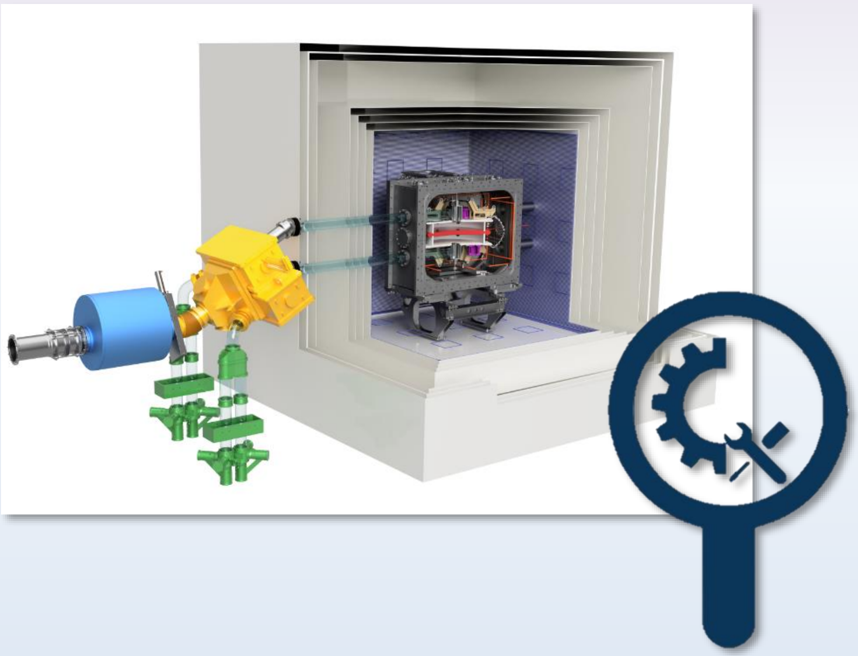
INTENSITY frontier GDR-InF



n2EDM

Commissioning progress

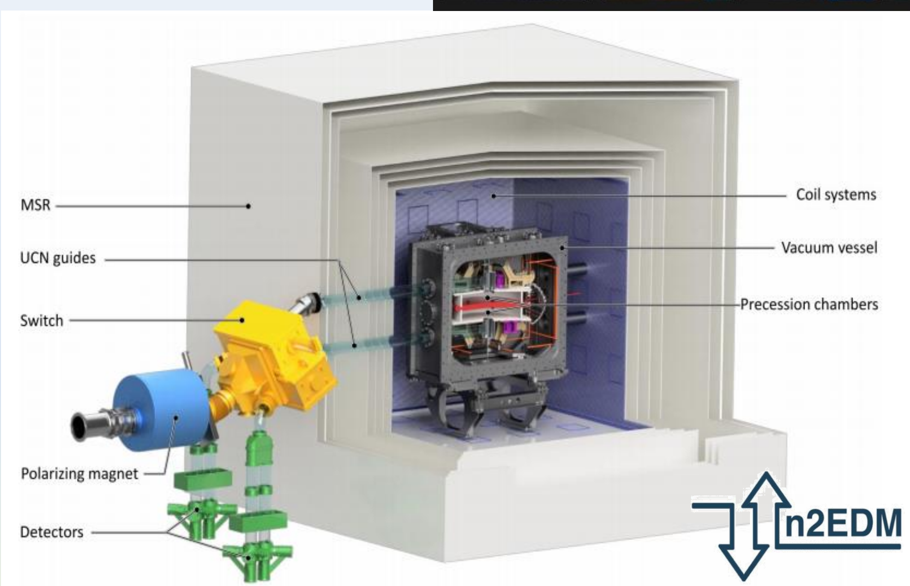
Kseniia Svirina
LPSC Grenoble

2-4 Nov 2022, Domaine Lyon Saint-Joseph

The nEDM collaboration

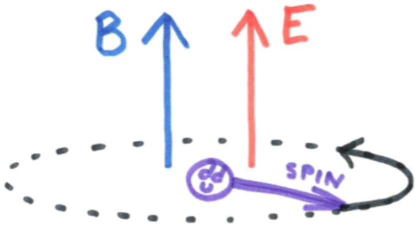
Search for the neutron EDM

PSI, Switzerland



under construction at the UCN source at the Paul Scherrer Institute (PSI)

Basics of nEDM measurement



Larmor frequency
$f = 30\ \mathrm{Hz} @ B = 1\ \mu\mathrm{T}$

$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar} |E|$$

If $d = 10^{-26}\ e\ \mathrm{cm}$ and $E = 11\ \mathrm{kV/cm}$
one full turn in a time

$$\frac{\pi\hbar}{dE} = 200\ \textbf{days}$$

To detect such a minuscule coupling
- Long interaction time
- High intensity/statistics
- Control the magnetic field

18:00 Discrete Symmetries Overview part 2: nEDM & nuclear β-decays
Speakers: Maud Versteegen (CENBG), Guillaume Pignol (LPSC)

The actual upper limit (2020)

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

C. Abel et al. Phys. Rev. Lett. 124, 081803

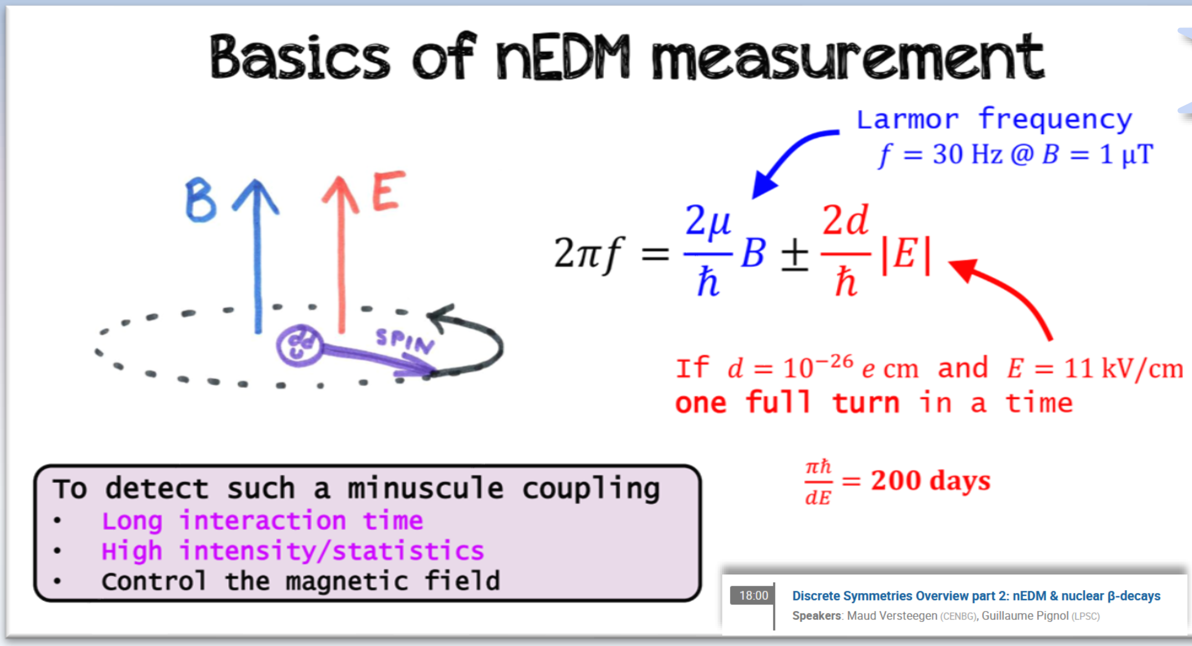
$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar}\ d\ E$$

$$d = \frac{\pi\hbar}{2|E|}\big(f(\uparrow\downarrow) - f(\uparrow\uparrow)\big)$$

The actual upper limit (2020)

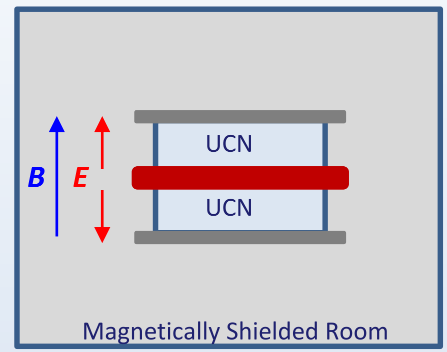
$$|d_n| < 1.8 \times 10^{-26}\, e\ \mathrm{cm}$$

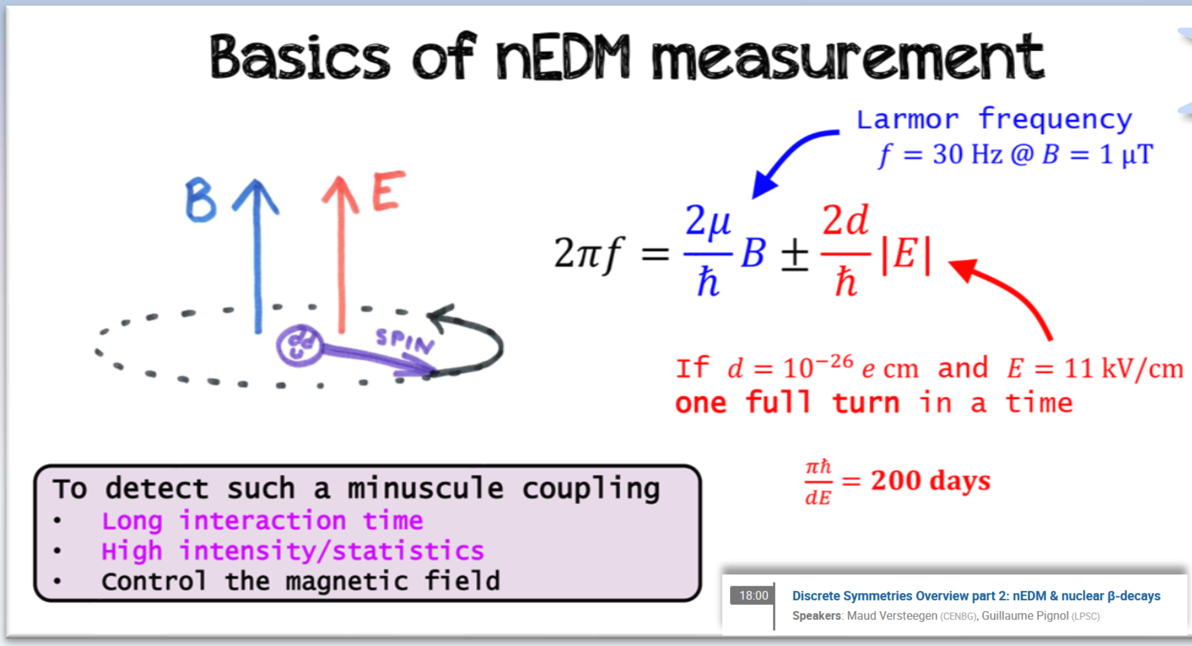
C. Abel et al. Phys. Rev. Lett. 124, 081803



$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar}\, d\, E$$

$$d = \frac{\pi\hbar}{2|E|}\left(f(\uparrow\downarrow) - f(\uparrow\uparrow)\right)$$





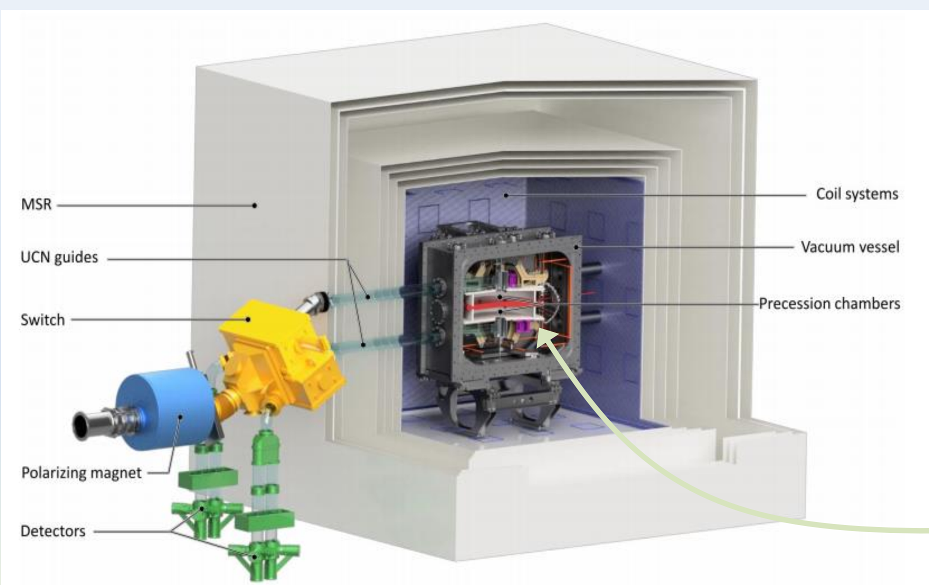
The actual upper limit (2020)

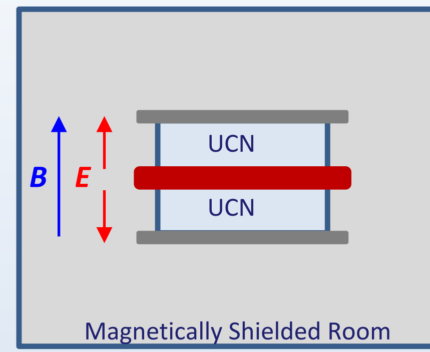
$$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$$

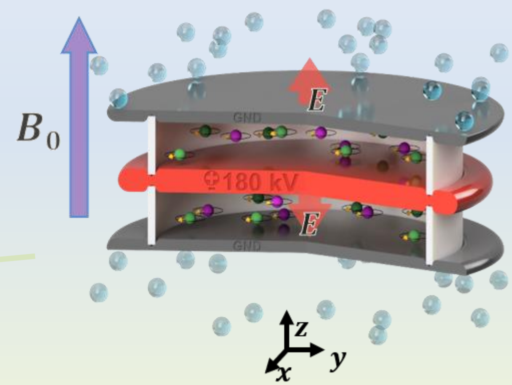
C. Abel et al. Phys. Rev. Lett. 124, 081803

$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar}\, d\, E$$

$$d = \frac{\pi\hbar}{2|E|}\left(f(\uparrow\downarrow) - f(\uparrow\uparrow)\right)$$

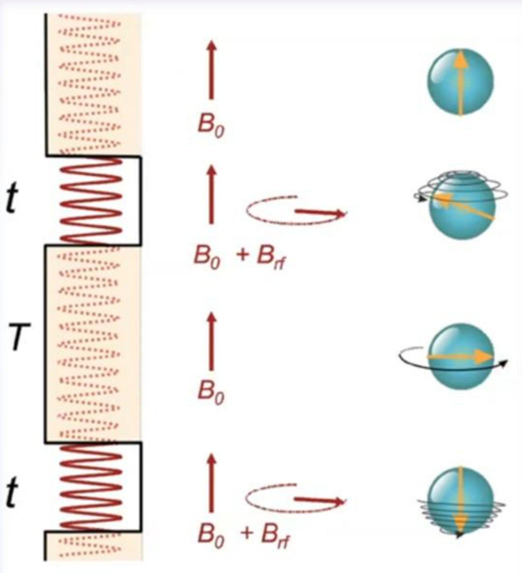






Measurement of the neutron EDM

Ramsey's method



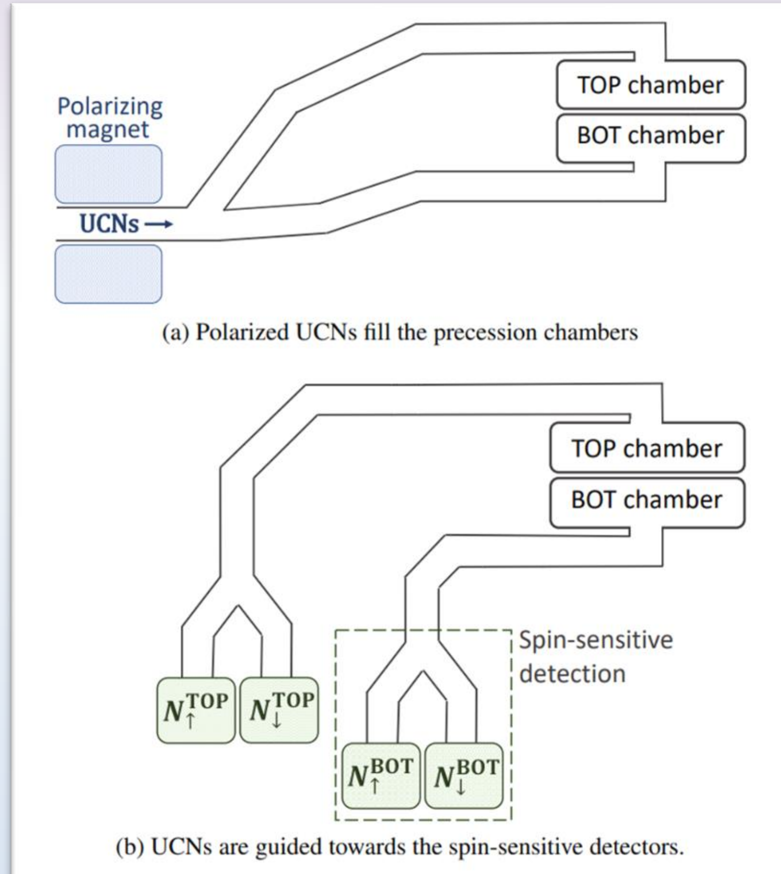
Neutron spin || B_0

Apply oscillating m.field ⊥ B_0

Let precess for 180 s

Again apply oscillating m.field ⊥ B_0

Obtain neutrons with spin either UP or DOWN,
Count the number of each, which depends on f_n



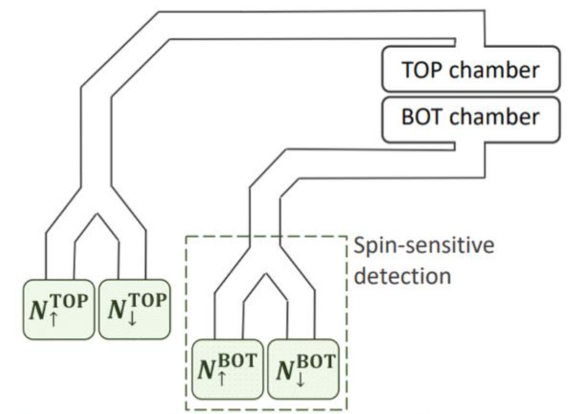
(a) Polarized UCNs fill the precession chambers

(b) UCNs are guided towards the spin-sensitive detectors.

Measurement of the neutron EDM

Asymmetry:

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

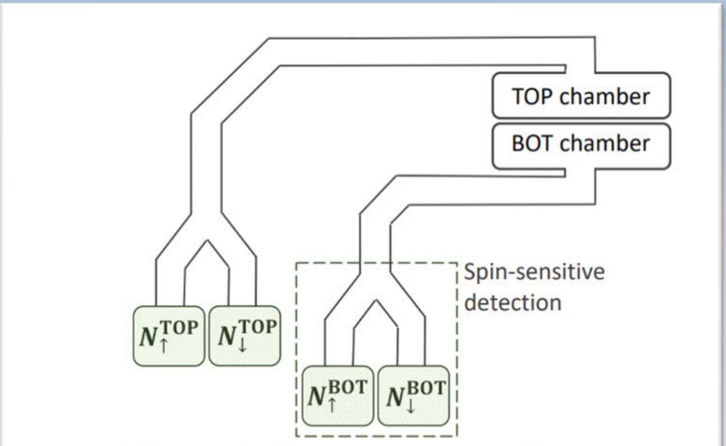


(b) UCNs are guided towards the spin-sensitive detectors.

Measurement of the neutron EDM

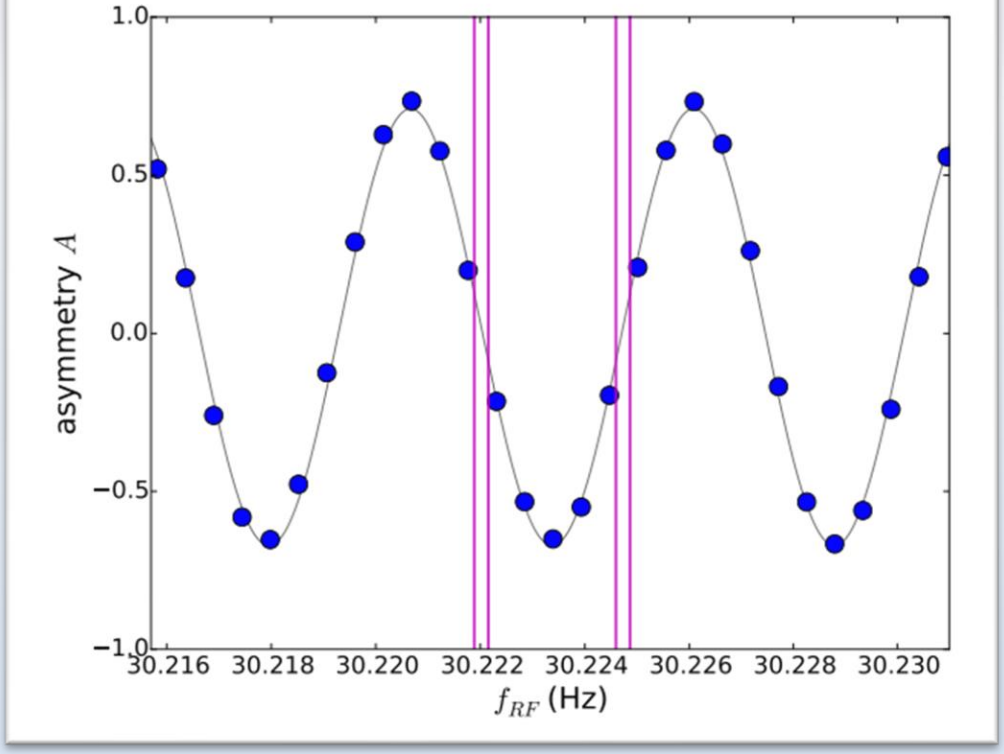
Asymmetry:

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



(b) UCNs are guided towards the spin-sensitive detectors.

The asymmetry as a function of the applied frequency

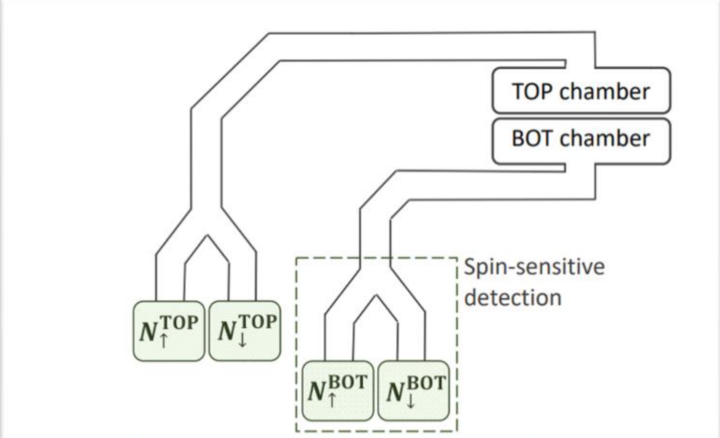


Example, nEDM experimental data (2017):
each point is a measurement cycle with a precession time of T = 180s performed with the nEDM apparatus (single-chamber),
the magnetic field: B0 = 1036.3 nT
which corresponds to a
Larmor precession frequency of 30.2235 Hz.

Measurement of the neutron EDM

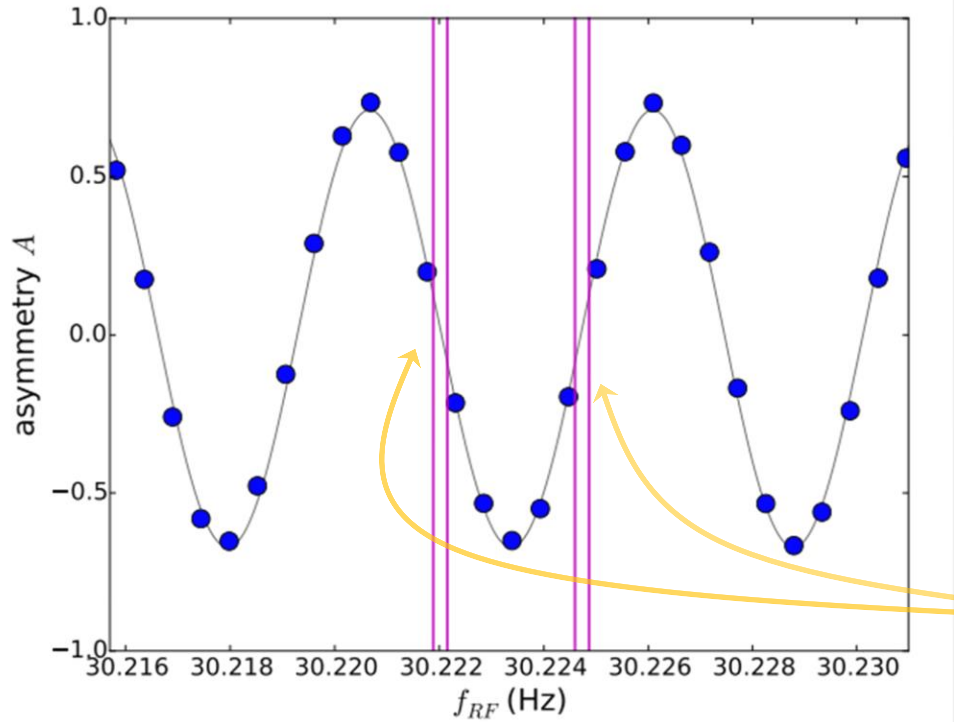
Asymmetry:

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



(b) UCNs are guided towards the spin-sensitive detectors.

The asymmetry as a function of the applied frequency



The maximal sensitivity is obtained for cycles measured at A = 0 where the slope of the resonance curve is highest.

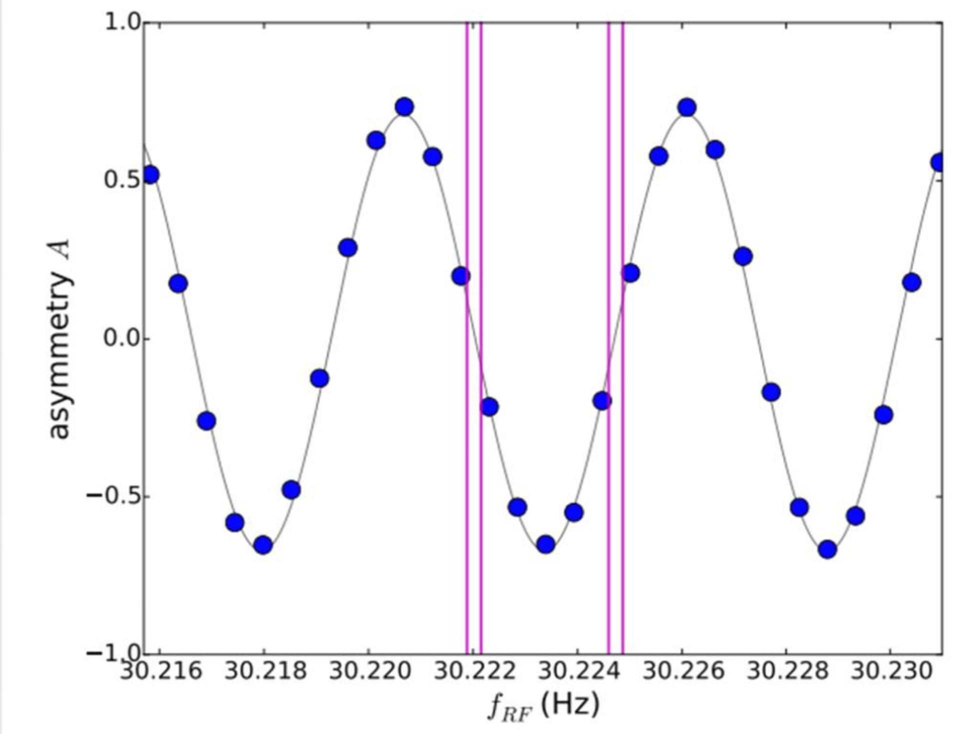
Example, nEDM experimental data (2017):
each point is a measurement cycle with a precession time of T = 180s performed with the nEDM apparatus (single-chamber),
the magnetic field: B0 = 1036.3 nT
which corresponds to a
Larmor precession frequency of 30.2235 Hz.

Measurement of the neutron EDM

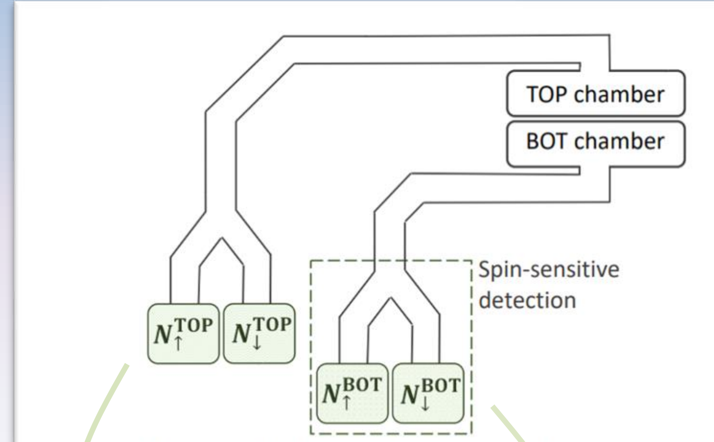
Asymmetry:

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

The asymmetry as a function of the applied frequency



Example, nEDM experimental data (2017):
each point is a measurement cycle with a precession time of T = 180s performed with the nEDM apparatus (single-chamber),
the magnetic field: B0 = 1036.3 nT
which corresponds to a
Larmor precession frequency of 30.2235 Hz.



(b) UCNs are guided towards the spin-sensitive detectors.

$$A^{TOP} = \frac{N_\uparrow^{TOP} - N_\downarrow^{TOP}}{N_\uparrow^{TOP} + N_\downarrow^{TOP}}$$

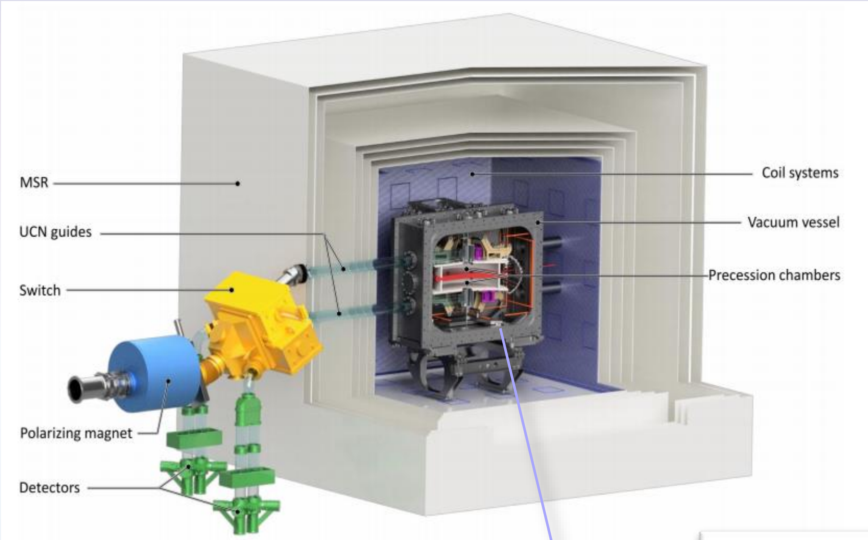
$$A^{BOT} = \frac{N_\uparrow^{BOT} - N_\downarrow^{BOT}}{N_\uparrow^{BOT} + N_\downarrow^{BOT}}$$

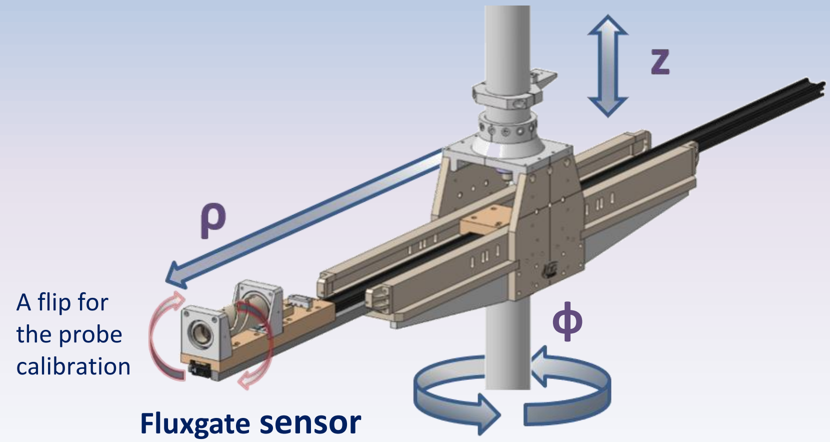
n2EDM:
the **applied frequency** is **common** to the **2 chambers,**

$\boldsymbol{f_{RF}}$ must be set close to the optimal points for the **2 chambers simultaneously**.

Requirement
on field production (B_0 coil):
$$-0.6\ \mathrm{pT/cm} < G_{1,0} < 0,6\ \mathrm{pT/cm}$$
"Top-Bottom resonance matching condition"
(maximum permitted vertical gradient of the magnetic field)

Magnetic commissioning of n2EDM: the 1st mapping campaign

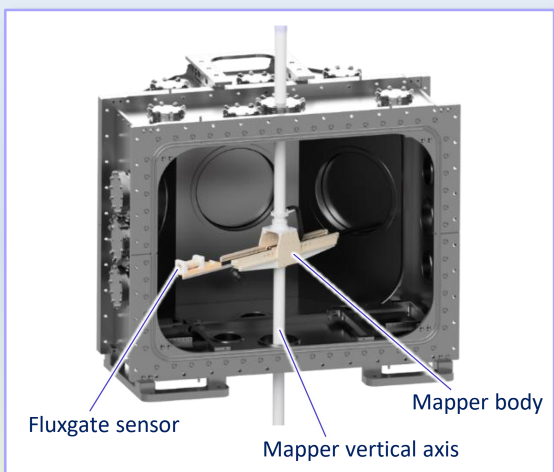




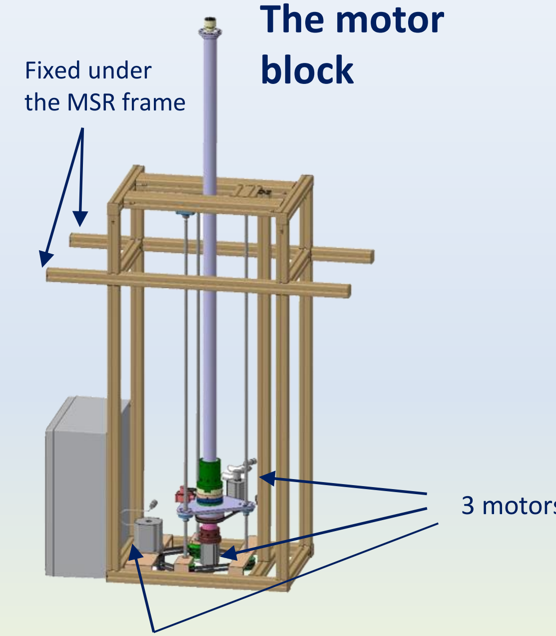
The mapping range

ρ	$0 - 780$ (mm)
φ	$0 - 360$ (deg.)
z	± 410 (mm)

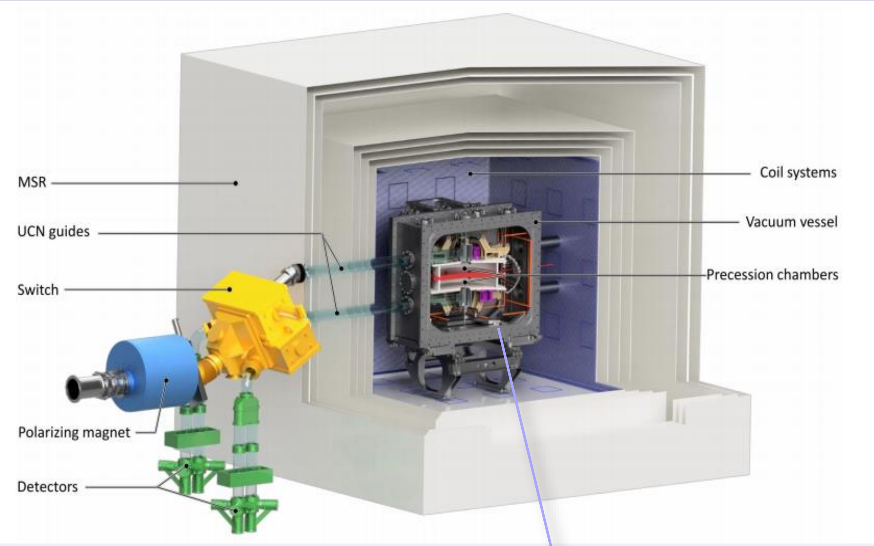
The magnetic-field mapper is designed to measure the magnetic field at any point of the cylindric volume inside the emptied vacuum vessel

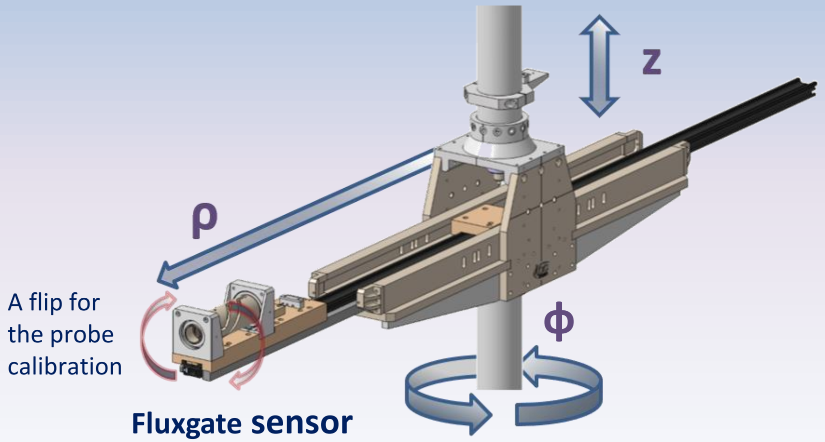


The motor block



Magnetic commissioning of n2EDM: the 1st mapping campaign

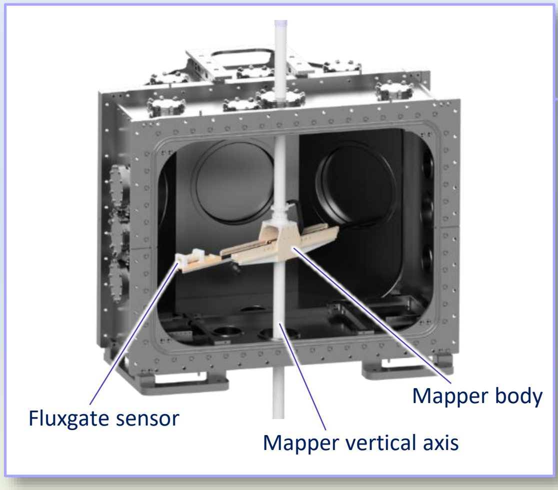




The mapping range

ρ	$0\ -780\ (\mathrm{mm})$
φ	$0\ -360\ (\mathrm{deg.})$
z	$\pm 410\ (\mathrm{mm})$

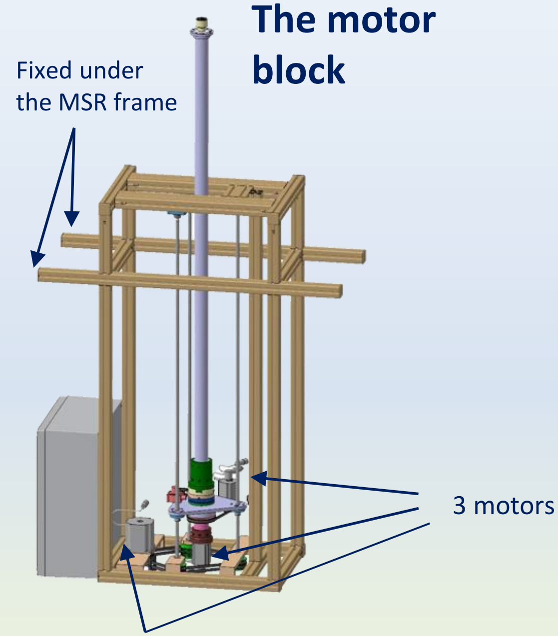
The magnetic-field mapper is designed to measure the magnetic field at any point of the cylindric volume inside the emptied vacuum vessel



Purposes:

- ✓ **Coil system cartography**
- ✓ Offline control of high-order gradients
- ✓ Searches for magnetic contamination

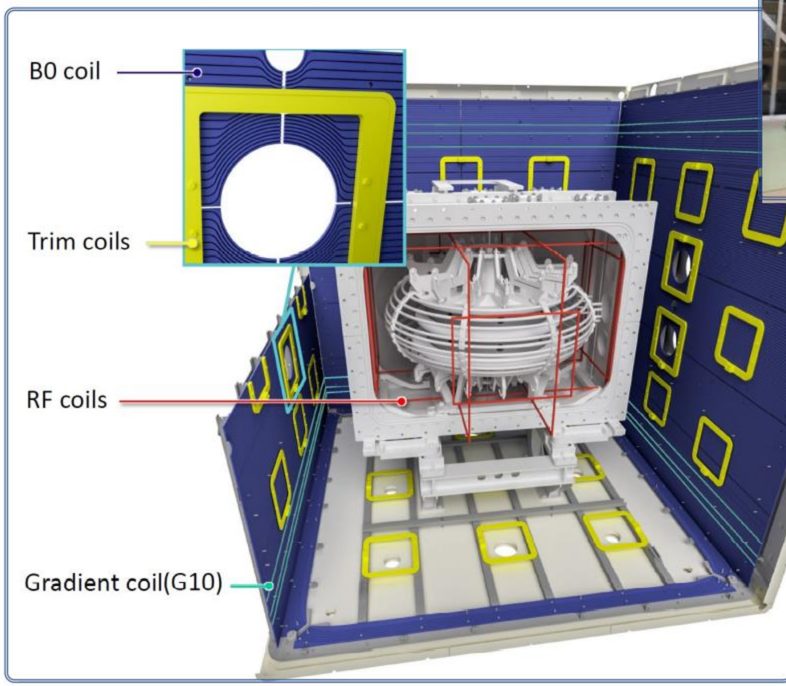
The motor block

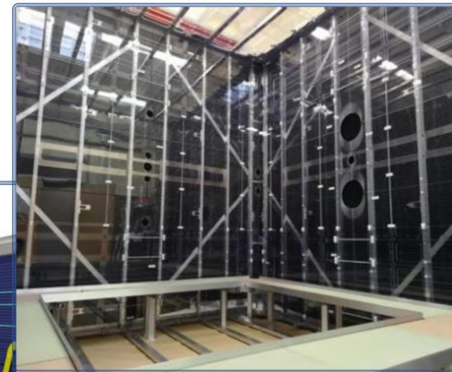


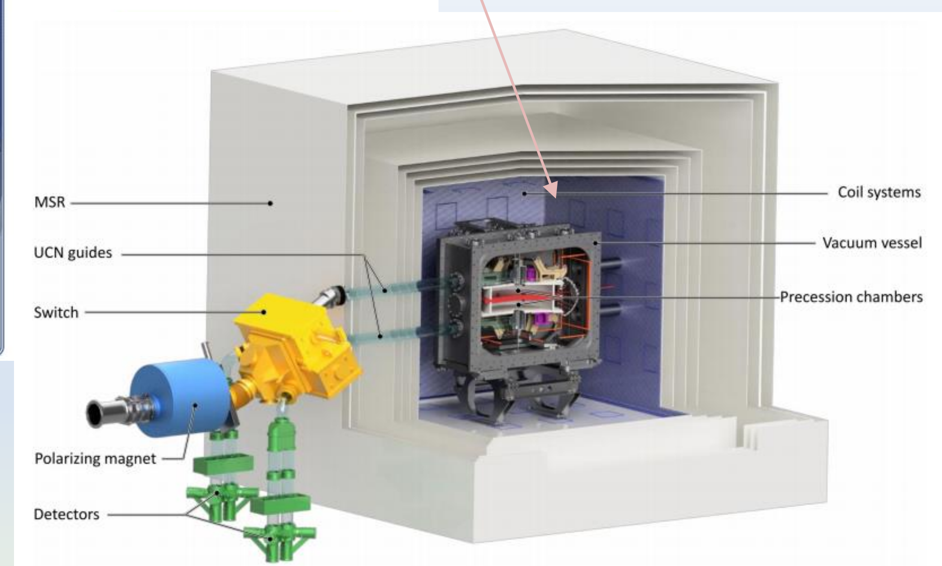
Magnetic commissioning of n2EDM: the 1st mapping campaign

Coil system installation

- Produce a very uniform B0 field (1μT)
- Produce specific gradients
- Hold the UCN polarisation
- Neutron spin manipulation



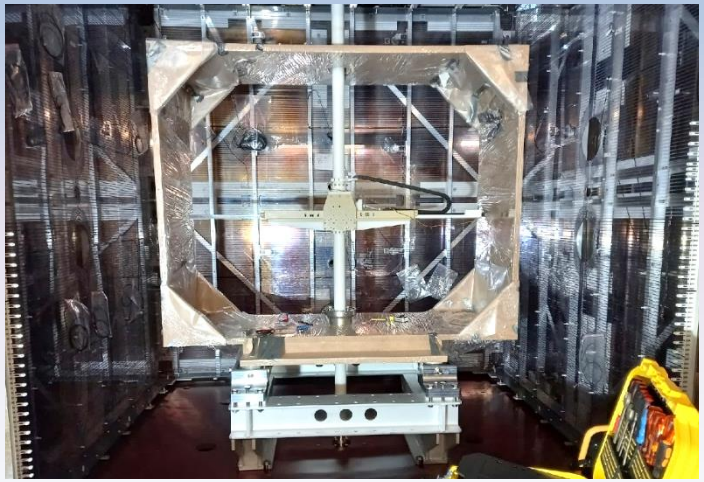




Magnetic commissioning of n2EDM: the 1st mapping campaign

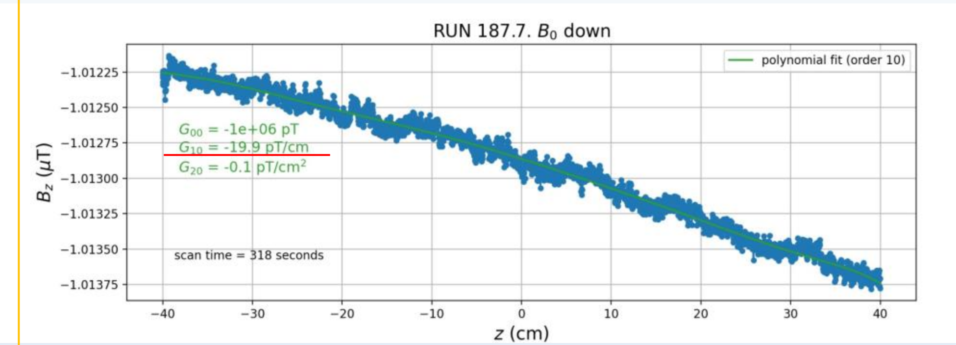
Map type:

Coil system installation



The first vertical map after the installation of the B_0 coil showed a deviation in the 1st-order gradient $\boldsymbol{G_{1,0}}$.

$$\boldsymbol{G_{1,0} = -19.9\ \mathrm{pT/cm}}$$



An example of a vertical scan of the B_z field component in **initial** B_0 coil position.

Requirement
on field production (B_0 coil):

$$\boldsymbol{-0.6\ \mathrm{pT/cm} < G_{1,0} < 0,6\ \mathrm{pT/cm}}$$

"Top-Bottom resonance matching condition"

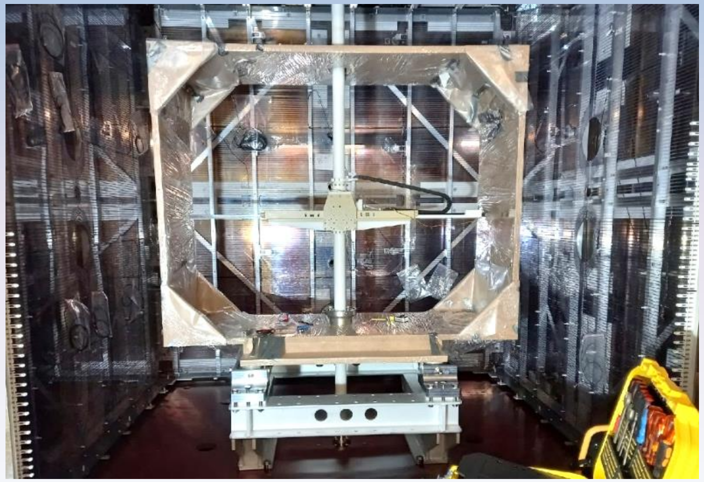
(maximum permitted vertical gradient of the magnetic field)

STAT.

Magnetic commissioning of n2EDM: the 1st mapping campaign

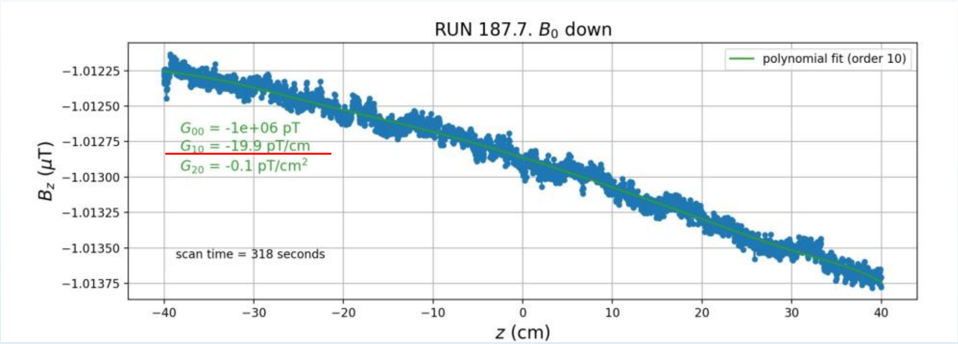
Coil system installation

Map type:



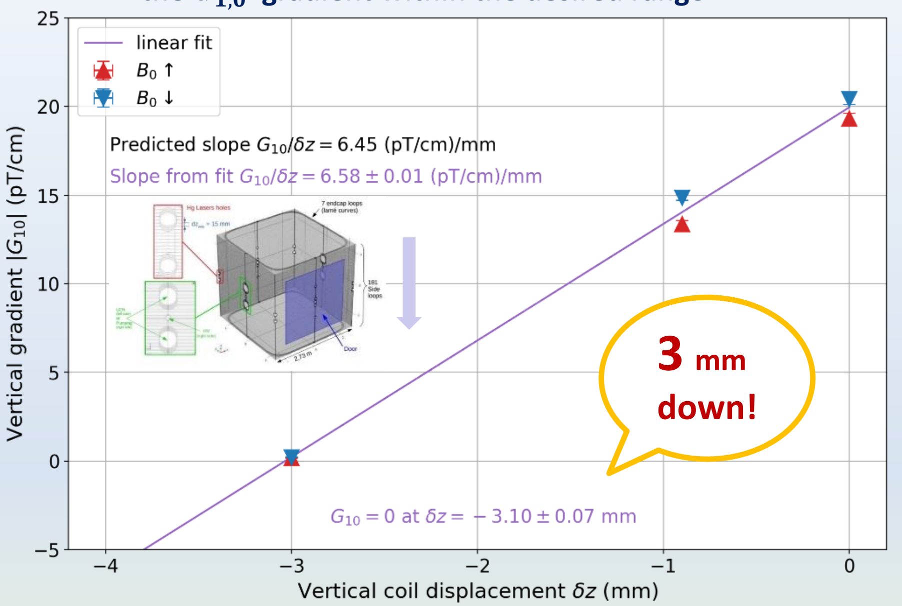
The first vertical map after the installation of the B_0 coil showed a deviation in the 1st-order gradient $\boldsymbol{G_{1,0}}$.

$\boldsymbol{G_{1,0} = -19.9\ \mathrm{pT/cm}}$ – compatible with a **vertical shift** of the entire coil system with respect to the MSR by $\Delta z = \mathbf{3mm}$



An example of a vertical scan of the B_z field component in **initial** B_0 coil position.

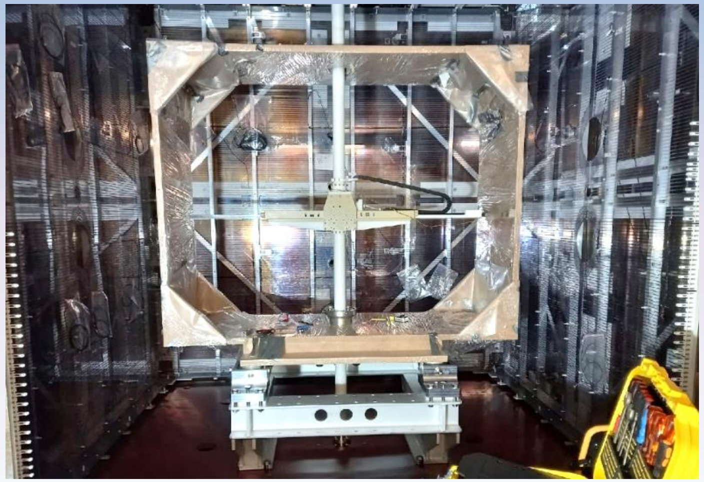
Evaluation of the vertical shift value in order to get the $\boldsymbol{G_{1,0}}$ gradient within the desired range



The values of $\boldsymbol{G_{1,0}}$ shown for each polarity of the B_0 coil are the averages of the values of $\boldsymbol{G_{1,0}}$ after degaussing in L6 and L6-crossed configurations.

Magnetic commissioning of n2EDM: the 1st mapping campaign

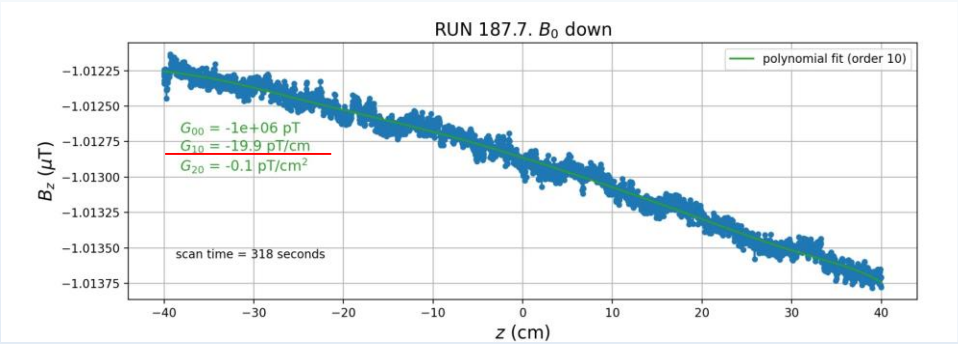
Map type:



Coil system installation

The first vertical map after the installation of the B_0 coil showed a deviation in the 1st-order gradient $\boldsymbol{G_{1,0}}$.

$\boldsymbol{G_{1,0} = -19.9\ \mathrm{pT/cm}}$ – compatible with a **vertical shift** of the entire coil system with respect to the MSR by $\Delta z = \mathbf{3mm}$



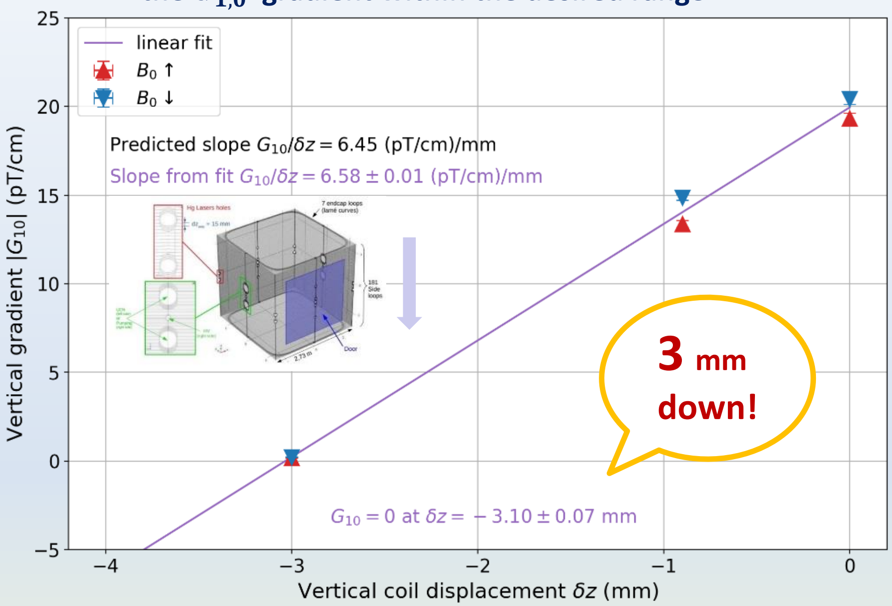
An example of a vertical scan of the B_z field component in **initial** B_0 coil position.

New result:

$\boldsymbol{G_{1,0} = -0.59\ \mathrm{pT/cm}}$

A vertical scan of the B_z field component **after** B_0 coil adjustment.

Evaluation of the vertical shift value in order to get the $\boldsymbol{G_{1,0}}$ gradient within the desired range



The values of $\boldsymbol{G_{1,0}}$ shown for each polarity of the B_0 coil are the averages of the values of $\boldsymbol{G_{1,0}}$ after degaussing in L6 and L6-crossed configurations.

Magnetic commissioning of n2EDM: the 1st mapping campaign

Summary

$G_{1,0} = -19.9$ pT/cm

Calculation,
Shift of the coil system

$G_{1,0} = -0.59$ pT/cm (B$_0$-down)

$G_{1,0} = 0.2$ pT/cm (average of B$_0$-down & B$_0$-up)

After the **vertical adjustment of the coil**, the new value of the 1st order gradient in the B$_0$-down configuration : $G_{1,0} = -0.59$ pT/cm.

The **average** of the $G_{1,0}$ measured for the two polarities of B$_0$ gives the value of 0.2 pT/cm i.e. it is **in perfect agreement with the prediction**, meets the requirement and demonstrates an **impressive sensitivity of the mapping**!

Requirement on field production (B$_0$ coil):

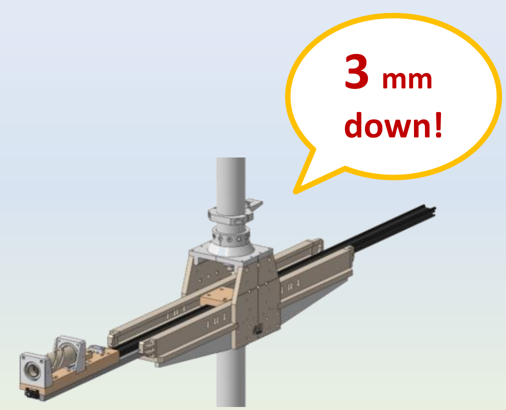
STAT.

-0.6 pT/cm < $G_{1,0} < 0,6$ pT/cm

"Top-Bottom resonance matching condition"

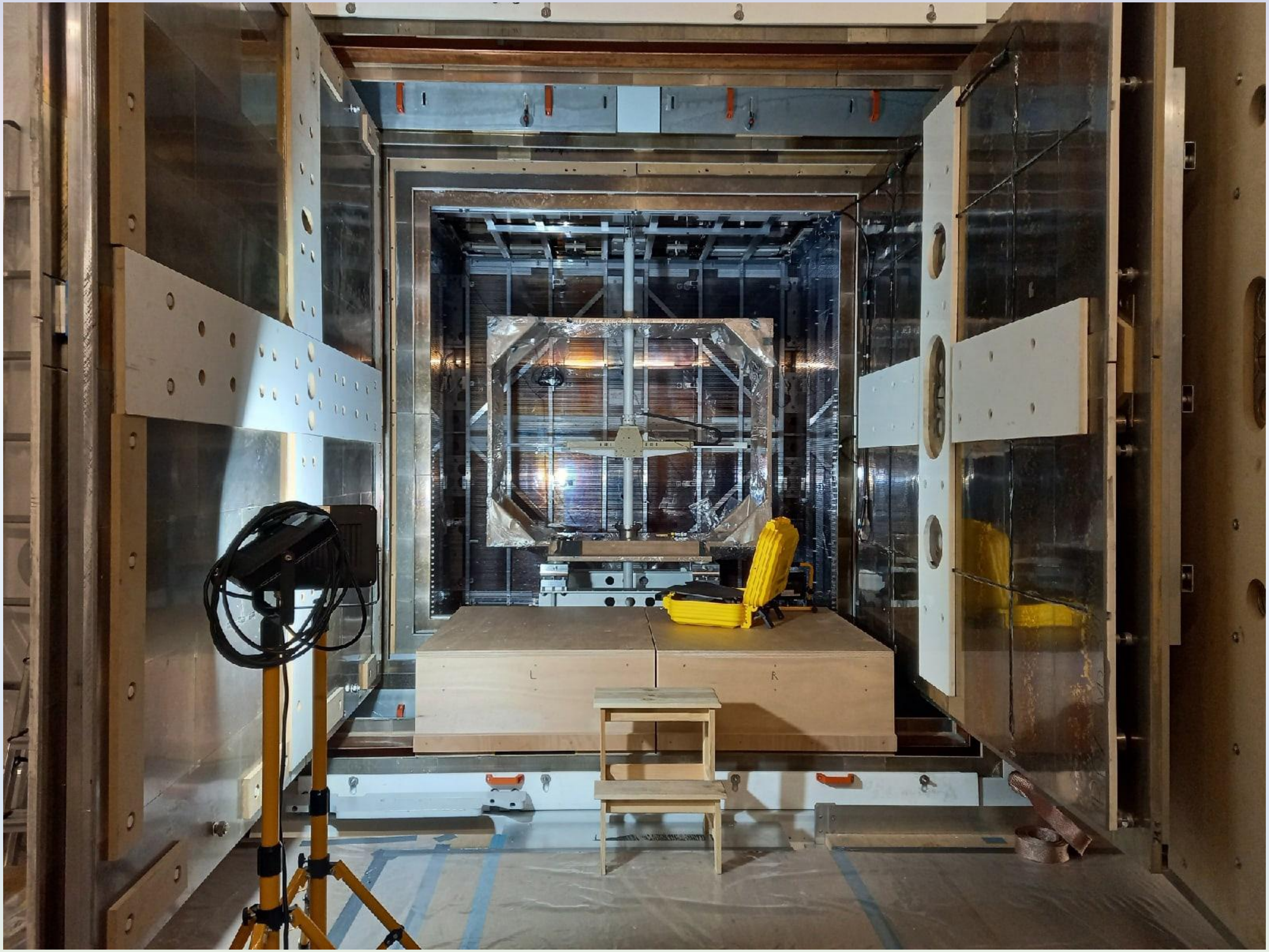
(maximum permitted vertical gradient of the magnetic field)

Fulfilled!




n2EDM
n2EDM
commissioning
... To be continued!
Thanks for your attention!
constructioncam2_2022-10-24_11-20-00.jpg

BACKUP SLIDES ➡



A weak magnetic field $B_0 \approx 1\ \mu T$ is applied in a volume of $>1m^3$. The field is considered to be purely static and very uniform, but the remaining nonuniformities have serious consequences.
To characterize them, a polynomial expansion of the magnetic field components is made [2] :

$$\vec{B}(\vec{r}) = \sum_{l,m} G_{l,m} \begin{pmatrix} \Pi_{x,l,m}(\vec{r}) \\ \Pi_{y,l,m}(\vec{r}) \\ \Pi_{z,l,m}(\vec{r}) \end{pmatrix}$$

where the **modes** $\vec{\Pi}_{l,m}$ are harmonic polynomials in x, y, z of degree l , and $G_{l,m}$ are the expansion coefficients.
This is convenient and satisfies Maxwell's equations:

$$\vec{\nabla} \cdot \vec{B}=0 \quad \text{and} \quad \vec{\nabla} \times \vec{B}=0.$$

Requirements

- **On field production – B0 coil**:

$$-0.6\ \mathbf{pT/cm} < G_{1,0} < 0,6\ \mathbf{pT/cm}$$

"Top-Bottom resonance matching condition"
i.e. B_z needs to be similar enough between the two chambers

$$\sigma(B_z) = \sqrt{\langle B_z^2 \rangle} < 170\ \mathbf{pT}$$

to prevent neutron depolarization

- **On field measurements – mapping**:

$\delta\acute{G}_3 < 20\ \mathbf{fT/cm}$ – accuracy of cubic mode
$\delta\acute{G}_5 < 20\ \mathbf{fT/cm}$ – accuracy of 5-order mode

$\acute{G}_3$ and $\acute{G}_5$ should be measured precisely enough to calculate $d_{n\leftarrow Hg}^{\mathrm{false}}$ (*) with a precision below

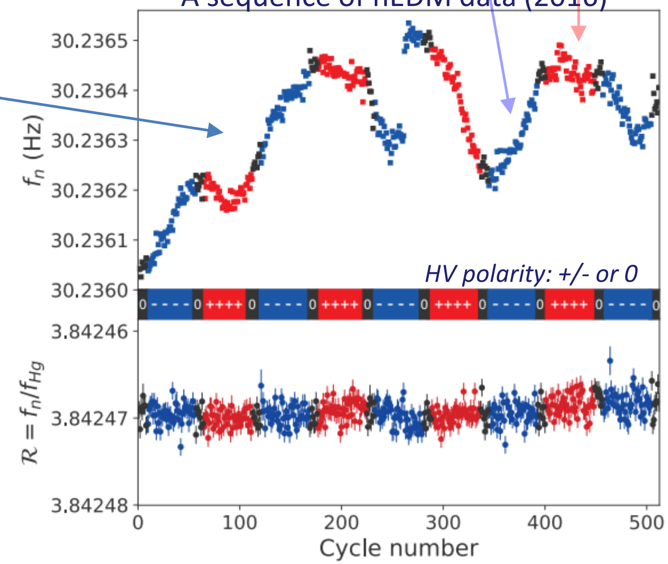
(*) - False EDM is a systematic effect arising from the relativistic motional field $\vec{E} \times \vec{v}/c^2$ experienced by the moving particles in combination with the residual magnetic gradients and leading to a frequency shift. The dominating contribution $d_{n\leftarrow Hg}^{\mathrm{false}}$ is the false EDM transferred from the co-magnetometer atoms Hg^{199}.

Measurement of the neutron EDM

$$d = \frac{\pi\hbar}{2|E|}\left(f(\uparrow\downarrow) - f(\uparrow\uparrow)\right)$$

f_n is affected by drifts of the magnetic field!

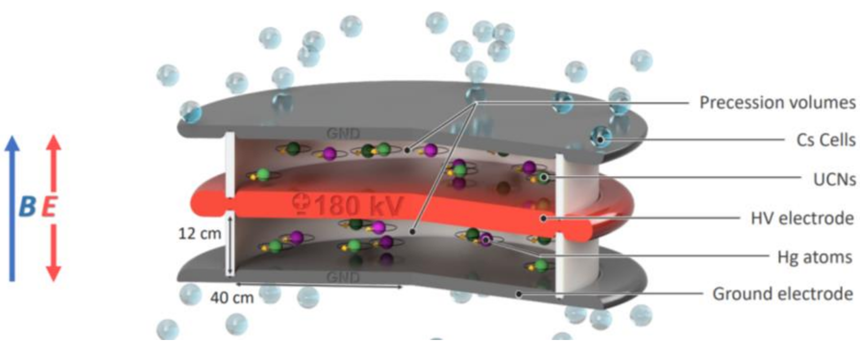
A sequence of nEDM data (2016)



Solution:

Mercury co-magnetometer

Polarized ^{199}Hg atoms precess in the same chambers



Simultaneous measurement of f_n and f_{Hg}

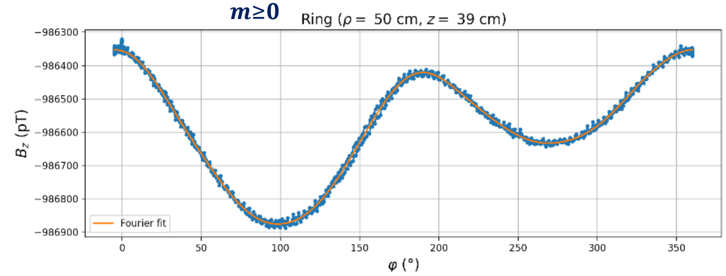
$$\mathcal{R} \equiv \frac{f_n}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right| \mp \frac{|E|}{\pi\hbar f_{\mathrm{Hg}}} d_{\mathrm{n}}$$

$$d_{\mathrm{n}} = \frac{\pi\hbar f_{\mathrm{Hg}}}{4|E|}\left(\mathcal{R}_{\uparrow\downarrow}^{\mathrm{TOP}} - \mathcal{R}_{\uparrow\uparrow}^{\mathrm{TOP}} + \mathcal{R}_{\uparrow\downarrow}^{\mathrm{BOT}} - \mathcal{R}_{\uparrow\uparrow}^{\mathrm{BOT}}\right).$$

f_{Hg} measurement principle:
a UV probe beam transverses the chambers
-> record the absorbtion of the light (an oscillating signal),
extract f_{Hg}

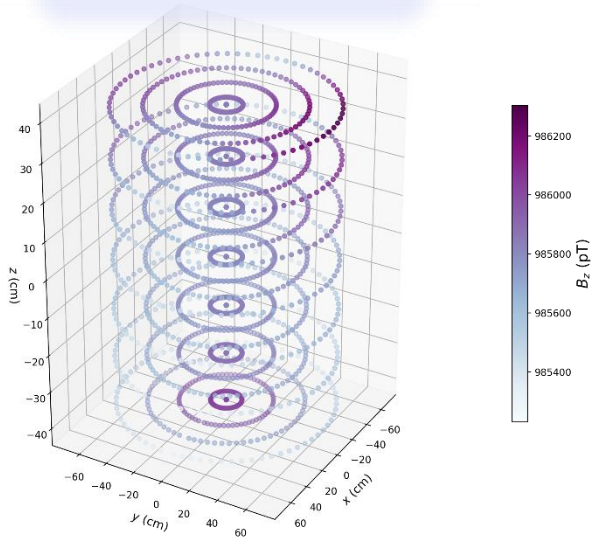
Ring by ring Fourier decomposition

$$B_z\,(\varphi) = \sum_{m\geq 0} a_{m,z}\cos(m\varphi) + b_{m,z}\sin(m\varphi)$$



Set of Fourier coefficients

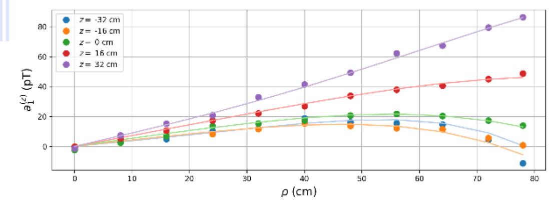
A field map: set of rings



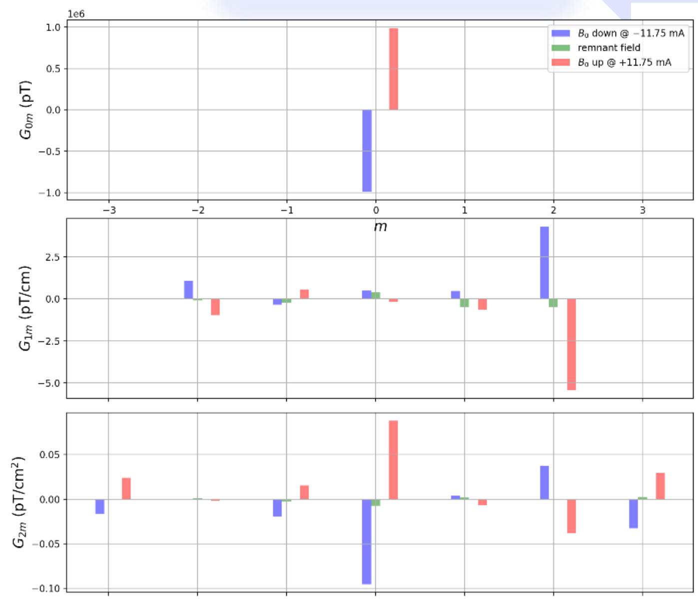
For one ring, since the radius ρ and height z are fixed, the magnetic field is simply a function of φ. We fit it with a Fourier series with the Fourier coefficients as parameters of the φ.
After having extracted a set of Fourier coefficients for each ring, the next step is to fit these coefficients with the harmonic functions of the field expansion.

Fourier coefficients fit with harmonic polynomials

$$a_{m,z}\,(\rho, z) = \sum_{l\geq 0} G_{l,m}\widehat{\Pi}_{l,m}(\rho, z)$$



Set of gradients $G_{l,m}$



The offline magnetic-field characterization using an automated magnetic field mapper. Here, the mapper was installed inside the MSR without the vacuum vessel in order to measure the remnant field and to test the coil system. The measurement volume is a cylinder of diameter 156 cm and height 82 cm.