PSI Center for Neutron and Muon Sciences

n2EDM

The n2EDM Experiment: A high sensitivity measurement of the Neutron Electric Dipole Moment

Victoria Kletzl, on behalf of the nEDM collaboration

Discrete 2024, December 3, 2024

What is an EDM?

Electric Dipole Moment

Classically: displacement of charges

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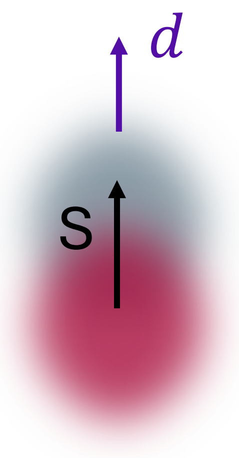
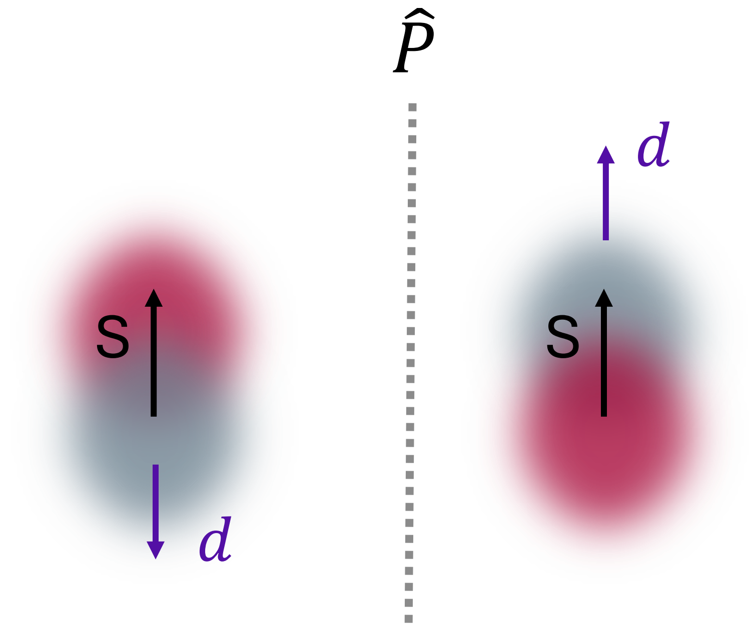


$$\hat{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E}$$

What is an EDM?

Electric Dipole Moment

Classically: displacement of charges



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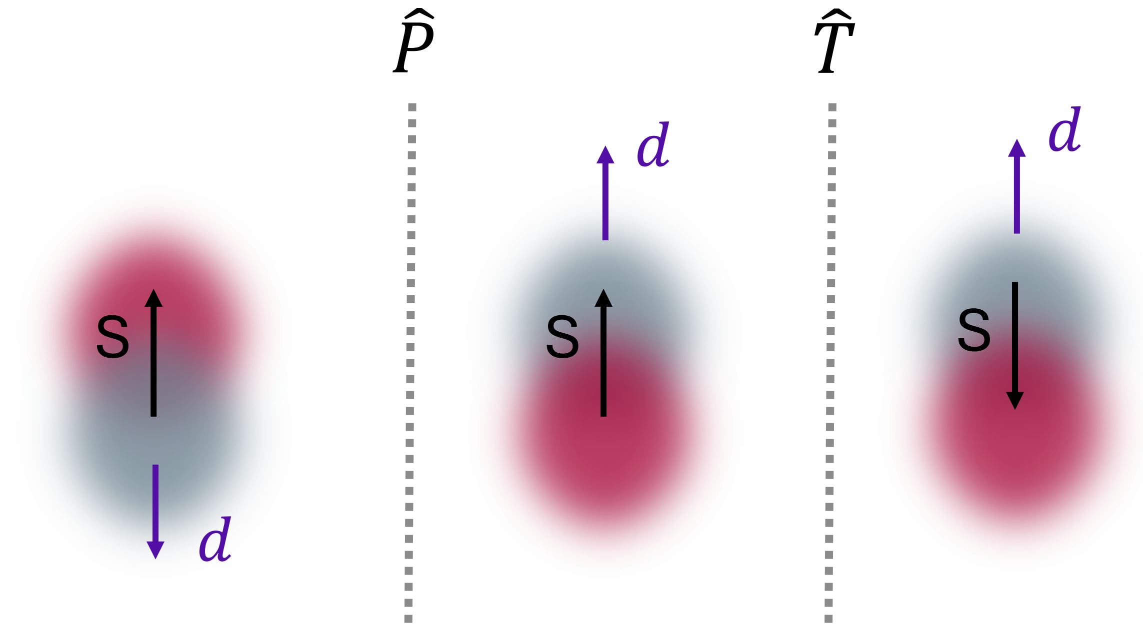
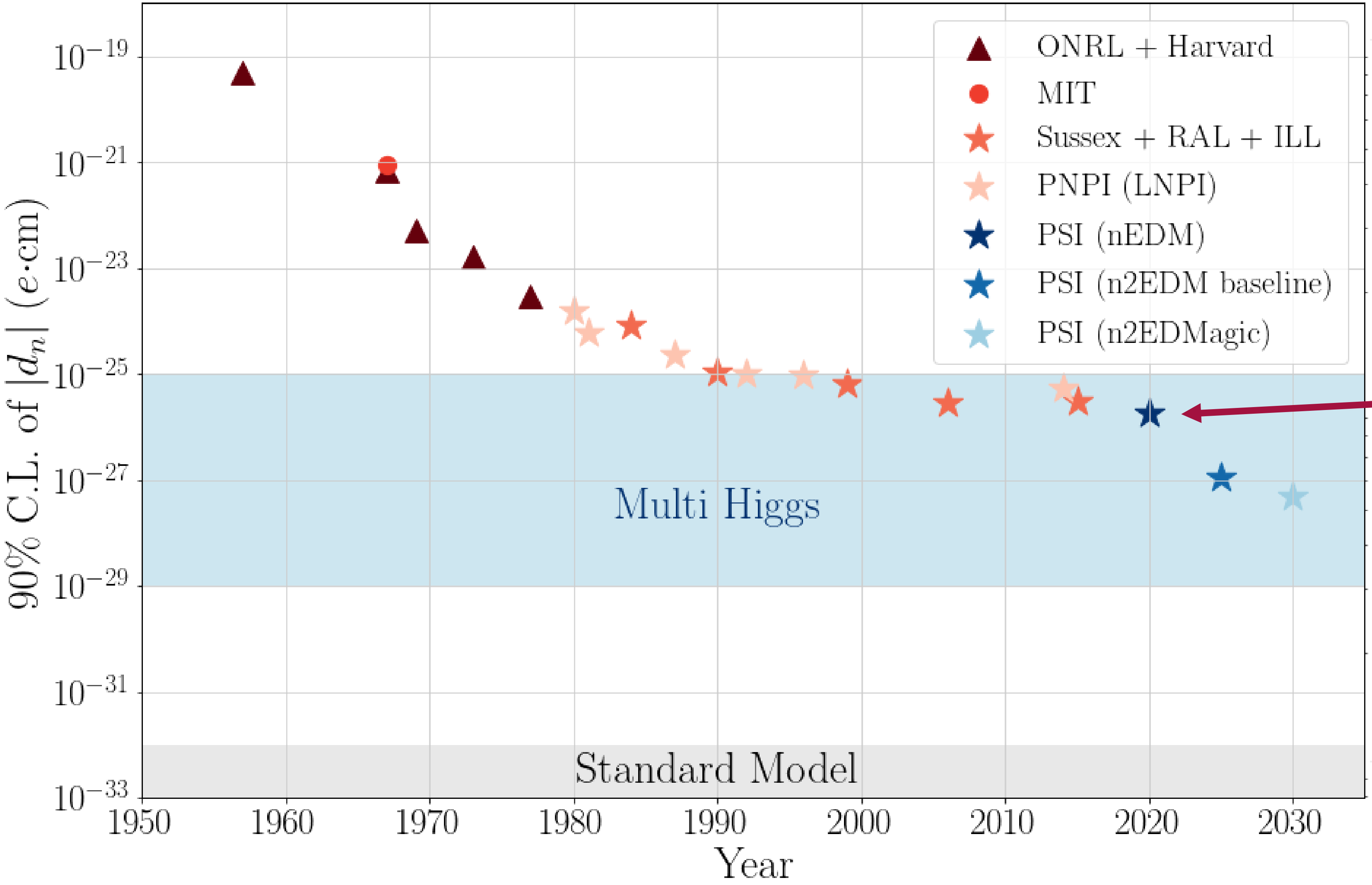
Electric Dipole Moment

Classically: displacement of charges



$$\hat{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E}$$

History of the neutron EDM



$|d_n| < 1.8 \cdot 10^{-26}\ e$ cm

[Abel et al., 2020.]

How to measure a nEDM?

How to measure a nEDM?

- The interaction of d_n to $\vec{E}$ is analogous to μ_n to $\vec{B}$
- If $\vec{E} = 0$: spin-degenerate energy states
- If $\vec{E} \neq 0$: energy splitting between states gives d_n

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Measure the transition frequency between states!

How to measure a nEDM?

- Measure transition frequency

$$hf_L = d_n E$$

- But:

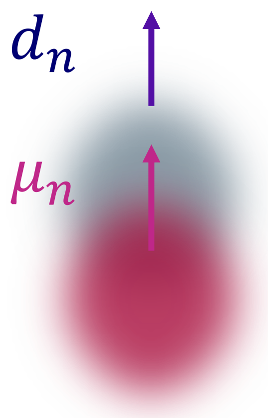
$$hf_L \approx 7 \text{ nHz } !$$

How to measure a nEDM?

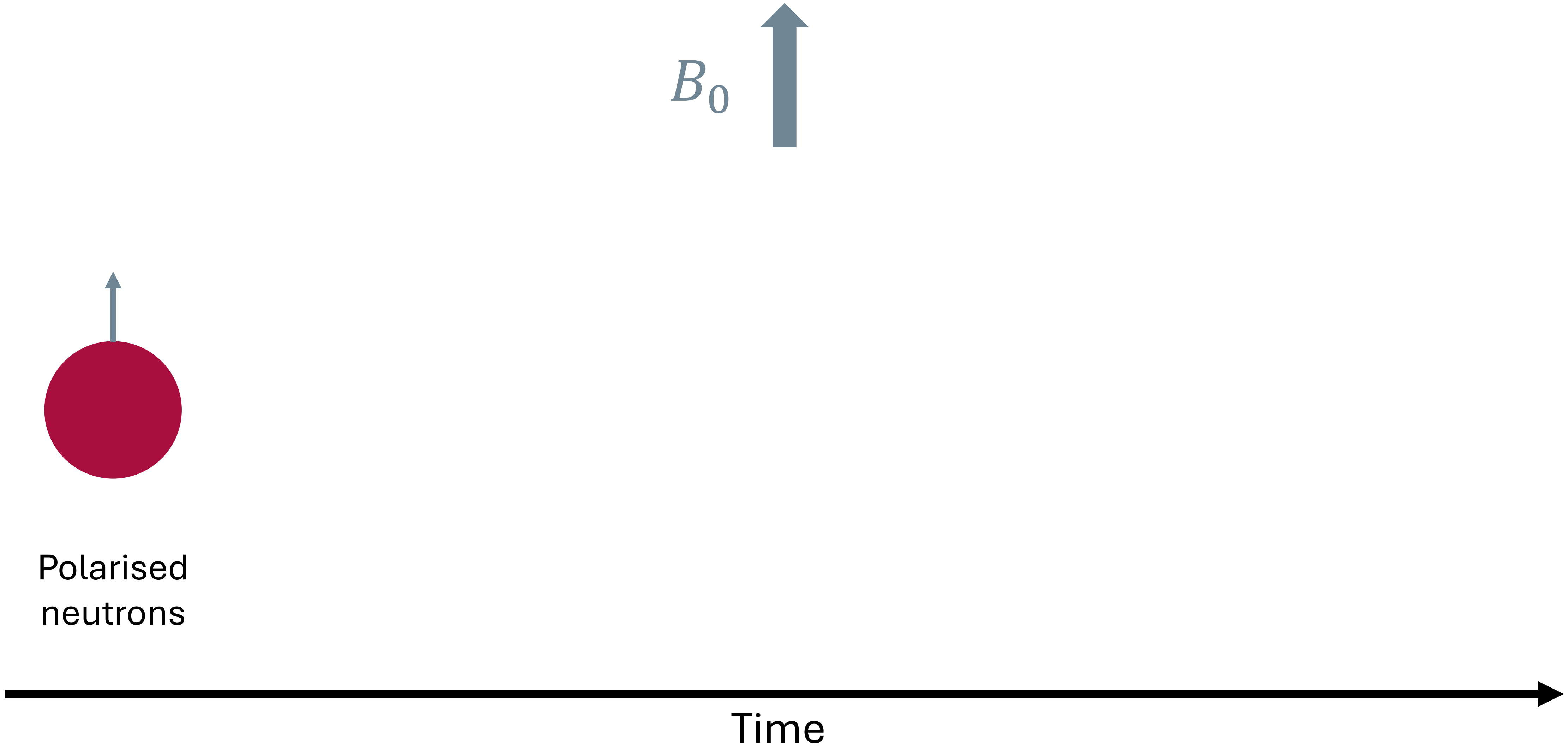
- Use the combined effect of d_n and μ_n
- Apply additional magnetic field $\overrightarrow{B_0}$
- Larmor precession f_L is combination of the two couplings:

Depends on field orientations!

$$hf_L = 2(\underbrace{\mu B_0}_{\approx\, 29\mathrm{Hz}} \pm \underbrace{d_n E}_{\approx\, 7\ \mathrm{nHz}})$$



Ramsey's method of separated oscillating fields



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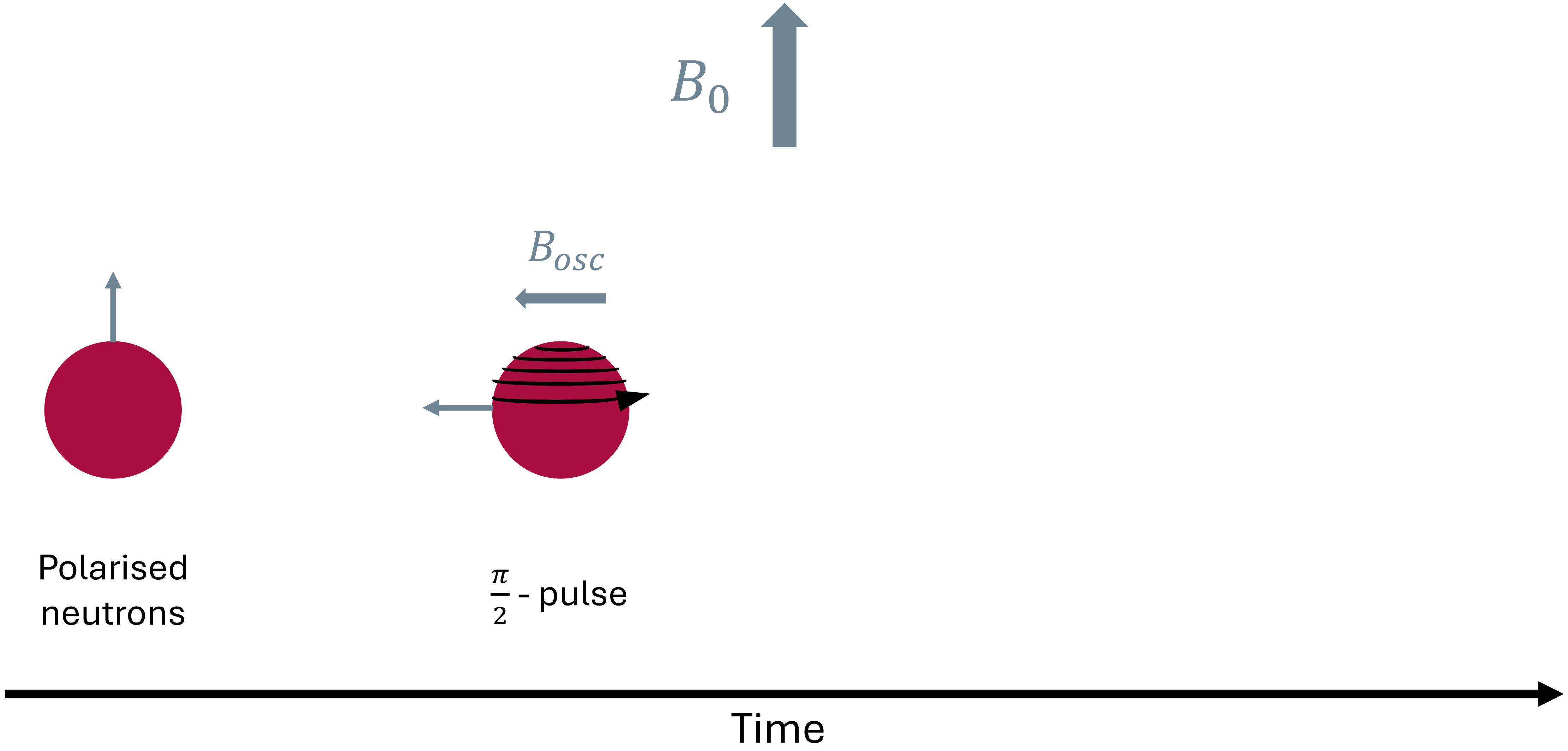

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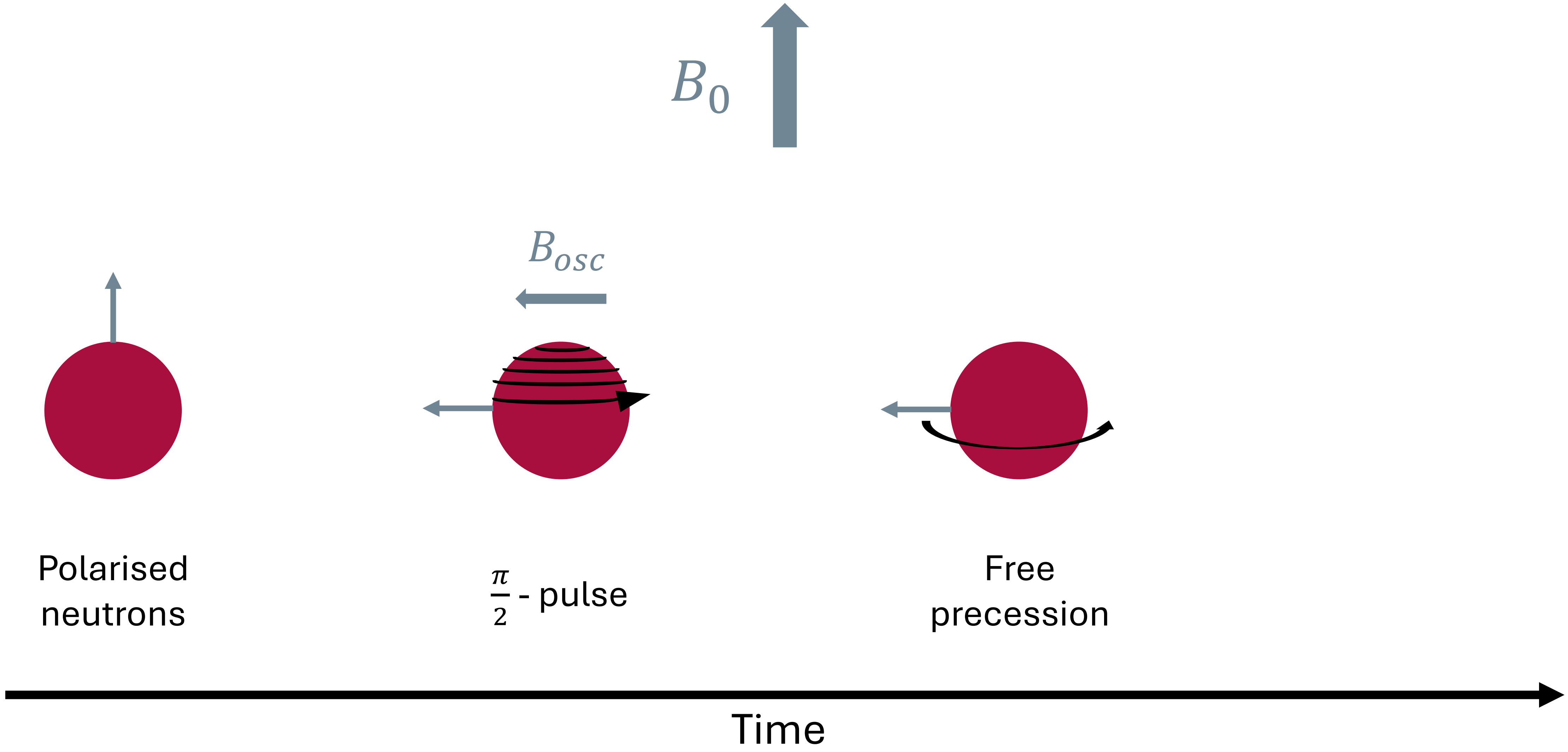
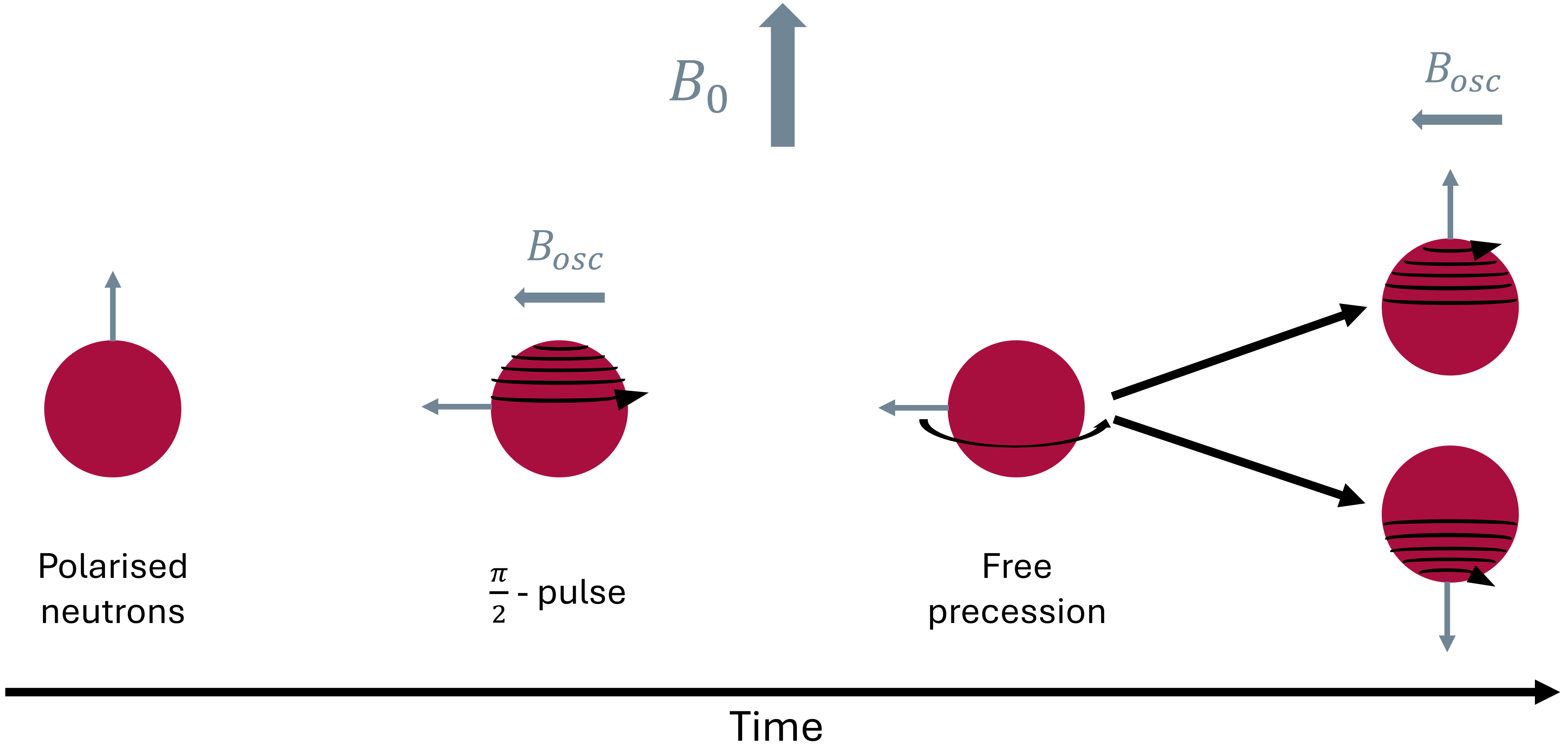
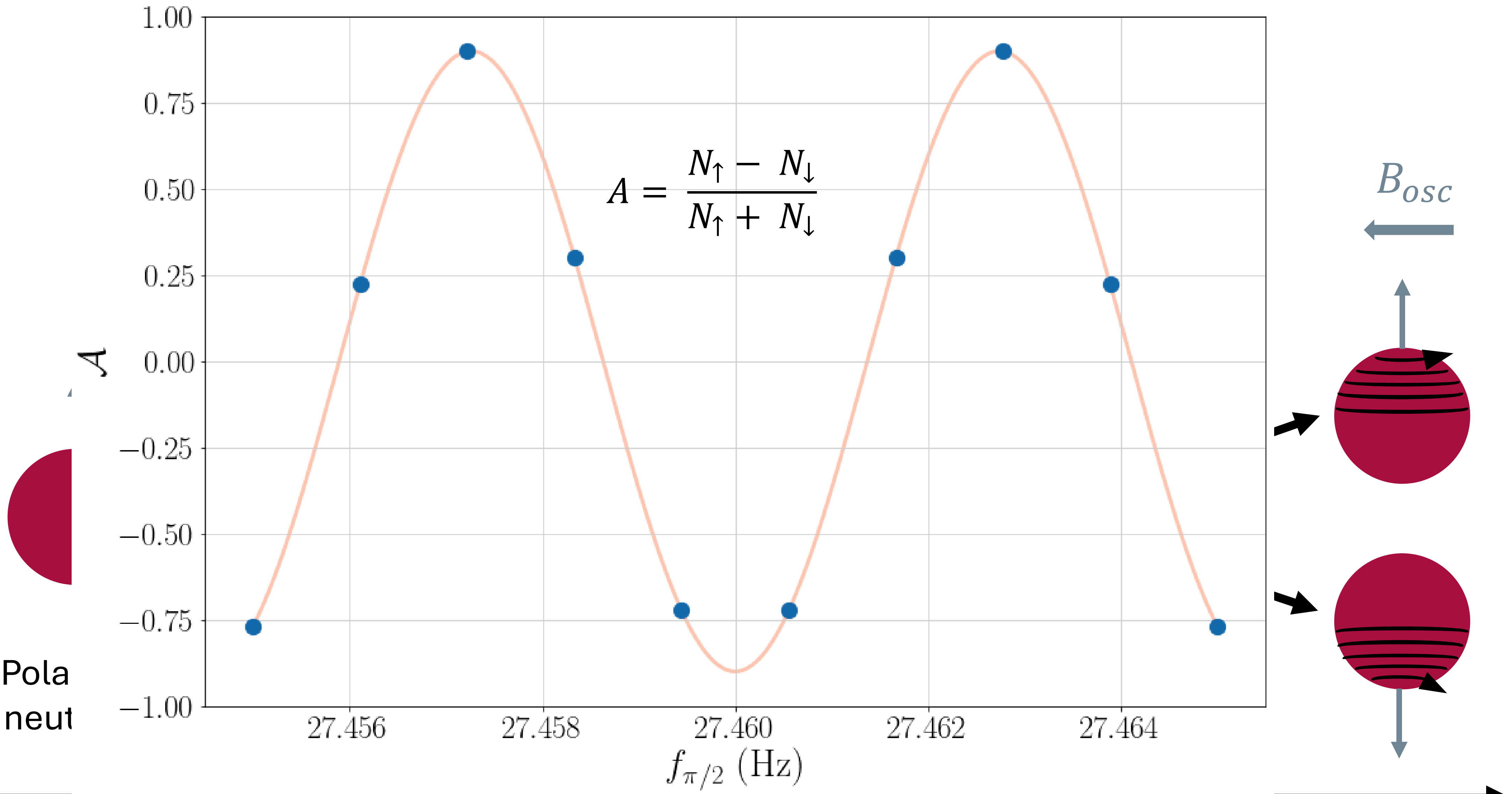


Ramsey's method of separated oscillating fields



Ramsey's method of separated oscillating fields



Time

Sensitivity of a nEDM Ramsey cycle

- High neutron statistics (N = 121.000 neutrons/cycle)
- Strong electric field (E = 15 kV/cm)
- Long interaction times (T = 180s)
- Excellent initial polarisation
- Supressed depolarisation

} $\alpha = 0.8$

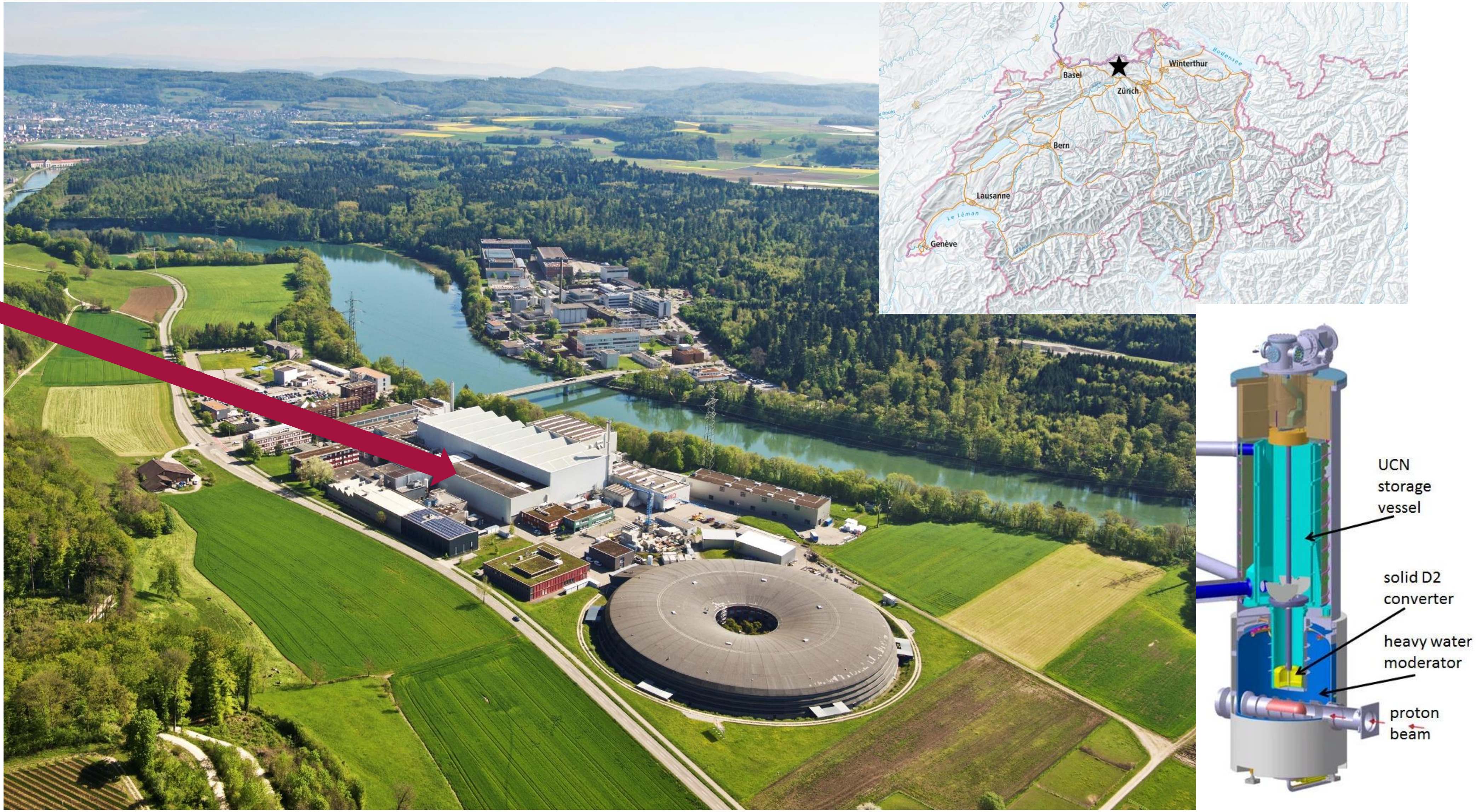
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

[Ayres et al., 2021.]

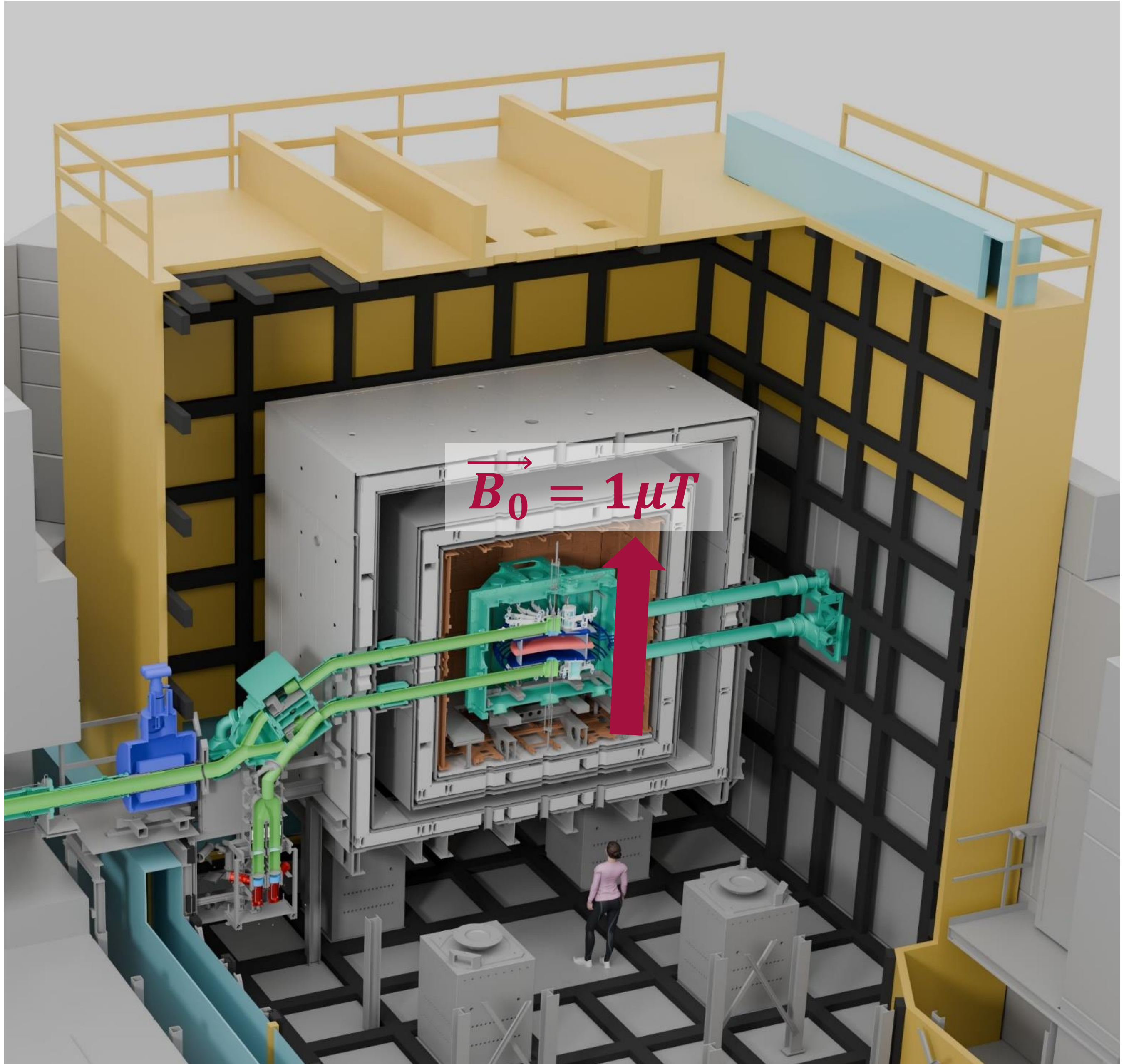
The n2EDM experiment @ PSI

The Paul Scherrer Institut

n2EDM



The n2EDM experiment: overview



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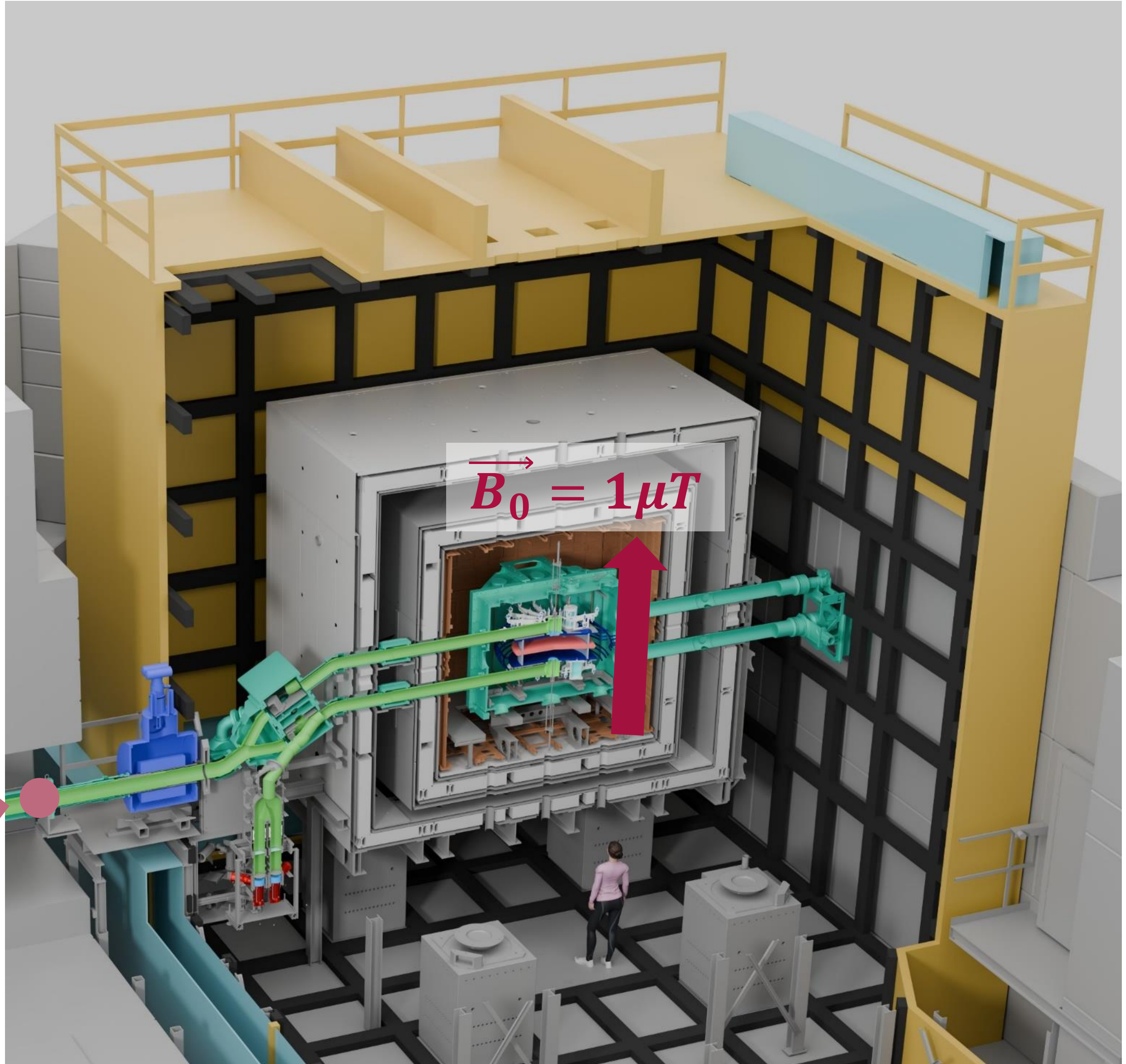
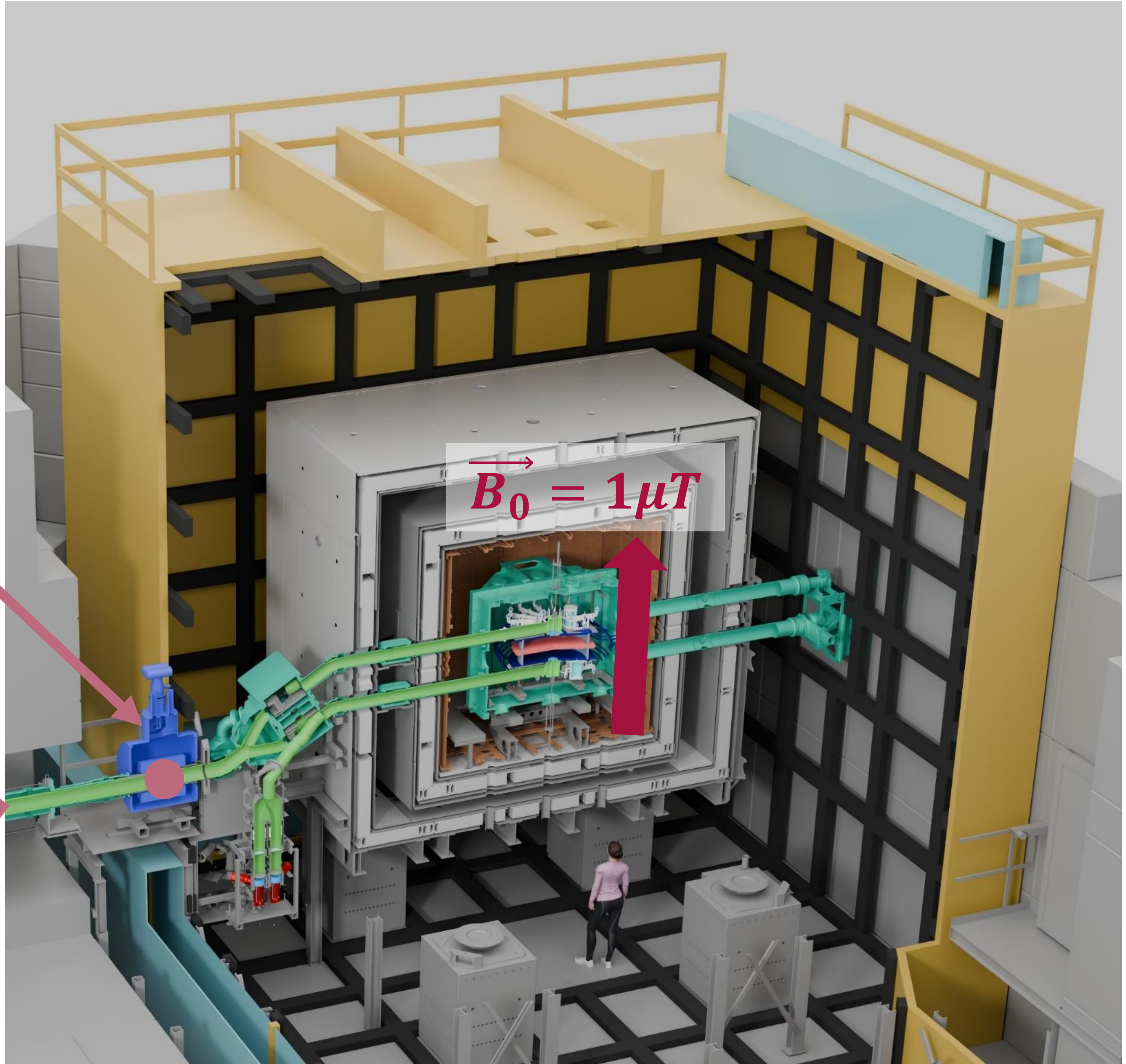


Ultracold
Neutrons

The n2EDM experiment: overview

Polarizing
Magnet
(5T)

Ultracold
Neutrons

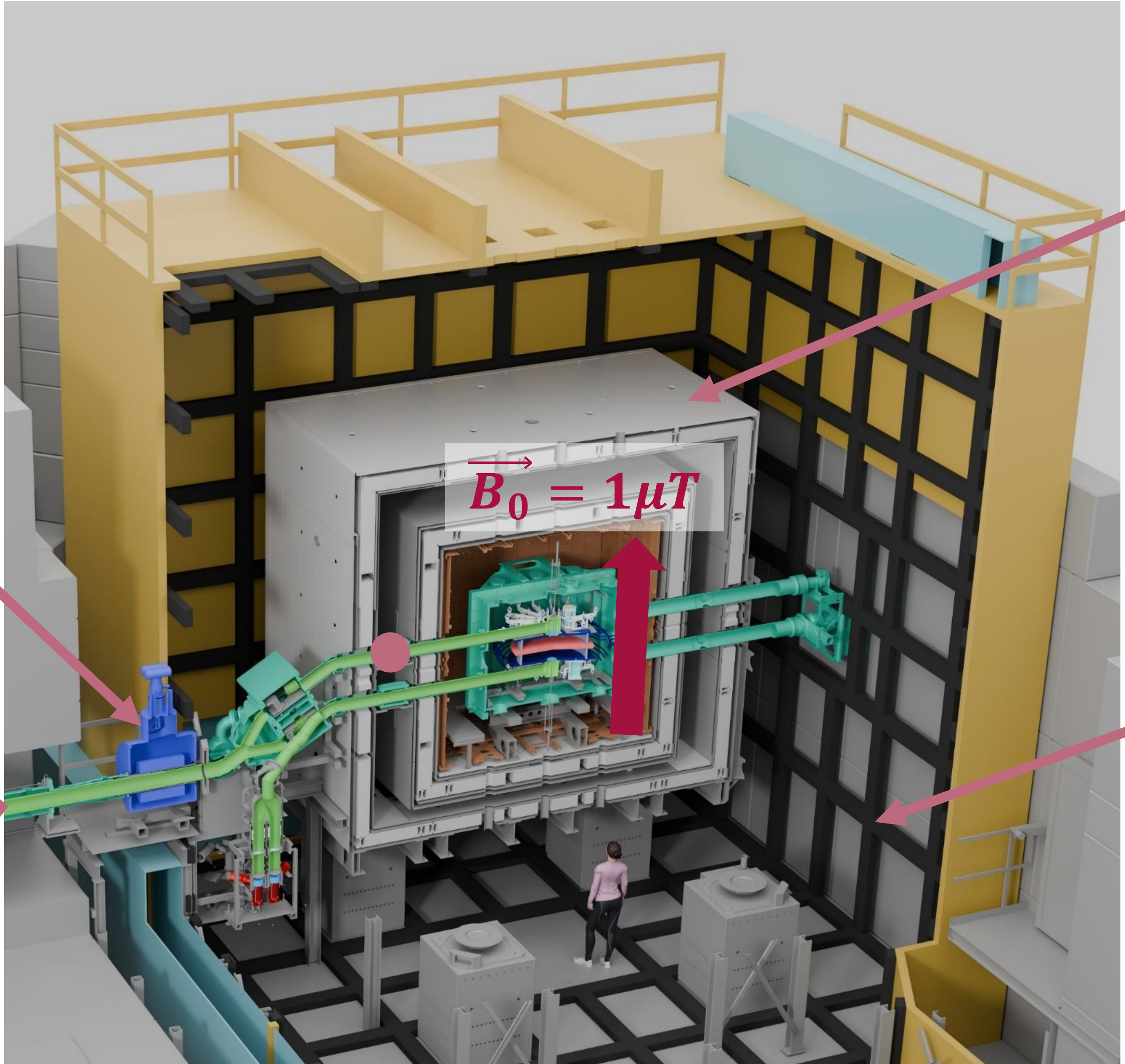


The n2EDM experiment: overview

n2EDM PSI

Magnetically Shielded Room

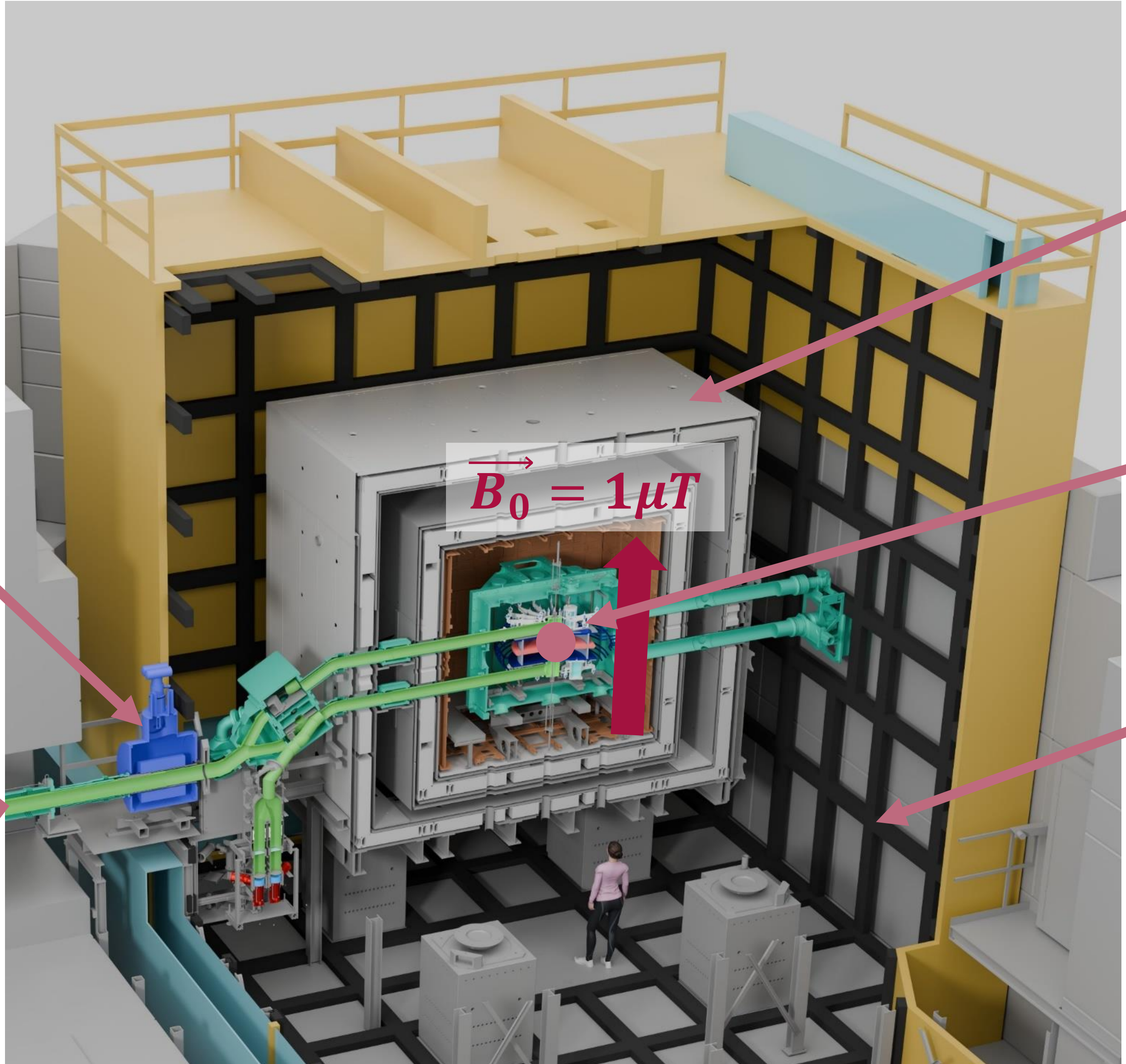
Polarizing Magnet (5T)



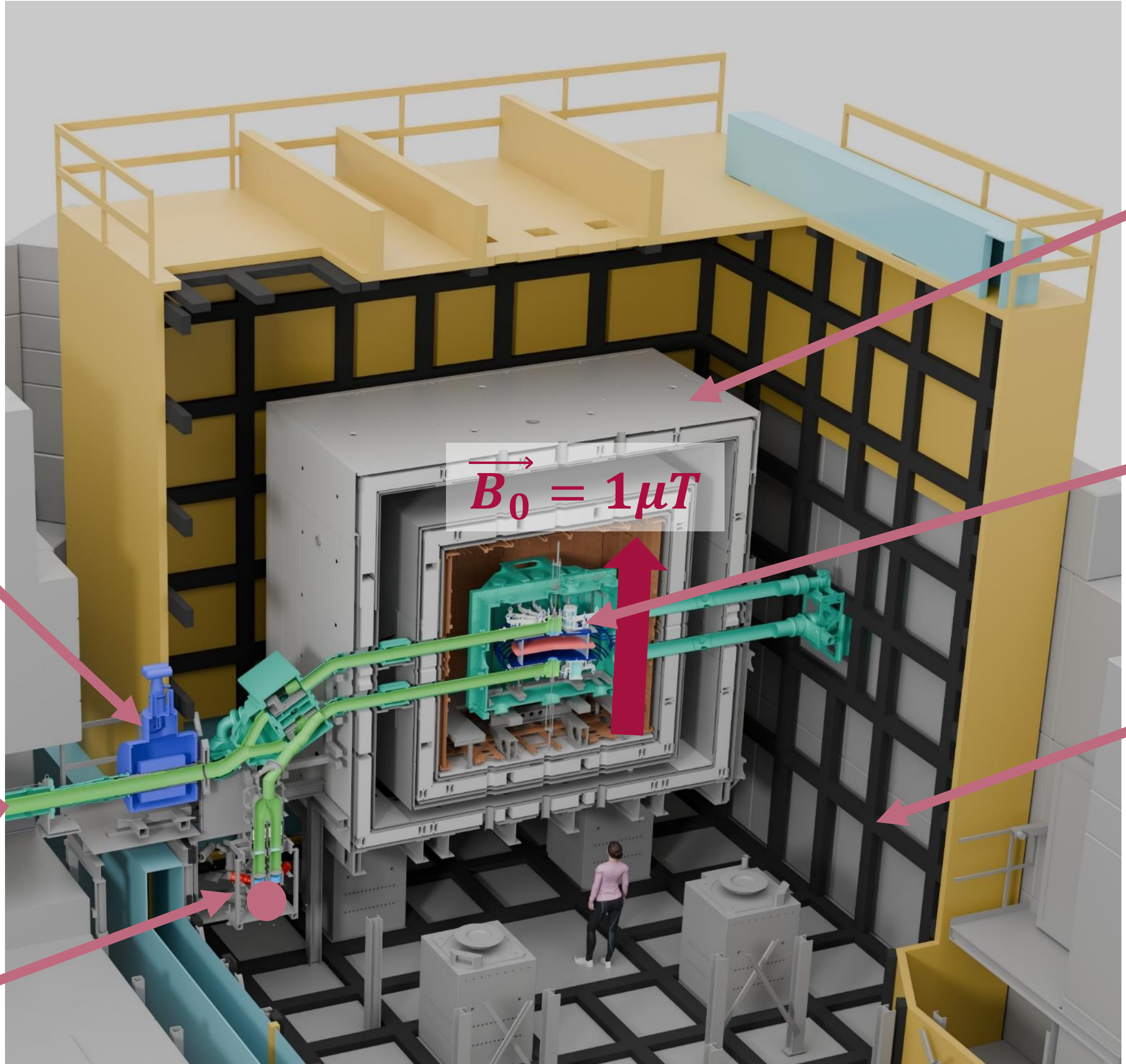
Active Magnetic Shielding

Ultracold Neutrons

The n2EDM experiment: overview



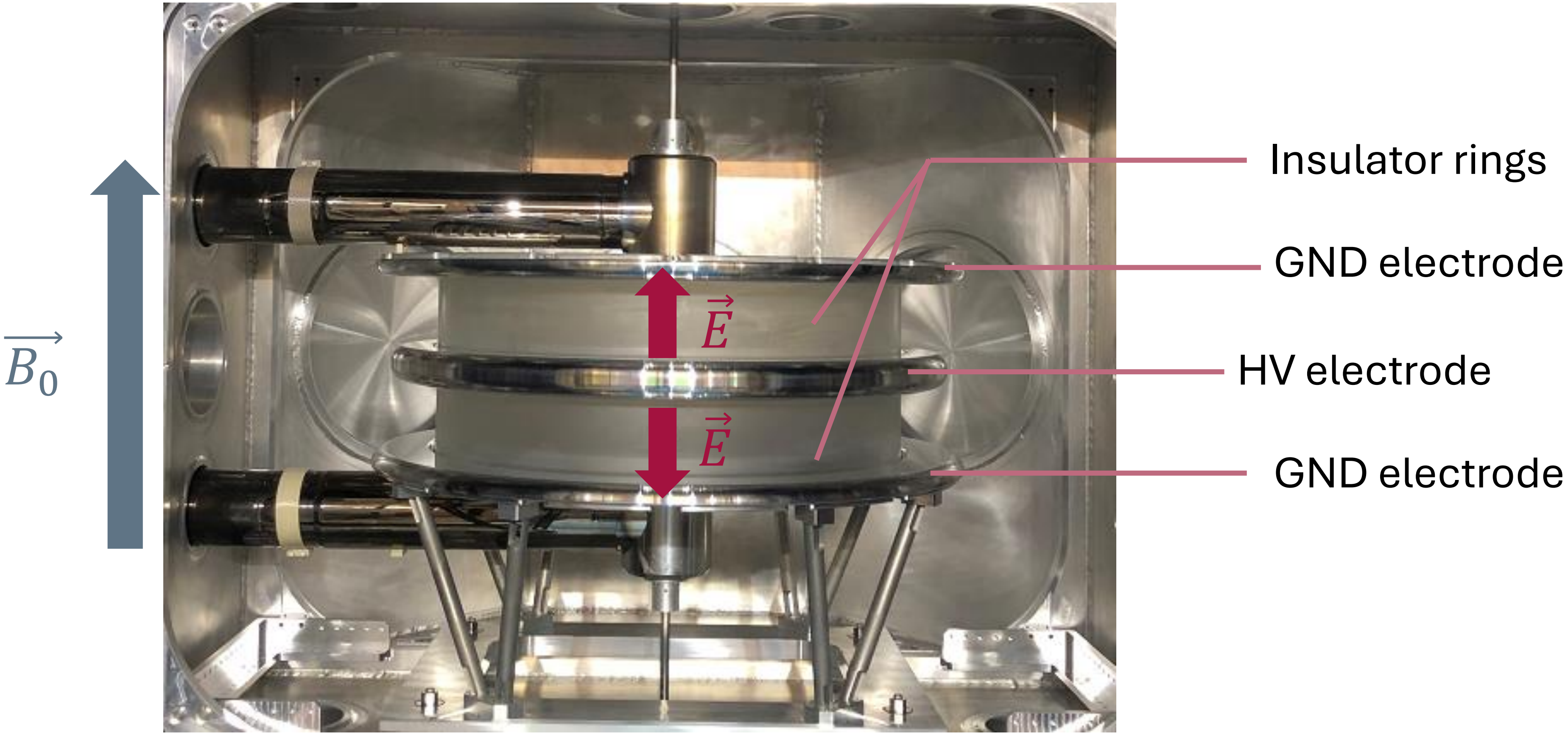
The n2EDM experiment: overview



The precession chambers

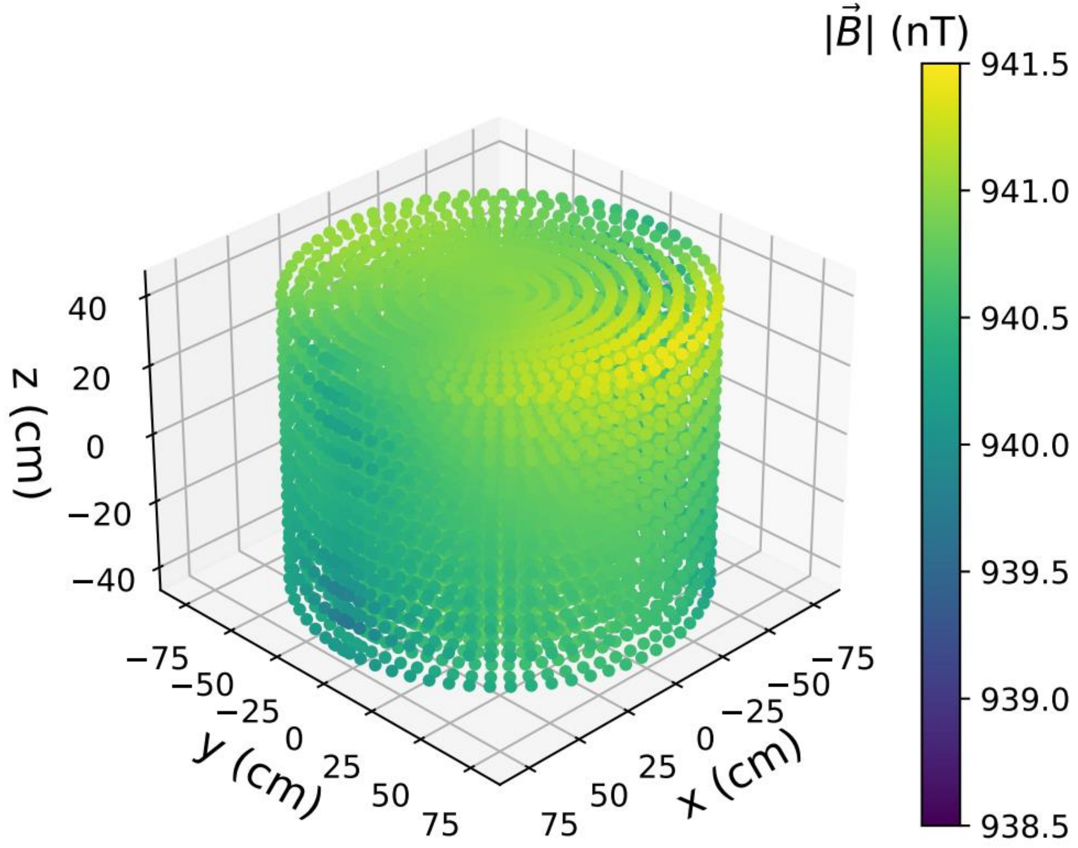
$$h(f_{n,\uparrow\uparrow} - f_{n,\uparrow\downarrow}) = 2(\mu|B_0| - d_n|E|) - 2(\mu|B_0| + d_n|E|)$$

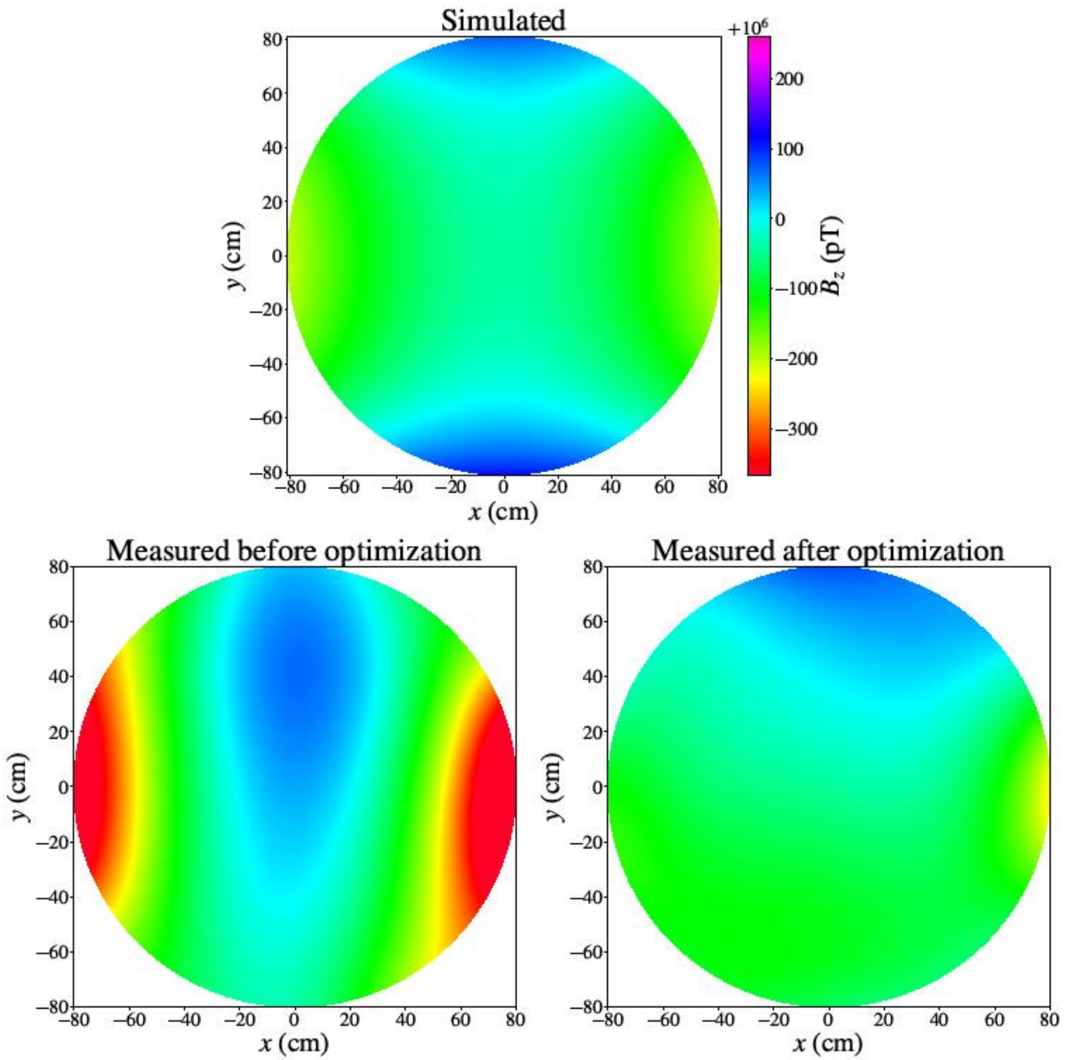
$$\rightarrow \quad d_n = -\frac{h(f_{n,\uparrow\uparrow} - f_{n,\uparrow\downarrow})}{4\,|E|}$$



Commissioning measurements: Recent successes

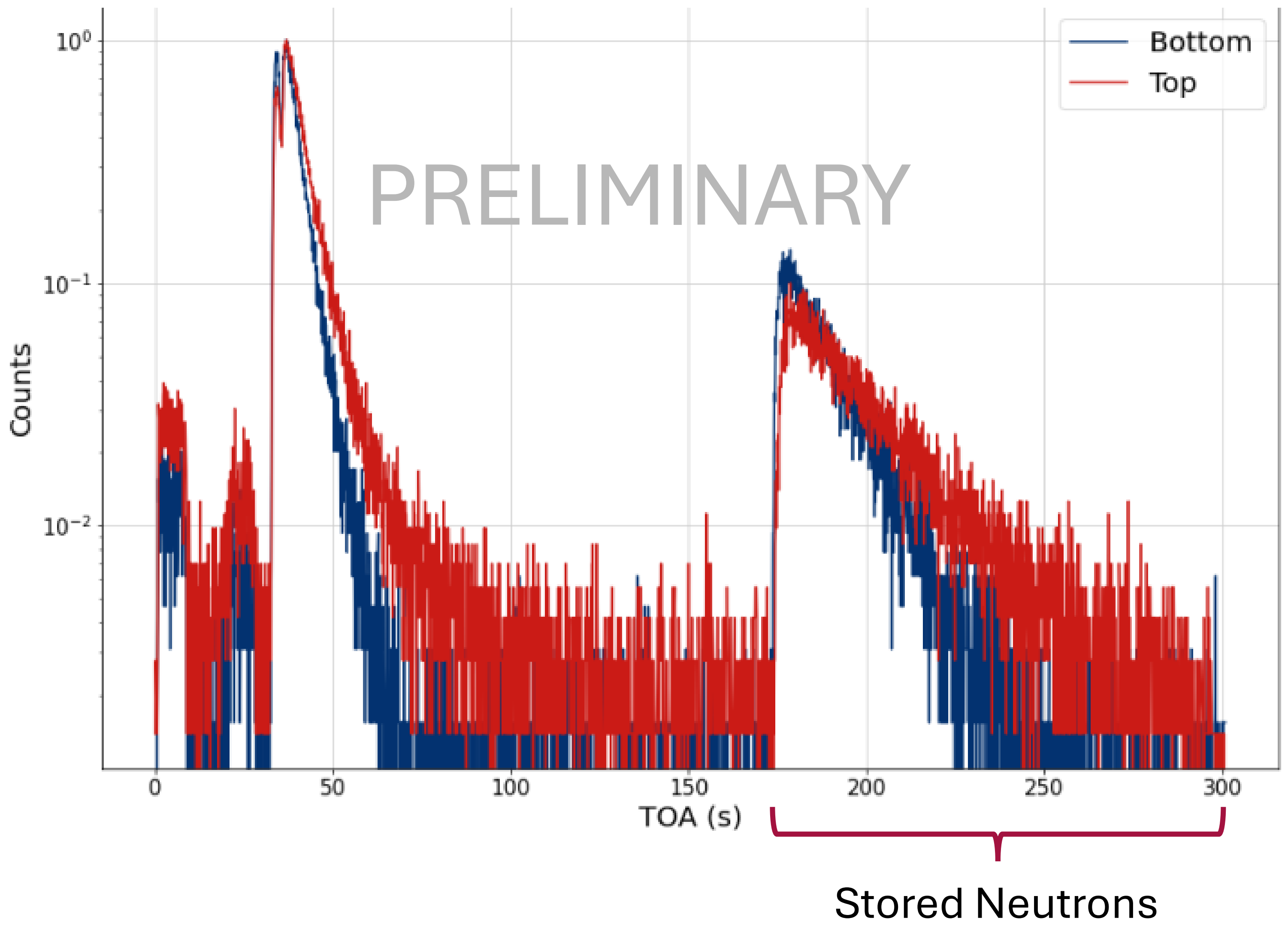
Characterisation of the B_0 coil in 2022





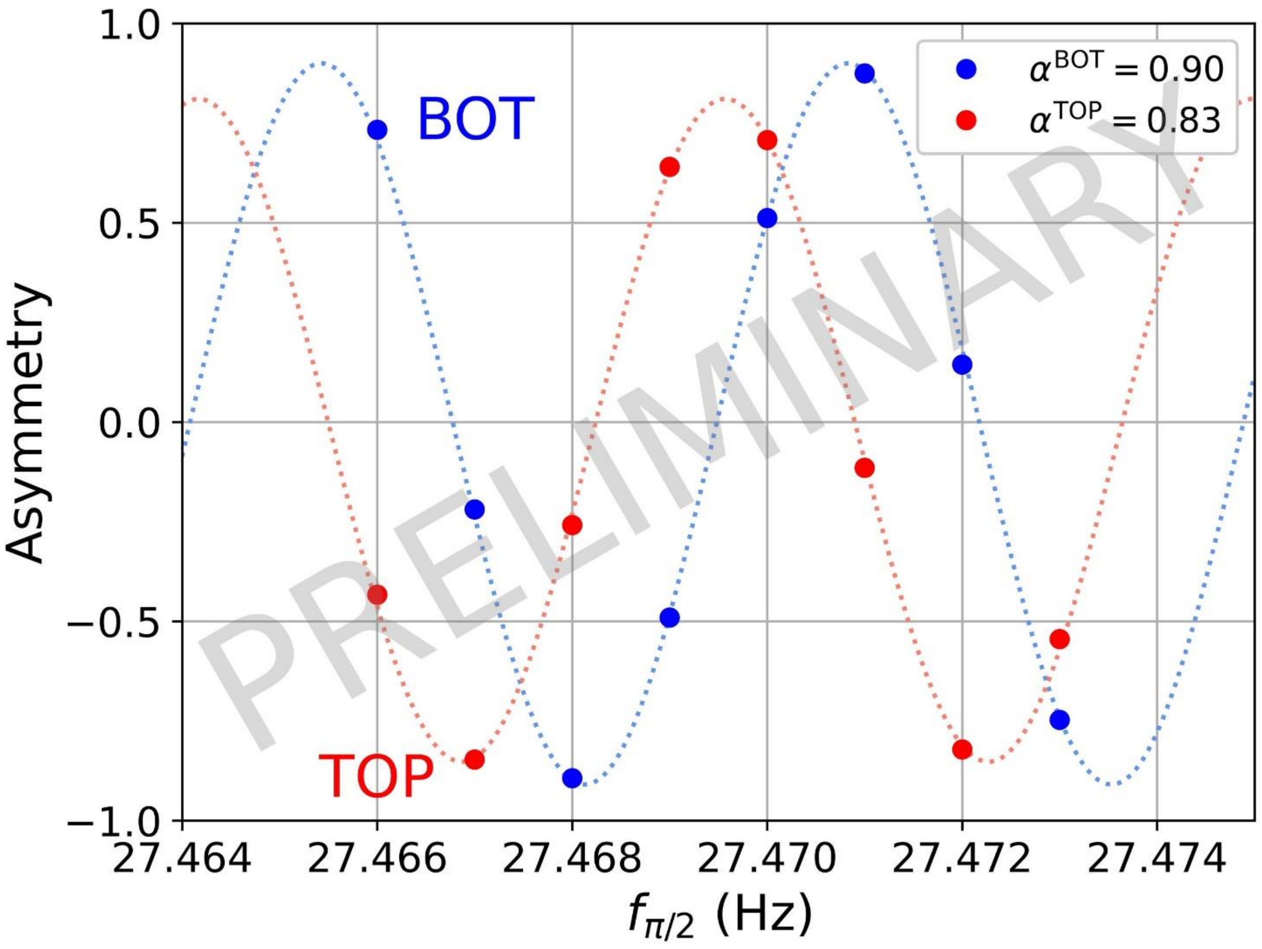
[Abel et al, 2024.]

First neutron storage in summer 2023



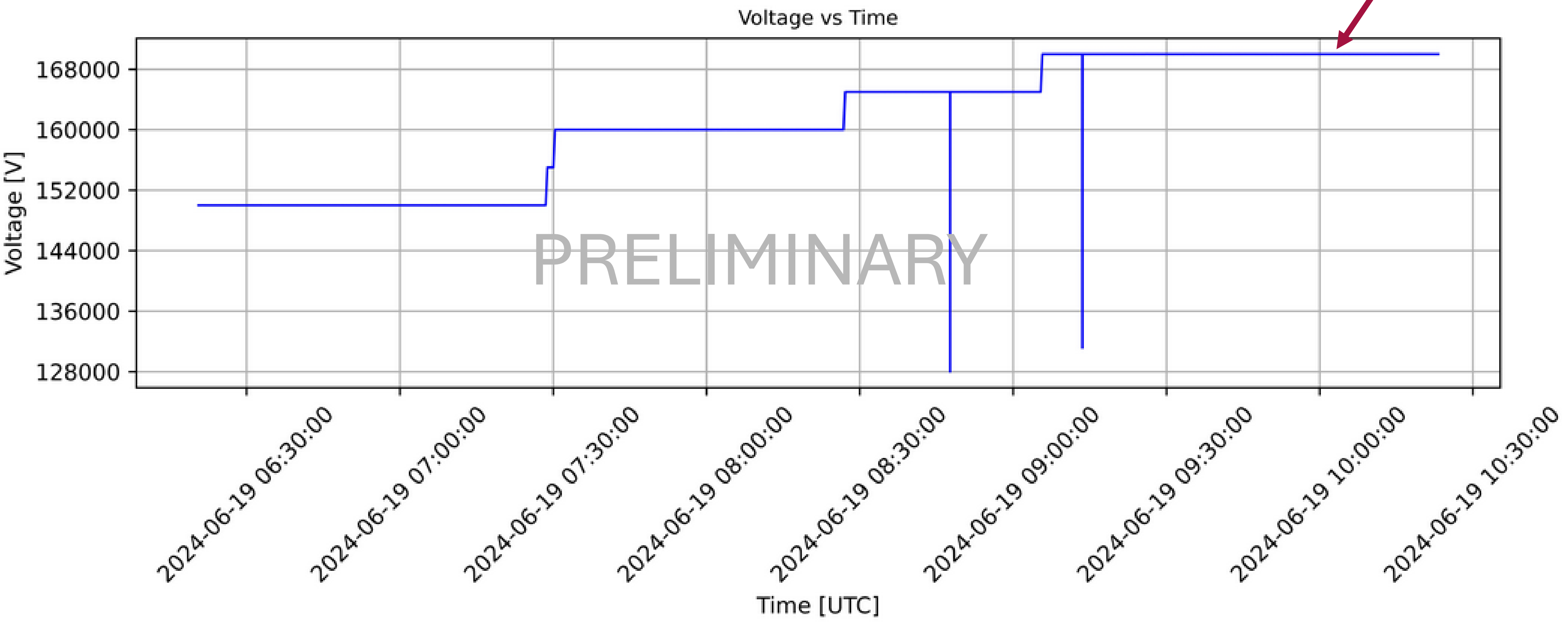
First Ramsey curves in 2023

$$A = -\alpha \cos\left(\pi \frac{f_{\pi/2} - f_L}{\Delta\nu}\right)$$



First high voltage tests in Spring 2024

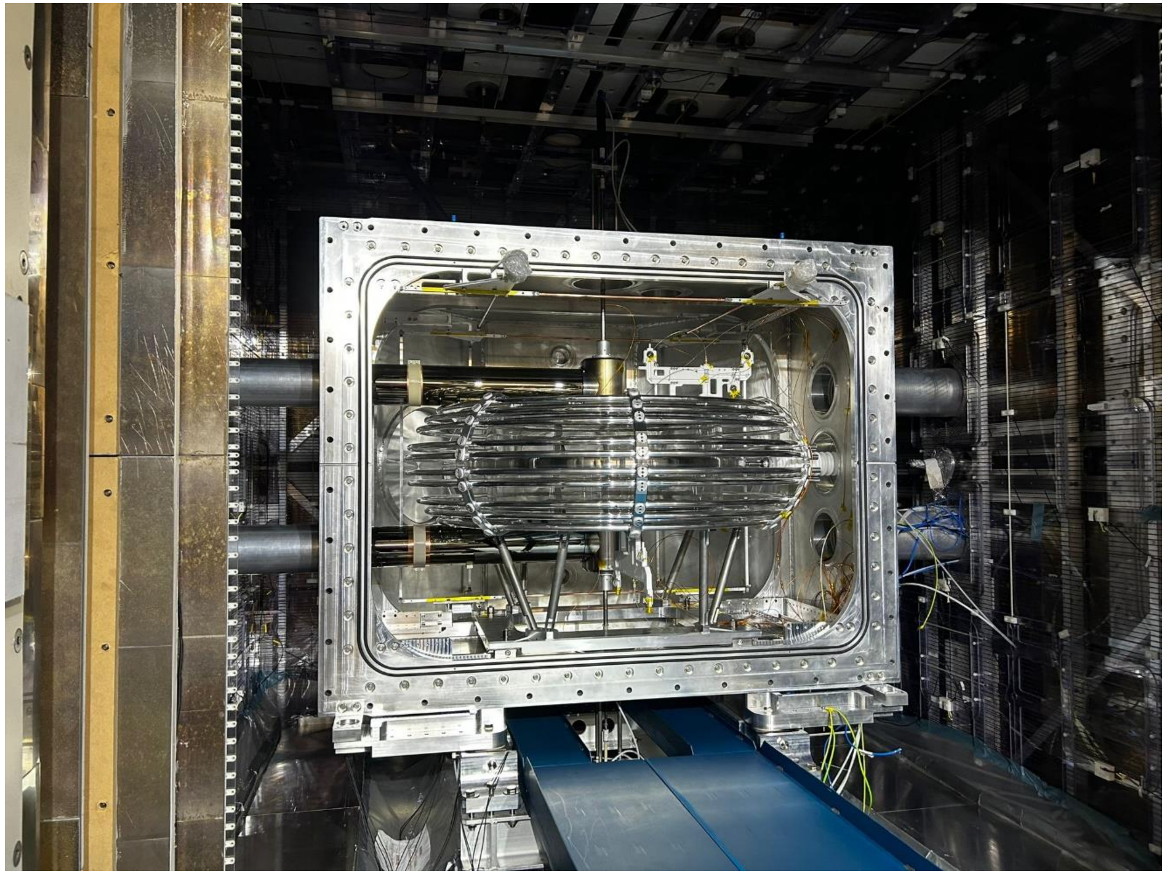
15 kV/cm



First EDM measurements in 2025!

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

- Neutron storage ✓
- Long precession times ✓
- High visibility ✓
- Electric fields ✓



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n2EDM

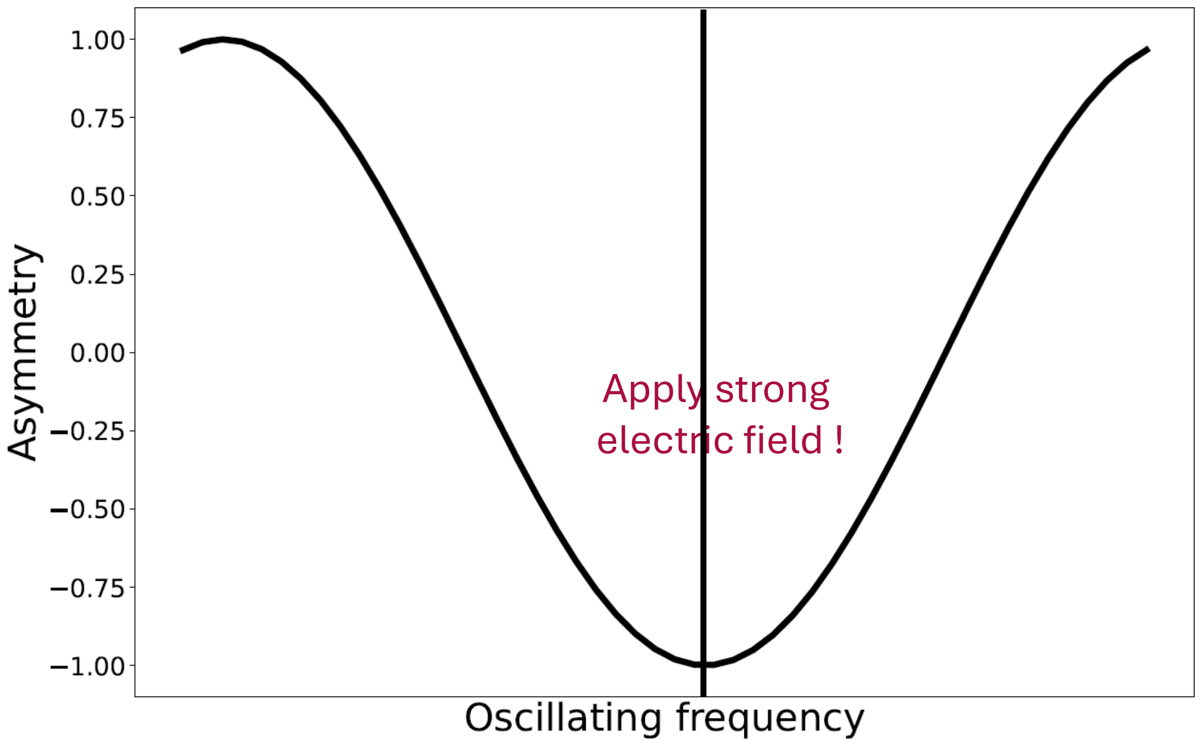
Thank you for your attention!

Changing the frequency of the oscillating field

We define an asymmetry between the neutrons in different spin states:

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

$f_L \approx 29$ Hz

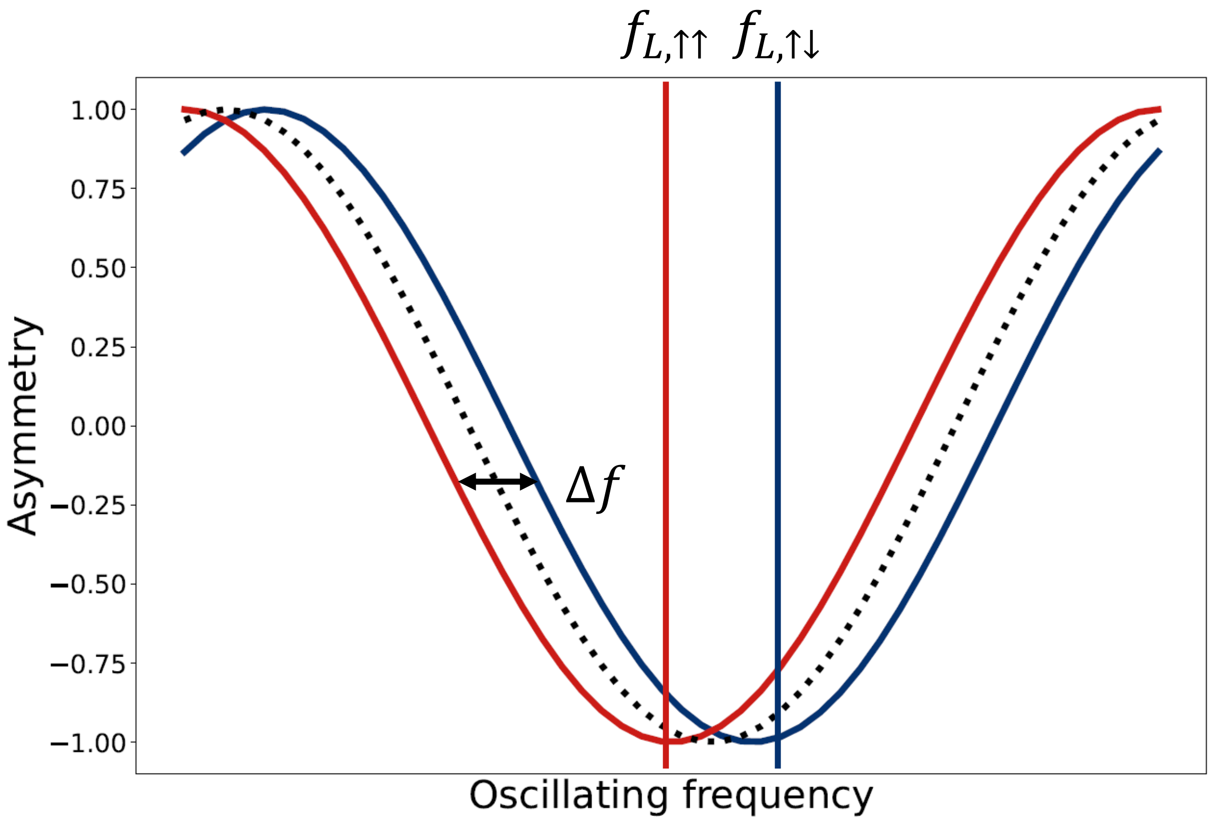


Changing the frequency of the oscillating field

Extract the neutron EDM:

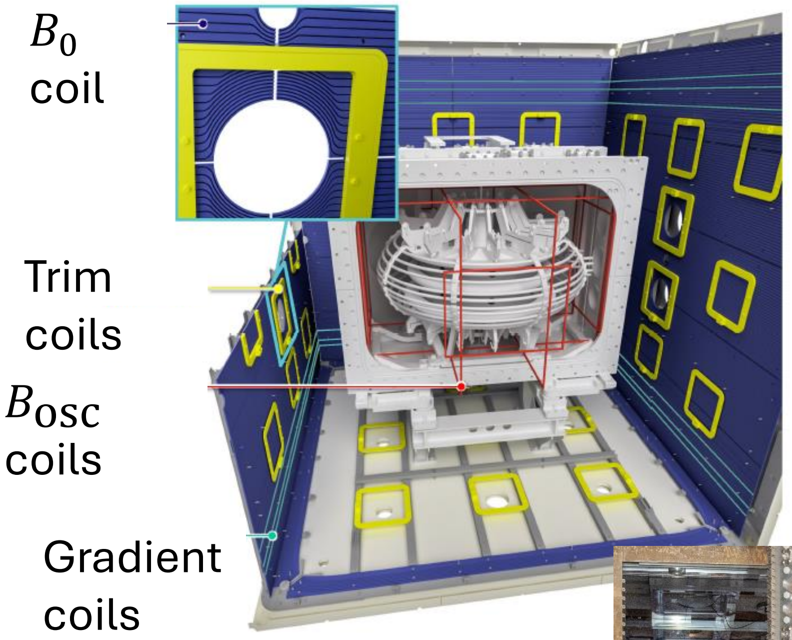
$$hf_L = 2(\mu B_0 \pm d_n E)$$

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



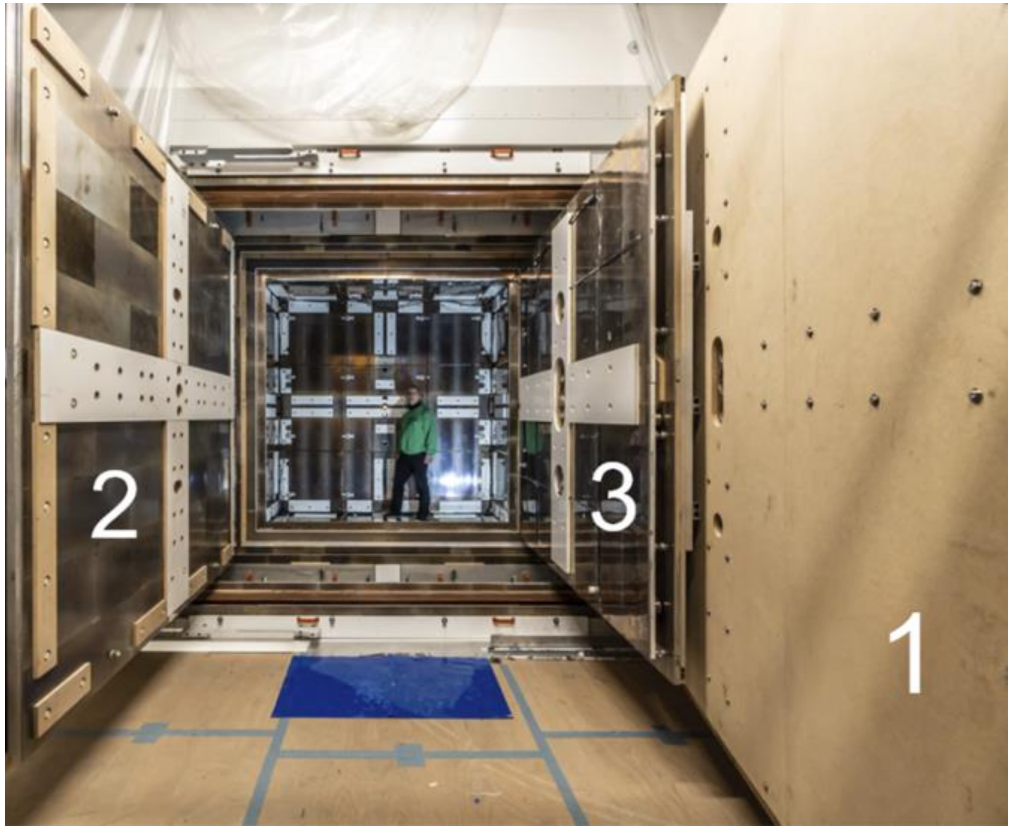
Magnetic field

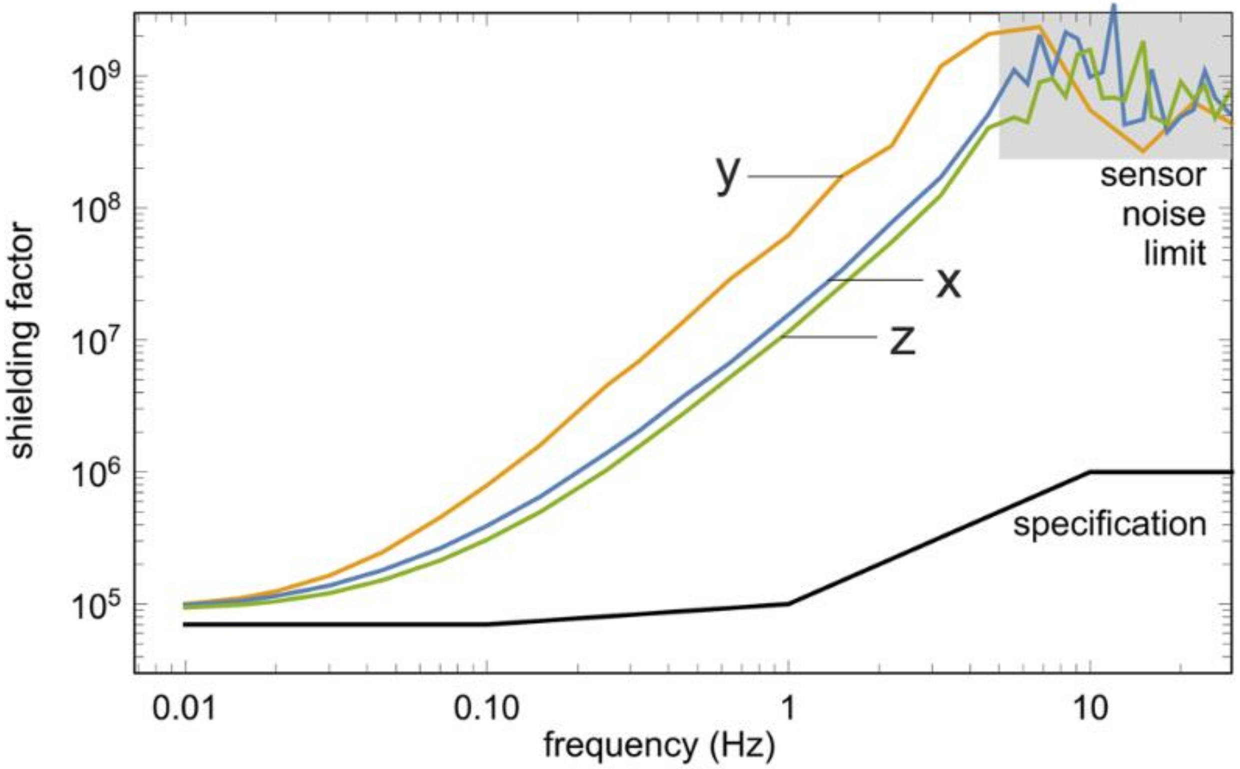
- Static 1 μT magnetic field
- 56 Trim coils for increased homogeneity
- Gradient coils for characterizing the system



The nEDM collaboration, Generating a highly uniform magnetic field inside a magnetic shielding room for the n2EDM experiment , in preparation.

The MSR

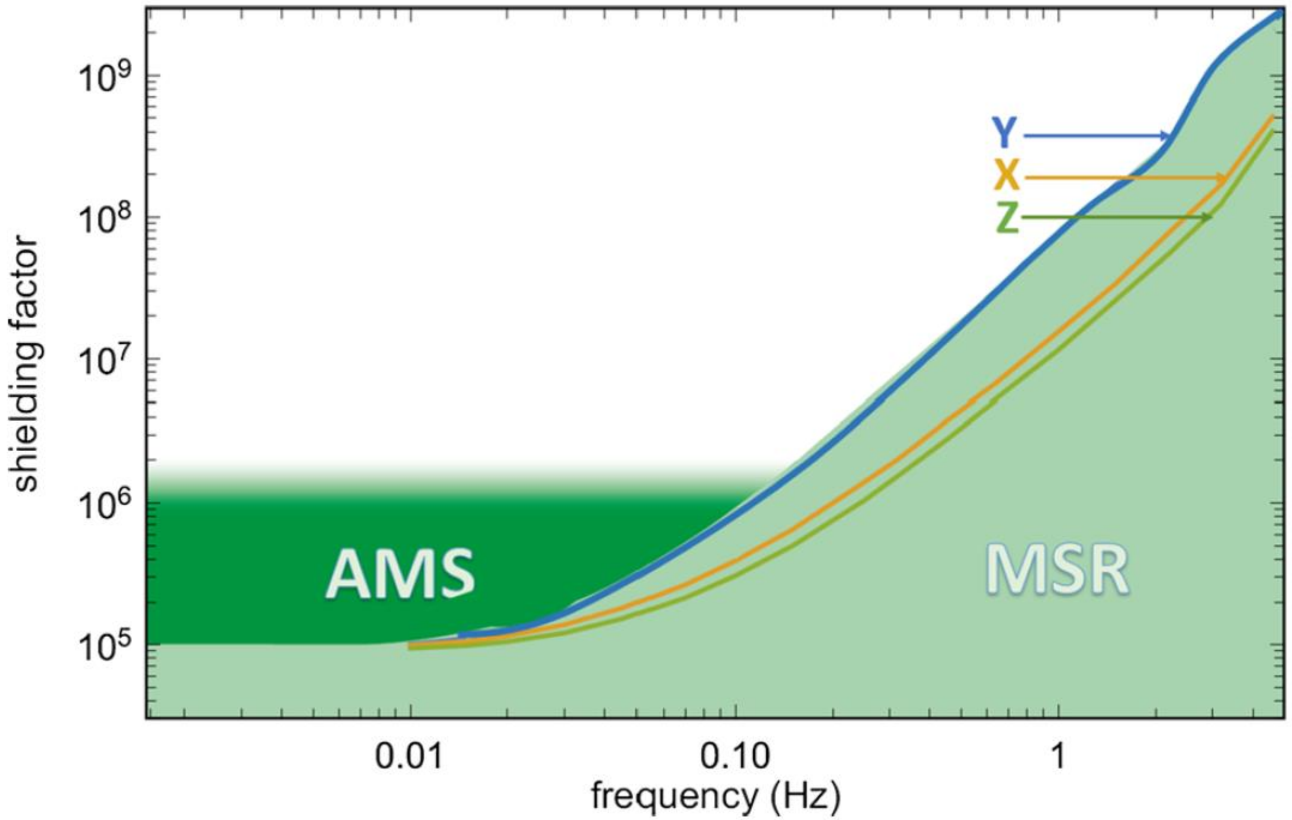

2
3
1


shielding factor
10^9
10^8
10^7
10^6
10^5
0.01
0.10
1
10
frequency (Hz)
y
x
z
sensor noise limit
specification

Magnetic shielding

- Magnetically Shielded Room (MSR)
  - 6 layers of mu-metal
  - 1 layer of aluminium
  - Shielding factor: 10^6 @ 0.1 Hz

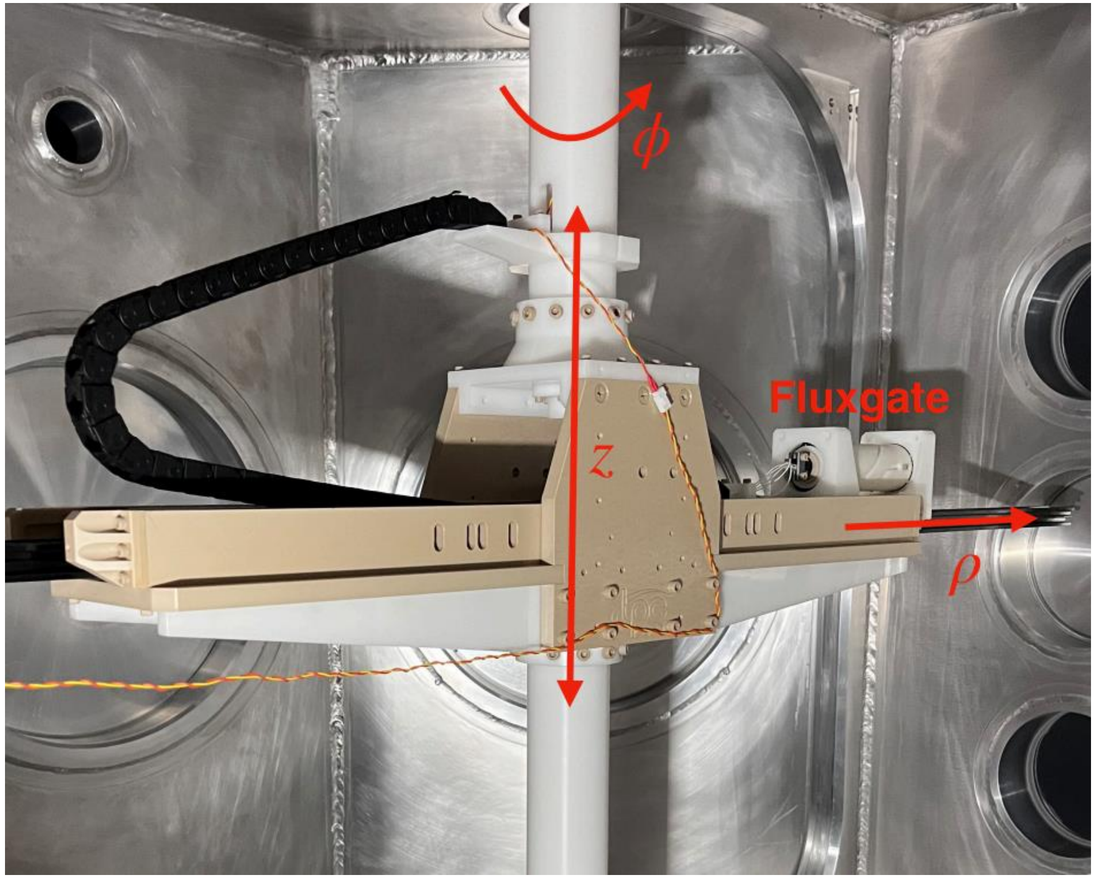
- Active magnetic shielding
  - 8 coils
  - 55 km of cables
  - Improves shielding factor by 10 for low frequencies



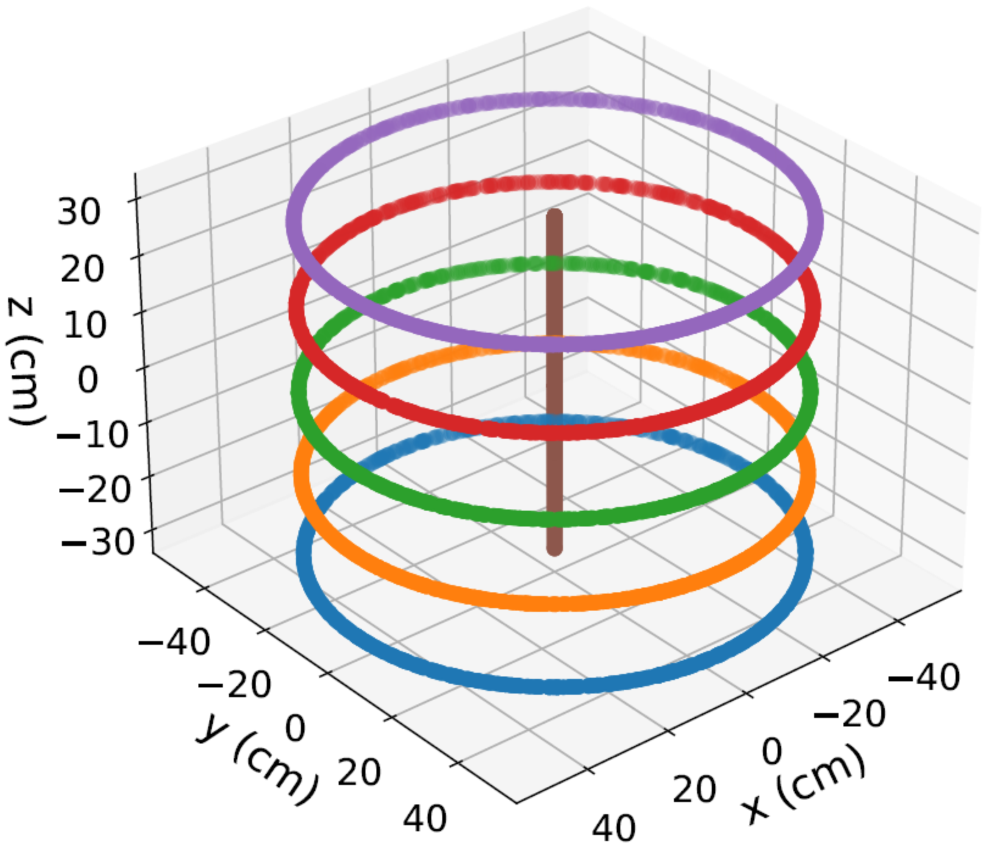
The nEDM collaboration, The very large n2EDM magnetically shielded room with an exceptional performance for fundamental physics measurements, 2022.

The nEDM collaboration, A large 'Active Magnetic Shield' for a high-precision experiment, 2023.

The Mapper



ϕ
Fluxgate
z
ρ



z (cm)
30
20
10
0
−10
−20
−30
y (cm)
−40
−20
0
20
40
x (cm)
−40
−20
0
20
40

Spin dependent neutron detectors

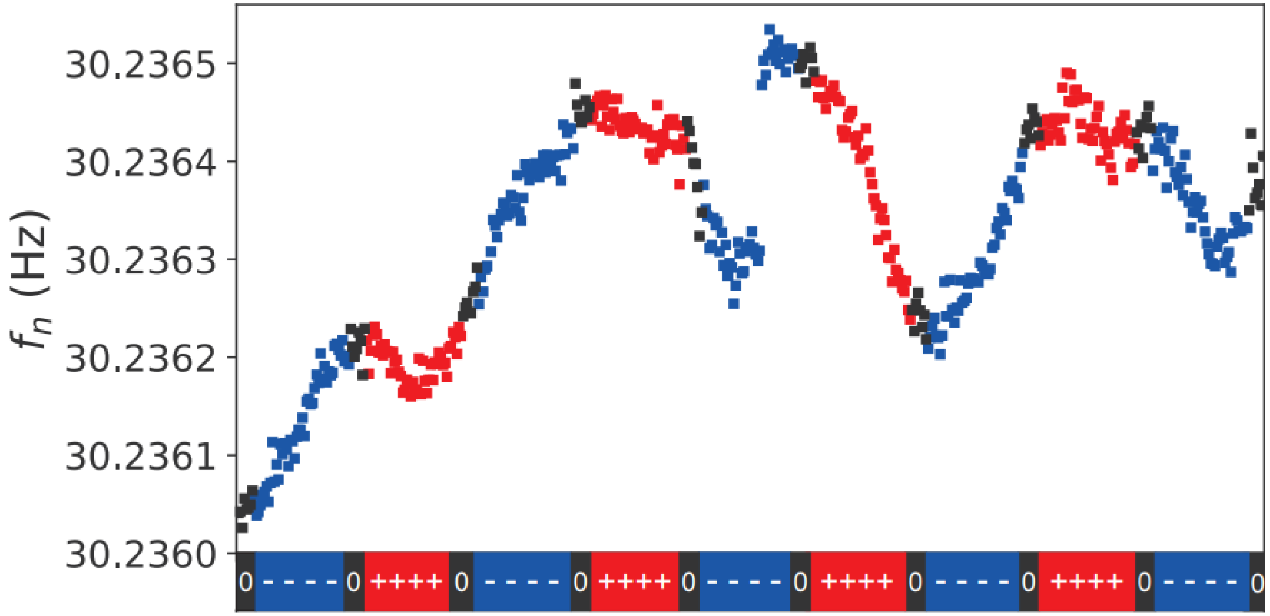
- In total 4 detectors
- 2 detectors per chamber
- Spin analysis via magnetised Fe coated Al foil
- Neutron detection via neutron capture
  $\mathrm{n} + {}^{3}\mathrm{He} \rightarrow \mathrm{p} + {}^{3}_{0}\mathrm{H}$
  and scintillation in CF_4

The nEDM collaboration, TDR, 2021,

Magnetic field drifts

Extracting the neutron frequency from each measurement point:

$$f_n = \frac{2\ \mu_n B_0}{h} \pm \frac{2\ d_n E}{h}$$



The nEDM collaboration, TDR, 2021,

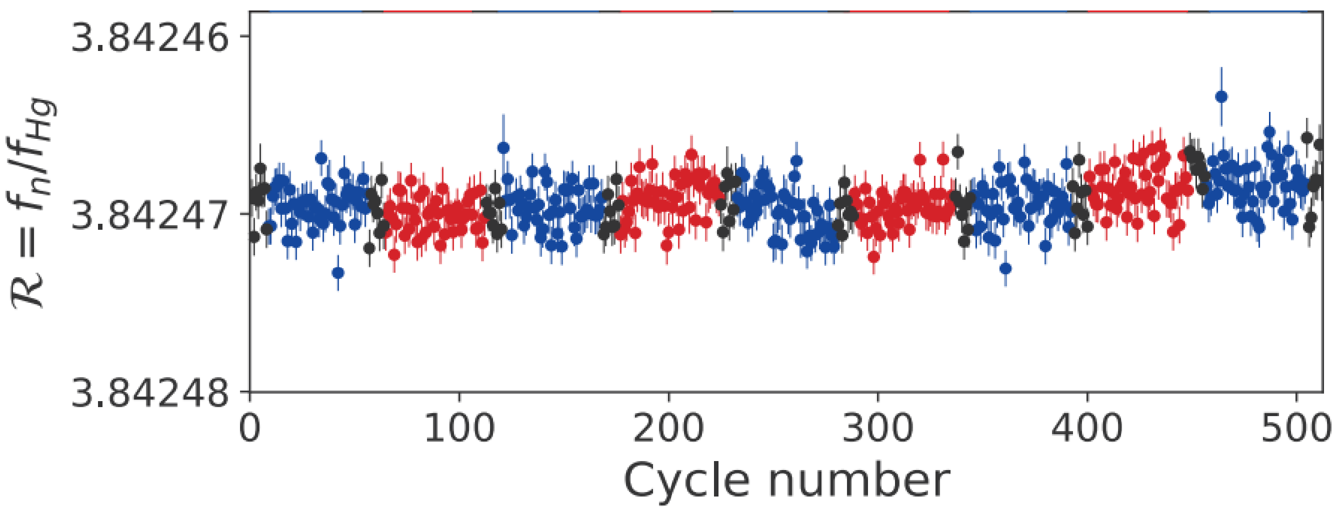
Magnetic field drifts

Use a co-magnetometer to determine a **ratio of frequencies** for each cycle:

$$f_n = \frac{2\,\mu_n B_0}{h} \pm \frac{2\,d_n E}{h}$$

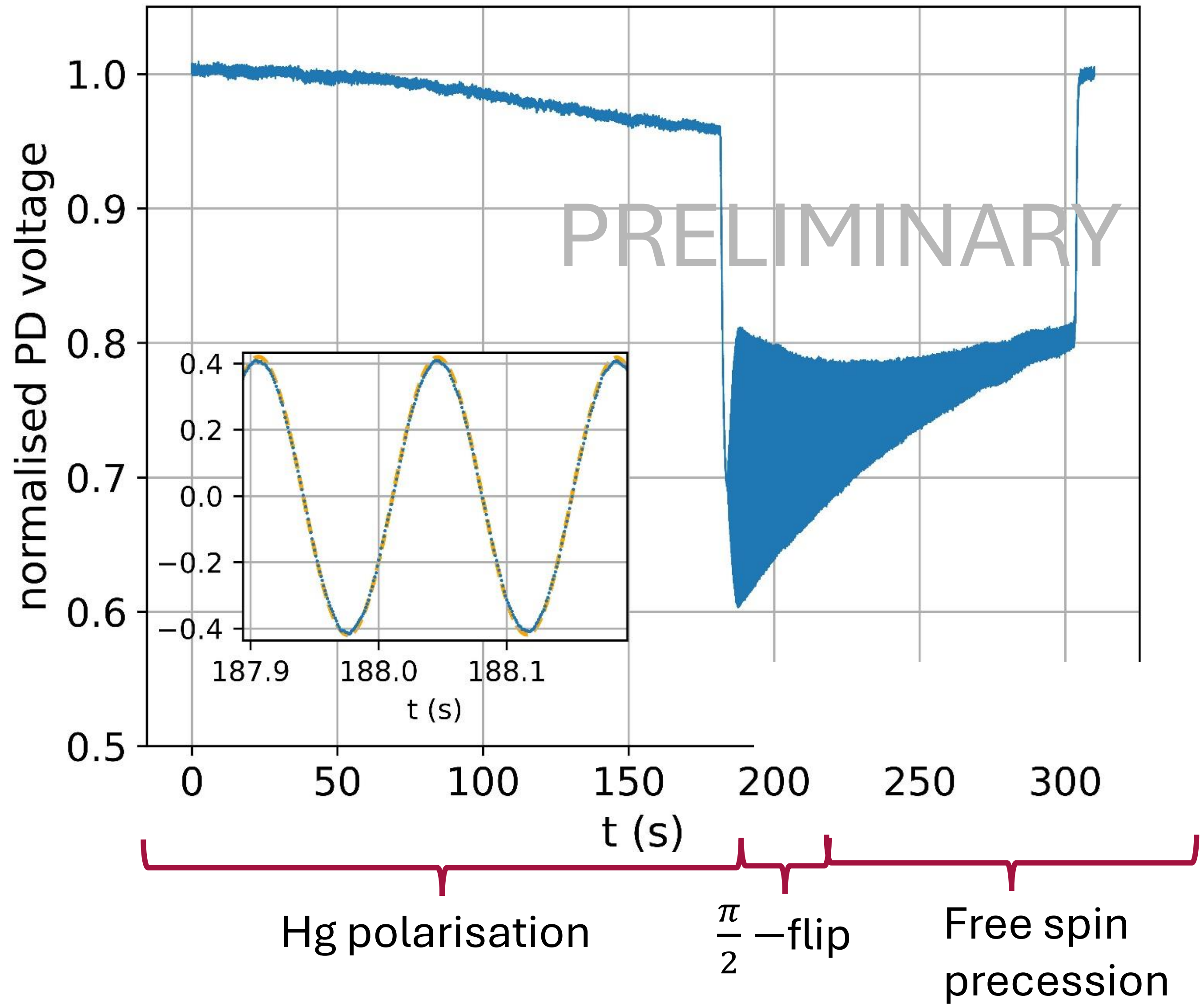
$$f_{\text{Hg}} = \frac{2\,\mu_{\text{Hg}} B_0}{h}$$

$$\mathcal{R} = \frac{f_n}{f_{\text{Hg}}} = \frac{\mu_n}{\mu_{\text{Hg}}} \pm \frac{2E}{h f_{\text{Hg}}} d_n$$



The nEDM collaboration, TDR, 2021,

First mercury precession in Spring 2024



Extracting the nEDM from a double chamber

- Extract the ratio from both chambers:

$$\mathcal{R} = \frac{f_n}{f_{\text{Hg}}} = \frac{\mu_n}{\mu_{\text{Hg}}} \pm \frac{2E}{hf_{\text{Hg}}} d_n$$

- Extract d_n:

$$d_n = \frac{hf_{\text{Hg}}}{4E} (R_{\uparrow\uparrow}^{\text{Top}} - R_{\uparrow\downarrow}^{\text{Bottom}})$$

- OR flip the electric field for suppressing systematics even more:

$$d_n = \frac{hf_{\text{Hg}}}{8E} (R_{\uparrow\uparrow}^{\text{Top}} - R_{\uparrow\downarrow}^{\text{Top}} - R_{\uparrow\downarrow}^{\text{Bottom}} - R_{\uparrow\uparrow}^{\text{Bottom}})$$

The co-magnetometer comes with a price

- Particles moving in an electric field experience a motional magnetic field:

$$\vec{B}_m = \vec{E} \times \frac{\vec{v}}{c^2}$$

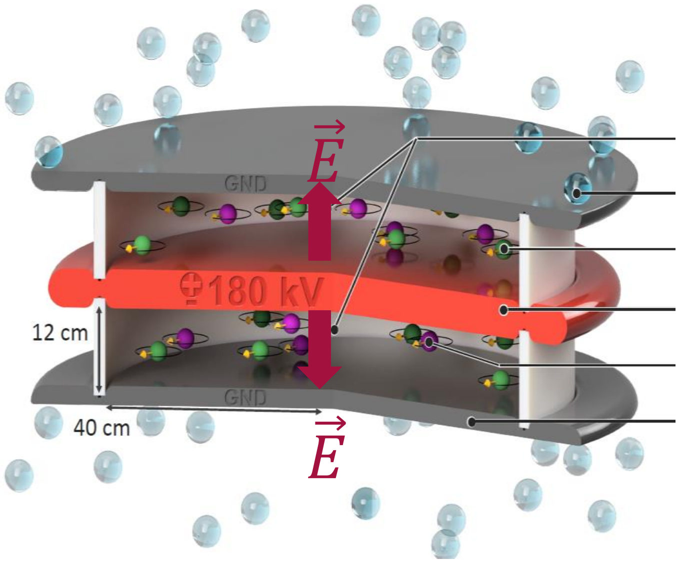
- If $\vec{B}_0 \neq$ uniform: d^{false} for neutrons and Hg-atoms

- Effect is not the same for neutrons and Hg-atoms!

	Neutrons	^{199}Hg
RMS velocity	few m/s	≈ 150 m/s
Larmor frequency	≈ 29 Hz	≈ 8 Hz

The d^{false} effect

- The $d_{\text{Hg}}^{\text{false}}$ leads to a shift in the ratio $\mathcal{R} = \frac{f_n}{f_{\text{Hg}}}$
- $d_{\text{Hg}\rightarrow n}^{\text{false}}$ can be of order $10^{-27}\,e$cm !
- Control magnetic field gradients using an additional magnetometer array



The nEDM collaboration, TDR, 2021,

Spherical Harmonics

- We can represent the magnetic holding field in spherical harmonics:

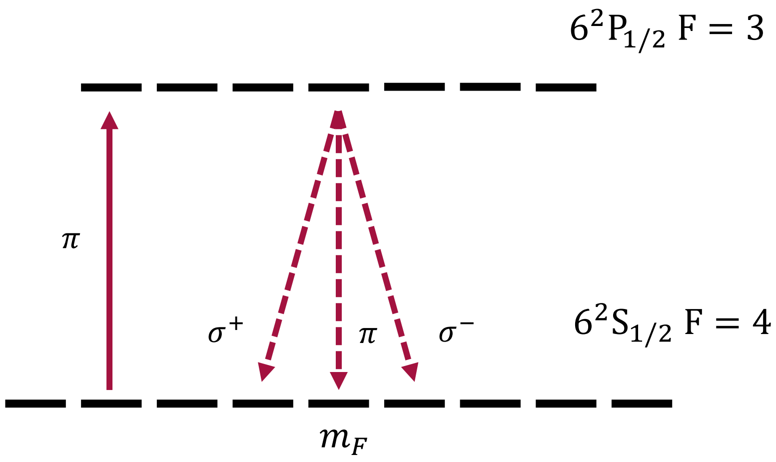
$$\vec{B}(\vec{r}) = \sum_{l\geq 0} \sum_{m=-l}^{l} G_{l,m} \Pi_{l,m}(\vec{r})$$

- With 112 magnetometers, we can measure gradients up to $l = 7$

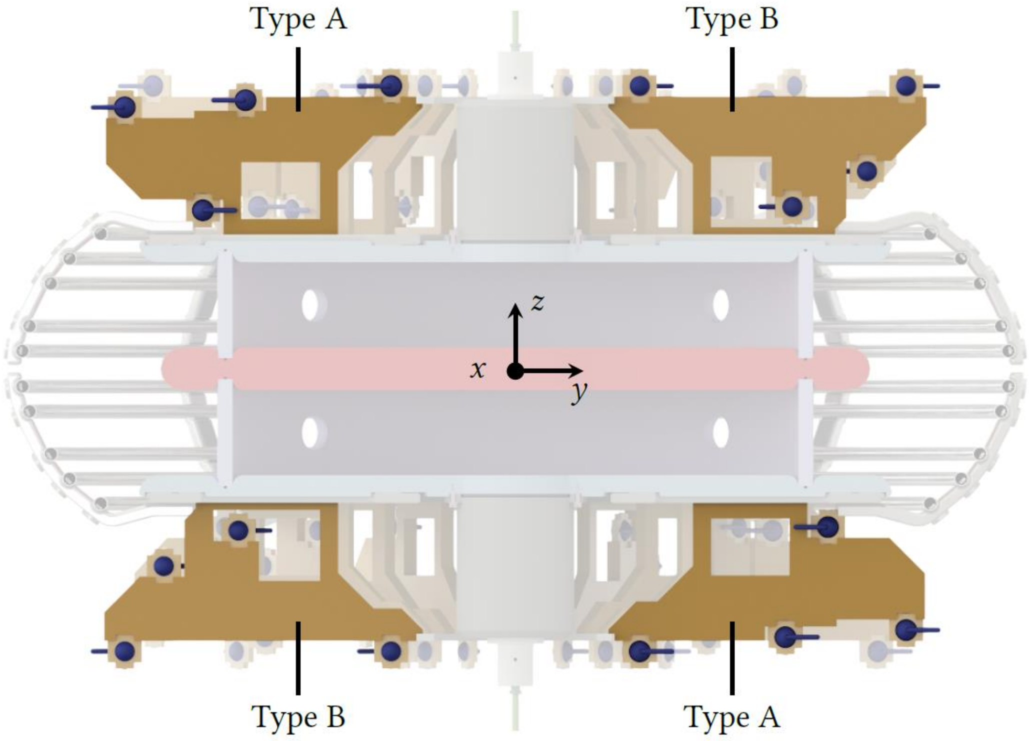
- Limit on cubic gradients: < 20 fT/cm

The Cesium magnetometer

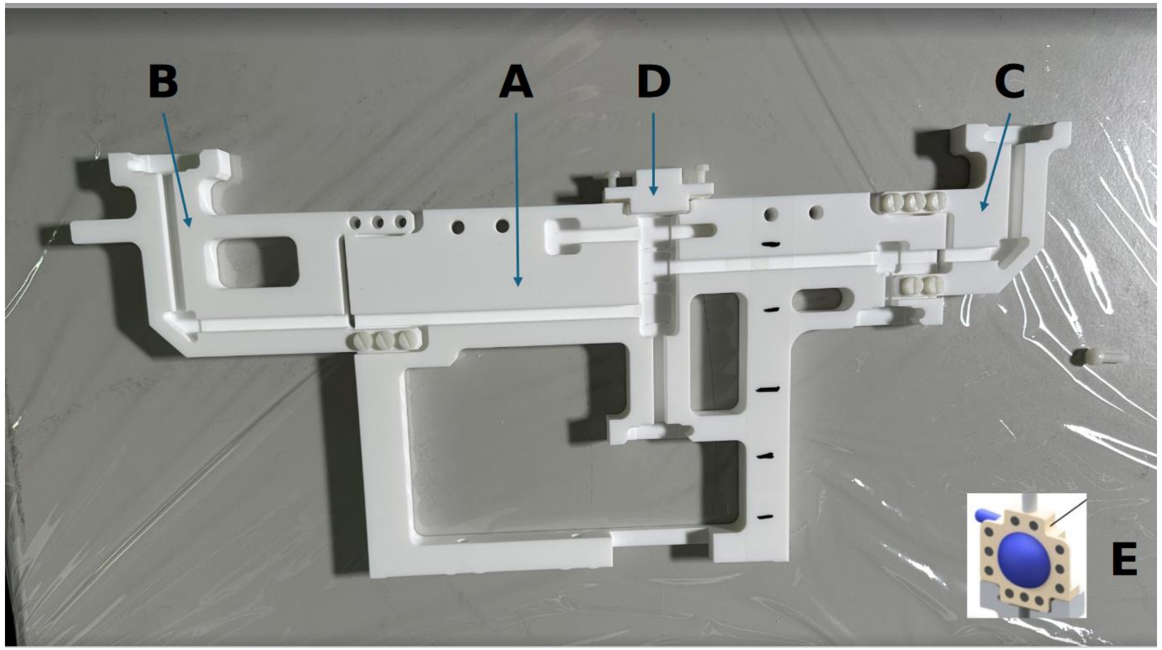
- 112 optically pumped Cesium vapor cells
- Pumping and probing on D_1 line with linearly polarized (π) light
- Detect m_F energy splitting via Larmor frequency
- $f_n(1\ \mu\mathrm{T}) = 7$ kHz



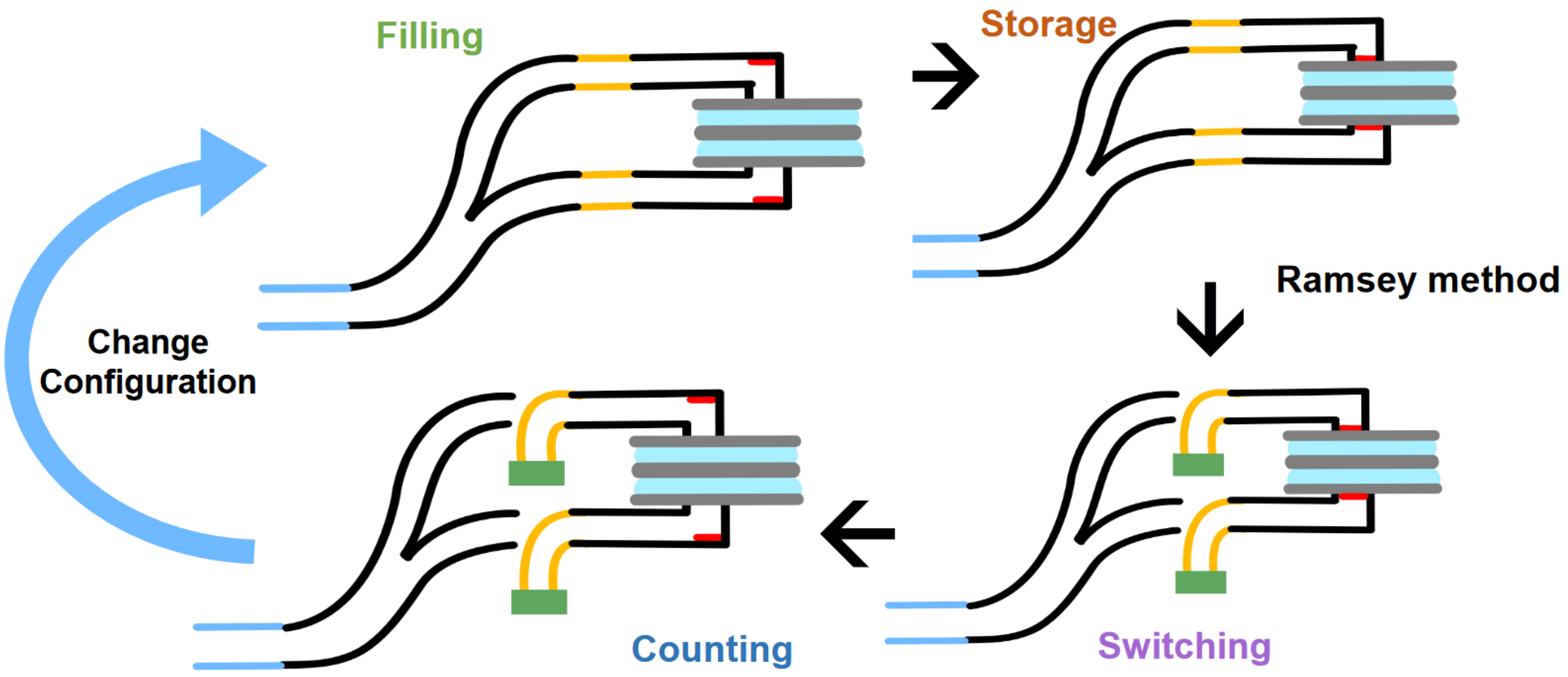
The Cesium magnetometer array



D. Pais, PhD Thesis, ETH Zurich, 2021.

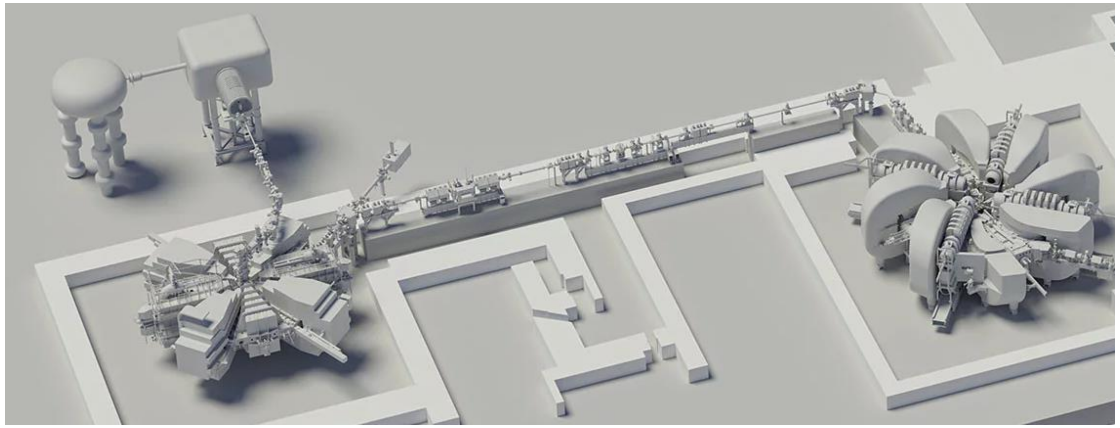


Switching of guide configuration

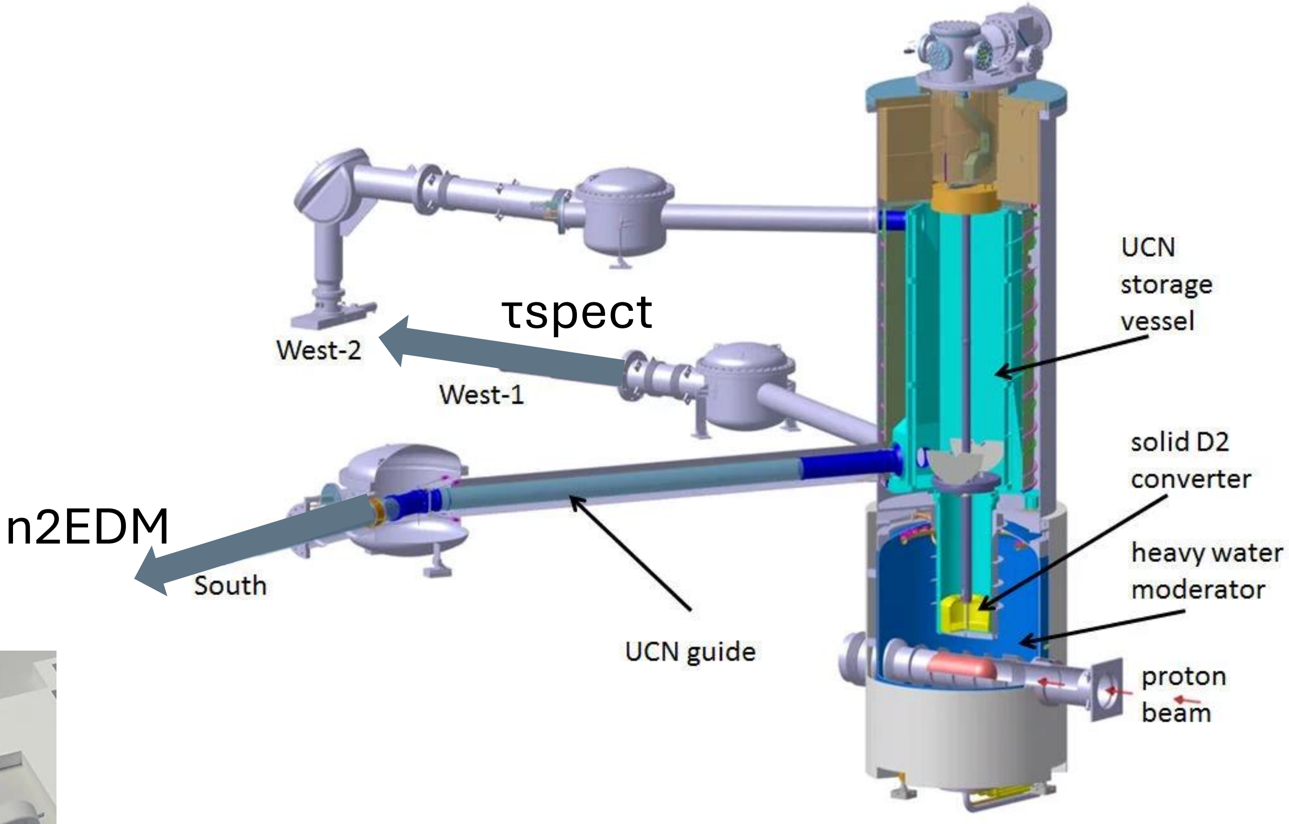


The PSI ultracold neutron source

- Spallation source
- Pulsed every 300s
- Proton beam current: ~ 2 mA
- Approx. 8 Neutrons/Proton



https://www.psi.ch/de/news/psi-stories/protonen-und-andere-teilchen-die-hipa-anlage-wird-50 Zurich, 2021.



https://www.psi.ch/en/ucn