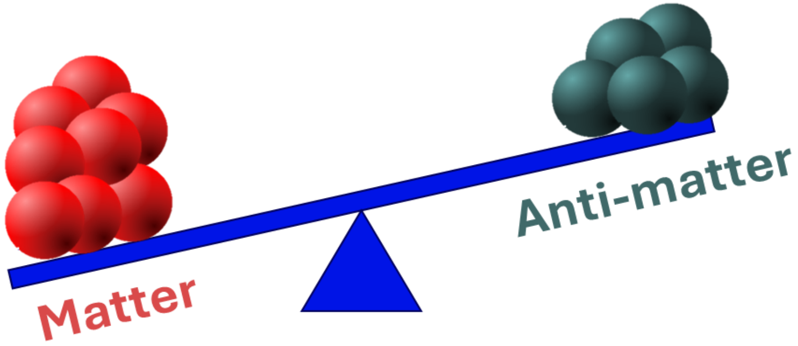
An overview of the n2EDM experiment

Gian Luca Caratsch
Bormio, 20 January 2026

We start from an observation ...

- Baryon asymmetry in the Universe



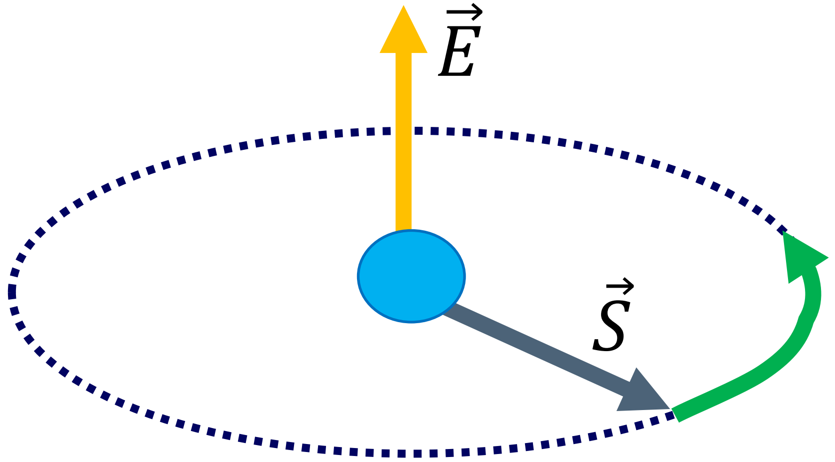
$$\eta_{obs} = \frac{n_b}{n_\gamma} \sim 10^{-10} > 10^{-18} = \eta_{SM}$$

Sakharov Conditions

Violation of the baryon number
CP violation
Thermal non-equilibrium

The neutron electric dipole moment

- Neutron electric dipole moment (nEDM)



$$\hat{H} = -\mu_n \frac{\vec{S}}{S} \cdot \vec{B} - d_n \frac{\vec{S}}{S} \cdot \vec{E}$$

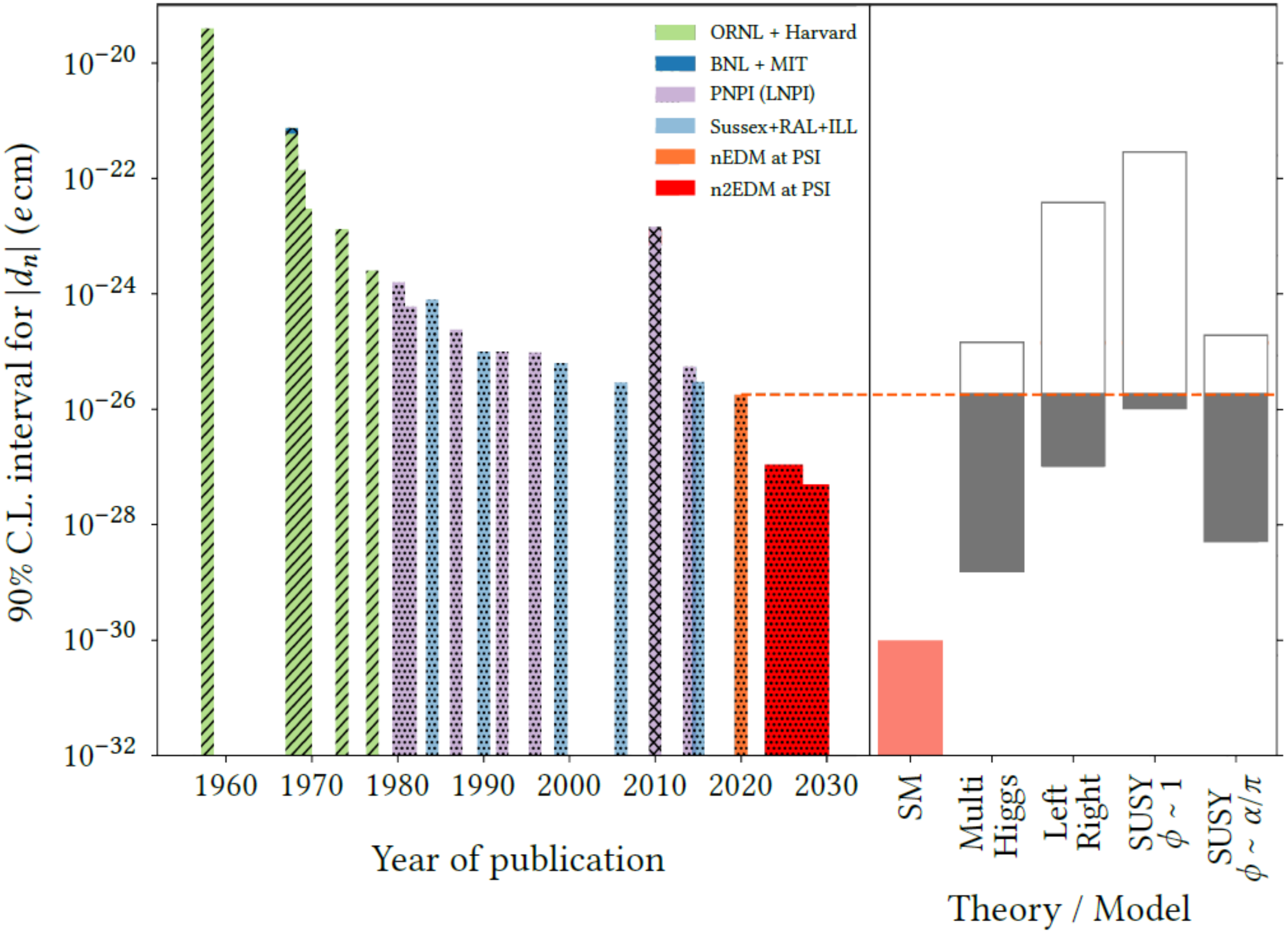
The nEDM as CP violating probe

$$\hat{H} = -\mu_n \frac{\vec{S}}{S} \cdot \vec{B} - d_n \frac{\vec{S}}{S} \cdot \vec{E}$$

CP/T

$$\hat{H} = -\mu_n \frac{\vec{S}}{S} \cdot \vec{B} + d_n \frac{\vec{S}}{S} \cdot \vec{E}$$

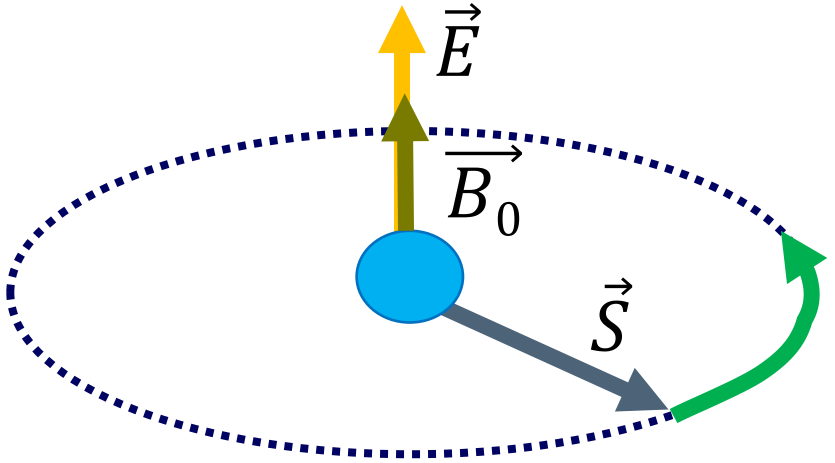
Where are we now?

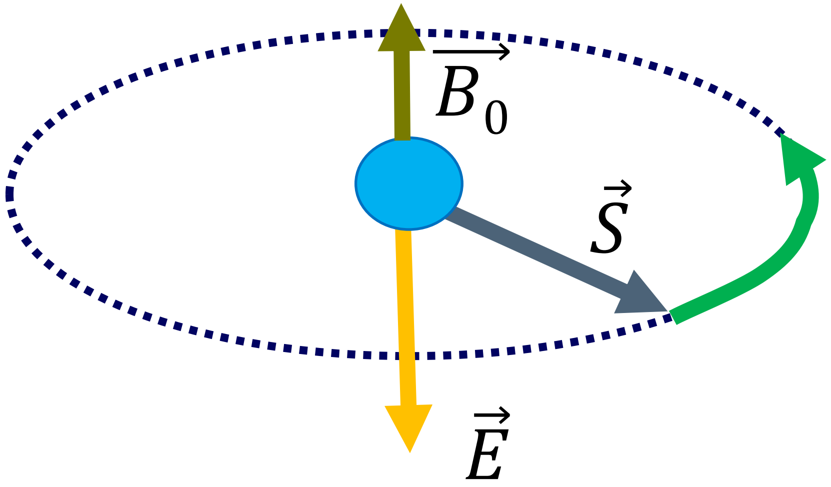


$$|d| < 1.8\times10^{-26}\, e\cdot\mathrm{cm}\ \text{(C.L. 90\%)}$$

https://doi.org/10.1103/PhysRevLett.124.081803

Principle of measurement

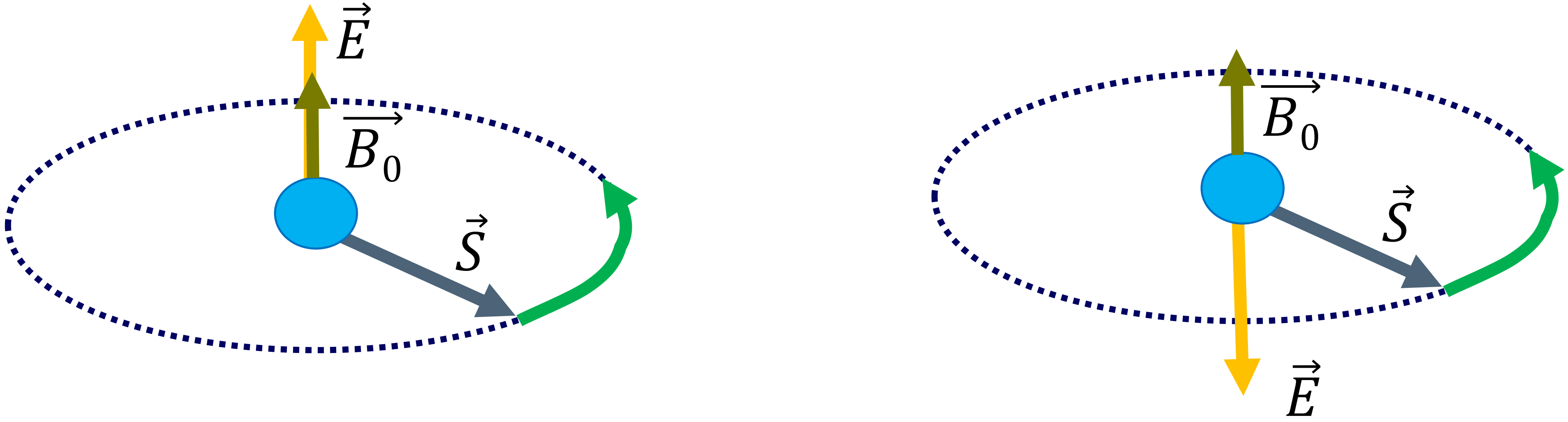




$$hf_{\uparrow\uparrow} = 2(\mu_n B_0 + d_n E)$$

$$hf_{\uparrow\downarrow} = 2(\mu_n B_0 - d_n E)$$

Principle of measurement

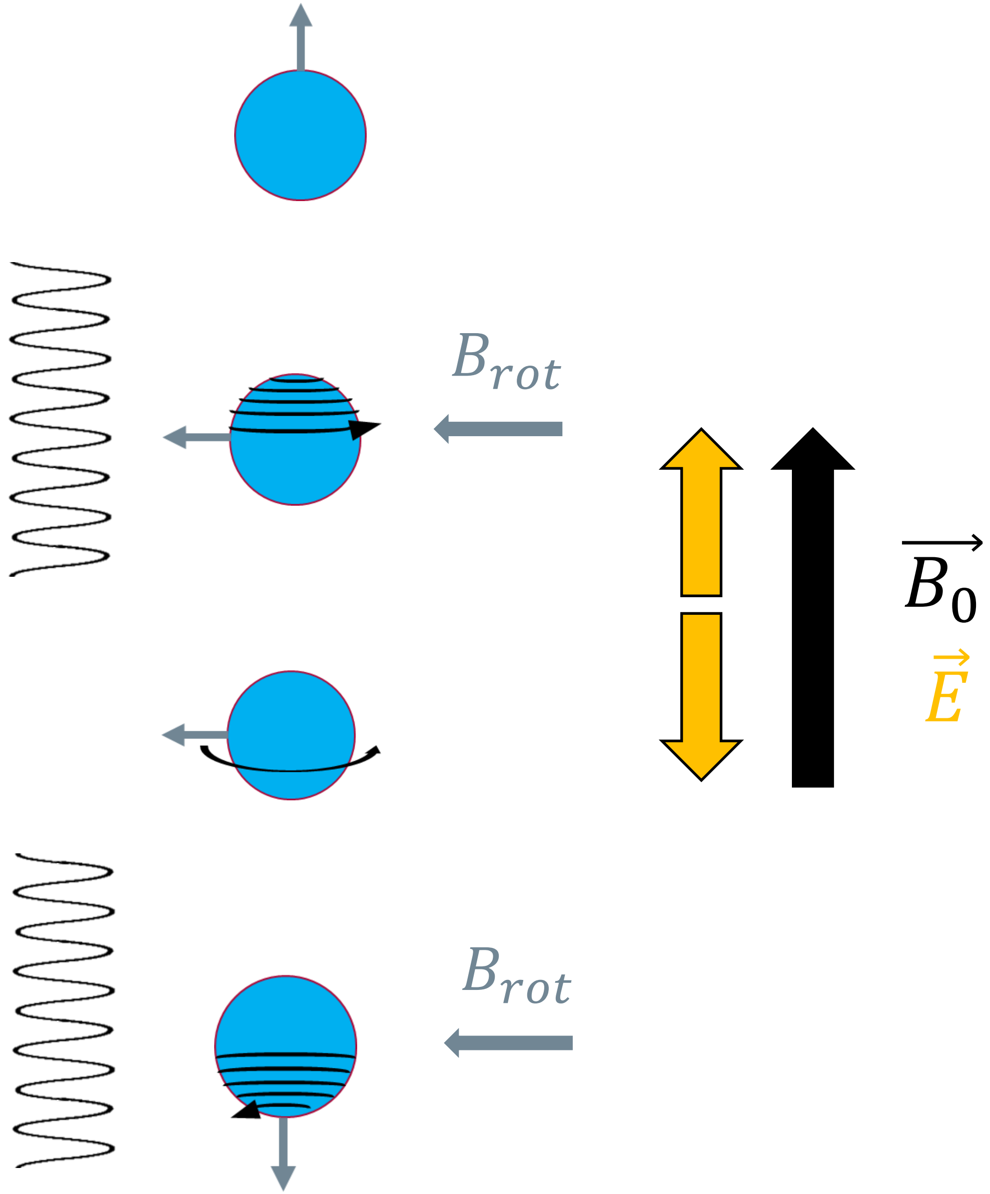


$$hf_{\uparrow\uparrow} = 2(\mu_n B_0 + d_n E)$$

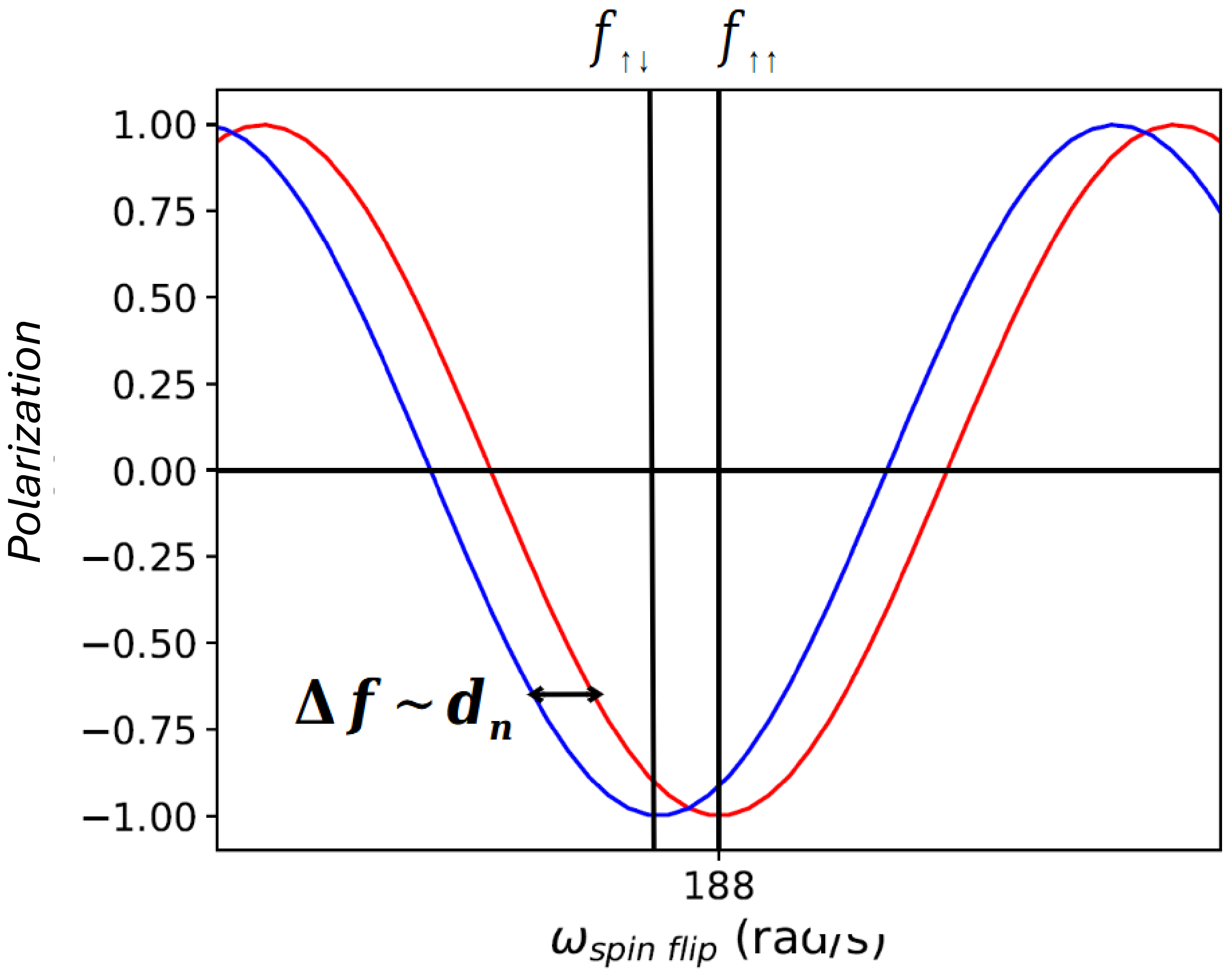
$$hf_{\uparrow\downarrow} = 2(\mu_n B_0 - d_n E)$$

$$\Rightarrow \quad d_n = \frac{h}{4E}\Delta f$$

Measuring frequency: Ramsey method of separated oscillatory fields



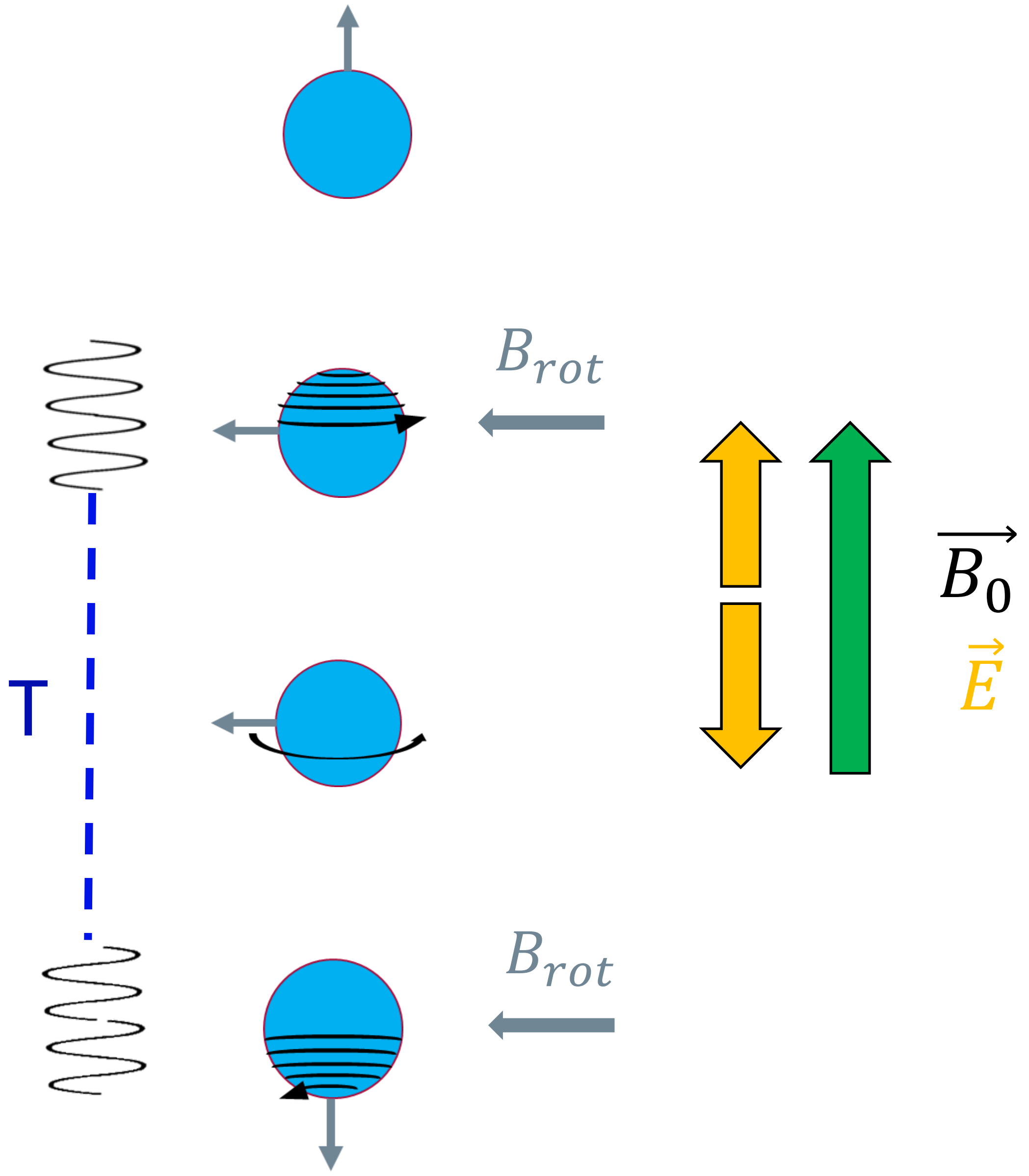
Measuring frequency: Ramsey method of separated oscillatory fields



Please note:
exagerated scales!

Measuring frequency: ramsey method of separated oscillatory fields

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$



Ultra-cold neutrons

PSI

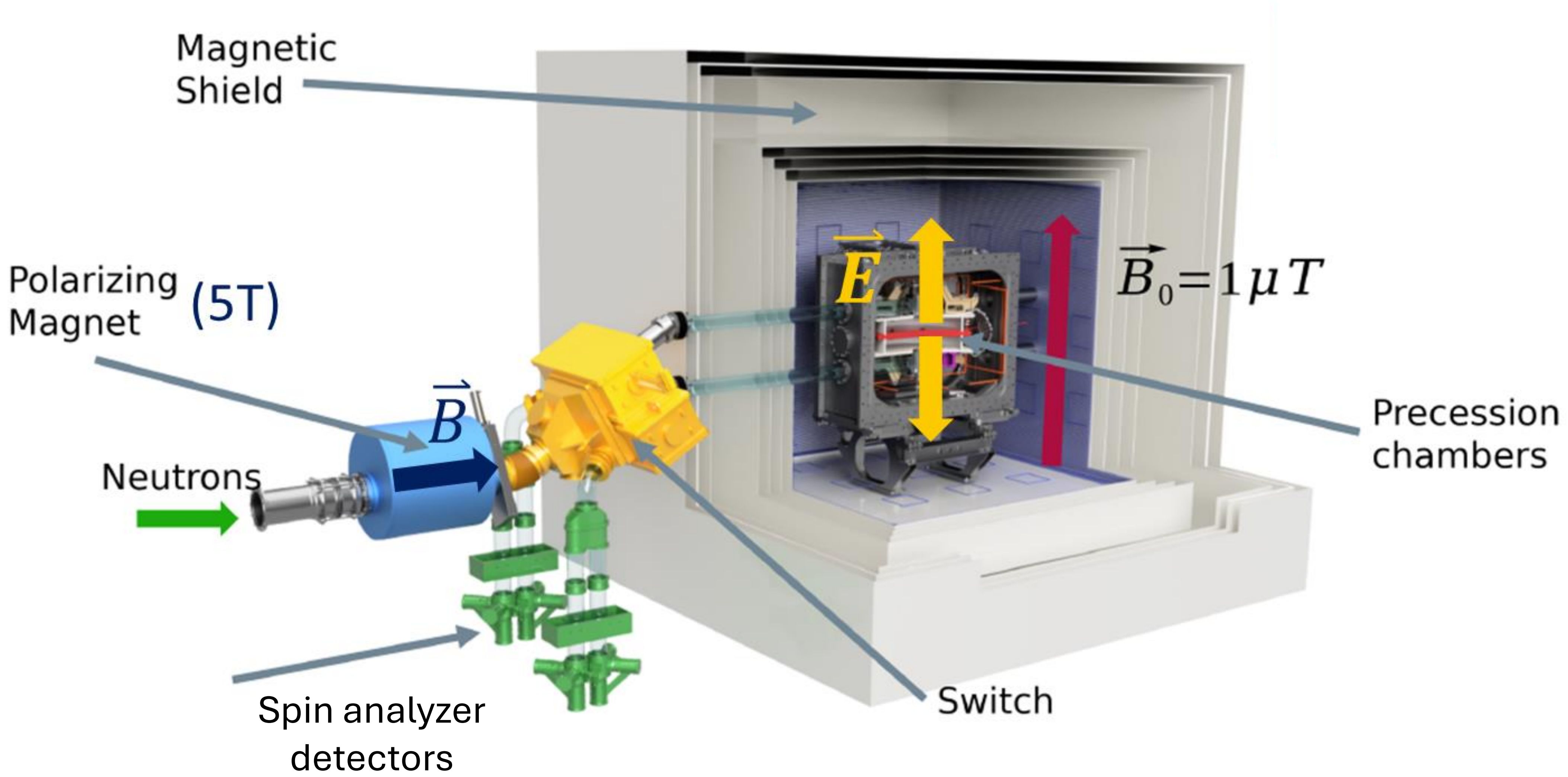
- Energy $E_n < 300\, neV$

- Total reflection

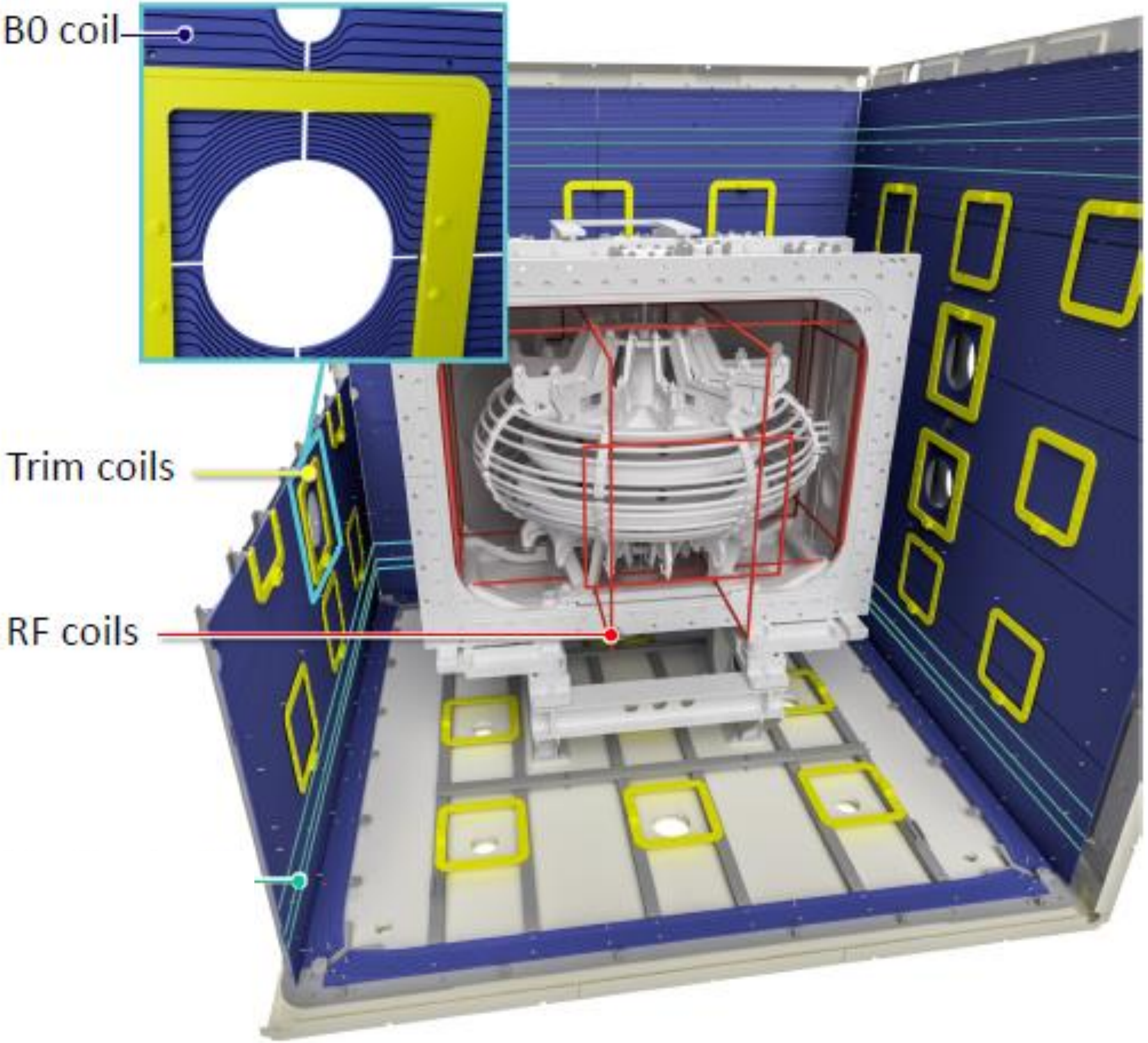
$$sin\Theta_{refl} < \sqrt{\frac{V_{nuclear}}{E_n}}$$

- UCN source at the Paul Scherrer Institute!

An overview of the n2EDM experiment

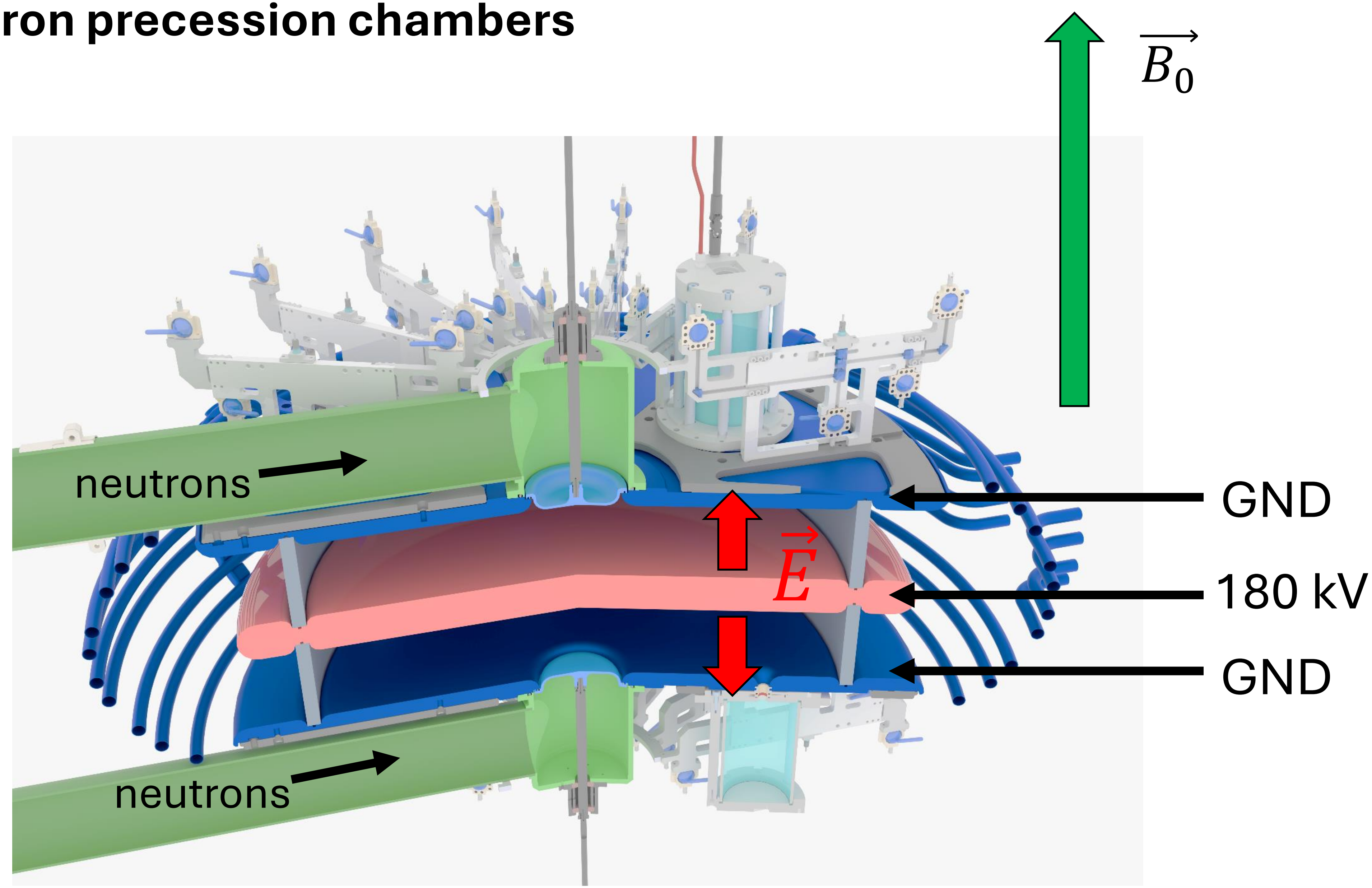


The B0 and trimcoil system



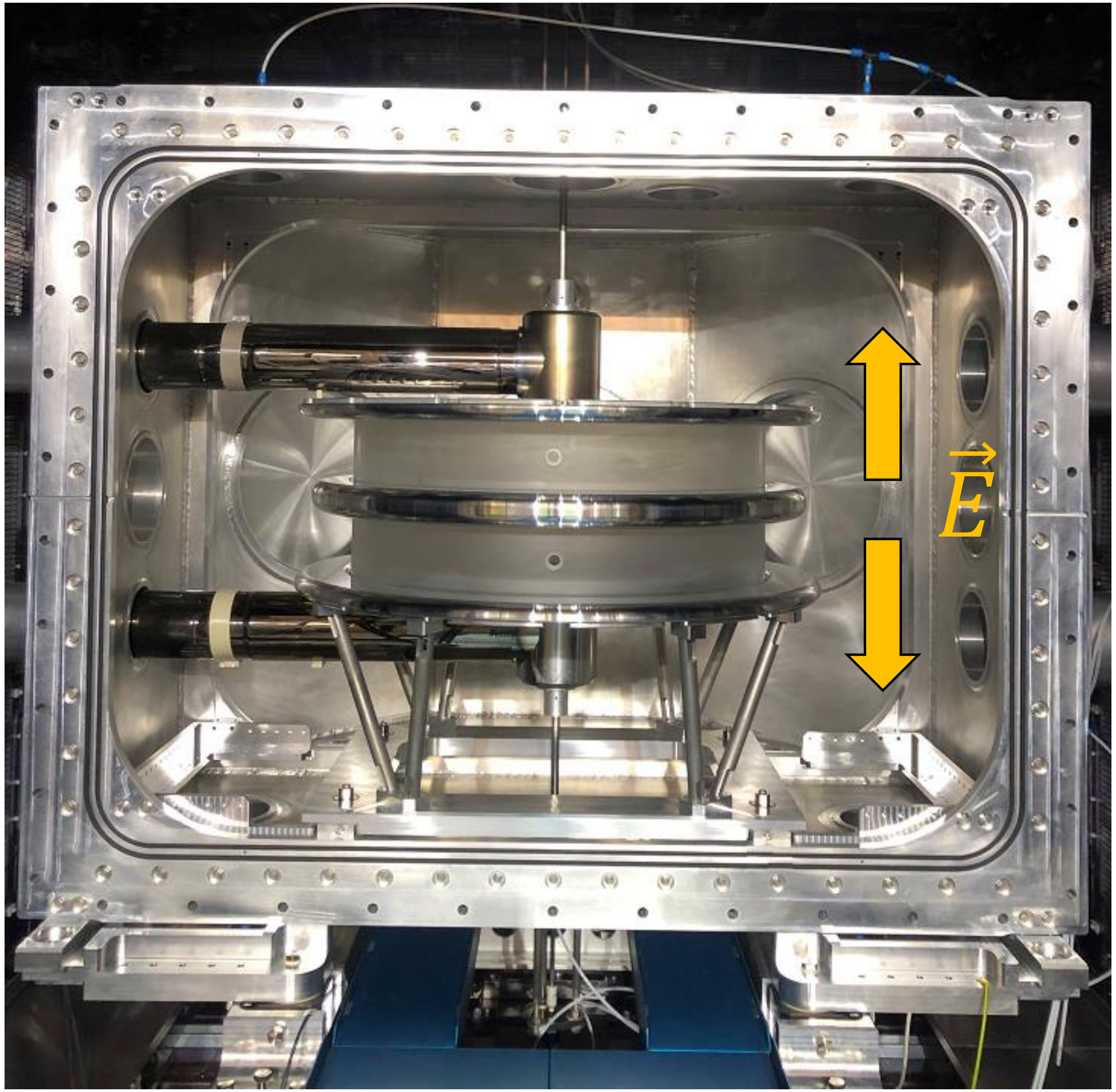
$$\overrightarrow{B_0} = 1\ \mu\mathrm{T} \cdot \hat{z}$$

Neutron precession chambers



Neutron precession chambers

$\overrightarrow{B_0}$



One challenging aspect: field non-uniformity

- Double chamber setup + B_0 non-uniformity → systematic effect

$$f_{\uparrow\uparrow} = 2(\overbrace{\frac{\mu_n}{h} B_0}^{\approx 30\text{Hz for } 1\ \mu\text{T}} + \underbrace{\frac{d_n}{h} E}_{\approx 7\ \text{nHz}})$$

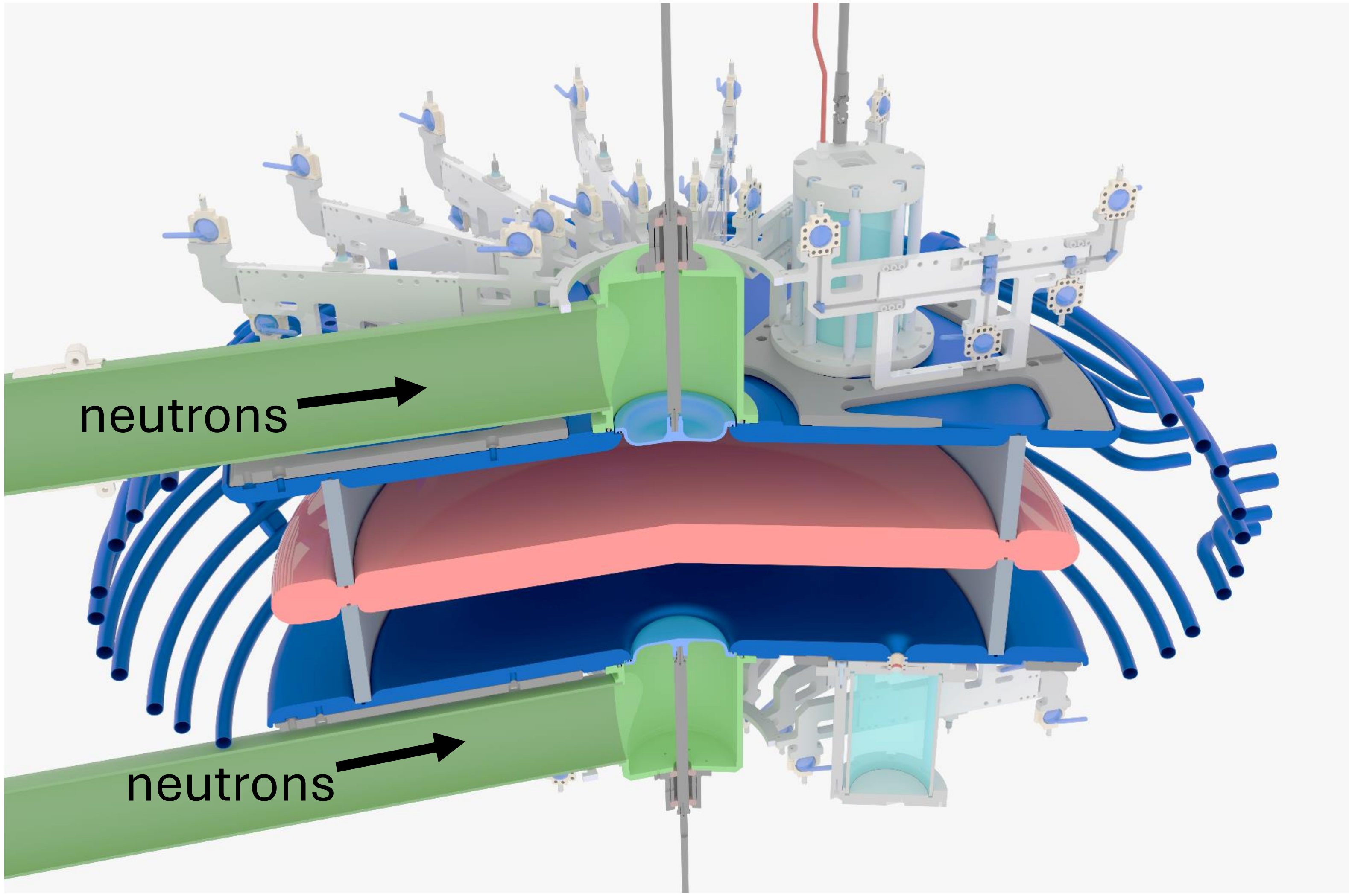
!

$$d_n = \frac{h}{4E} \Delta f$$

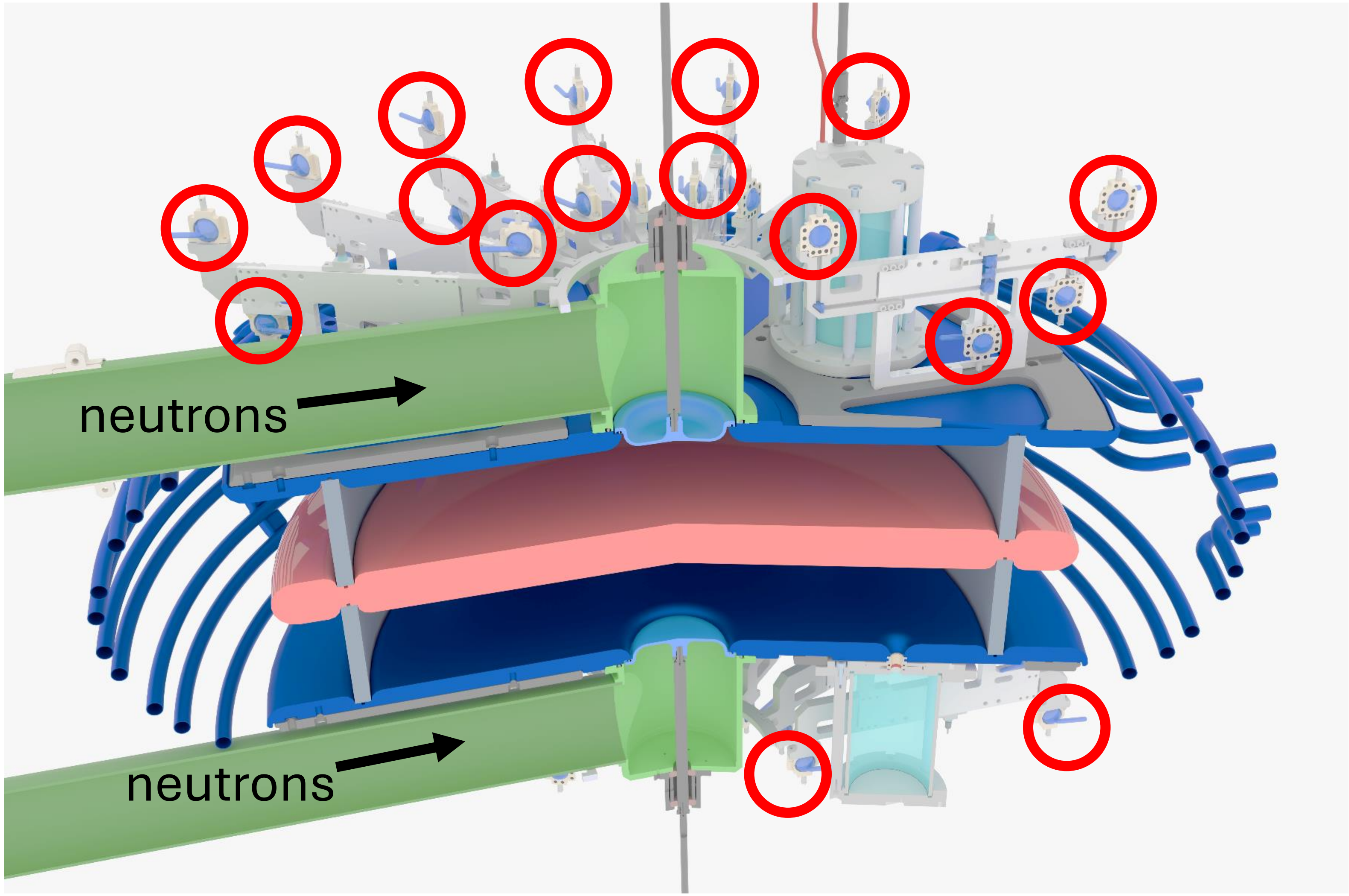
if $d_n \sim 10^{-26}\ e\ cm$ & $E \sim 10$ kV/cm

- Solution: monitor the field non-uniformities

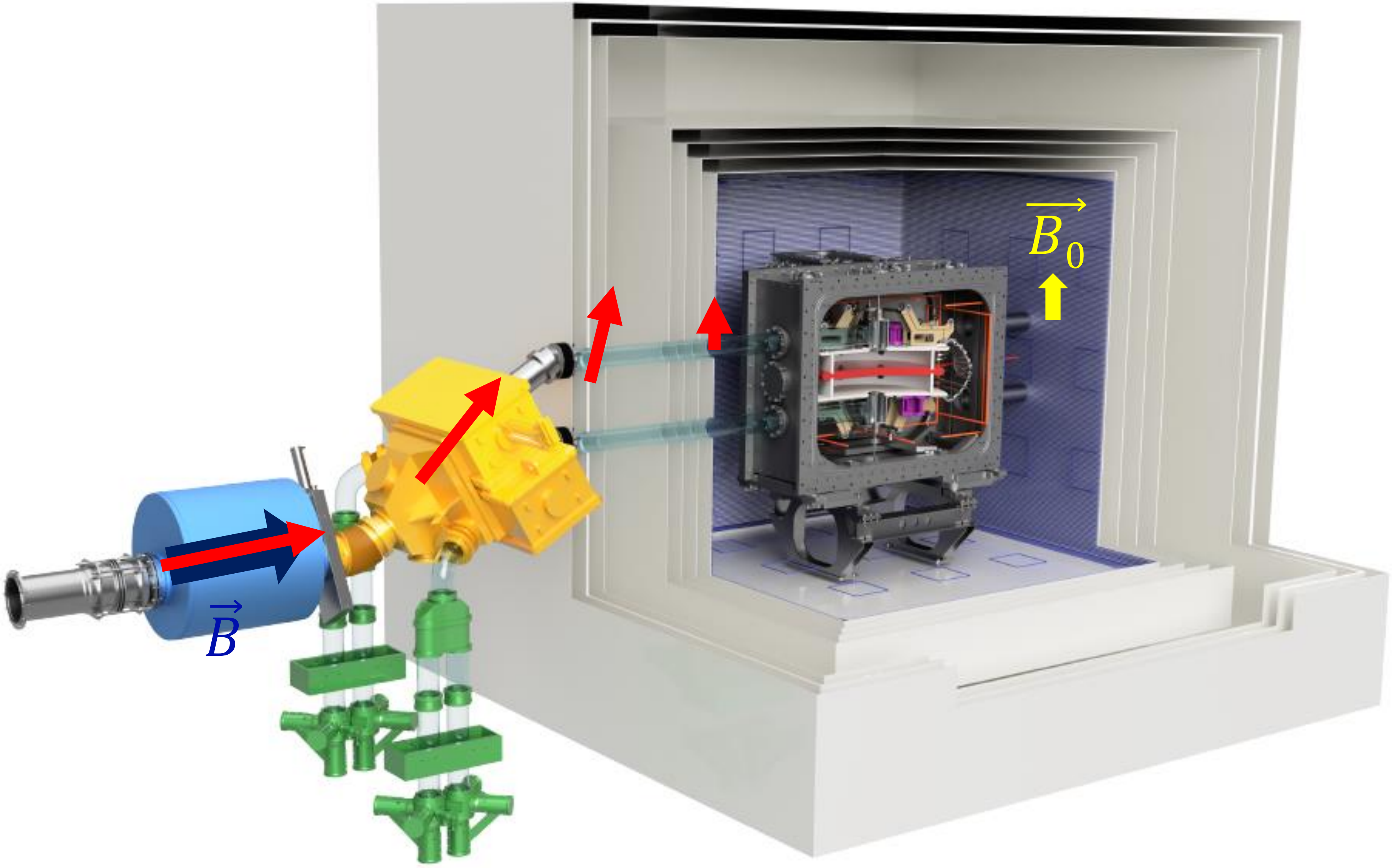
Mercury co-magnetometer



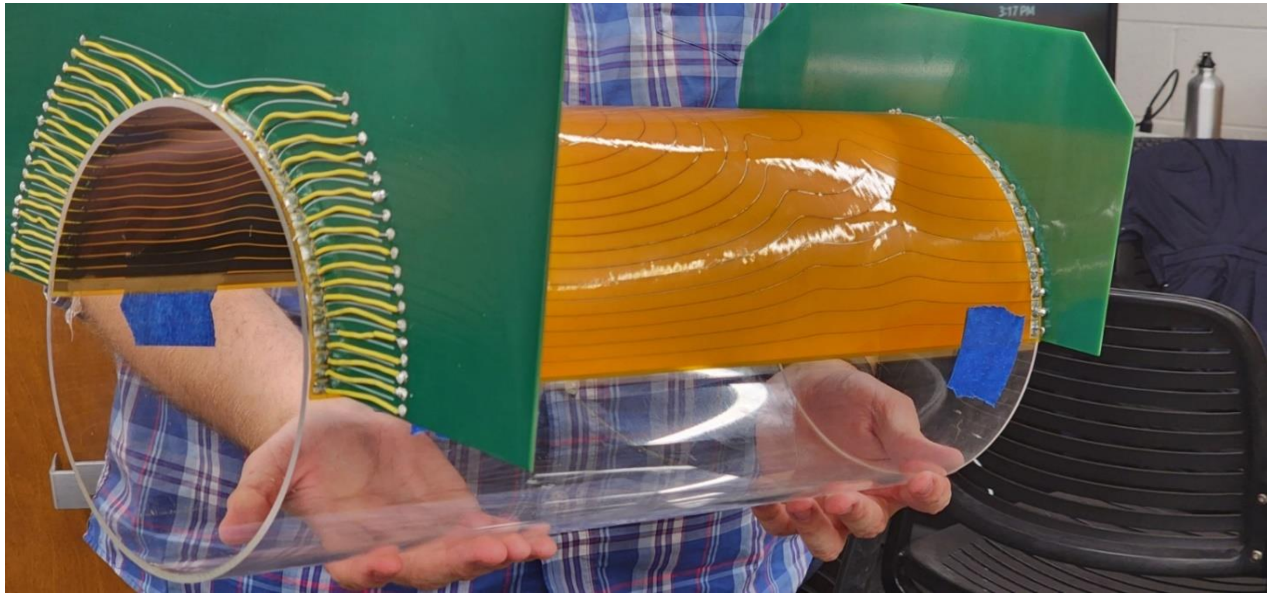
Mercury co-magnetometer

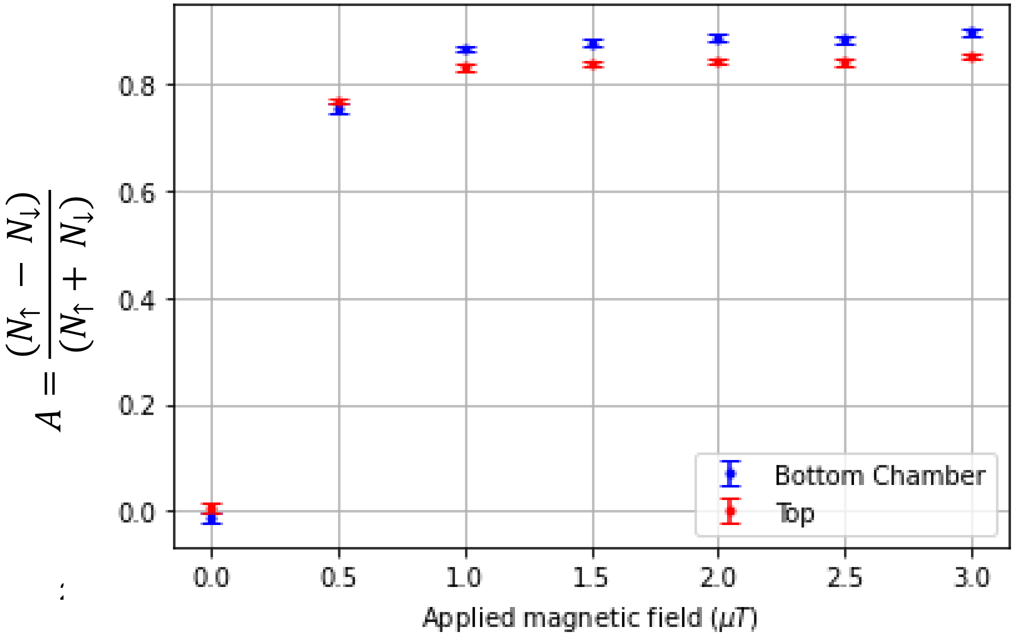


Another challenging aspect: spin transport



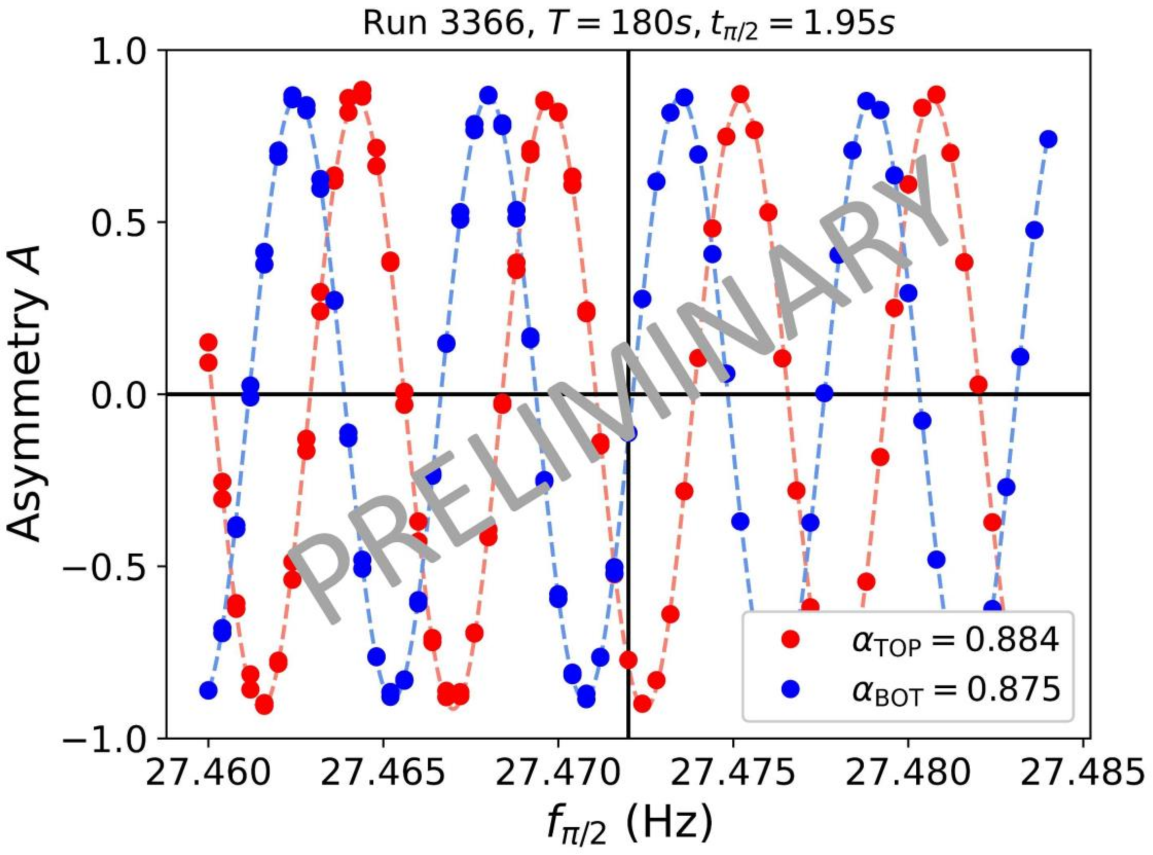
The spin transport coils

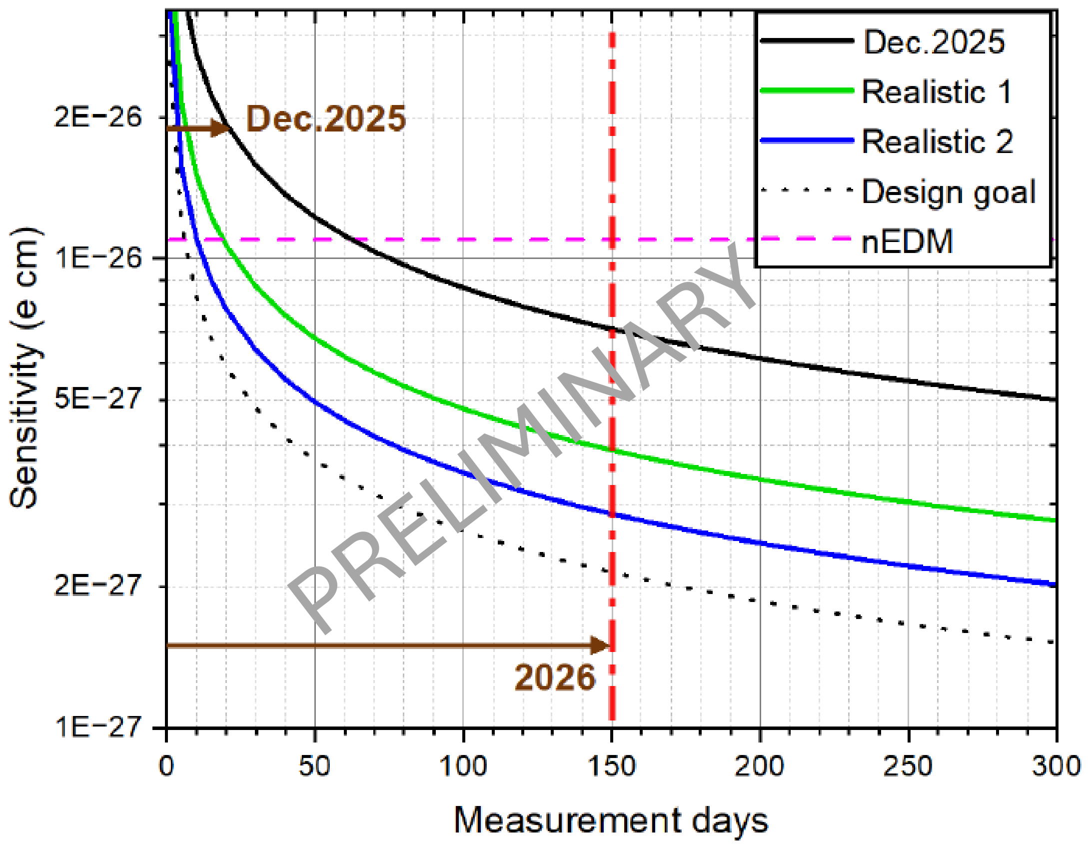




Achieved efficiency: >99% !

Present situation: we're ready for taking data!





Next: sensitivity goal 10^{-27} e cm!

Thanks for your attention!

Time for a few questions ☺

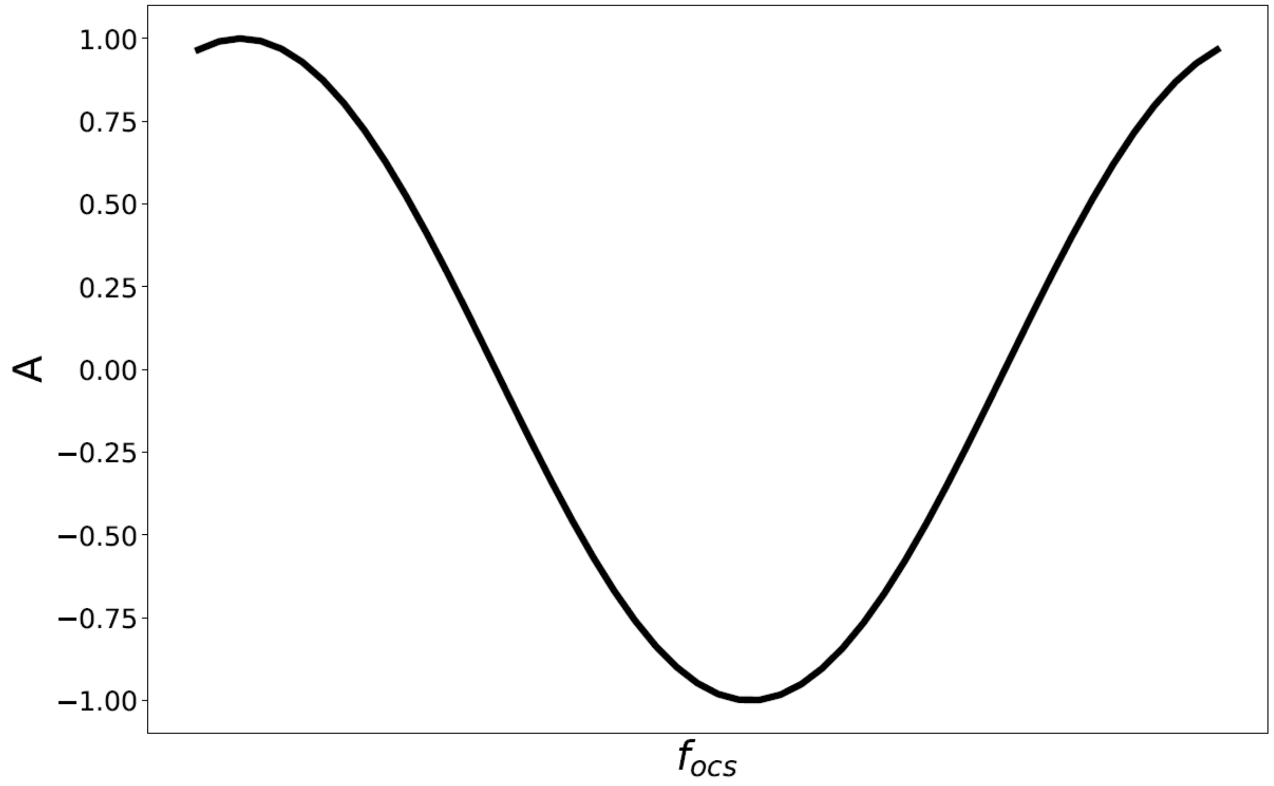
Gian Luca Caratsch
Bormio, 20 January 2026

Backup

The asymmetry

$$A = \frac{(N_{\uparrow} - N_{\downarrow})}{(N_{\uparrow} + N_{\downarrow})}$$

$$A = P \times \alpha$$



parameter	Dec.2025	Realistic 1	Realistic 2	Design
pulse period (s)	400	350	350	300
pulses/day[i]	209	239	239	281
UCN/pulse	66'000	79'000	111'000[ii]	121'000
storage time (s)	180	180	180	180
high voltage (kV)	110	140	150	180
visibility α	0.84	0.85	0.85	0.8
NLK W1[iii]	open	closed	closed	closed
data taking efficiency[iv]	0.55	0.80	0.90	1.00
daily sensitivity $\times 10^{-26}$ e·cm	8.7	4.8	3.5	2.6

Table 2: Parameters used in the sensitivity plot Fig. 16 for the different scenarios:
1) December 2025 - achieved averaged performance of the apparatus and data taking over 21 days in December 2025.
2) Realistic 1: Scenario achieved with all parameters in 2025 and area West served subsequently. Shortening the proton pulse period will be possible with some optimization.
3) Realistic 2: in addition, UCN performance with all electrodes well coated and O-rings with higher Fermi potential, as measured in Oct.2025.
4) Design parameters as published in the Technical Design Report [3, 11].

iv) The data taking efficiency was low in Dec.2025, as we had to open the vacuum tank during that time and replace parts due to high-voltage damage, 3 days of unplanned proton accelerator down time, other unusual losses were due to Hg laser-lock loss and one detector DAQ problem, and also includes a naive, very conservative accounting for different statistics in the two E-field polarities, namely taking simply the lower integral number of UCN counts. We assume that most of these problems are solved and hence assume better efficiency for 2026.

Ultra-cold neutrons

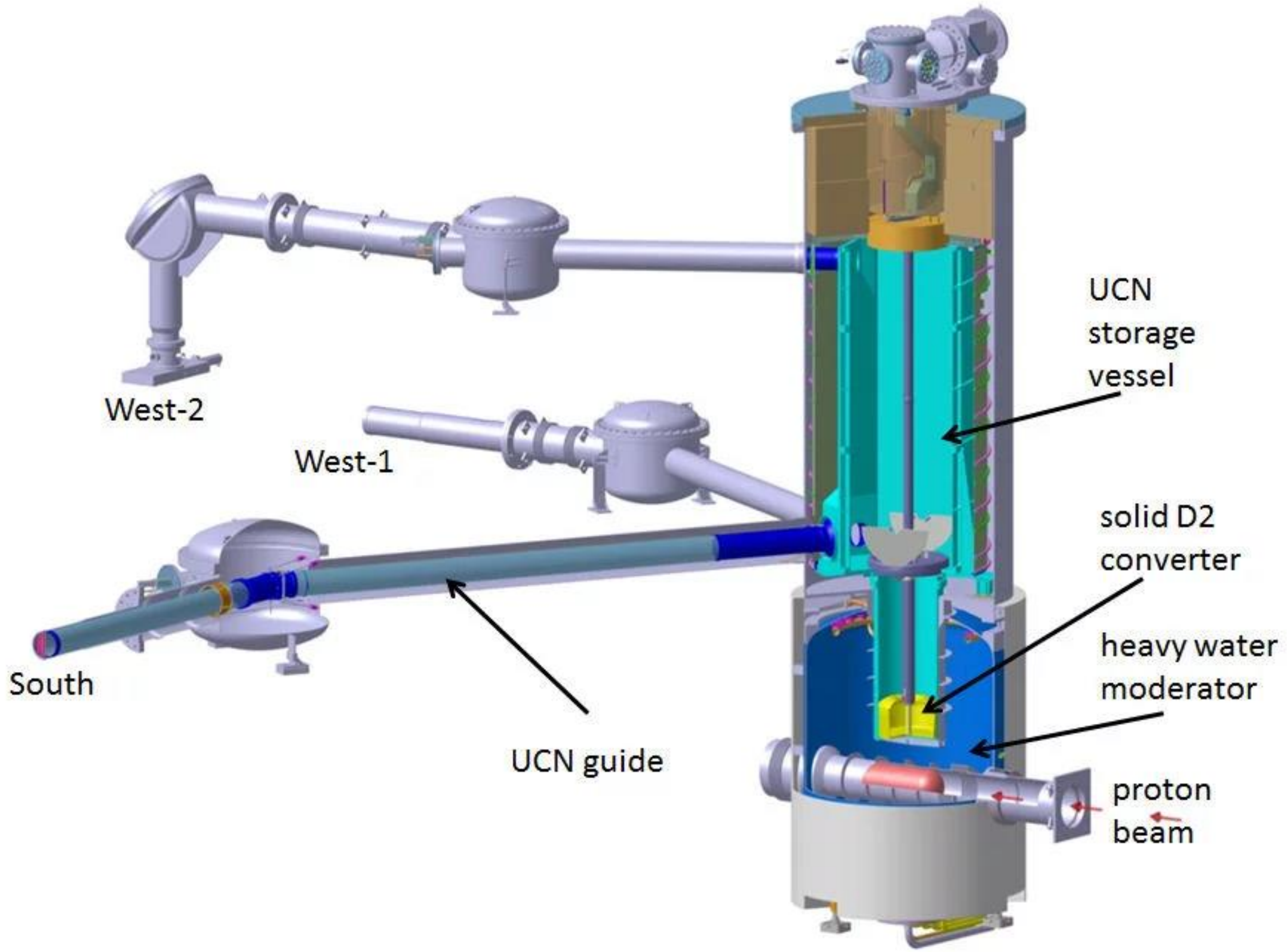
Properties

< 300 neV

5 m/s

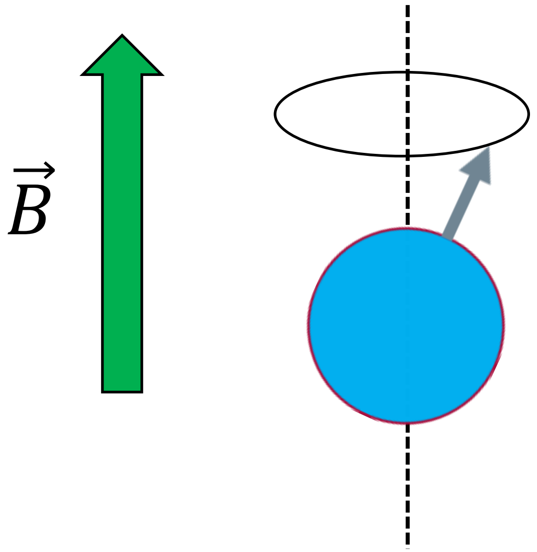
Reflected off materials: storage possible!

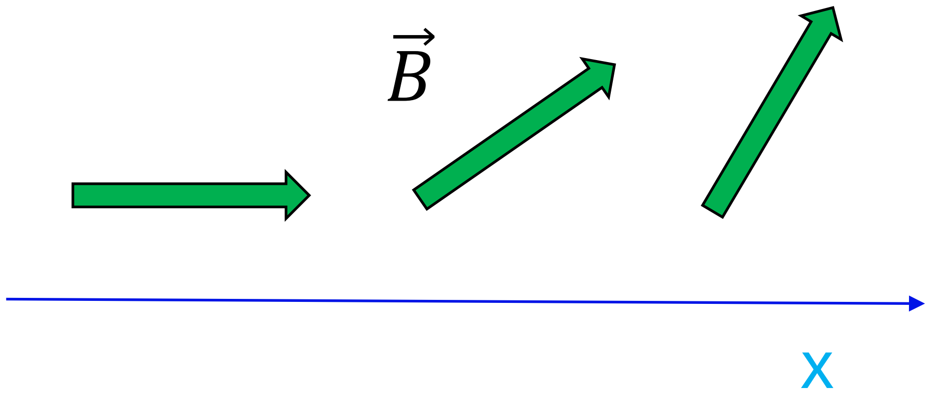
At PSI: ultra-cold neutron spallation source →



Spin transport = high adiabaticity

$$K = \frac{\omega_L}{\omega_\theta}$$





STC efficiency calculation

PSI

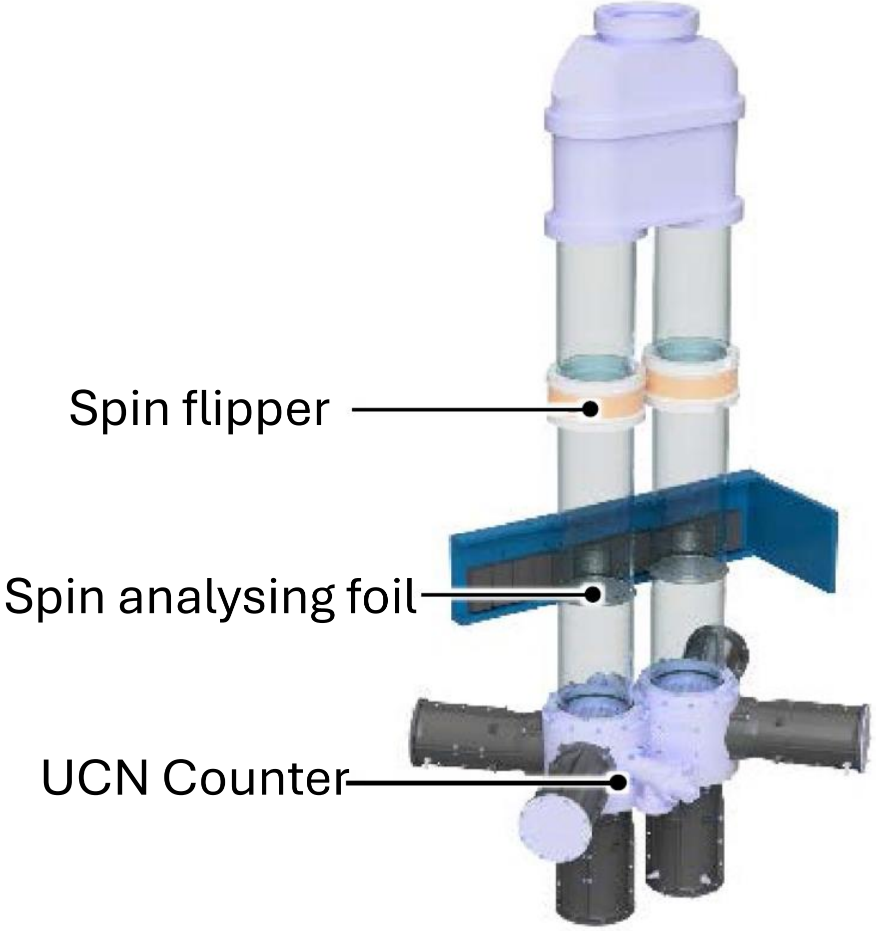
$$A(t) = A_d \cdot \epsilon_{\mathrm{STC}}^2 \cdot (1 - D(t)) = A(0) \cdot e^{-t/T_1}$$

Direct shot into the detectors (without storage)

Depolarization in the chambers

Neutron detectors @n2EDM

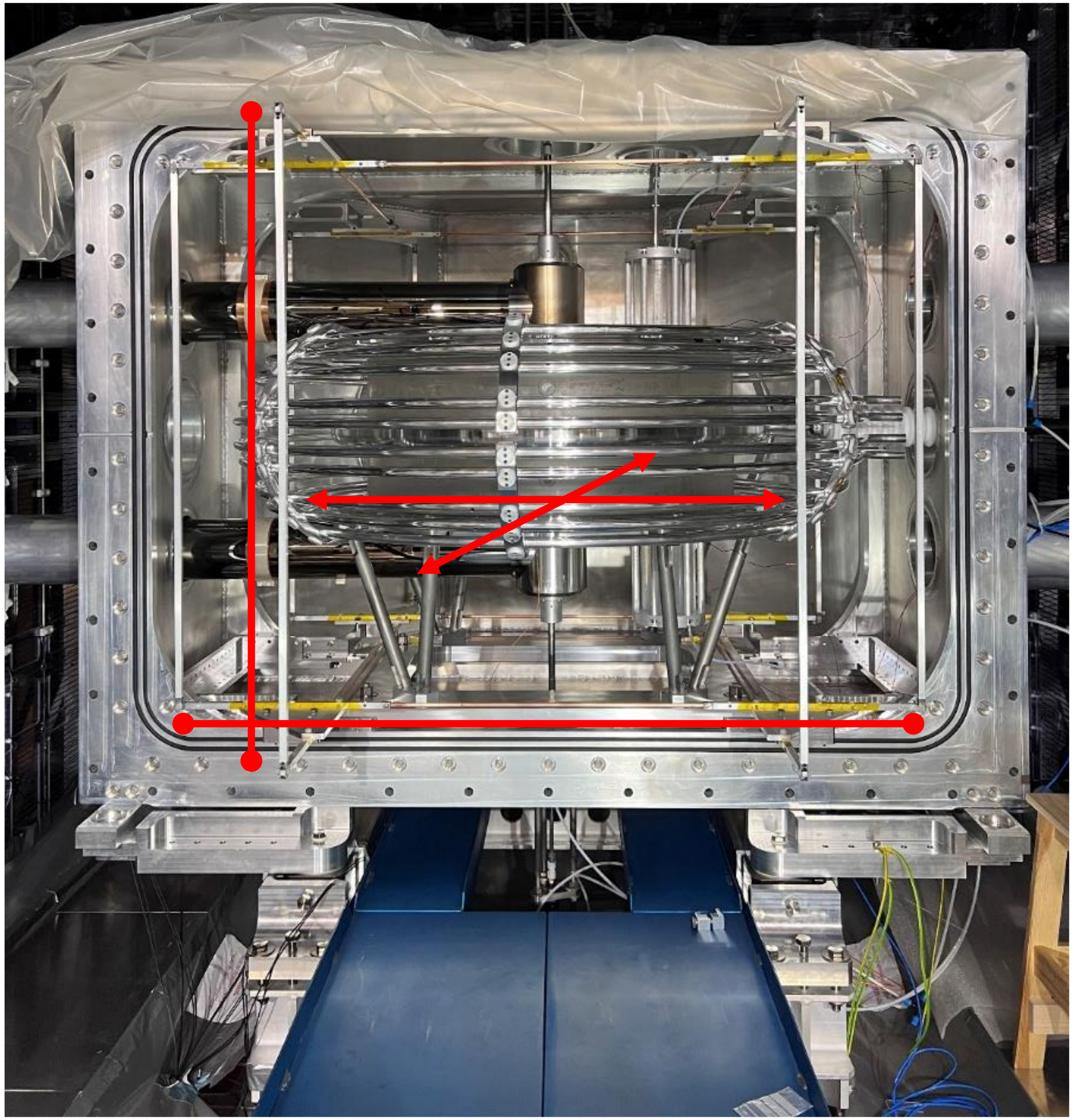
Spin dependent neutron detection



- 2 Detectors per chambe
  1. Spin Up
  2. Spin Down
- Gaseous detector
- Capture neutrons:

  $\mathrm{n} + {}^{3}\mathrm{He} \rightarrow \mathrm{p} + {}^{3}_{0}\mathrm{H}$
- Scintillation in CF_4

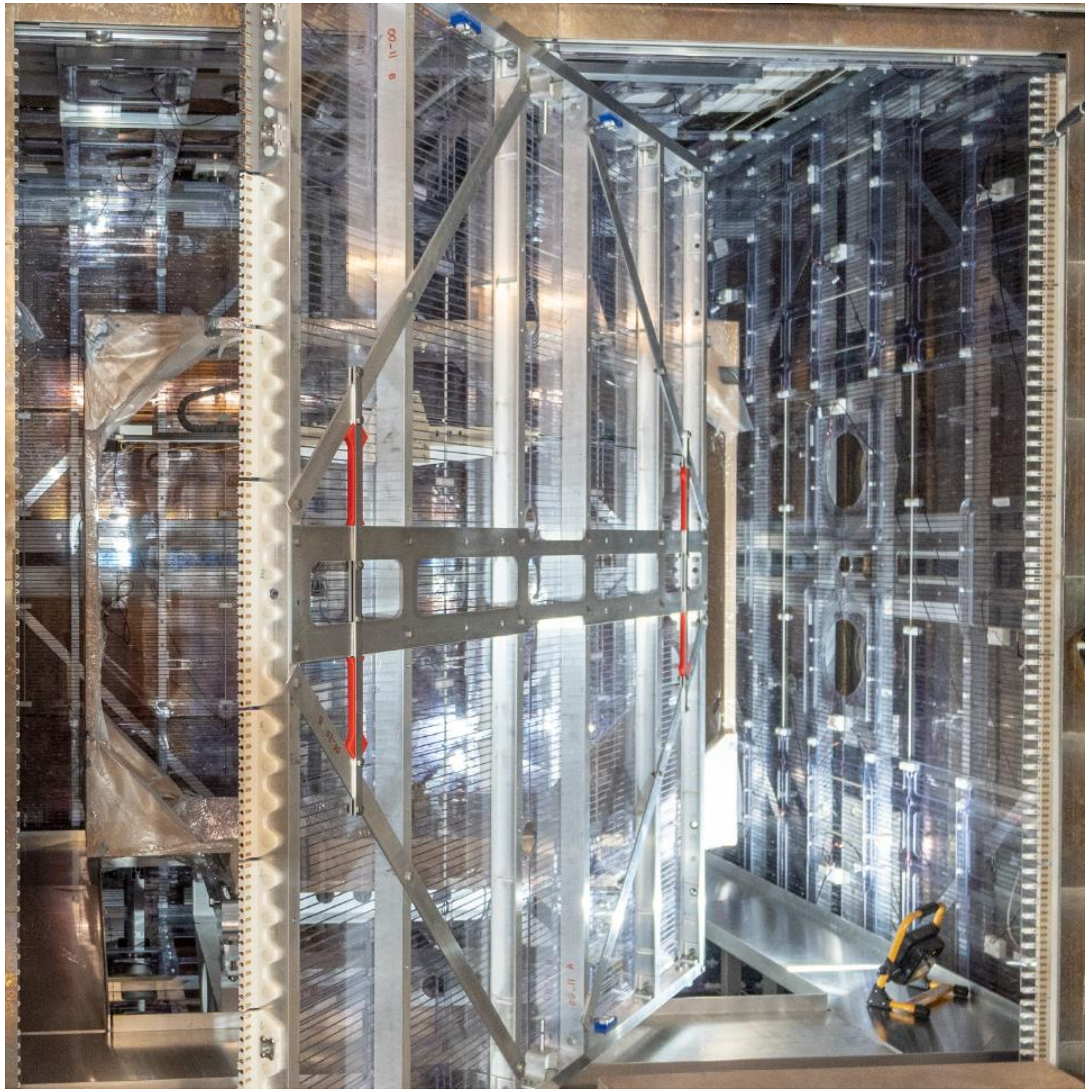
Spin-flip rotating field

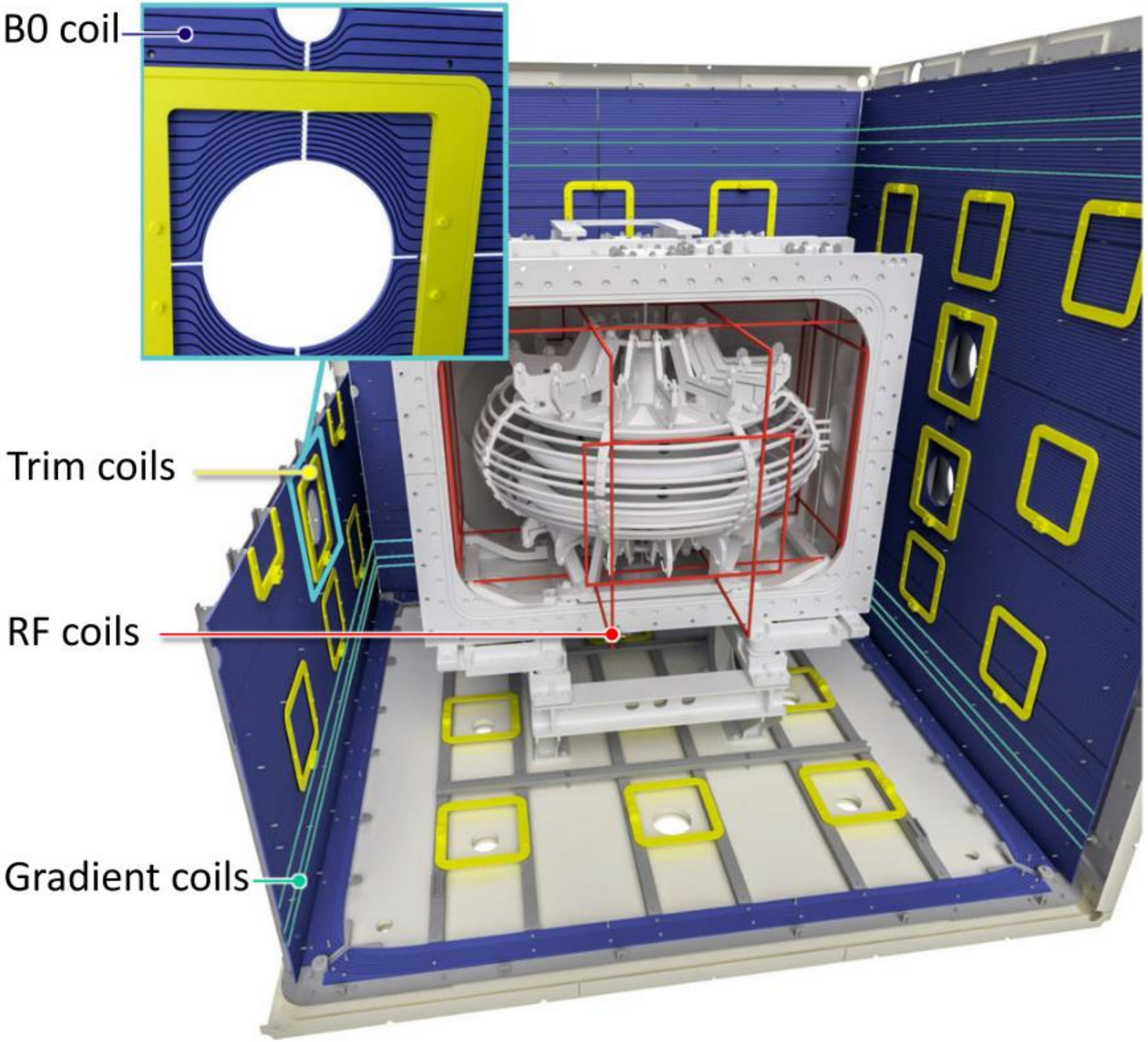


Perform “Ramsey cycle”

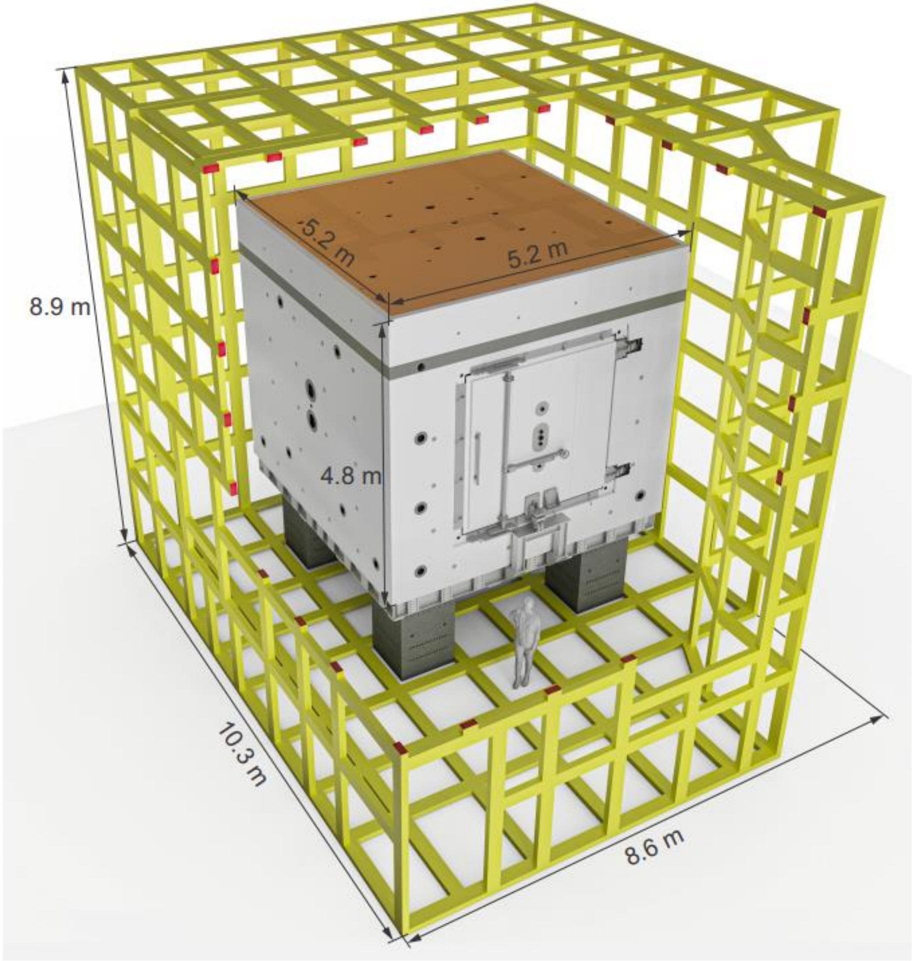
- 2 independent coils in to produce $B_{\perp}$ in x, y
- **Same** spin-flip pulse for TOP and BOT chambers

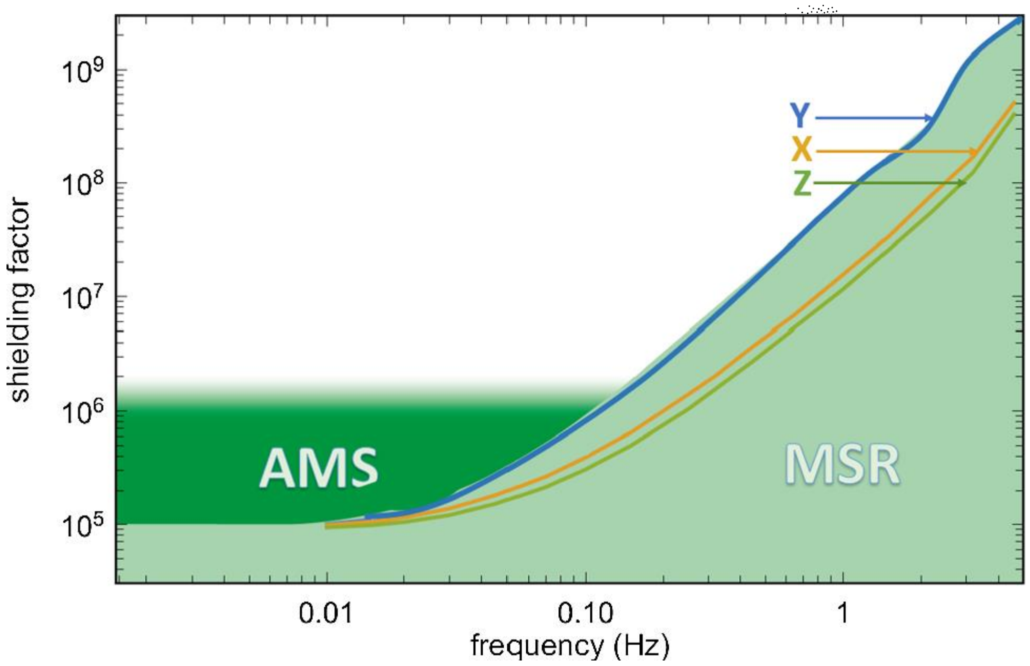
B0 coil





Active magnetic shield (AMS)



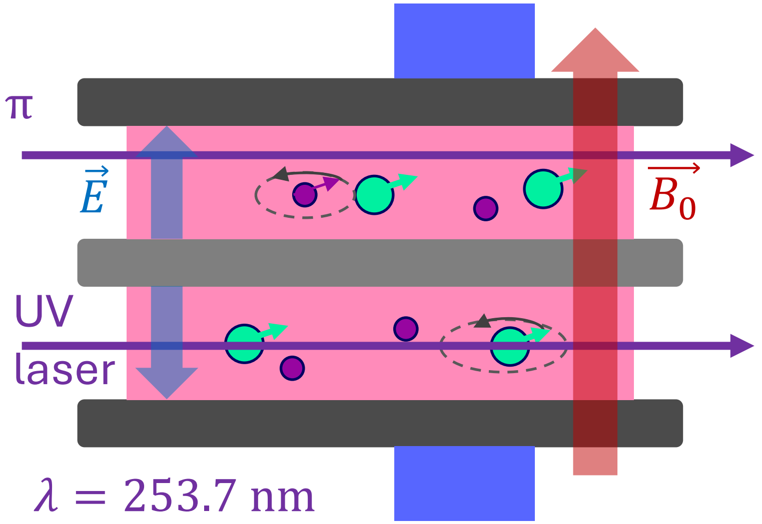


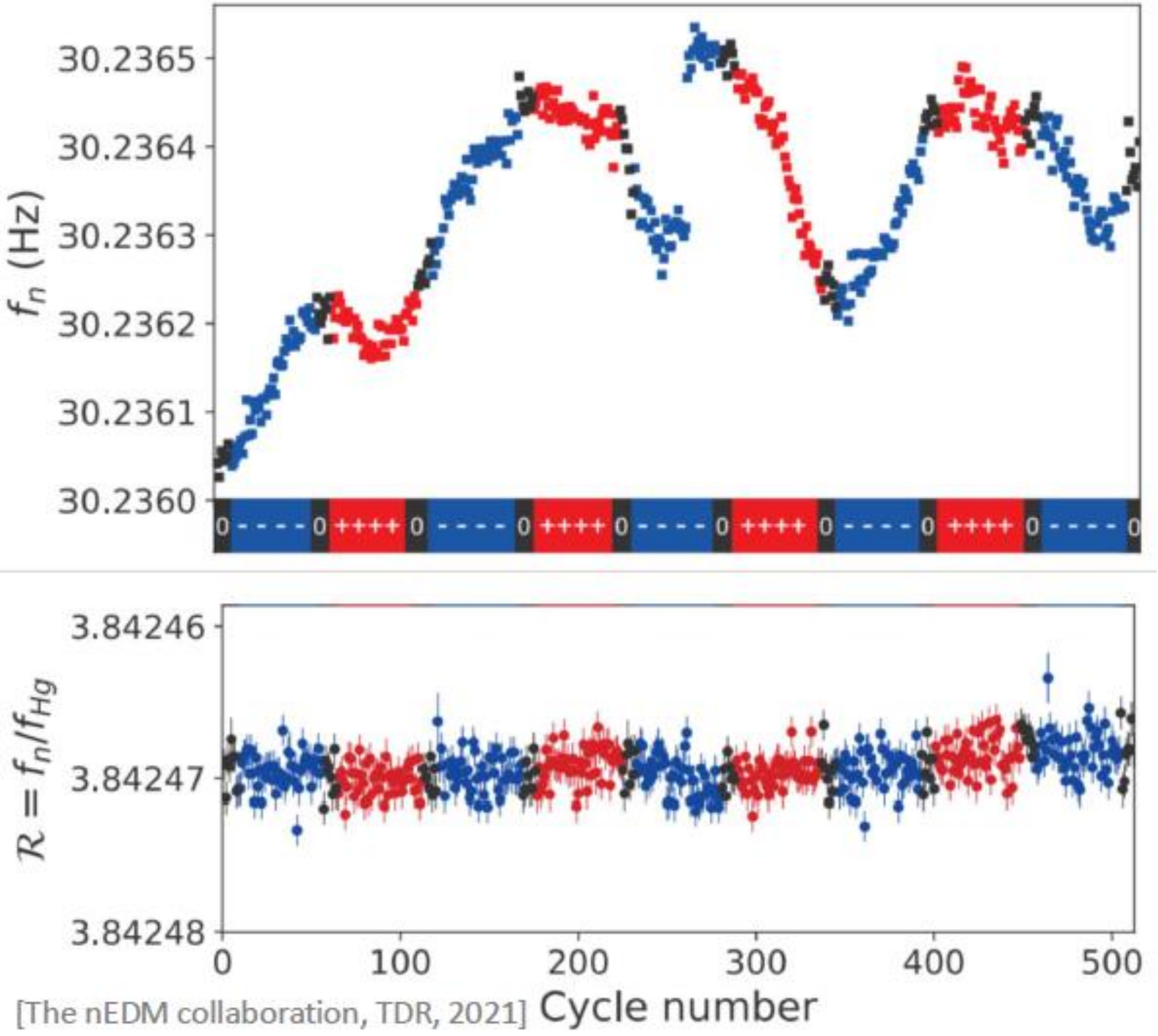
- 8 independent coils
- 55 km of wires
- kW heat dissipated

Eur. Phys. J. C **83**, 1061 (2023). https://doi.org/10.1140/epjc/s10052-023-12225-z

Optical Detection of f_{Hg}

1) spin-polarize the ^{199}Hg atoms along the magnetic field axis, spins stay oriented in the holding $\overrightarrow{B_0}$ field
2) release ^{199}Hg into the precession chambers
3) apply RF pulse in xy-direction to flip spins by 90°
4) spins precess at Larmor frequency
5) Probe with a linearly (π) polarized UV laser

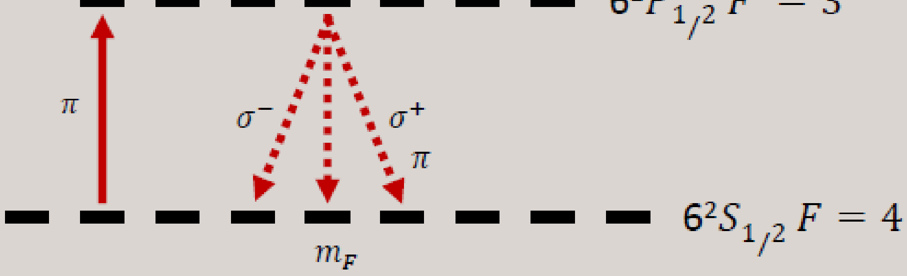




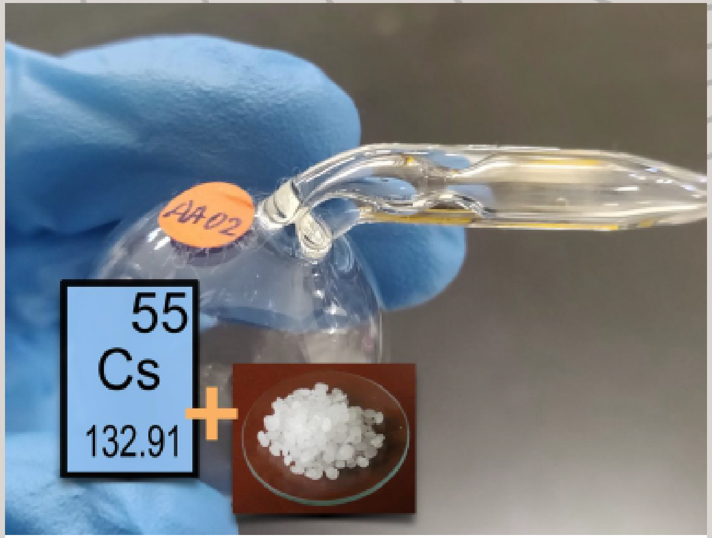
[The nEDM collaboration, TDR, 2021]

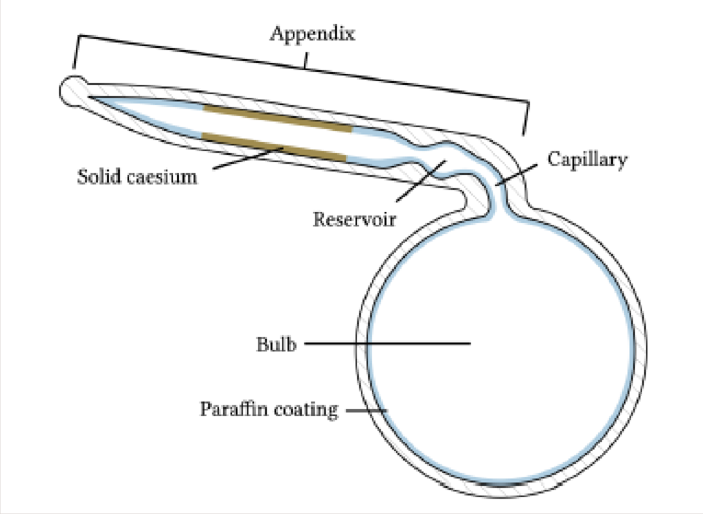
The Cesium Magnetometer

- Each glass cell is filled with Cesium & coated in paraffin
- Cs atoms are optically pumped into alignment with linearly polarized laser light (894 nm) on the D1 transition ($F = 4 \rightarrow F' = 3$)



Selection rules: π light drives transitions with $\Delta m_F = 0$, while σ± correspond to $m_F = \pm 1$





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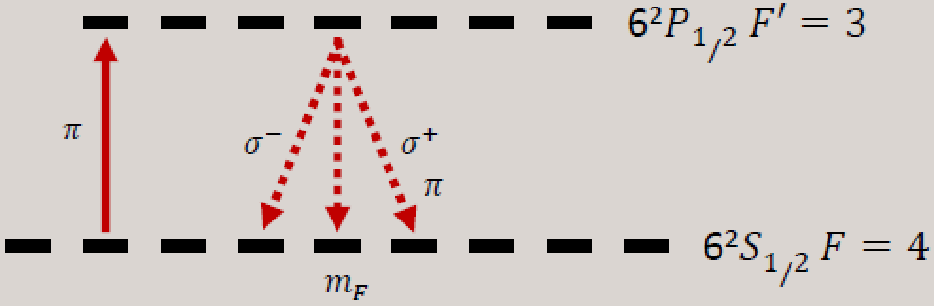
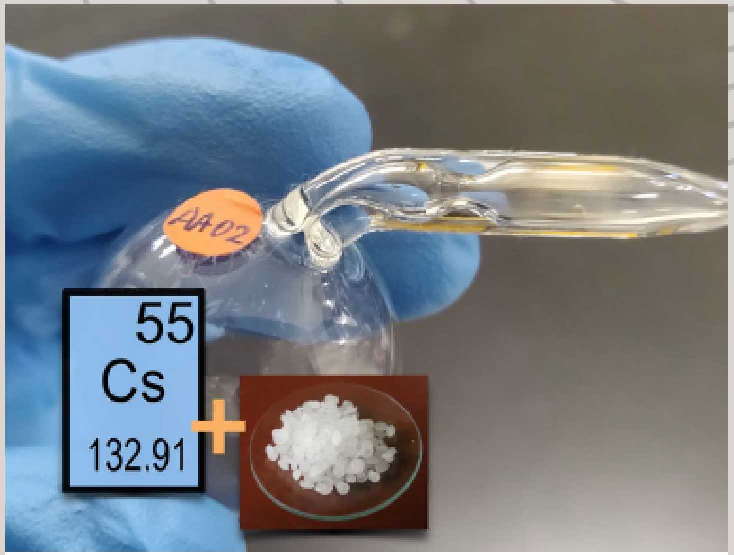
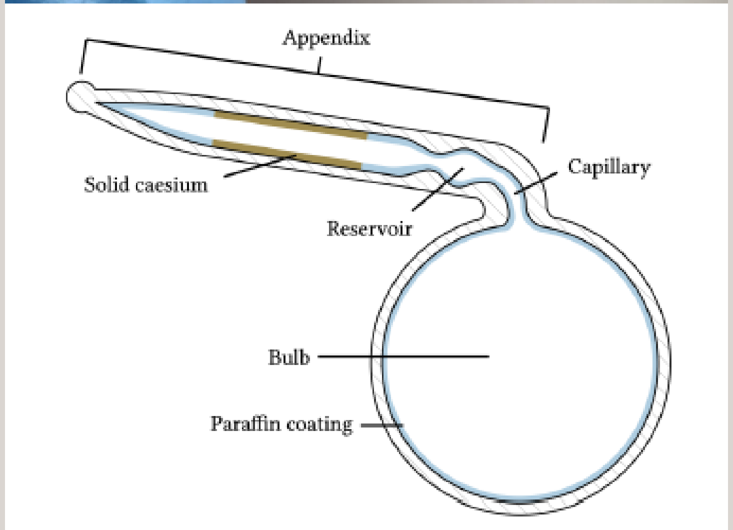


Optical pumping: Repeated absorption and spontaneous emission move atoms into the $m_F = \pm 4$ "dark states" which cannot be excited by π light





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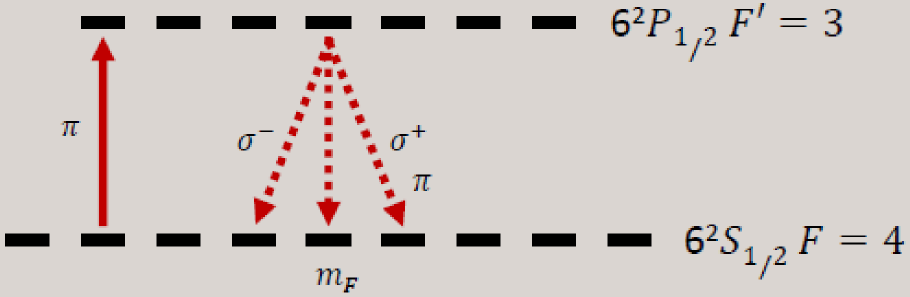
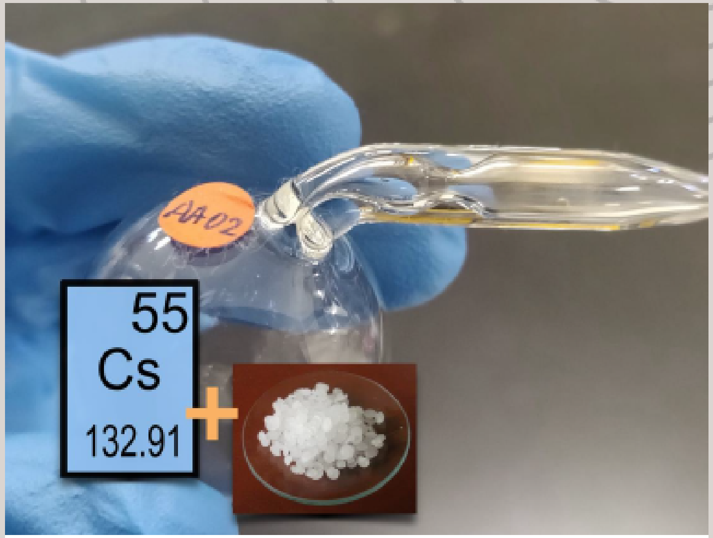
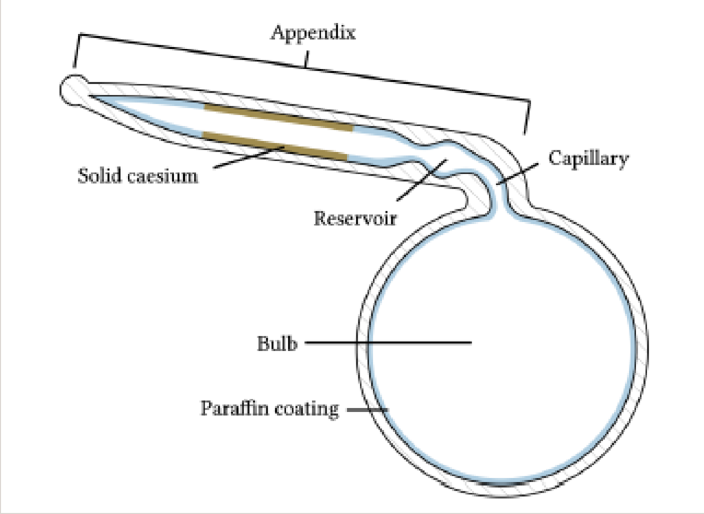


Magnetic sensitivity: In an external magnetic field $\vec{B}$, Zeeman splitting (energy levels of Cs atoms split) shifts the m_F sublevels by $\Delta E = m_F g_F \mu_B B$





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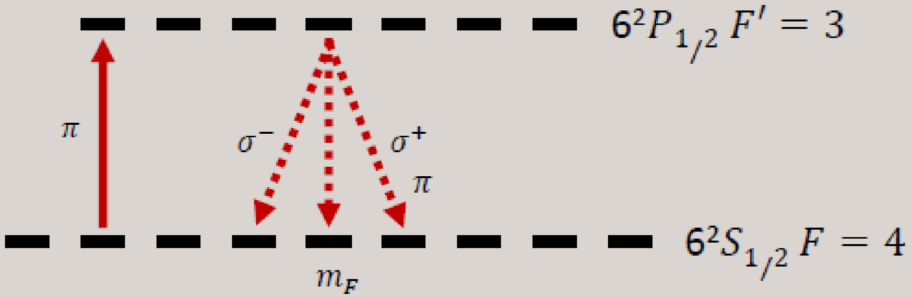
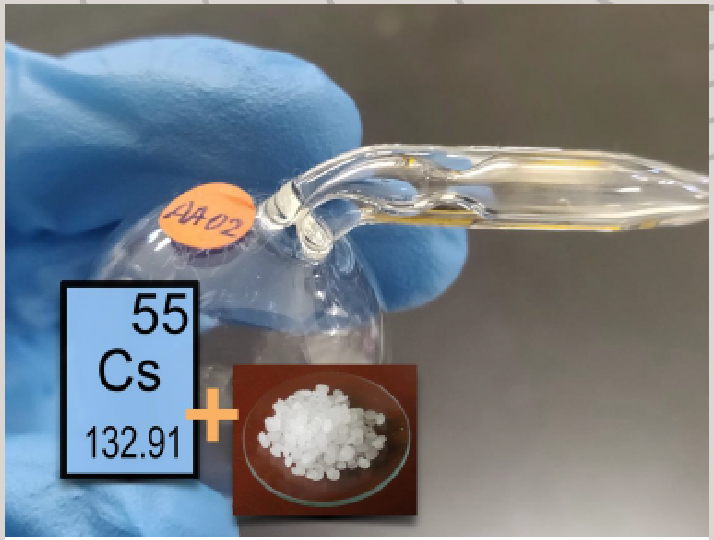
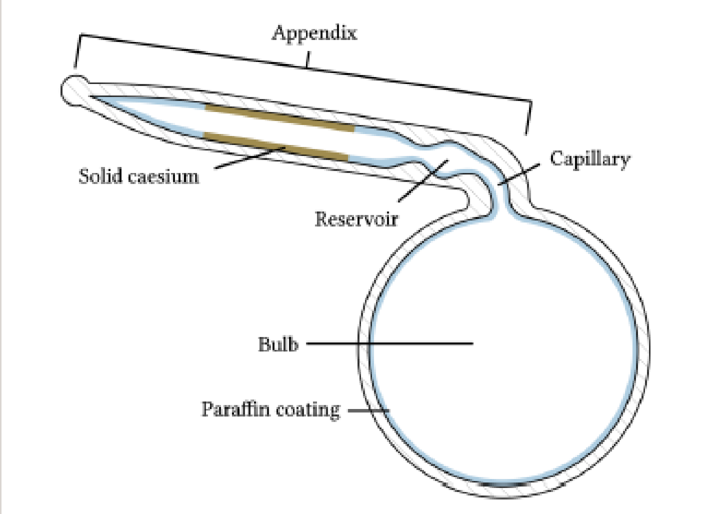


Larmor precession: The collective spin orientation of the ensemble then precesses around the magnetic field at a frequency $\omega_L = \gamma_F|\vec{B}|$





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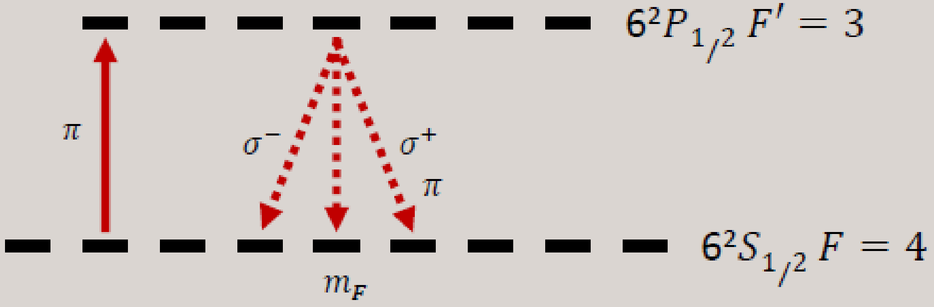

Detection principle: Probing the transmitted light gives a measure of this precession, which directly reflects the magnetic field strength (free alignment precession)