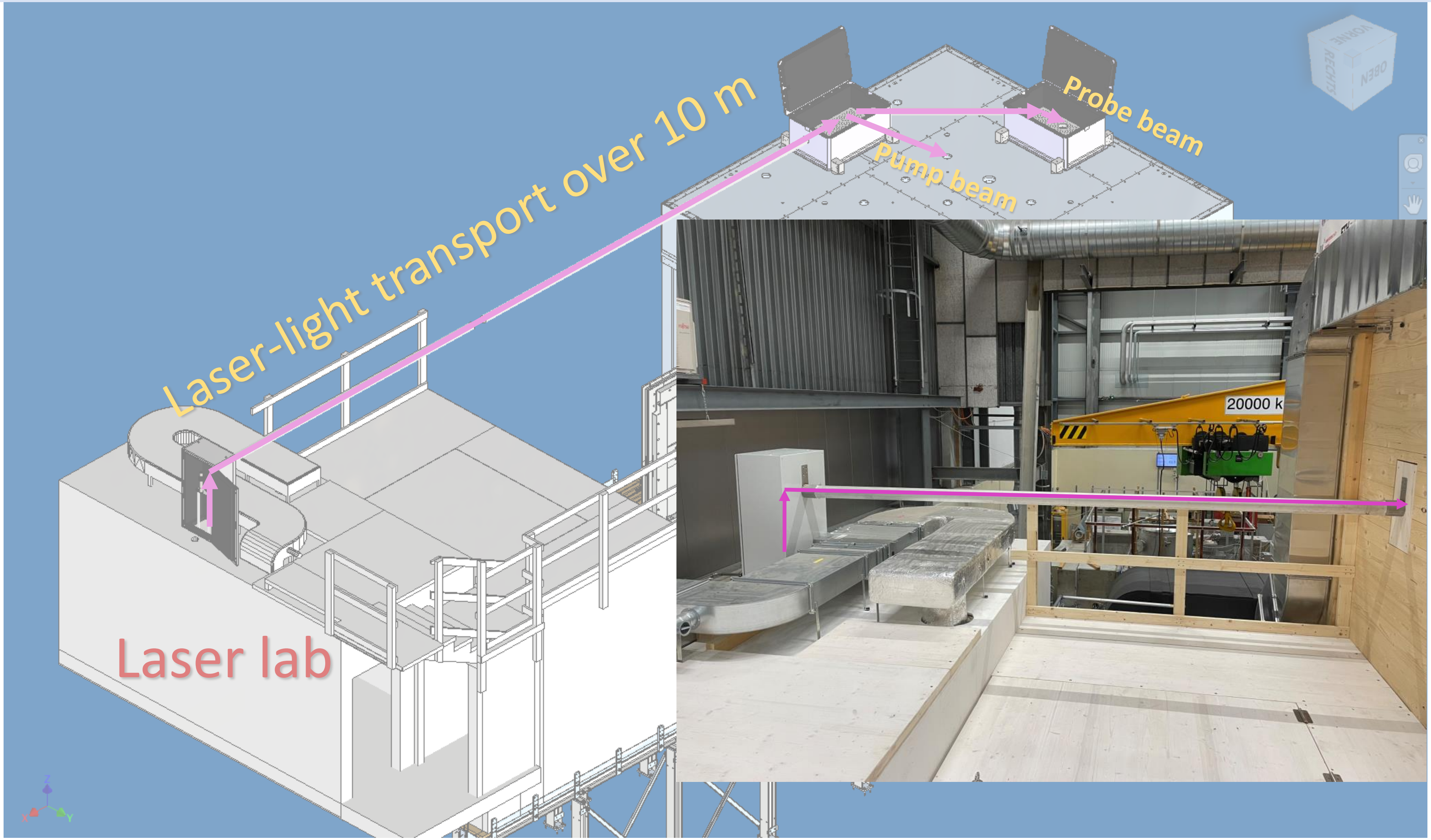
Simulated photodiode signal probing the Hg spin precession

Hardware Status

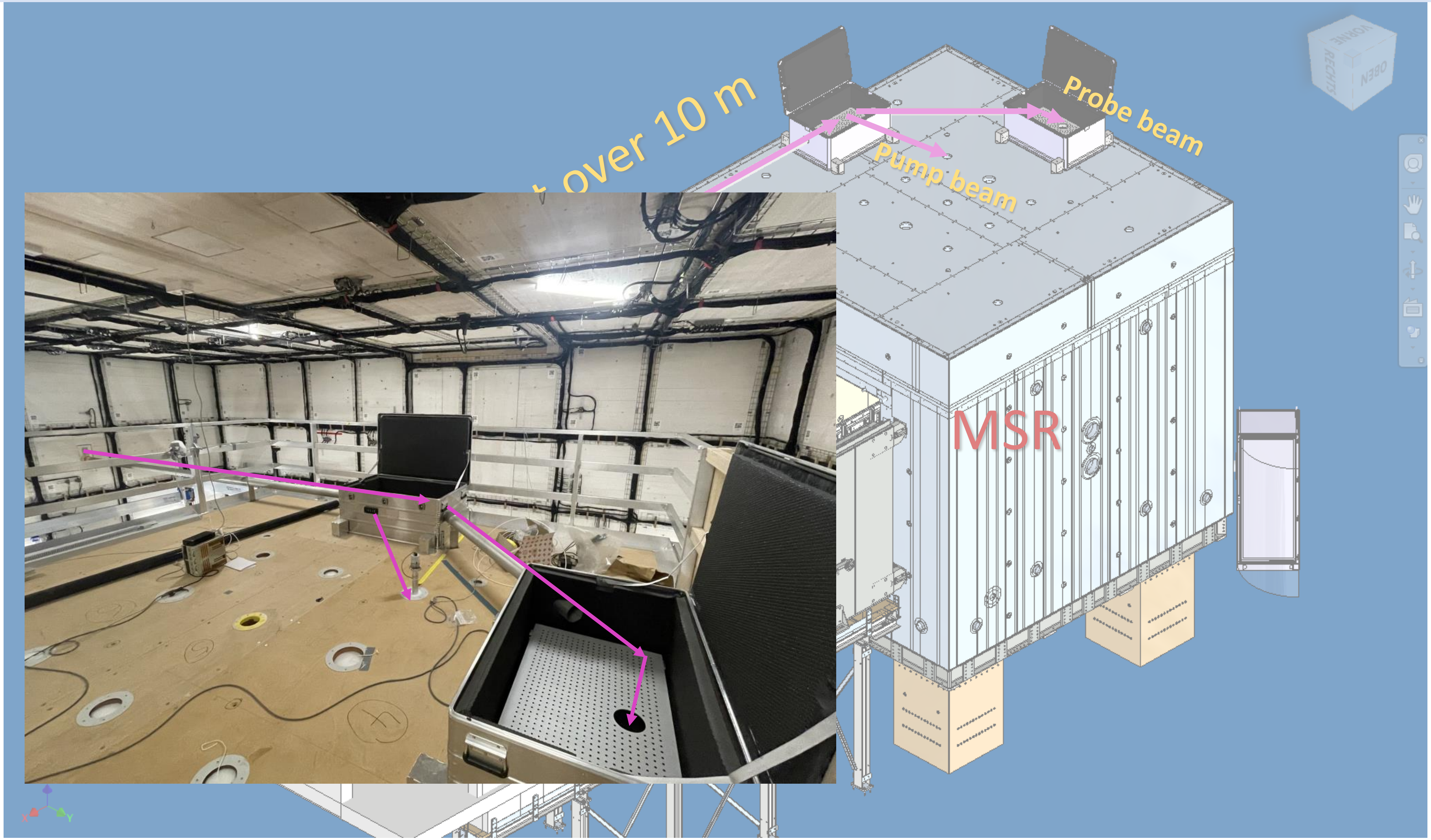
Laser-light path



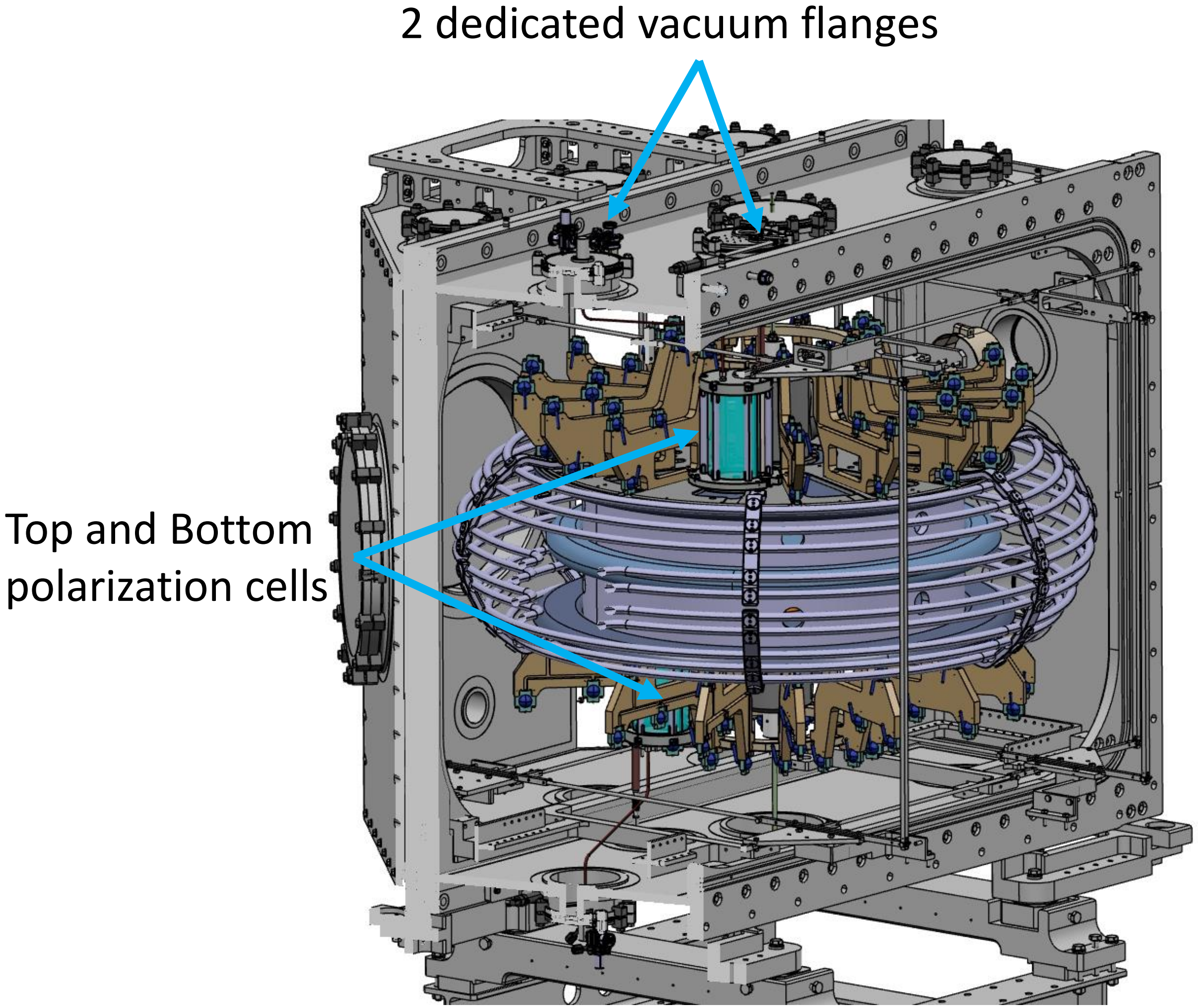
Laser-light path



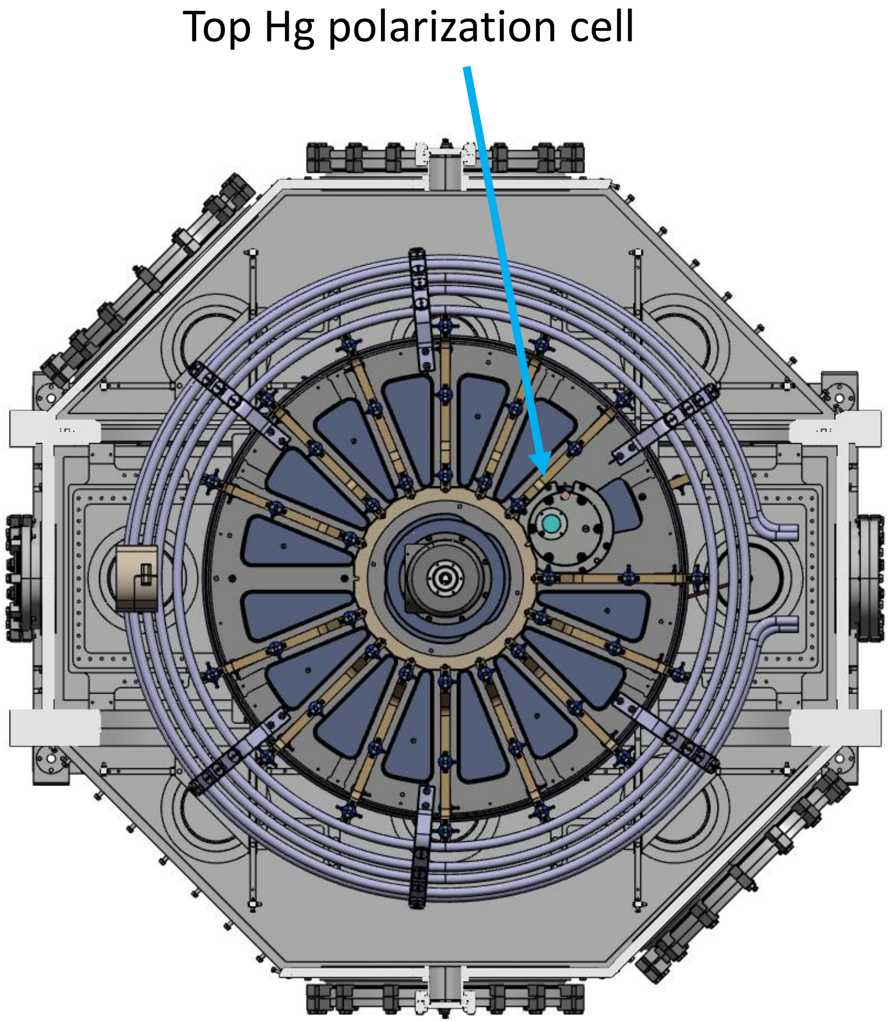
Laser-light path



Overview of the ^{199}Hg co-magnetometer

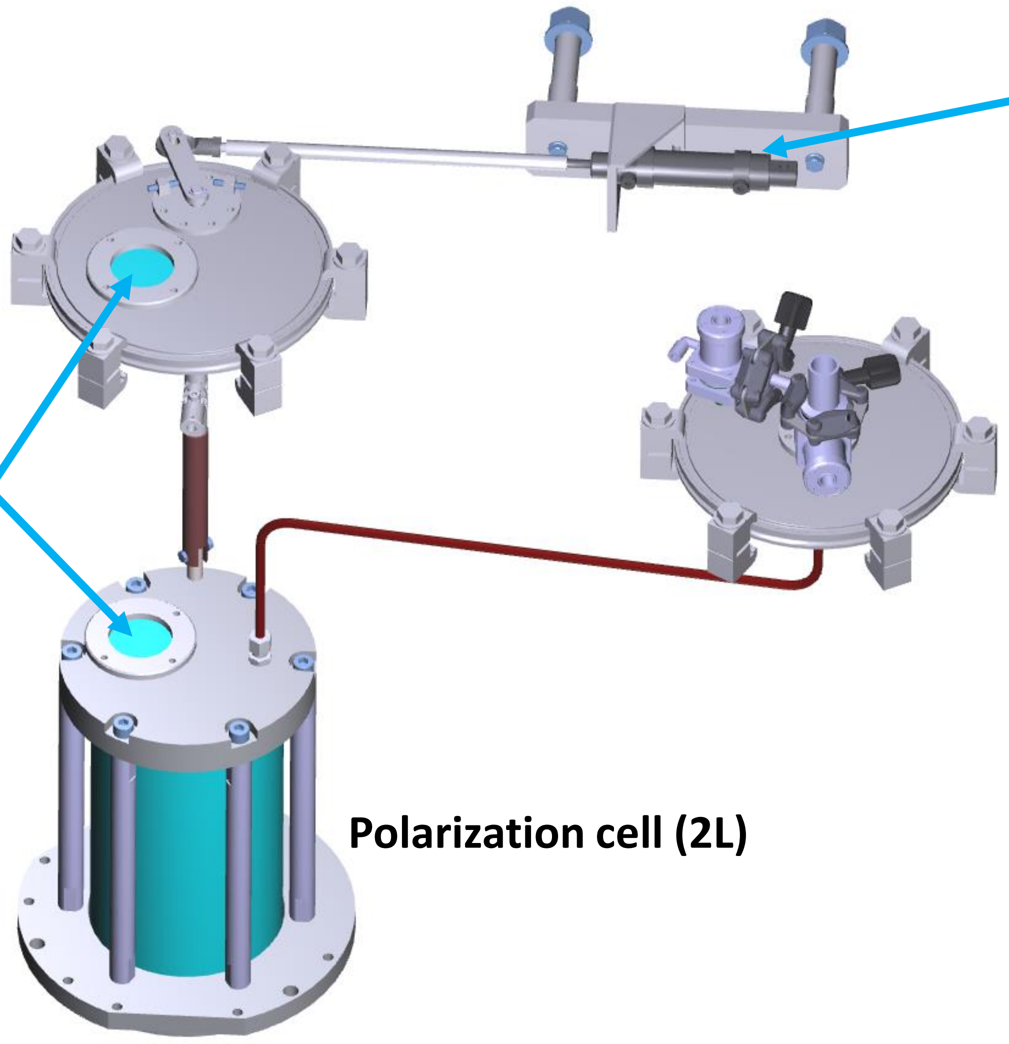


Double precession chamber stack



Top view

Polarization cell and interfaces



Pneumatic jack

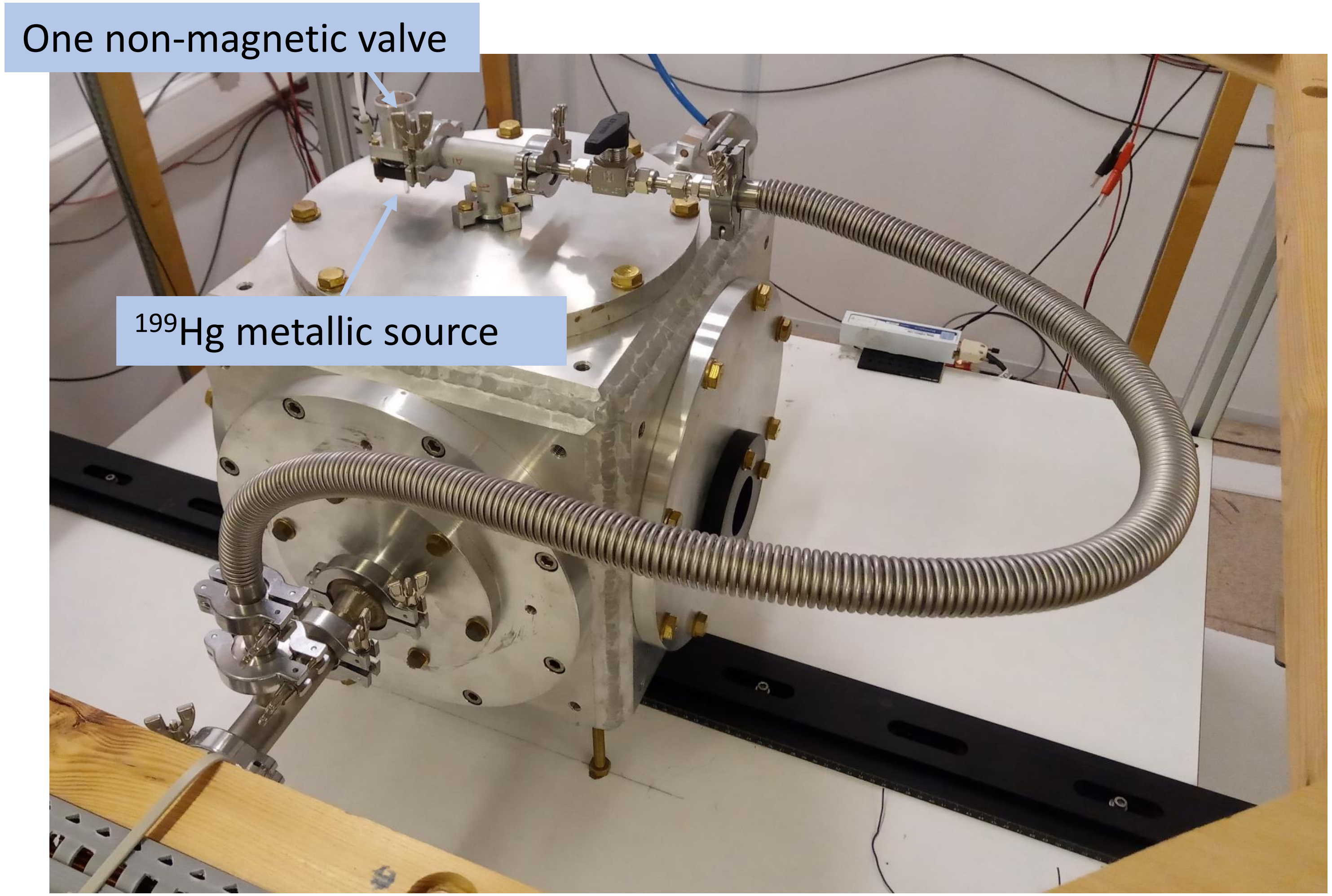
Vacuum flange 1
- Hg valve operation
- Pump beam

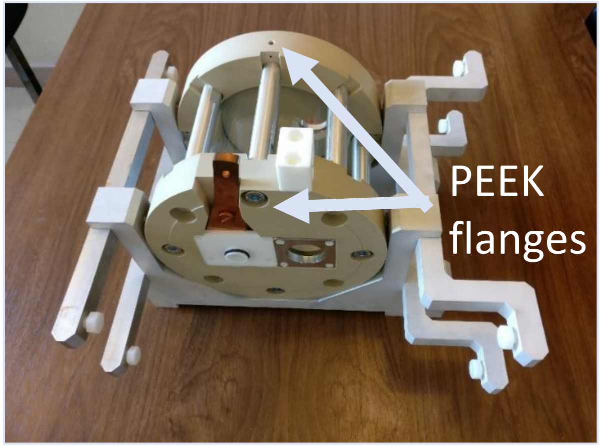
Optical windows
(Pump beam)

Vacuum flange 2
- Hg injection control
- O_2 inlet + vacuum system

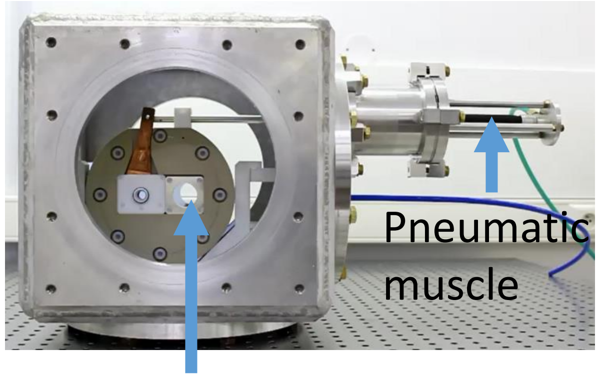
Polarization cell (2L)

Hg cell test setup



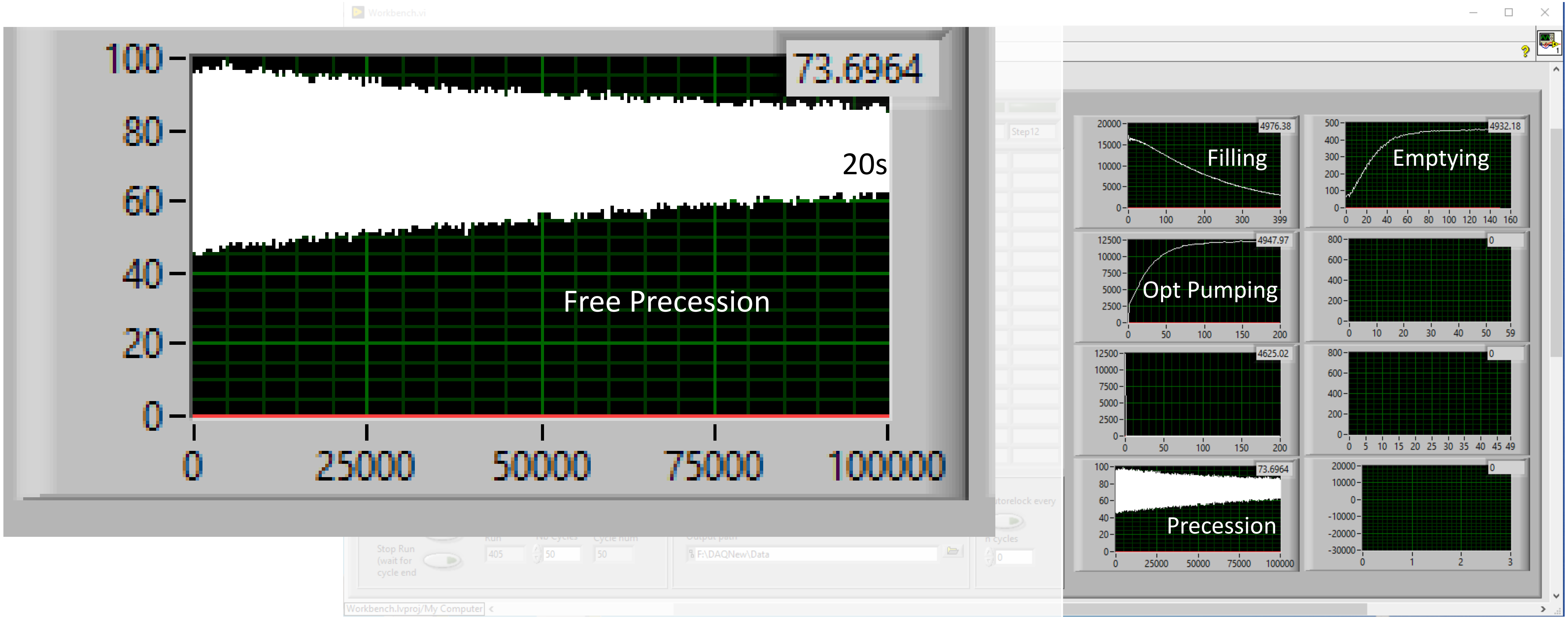


Hg cell prototype



Optical Windows for laser

Hg test with the prototype



DAQ interface using a Hg cell prototype in Grenoble

Stabilization of the system

Challenges:

A long beam-path causes instability

Need to lock to the resonance of $^{199}Hg\ 6^1S_0 \rightarrow 6^3P_1$ transition

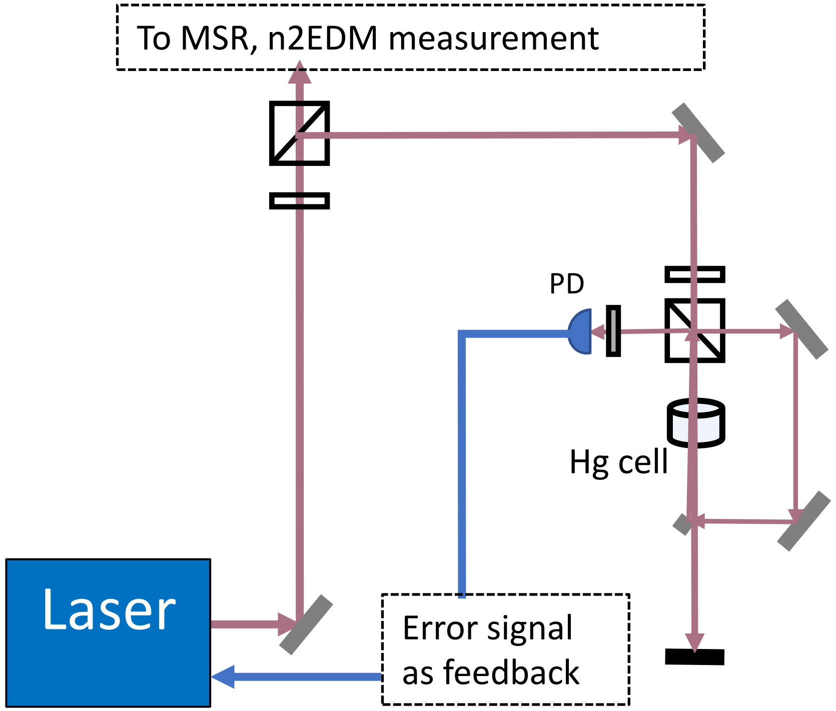
→ 3 kinds of stabilization are essential!

- Frequency locking
- Position stabilization to avoid beam moving during measurement.
- Power stabilization to avoid power drifts in signal probing.

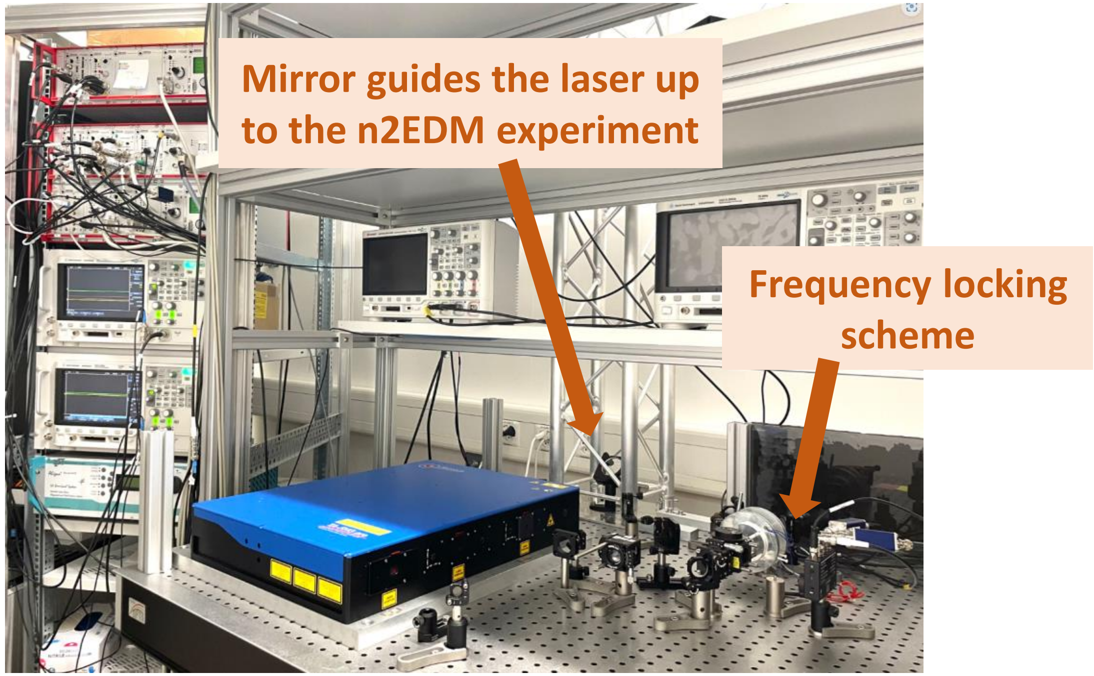
→ For stabilization we always need a feedback loop.

Frequency locking scheme

Use Doppler-free saturated spectroscopy with frequency modulation

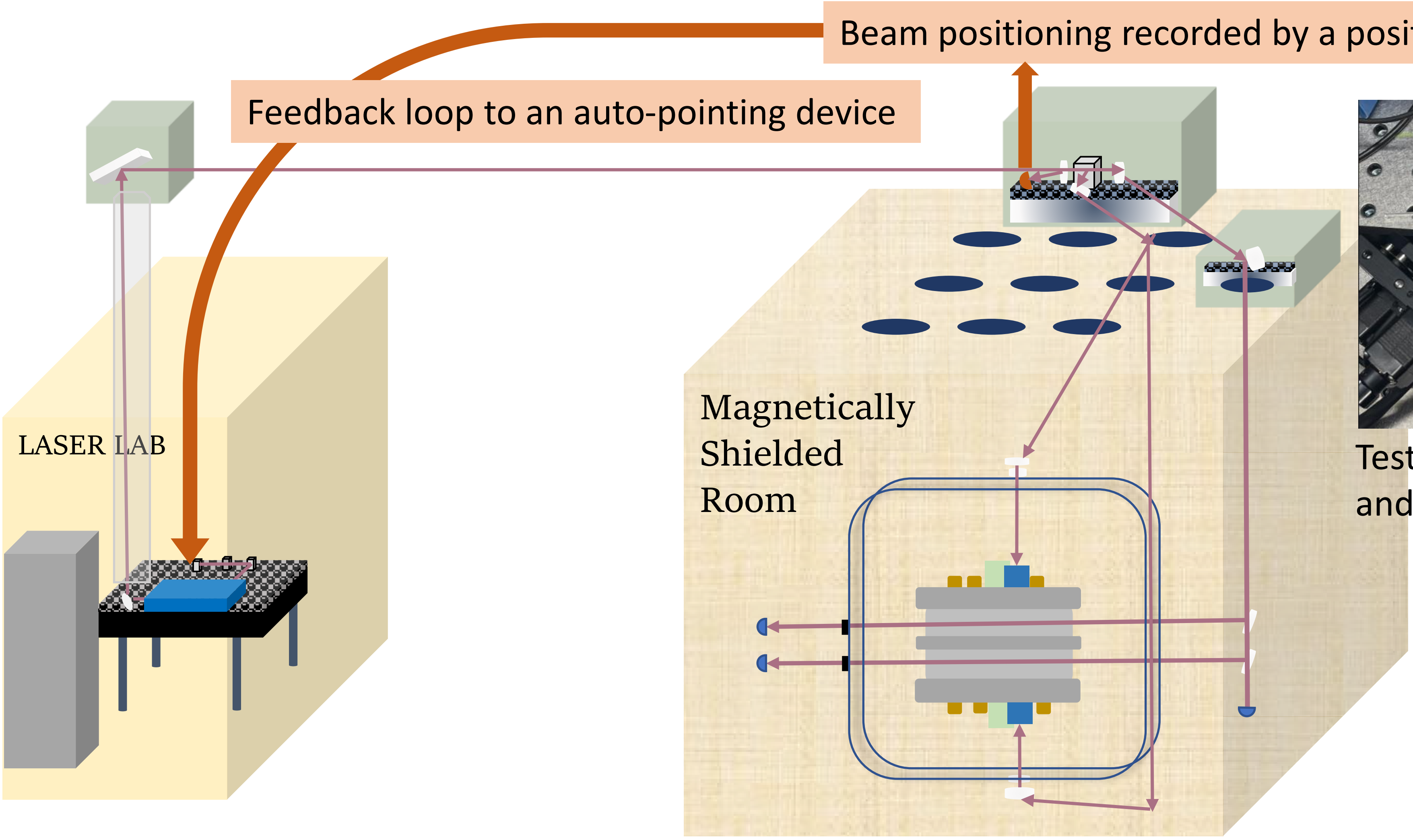


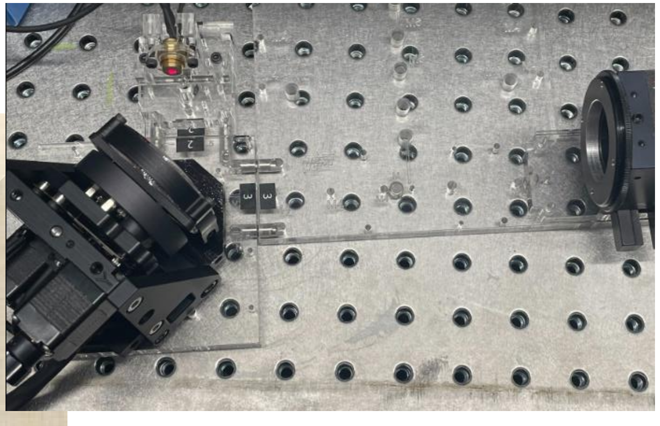
Feedback loop to the diode laser



A photo of the laser table

Positioning stabilization

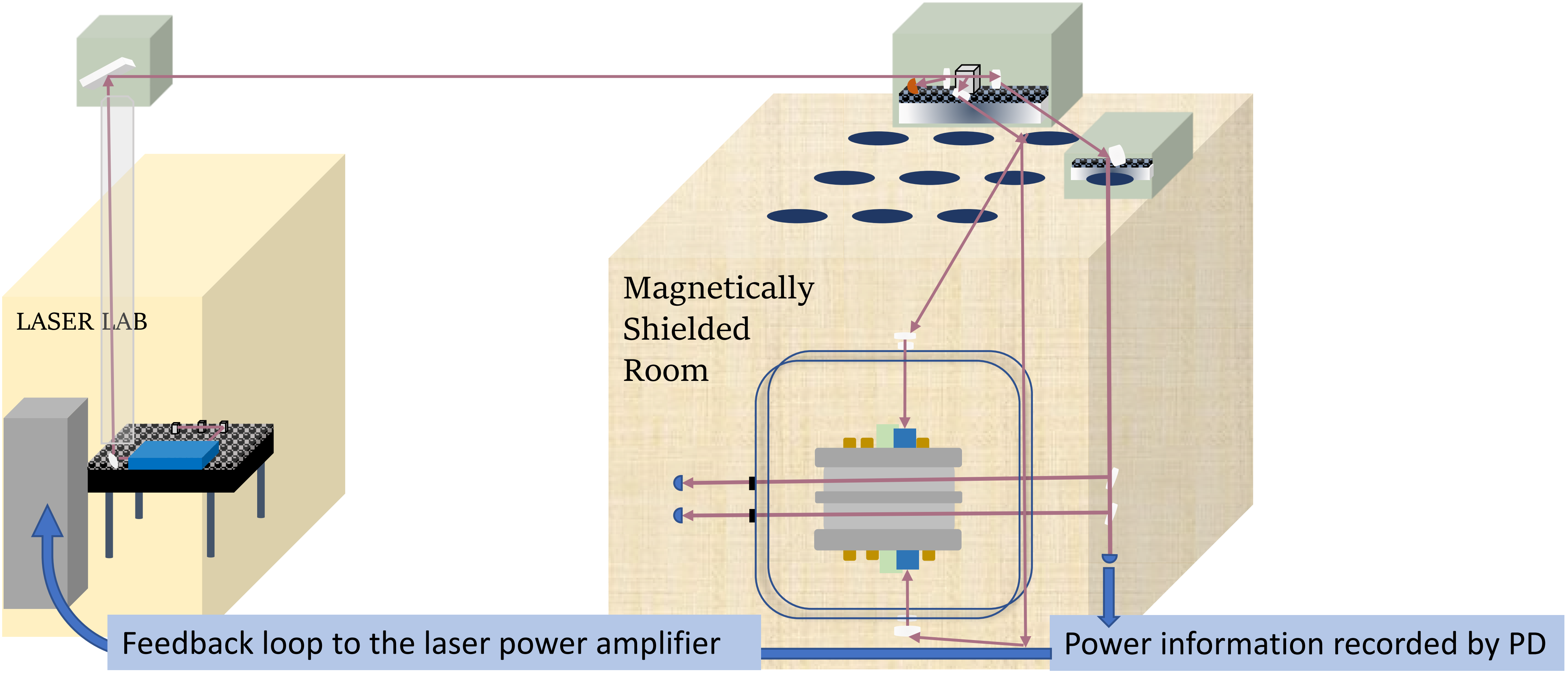




Test setup with a motorized mirror and a PSD

Power stabilization

Signal detection close to the shot-noise limit has been demonstrated.



Hg related systematics

Study on systematic effects

$$R_{\mp} = \frac{f_{\mathrm{n},\mp}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \mp \frac{|E|}{\pi\hbar f_{\mathrm{Hg}}} d_{\mathrm{n}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| (1 \mp \delta_{\mathrm{nEDM}}^{\mathrm{true}})$$

$$R_{\mp} = \frac{f_{\mathrm{n},\mp}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| (1 \mp \delta_{\mathrm{nEDM}}^{\mathrm{true}} \mp \delta_{\mathrm{Hg}\to\mathrm{nEDM}}^{\mathrm{true}} + \delta_{\mathrm{nEDM},\mp}^{\mathrm{false}} + \delta_{\mathrm{Hg}\to\mathrm{nEDM},\mp}^{\mathrm{false}} + \delta_{\mp}^{\mathrm{others}})$$

For the extraction of nEDM: $d_n = \frac{\pi\hbar <f_{\mathrm{Hg}}>}{2|E|}(R_+ - R_-) \Rightarrow$ some δs will be canceled if $\delta_- = \delta_+$.

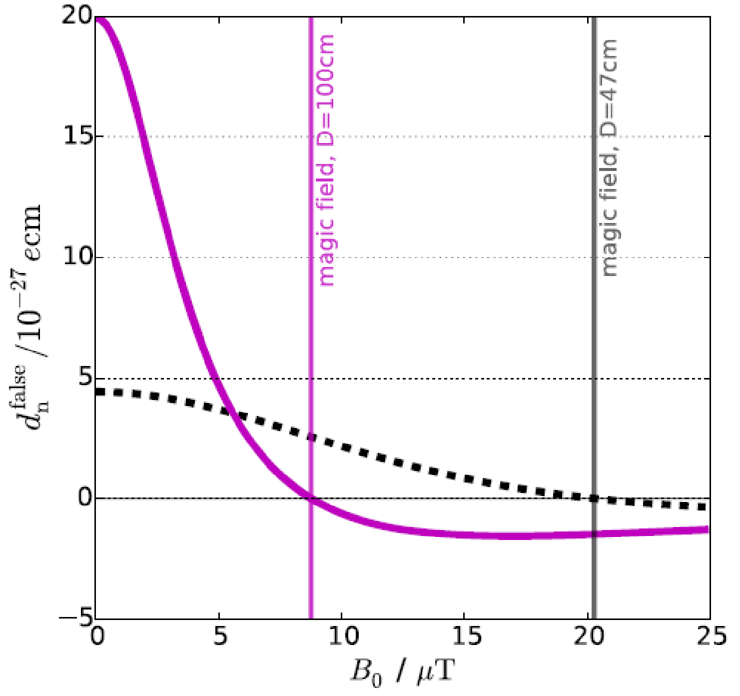
$v \times E$ effect

Dominant term $\delta^{\text{false}}_{\text{nEDM,m,}\mp} + \delta^{\text{false}}_{\text{Hg}\rightarrow\text{nEDM,m,}\mp}$ from the motional magnetic field:

$$\overrightarrow{B_m} = \vec{E} \times \vec{v} \,/c^2,$$

Which leads to a shift $\delta f = \delta f_{B^2} + \delta f_{BE} + \delta f_{E^2}$

- δf_{B^2}, relates to B only, identical in two chambers;
- $\delta f_{E^2} \propto E^2$, identical in two chambers if $|E|$ unchanged;
- $\delta f_{BE} \propto E \partial_z B_z$
  - $\Rightarrow$ $\delta^{\text{false}}_{\text{nEDM,m,}\mp} + \delta^{\text{false}}_{\text{Hg}\rightarrow\text{nEDM,m,}\mp}$ asymmetric when flipping $\vec{E}$!
  - $\Rightarrow$ δs goes to $d^{\text{false}}_{\text{n}\leftarrow\text{Hg}}$ & $d^{\text{false}}_{\text{n}}$
  - $\Rightarrow$ false EDM to be studied by changing $E, \partial_z B_z, B_0$.



A magic field to measure the nEDM

G. Pignol, Physics Letters B 793 440-444 (2019)

Pseudo-magnetic field

Nuclear interaction between neutron and Hg nucleus results in a pseudo B-filed:

$$B^* = -\frac{4\pi\hbar}{\sqrt{3}\mathrm{m_n}\gamma_n}\mathrm{b_i}n_{\mathrm{Hg}}\boldsymbol{P}$$

Which then causes a relative shift of in R-ratio: $\delta_{psmag} = \pm\frac{2\hbar}{\sqrt{3}m_n f_n}\mathrm{b_i}n_{\mathrm{Hg}}P_{||}$

Variable control:

- Variate n_{Hg} by changing the valve opening duration
- Reduce $P_{||}$ by optimizing the oscillating field in the spin-flipping stage

Summary

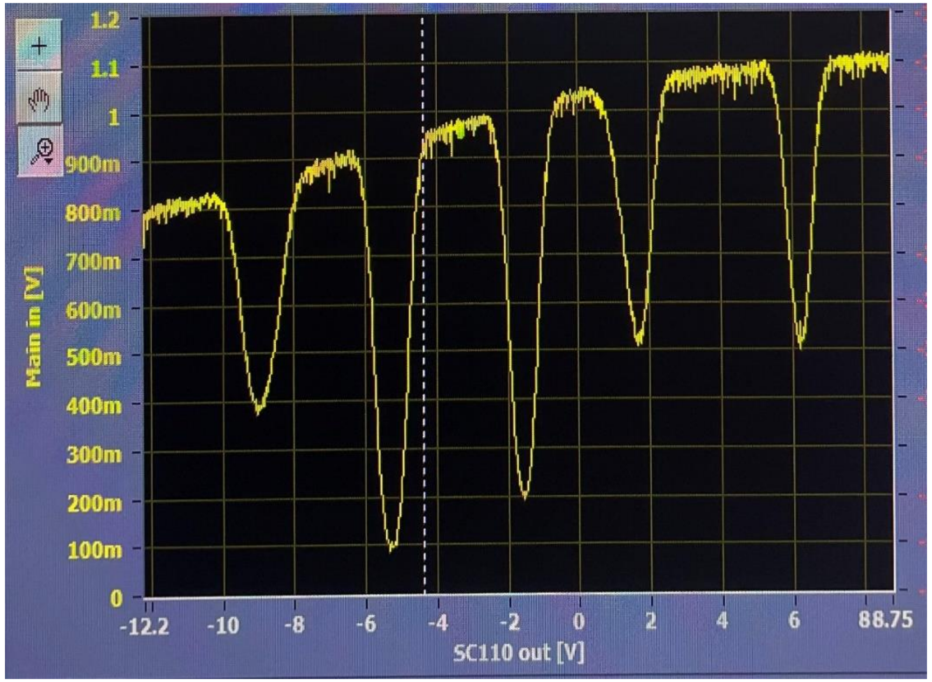
- We are implementing a ^{199}Hg co-magnetometer to correct the magnetic field drifts for the n2EDM experiment.
- The co-magnetometer works by probing the Larmor frequency of the polarized ^{199}Hg atoms.
- Challenges are the transportation of the laser beam over long distance, the beam-path with non-magnetic optics inside MSR, and optimizing the relaxation time.
- Systematic effects resulting from Hg setup will be studied and controlled.

Thank you for your attention!

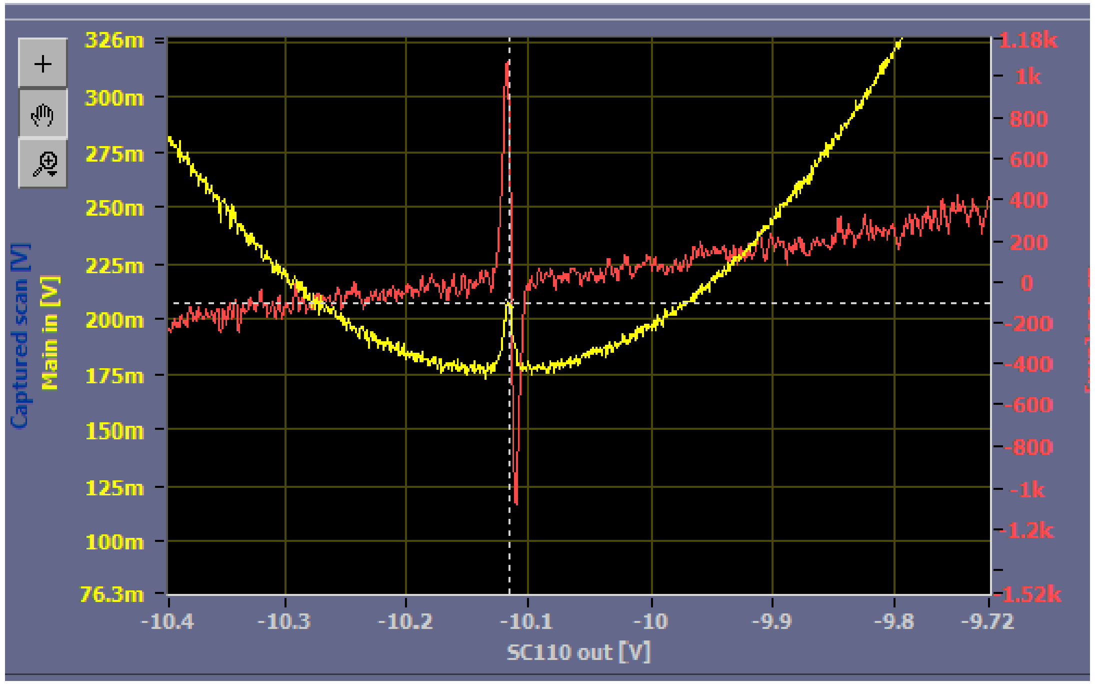
Backup

Laser frequency locking

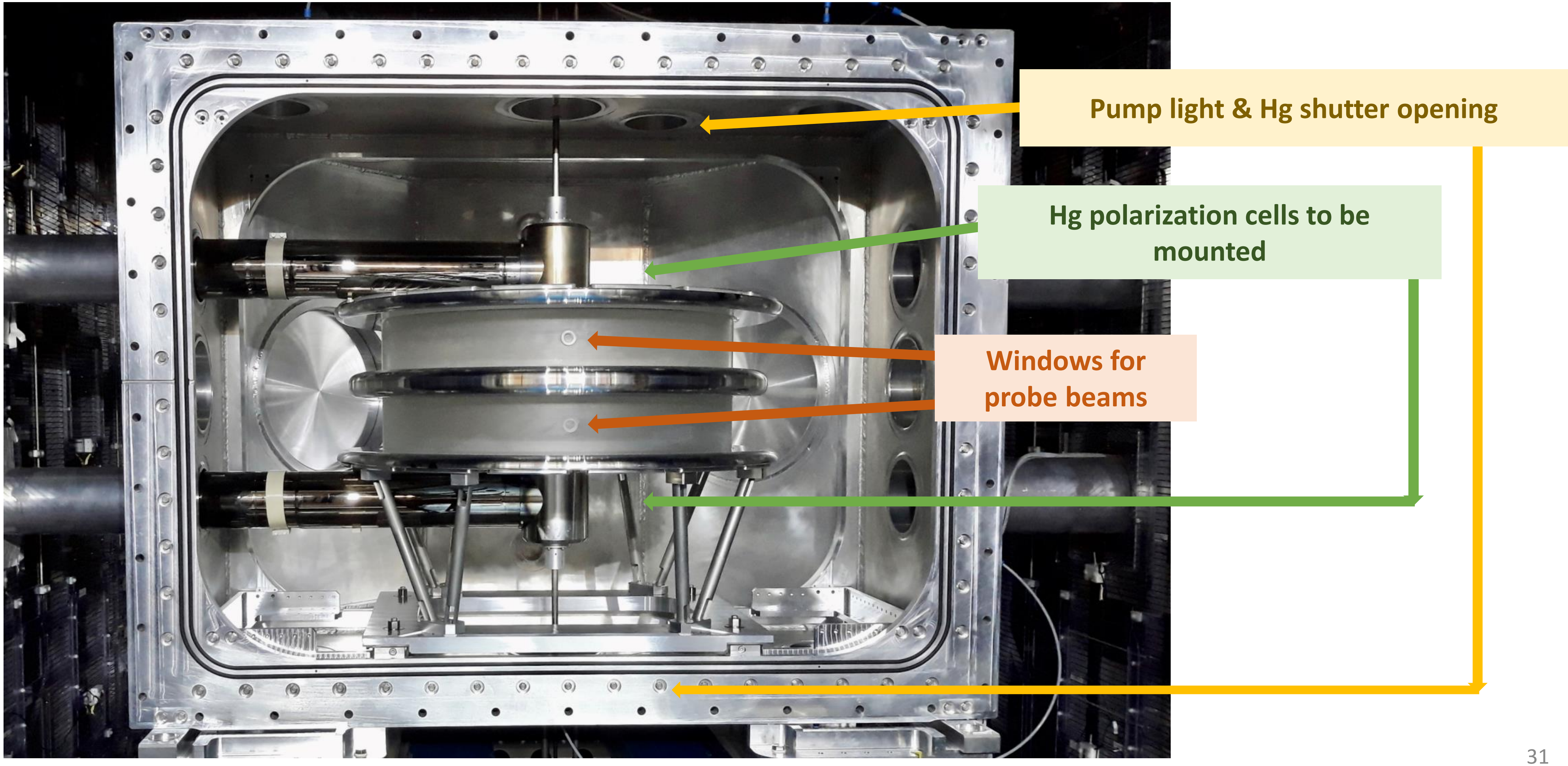
Natural Hg absorption spectrum



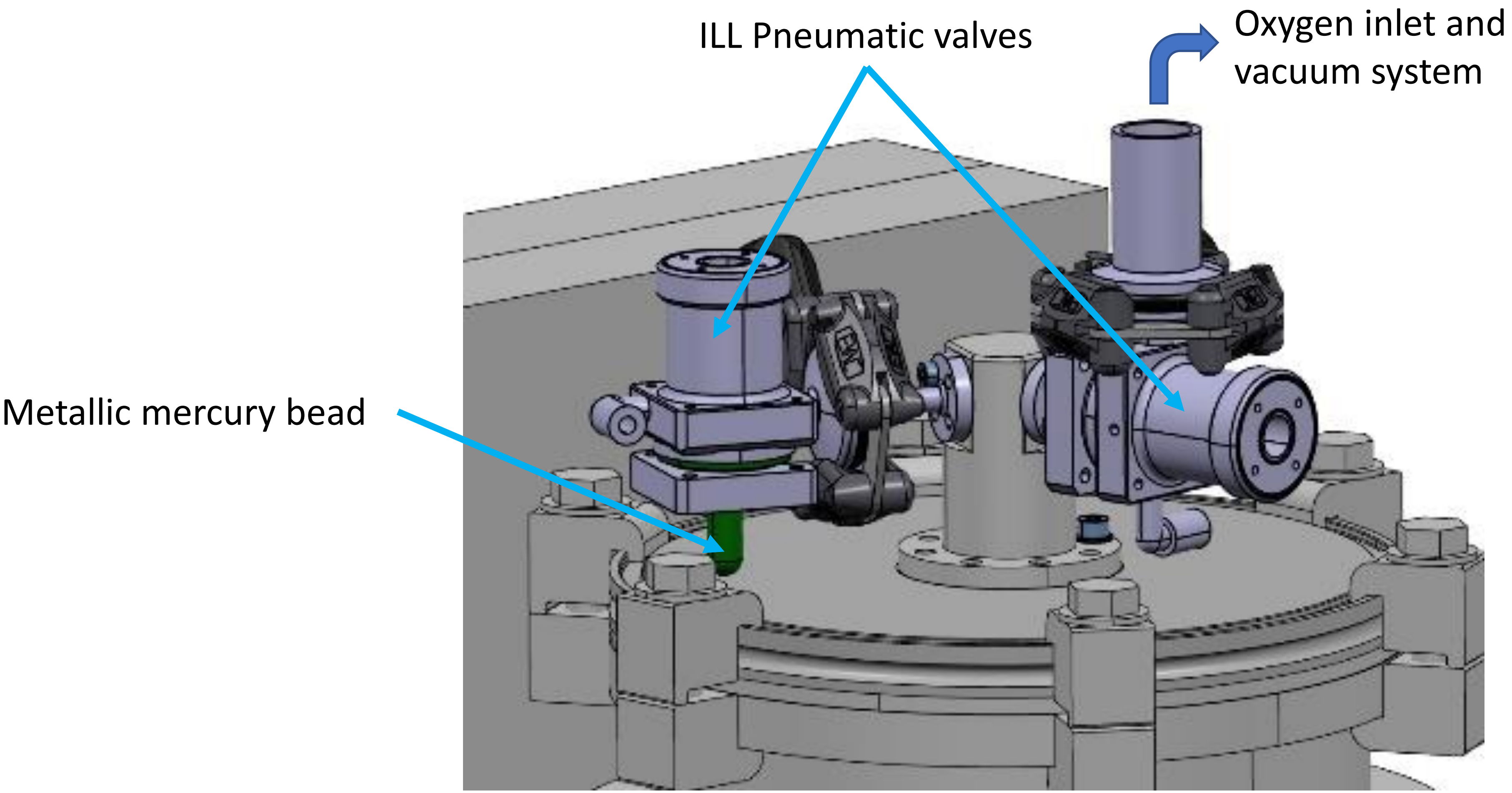
Example of a Doppler-free peak (not ^{199}Hg)



Laser-light path



Metallic Hg source



VACUUM FLANGE 2

Light absorption

The light absorption of Hg atoms:

$$\delta\Gamma = \delta\Gamma_0 + \vec{\mu} \cdot \delta\,\overrightarrow{\Gamma_1}, \quad \vec{\mu} = \gamma\vec{I}$$ (nuclear magnetic dipole moment)

Absorption cross-section is dependent on the angle of Hg spin and light propagation

Scalar absorption rate, corresponding to unpolarized light

Why does T2 exist

Transverse relaxation time T_2 in the equation: $\mathbf{A(t) = a\, e^{-\frac{t}{T_2}} \sin(2\pi\, f_{Hg} t + \phi_0)}$

Why T_2 exists?

$$\frac{1}{T_2} = \frac{1}{T_{mag}} + \frac{1}{T_{wall}} + \frac{1}{T_{light}}$$

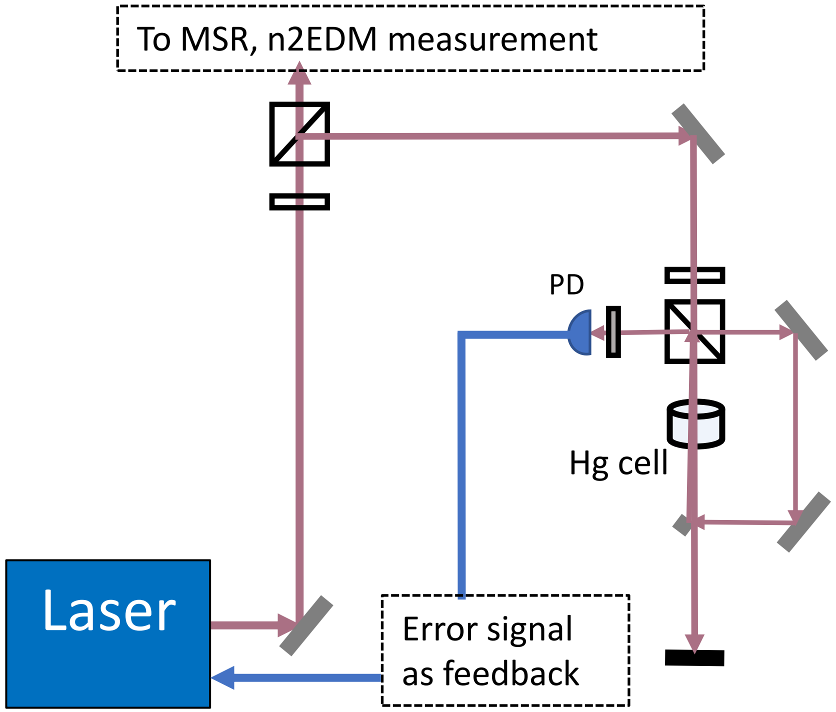
T_{mag} from inhomogeneity of magnetic field.
T_{wall} due to collisions of atoms and chamber.
T_{light} Hg are depolarized during light detection process.

(In this T_2 definition, we neglect the decay due to Hg leakage)

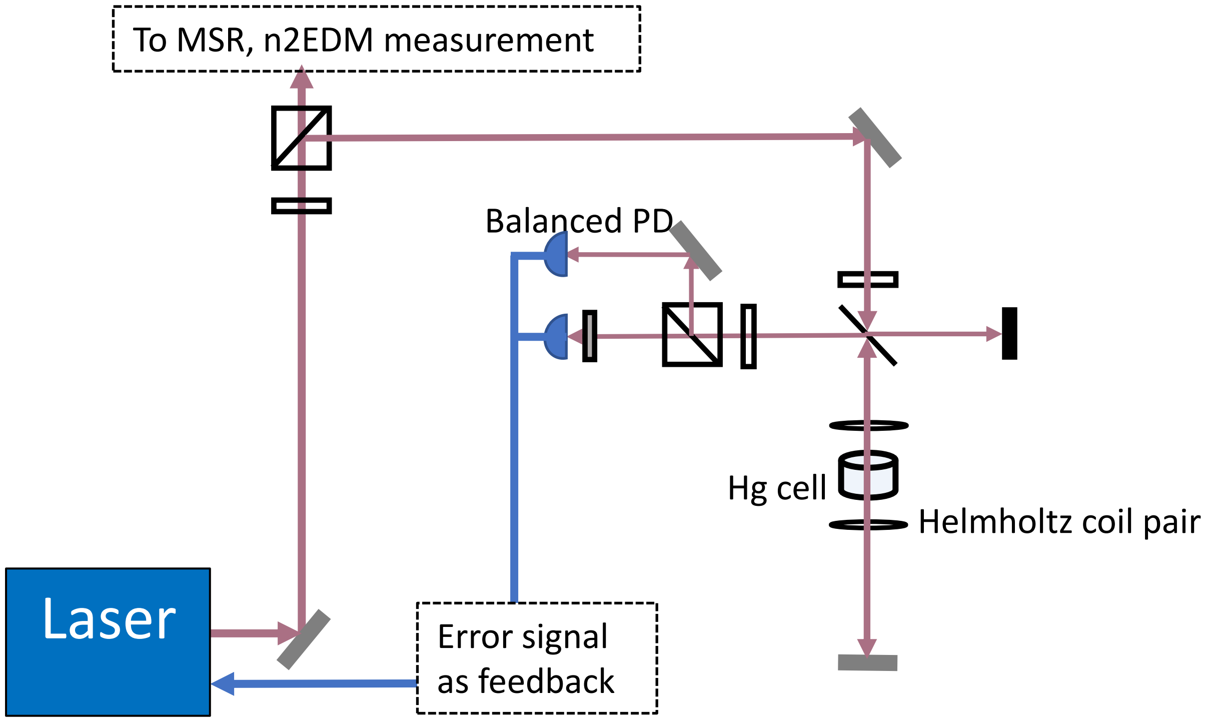
Laser frequency locking

We have tried two locking schemes:

Doppler-free saturated spectroscopy
with frequency modulation

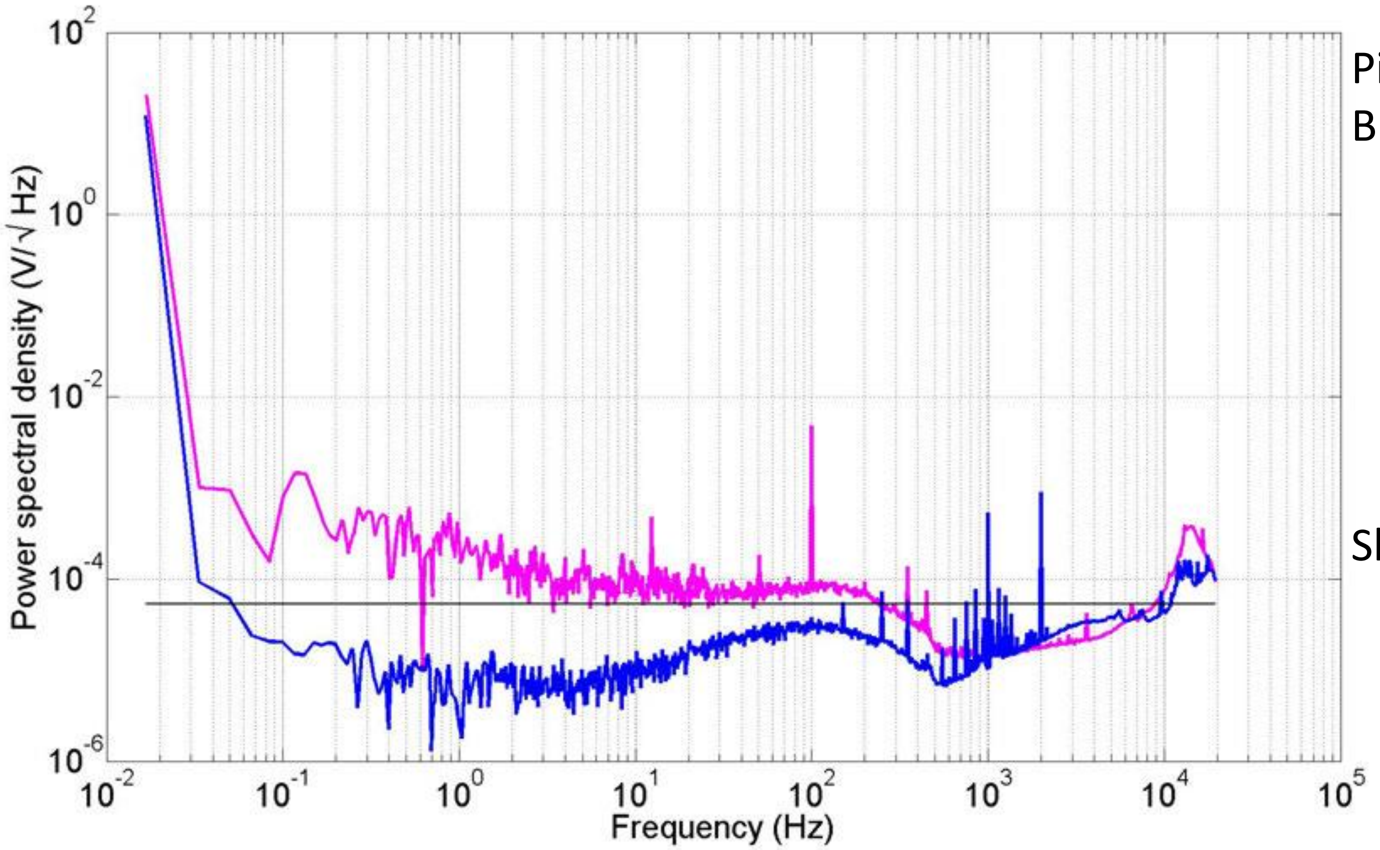


Sub-Doppler dichroic atomic vapor laser lock (SD-DAVLL)
with magnetic field



Probe signal detection

- In the region of the 8Hz Hg precession frequency, the measured noise density is only a factor 1.5 away from shot noise.



Pink: with laser light

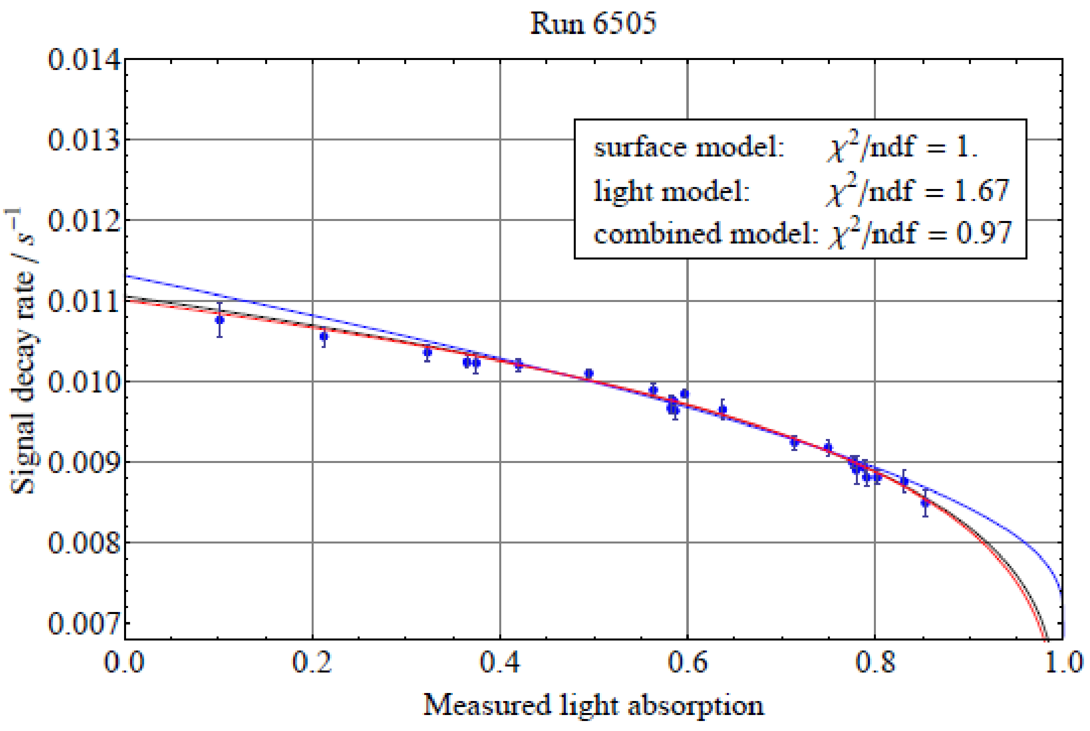
Blue: without laser light

Shot noise level

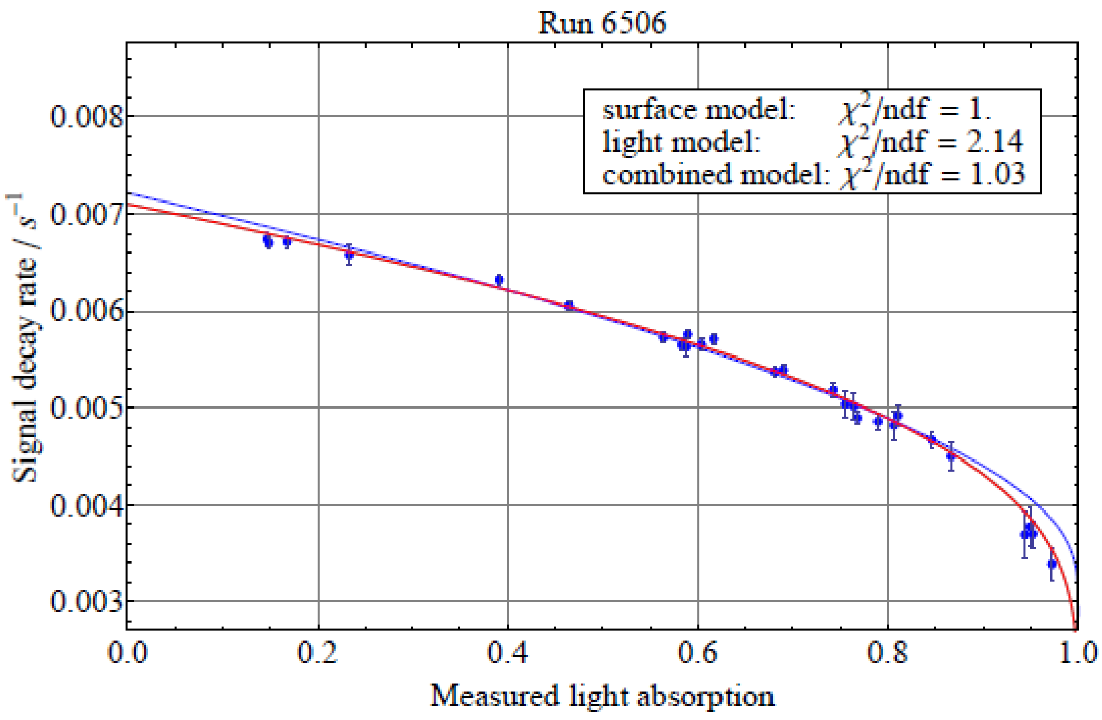
Power spectral density of the laser beam
measured in the nEDM measurement

S. Komposch, ETH PhdThesis (20.500.11850/174468)

Discharge cleaning



(a) *Before* discharge cleaning.



(b) *After* discharge cleaning.

Spin relaxation rate comparison: before and after discharge cleaning. **M. Fertl, ETH PhdThesis (20.500.11850/77320)**

Pseudo-magnetic field

A shift of in R-ratio: $\delta_{psmag} = \pm \frac{2\hbar}{\sqrt{3} m_n f_n} \mathrm{b_i} n_{\mathrm{Hg}} P_{||}$

- Thanks to the double chamber design, the 1st order resulting Hg $P_{||}$ will be canceled out.
- Residual effect coming from the difference of $P_{||}$ (field inhomogeneity) and n_{Hg} in two chambers.

Hg density check

→ get mean and St. dev of $n_{\mathrm{Hg},+}$, $n_{\mathrm{Hg},-}$

π or 3/4 π, 7/4 π-flip measurement

→ get mean and St. dev of $P_{||,+}$, $P_{||,-}$

For n2EDM measurement

Estimate the systematic shift and the standard error due to this effect.

Check if we can achieve the sensitivity goal of the Hg co-magnetometer

$v \times E$ effect

Dominant term $\delta^{\text{false}}_{\text{nEDM,m,}\mp} + \delta^{\text{false}}_{\text{Hg}\to\text{nEDM,m,}\mp}$ from the motional magnetic field:

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  - $\Rightarrow$ false EDM to be studied by changing $E, \partial_z B_z, B_0$.

$$d_n^{\text{false}} = -\frac{\hbar v_h^2}{4c^2 B_0^2} G_{1,0} = -\frac{G_{1,0}}{1\ \text{pT/cm}} \times 1.65 \times 10^{-28}\ e\ \text{cm},$$

$$d_{n\leftarrow\text{Hg}}^{\text{false}} = \frac{\hbar |\gamma_\text{n}\gamma_\text{Hg}| R^2}{8c^2} G_{1,0} = \frac{G_{1,0}}{1\ \text{pT/cm}} \times 1.28 \times 10^{-26}\ e\ \text{cm}$$