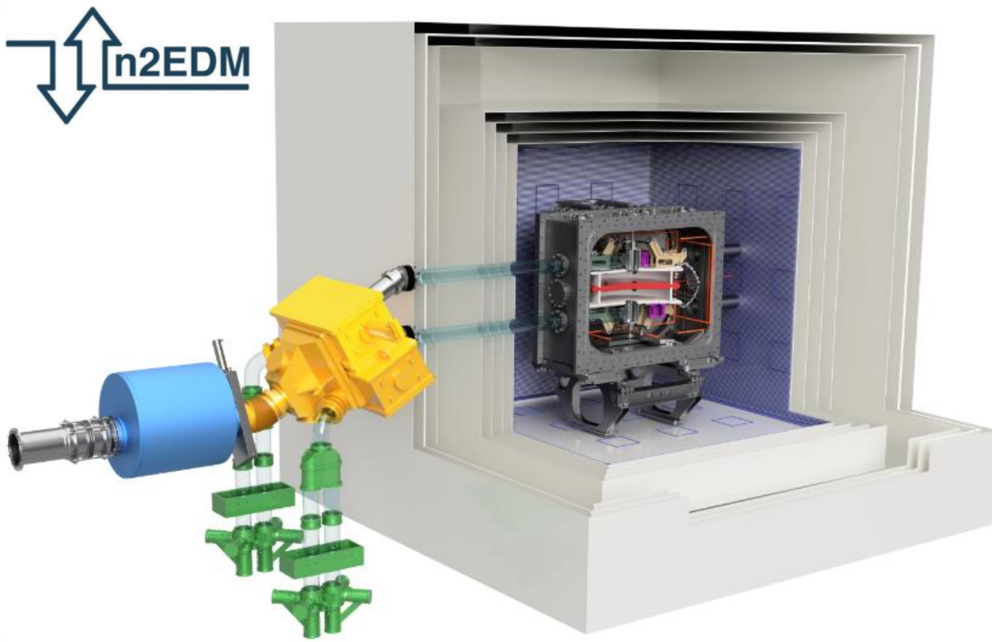
The n2EDM experiment

searching for a neutron electric dipole moment



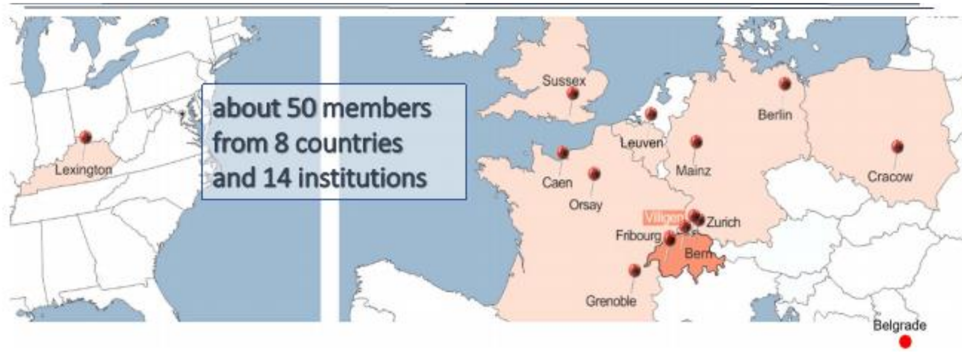
Kseniia Svirina
LPSC, Université Grenoble Alpes, FR
svirina@lpsc.in2p3.fr

On behalf of the nEDM collaboration

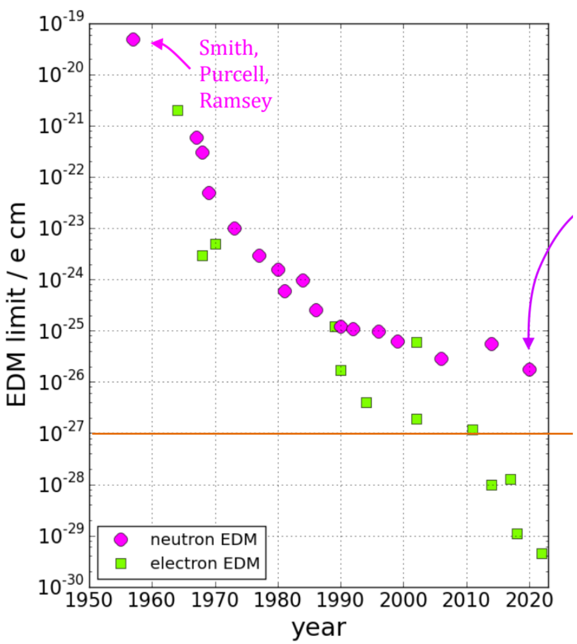
Vienna, May 22-26 2023

The nEDM collaboration


Collaboration meeting May 2023, Krakow




Collaboration meeting May 2022, PSI



Neutron EDM measured by the nEDM collaboration (2020):

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

C. Abel *et al.*, Phys. Rev. Lett. 124 (2020), 081803

← The next goal: n2EDM

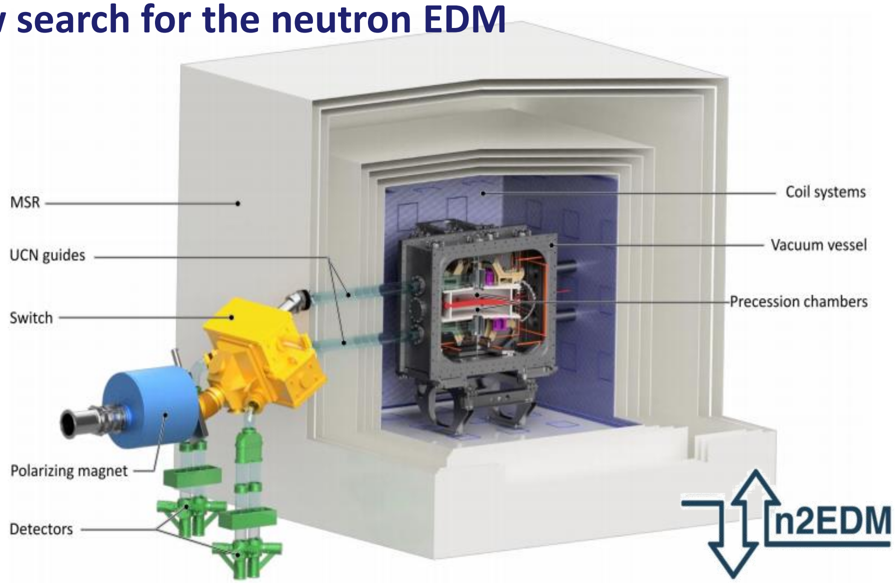
The nEDM collaboration


Collaboration meeting May 2023, Krakow


Collaboration meeting May 2022, PSI

[1] C. Abel *et al.*, Phys. Rev. Lett. 124 (2020), 081803

New search for the neutron EDM



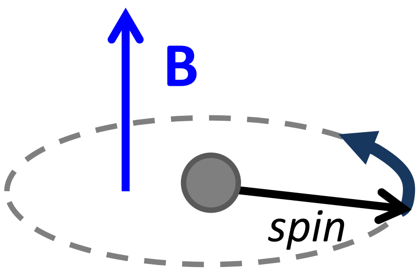
under construction at the UCN source at the Paul Scherrer Institute (PSI)

PSI, Switzerland

nEDM measurement. The motivation:

To probe the CP violation

Neutron spin precession around the magnetic field



SM:

*No **sizable** CP violation*

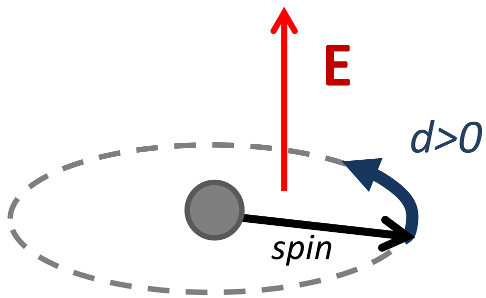
⇩

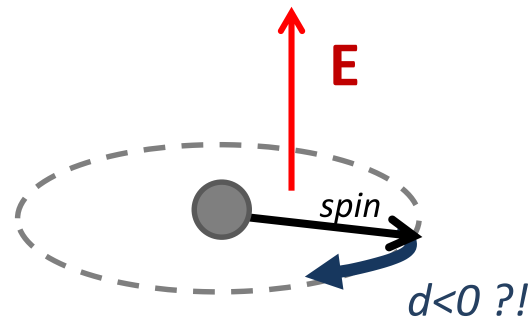
vanishingly small nEDM

& no explanation of baryon asymmetry of the Universe

→ *BSM*

Non-zero neutron EDM:
spin precession around the electric field





>> PLAY >>

<< REWIND <<

The process and its time-reversed version are different!

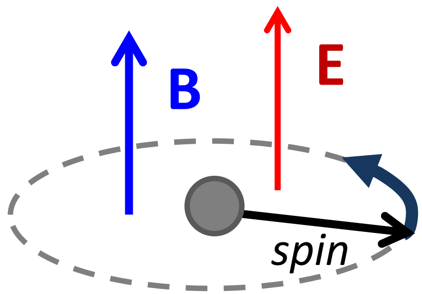
⇩

violation of **T** symmetry

CPT theorem

violation of **CP** symmetry
(matter - anti-matter symmetry)

nEDM measurement. The idea:



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

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

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

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

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

The actual upper limit (2020)

$$|d_n| < 1.8 \times 10^{-26}\ e\,\text{cm} \quad (90\%\ \text{C.L.})$$

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

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

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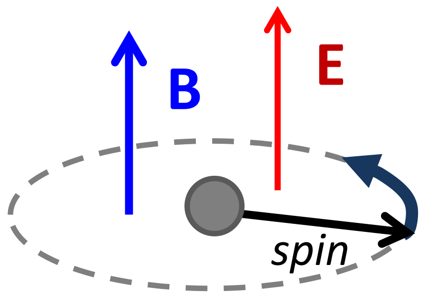

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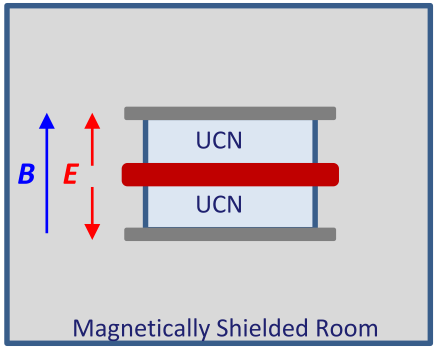

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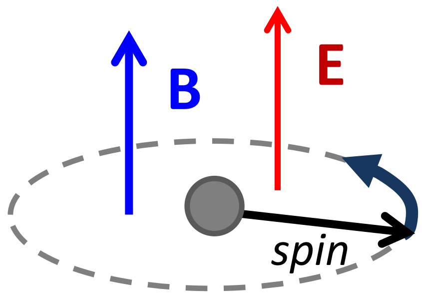

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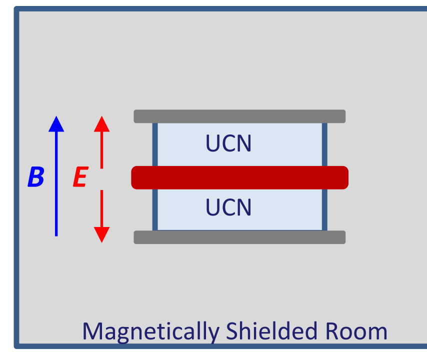
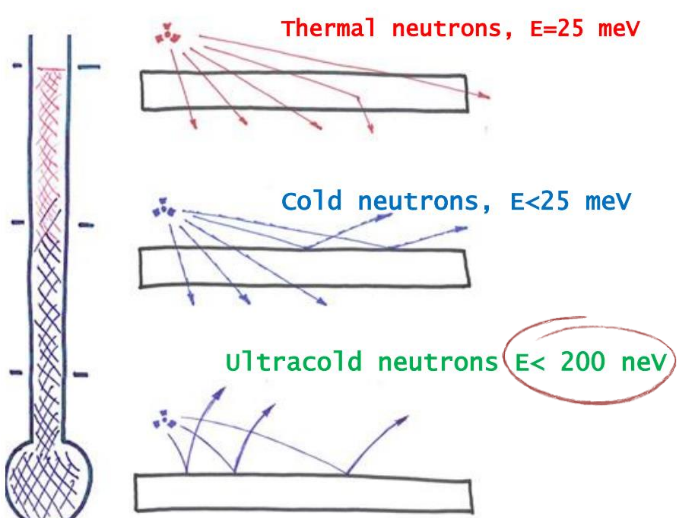
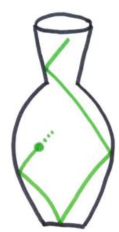


UCN – Ultra Cold Neutrons



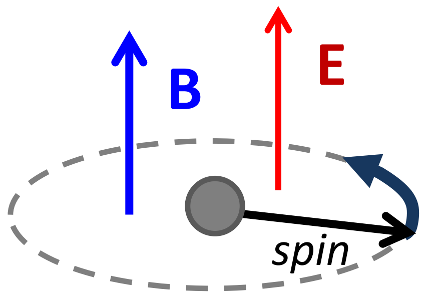


Neutrons with energy < 200 neV, are totally reflected by material walls.

They can be stored in material bottles for long times , up to 15 minutes.

They are significantly affected by gravity.

nEDM measurement. The idea:



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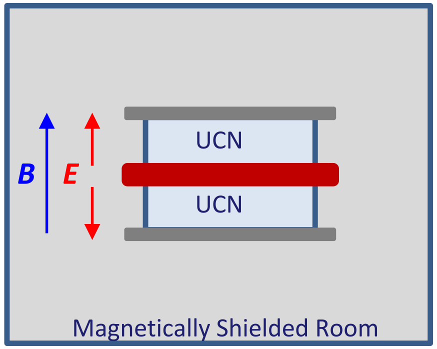
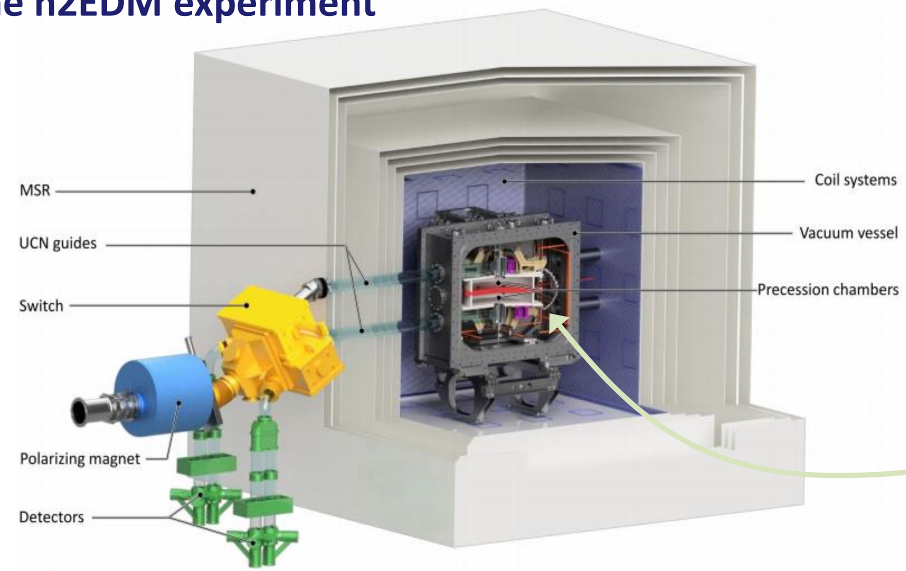
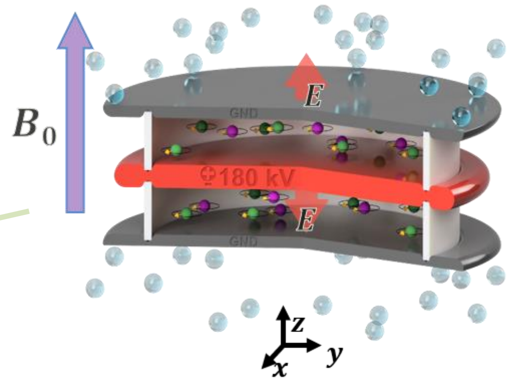


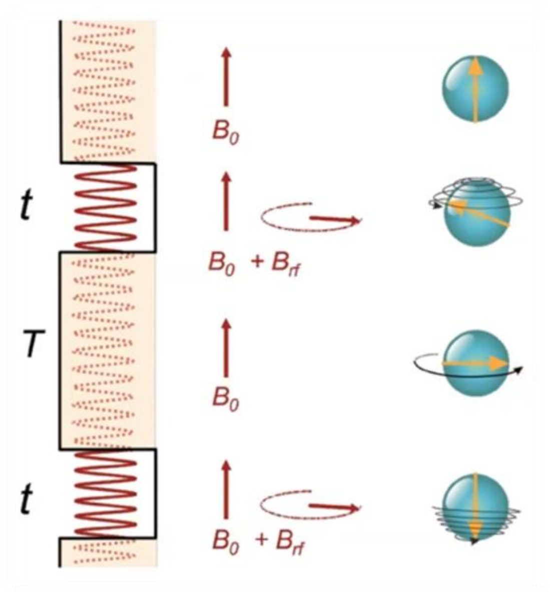
The n2EDM experiment





nEDM measurement. The method:

Ramsey's method

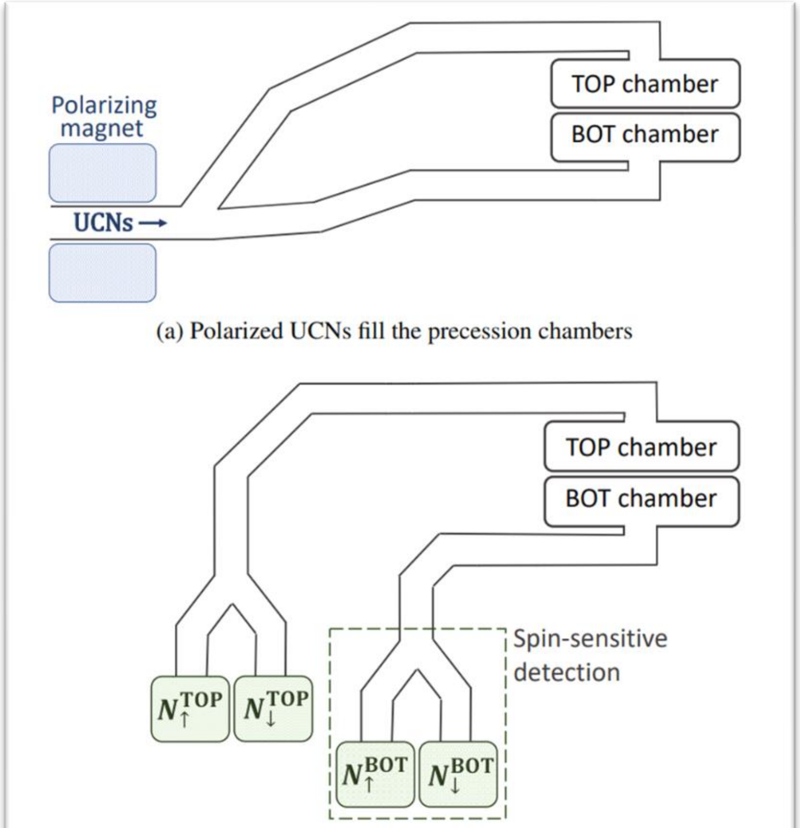


Neutron spin ‖ B_0

Apply oscillating m.field ⊥ B_0

Let precess for 180 s

Again apply oscillating m.field ⊥ B_0



(a) Polarized UCNs fill the precession chambers

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

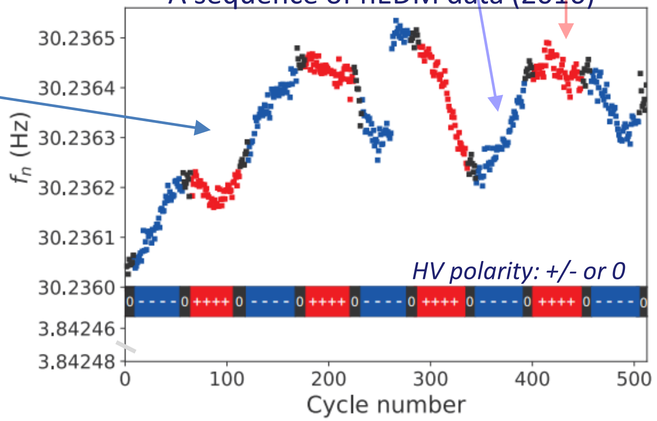
Obtain neutrons with spin either UP or DOWN, **Count the number** of each, which depends on f_n

nEDM measurement. The method:

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

f_n is affected by drifts of the magnetic field!

A sequence of nEDM data (2016)



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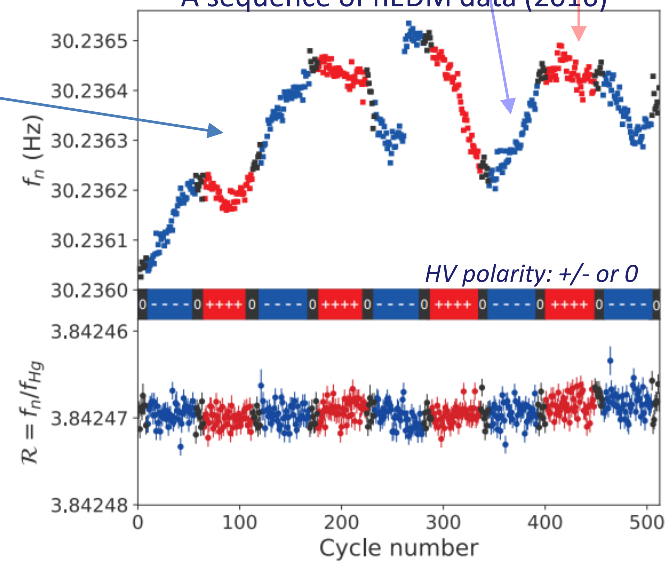


Simultaneous measurement of f_n and f_{Hg}

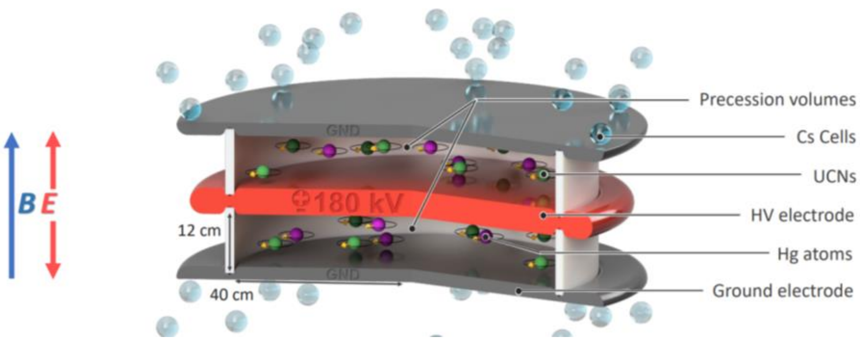
$$\mathcal{R} \equiv \frac{f_n}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\right| \mp \frac{|E|}{\pi\hbar f_{\mathrm{Hg}}} d_{\mathrm{n}}$$

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

Solution:

Mercury co-magnetometer

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

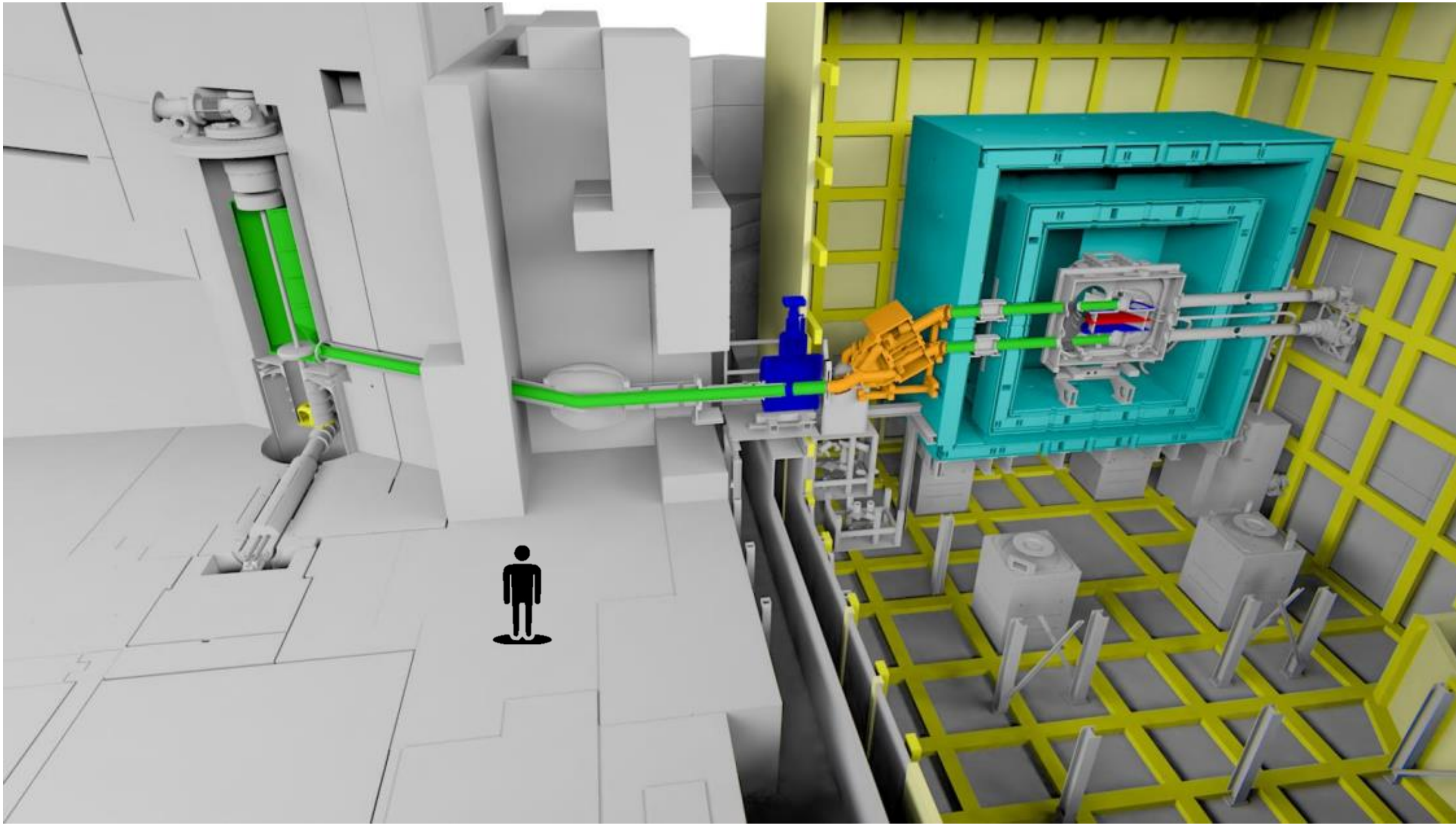


f_{Hg} measurement principle:

a UV probe beam transverses the chambers

→ record the absorbtion of the light (an oscillating signal), extract f_{Hg}

n2EDM experiment overview



[The design of the n2EDM experiment,](#)
Ayres et al, EPJC (2021)

n2EDM experiment overview

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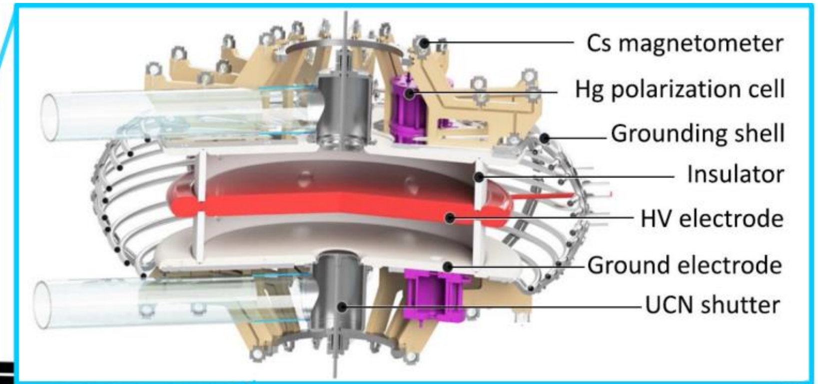
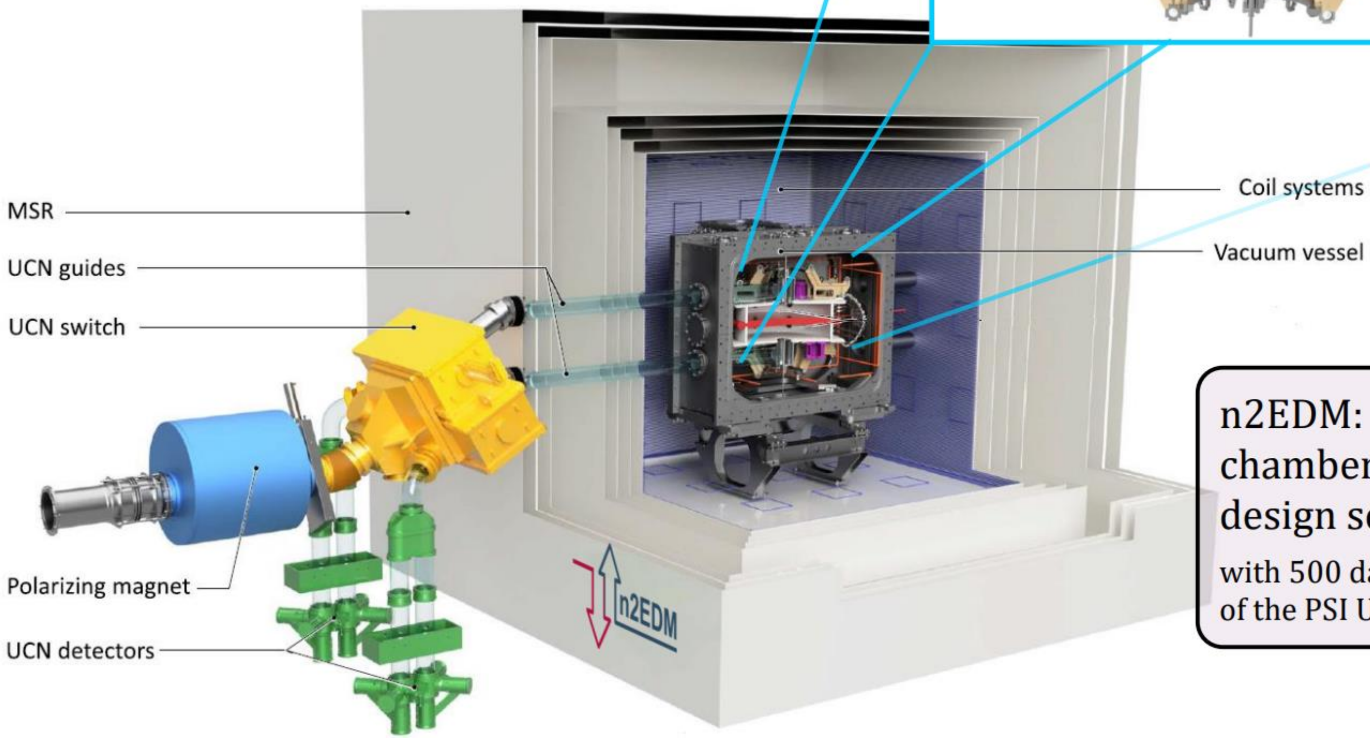
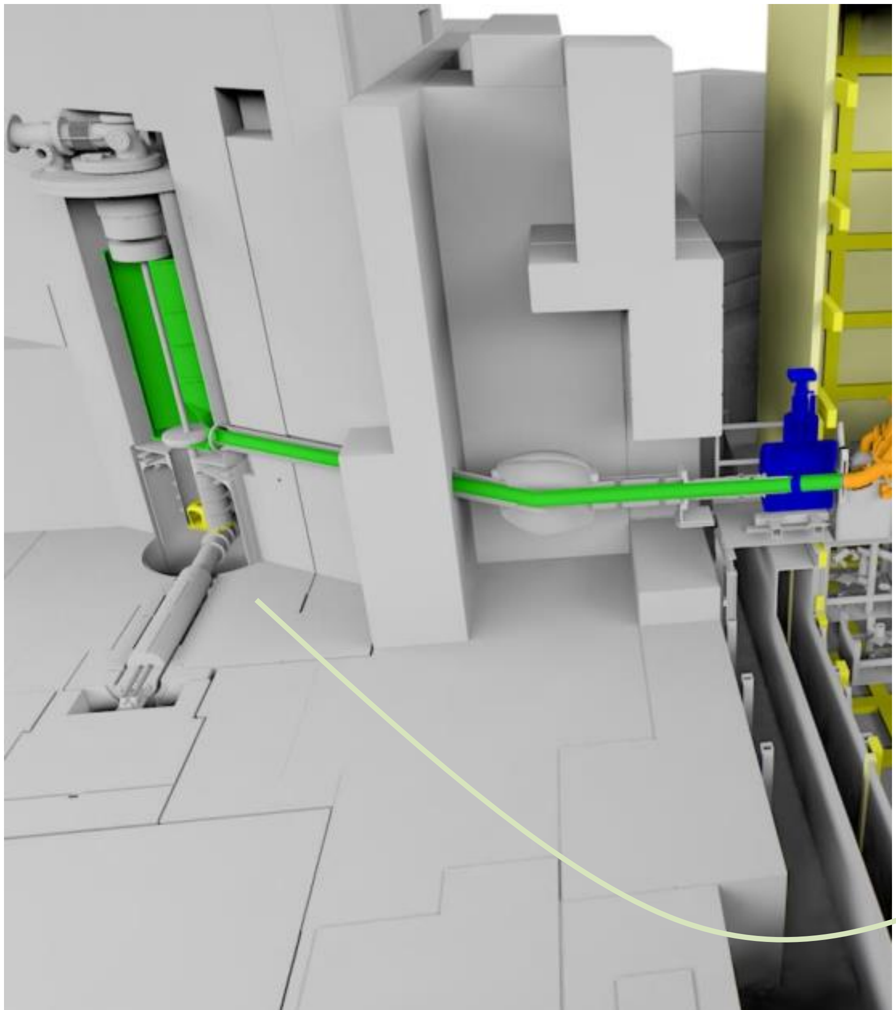




n2EDM: A large (Ø 80 cm) double-chamber UCN apparatus,
design sensitivity 1×10^{-27} e cm
with 500 data days, based on the performance of the PSI UCN source established in 2016

n2EDM experiment overview

The PSI UCN source

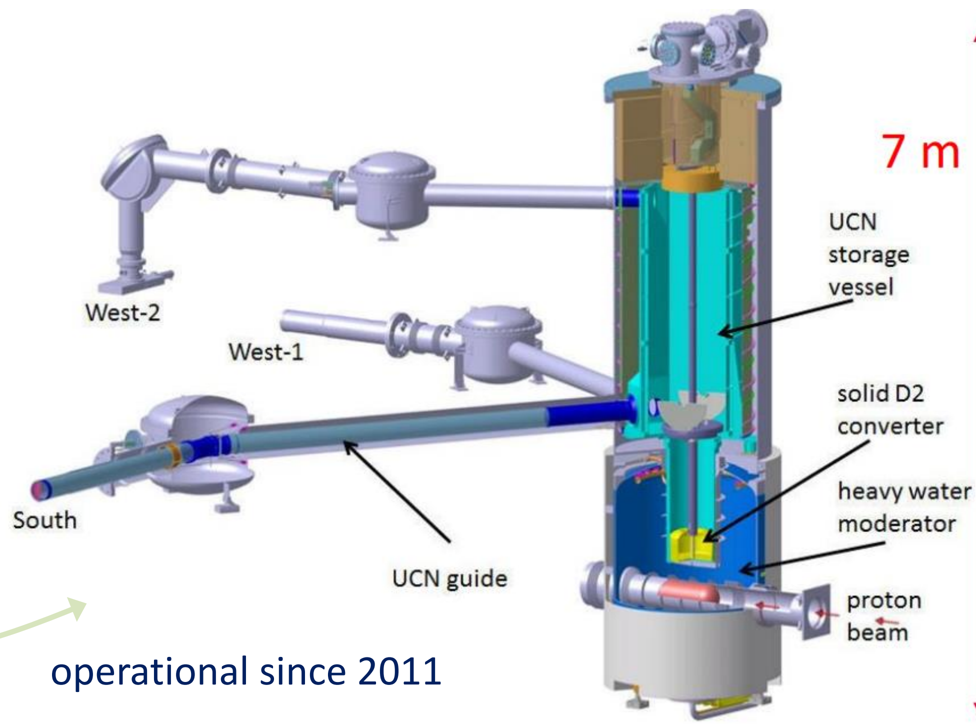


Pulsed UCN source:

Very intense **proton beam**: 590 MeV, 2.2 mA on spallation target, to produce neutrons

- one 8s kick every 5 min

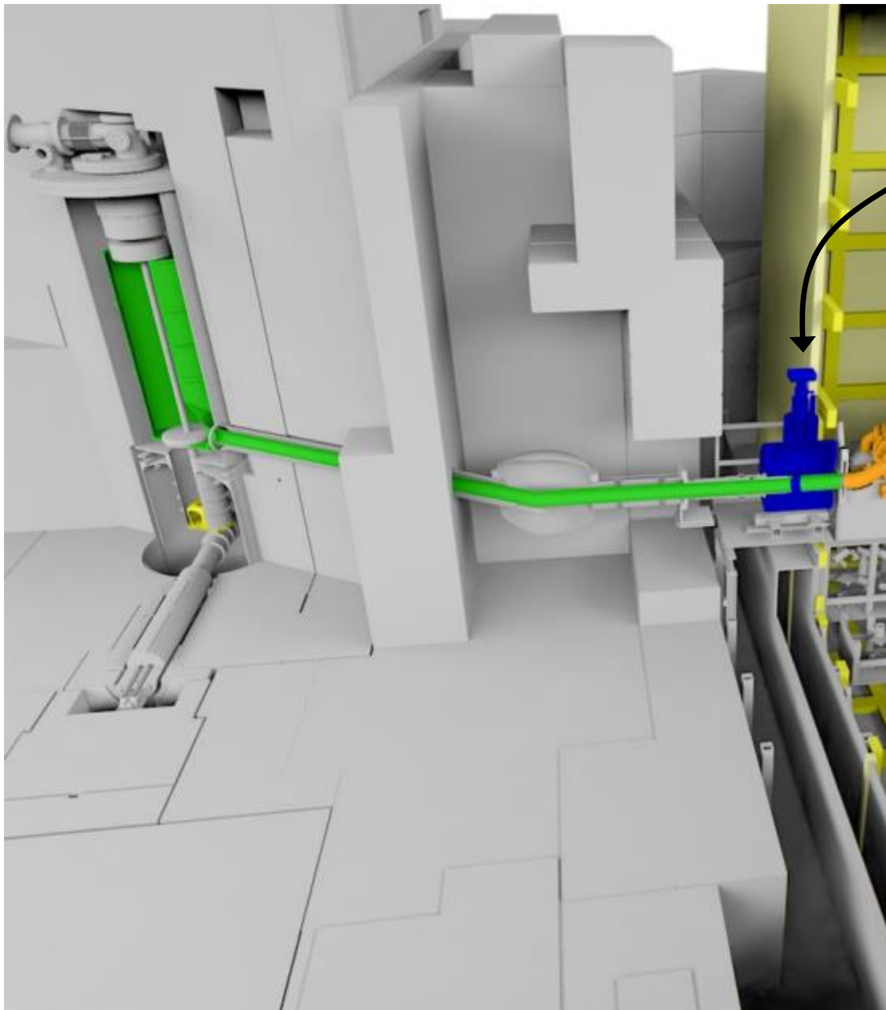
Neutrons are moderated to UCN and guided to the experiment

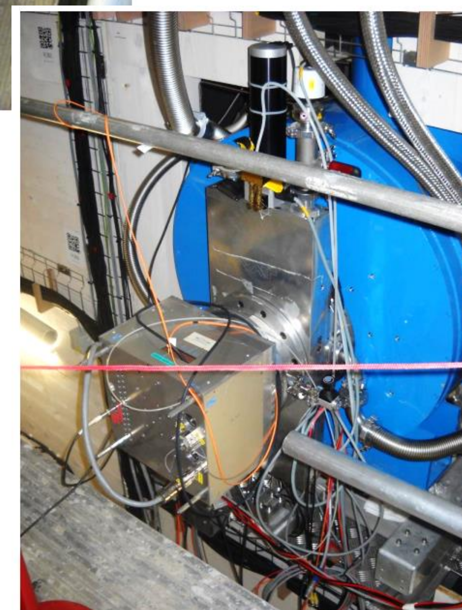


operational since 2011

n2EDM experiment overview

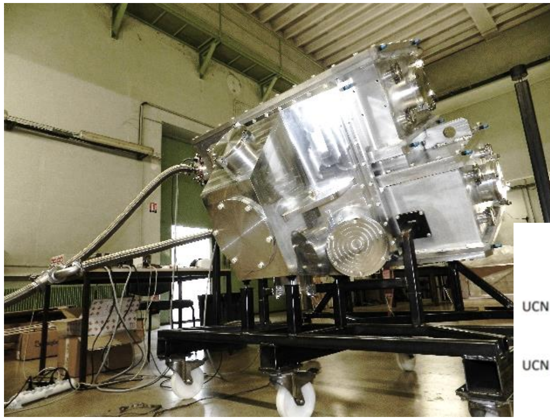
5T superconducting magnet for UCN polarization

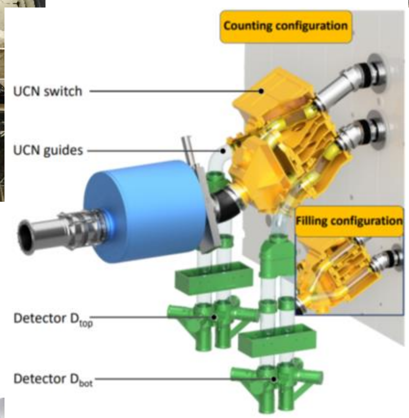


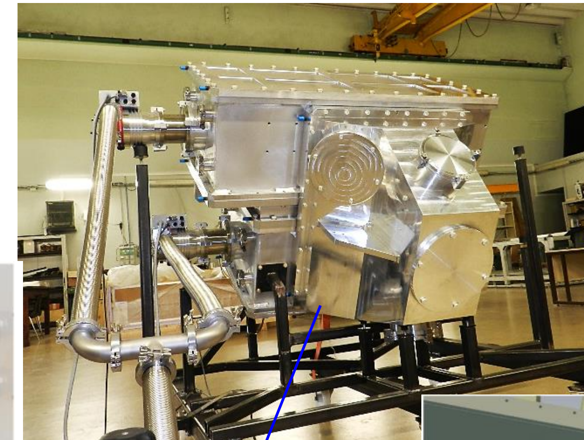


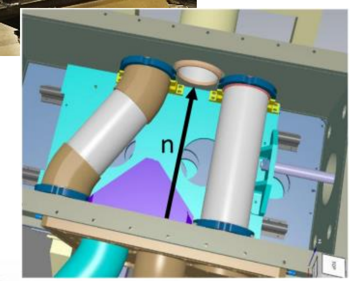
n2EDM experiment overview

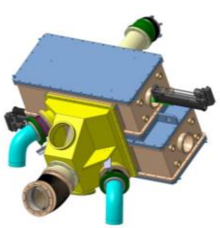
The switch



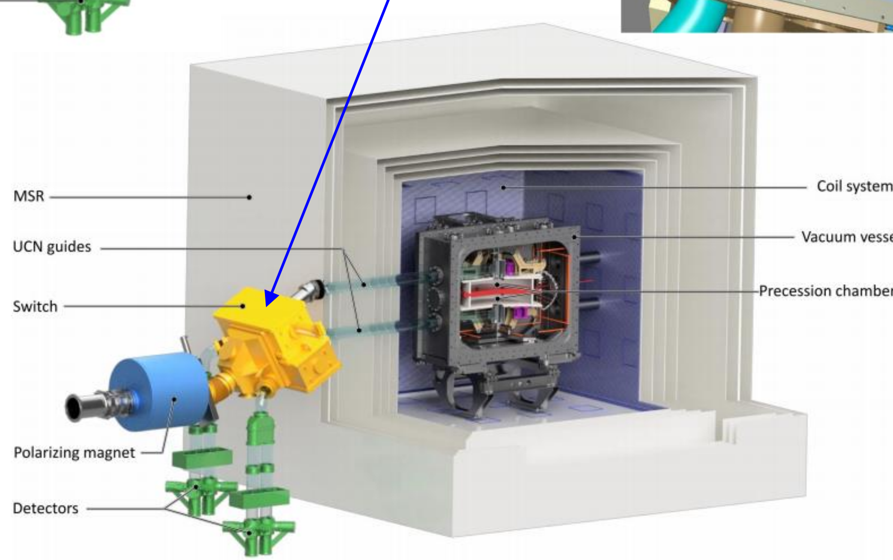








Made at LPSC Grenoble, FR

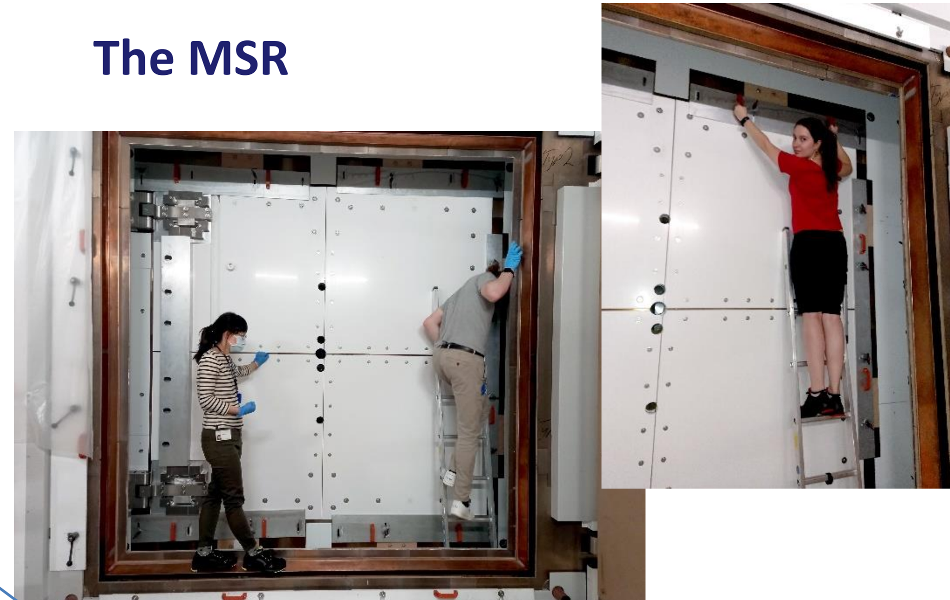


n2EDM experiment overview

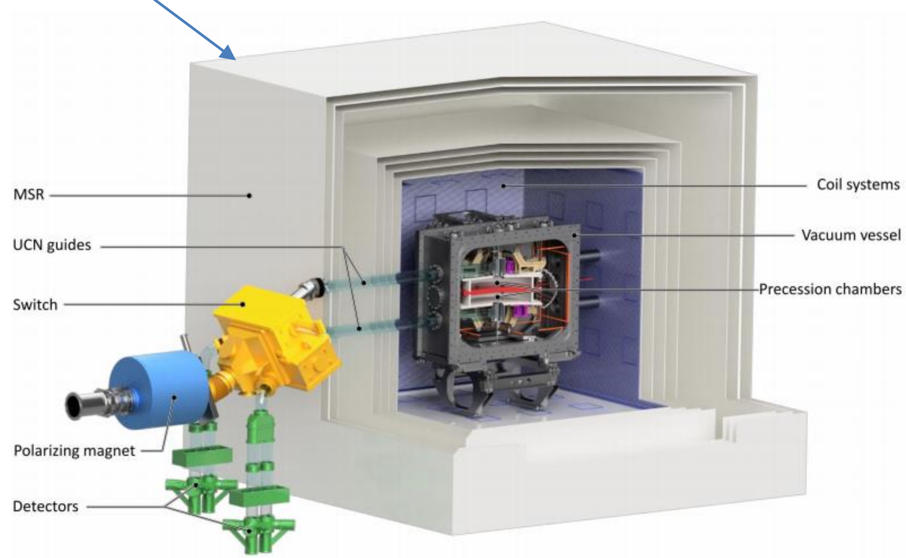
n2EDM experiment overview

The MSR

Internal shielded volume ~ 25 m3



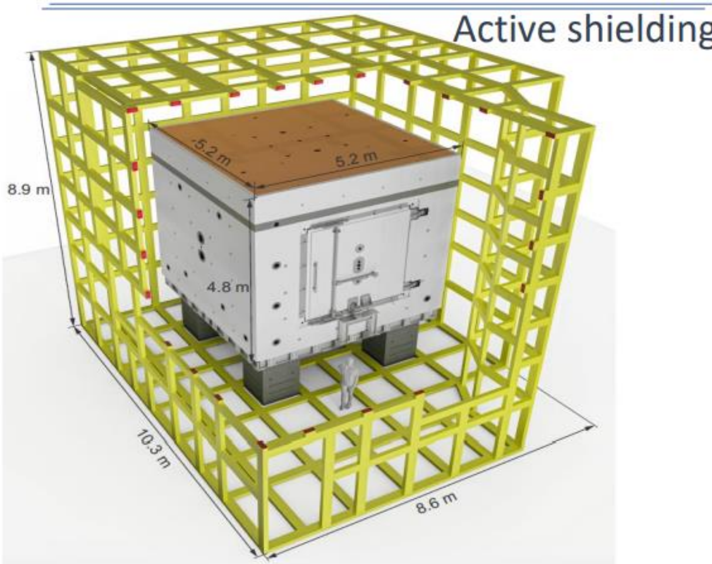
- 6 mu-metal layers
- Inner dimensions 2.93m x 2.93m x 2.93m
- Quasi-static shielding factor 100’000
- Residual fields < 150 pT (in central volume)



The very large n2EDM magnetically shielded room with an exceptional performance for fundamental physics measurements, Review of Scientific Instruments 93, 095105 (2022)

n2EDM experiment overview

The AMS

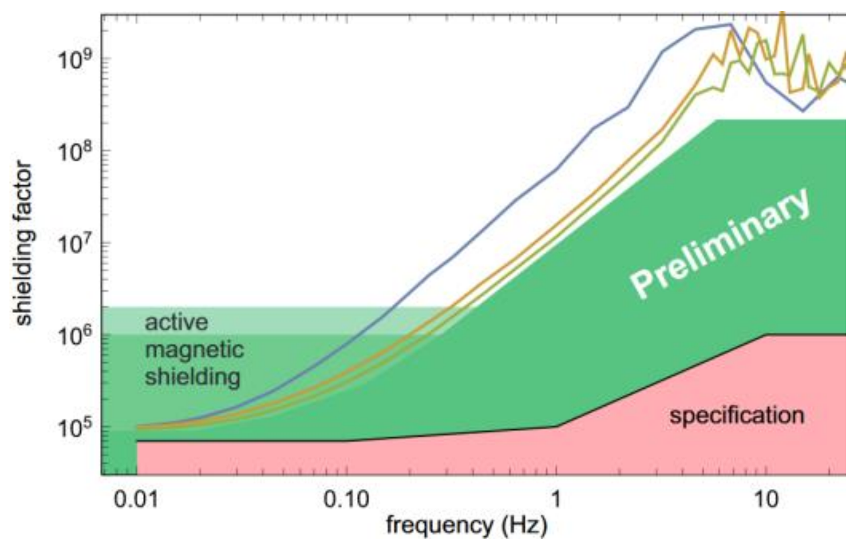


M. Rawlik *et al.*, Am. J. Physics 86(8), 602 (2018)

- 8 actively-controlled coils
- Spanning a volume of ~1000m^3
- Compensates field disturbances from outside
- Stable and uniform magnetic field around MSR

Made by ETH Zurich, CH

The Thermohouse

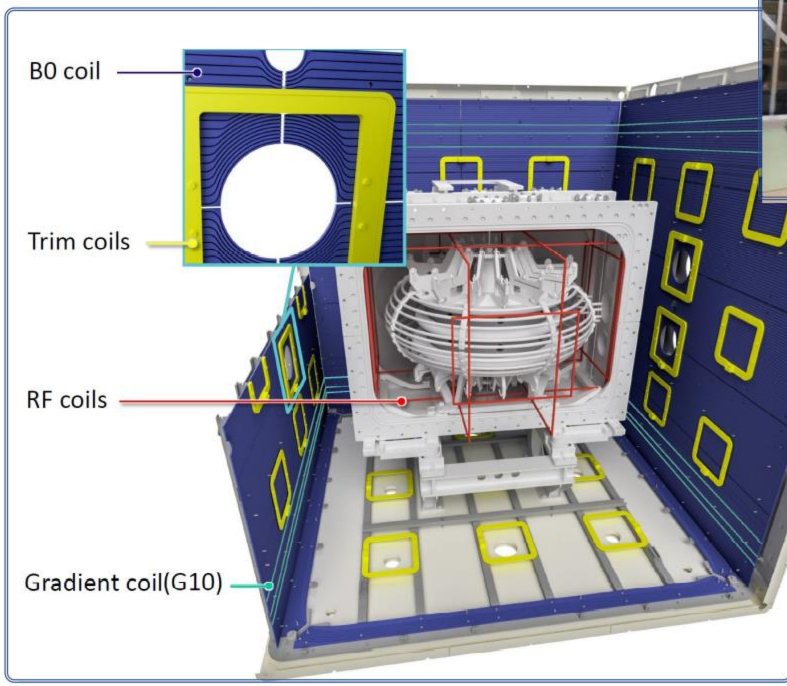


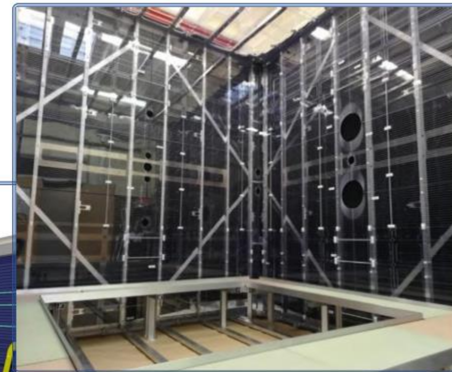
“A large ‘Active Magnetic Shield’ for a high-precision experiment”, paper **coming soon**

n2EDM experiment overview

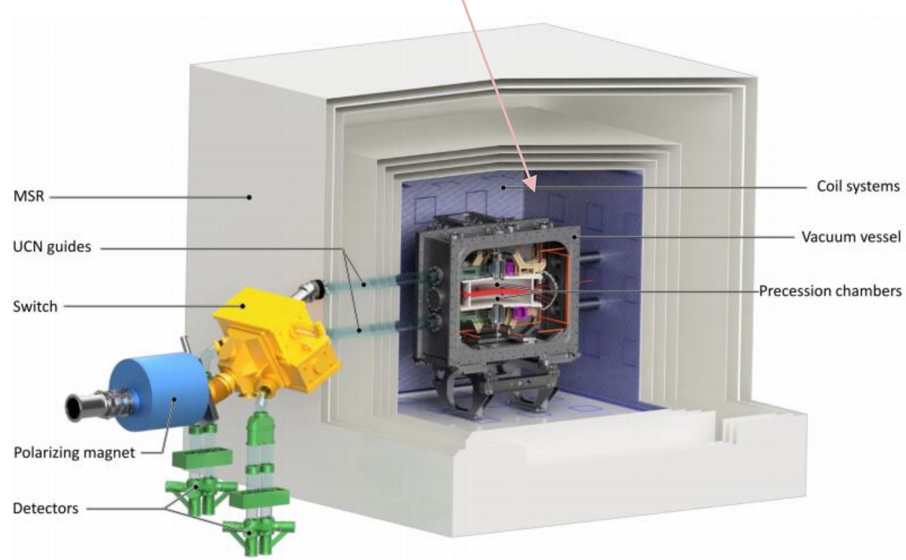
Coil systems

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





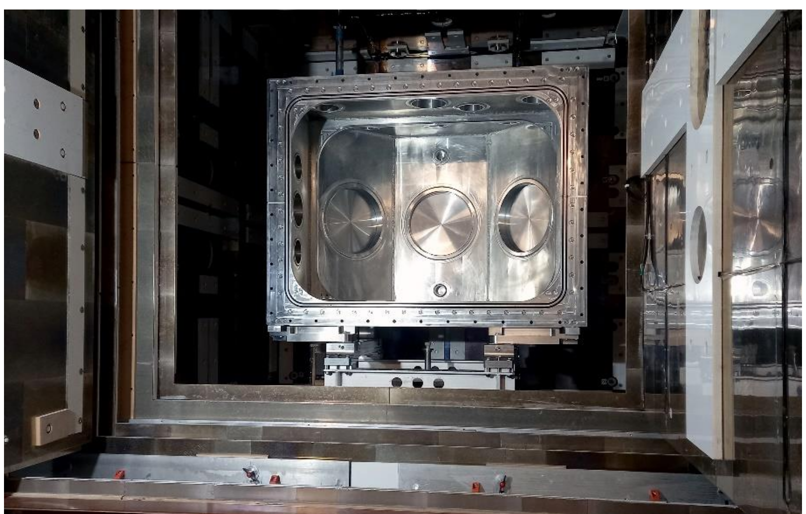
Made at LPC Caen, FR

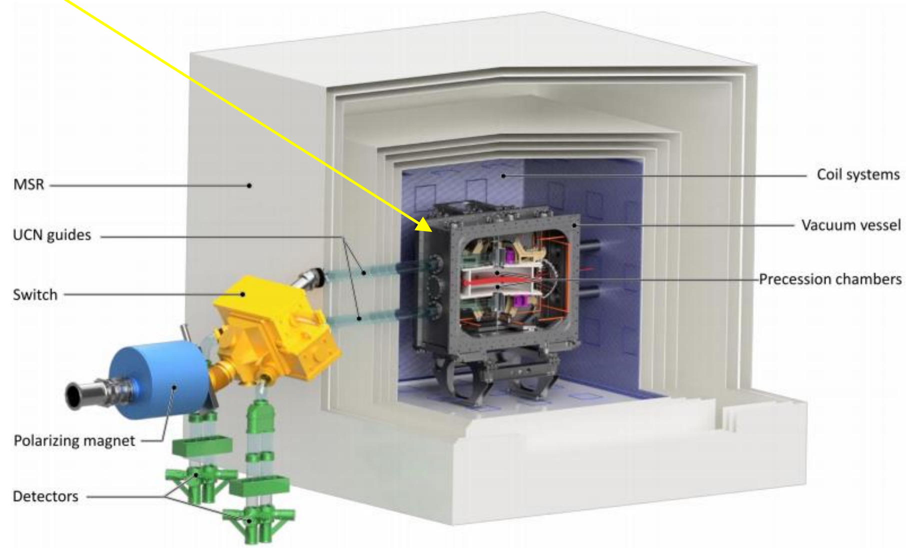


n2EDM experiment overview

The Vacuum vessel

Made at LPC Caen, FR

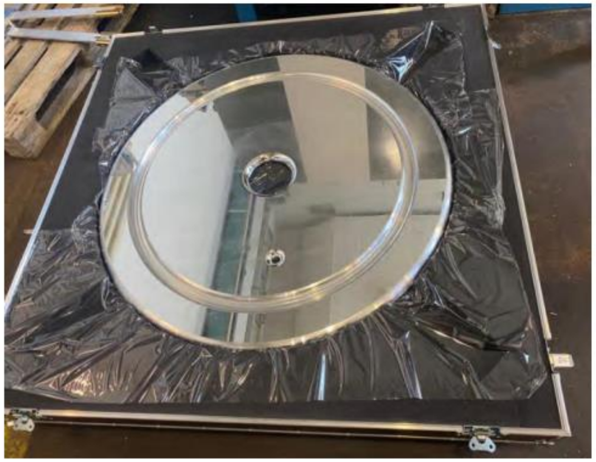




Non-magnetic aluminium vacuum tank
Internal volume: 1.6 m x 1.6 m x 1.2 m
Ultimate pressure: ~10^{-6} mbar

n2EDM experiment overview

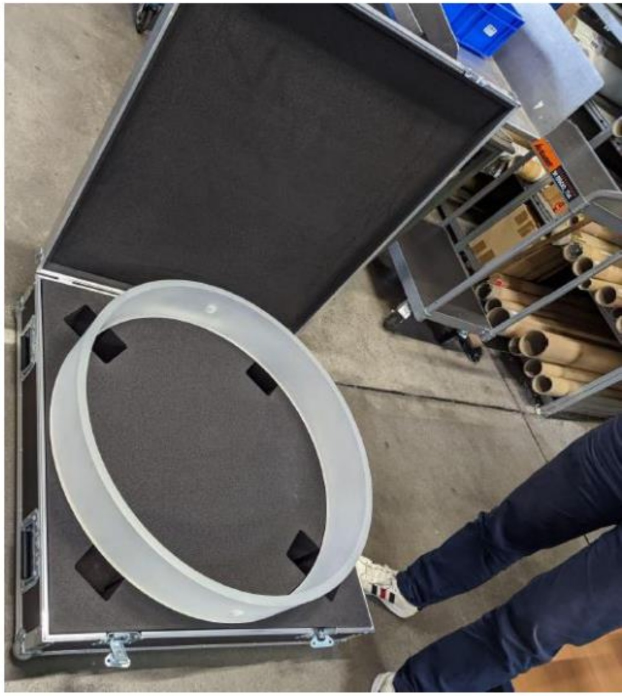
Production of the precession chambers



Ground electrodes

Made at University of Bern, CH

High Voltage electrode

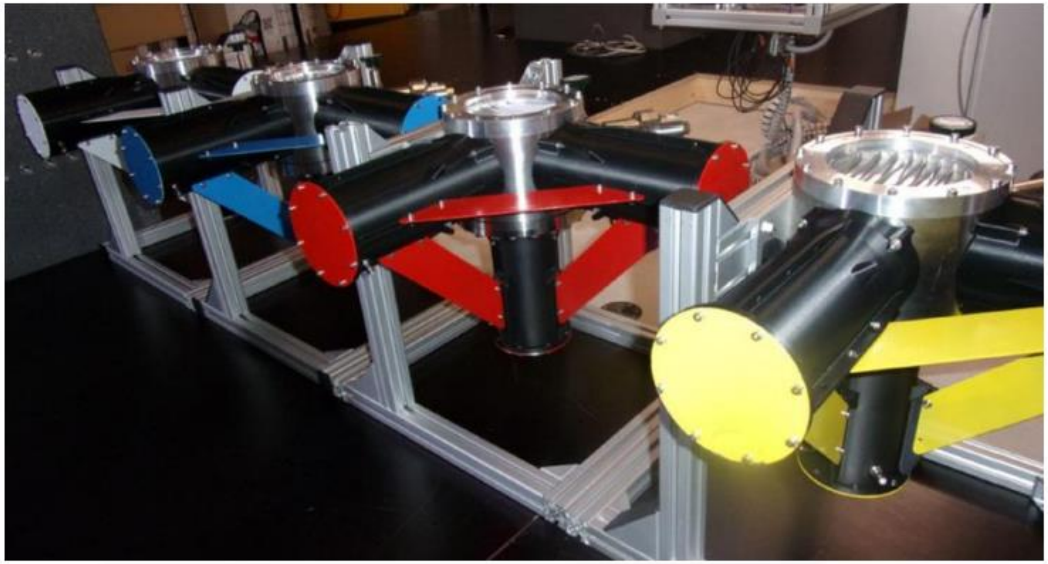


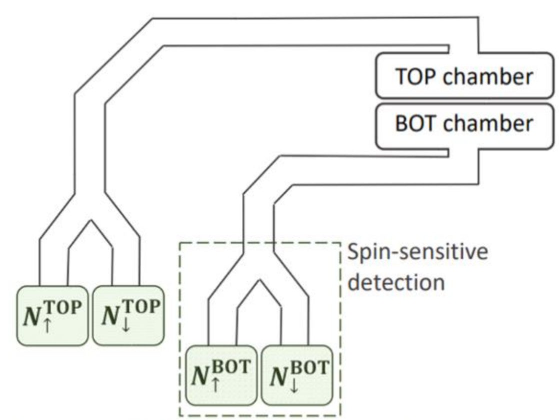
Insulator ring

Made at Institut für Physik, Mainz, DE

n2EDM experiment overview

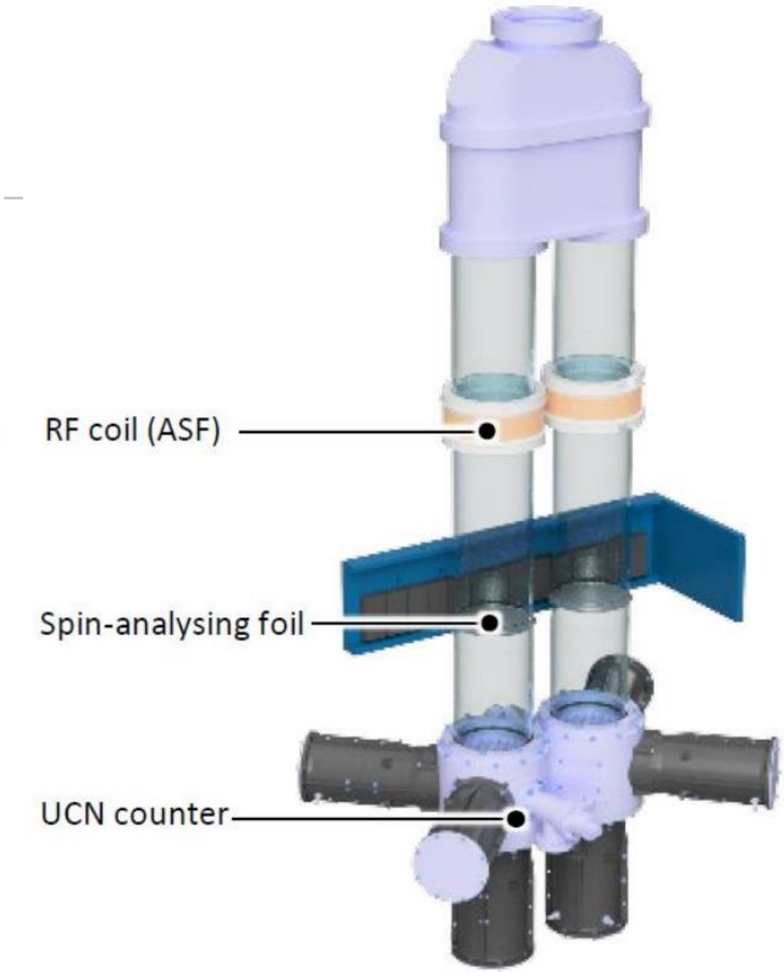
The four UCN detectors





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

Made at LPC Caen, FR

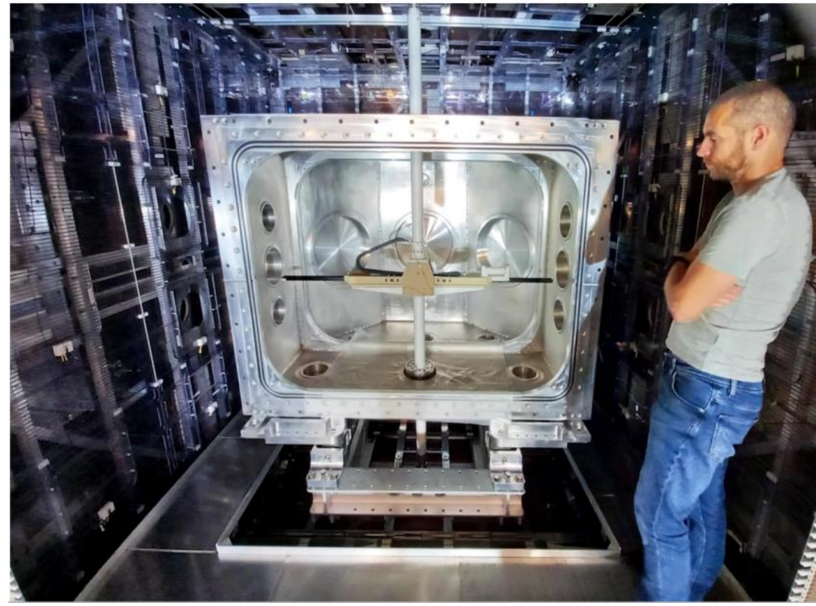


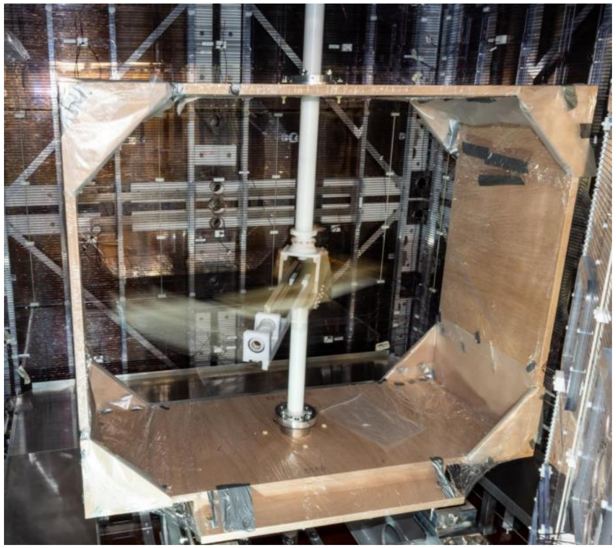
Simultaneous spin analyzer. Each arm is equipped with an adiabatic spin-flipper (RF coil), a spin-analyzing foil and a UCN counter.

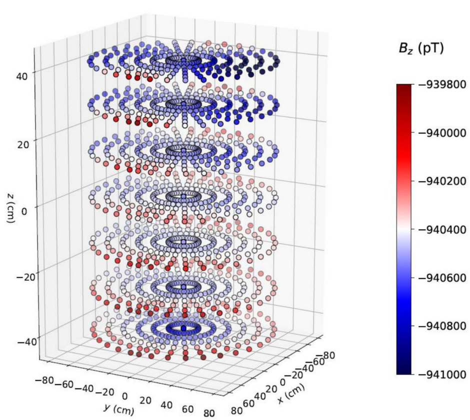
n2EDM experiment overview

The magnetic field mapper

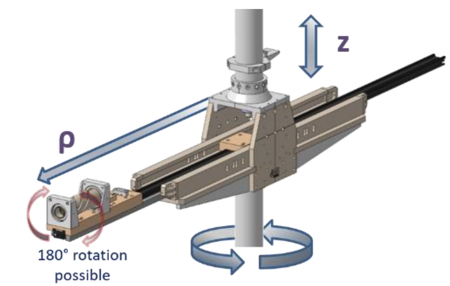
- coil system cartography
- offline control of high-order gradients
- searches for magnetic contamination

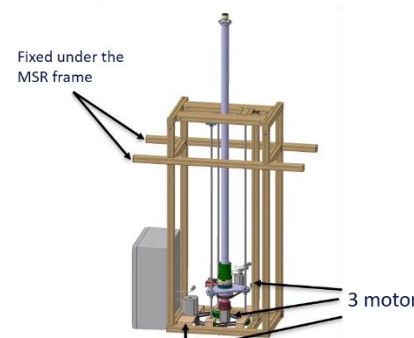






Made at LPSC Grenoble, FR



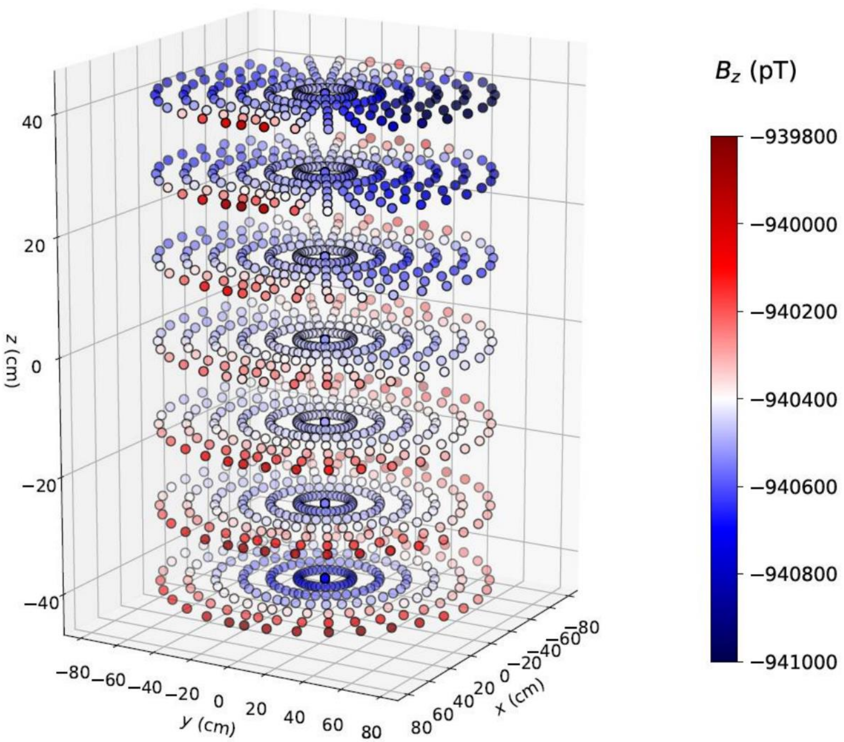


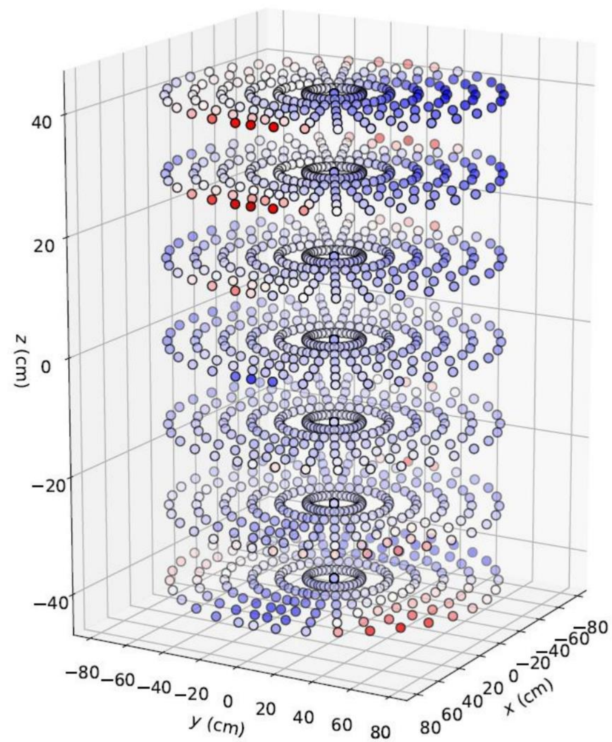
n2EDM experiment status

Characterization of the magnetic environment

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

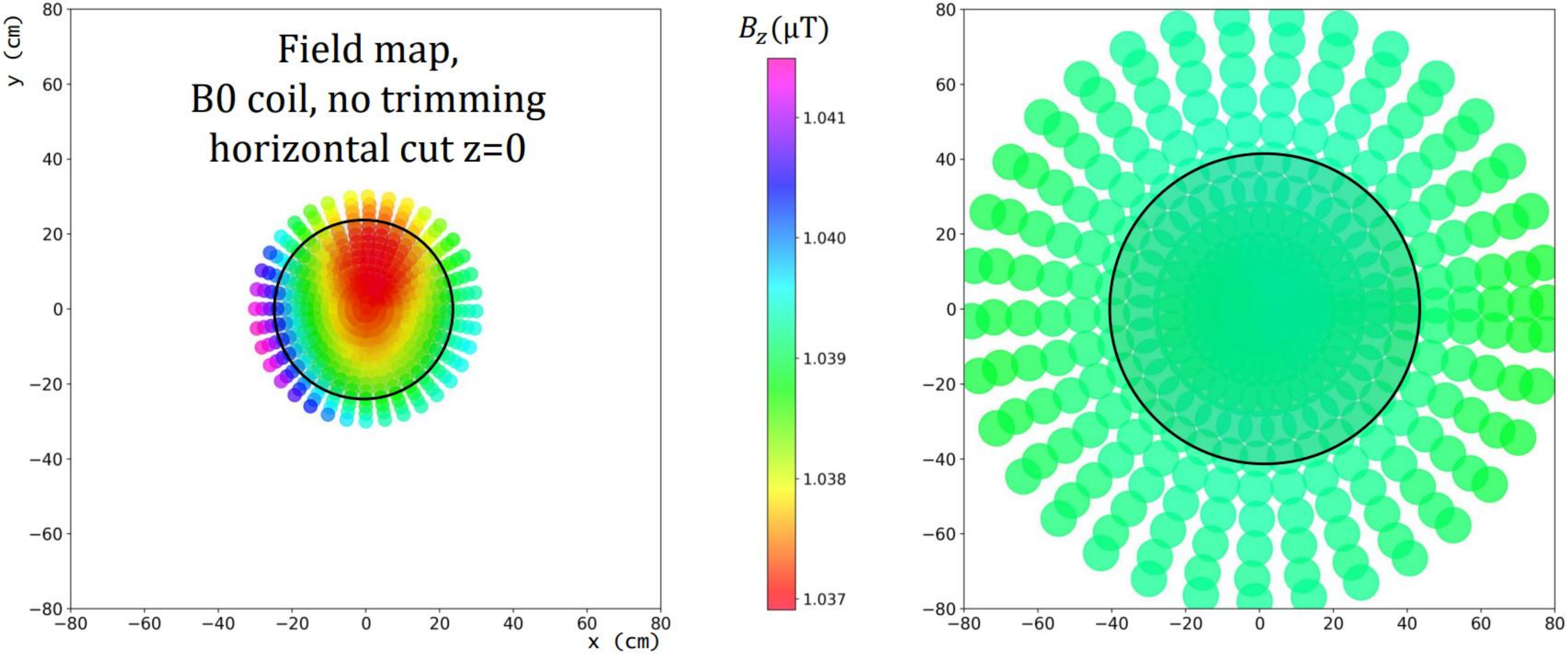
$\sigma(B_z) \approx 60\ \mathrm{pT} < 170\ \mathrm{pT}$ specification

✓ Optimized B0 coil at 1μT

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

Characterization of the magnetic environment

Uniformity of the vertical B-field
in nEDM vs n2EDM



nEDM 2017 $\sigma(B_z) = 900$ pT

In the precession chamber Ø 47 cm

n2EDM 2022 $\sigma(B_z) = 60$ pT

In one chamber Ø 80 cm

Successful commissioning of the internal field generation. Ready for physics!

Conclusions

n2EDM is magnetically operational (MSR+B0)

- Big volume: 6 fold increased /nEDM
- Order of magnitude improved shielding factor
- Order of magnitude improved field uniformity

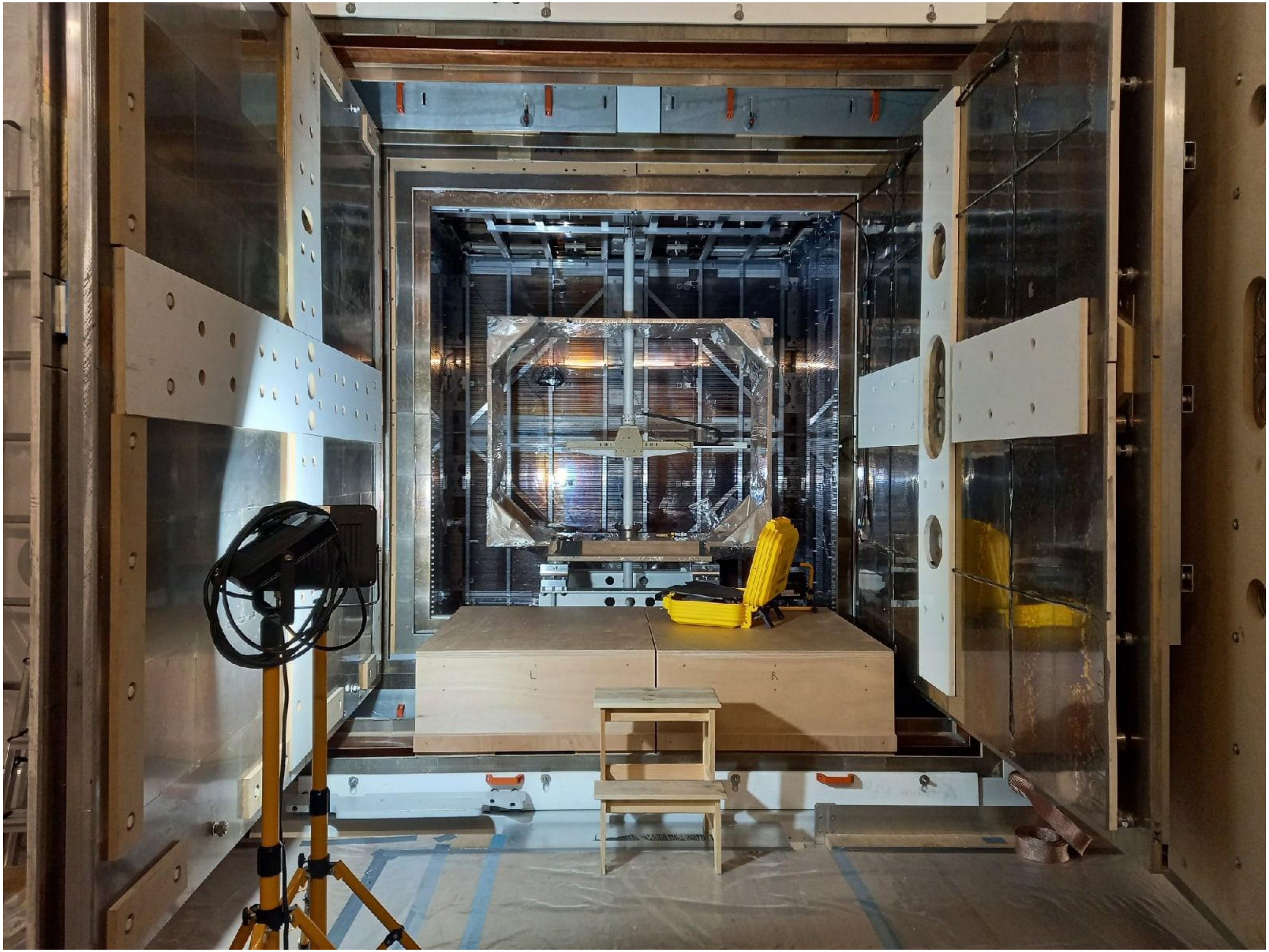
→ Satisfies the requirements, ready for physics!

- UCN transport, storage, detection:
most of it is ready for installation

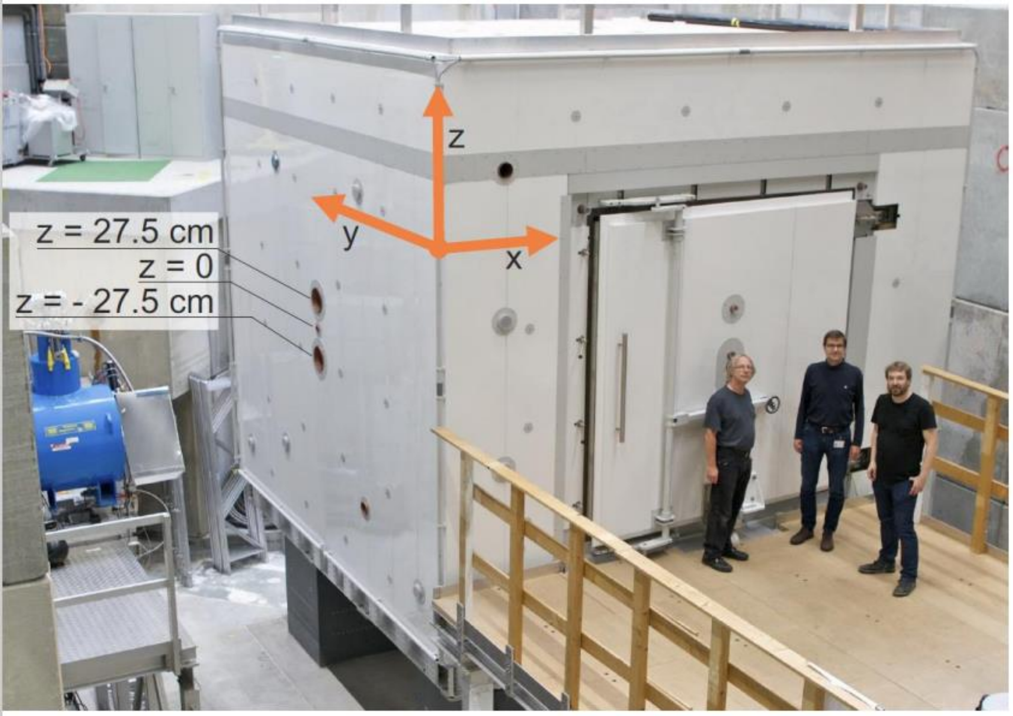
Schedule:
n2EDM ready for physics end of 2023

Thanks for your attention!

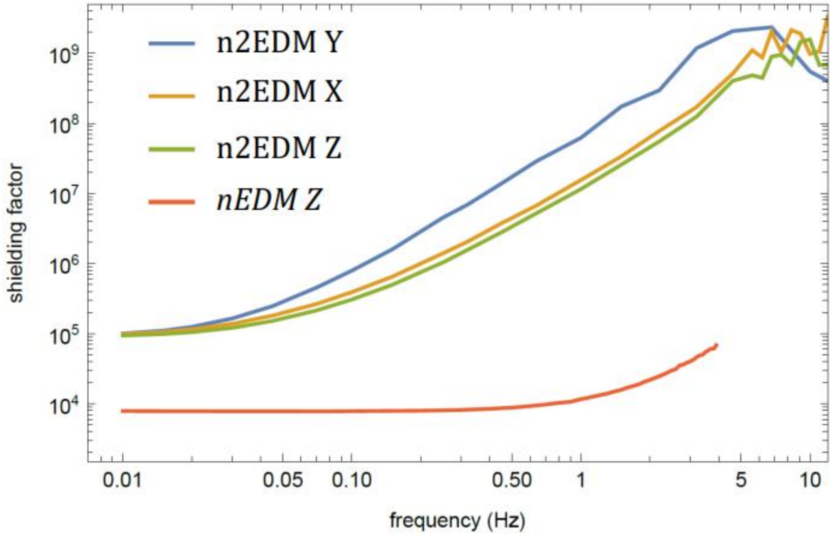
BACKUP SLIDES



Commissioning of the MSR in 2020



- Setup and optimization of the degaussing
- Characterization of the remanent field
- Measurement of the shielding factors

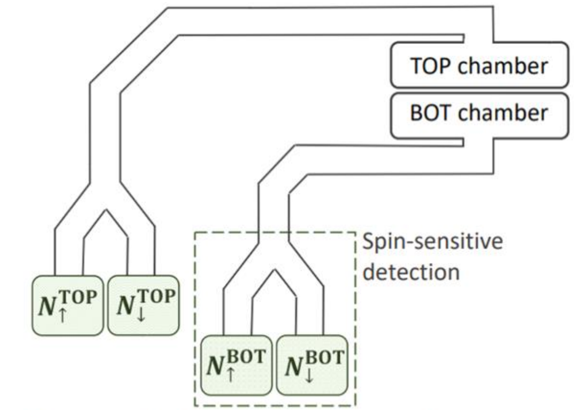


[The very large n2EDM magnetically shielded room with an exceptional performance for fundamental physics measurements, Review of Scientific Instruments 93, 095105 (2022)]

Measurement of the neutron EDM

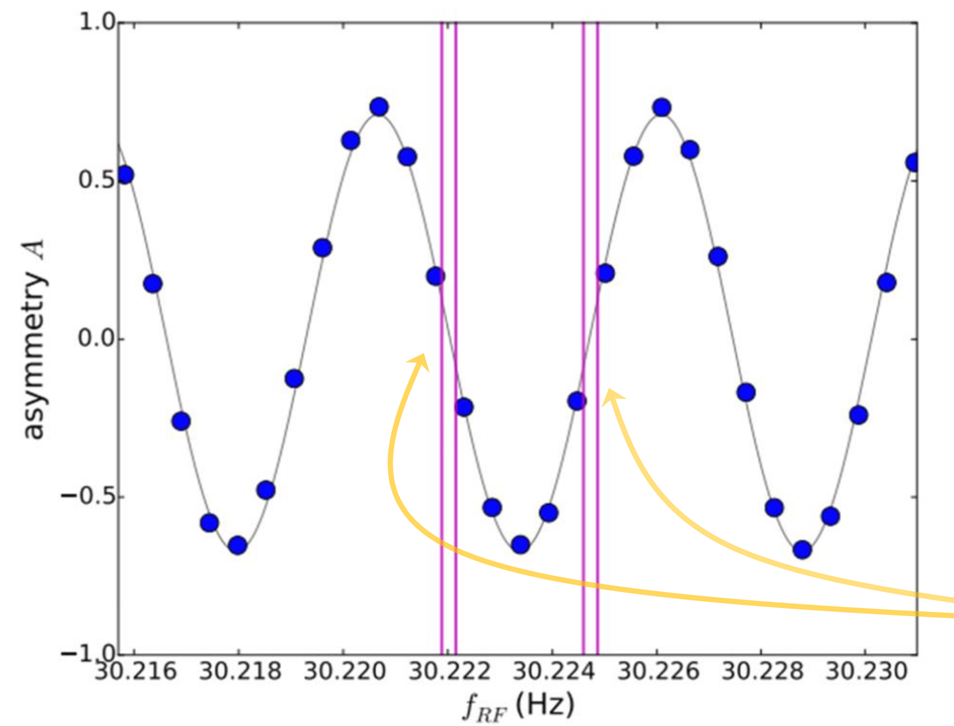
Asymmetry:

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



(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:

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

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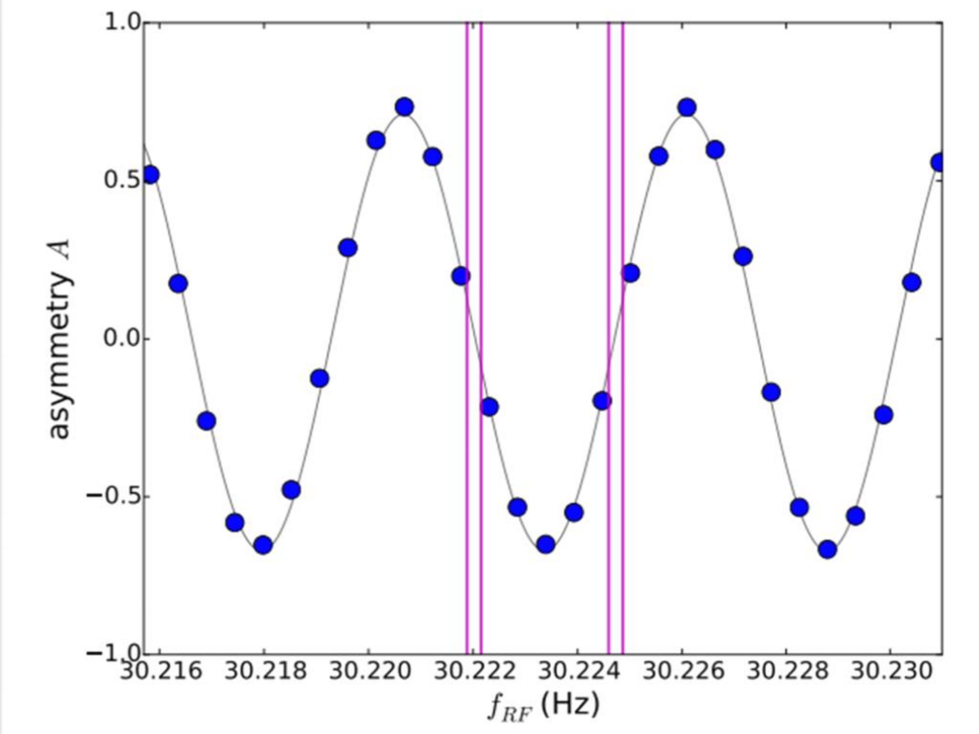

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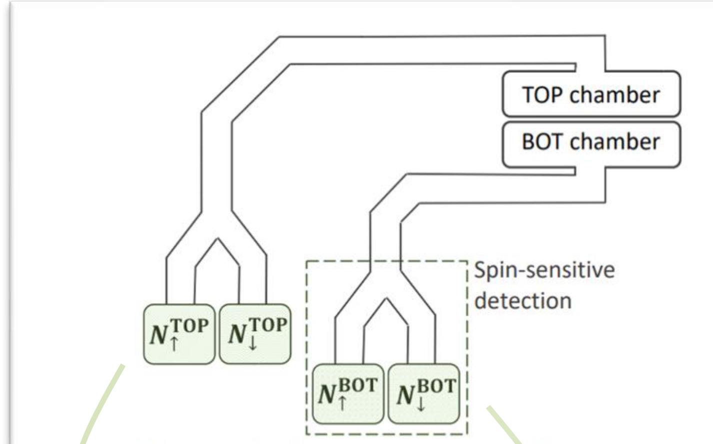


(b) UCNs are guided towards the spin-sensitive detectors.

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

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

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

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

⇕

STAT.

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)

A weak magnetic field $B_0 \approx 1$ µT is applied in a volume of >1m³. 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 and $\vec{\nabla} \times \vec{B}$=0.

Requirements

- **On field production – B0 coil**:

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

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

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

to prevent neutron depolarization

- **On field measurements – mapping**:

$\delta \acute{G}_3 < 20\ \mathrm{fT/cm}$ – 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 $d_{n \leftarrow Hg}^{\mathrm{false}}$ (*) 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}.

Magnetic commissioning of n2EDM

Field parametrization

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

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

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

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

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

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

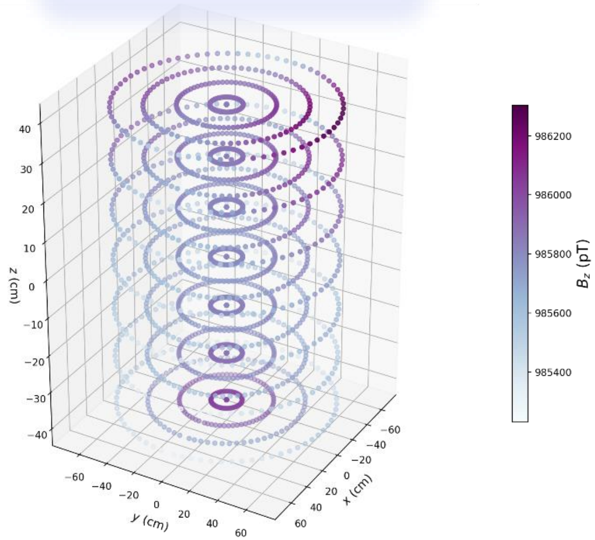
to prevent neutron depolarization

- **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 $d_{n\leftarrow Hg}^{\text{false}}$ with a precision below 10^{-28}e cm.

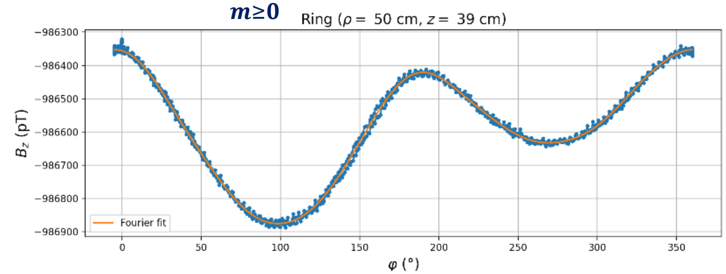
A field map: set of rings



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

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

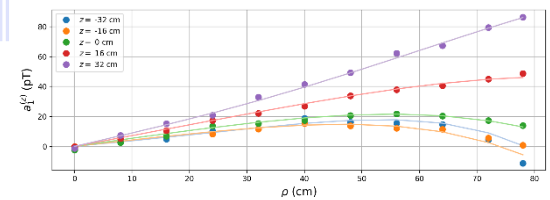


For one ring, since the radius ρ and height z are fixed, the magnetic field is simply a function of φ. We fit it with a Fourier series with the Fourier coefficients as parameters of the φ.
After having extracted a set of Fourier coefficients for each ring, the next step is to fit these coefficients with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

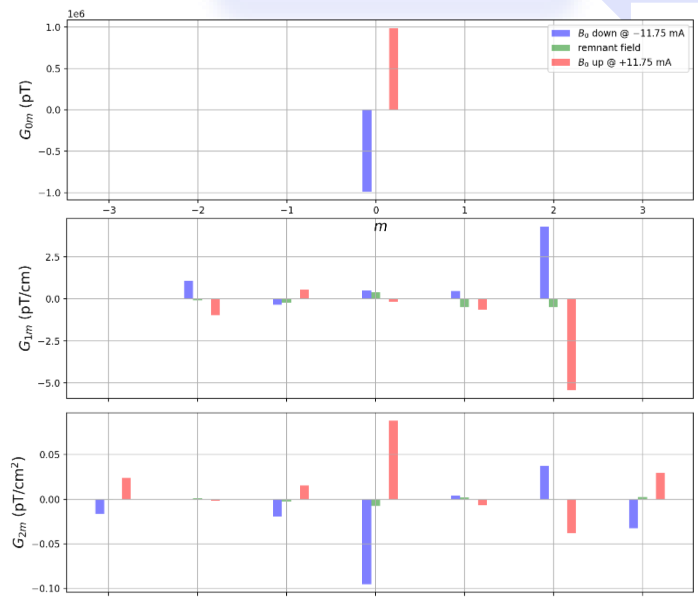
Set of Fourier coefficients

Fourier coefficients fit with harmonic polynomials

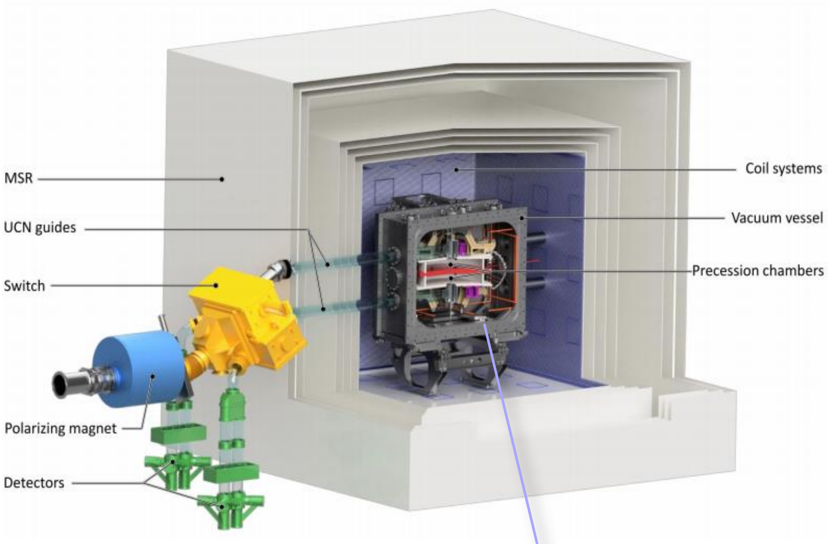
$$a_{m,z}(\rho, z) = \sum_{l\geq 0} G_{l,m}\hat{\Pi}_{l,m}(\rho, z)$$

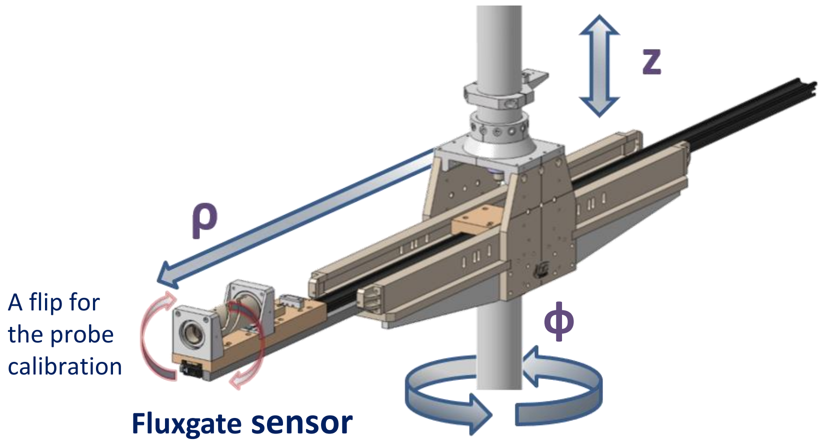


Set of gradients $G_{l,m}$



Magnetic commissioning of n2EDM: the 1st mapping campaign

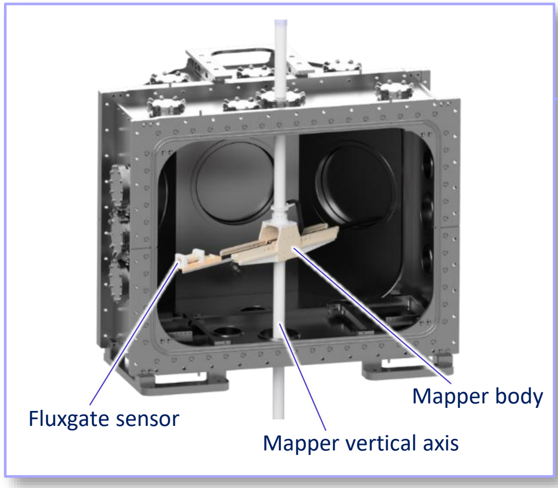




The mapping range

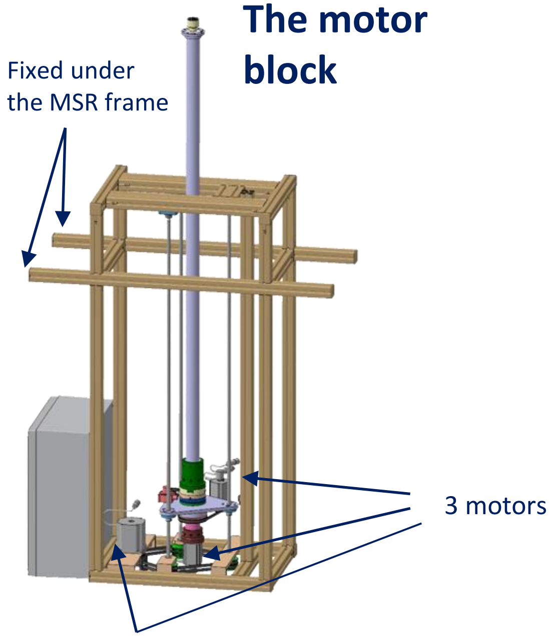
ρ	$0 - 780$ (mm)
φ	$0 - 360$ (deg.)
z	± 410 (mm)

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



Purposes:

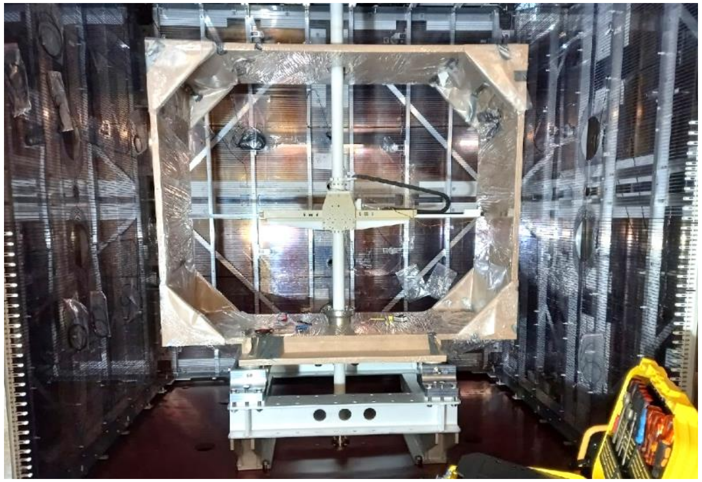
- ✓ **Coil system cartography**
- ✓ Offline control of high-order gradients
- ✓ Searches for magnetic contamination



Magnetic commissioning of n2EDM: the 1st mapping campaign

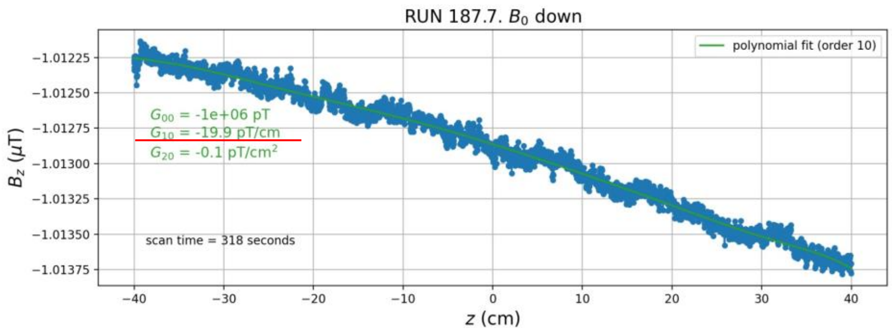
Coil system installation

Map type:



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

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



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):
STAT.

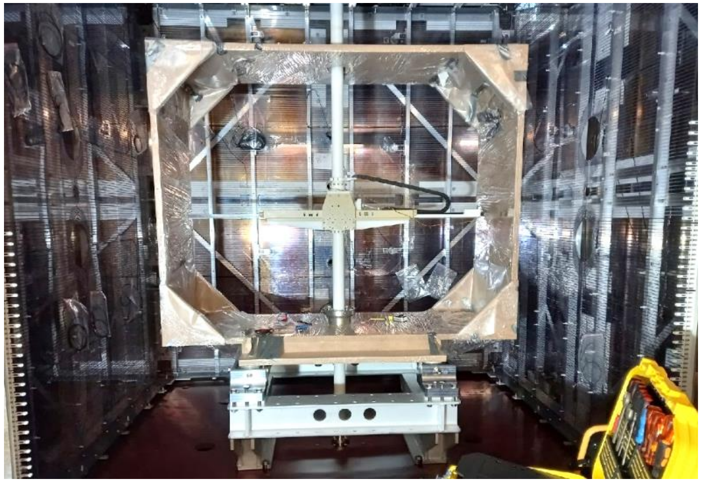
$$-0.6\ \mathrm{pT/cm} < G_{1,0} < 0,6\ \mathrm{pT/cm}$$

"Top-Bottom resonance matching condition"

(maximum permitted vertical gradient of the magnetic field)

Magnetic commissioning of n2EDM: the 1st mapping campaign

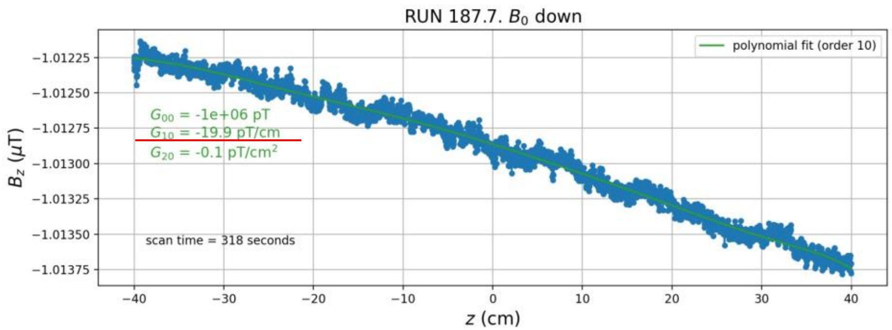
Map type:



Coil system installation

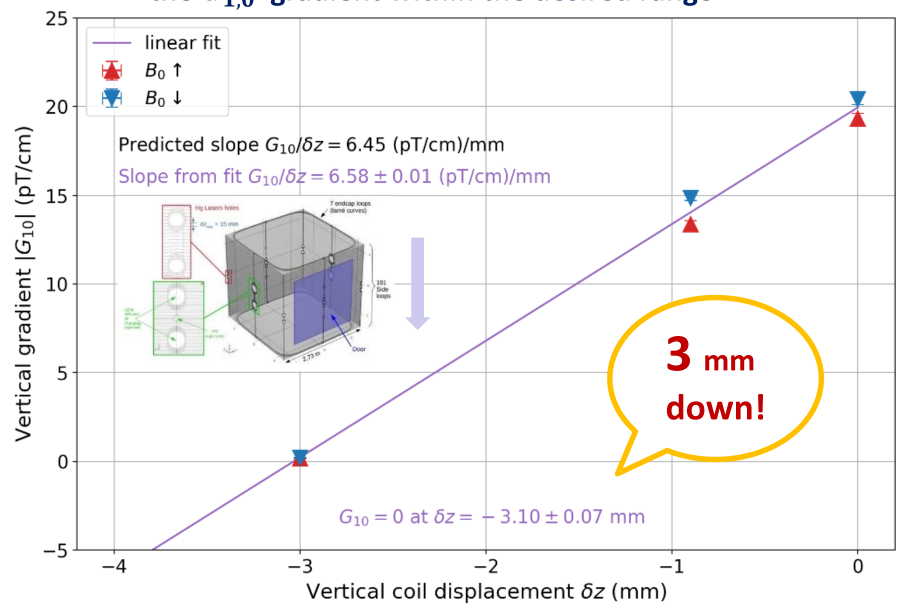
The first vertical map after the installation of the B_0 coil showed a deviation in the 1st-order gradient $G_{1,0}$.

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



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 $G_{1,0}$ gradient within the desired range

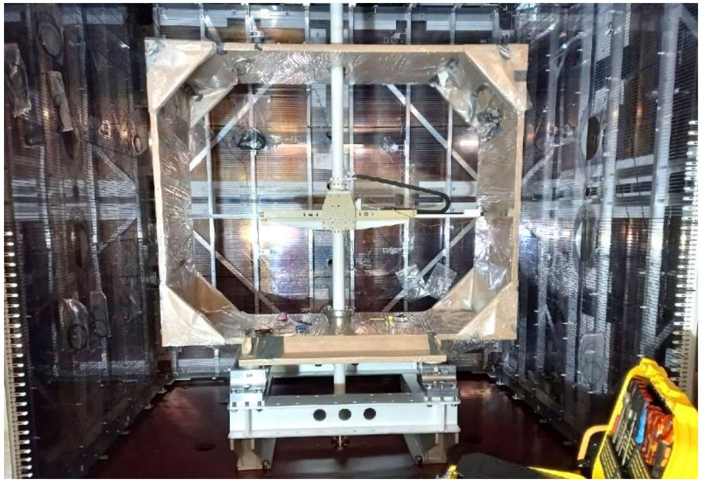


The values of $G_{1,0}$ shown for each polarity of the B_0 coil are the averages of the values of $G_{1,0}$ after degaussing in L6 and L6-crossed configurations.

Magnetic commissioning of n2EDM: the 1st mapping campaign

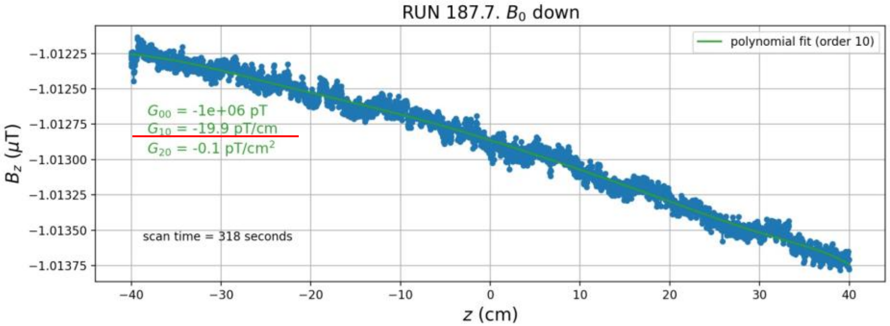
Coil system installation

Map type:

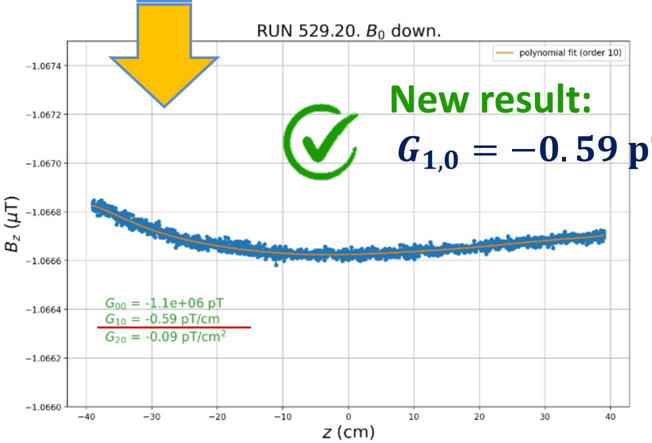


The first vertical map after the installation of the B_0 coil showed a deviation in the 1st-order gradient $G_{1,0}$.

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



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

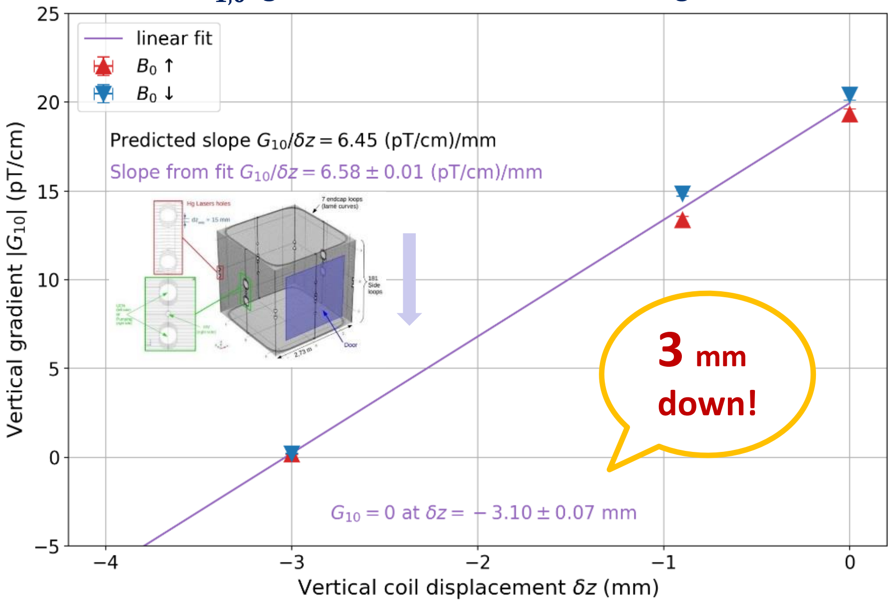


New result:

$G_{1,0} = -0.59$ 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 $G_{1,0}$ gradient within the desired range



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

Magnetic commissioning of n2EDM: the 1st mapping campaign

Summary

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

Calculation,
Shift of the coil system

After the **vertical adjustment of the coil**, the new value of the 1st order gradient in the B_0-down configuration : $G_{1,0} = -0.59\ \mathrm{pT/cm}$.

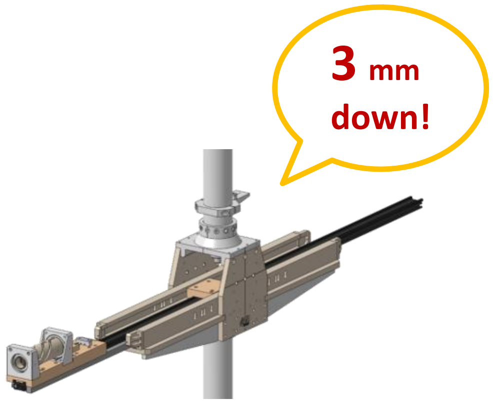
The **average** of the $G_{1,0}$ measured for the two polarities of B_0 gives the value of $0.2\ \mathrm{pT/cm}$ i.e. it is **in perfect agreement with the prediction**, meets the requirement and demonstrates an **impressive sensitivity of the mapping**!

$G_{1,0} = -0.59\ \mathrm{pT/cm}$ **(B_0-down)**

$G_{1,0} = 0.2\ \mathrm{pT/cm}$ **(average of B_0-down & B_0-up)**

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)

Fulfilled!



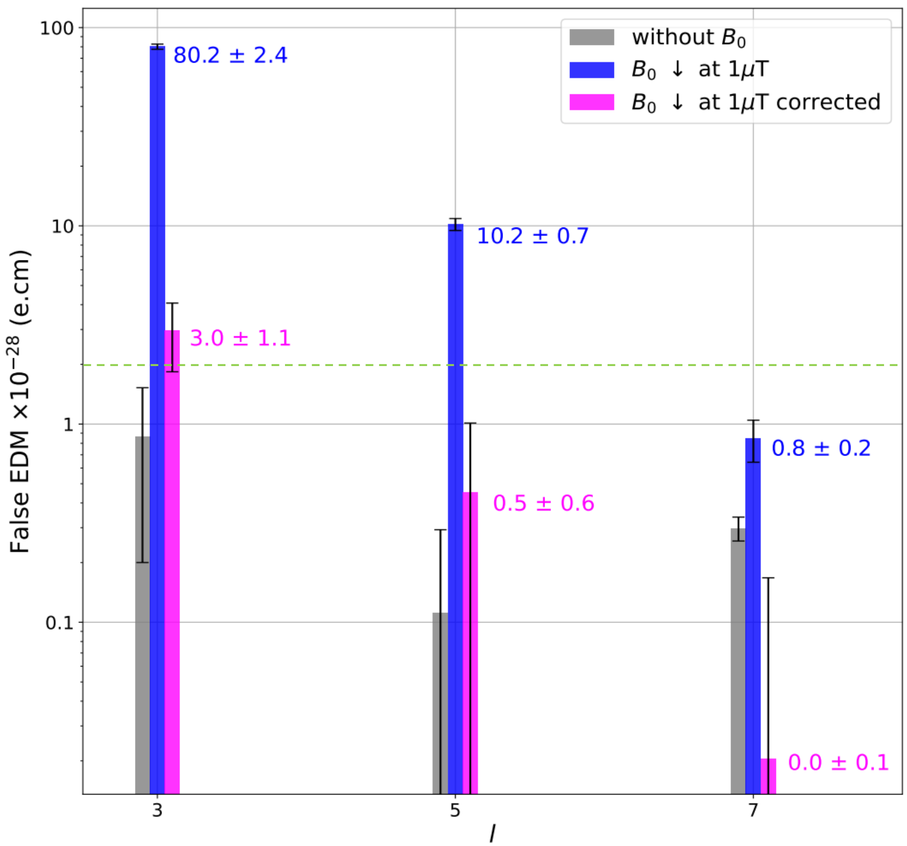
Control of all coils → B_0 field optimization

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

Contribution of the false EDM produced by gradients $\boldsymbol{G_{3,0}}$, $\boldsymbol{G_{5,0}}$, $\boldsymbol{G_{7,0}}$ 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 $\boldsymbol{d_{n\leftarrow Hg}^{\text{false}}}$ with a good precision.

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



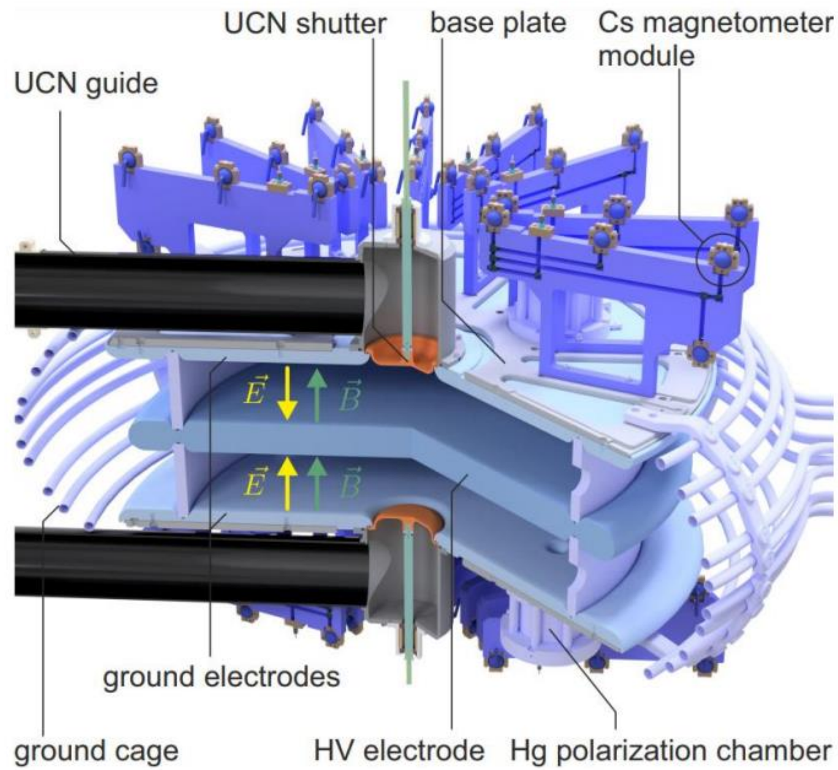
Optically pumped magnetometers

114 Cs magnetometers: position optimize for extraction of gradient components

Goal accuracy < 5 pT

Position placement ± 0.5 mm

Characterise in 4 layer mu-metal shielding



USSA/UCN detectors

USSA for each UCN volume

Simultaneous neutron spin discrimination

UCN counters: fast gaseous detector

Gas mixture of ^{3}He and CF_4

Process: neutron capture produces proton and triton, creating scintillation of CF_4