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Mapping of the magnetic field in the n2EDM experiment

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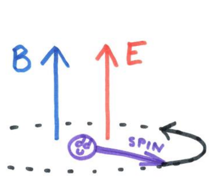
MEASUREMENT OF THE NEUTRON EDM

Neutron spin precession in a weak magnetic and strong electric field



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

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

$B = 1\,\mu\mathrm{T}$ — Larmor freq. $30\ \mathrm{Hz}$ — Large!

$E = 15\ \mathrm{kV/cm}$ — $10^{-8}\mathrm{Hz}$ — Too tiny!

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

Solution:

- ✓ Use UCNs (up to 15 min storage) – to maximize the exposure in E
- ✓ Large storage volume, good transport – to maximize the statistics
- ✓ Control of the magnetic field:
  Hg co-magnetometer; shielding: MSR, AMS
  checks of the magnetic field uniformity: mapping

FIELD PARAMETRIZATION

A purely static and very uniform 1 μT magnetic field. The remaining nonuniformities are characterized by a polynomial expansion [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:

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

REQUIREMENTS

- **On field production – B0 coil:** STAT

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

"Top-Bottom resonance matching condition" [3]

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

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

to prevent neutron depolarization

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

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

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

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

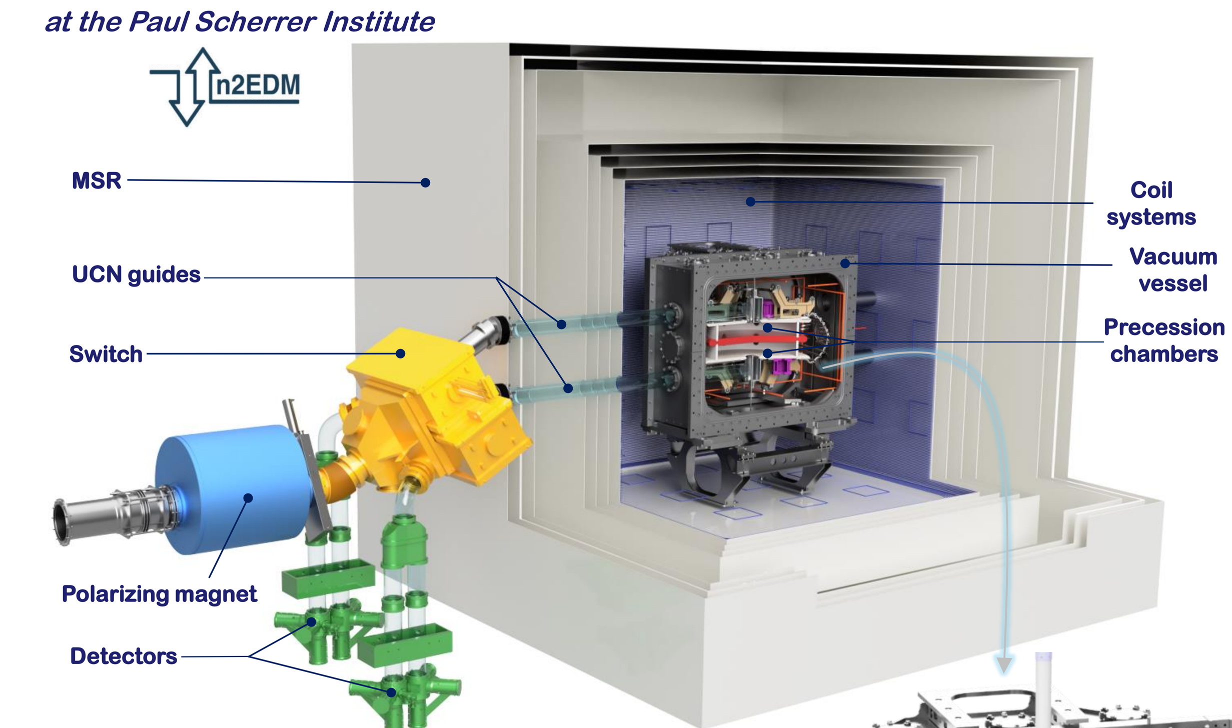
(False EDM is a systematic effect arising from the relativistic motional field $\vec{E} \times \vec{v}/c^2$ experienced by the moving particles in combination with the residual magnetic gradients and leading to a frequency shift. The dominating contribution $d^{false}_{n\leftarrow Hg}$ is the false EDM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

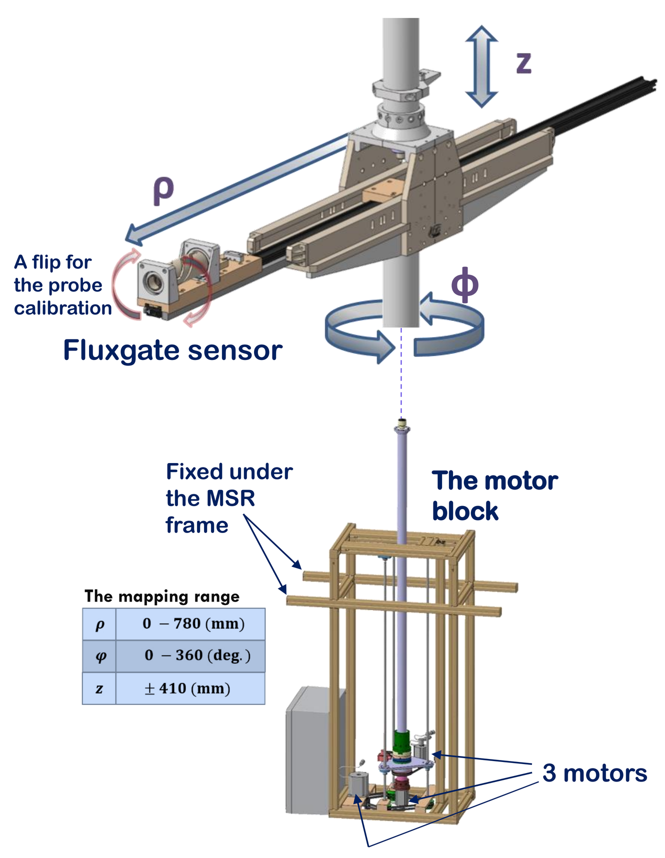
MAGNETIC FIELD MAPPER

PAUL SCHERRER INSTITUT PSI

n2EDM experiment

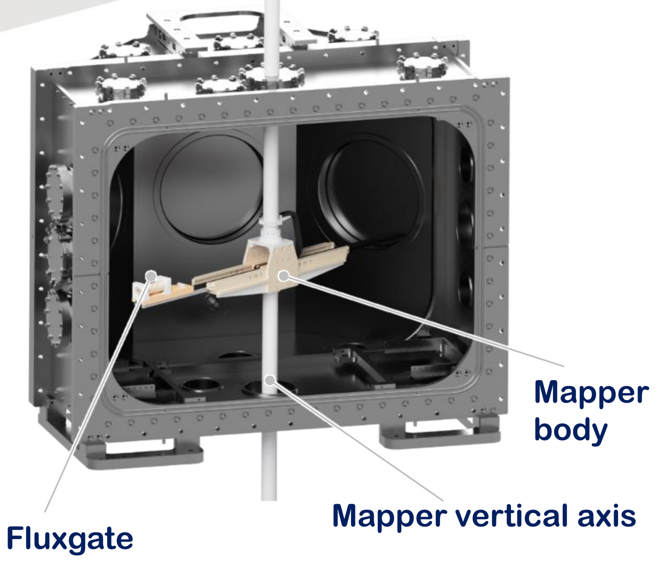
under construction at the UCN source at the Paul Scherrer Institute





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.

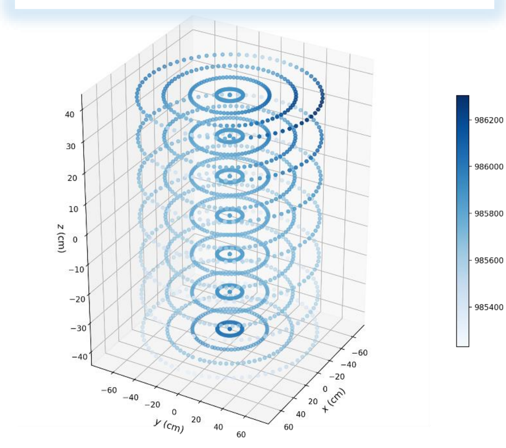
Purposes:

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

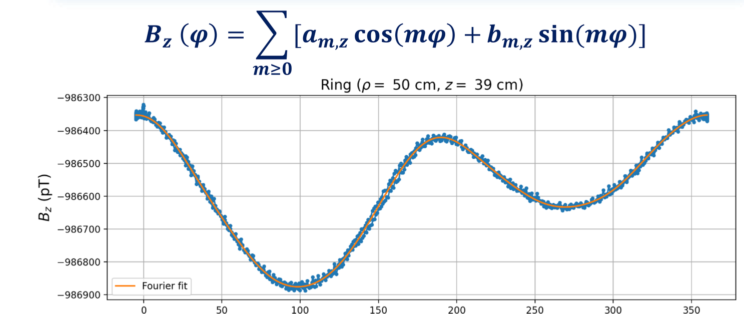
MADE IN FRANCE

FROM RAW DATA TO RESULTS

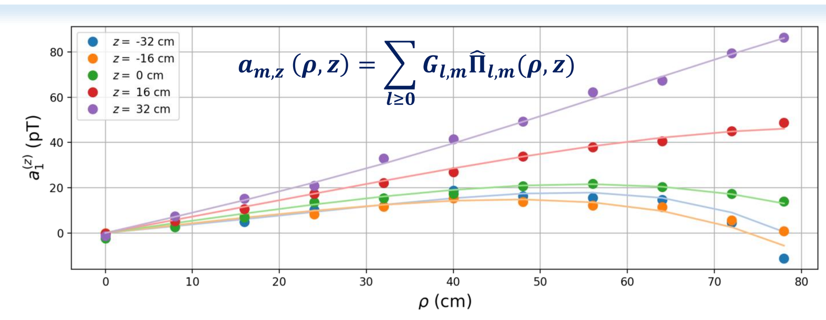
A field map: set of rings → Ring by ring Fourier decomposition → Set of Fourier coefficients → Fourier coefficients fit with harmonic polynomials → Set of gradients $G_{l,m}$



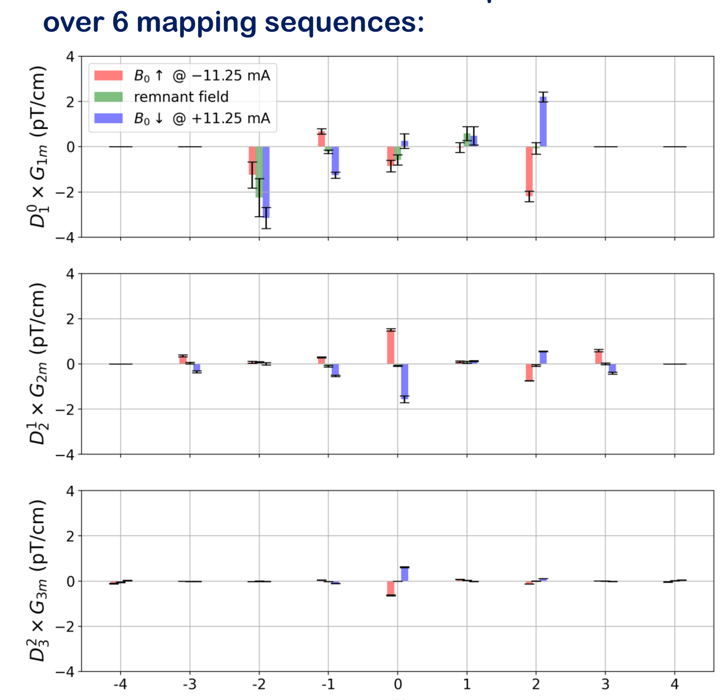
$$B_z(\varphi) = \sum_{m \geq 0} [a_{m,z}\cos(m\varphi) + b_{m,z}\sin(m\varphi)]$$



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



First three l-modes of the B0 spectrum over 6 mapping sequences:



The bars at each l, m value correspond to the average normalized first-order gradient $G_{l,m}$ of 6 mapping sequences. The error-bars on each bar correspond to the reproducibility of the measurement.

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

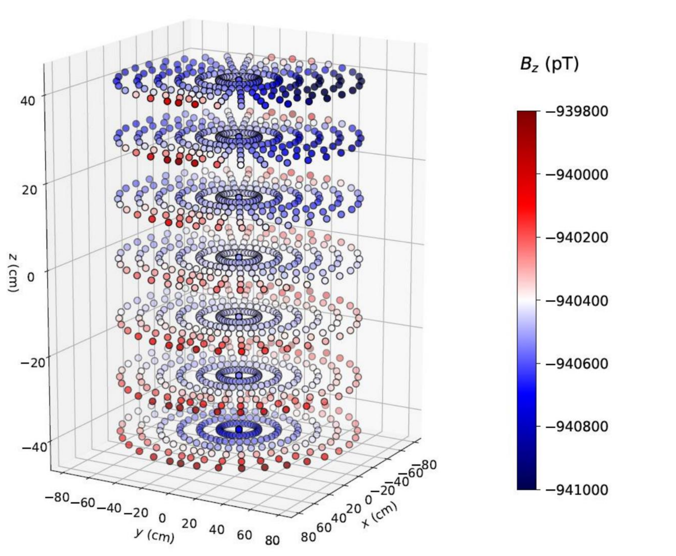
We have qualified the B_0 coil to the specifications:

- ✓ The top-bottom resonance matching condition on $G_{1,0}$ is satisfied after the height adjustment *(see the block below).*
- ✓ $\sigma(B_z) \approx 60\ \mathrm{pT}$ (arises mainly from $G_{2,0}$), fulfills the requirement on the neutron depolarization rate: $\sigma(B_z) < 170\ \mathrm{pT}$.

CONCLUSION: SUCCESSFUL COMMISSIONING OF THE INTERNAL FIELD GENERATION. READY FOR PHYSICS!

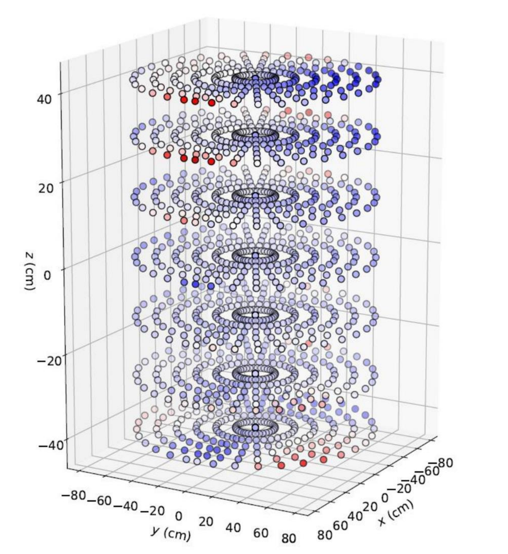
CONTROL OF ALL COILS → B_0 FIELD OPTIMIZATION

- ✓ Mapping 63 correction coils.
- ✓ Catalogue of all coil constants $G_{l,m}$
- ✓ Calculated set of currents to produce the correction for $G_{2,0}$, $G_{2,2}$, $G_{3,0}$, $G_{5,0}$



✓ Bare B0 coil at 1μT

$\sigma(B_z) \approx 60\ \mathrm{pT} < 170\ \mathrm{pT}$



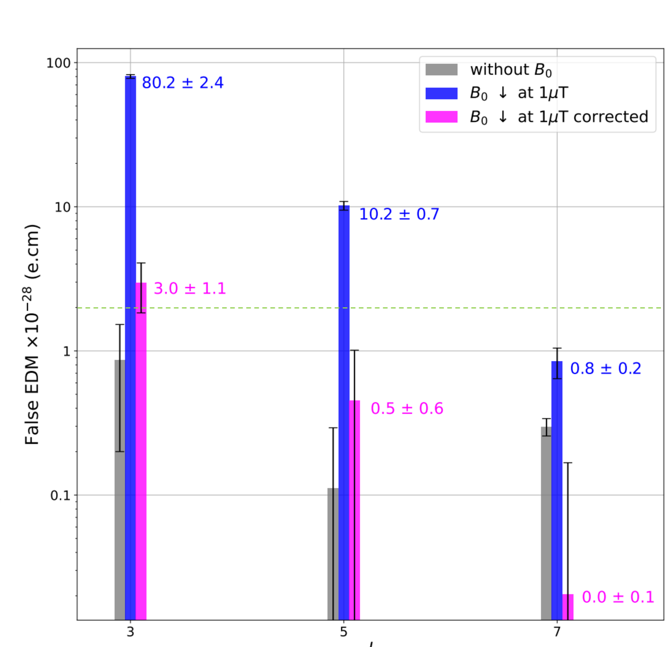
✓ Optimized B0 field at 1μT

$\sigma(B_z) \approx 20\ \mathrm{pT} \ll 170\ \mathrm{pT}$

Contribution of the false EDM produced by gradients $G_{3,0}$, $G_{5,0}$, $G_{7,0}$ with and without correction.

Option 1: data-taking with the bare B0 field at 1μT. The false EDM of orders 3 and 5 is not negligible, but the reproducibility of the gradients is good enough to calculate $d^{false}_{n\leftarrow Hg}$ with a good precision.

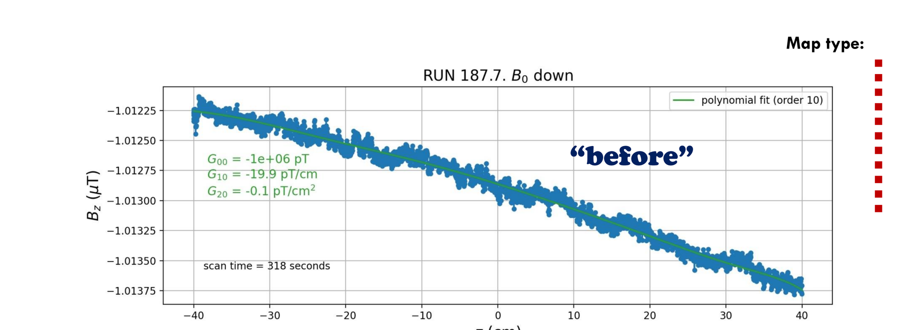
Option 2: data-taking with the optimized field at 1μT. The false EDM reduced to essentially zero.



VERTICAL ADJUSTMENT OF THE COIL SYSTEM

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.

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



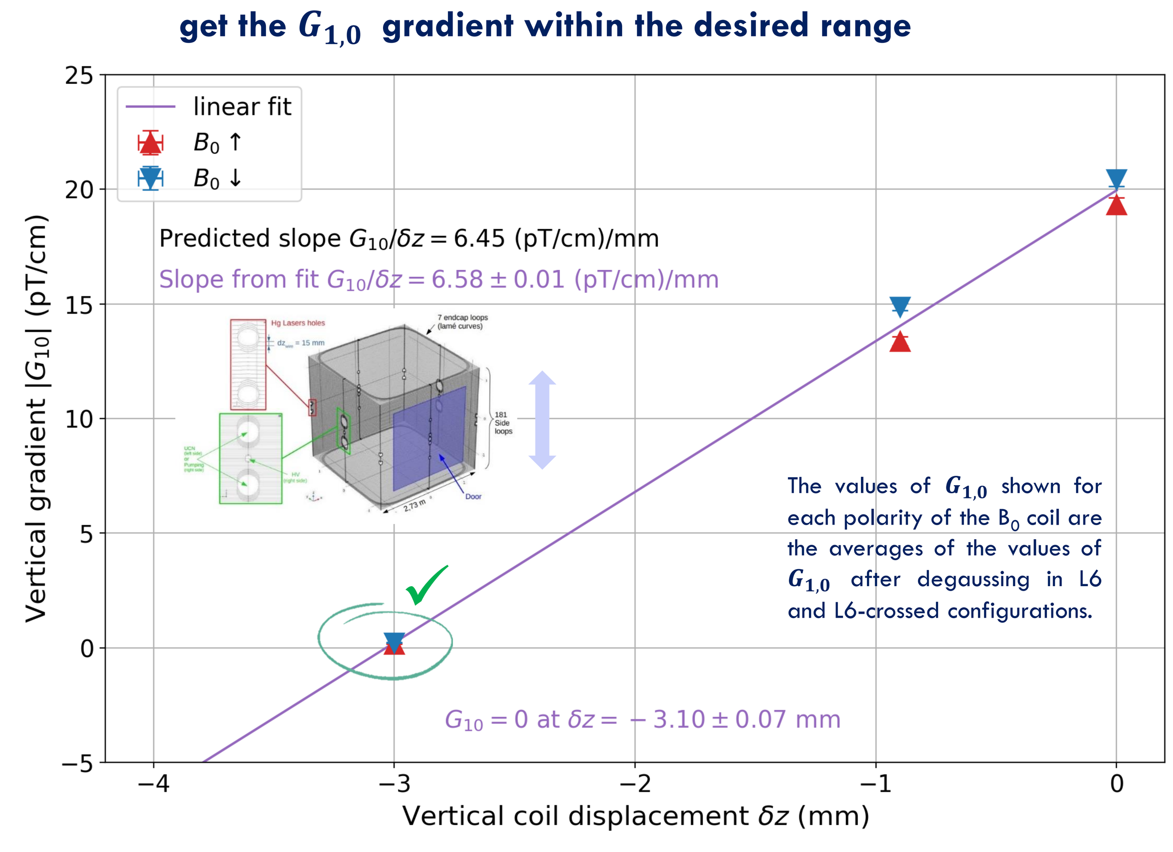
An example of a vertical scan of the B_z field component in **initial** B_0 coil position.

The 1st and 2nd-order gradients:

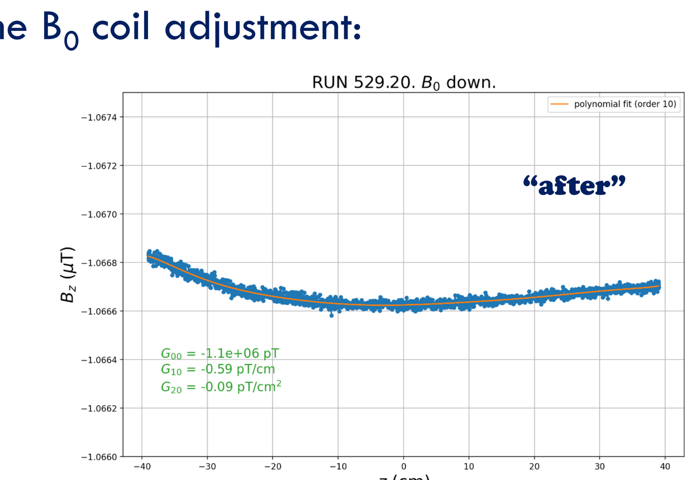
⚠ $G_{1,0} = -19.9\ \mathrm{pT/cm}$ – compatible with a **vertical shift** of the entire coil system with respect to the MSR by $\Delta z = 3\mathrm{mm}$

✓ $G_{2,0} = (-7 \pm 1) \times 10^{-2}\mathrm{pT/cm^2}$ – **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** the B_0 coil adjustment:



✓ The new value of the 1st order gradient in the B_0-down configuration: $G_{1,0} = -0.59\ \mathrm{pT/cm}$, i.e. it is in agreement with the prediction and meets the requirement. This example demonstrates the impressive sensitivity of the mapping!

erc European Research Council

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