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

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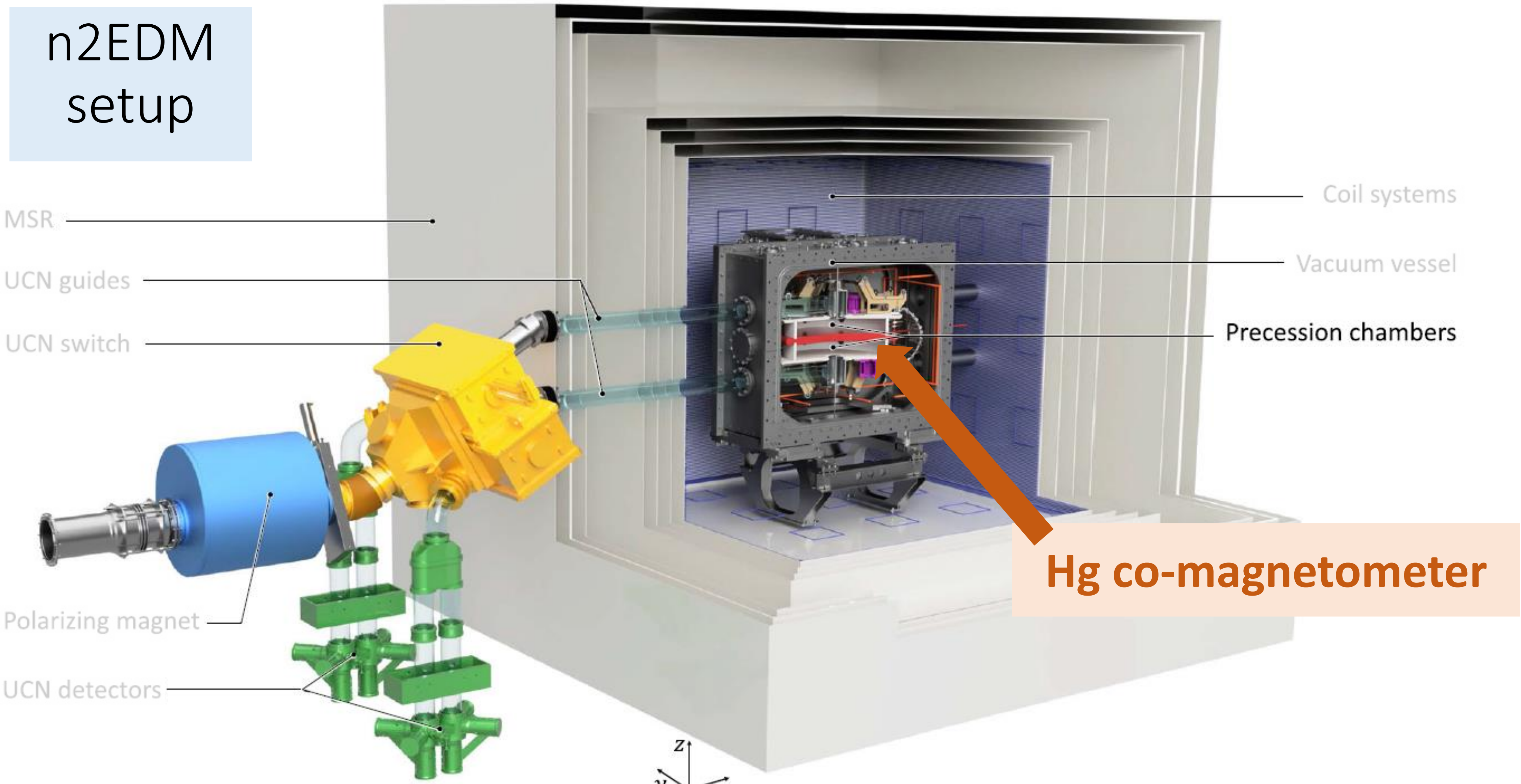
on behalf of nEDM collaboration

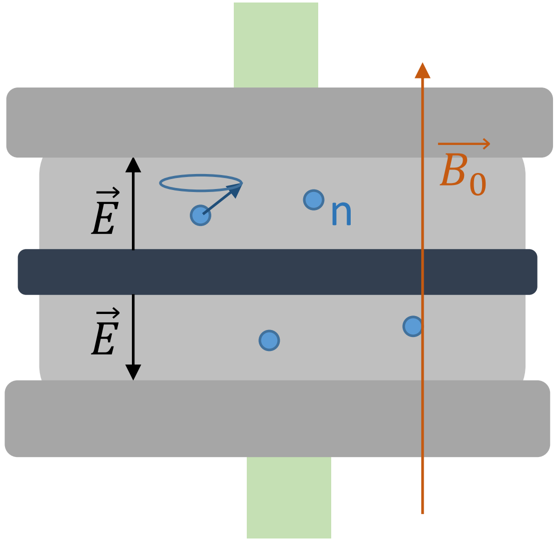
n2EDM setup



MSR
UCN guides
UCN switch
Polarizing magnet
UCN detectors
Coil systems
Vacuum vessel
Precession chambers
Hg co-magnetometer
z
y
x

The n2EDM experiment

which searches for permanent neutron electric dipole moment d_{n}.



- We will store the neutron in material bottle, apply $\vec{B}, \vec{E}$ fields.

- We extract d_{n} from the neutron Larmor frequency:

$$f_{n,\mp} = \left|\frac{\gamma_{\mathrm{n}}}{2\pi} B_0\right| \mp \frac{d_{\mathrm{n}}}{\pi\hbar} |E|$$

$-$: parallel $\vec{B}, \vec{E}$ $+$: anti-parallel $\vec{B}, \vec{E}$

How do Hg atoms join the n2EDM experiment

Hg atoms precess in the same field:

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

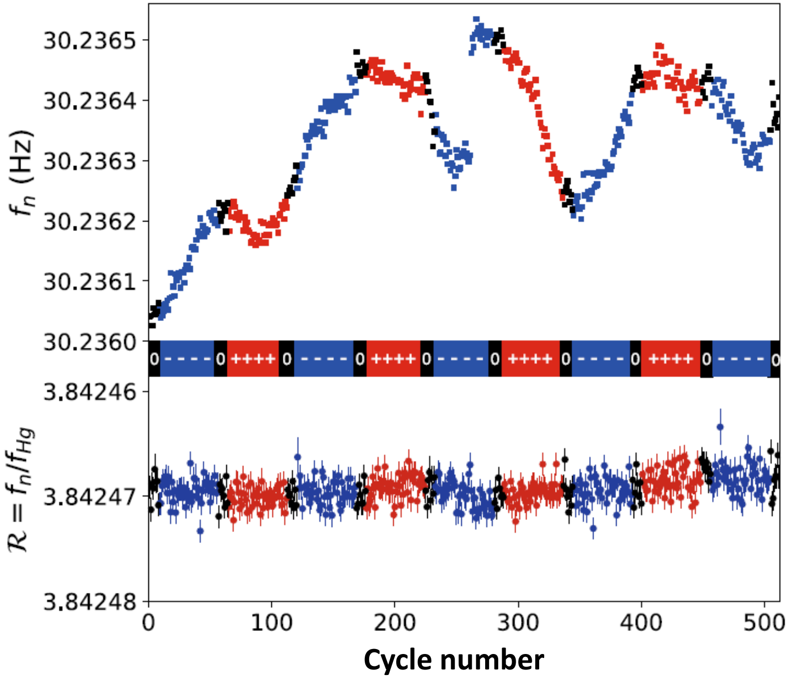
⇒ allow us to cancel the magnetic field drifts!

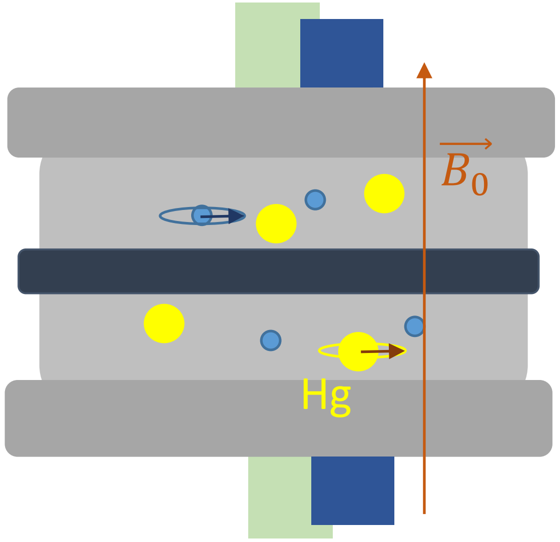
Use a ratio

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

Then extract

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



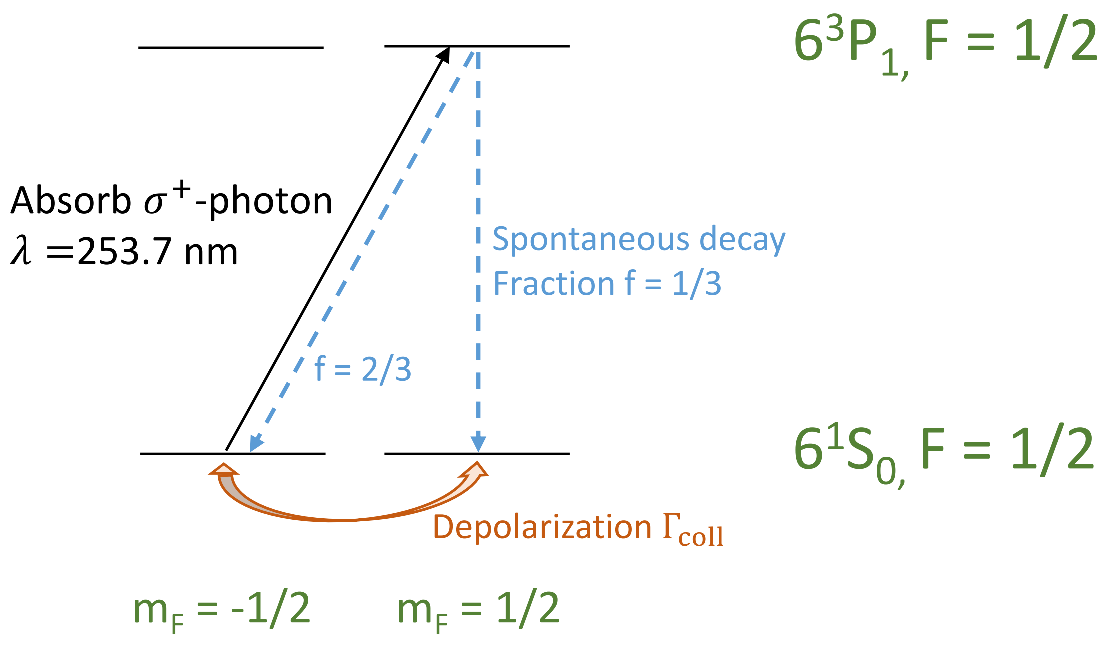


Upper plot: neutron frequency as a function of cycle number;
Lower plot: R ratio is nearly free from the magnetic field drifts.

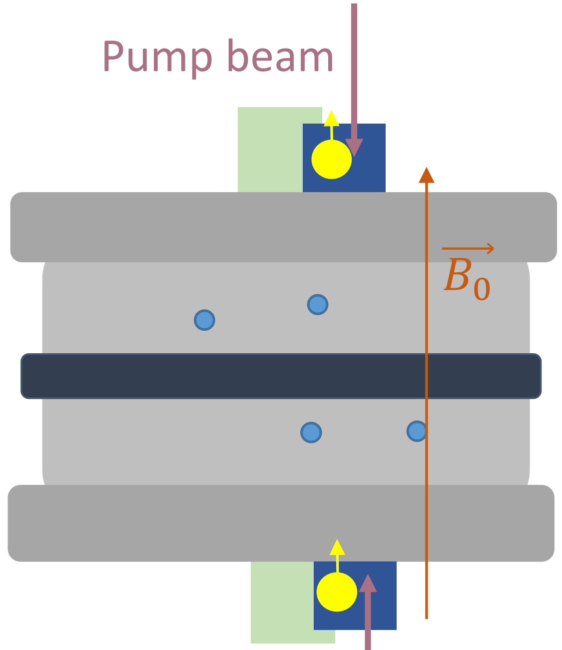
N.J. Ayres et al., The design of the n2EDM experiment. Eur. Phys. J. C 81, 512 (2021).

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

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



optical pumping of ^{199}Hg atoms



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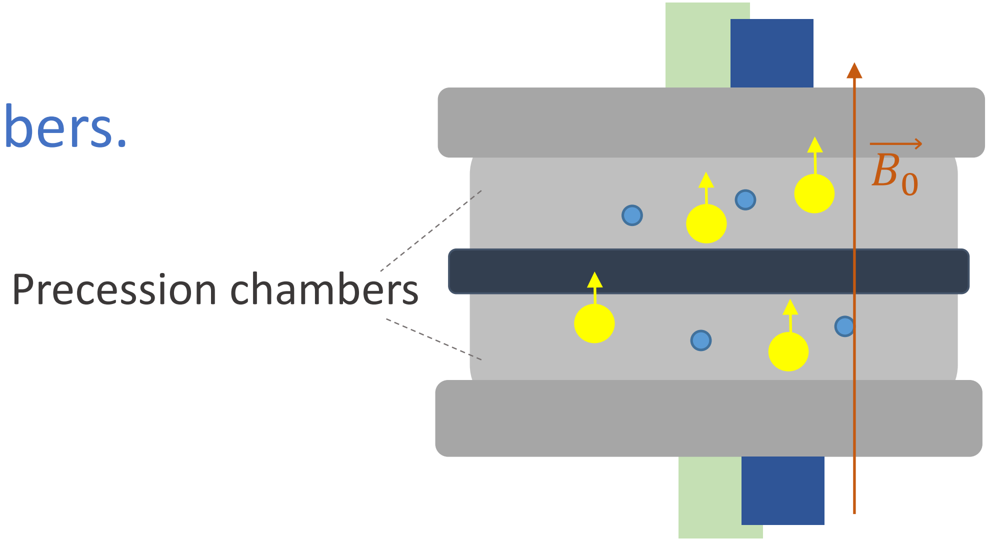
Use UV laser to spin-polarize the ^{199}Hg atoms.

Release the polarized atoms into precession chambers.



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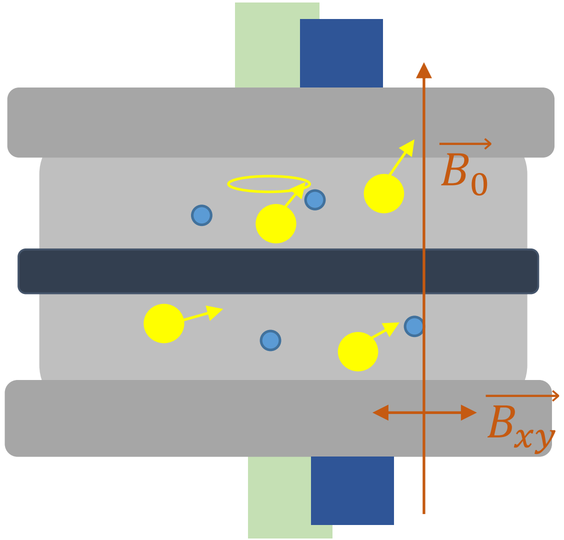
Apply oscillating field $\overrightarrow{B_{xy}}$ to flip the ^{199}Hg spin by 90°.



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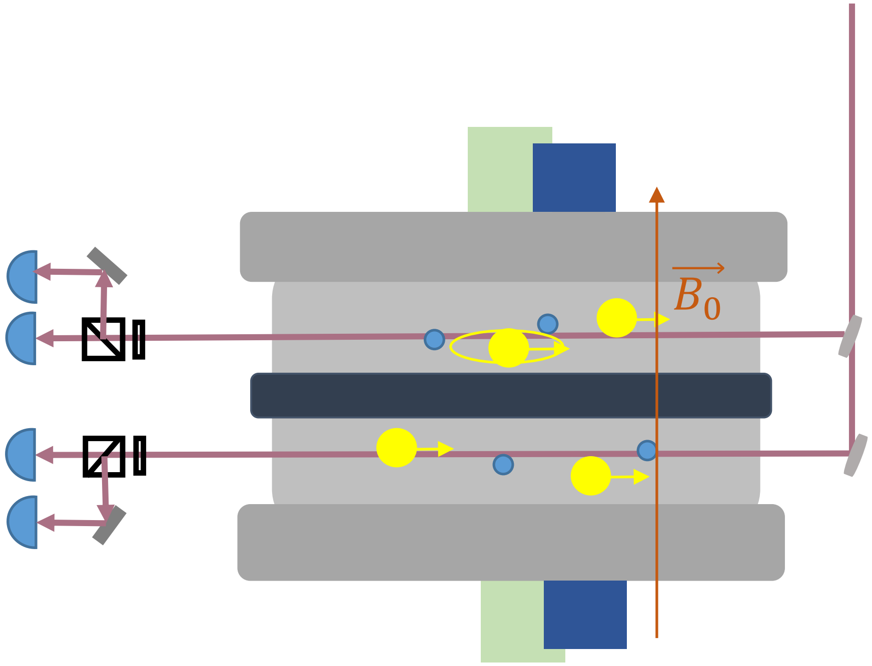
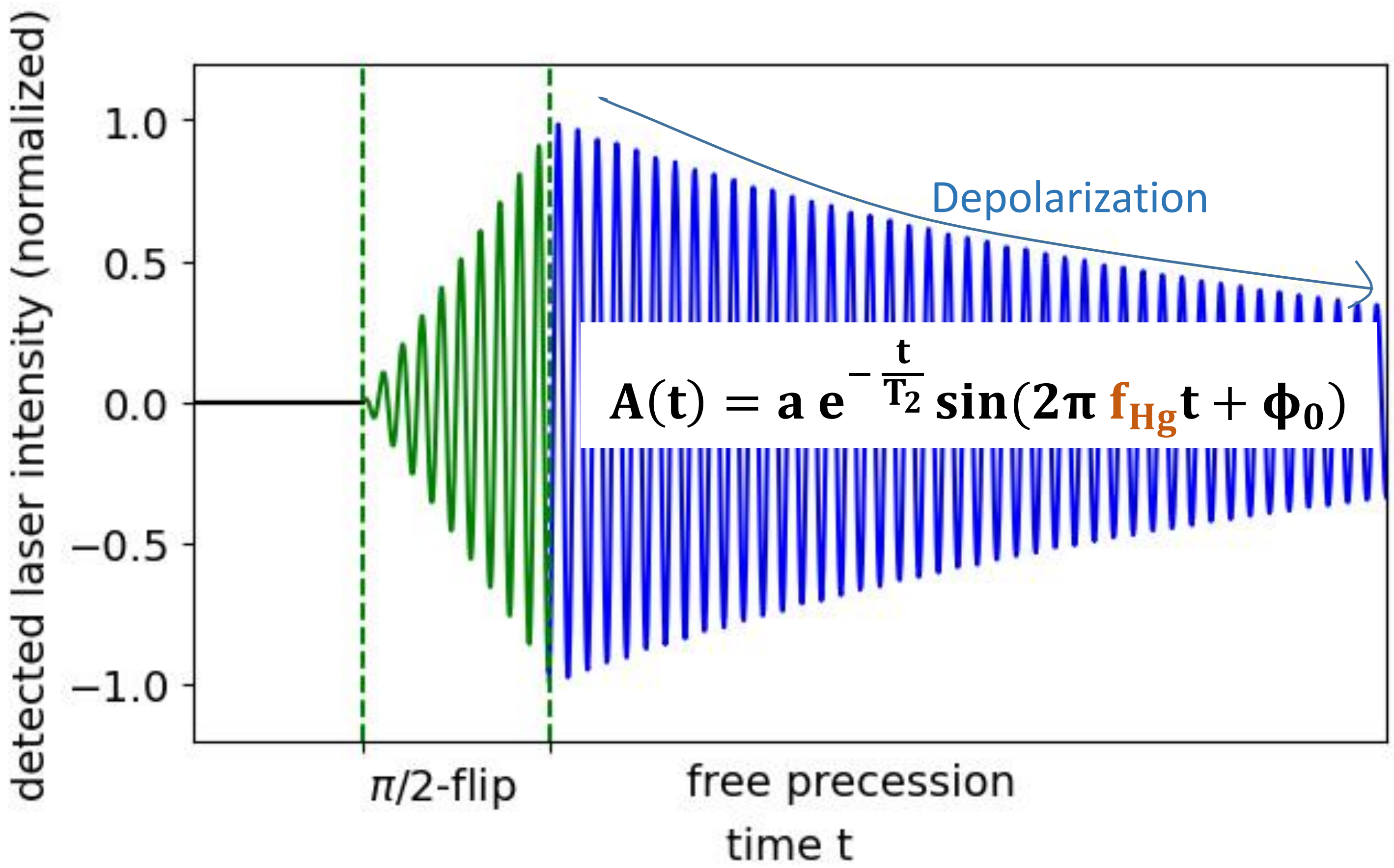
Probe the precession of ^{199}Hg atoms by UV laser.

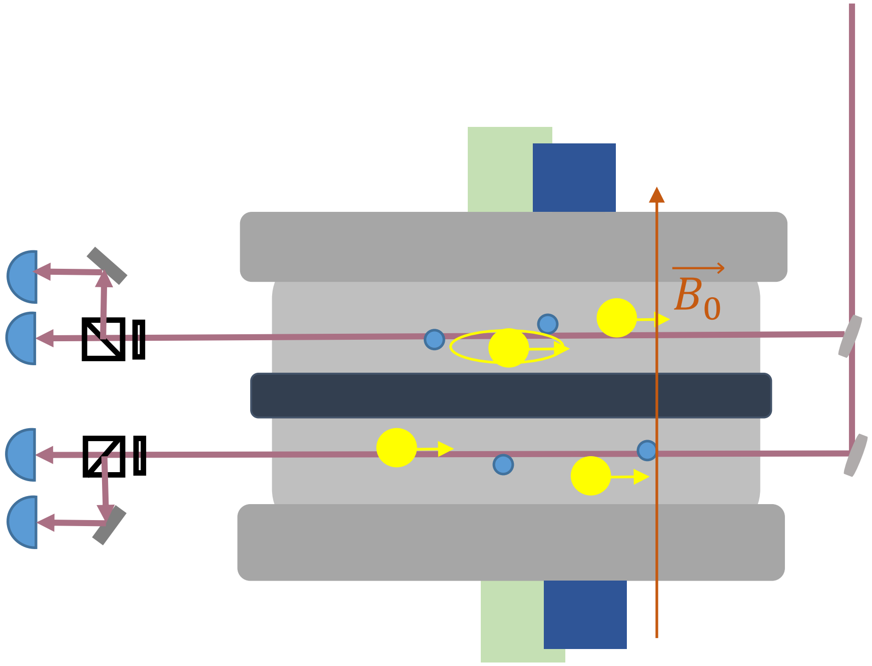
Light absorption cross-section depends on the orientation of ^{199}Hg spin and the light propagation.

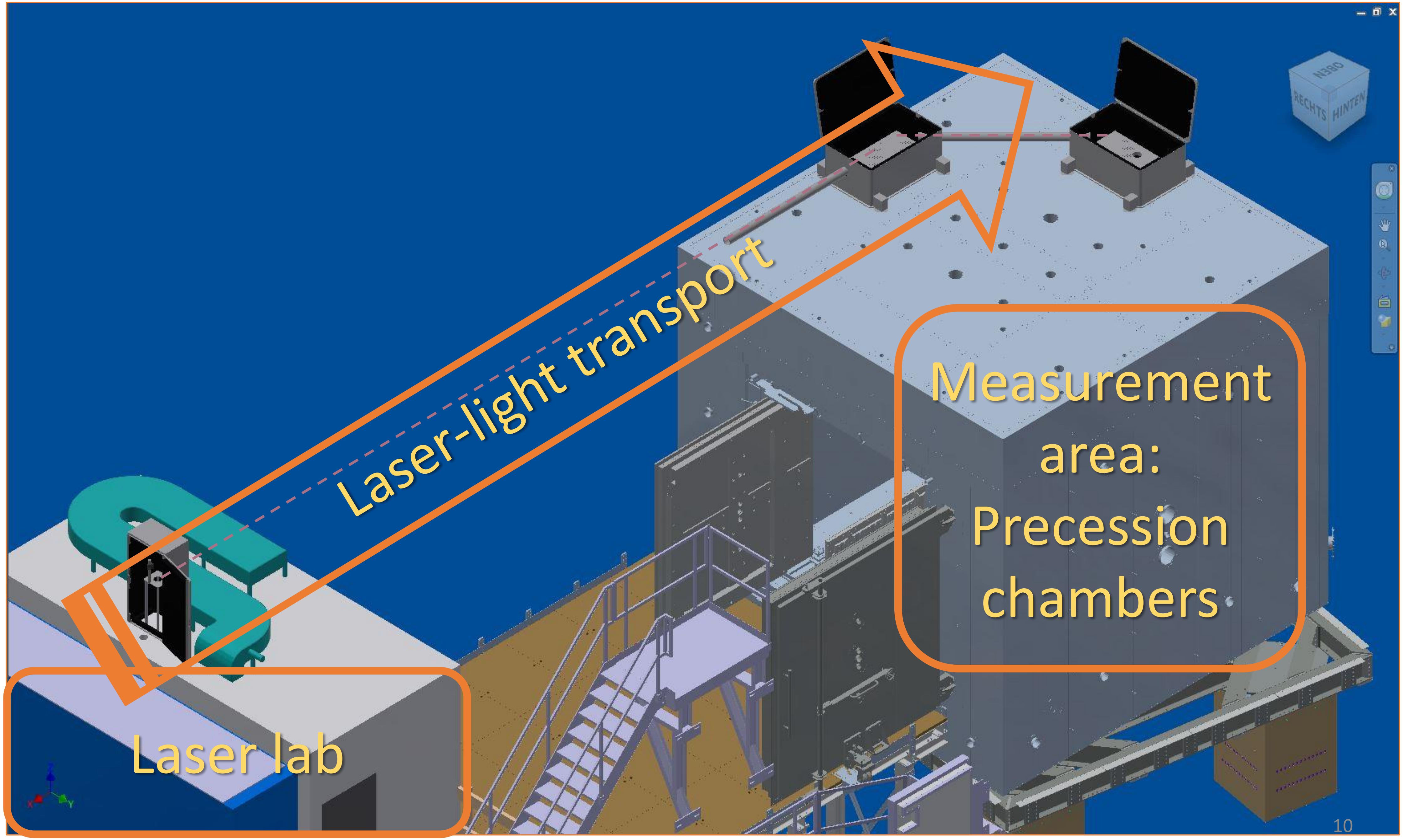


How do we extract $< f_{\mathrm{Hg}} >$?



$$\mathbf{A(t) = a\, e^{-\frac{t}{T_2}} \sin(2\pi\, f_{Hg} t + \phi_0)}$$




Laser-light transport
Measurement area: Precession chambers
Laser lab
RECHTS
HINTEN
OBEN

Stabilization of the system

- To pump the Hg atoms sufficiently

  → we want to lock the laser frequency to the ^{199}Hg $6^1S_0 \rightarrow 6^3P_1$ transition.

  → **Frequency locking**

- To transport the laser-light from the source

  → We expect less movement in position of the beam.

  → **Position stabilization**

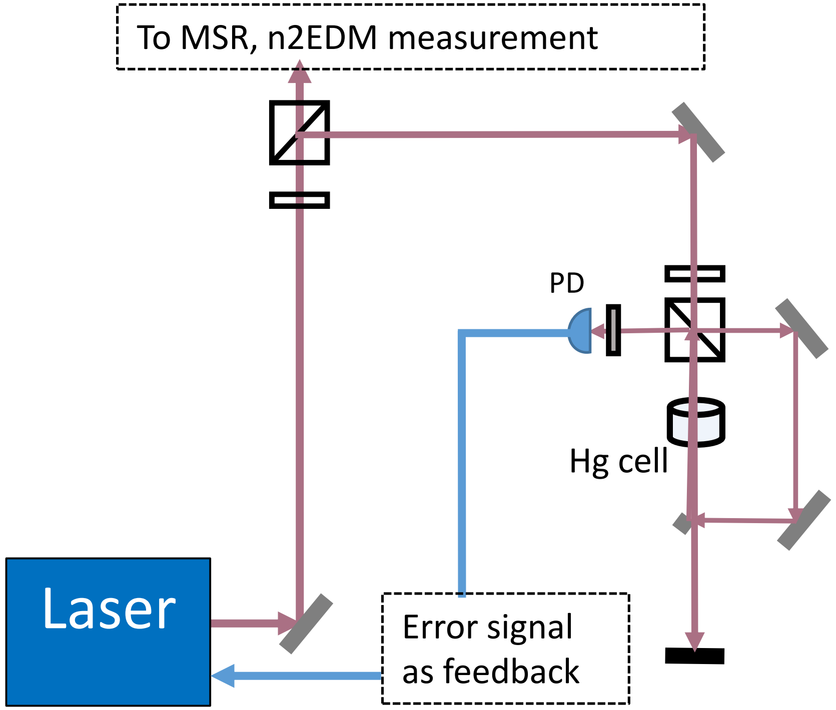
- We measure the intensity change of probe beam and avoid power variation

  → **Power stabilization**

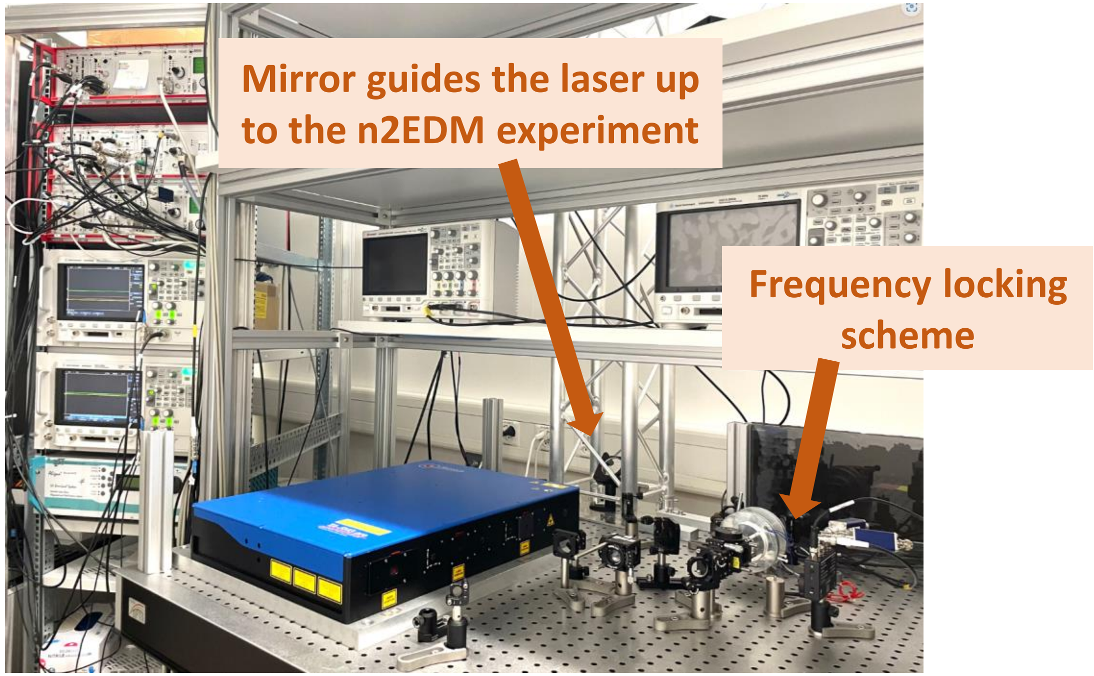
For stabilization we always need a feedback loop.

Frequency locking scheme

Use Doppler-free saturated spectroscopy with frequency modulation

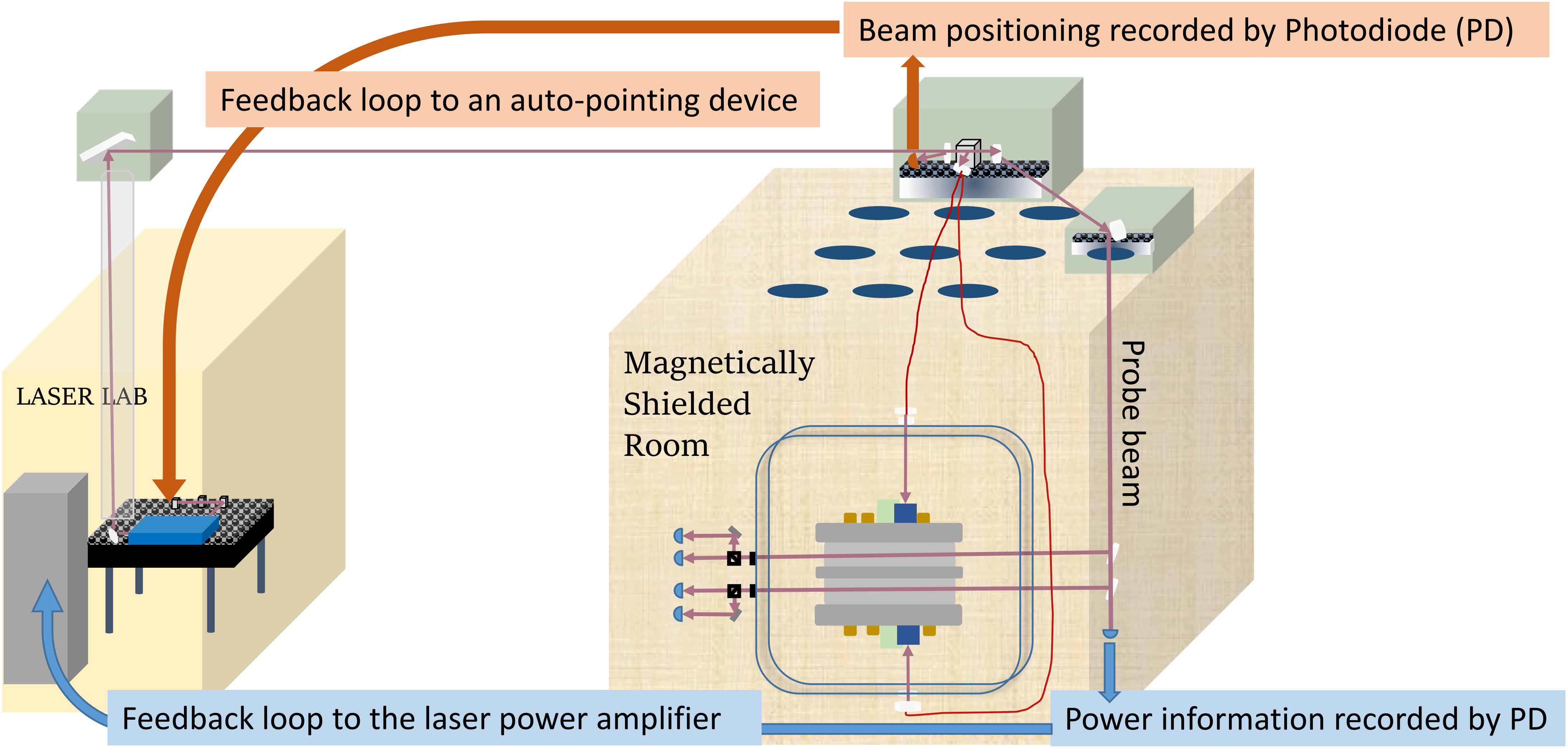


Feedback loop to the diode laser



A photo of the laser table

Power & positioning stabilization

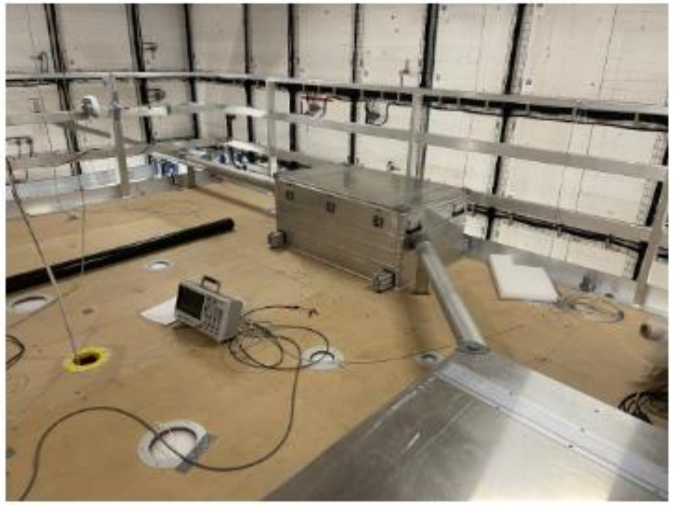


Laser-light transport

Free-space beam:

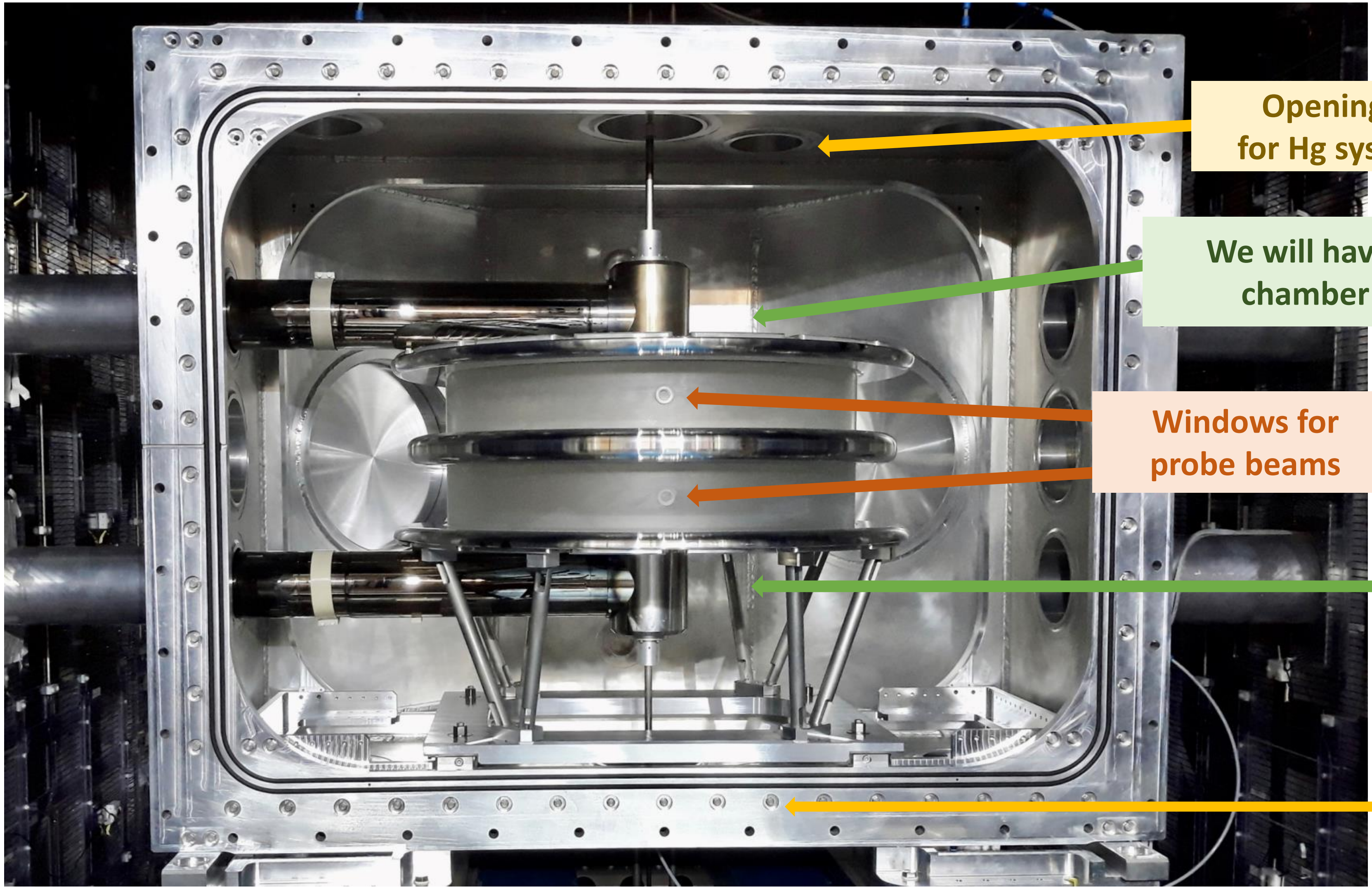
A tower sitting on the laser table supports an optical breadboard

Cabinet and light transport tube



Laser safety boxes on the top of MSR

Laser-light transport

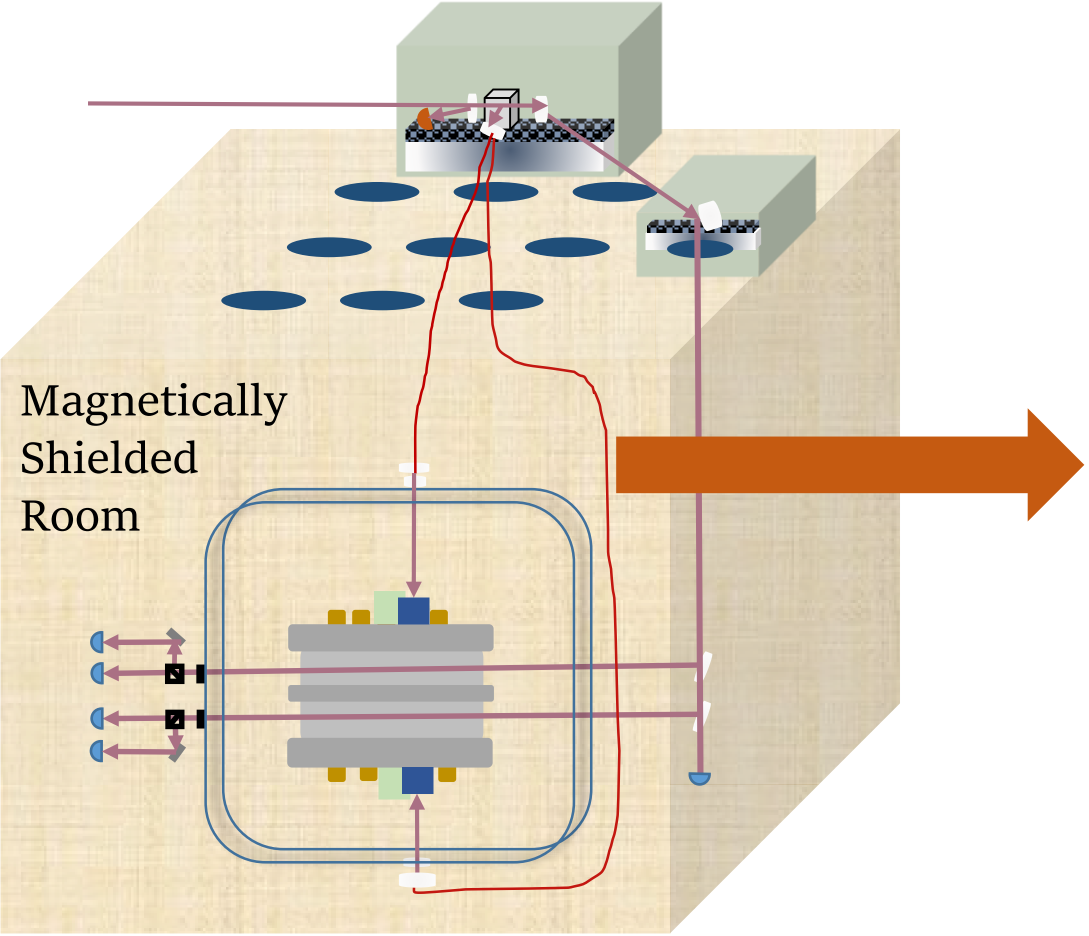


Opening on vacuum tank reserved for Hg system (fiber + shutter control)

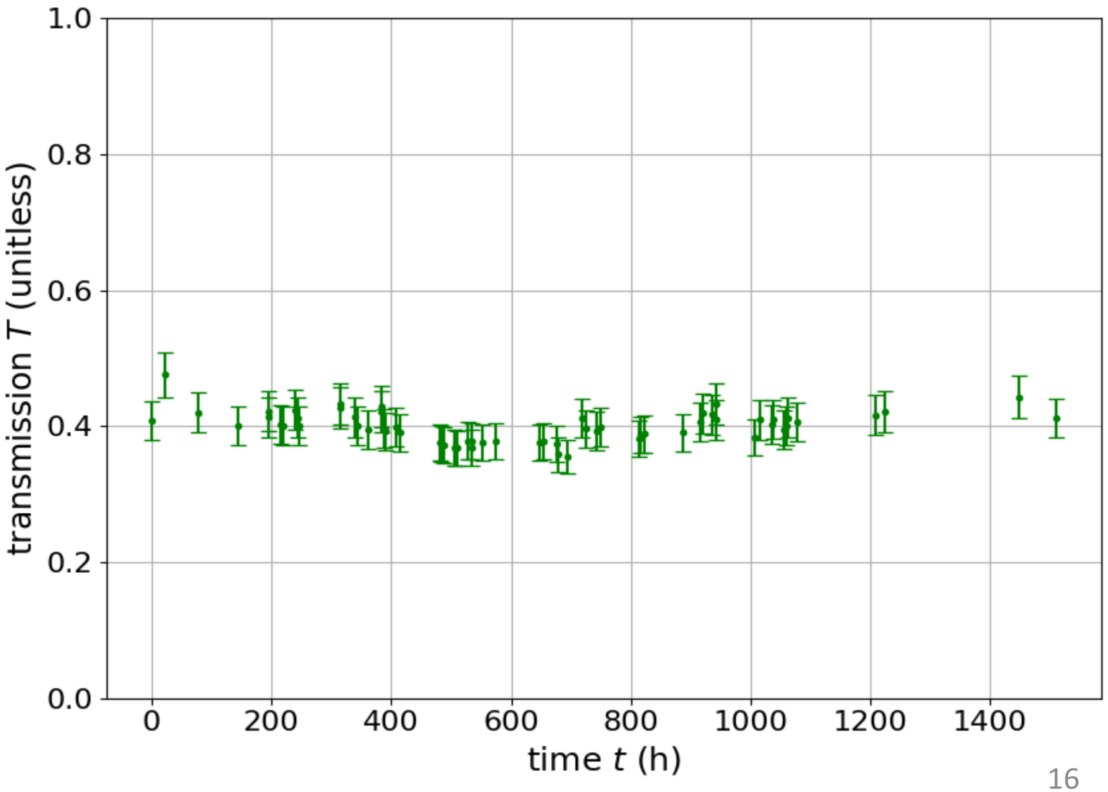
We will have Hg polarization chamber mounted here

Windows for probe beams

Light transport: Fiber test



Result: transmission of a 10 m fiber has been stable at 40% over 50 days under 253.7 nm UV exposure.
→ good for transportation.



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 $\delta_- = \delta_+$.

Study on systematic effects

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 $d^{\text{false}}_{\text{n}}$& $d^{\text{false}}_{\text{n}\leftarrow\text{Hg}}$
  $\Rightarrow$ false EDM to be studied by changing $E, \partial_z B_z, B_0$.

Summary

- We develop 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.
- One challenge of this work is to transport the light to the main experiment area.
- Systematic effects resulting from Hg setup will be studied and controlled.

Thank you for your attention!

Systematic effects introduced by Hg

Reasons	Systematic effects
Hg, UCN moving differently, experience different fields	Gravitational shift
Nuclear interaction between UCN & Hg nucleus	Spin-dependent pseudo B-field
Frequency shift coming from the Hg system itself	Montional field, light shift…
Action to the Hg system impacts neutron	Spin-flip on Hg impacts UCN spin

Pseudo-magnetic field (sys. effect)

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

- Spin-dependent

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

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

Hg depolarization

Spin relaxation time T2 in the equation: $\mathbf{A(t) = a\, e^{-\frac{t}{T_2}} \sin(2\pi\, f_{Hg} t + \phi_0)}$

It is a time constant for the transverse polarization decay

(Neglect the decay due to Hg leakage)

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

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.

Light absorption

The light absorption of Hg atoms:

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

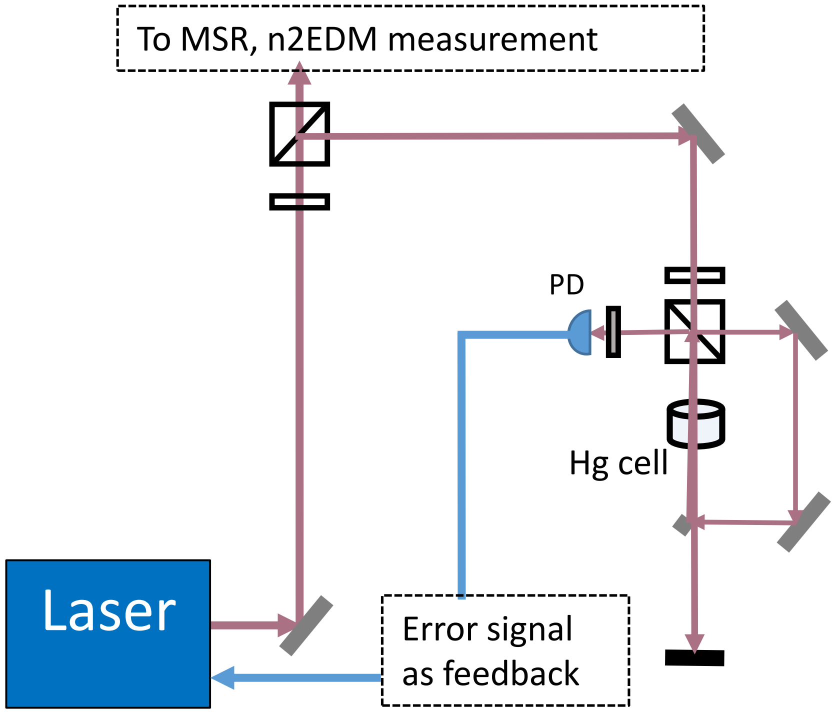
Absorption cross-section is dependent on the relation of Hg spin and light propagation

Scalar absorption rate, corresponding to unpolarized light

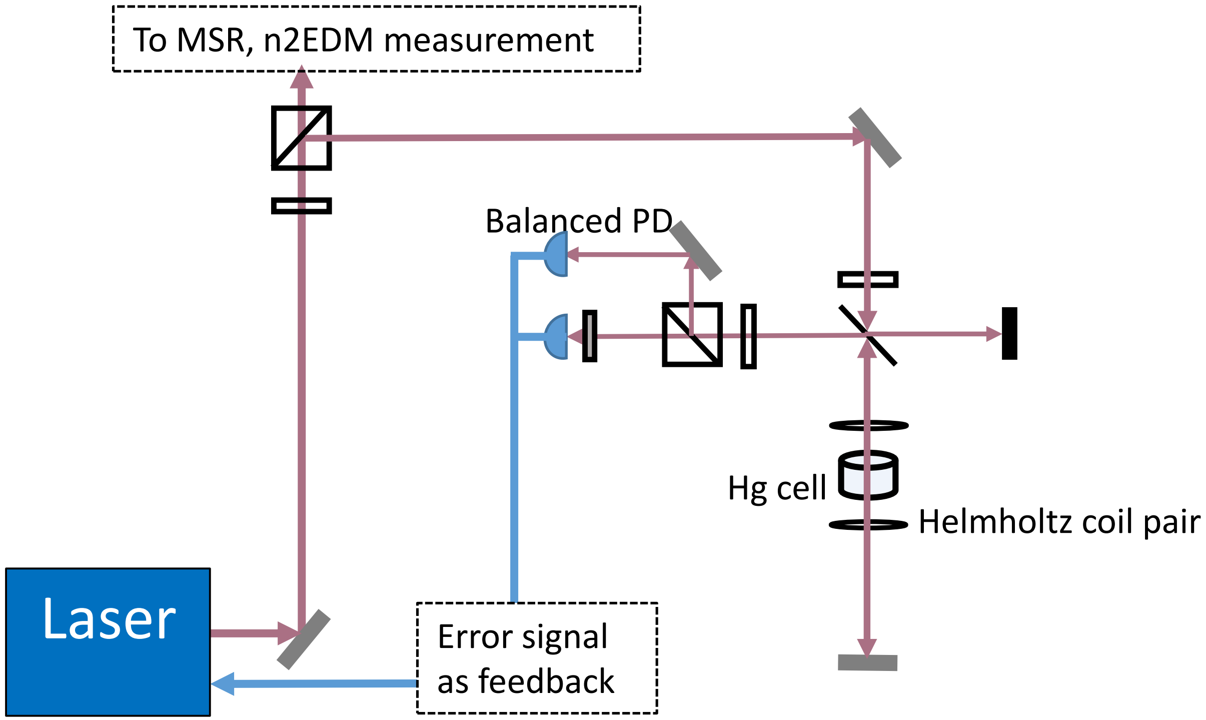
Laser frequency locking

To investigate two locking schemes:

Doppler-free saturated spectroscopy
with frequency modulation

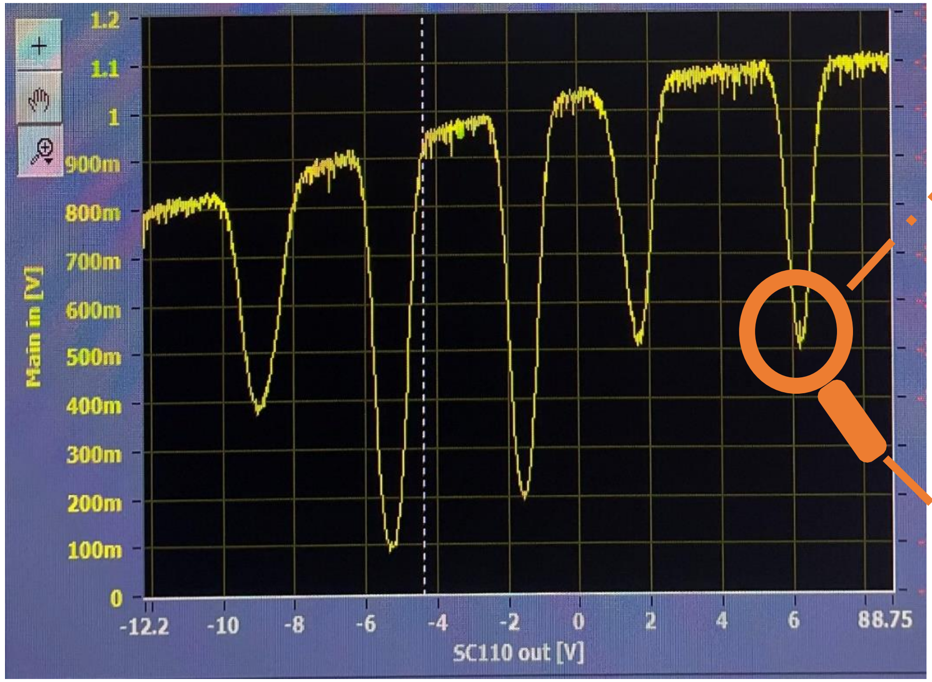


Sub-Doppler dichroic atomic vapor laser lock (SD-DAVLL)
with magnetic field



Laser frequency locking

Natural Hg absorption spectrum



Doppler-free peak