n2EDM

The n2EDM experiment at PSI

↓

neutron Electric Dipole Moment

FPCP 2023

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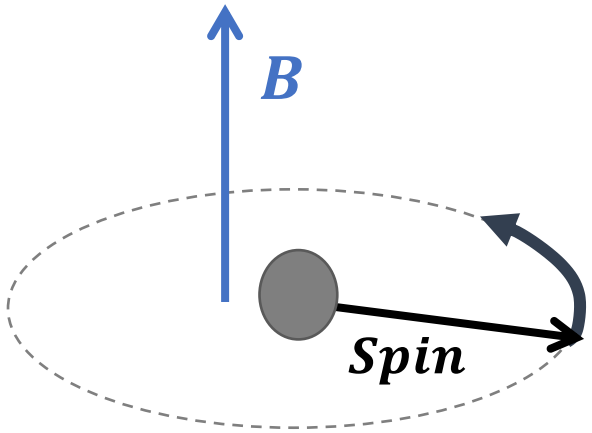
17/03/2022

Université Grenoble Alpes

LPSC GRENOBLE | MODANE

What is the electric dipole moment?



Motion of a spin ½ particle in a magnetic field:

- $H = -\mu\, \boldsymbol{\sigma} \cdot \boldsymbol{B}$
- If $\boldsymbol{B} = B_0 \boldsymbol{u_z}$, precession motion with frequency given by $\hbar 2\pi f = 2\mu\, B_0$
- Neutron in $B_0 = 1\ \mu\mathrm{T}$ → $f \approx 30\ s^{-1}$

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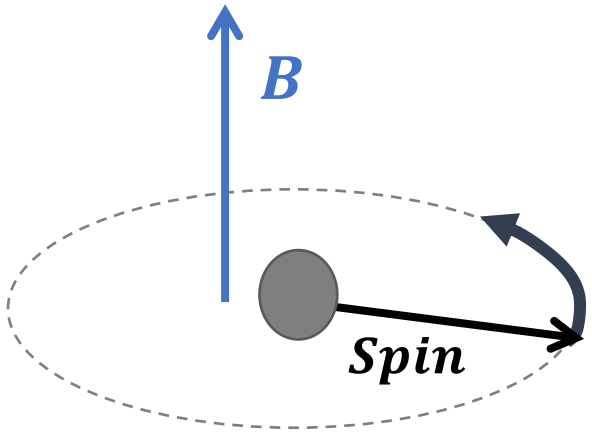

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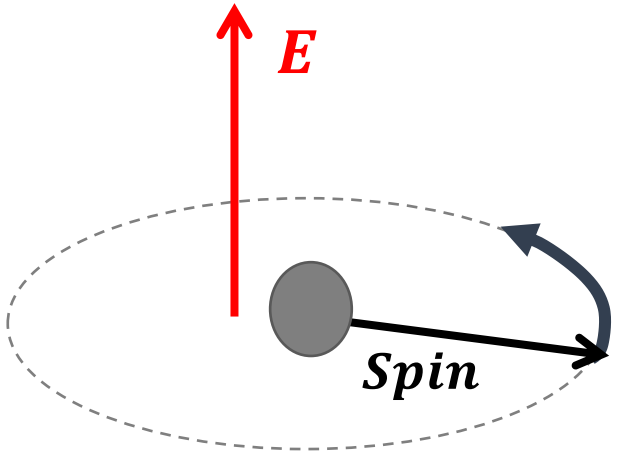

What about a spin ½ particle in an electric field?

- $H = -d\, \boldsymbol{\sigma} \cdot \boldsymbol{E}$
- If $\boldsymbol{E} = E_0 \boldsymbol{u_z}$, precession motion with frequency given by $\hbar 2\pi f = 2d\, E_0$
- Neutron in $E = 15\ k\mathrm{V/cm}$ → $f < 2\ \mathrm{year}^{-1}$

With current limit $d_n < 10^{-26} e.\mathrm{cm}$

Why measure the neutron EDM?

Cosmological motivation: explain baryon asymmetry $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$

Sakharov conditions for baryogenesis:

1. Non-conservation of baryonic number
2. Out-of-equilibrium thermal interactions
3. **Violation of C and CP symmetries**

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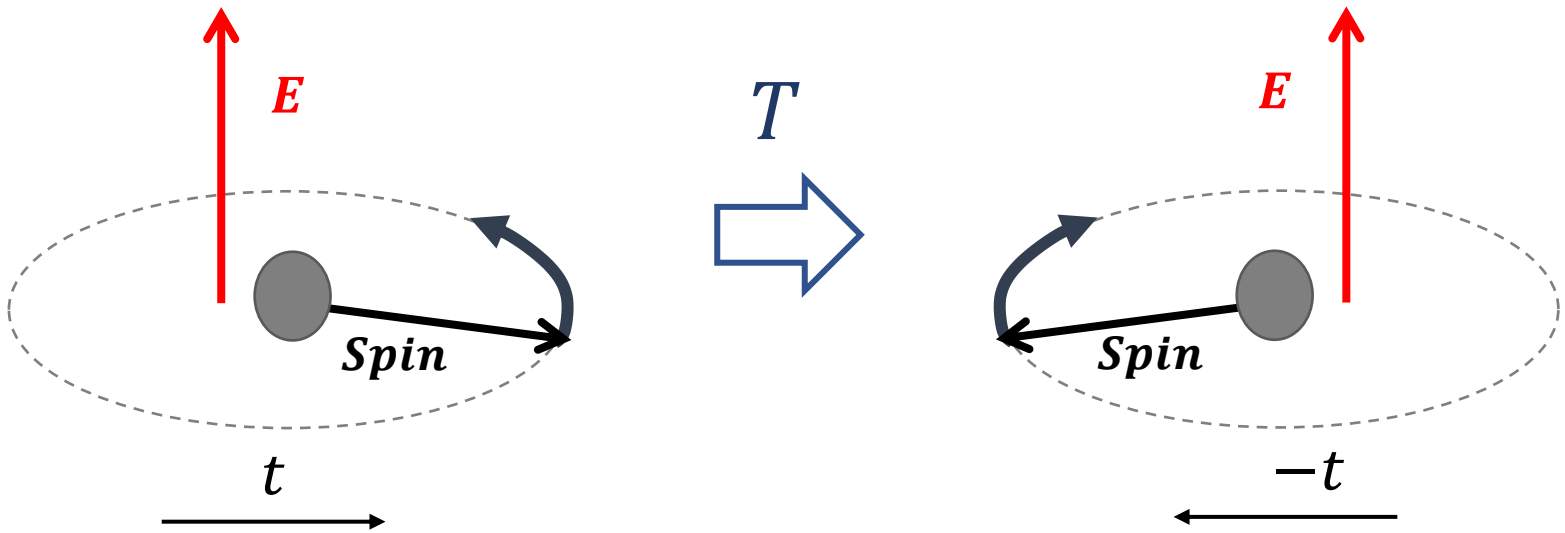
3. **Violation of C and CP symmetries**

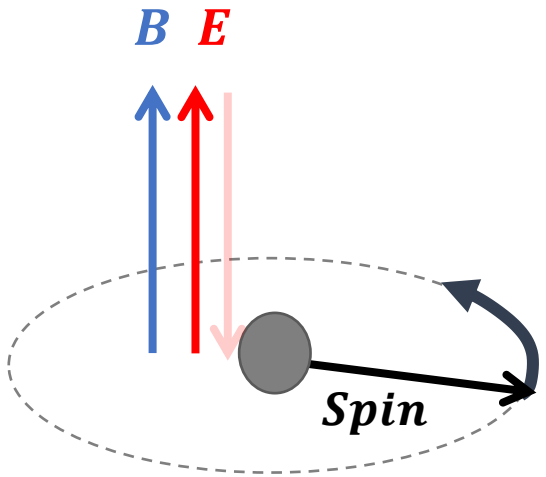
CP: $id\bar{f}\sigma_{\mu\nu}\gamma_5 f\ F^{\mu\nu} \rightarrow -id\bar{f}\sigma_{\mu\nu}\gamma_5 f\ F^{\mu\nu}$

T: $-d\ \boldsymbol{\sigma}\cdot\boldsymbol{E} \rightarrow +d\ \boldsymbol{\sigma}\cdot\boldsymbol{E}$

EDMs are described by couplings that violate CP (or T by CPT)



How do we measure the neutron EDM?



$$2\pi f_n = \frac{2\mu_n}{\hbar} B_0 \pm \frac{2d_n}{\hbar} E_0 \quad \Rightarrow \quad f_n(\uparrow\uparrow) - f_n(\uparrow\downarrow) = -\frac{2}{\pi\hbar} d_n E_0$$

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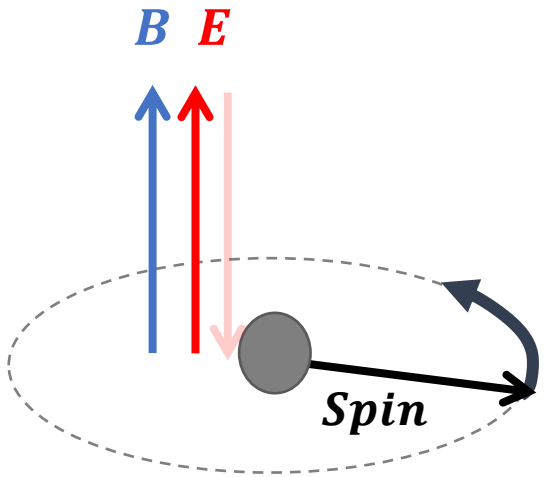

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$f_{\mathrm{n,larmor}} \approx 30\ s^{-1}$

at $B_0 = 1\mu\mathrm{T}$

If $d_n = 10^{-26} e.\mathrm{cm}$:

$f_{n,\mathrm{elec}} \approx 2\ \mathrm{year}^{-1}$

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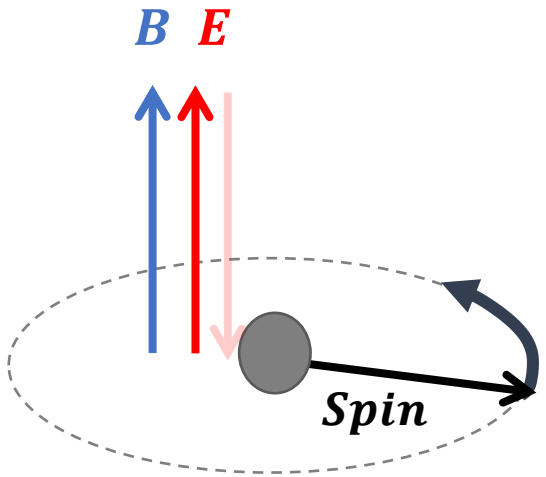

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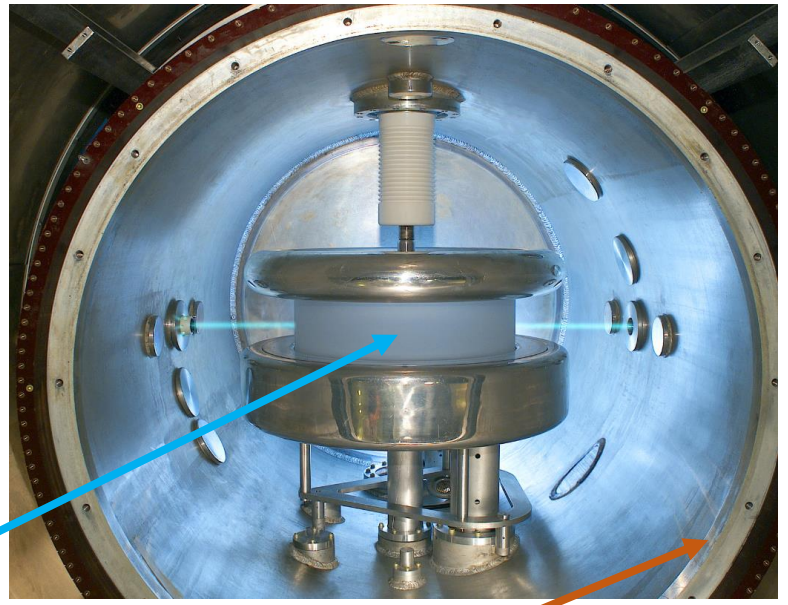
Previous experiment: nEDM @ILL



What can we do to detect something that small?

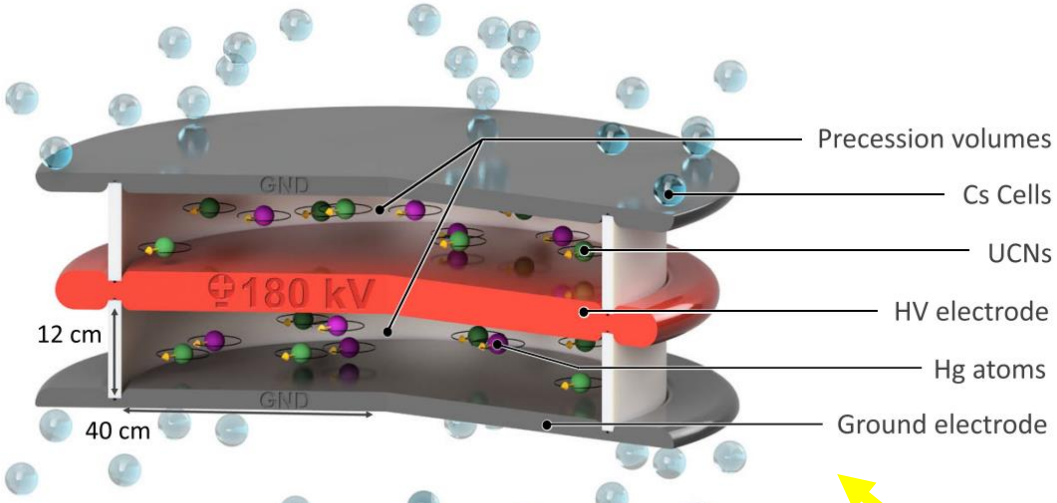
- Maximize the interaction time
- Maximize the statistics
- Control the magnetic field

→ Ultra Cold Neutrons (UCNs).

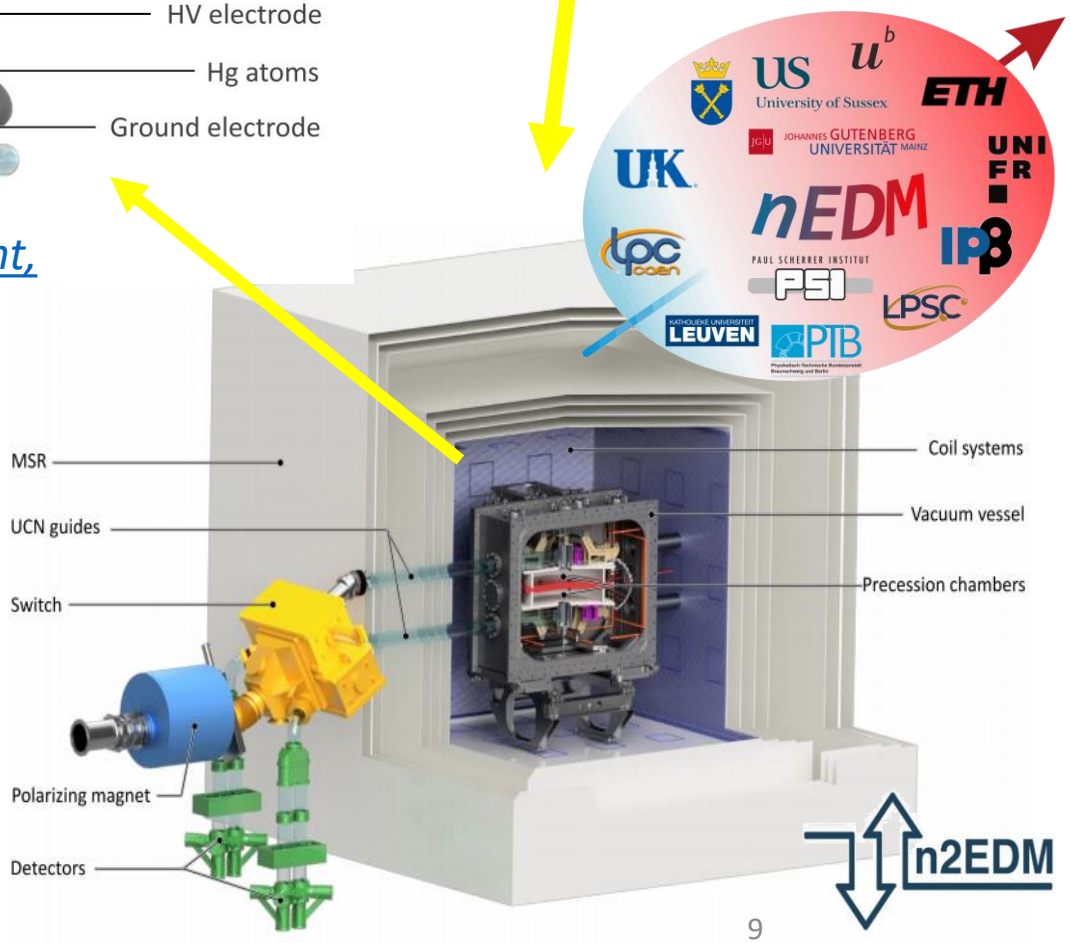
→ Large cell volume, efficient UCN transport.

→ Co-magnetometry, magnetic shielding.

The n2EDM concept



The design of the n2EDM experiment, Ayres et al, EPJC (2021).



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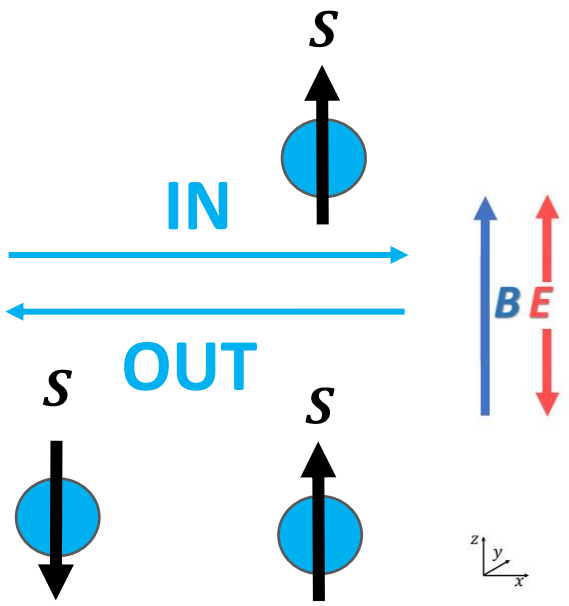
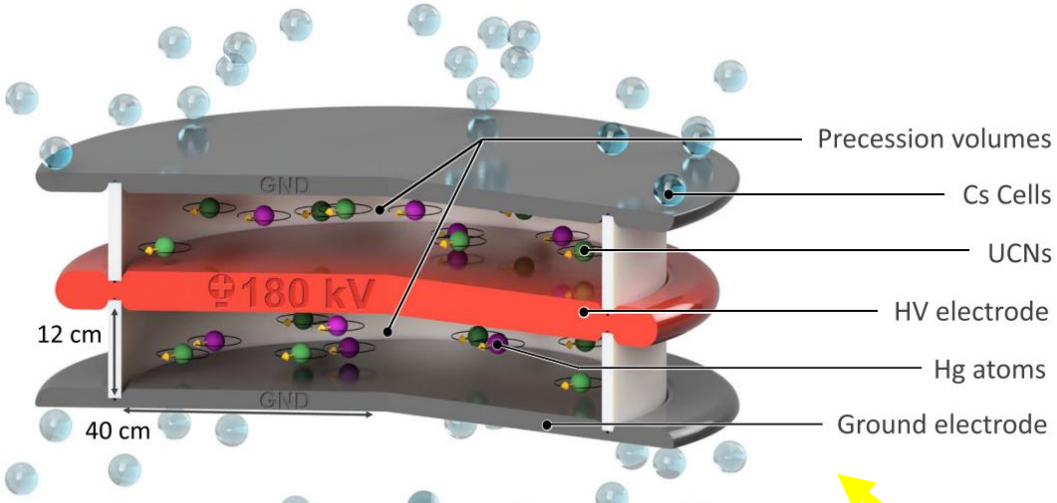
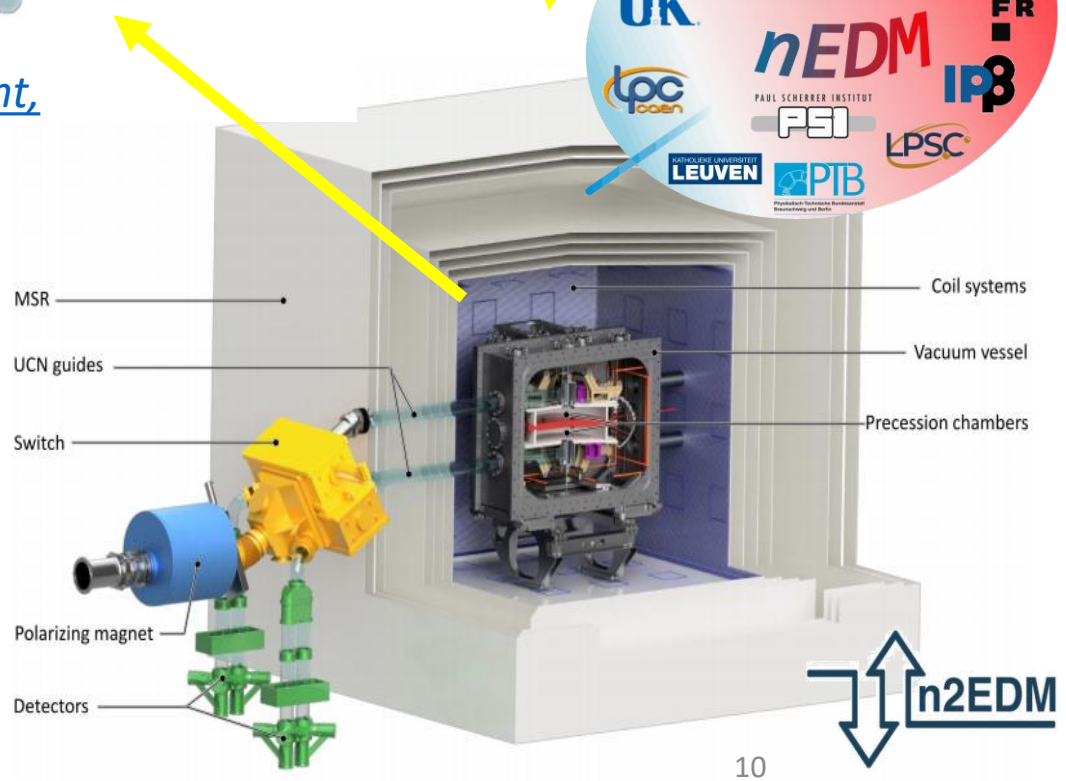




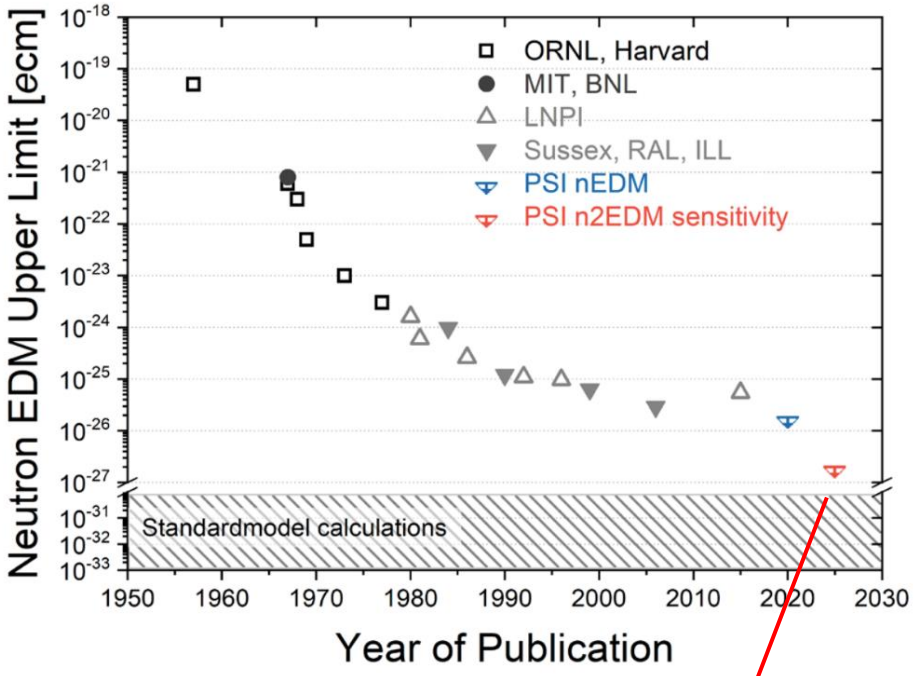
The design of the n2EDM experiment, Ayres et al, EPJC (2021).

- Polarized UCNs precess in two chambers with opposite electric / magnetic configuration.
- If non-zero EDM, $f_n^{\mathrm{TOP}} - f_n^{\mathrm{BOT}} > 0$.
- f_n^{TOP} and f_n^{BOT} extracted from the asymmetry of ↑ and ↓ spin states after precession: « **Ramsey method** ».



The sensitivity of n2EDM

50 years of neutron EDMs



→ Current limit held by the nEDM collab

→ **n2EDM d_n target sensitivity:**

$$\mathbf{1 \times 10^{-27} e.cm}$$

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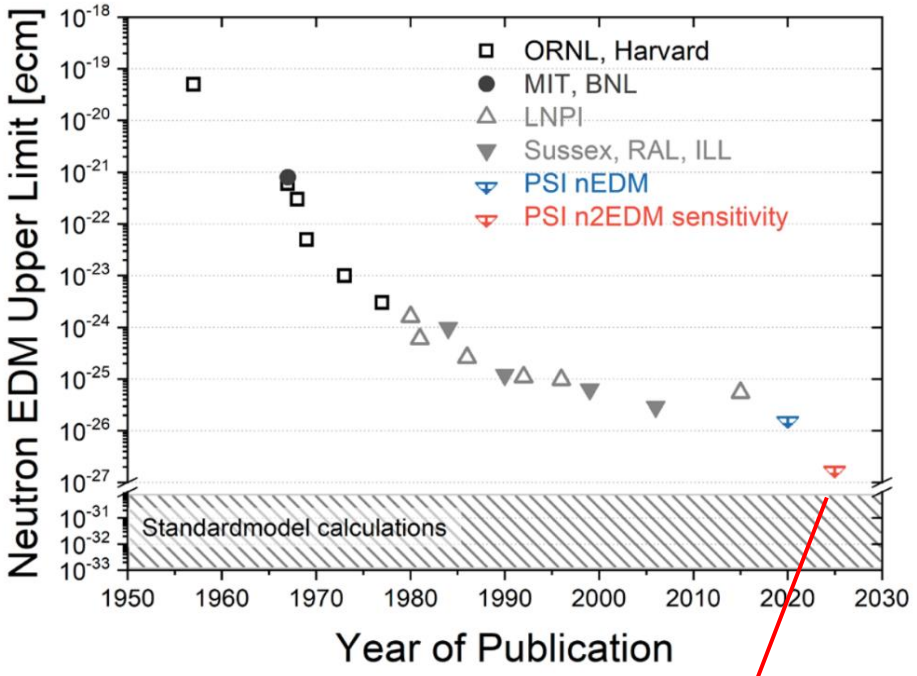

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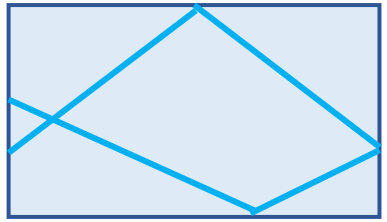
1) Maximizing the neutron statistics:

	nEDM 2016	n2EDM
Larger chambers → more UCNs		
Diameter D	47 cm	80 cm
N (per cycle)	15,000	121,000
T	180 s	180 s

UCNs with $v < 7\mathrm{m/s}$ easily storable



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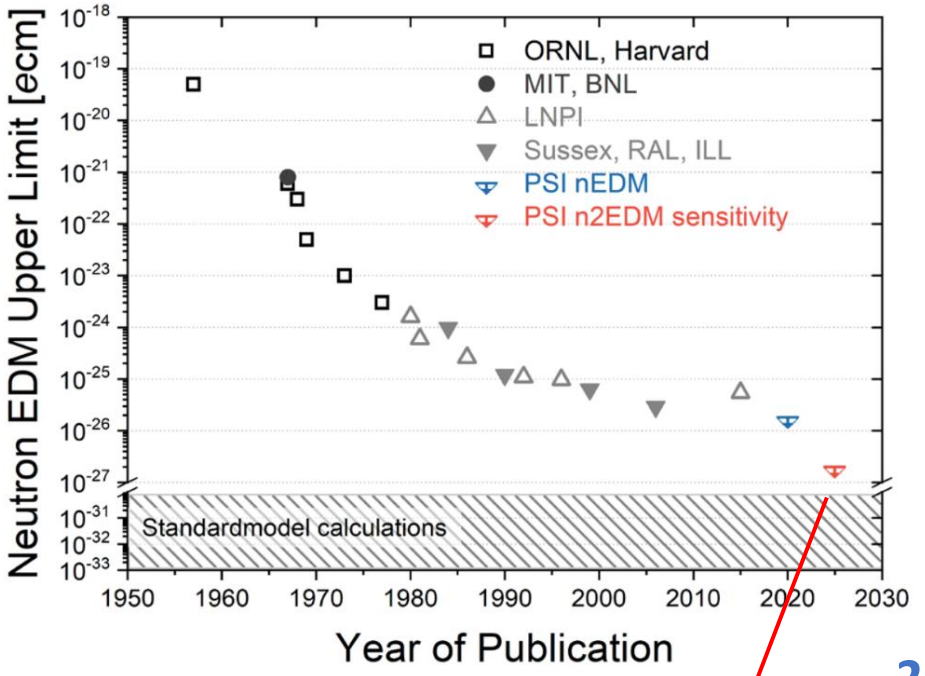

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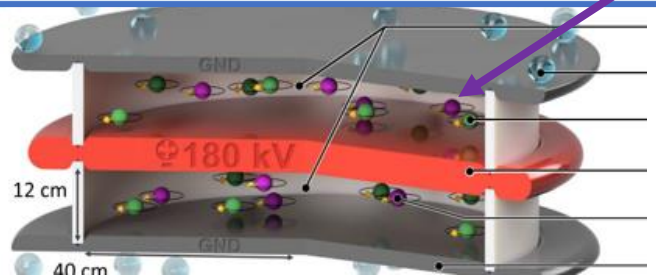

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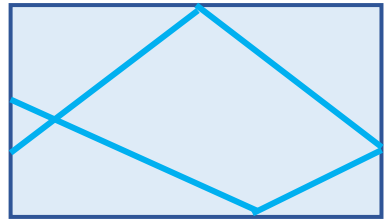
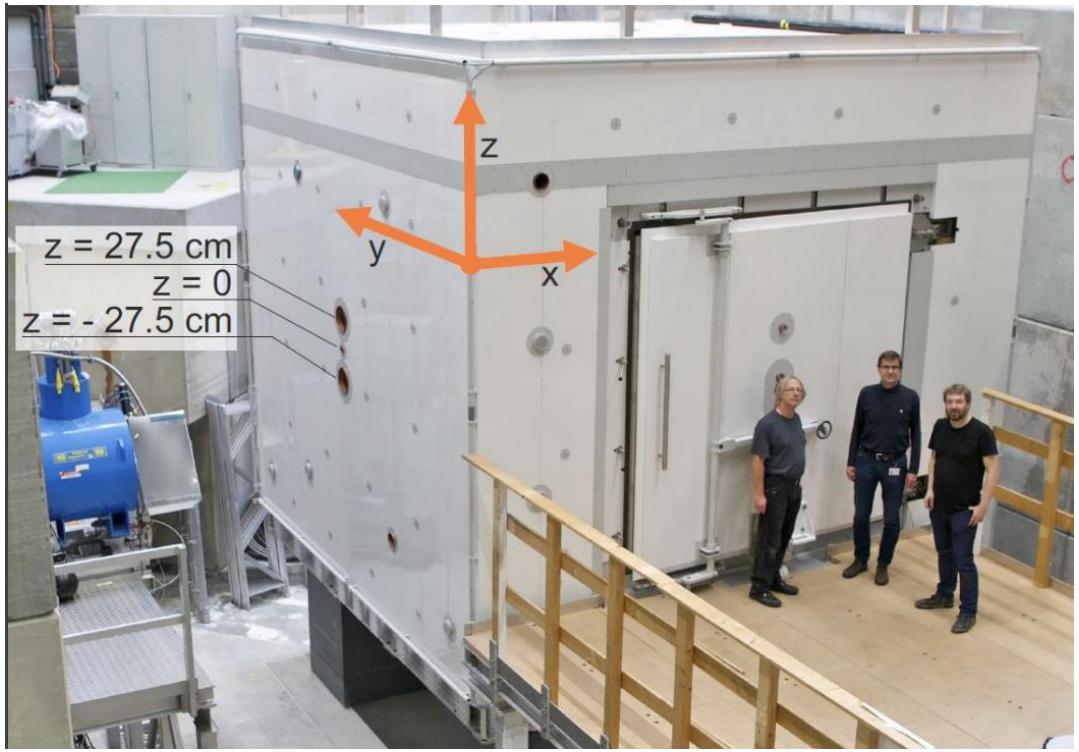


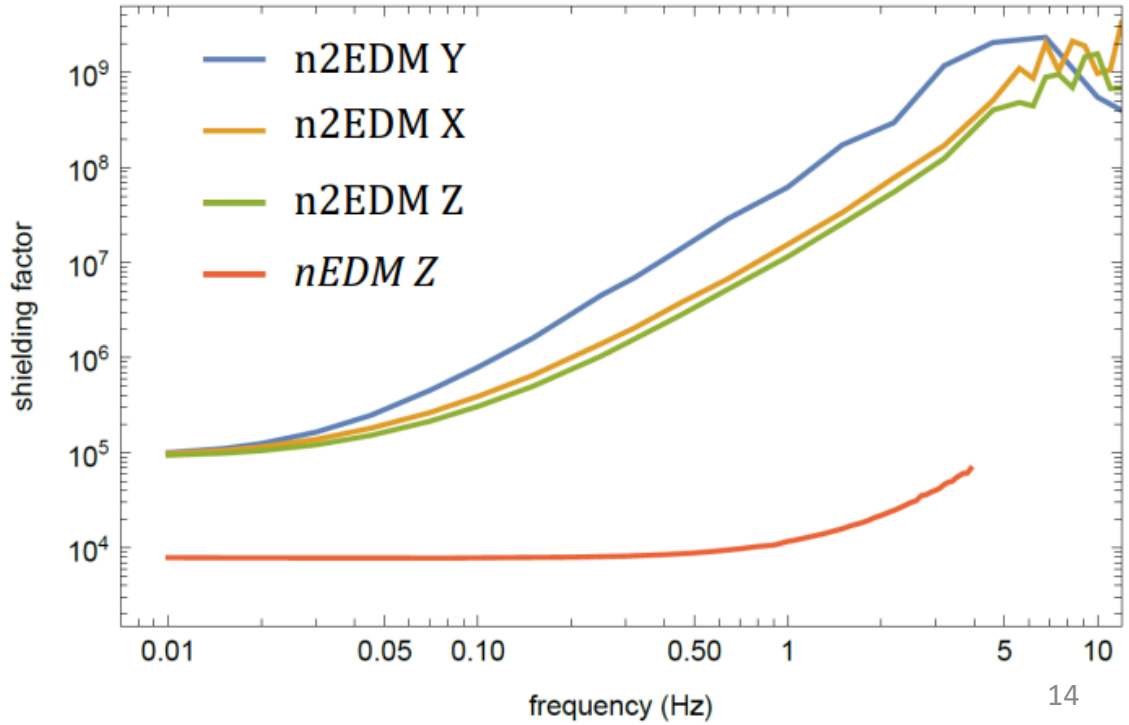
2) Minimizing the magnetic field related systematics:

- **Mercury co-magnetometry** to compensate field fluctuations: measure $\mathcal{R} = f_n/f_{Hg}$ instead of f_n.
- **Active Magnetic Shield (AMS)** to cancel external fields.
- **Magnetic Shielding Room (MSR)** to suppress non-uniformities.

2020: commissioning of the Magnetic Shielding Room



- 6 layer of mumetal around a $25\mathrm{m}^3$ volume.
- 10^5 shielding factor at low frequency.
- Equipped with degaussing coils to reach residual field $< 100\ p\mathrm{T}$



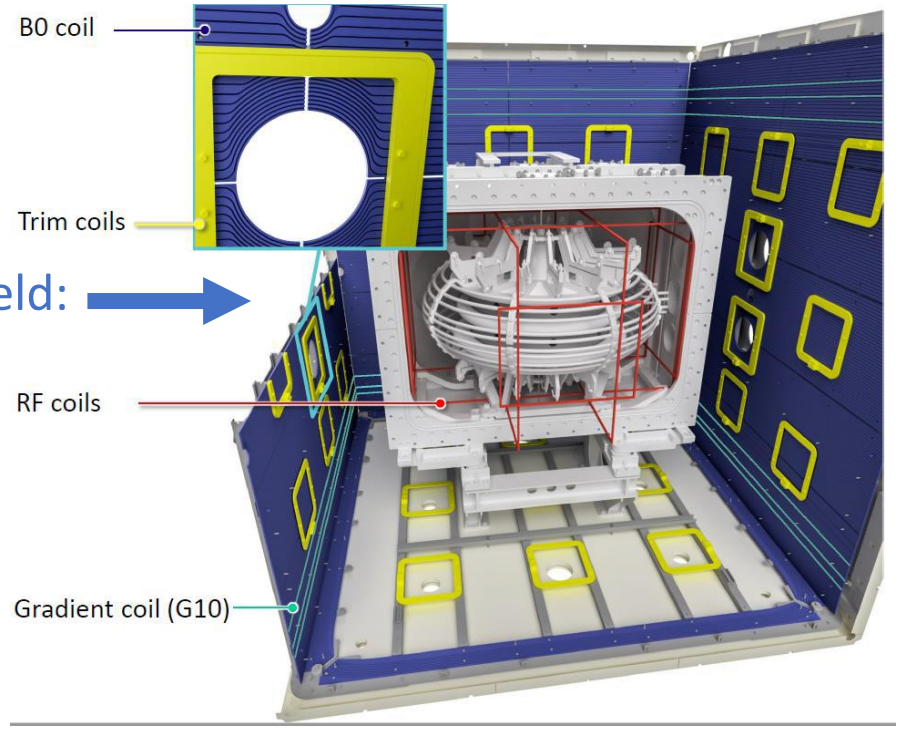
The very large n2EDM magnetically shielded room with an exceptional performance for fundamental physics measurements, Ayres et al, Review of Scientific Instruments (2022).

2022: commissioning of the B_0 field

Coil system to produce uniform field:

- 1 main B_0 coil .
- 62 correcting coils.

.



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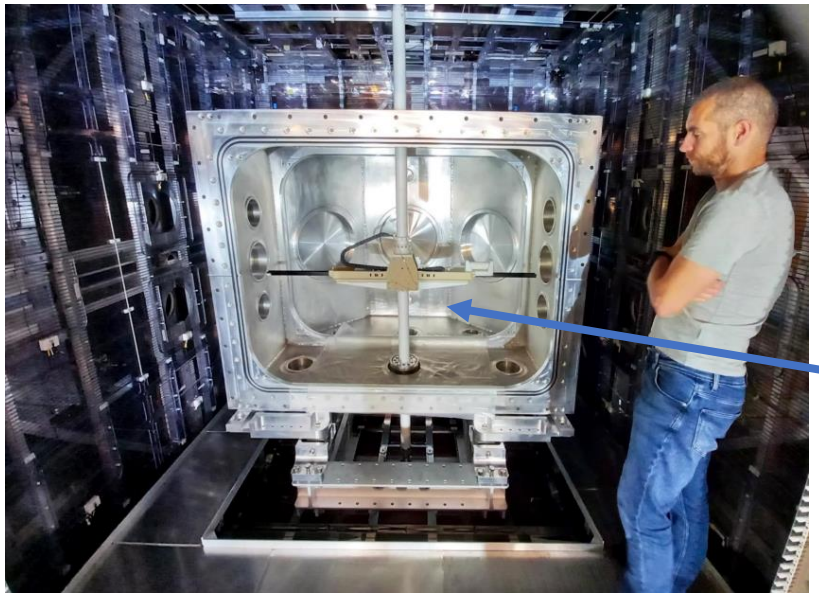

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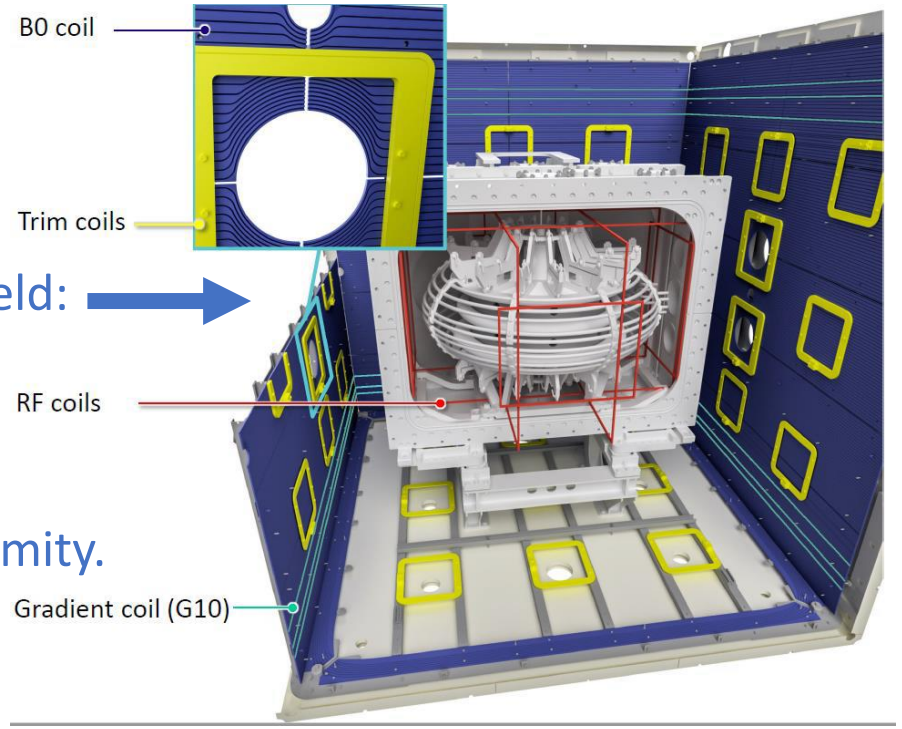
Robotic **“mapper”** to check uniformity.



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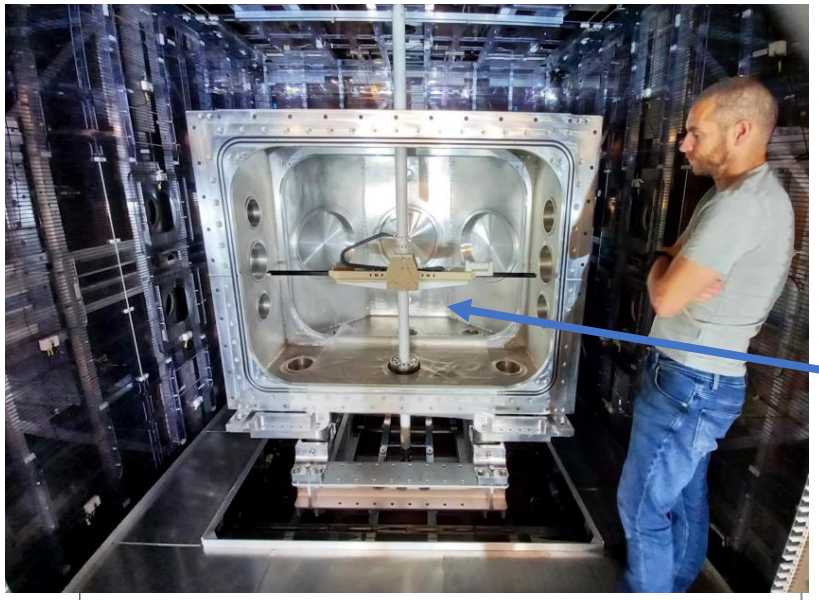

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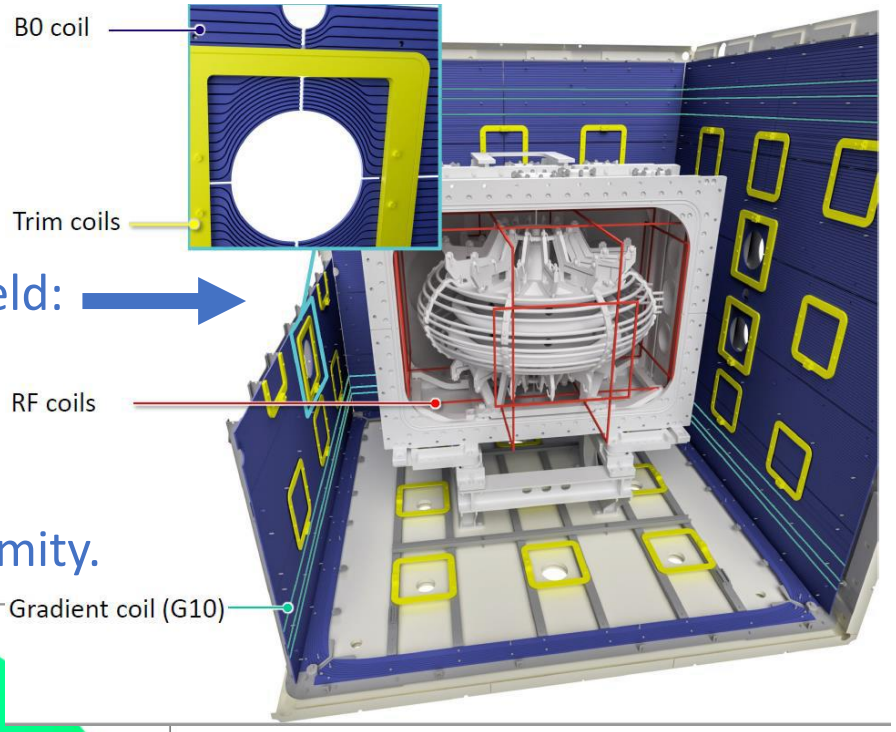
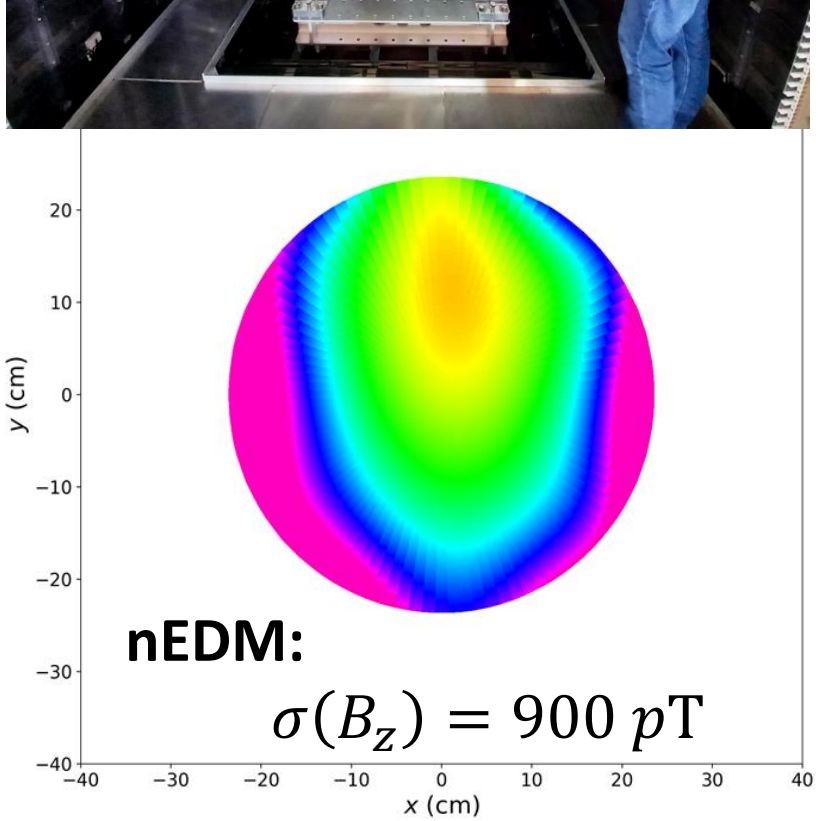
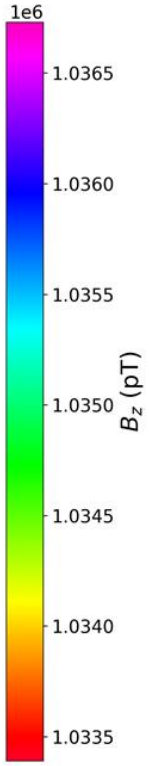
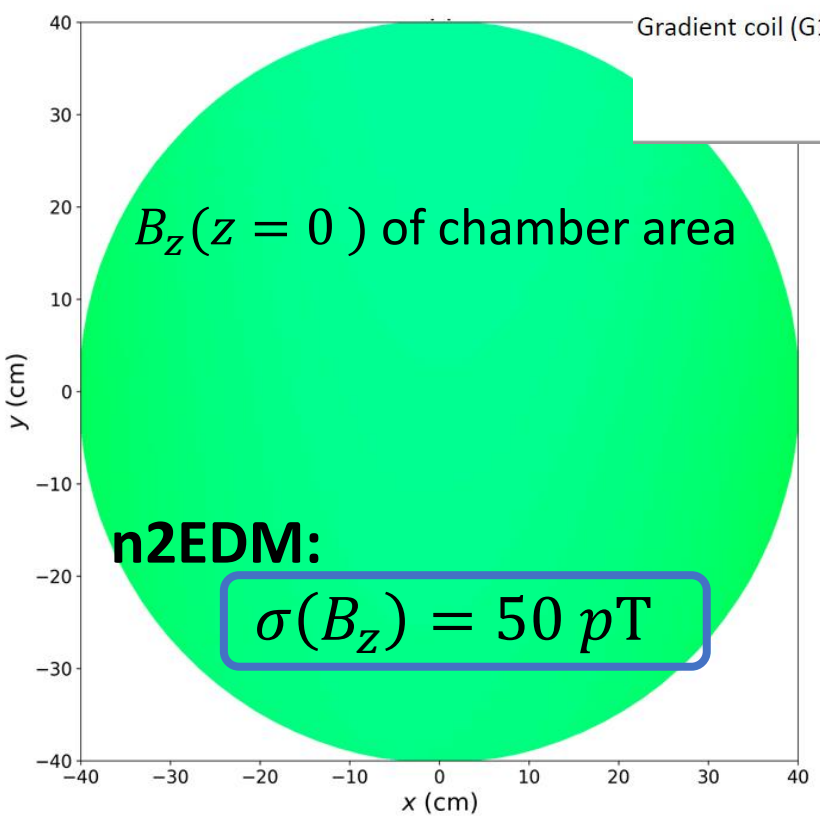




nEDM:

$$\sigma(B_z) = 900\ p\mathrm{T}$$





$B_z(z = 0)$ of chamber area

n2EDM:

$$\sigma(B_z) = 50\ p\mathrm{T}$$

- ✓ **Record field uniformity.**
- ✓ **Satisfies systematical requirements to reach $10^{-27} e.\mathrm{cm}$ sensitivity!**

Conclusion and future prospects

n2EDM@PSI aims to reach unprecedented sensitivity on the neutron EDM thanks to:

- Efficient UCN production/transport and large storage volume.
- A remarkable control of magnetic field uniformity.

As of 2023:

- ✓ Magnetic shielding apparatus fully commissioned.
- ✓ Magnetic field ready for physics measurements.

Future prospects:

- UCNs in precession chambers in 2024.
- Start data taking in 2025.

Backup slides

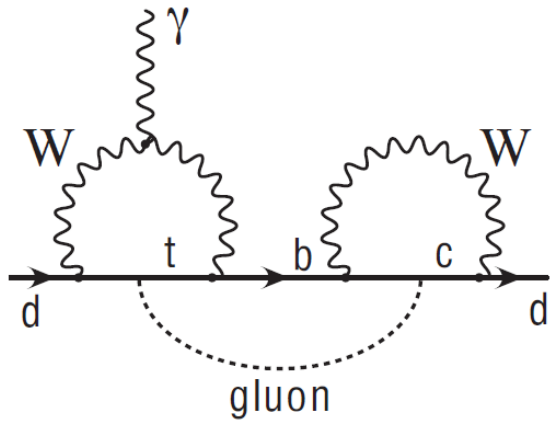
Formally: CP violating term (EM field and quark coupling)

$$\mathcal{L} = \frac{\mu}{2}\bar{f}\sigma_{\mu\nu}f\ F^{\mu\nu} - \frac{id}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f\ F^{\mu\nu} \xrightarrow{CP} \mathcal{L} = \frac{\mu}{2}\bar{f}\sigma_{\mu\nu}f\ F^{\mu\nu} + \frac{id}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f\ F^{\mu\nu}$$

$$H = -\mu\,\boldsymbol{\sigma}\cdot\boldsymbol{B} - d\,\boldsymbol{\sigma}\cdot\boldsymbol{E} \qquad H = -\mu\,\boldsymbol{\sigma}\cdot\boldsymbol{B} + d\,\boldsymbol{\sigma}\cdot\boldsymbol{E}$$

<u>In the Standard Model:</u> ☹

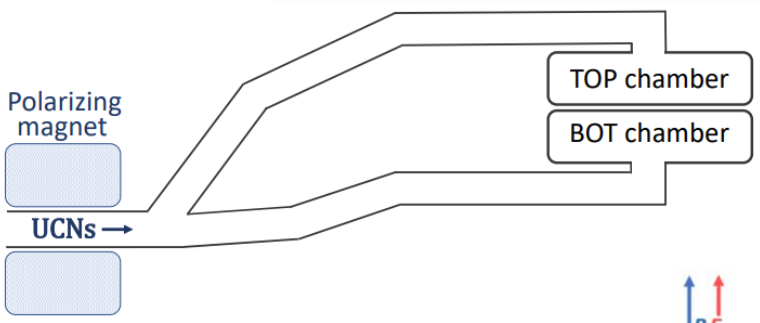
- CKM phase contribution to quark EDMs through at least 3 loops diagrams → very negligible ($d_n \sim 10^{-32} e.\mathrm{cm}$).
- QCD contribution $\frac{\alpha}{8\pi}\bar{\theta}\,G^{\mu\nu}\widetilde{G_{\mu\nu}}$ should generate huge EDMs ($d_n \sim 10^{-16} e.\mathrm{cm}$). : **current limit $\boldsymbol{d_n < 10^{-26} e.cm} \Rightarrow \bar{\theta} < 10^{-10}$**(strong CP problem).



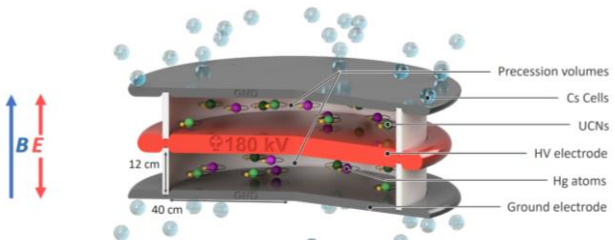
<u>Beyond the SM:</u>

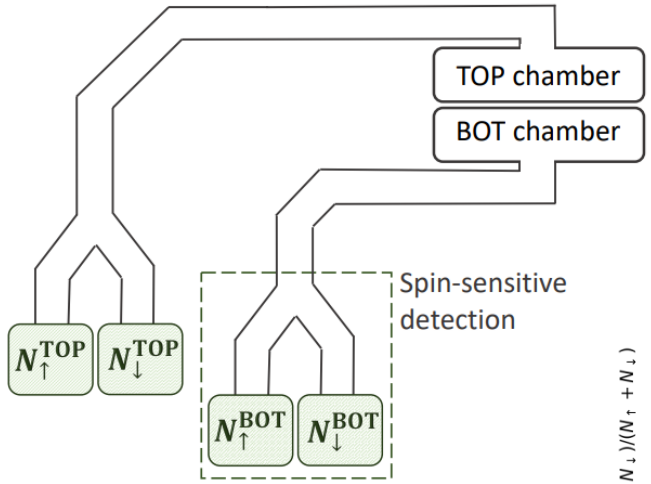
- (ex) modified Higgs-fermion Yukawa coupling $\mathcal{L} = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f\ \bar{f}\gamma_5 f h\right)$ generates EDM at 2 loops.

Counting spins with the Ramsey method

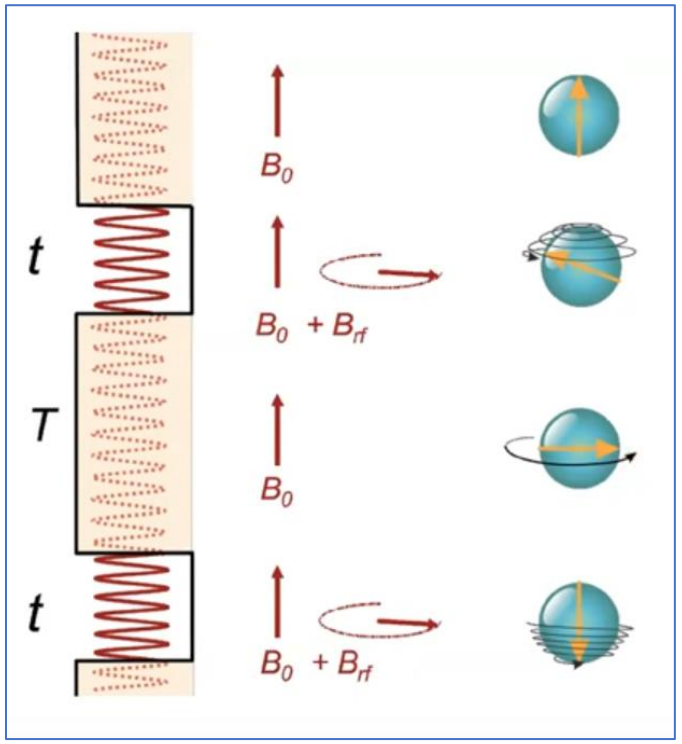


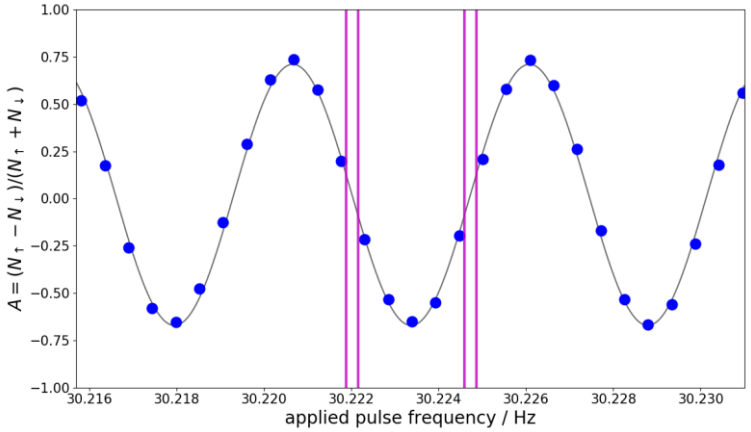
(a) Polarized UCNs fill the precession chambers





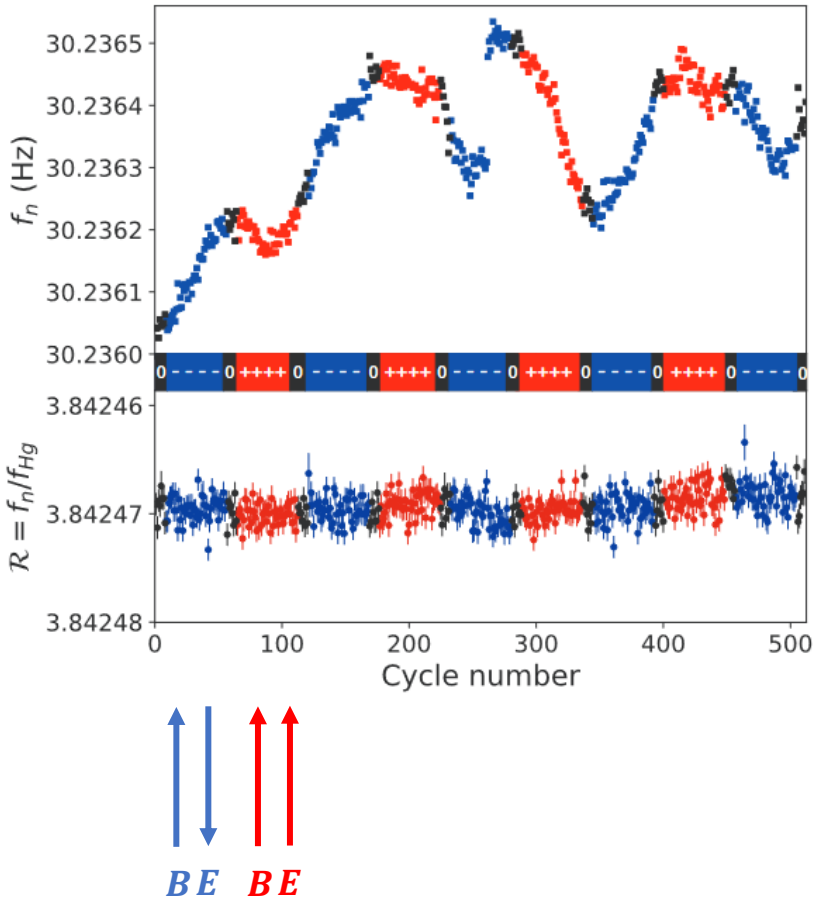
(b) UCNs are guided towards the spin-sensitive detectors.





Up-down spin asymmetry A → precession frequency f_n

Hg co-magnetometry to compensate magnetic field fluctuations



Problem:
Uncertainty on f dominated by magnetic field fluctuations!

Solution:
Measure instead the ratio of mercury and neutron frequencies:

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

Contribution from EDM

$$f_n = \left|\frac{\gamma_n}{2\pi}\right| B_0 \mp \frac{d_n}{\pi\hbar}|E|$$

No contribution from EDM!

$$f_{Hg} = \left|\frac{\gamma_{Hg}}{2\pi}\right| B_0$$

…which is free from the magnetic field fluctuations!

How do we parametrize the magnetic field?

Polynomial field expansion

$$\boldsymbol{B}(\boldsymbol{r}) = \sum_{l=0}^{+\infty} \sum_{m=-l}^{l} G_{lm} \boldsymbol{\Pi}_{\boldsymbol{lm}}(\boldsymbol{r})$$

Maxwell's equations

$\boldsymbol{\nabla} \cdot \boldsymbol{B} = 0$ and $\boldsymbol{\nabla} \times \boldsymbol{B} = \boldsymbol{0}$

$$\boldsymbol{B}(\boldsymbol{r}) = \boldsymbol{\nabla}\Sigma(\boldsymbol{r})$$

with

$$\Delta\Sigma(r, \varphi, \theta) = 0$$

Laplace equation in spherical coordinates

Harmonic modes $\boldsymbol{\Pi}_{\boldsymbol{lm}}(\boldsymbol{r})$ deduced from solutions of Laplace equation

TABLE IV. The basis of harmonic polynomials sorted by degree in cylindrical coordinates.

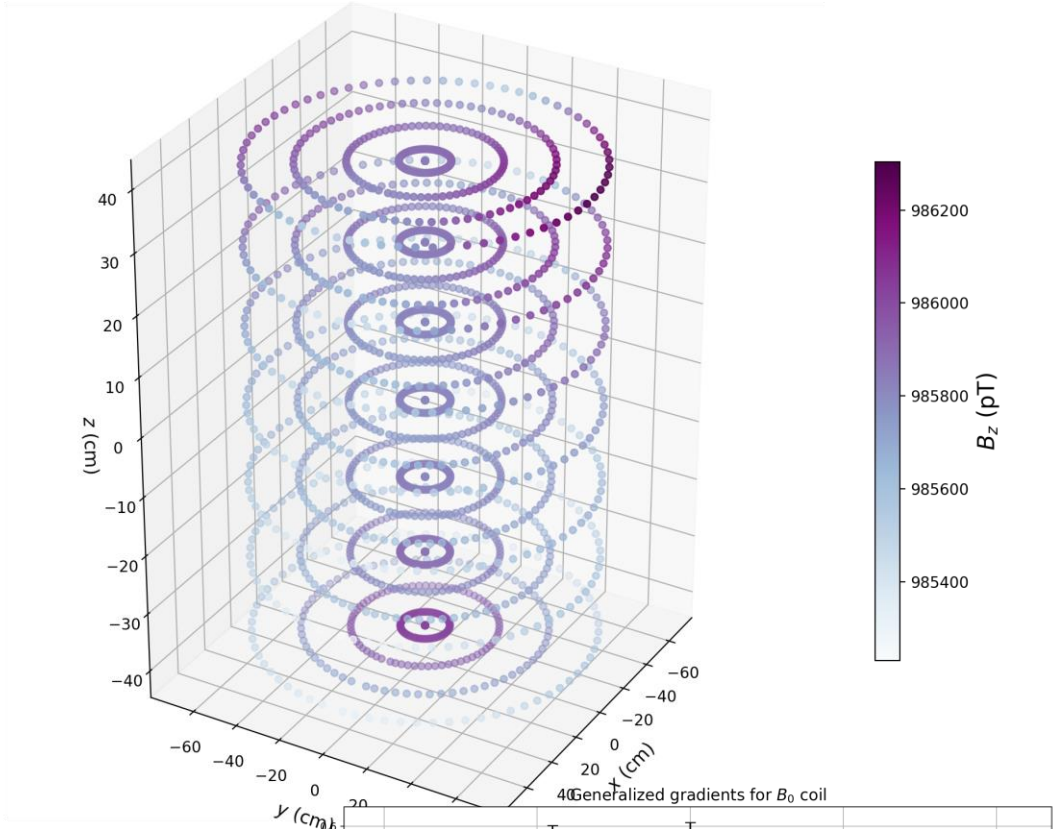
l	m	Π_ρ	Π_ϕ	Π_z
0	−1	$\sin\phi$	$\cos\phi$	0
0	0	0	0	1
0	1	$\cos\phi$	$-\sin\phi$	0
1	−2	$\rho\sin 2\phi$	$\rho\cos 2\phi$	0
1	−1	$z\sin\phi$	$z\cos\phi$	$\rho\sin\phi$
1	0	$-\frac{1}{2}\rho$	0	z
1	1	$z\cos\phi$	$-z\sin\phi$	$\rho\cos\phi$
1	2	$\rho\cos 2\phi$	$-\rho\sin 2\phi$	0
2	−3	$\rho^2\sin 3\phi$	$\rho^2\cos 3\phi$	0
2	−2	$2\rho z\sin 2\phi$	$2\rho z\cos 2\phi$	$\rho^2\sin 2\phi$
2	−1	$\frac{1}{4}(4z^2-3\rho^2)\sin\phi$	$\frac{1}{4}(4z^2-\rho^2)\cos\phi$	$2\rho z\sin\phi$
2	0	$-\rho z$	0	$-\frac{1}{2}\rho^2+z^2$
2	1	$\frac{1}{4}(4z^2-3\rho^2)\cos\phi$	$\frac{1}{4}(\rho^2-4z^2)\sin\phi$	$2\rho z\cos\phi$
2	2	$2\rho z\cos 2\phi$	$-2\rho z\sin 2\phi$	$\rho^2\cos 2\phi$
2	3	$\rho^2\cos 3\phi$	$-\rho^2\sin 3\phi$	0

So what do we measure? The *generalized gradients* G_{lm} :

- "Online" with mercury co-magnetometry and cesium magnetometers.
- "Offline" with the mapper.

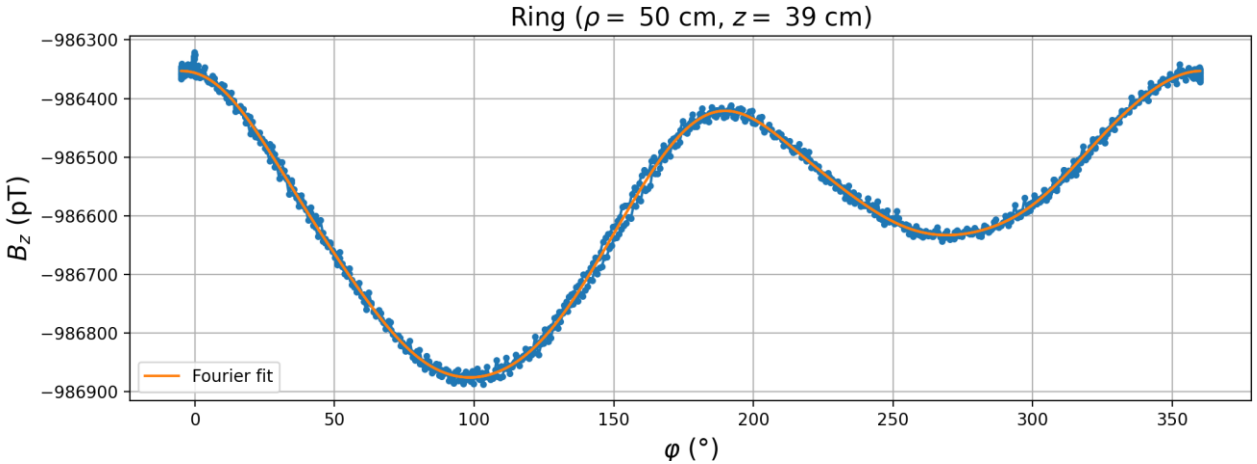
Reminder: extraction of the harmonic spectrum

1) Do cylindrical map $B_z(\rho, \varphi, z)$



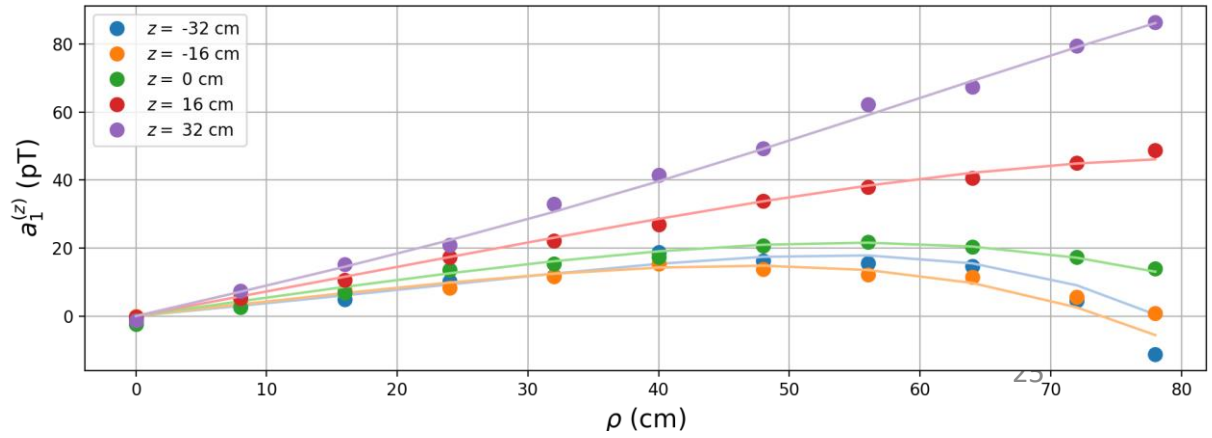
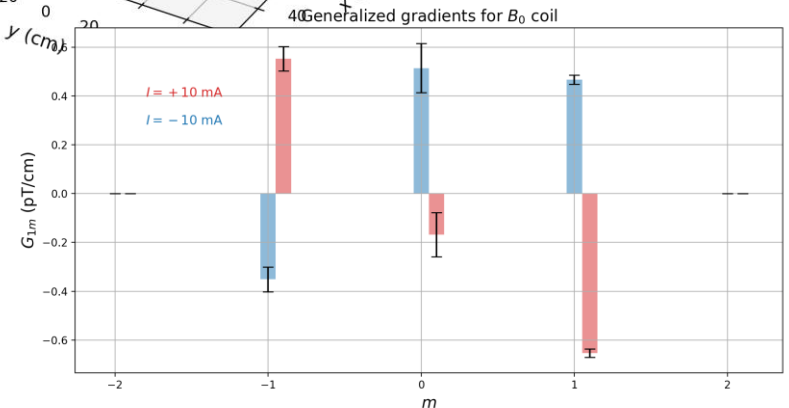
2) Fit rings with fourier series:

$$B_z(\rho, \varphi, z) = \sum_{m \geq 0} a_m^{(z)}(\rho, z)\cos(m\varphi) + b_m^{(z)}(\rho, z)\sin(m\varphi)$$



3) Fit fourier coefficients with harmonic polynomial:

$$a_m^{(z)}(\rho, z) = \sum_{l \geq 0} G_{lm}\widehat{\Pi}_{lm}(\rho, z)$$



4) Get G_{lm} spectrum