MAPPING OF THE MAGNETIC FIELD IN THE N2EDM EXPERIMENT @PSI

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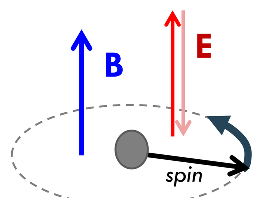
Measurement of the neutron EDM

Neutron spin precession in a weak magnetic and strong electric field



$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar}|E| \Rightarrow f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar} d\, E$$

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

$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}\, e\,cm$ [1]

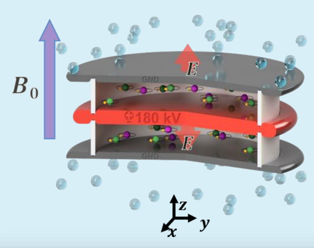
$B = 1\,\mu T$ — $\boxed{30\text{ Hz}}$ *Larmor frequency* — *Large!*

$E = 15\,kV/cm$ — $\boxed{10^{-8}\text{Hz}}$ *if $d = 10^{-26}$ e cm, 1 full turn of the spin: ~160 days* — *Too tiny!*

Solution:

- Maximize the exposure of the neutrons in E
  use UCNs (can be stored up to 15 min)
- Maximize the statistics
  good UCN transport system, large UCN storage volume
- Control of the magnetic field
  Hg co-magnetometer; shielding: MSR, AMS
  checks of the magnetic field uniformity: **mapping**

Field parametrization



A weak magnetic field $B_0 \approx 1\,\mu T$ is applied in a volume of $>1 m^3$. 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:** STAT

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

"Top-Bottom resonance matching condition" [3]

i.e. B_z needs to be similar enough between the two chambers

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

to prevent neutron depolarization

- **On field measurements – mapping:** SYST

$\delta\acute{G}_3 < 20\text{ fT/cm}$ – accuracy of cubic mode

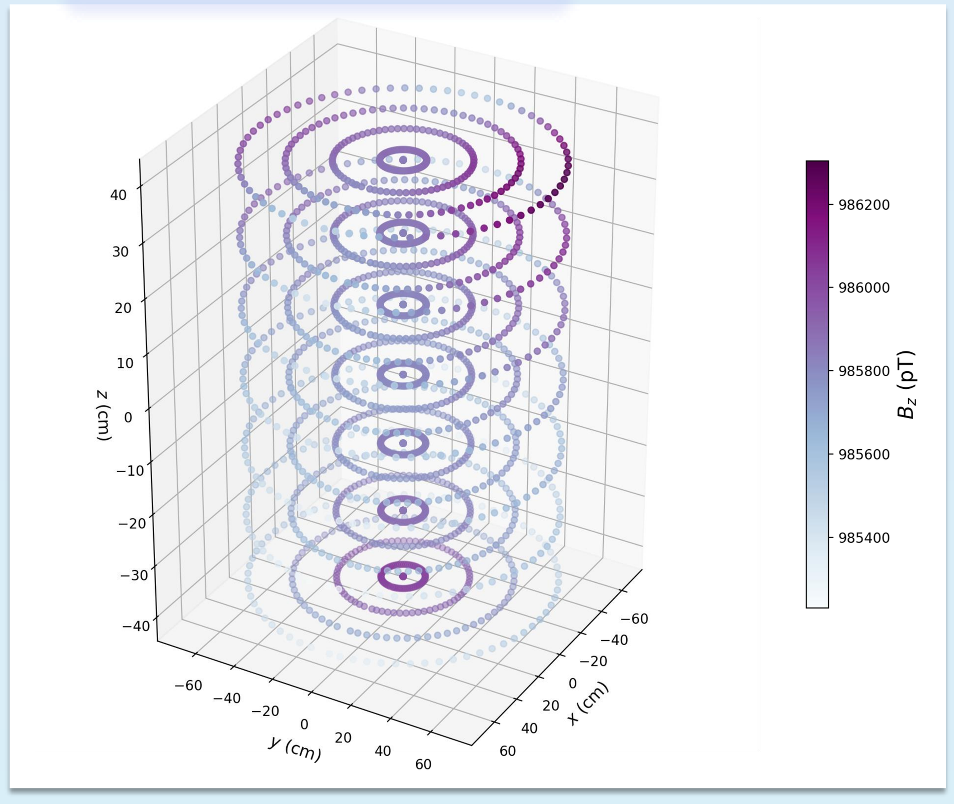
$\delta\acute{G}_5 < 20\text{ fT/cm}$ – accuracy of 5-order mode

$\acute{G}_3$ and $\acute{G}_5$ should be measured precisely enough to calculate $d^{\text{false}}_{n\leftarrow Hg}$ with a precision below 10^{-28}e cm

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 $d^{\text{false}}_{n\leftarrow Hg}$ is the false EDM transferred from the co-magnetometer atoms Hg^{199}.

From raw data to results

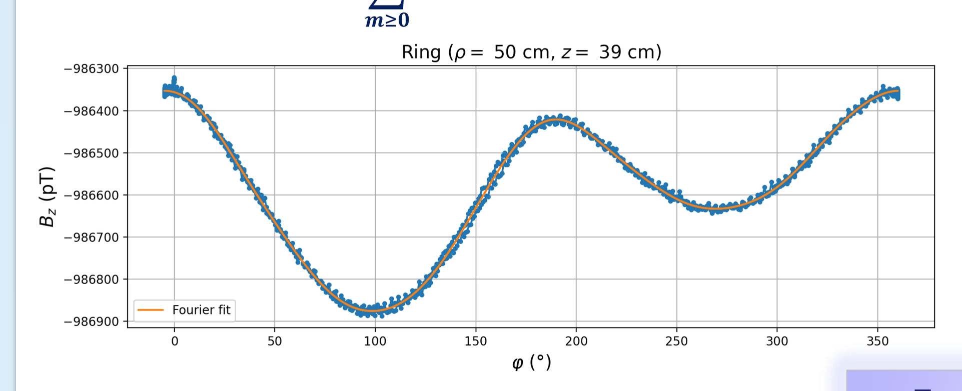
A field map: set of rings



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.

Ring by ring Fourier decomposition

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

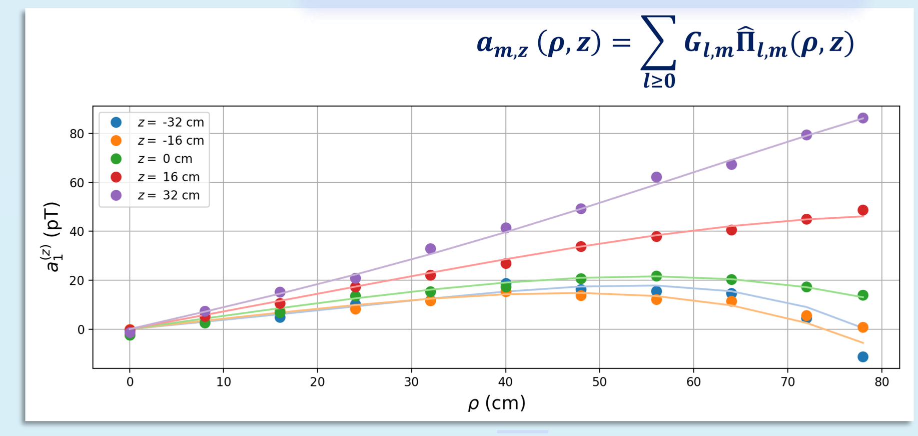


For one ring, since the radius ρ and height z are fixed, the magnetic field is simply a function of φ. We fit it with a Fourier series with the Fourier coefficients as parameters of the φ. After having extracted a set of Fourier coefficients for each ring, the next step is to fit these coefficients with the harmonic functions of the field expansion [4].

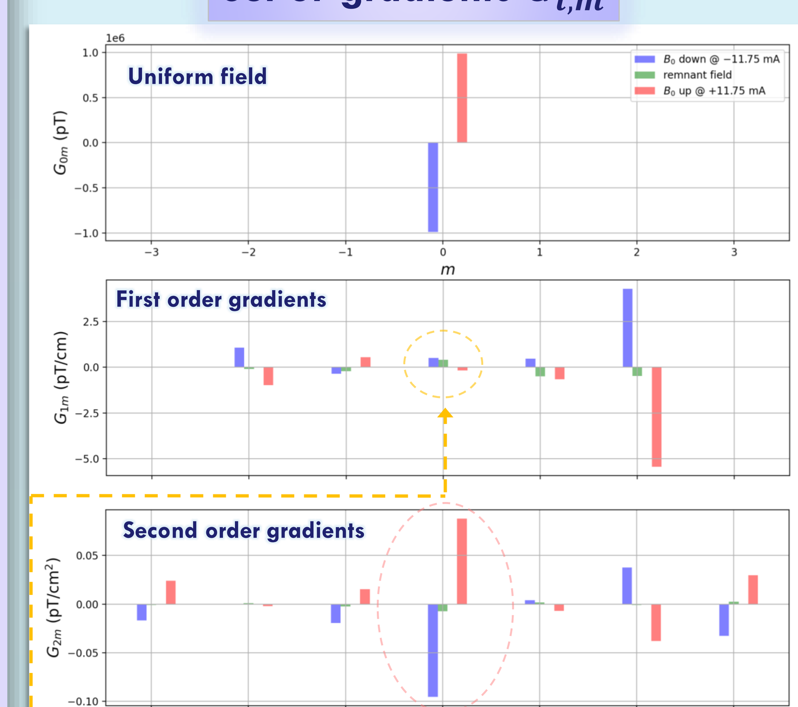
Set of Fourier coefficients

Fourier coefficients fit with harmonic polynomials

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



Set of gradients $G_{l,m}$



Magnetic field mapper

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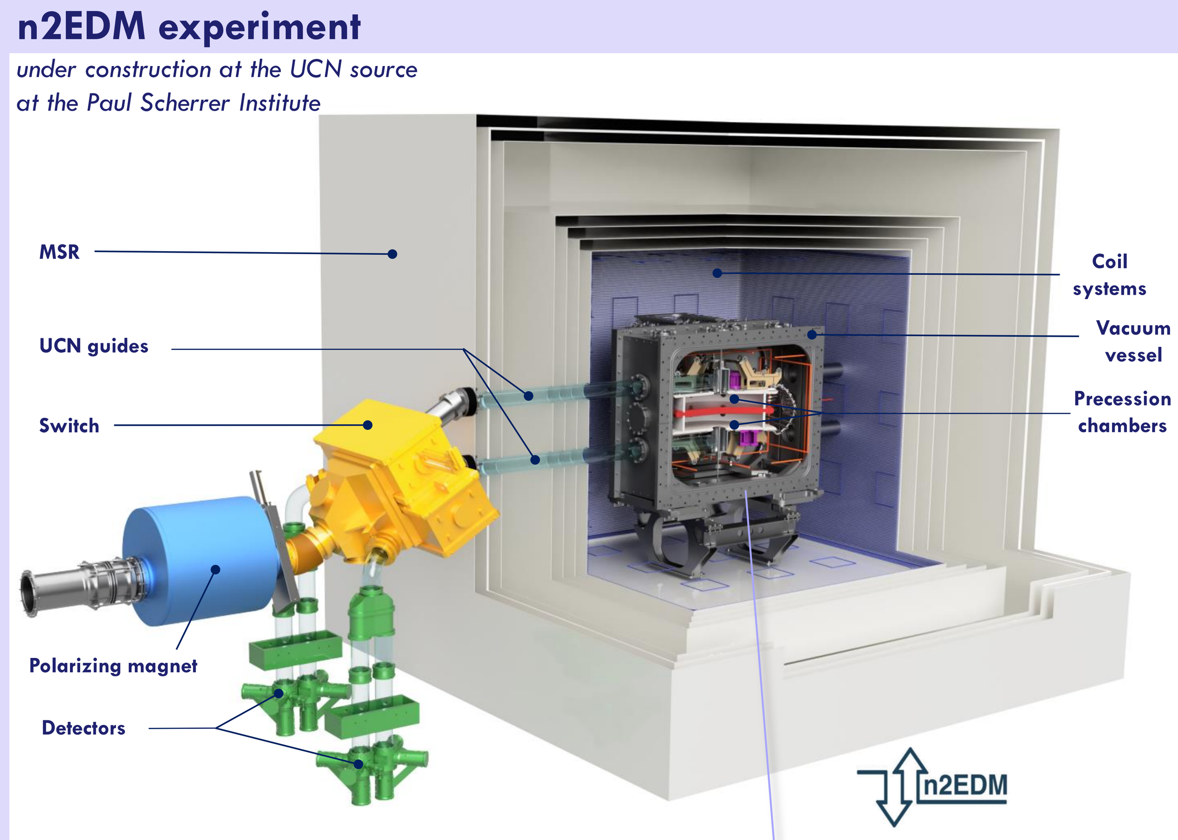
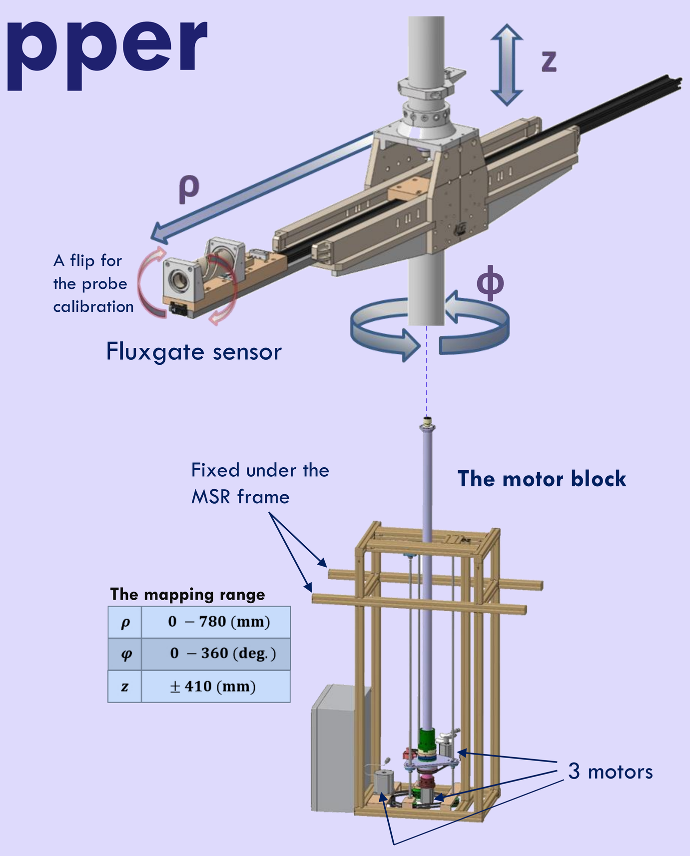
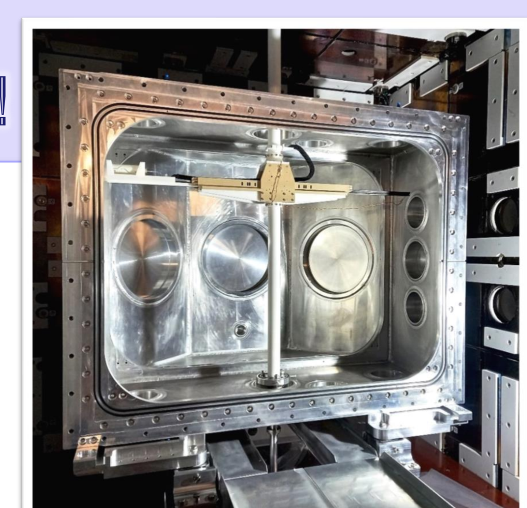
n2EDM experiment

under construction at the UCN source at the Paul Scherrer Institute





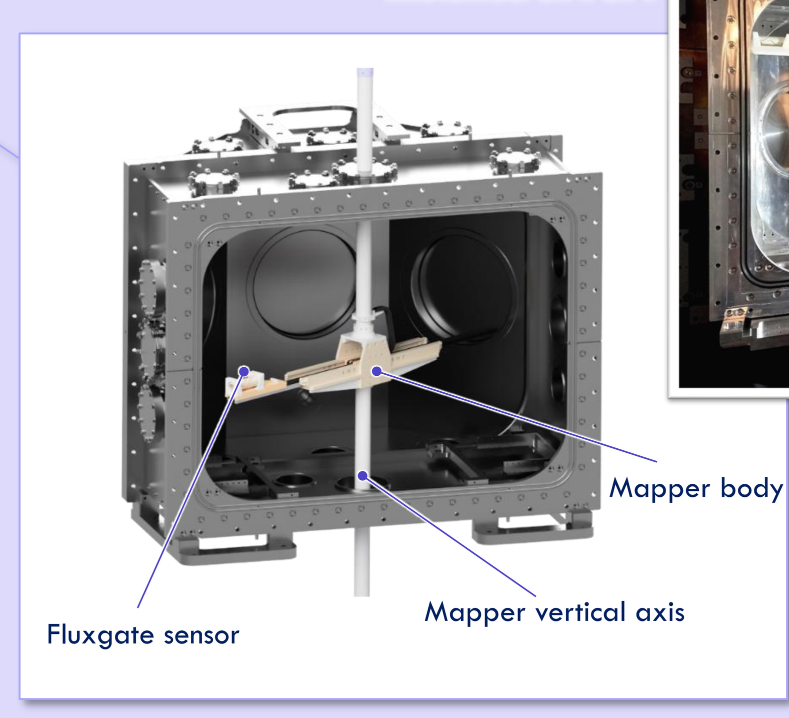
Installed at PSI !



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



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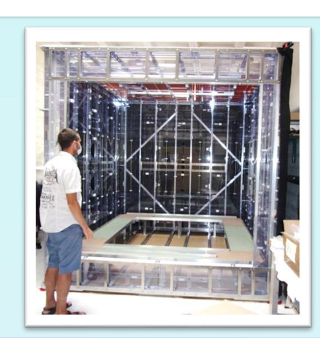
The goals of the 1st mapping campaign are to qualify the subsystems to the main requirements on the field production, and to search for a magnetic contamination of the vacuum vessel.

Conclusion

The generalized gradients shown above provide the full information about the field produced by the B_0 coil inside the MSR.

We have qualified the B_0 coil to the specifications:

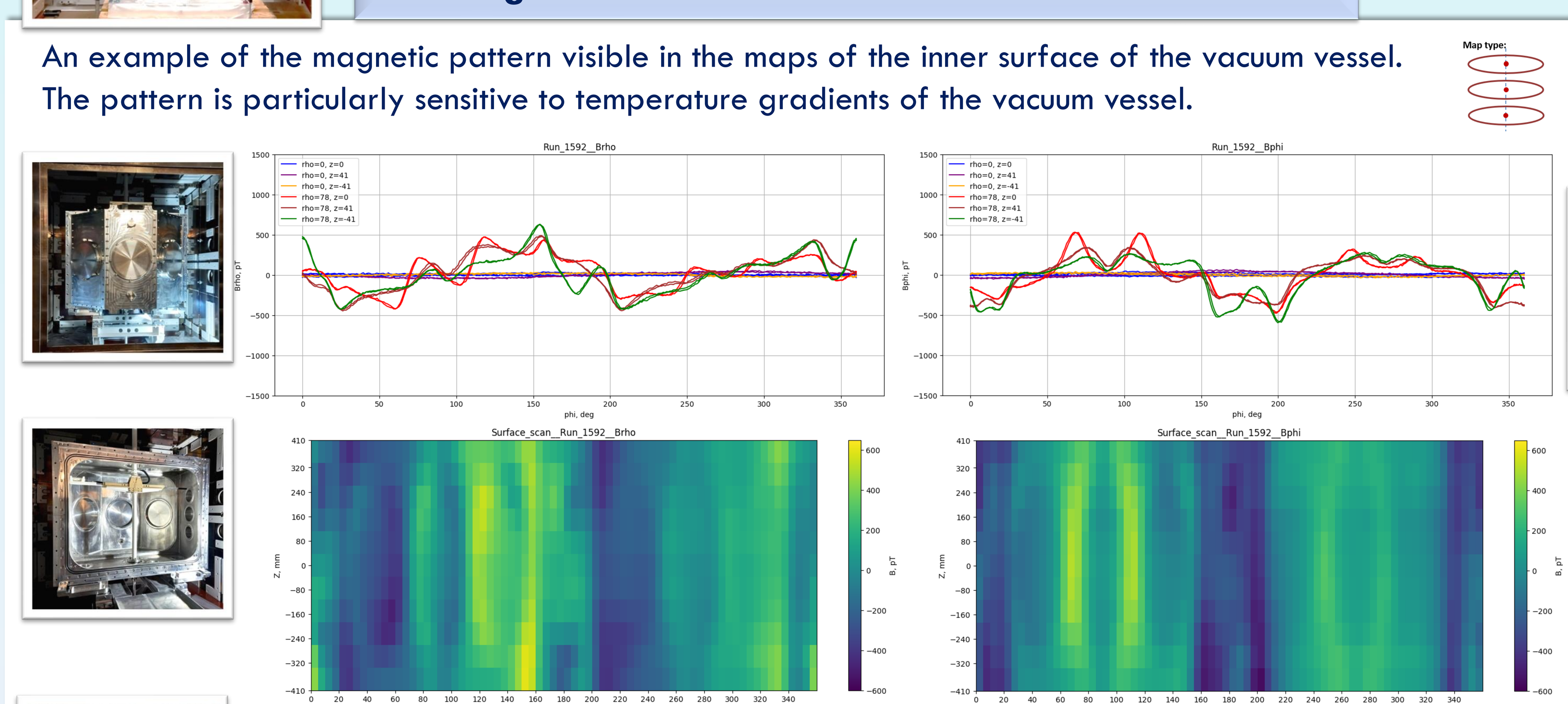
- ✓ The top-bottom resonance matching condition on $G_{1,0}$ is satisfied after the height adjustment *(see the block below)*.
- ✓ The dominant contribution to $\sigma(B_z)$ arises from $G_{2,0}$ and is equal to 35.7 pT . Considering all modes up to $l = 2$ included, we get $\sigma(B_z) = 57.1$ **pT**, which fulfills the requirement on the neutron depolarization rate: $\sigma(B_z) < 170$ pT.



Illustrative achievements & work in progress within the 1st mapping campaign

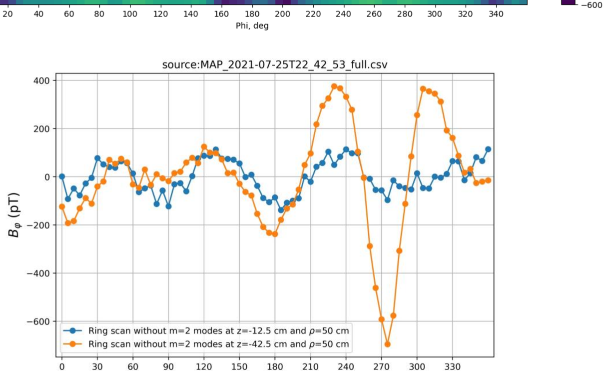
Magnetic characterization of the vacuum vessel

An example of the magnetic pattern visible in the maps of the inner surface of the vacuum vessel. The pattern is particularly sensitive to temperature gradients of the vacuum vessel.



An illustrative finding:

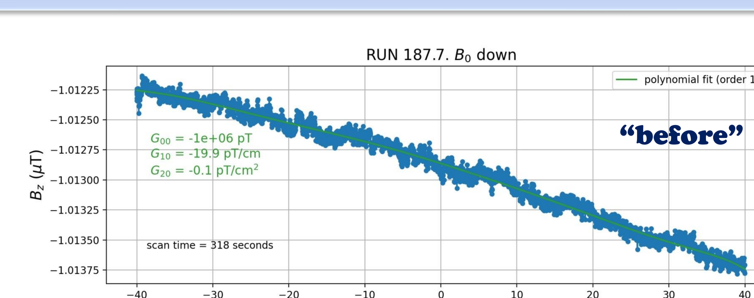
A very clear evidence of a presence of a magnetic element inside the flange located on the bottom surface of the vacuum vessel. The middle- and the lowest- z rings (preliminary mapping of the vacuum vessel in July 2021).



Vertical adjustment of the coil system

Map type:

The first vertical map after the installation of the B_0 coil showed a deviation in $G_{1,0}$ which was an evidence of a vertical displacement of the entire coil. This was anticipated, and a possibility of mechanical adjustment was taken into account by the design.



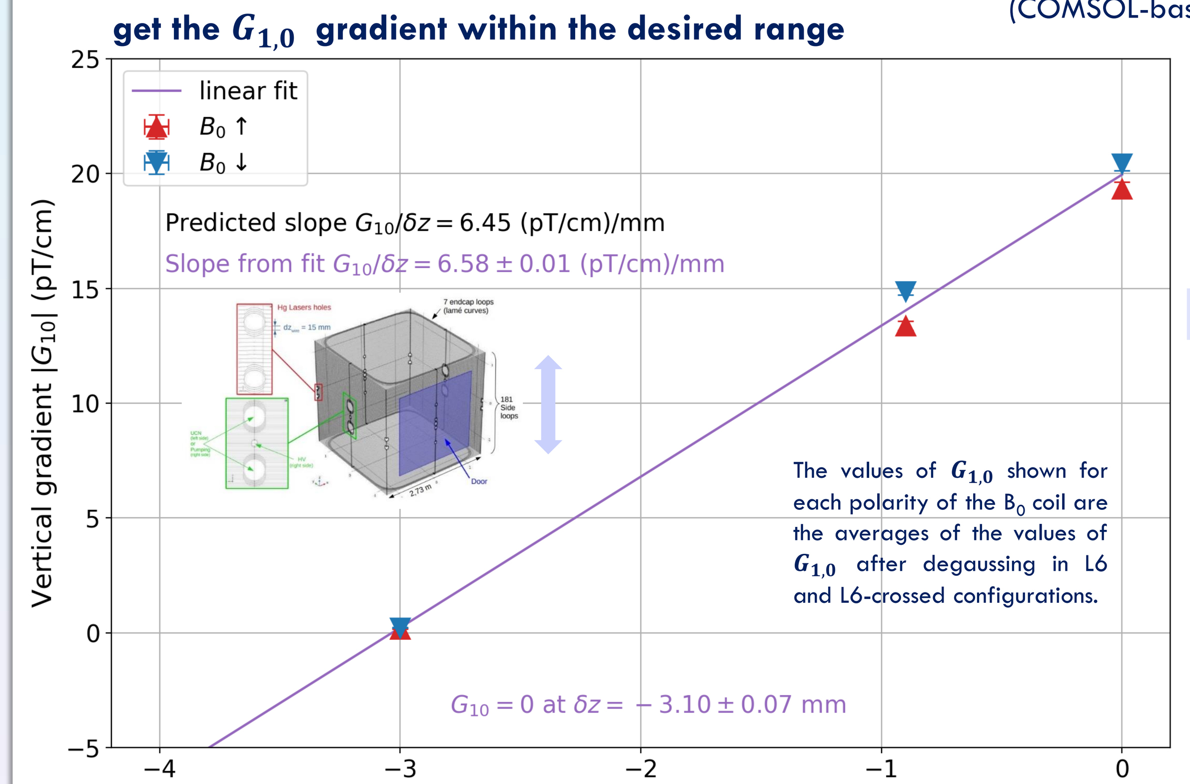
An example of a vertical scan of the B_z field component in **initial** B_0 coil position. The 1st and 2nd-order gradients:

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

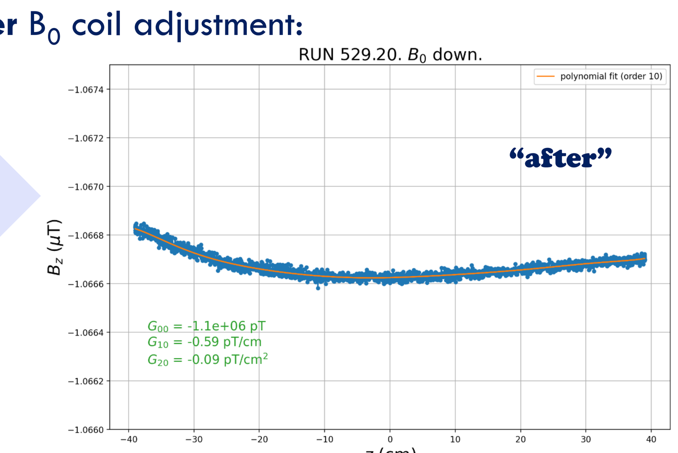
⚠ $G_{1,0} = -19.9\text{ pT/cm}$ – compatible with a **vertical shift** of the entire coil system with respect to the MSR by $\Delta z = 3\text{mm}$

✓ $G_{2,0} = (-7 \pm 1)\times 10^{-2}\text{pT/cm}^2$ – **meets the expectations** (COMSOL-based simulations).

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



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



✓ **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 agreement with the prediction, meets the requirement and demonstrates an impressive sensitivity of the mapping!**

Literature

[1] C. Abel *et al.*, Phys. Rev. Lett. 124 (2020), 081803
[2] C. Abel *et al.*, Phys.Rev.A 99 (2019) 4, 042112
[3] N.J. Ayres *et al.*, Eur.Phys.J.C 81 (2021) 6, 512
[4] C. Abel *et al.*, Phys.Rev.A 106 (2022) 3, 032808