ETH zürich

n2EDM

The n2EDM experiment

Patrick Mullan

on behalf of the nEDM collaboration at Paul Scherrer Institut

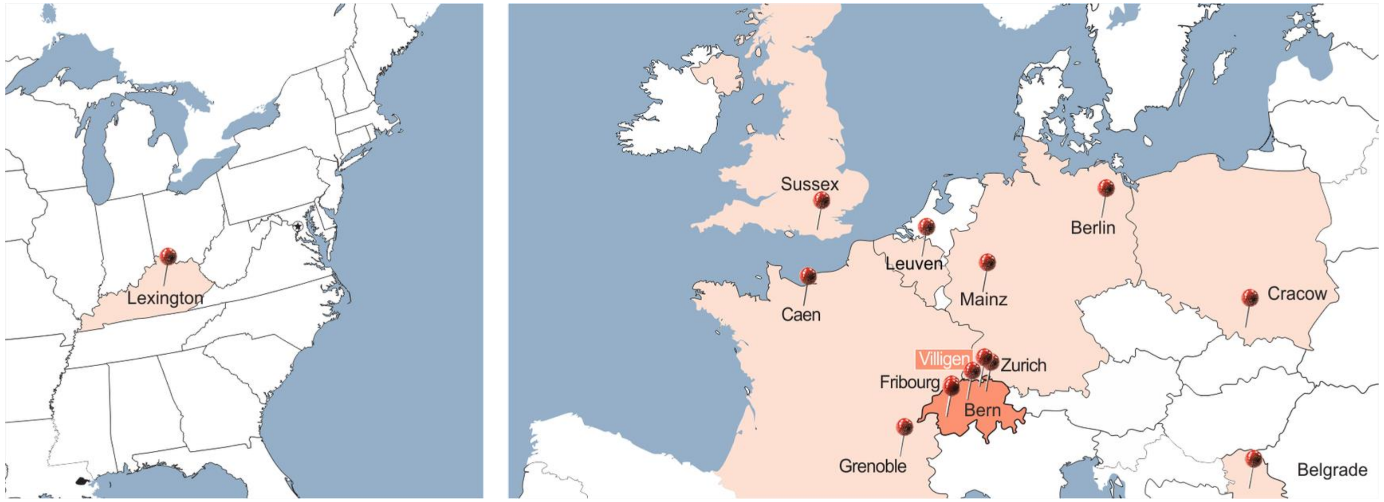
ECT* Workshop | EDMs, Trento

Who are we?

Second generation neutron EDM experiment with experience of previously successful measurement

PSI: $d_n < 1.8 \times 10^{-26} e\ cm\ (90\%\ C.L.)$

Standard Model expectation: $10^{-32} e\ cm$



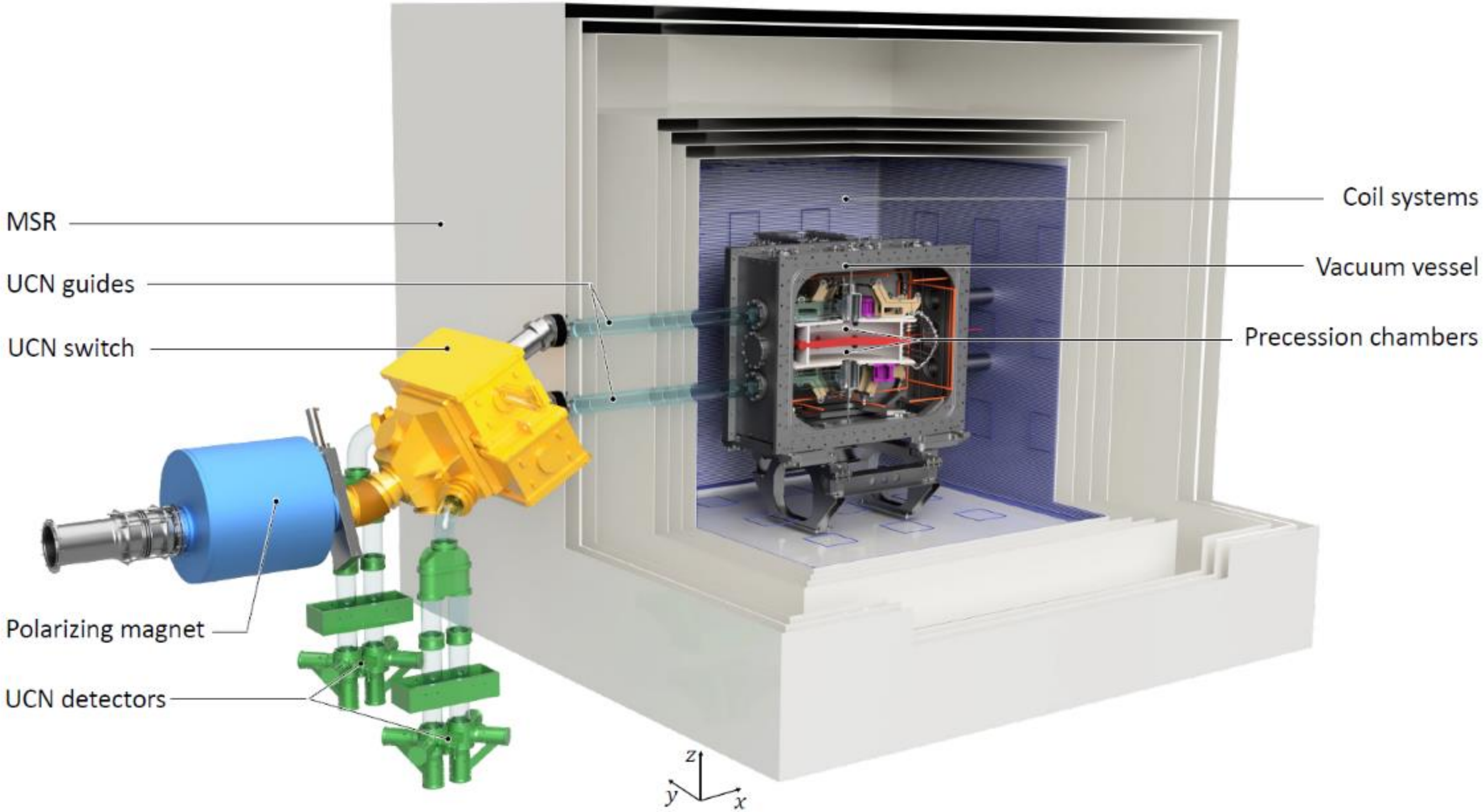
Ultra cold neutron source and n2EDM

Phase 1 n2EDM target sensitivity $d_n \approx 10^{-27} e\ cm$

- ***Improved neutron statistics:*** *larger neutron storage volume, improved source, etc.*
- ***Improved systematics:*** *Better magnetometry and magnetic field control*

[PSI nEDM limit] doi:10.1103/PhysRevLett.124.081803 (2020)

This is the n2EDM apparatus



How to observe a neutron EDM

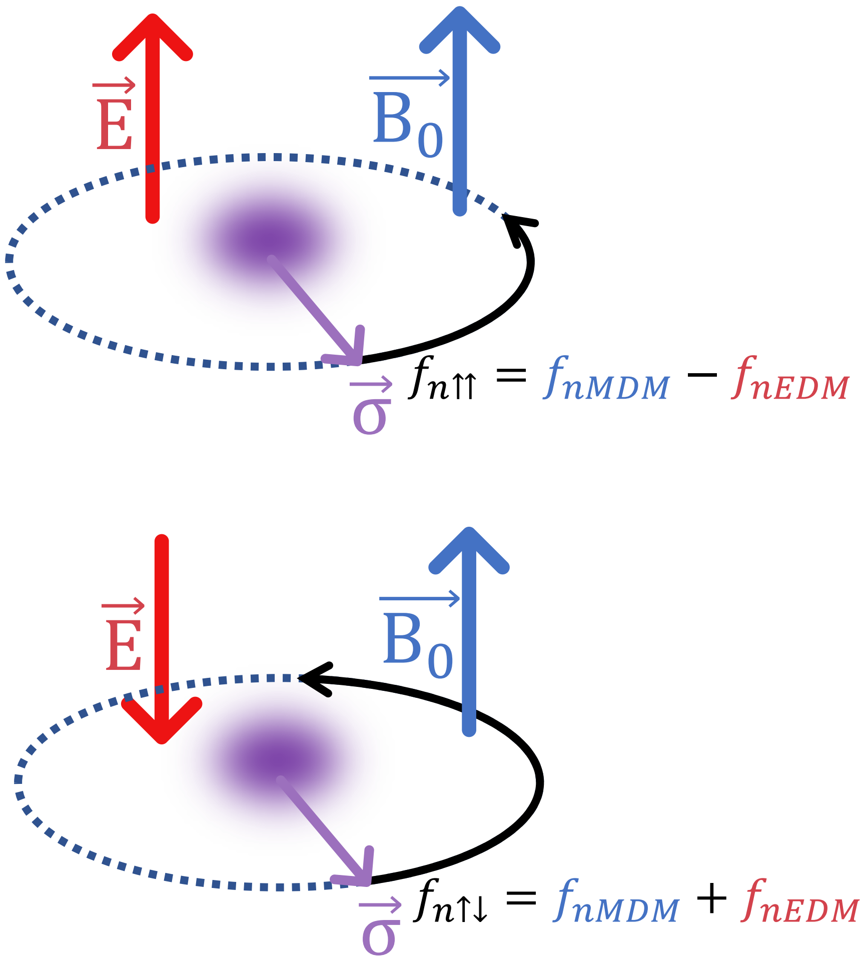
Compare precession frequencies of ↿↾ and ↑↓:

$$d_n = \frac{\pi\hbar}{2\left|\vec{E}\right|}\left(f_{n\uparrow\downarrow} - f_{n\upuparrows}\right)$$

- *Measure simultaneously in different volumes*
- *Measure in the same volume, but at a different time*

Problem: magnetic field varies in time and space

$$f_{n\uparrow\downarrow} \coloneqq f_{n\uparrow\downarrow}\left(\left|\vec{B_0}\right|\right) \text{ and } f_{n\upuparrows} \coloneqq f_{n\upuparrows}\left(\left|\vec{B_0}\right|\right)$$



How to observe a neutron EDM

Compare precession frequencies of ⇈ and ↑↓:

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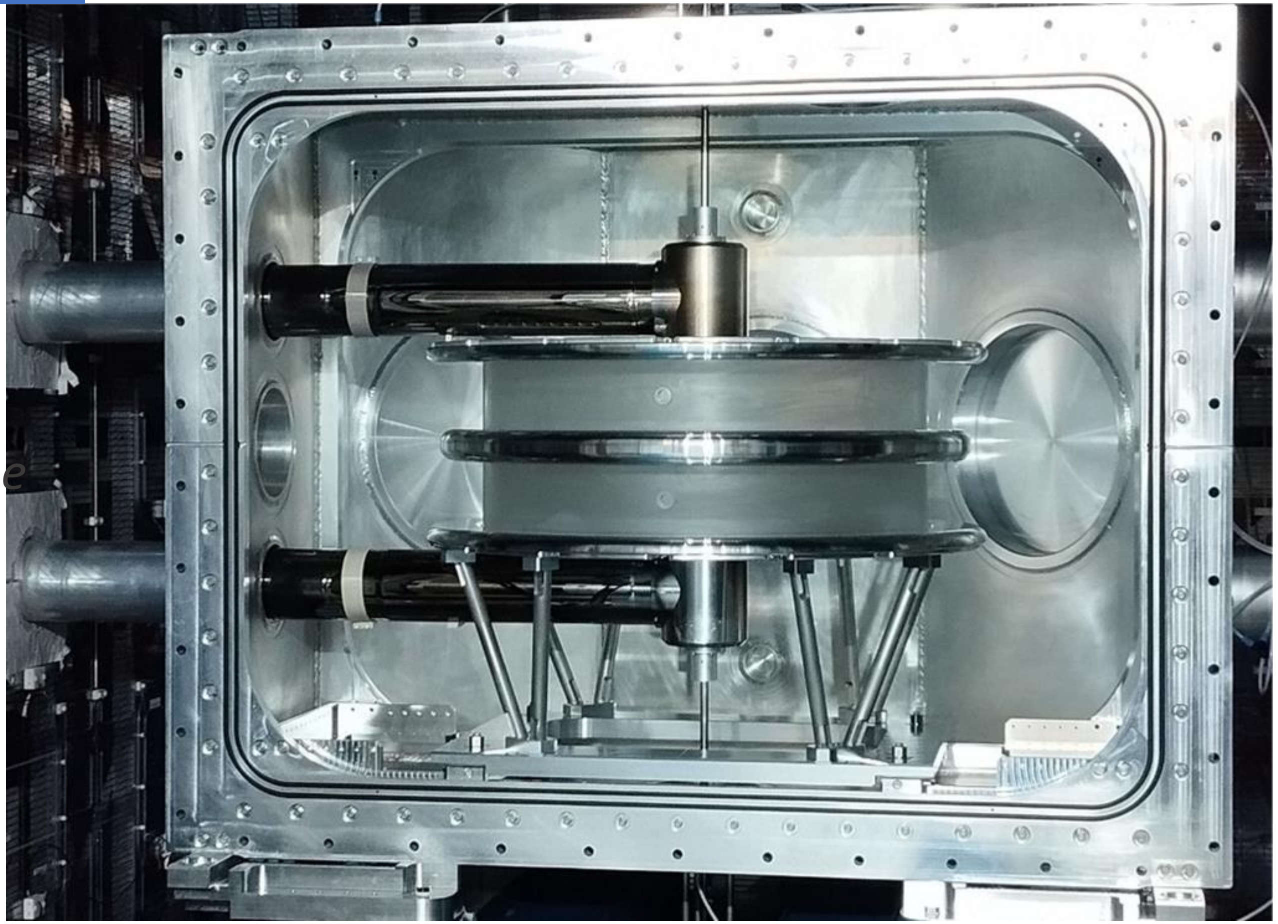

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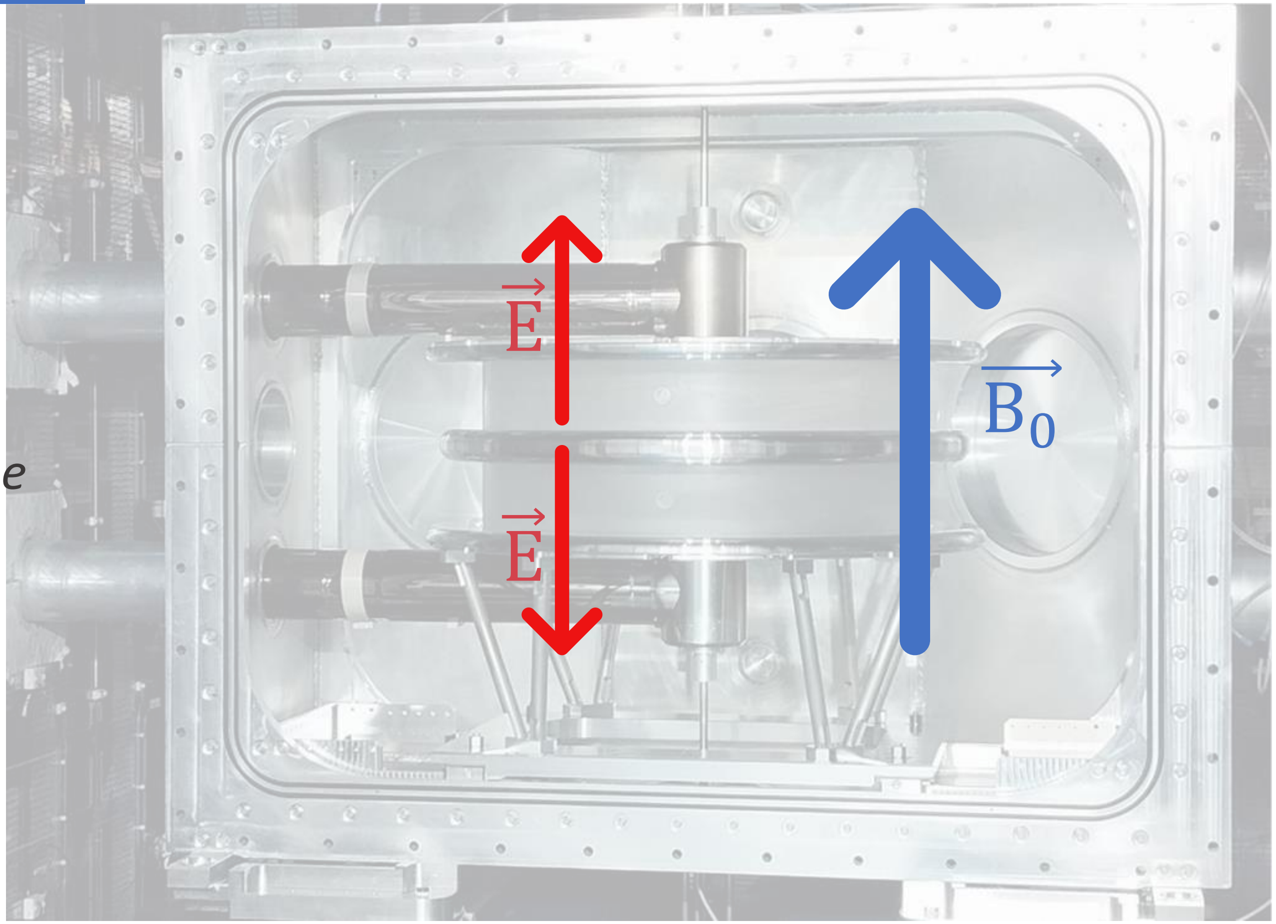

How to observe a neutron EDM

Compare precession frequencies of ↑↑ and ↑↓:

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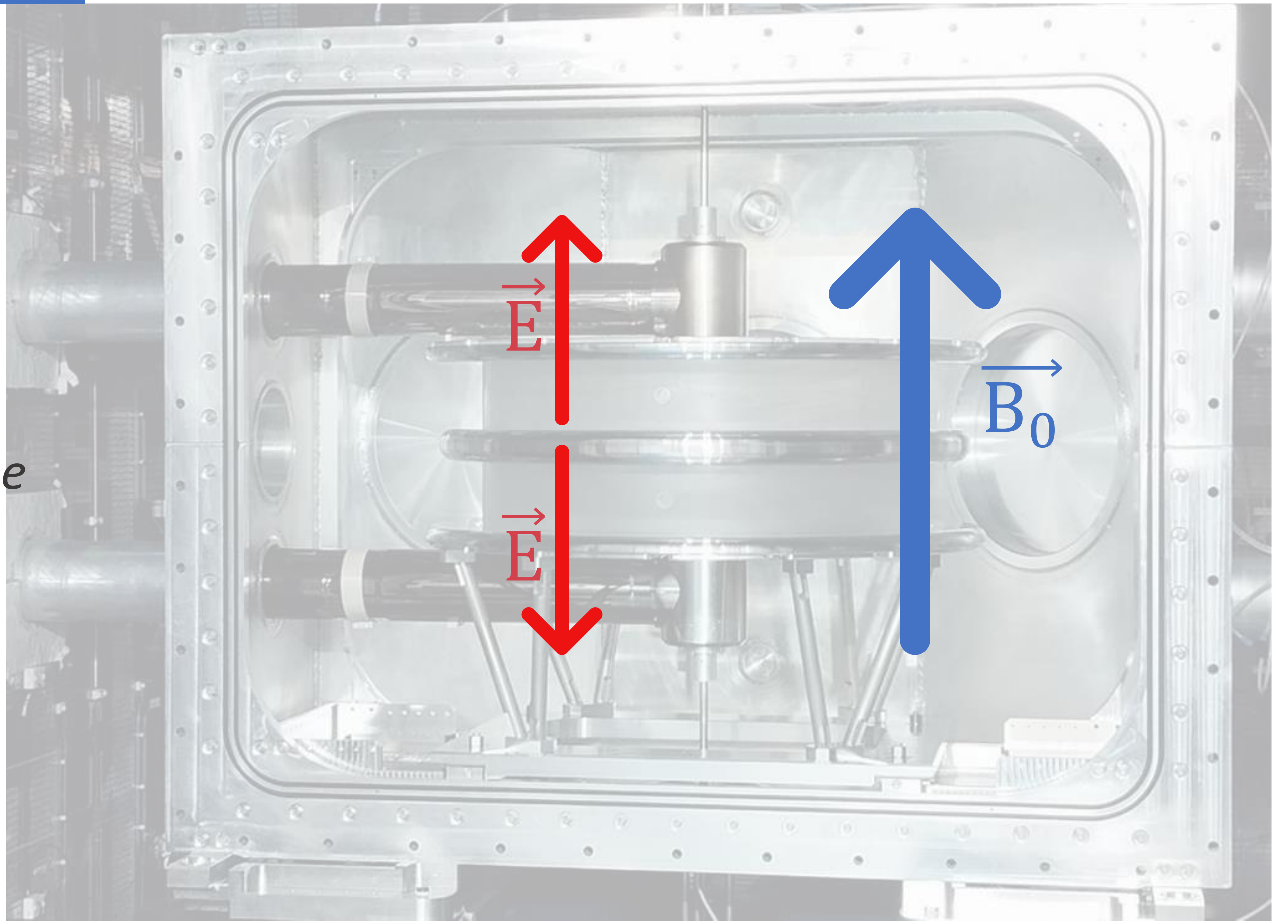

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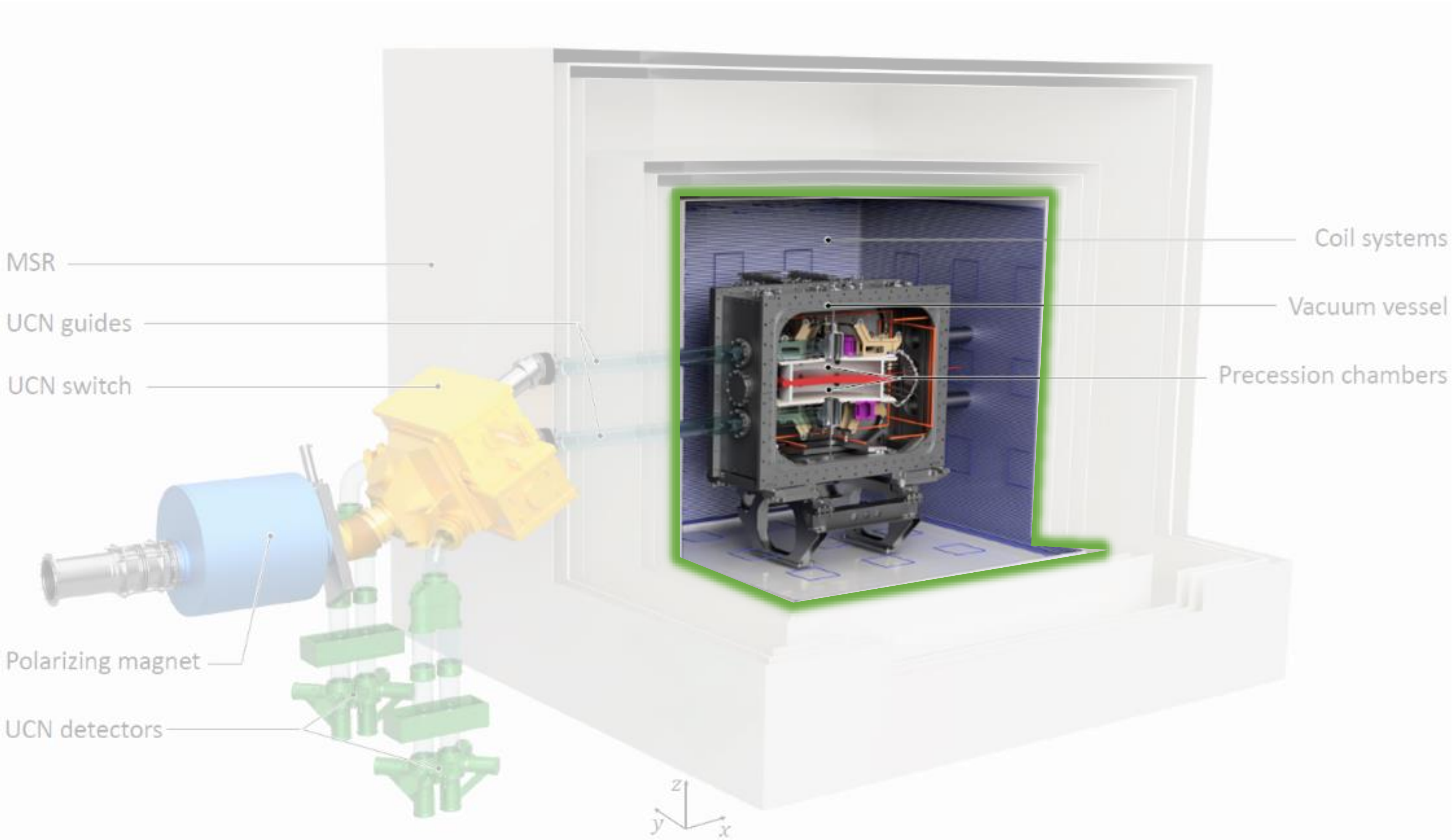
Solution:

- *Create a stable and ideal homogeneous field*
- *Measure the magnetic field very precisely*

Let’s focus on the neutron storage chambers

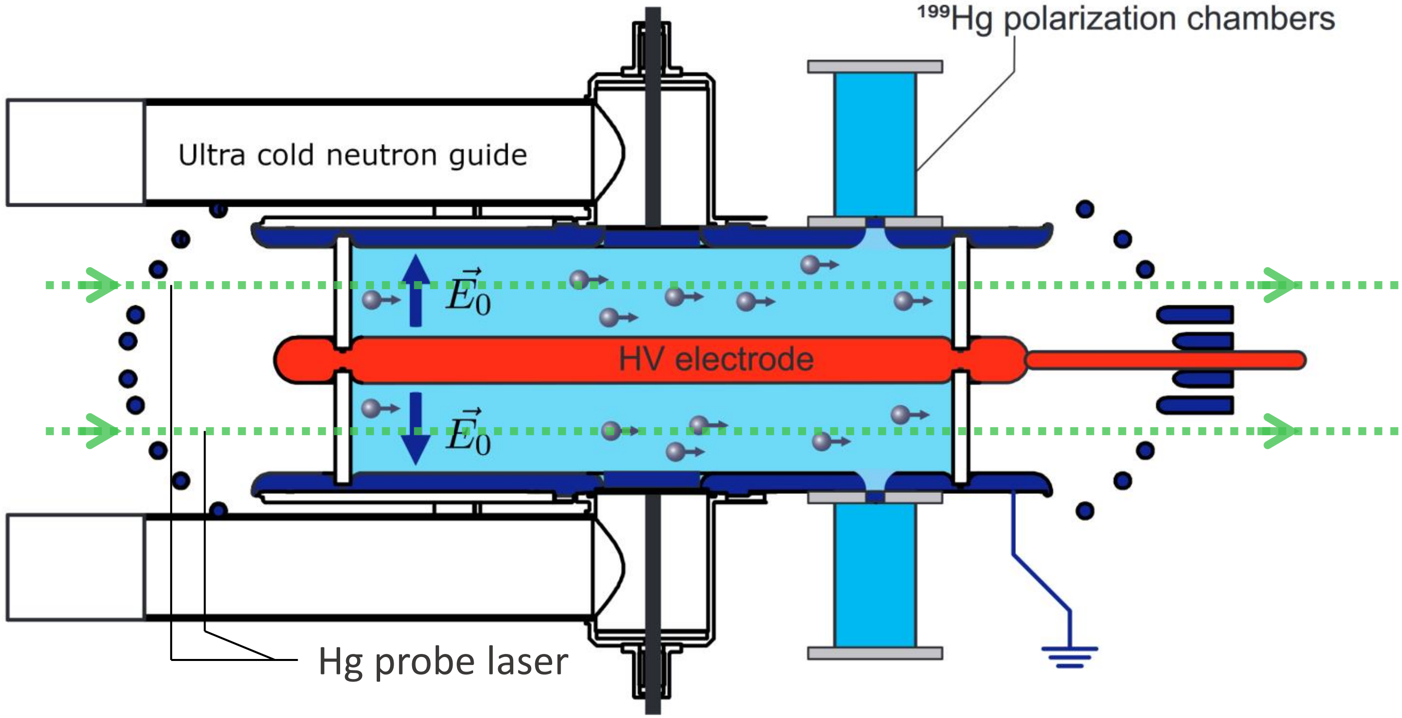


How is the magnetic field inside the precession chambers measured?

Mercury, Hg, comagnetometer

- *Polarised mercury vapour leaked into the precession chamber*
- *Apply a $\pi/2$ pulse*
- *Probe free precession*

$$\mathcal{R} = \frac{f_n}{f_{Hg}} = \left|\frac{4\pi\mu_n}{\hbar\gamma_{Hg}}\right| \mp \frac{d_n}{\pi\hbar f_{Hg}}|E|$$



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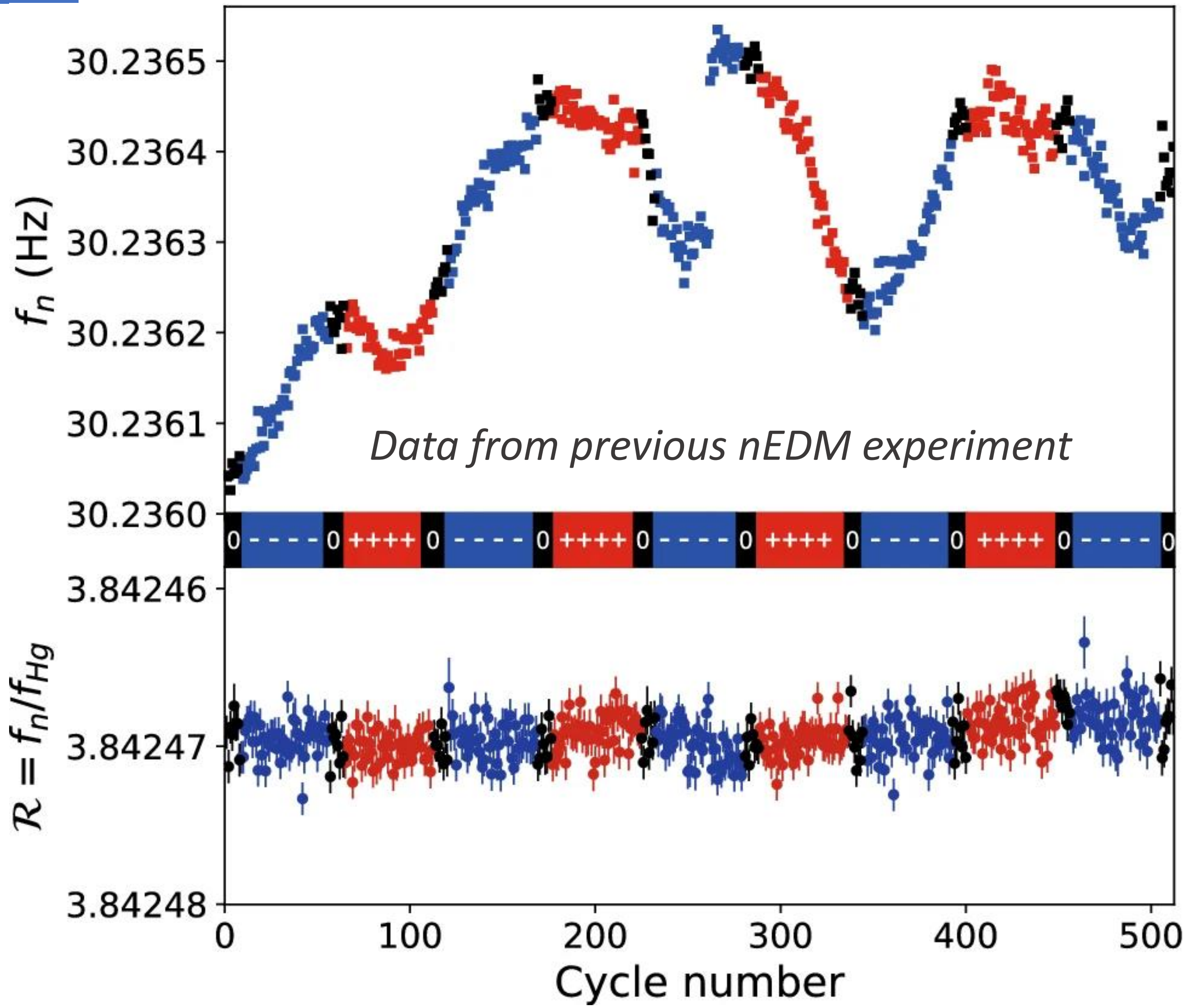

[n2EDM design] doi:10.1140/epjc/s10052-021-09298-z (2021)

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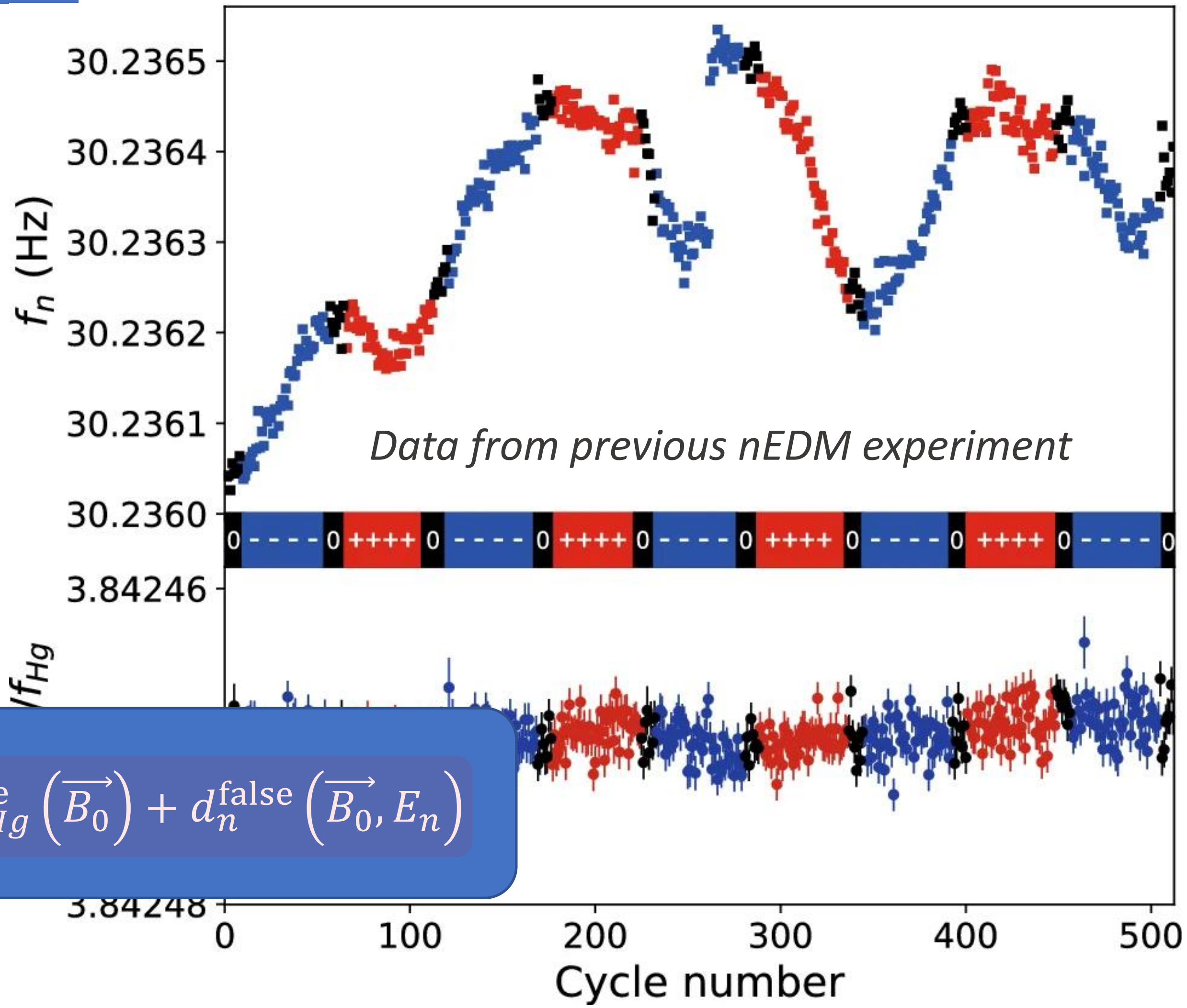
$$d_n = \frac{\pi\hbar f_{Hg}}{2|E|}\left(\mathcal{R}_{\uparrow\downarrow}^{\mathrm{TOP}} - \mathcal{R}_{\uparrow\uparrow}^{\mathrm{TOP}} + \mathcal{R}_{\uparrow\downarrow}^{\mathrm{BOT}} - \mathcal{R}_{\uparrow\uparrow}^{\mathrm{BOT}}\right) + d_{n\leftarrow Hg}^{\mathrm{false}}\left(\overrightarrow{B_0}\right) + d_n^{\mathrm{false}}\left(\overrightarrow{B_0}, E_n\right)$$



[n2EDM design] doi:10.1140/epjc/s10052-021-09298-z (2021)

Mercury comagnetometers only measure average $\left|\overrightarrow{B_0}\right|$ is this enough?

$$d_{n\leftarrow Hg}^{\text{false}}\left(\overrightarrow{B_0}\right) + d_n^{\text{false}}\left(\overrightarrow{B_0}, E_n\right)$$

Phantom modes*:*

$$\langle G_{TB}\rangle_{\text{Hg}} = \left\langle \frac{\left|B_{\text{Hg}}^{\text{TOP}} - B_{\text{Hg}}^{\text{BOT}}\right|}{\text{Height of double chambers}} \right\rangle$$

$$G_{TB} = G_{1,0} - L_3^2 G_{3,0} + L_5^2 G_{5,0} - \cdots$$

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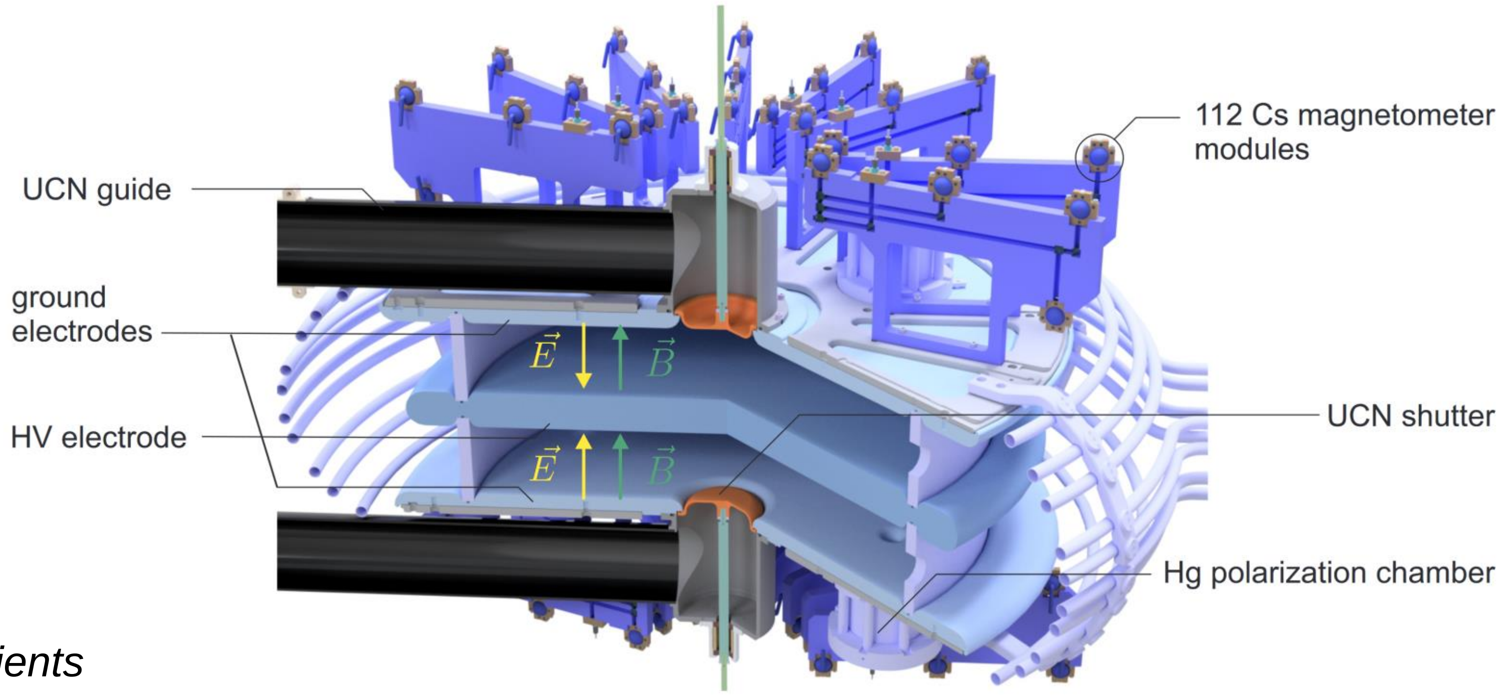


Solution: Caesium magnetometer array

- *Live measurements of up to 3rd order gradients*

[n2EDM design] doi:10.1140/epjc/s10052-021-09298-z (2021)

n2EDM slow magnetic environment

Goal (Top-bottom resonance match condition):

$$-0.6\ \mathrm{pT/cm} < \frac{dB}{dz} < +0.6\ \mathrm{pT/cm}$$

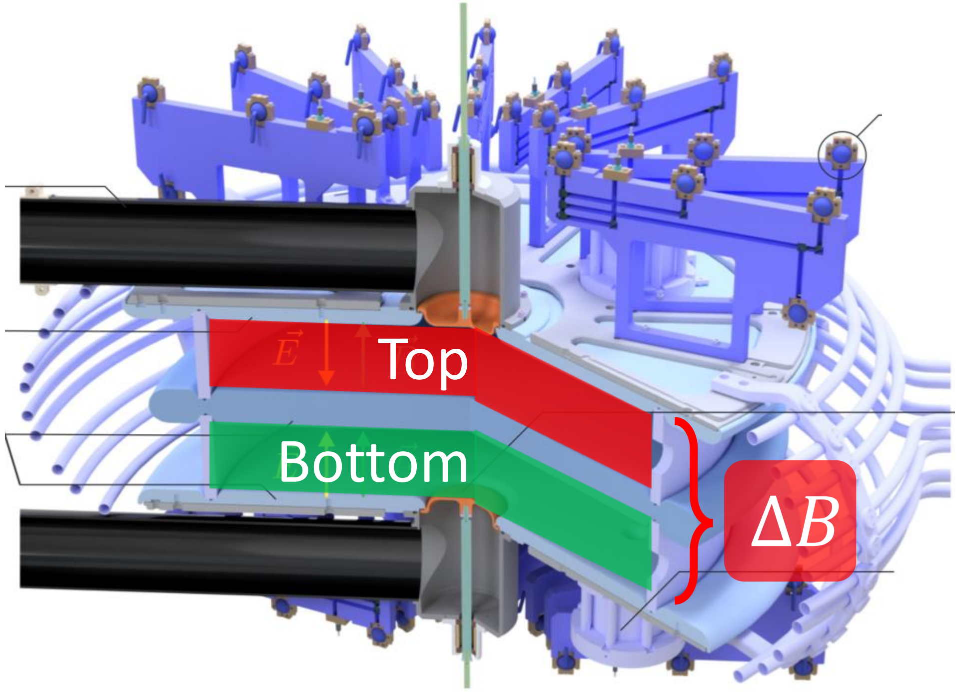
An internal field difference of less than 10 pT over 180 seconds (storage cycle)

Reality:

the Magnetic environment fluctuation $\sim$ 10 μT

Requirement:

A shielding factor of at least 1 million



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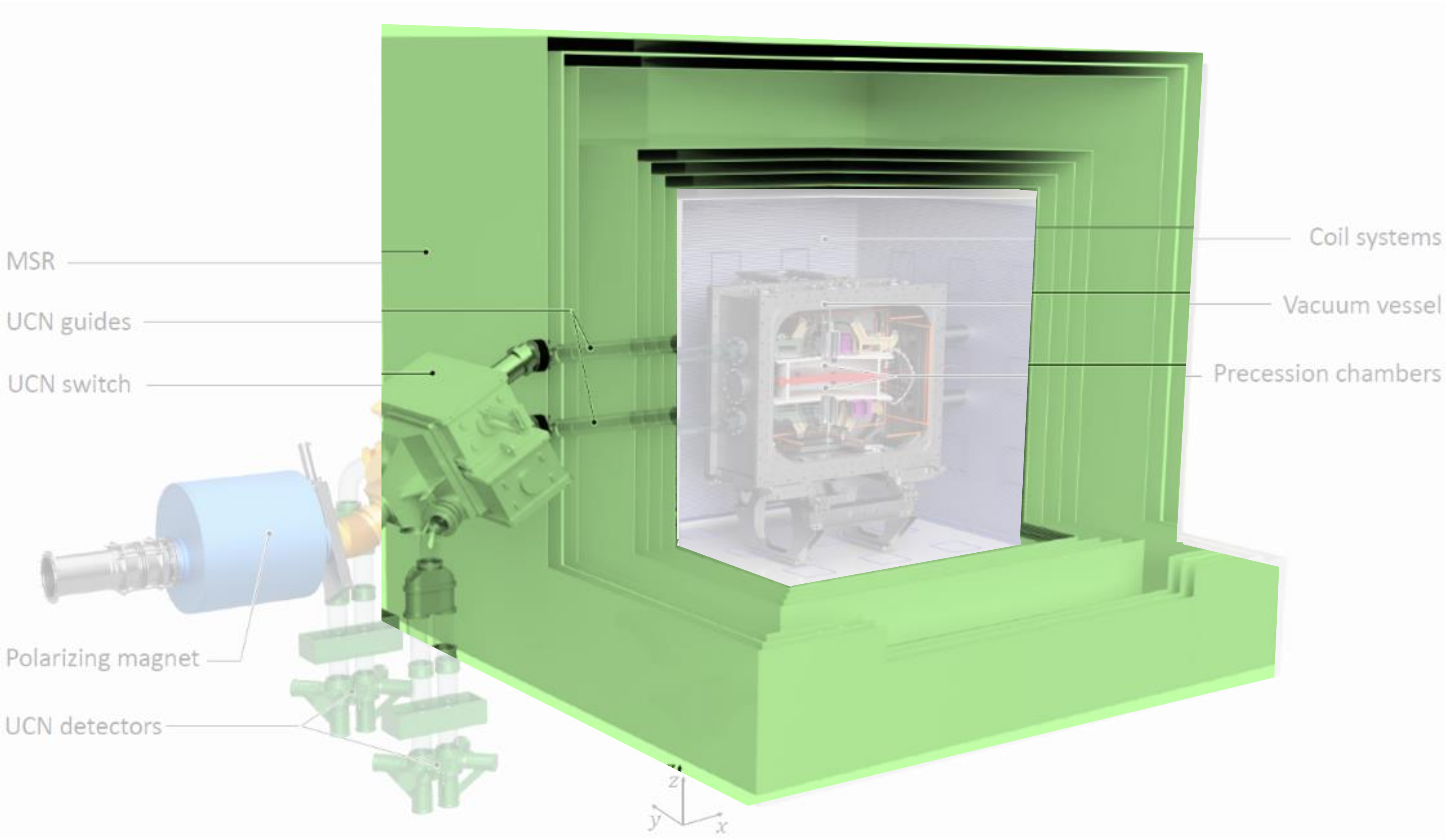
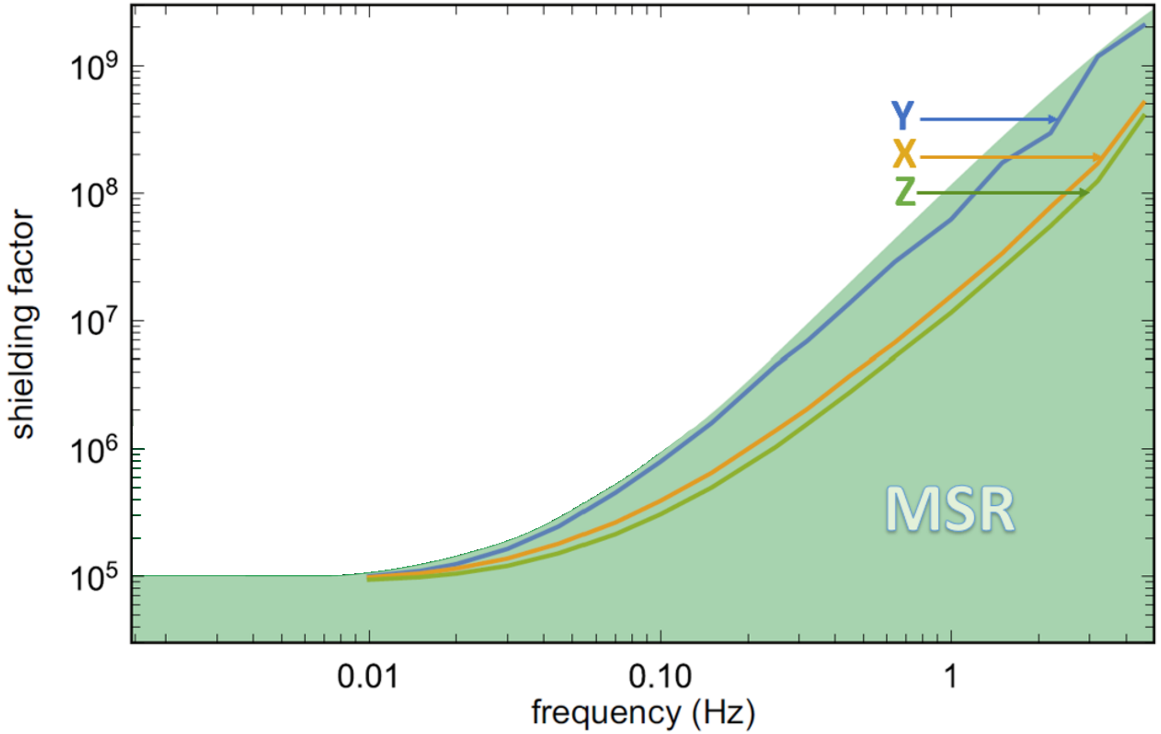
Let’s focus on passive magnetic shielding



How to work within a magnetically noisy environment?

Magnetically shielded room (MSR):

- *Six layers of mu-metal*
- *One Aluminium eddy-current shield + RF shield*
- *Interior volume of* $(2.92\,m)^3$



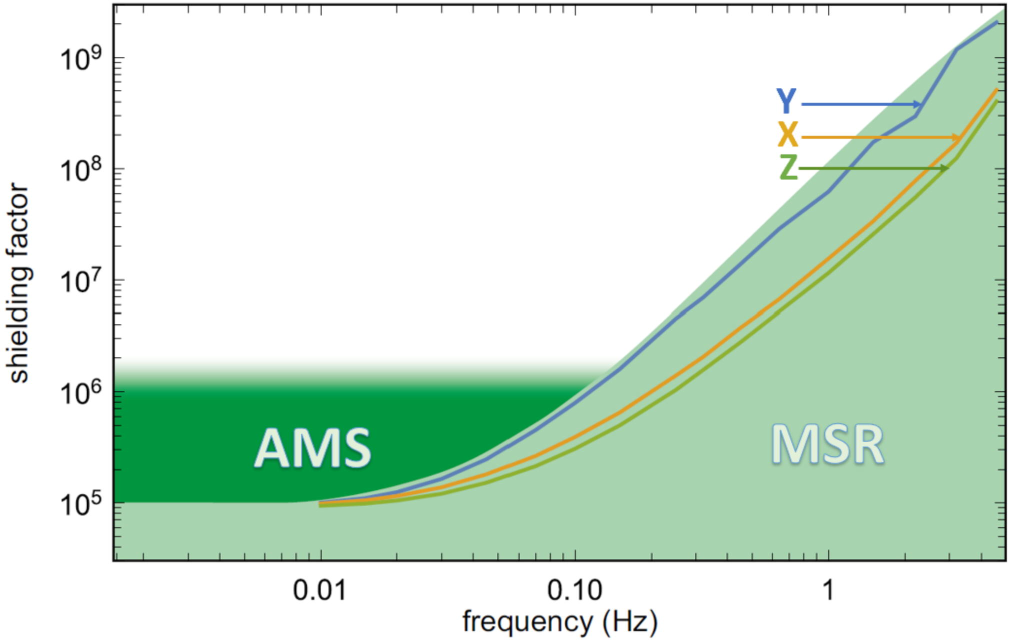
[MSR] doi:10.1063/5.0101391 (2022)

Let’s focus on active magnetic shielding

How to work with low frequency magnetic noise?

Active magnetic shield (AMS):

- *Over 300 rectangular tiles*
- *55 km of wire*
- *Homogenous coils range: +/- 50 µT*
- *Gradient Coils range: +/- 5 µT/m*



[AMS] doi:10.1140/epjc/s10052-023-12225-z (2023)

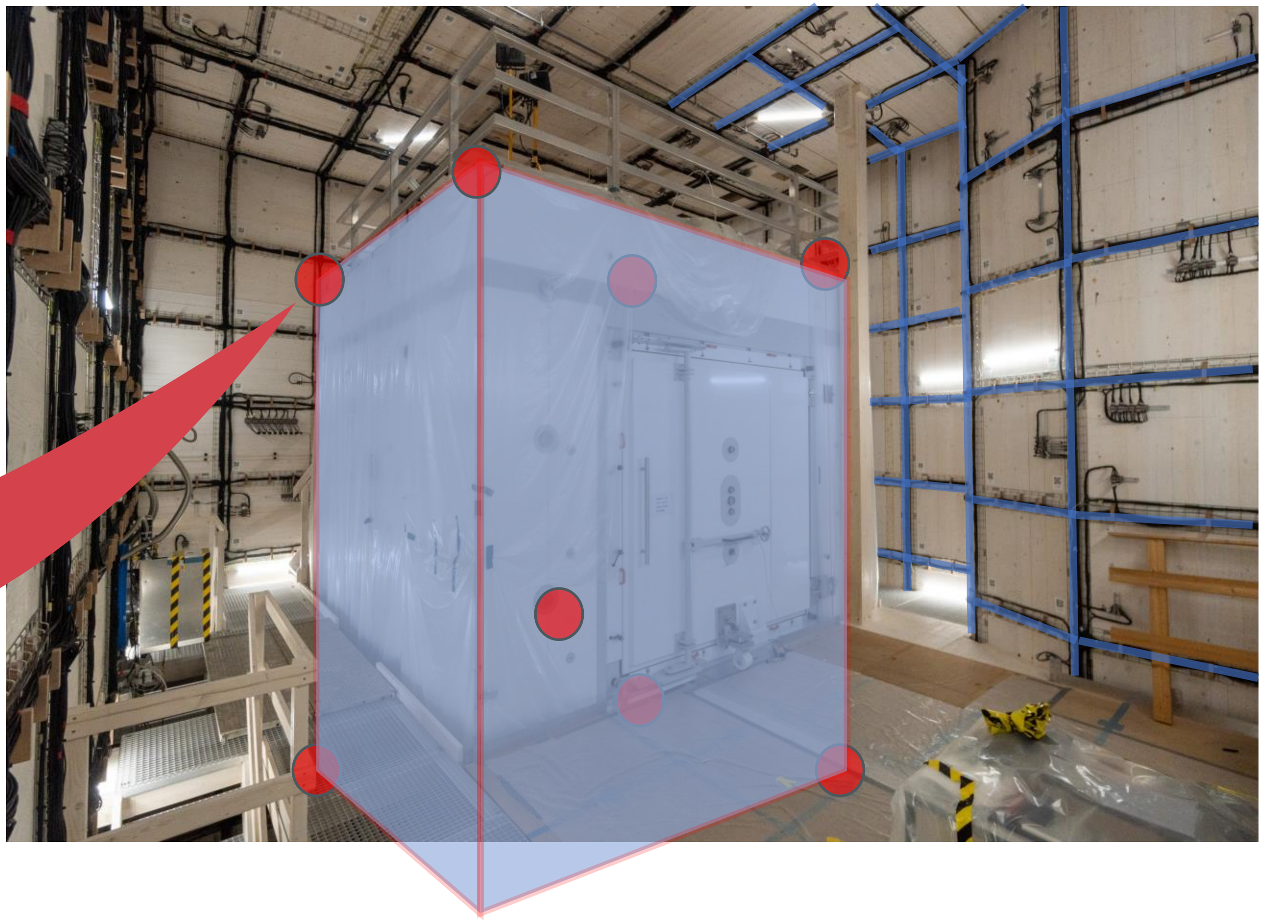
How to work with low frequency magnetic noise?

8 Fluxgate (3 axis magnetic sensors) placed near corners of MSR

Control hardware introduced and commissioned

Current Source with 3 channels for each coil

Feedback algorithm implemented (Proportional feedback)



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How to work within a magnetically noisy environment?

8 Fluxgate (3 axis magnetic sensors) placed near corners of MSR

Control hardware introduced and commissioned

Current Source with 3 channels for each coil

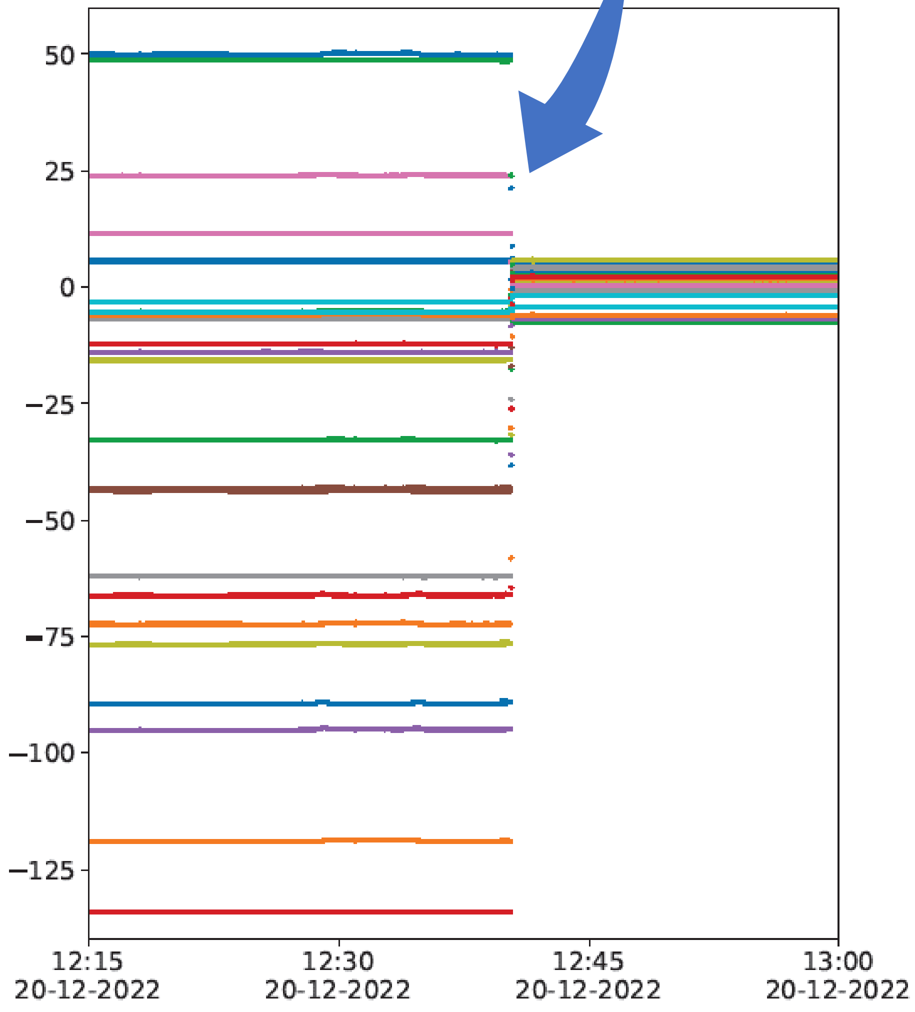
Feedback algorithm implemented (Proportional feedback)

Initial B-field min-max: $\sim 100\ \mu$T

Suppressed B-field min-max: $\sim 10\ \mu$T

External Fluxgate Values (μT)

Start Active Feedback



[AMS] doi:10.1140/epjc/s10052-023-12225-z (2023)

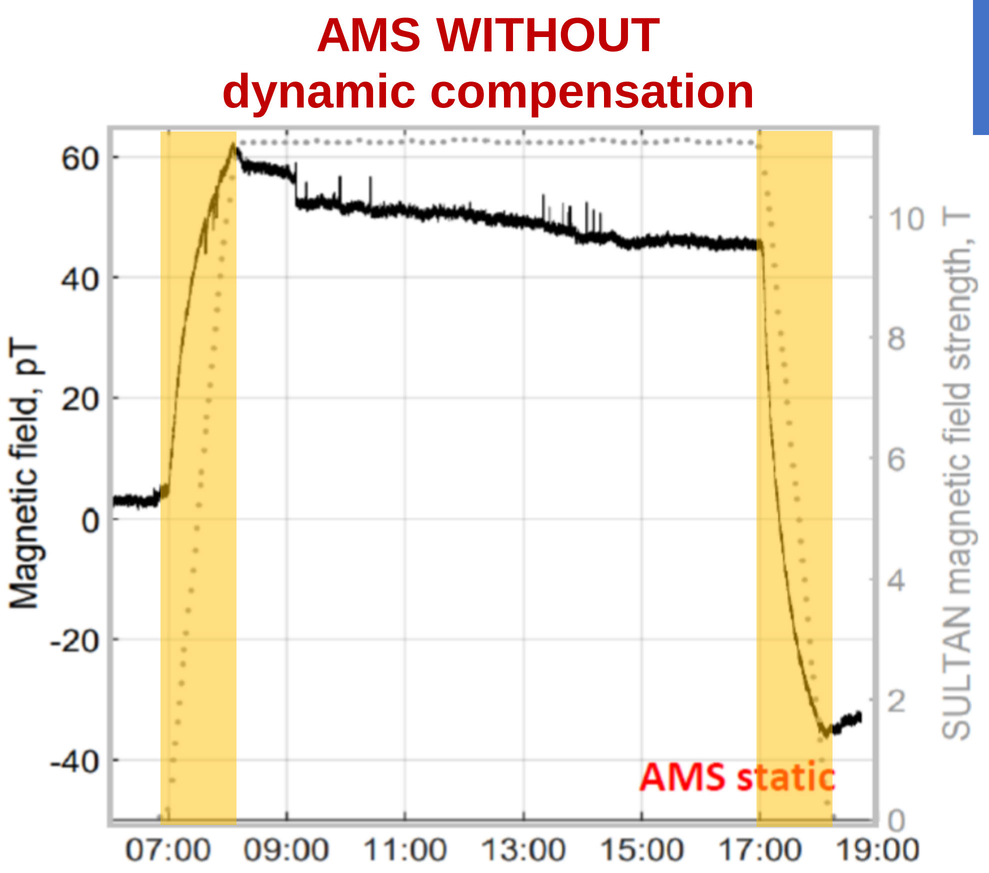
What is seen inside in the neutron storage volume?

External field source:
SULTAN magnet

The AMS performance depends upon the magnitude of the field source, i.e. difficult to quantify its performance.

?

QuSpin placed inside MSR



SULTAN magnet Ramp

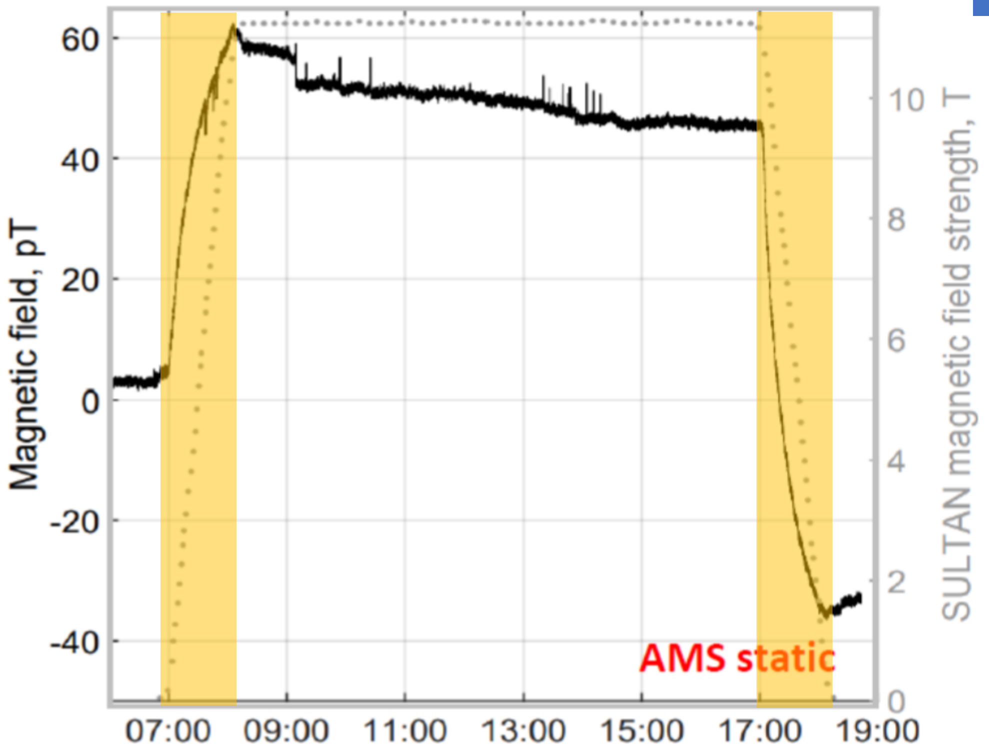
What is seen inside in the neutron storage volume?

External field source:

SULTAN magnet

Suppression of SULTAN magnet to 8 pT

AMS WITHOUT dynamic compensation



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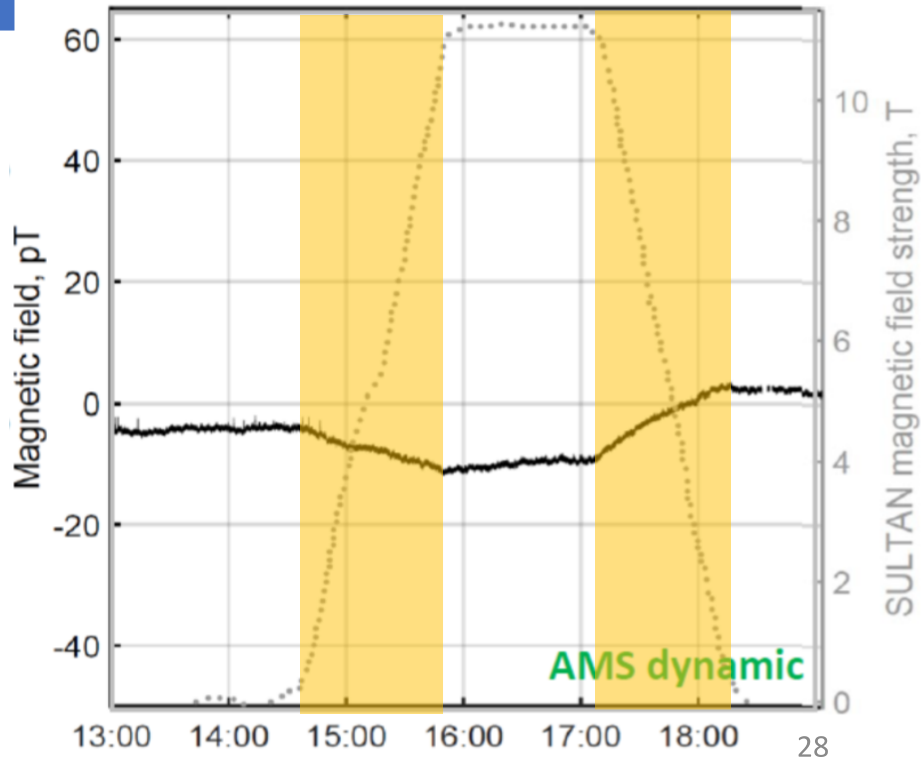
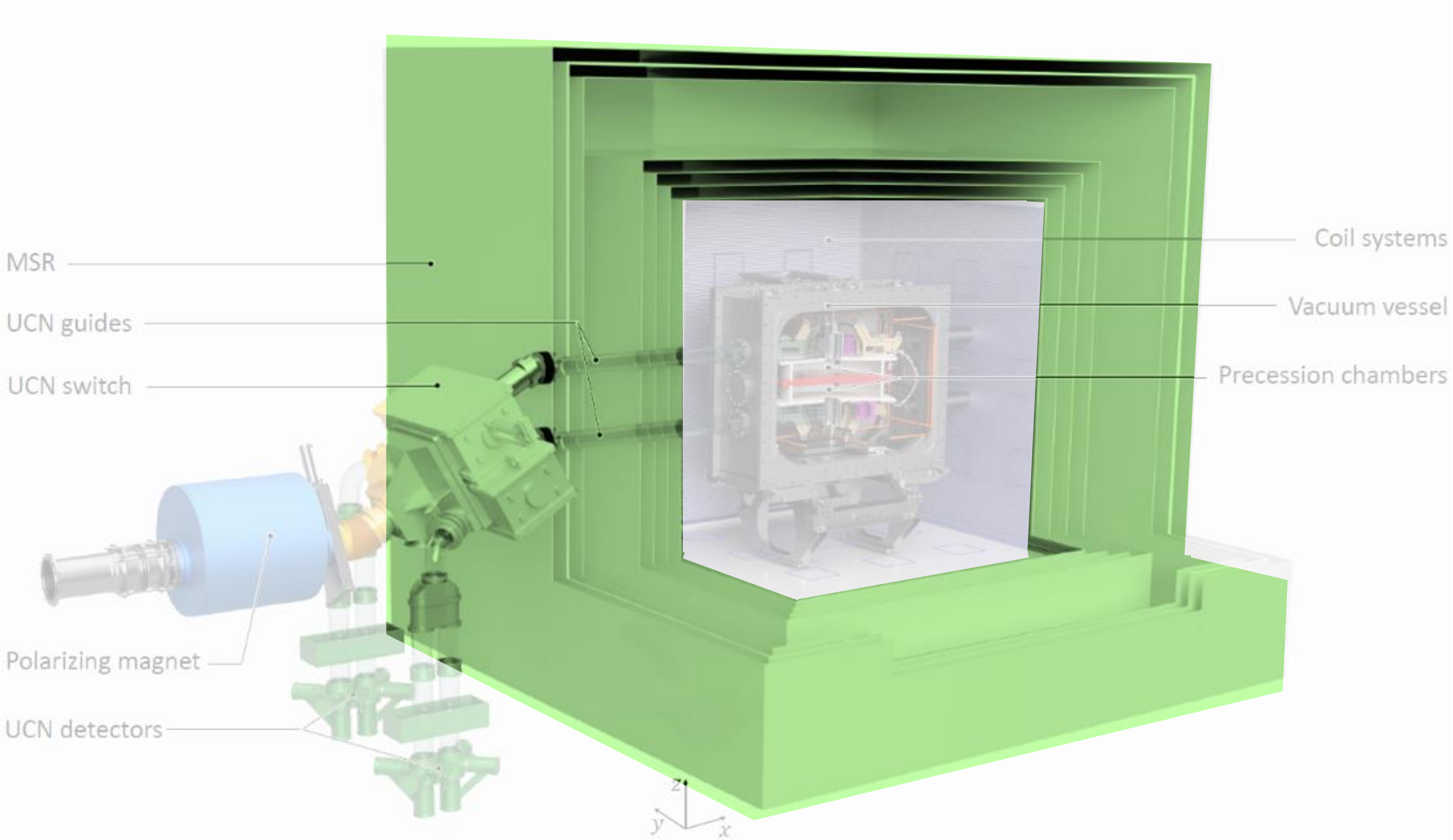


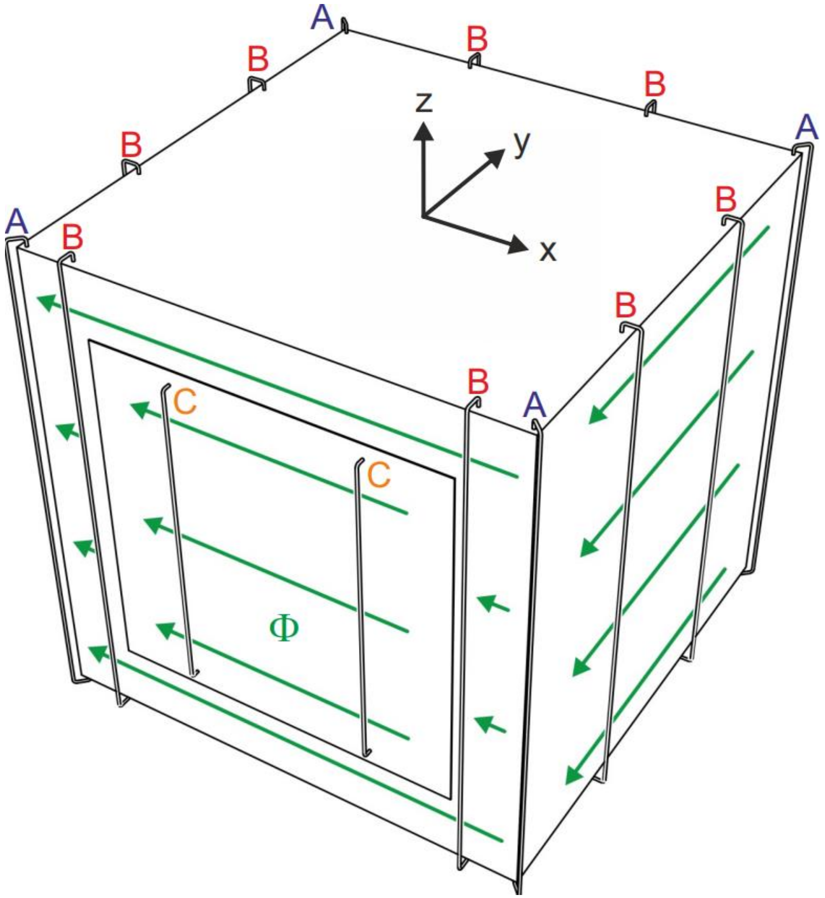
Again, let's focus on passive magnetic shielding



How to minimise the magnetic fields inside the magnetically shielded room?

Degaussing:

- *Coils integrated onto layers of the magnetically shielded room*



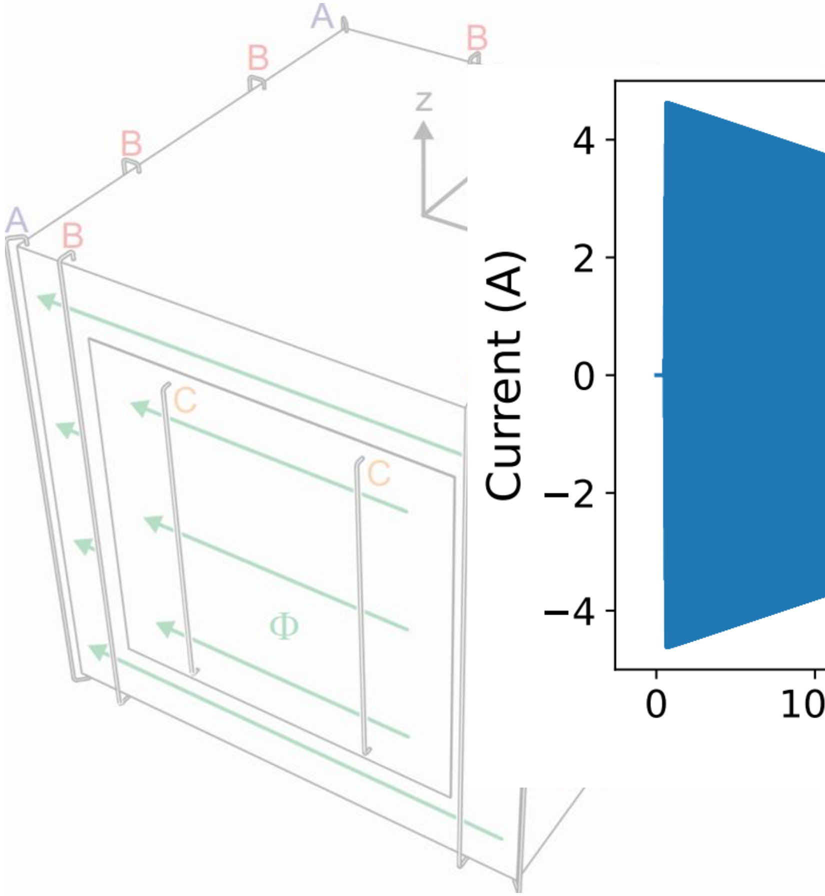
[MSR] doi:10.1063/5.0101391 (2022)
[Degaussing] *doi:*10.1140/epjc/s10052-023-12351-8 (2024)

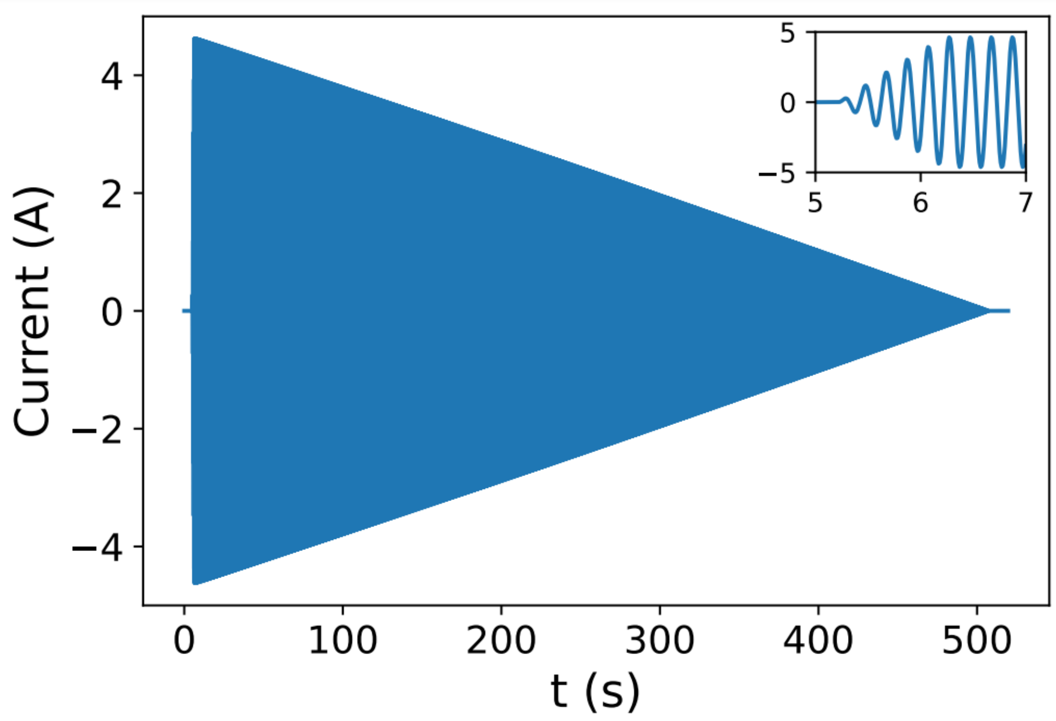
How to minimise the magnetic fields inside the magnetically shielded room?

Degaussing:

- *Coils integrated onto layers of the magnetically shielded room*

1. *Gradually Induce alternating currents into each layer until **saturation of the magnetization***
2. *Ramp down alternating current to zero to **minimize residual magnetization***





[Degaussing] *doi:*10.1140/epjc/s10052-023-12351-8 (2024)

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- *Coils integrated onto layers of the magnetically shielded room*

1. *Gradually Induce alternating currents into each layer until **saturation of the magnetization***
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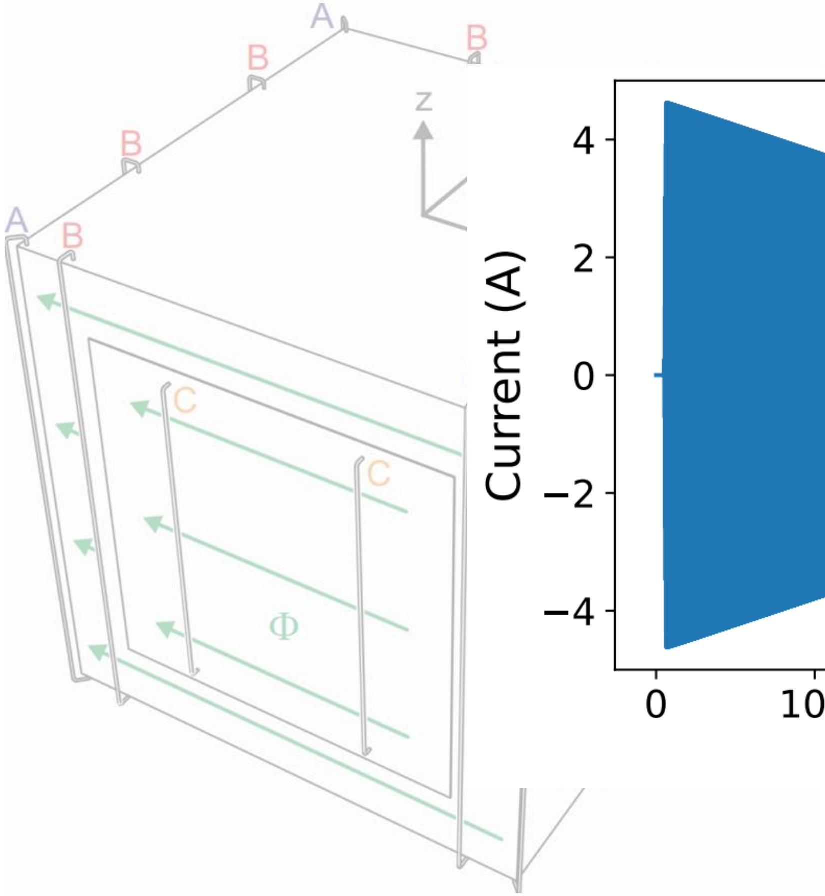
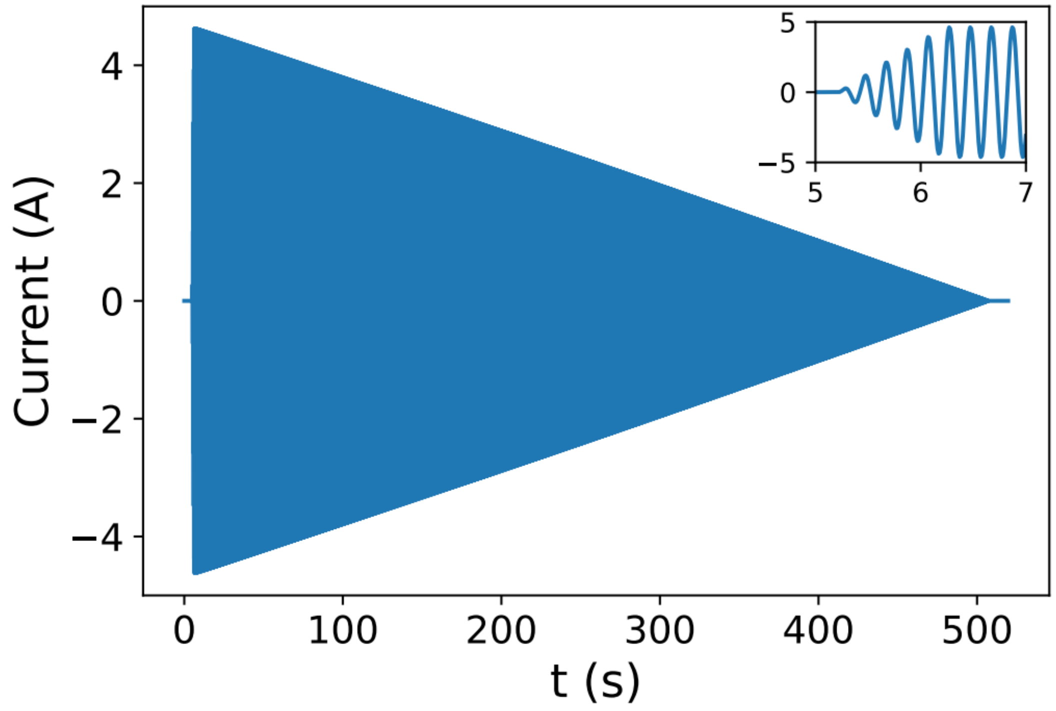
Induced heat into each layer, needs time to cool before measurements

Optimization

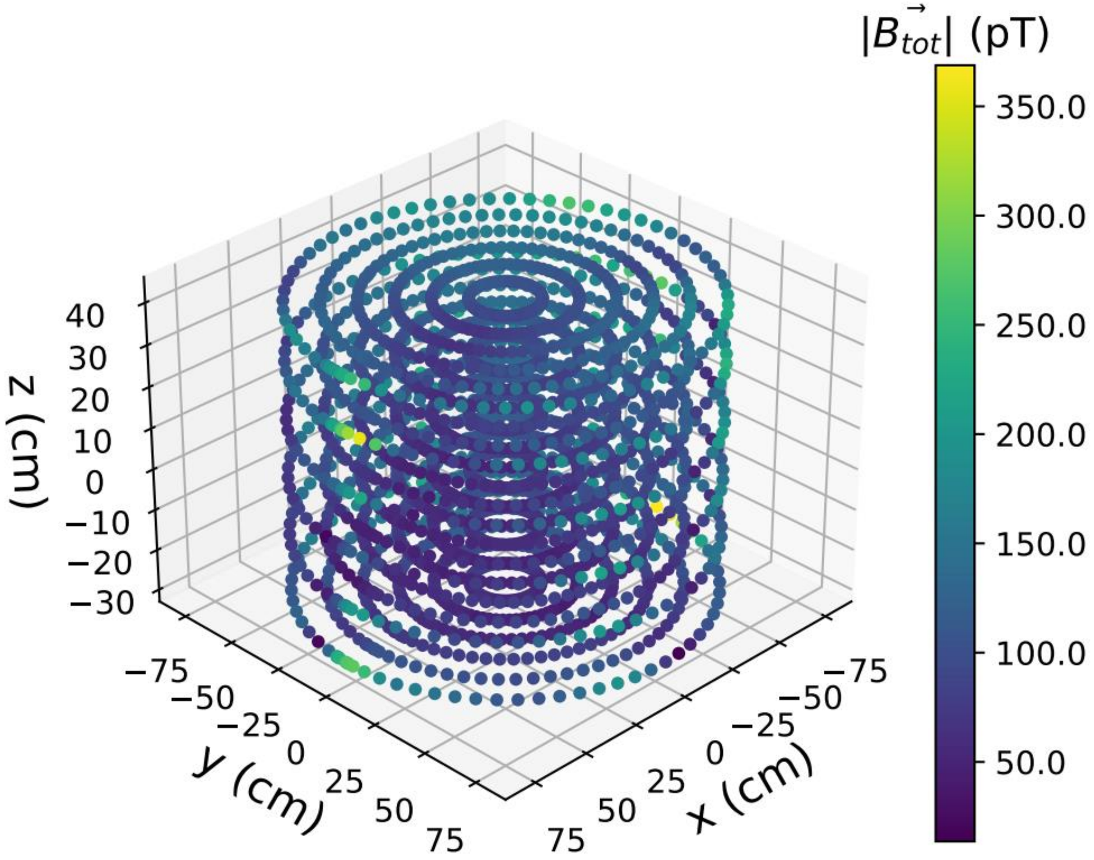
- *Further reduce the residual magnetization*
- *Reduce duration of degaussing + thermal relaxation from **12 hours to 1.5 hours***

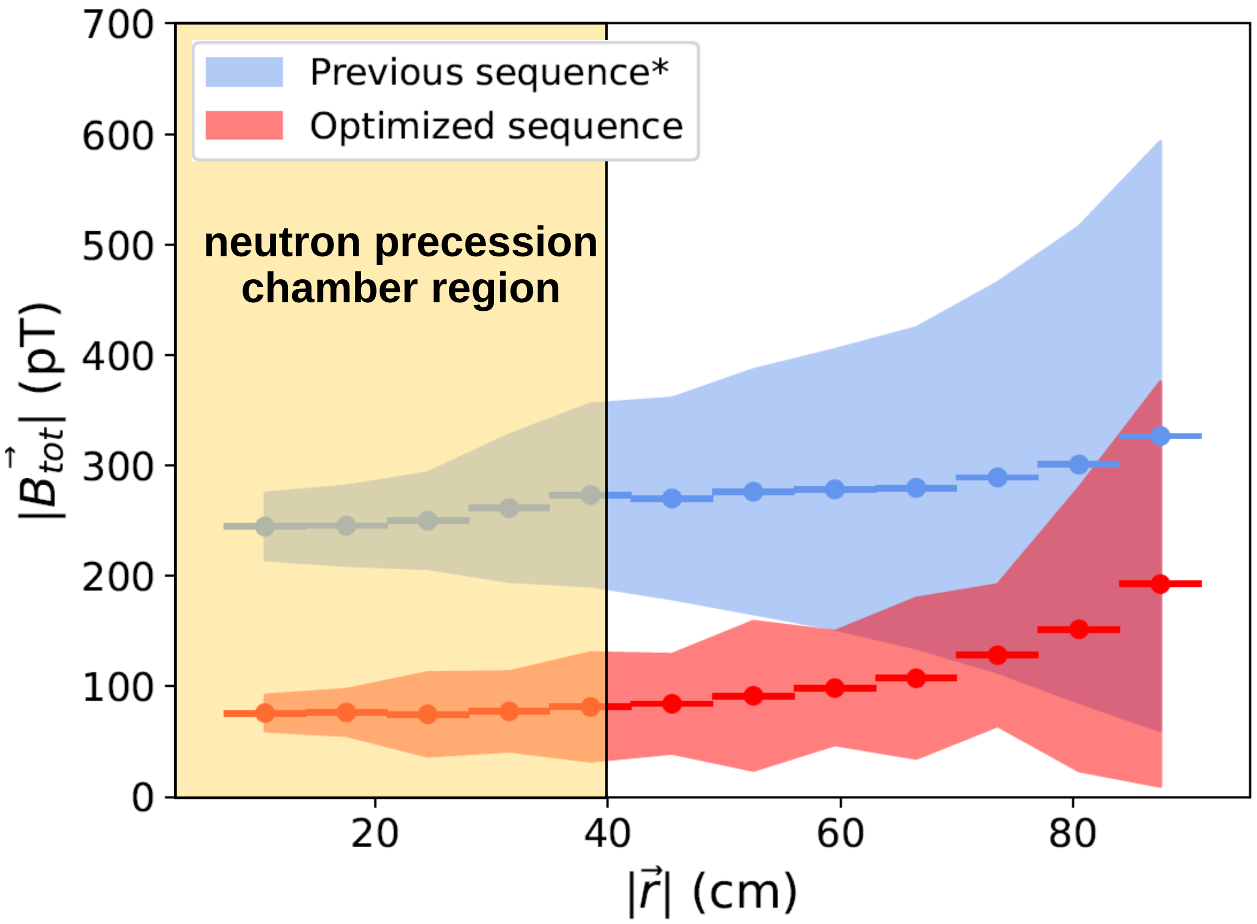




[Degaussing] *doi:*10.1140/epjc/s10052-023-12351-8 (2024)

After degaussing what residual magnetic fields are observed?





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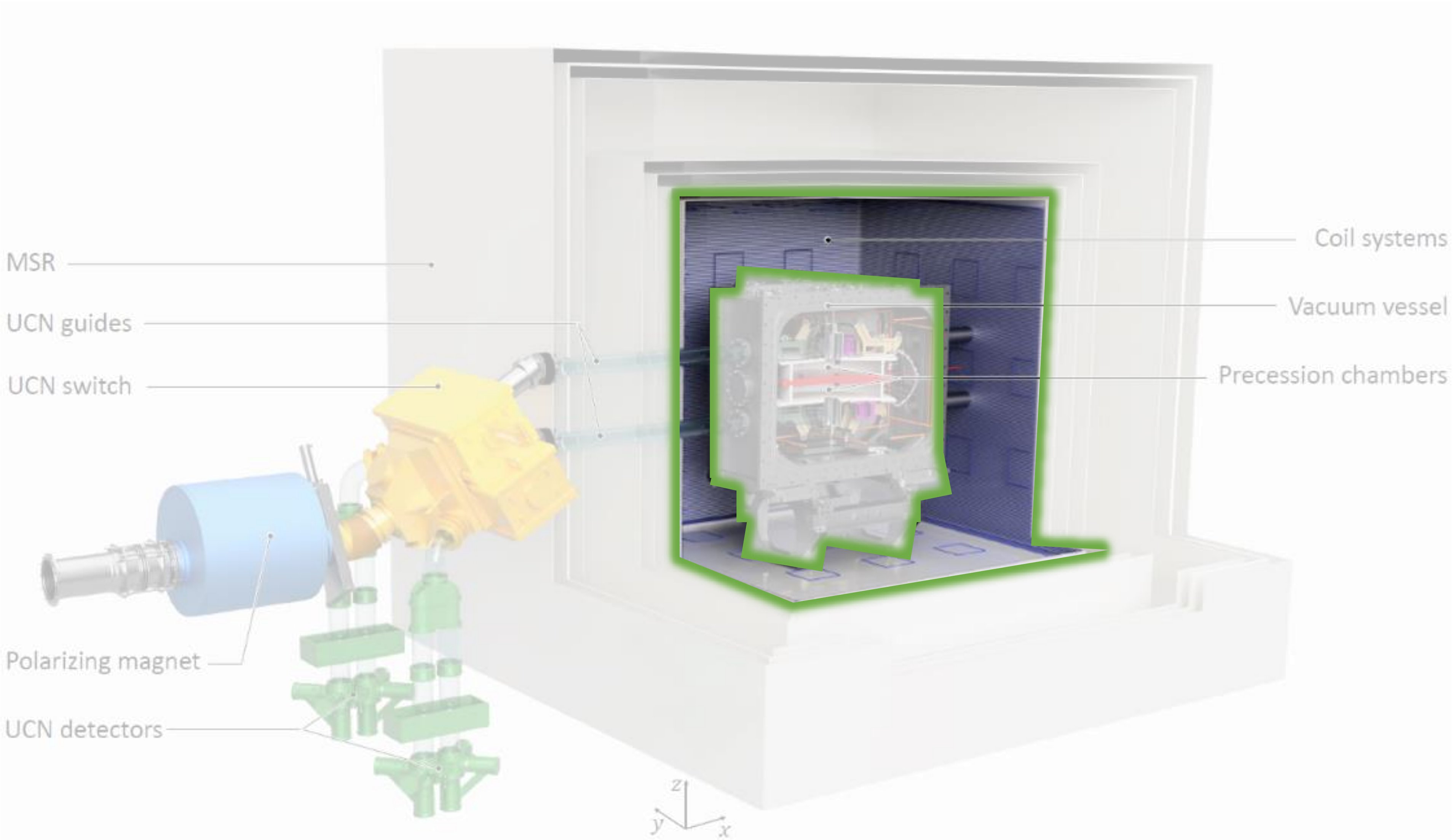
Let’s focus on the vertical magnetic field



What magnetic field do the neutrons precess within?

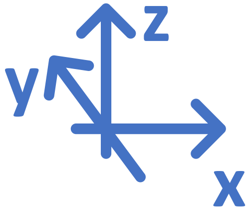
Cubic cage of overlaying coils including a Vertical solenoid

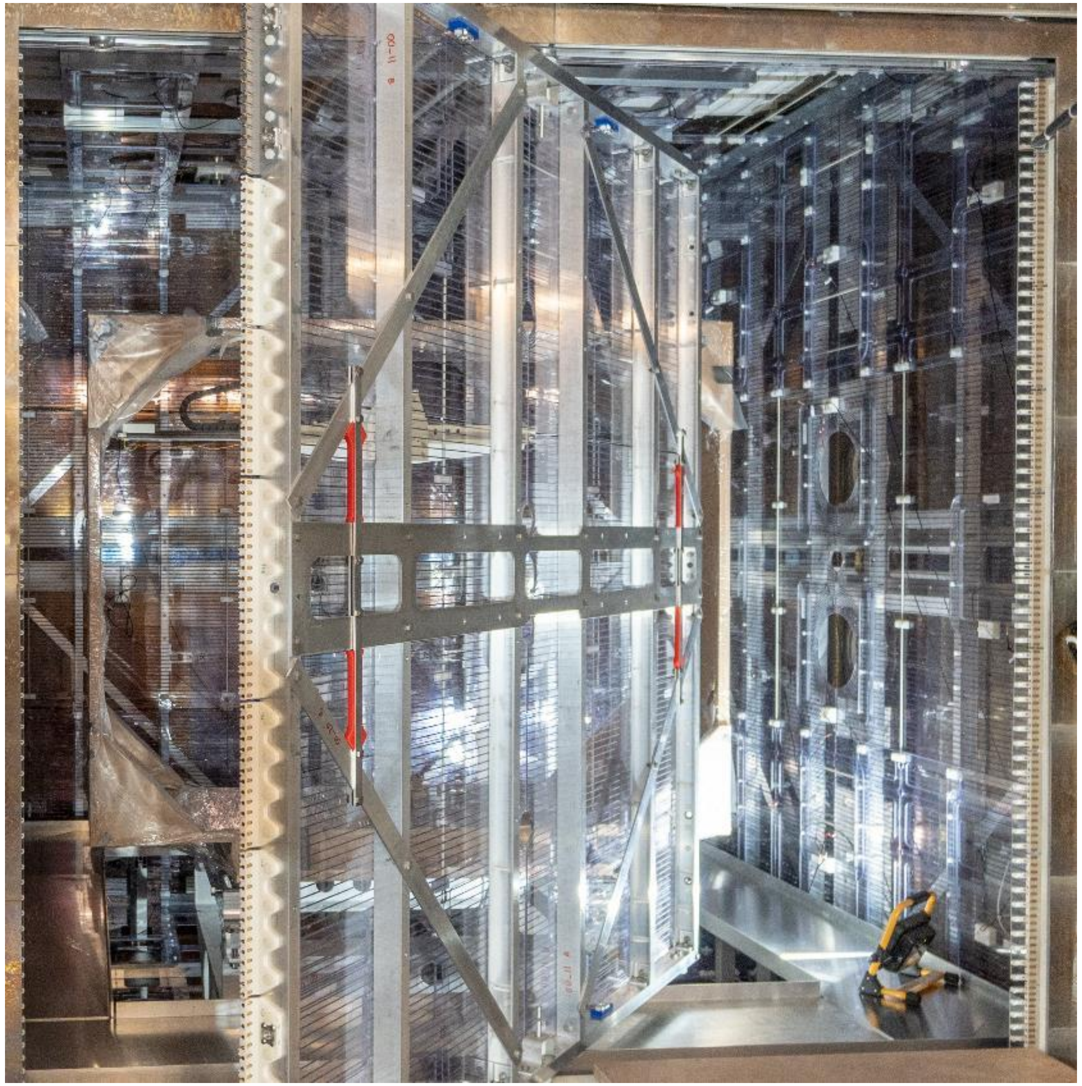
Positioned independently of vacuum chamber

$B_z = 1\mu T$ **vertical holding field,** B_0

Target performance:

- Within 100pT of ideal field within volume surrounding storage chambers
- Tens of fT stability over a few minutes





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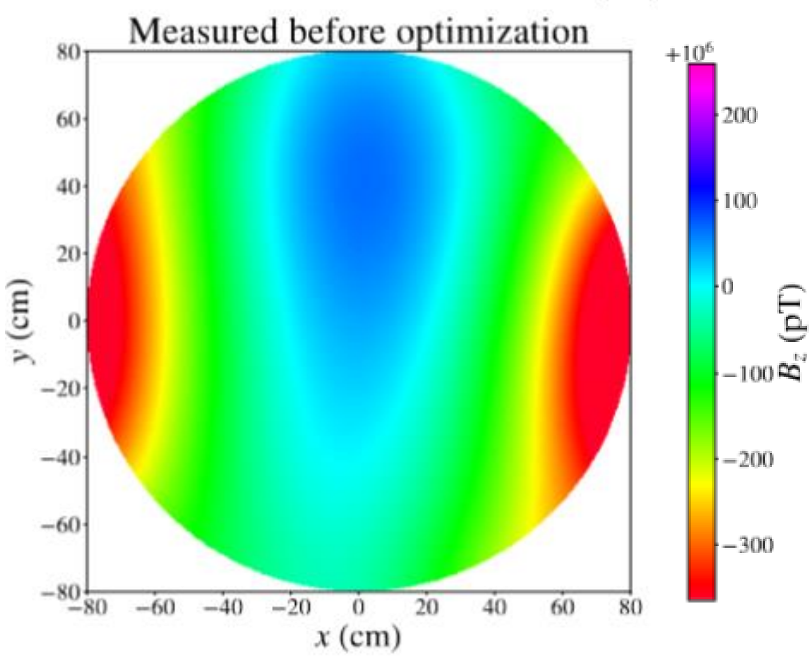
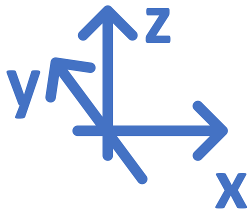
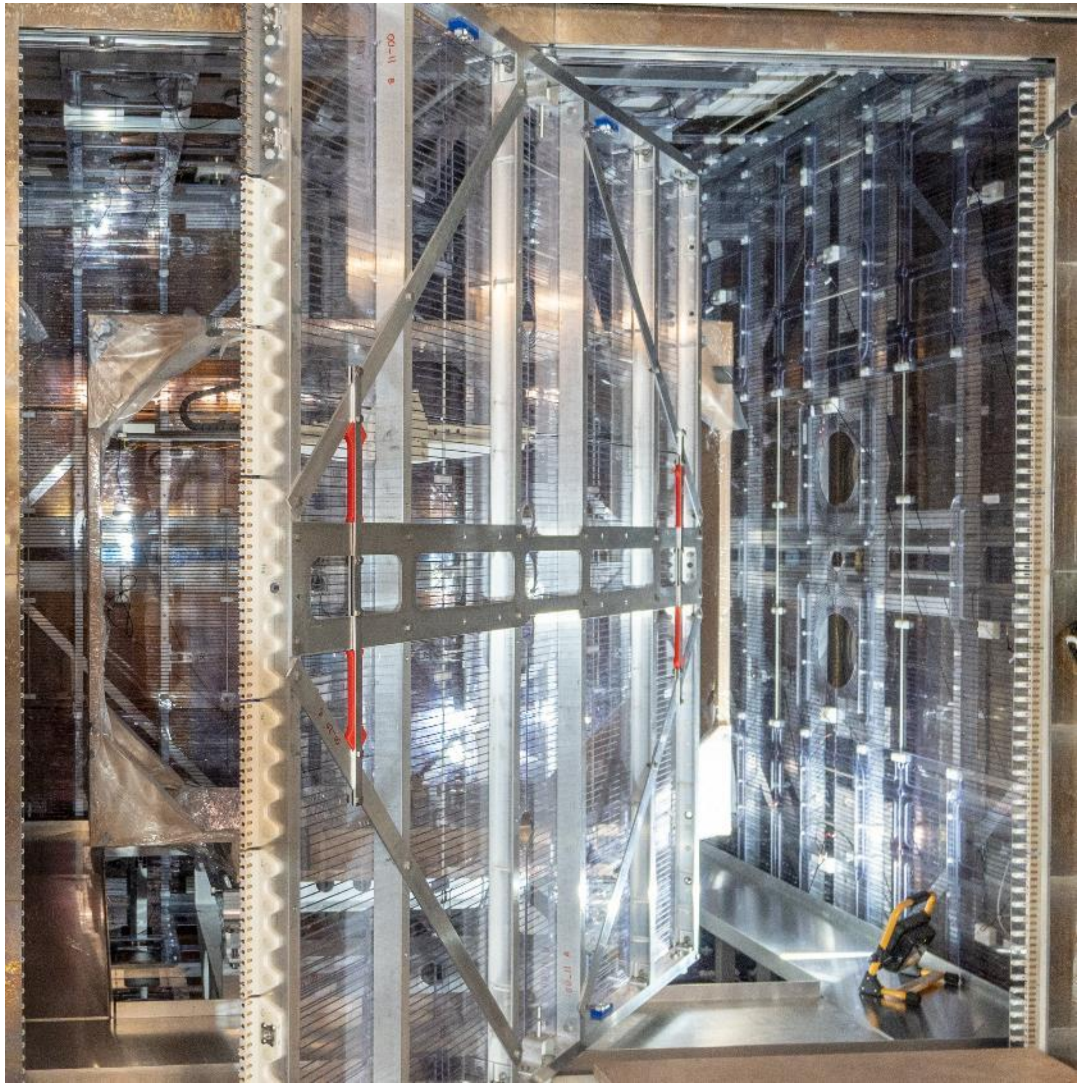






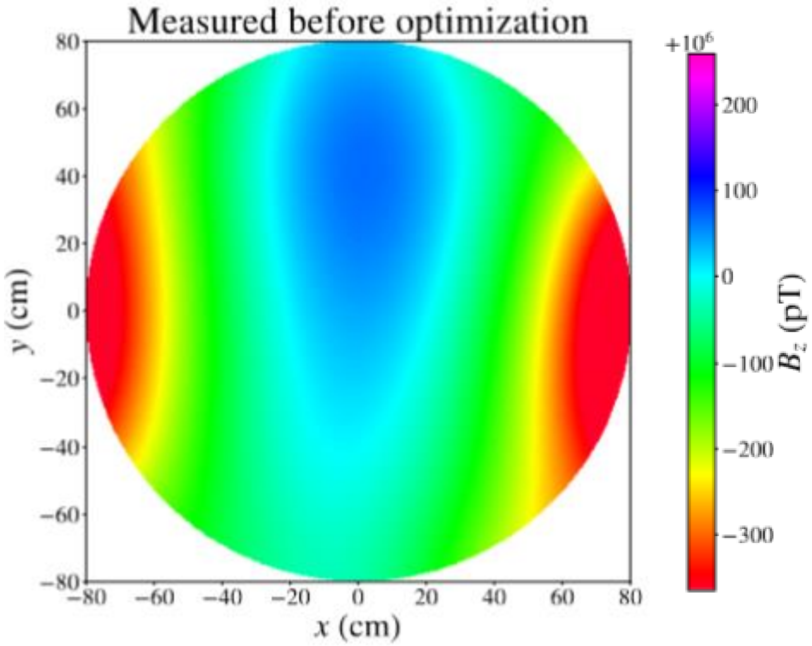
We can tune the B_0 field

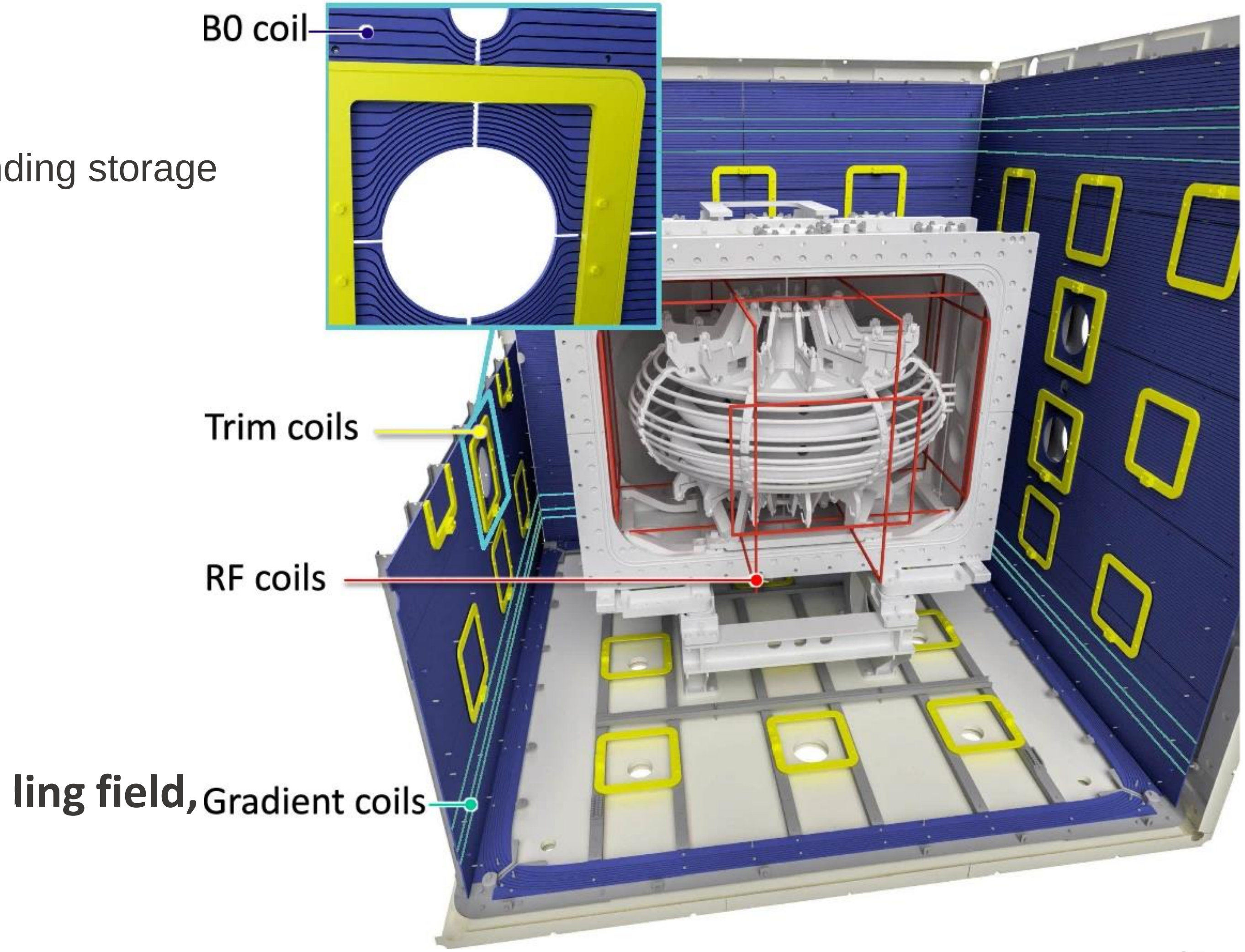
$B_z = 1\mu T$ **vertical holding field,** B_0

Target performance:

- 100pT of ideal field within volume surrounding storage chambers

In addition: *56 trim coils*





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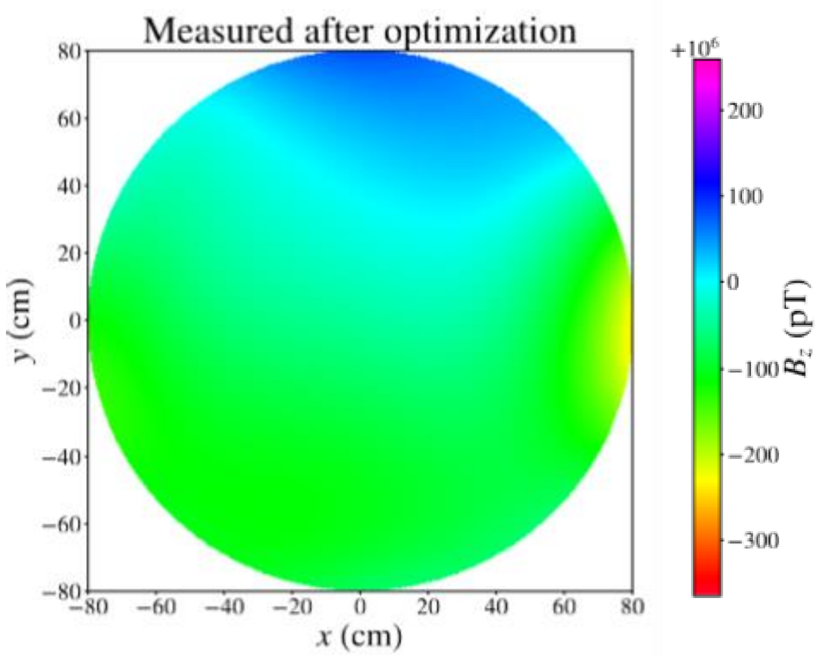

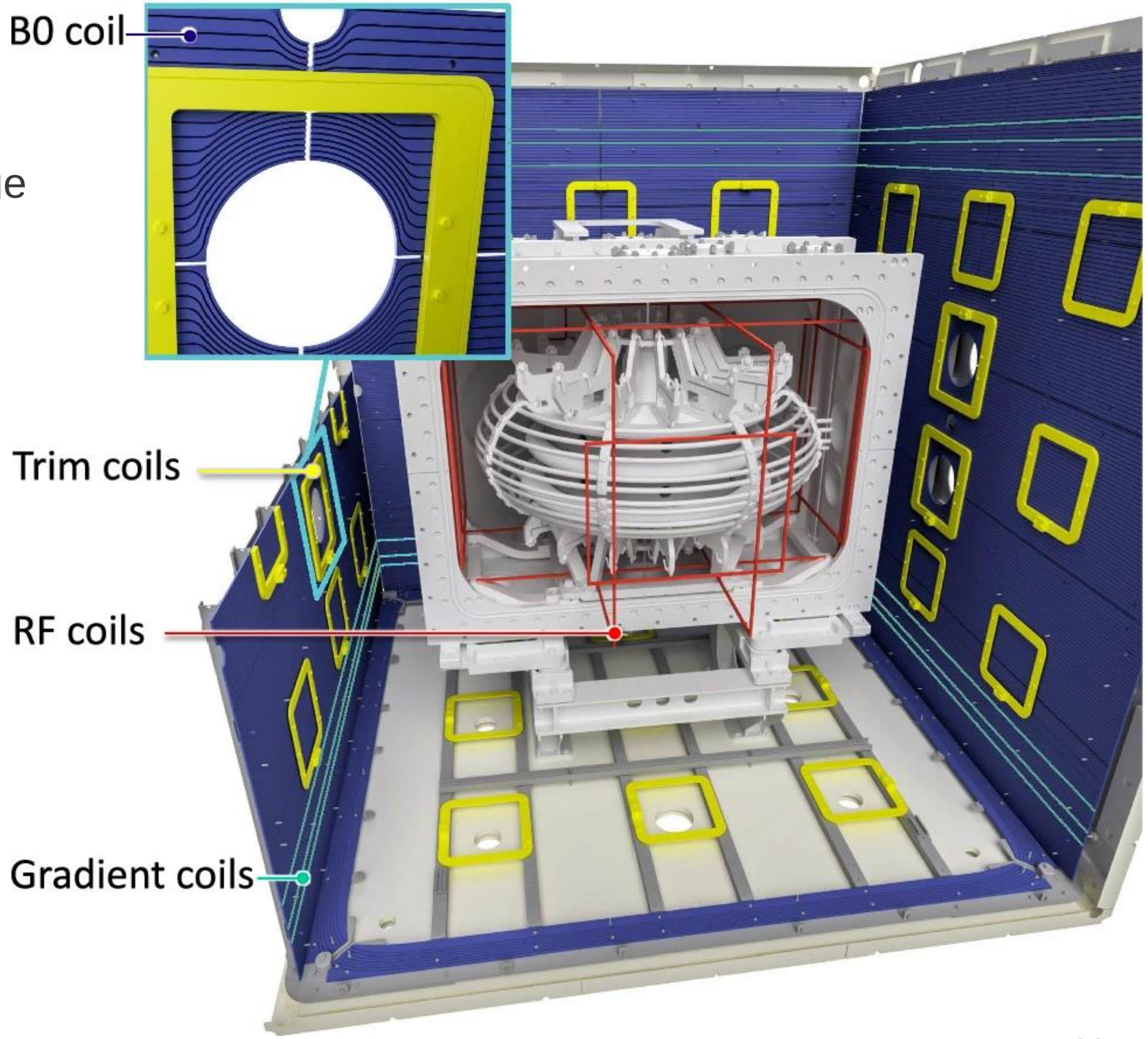

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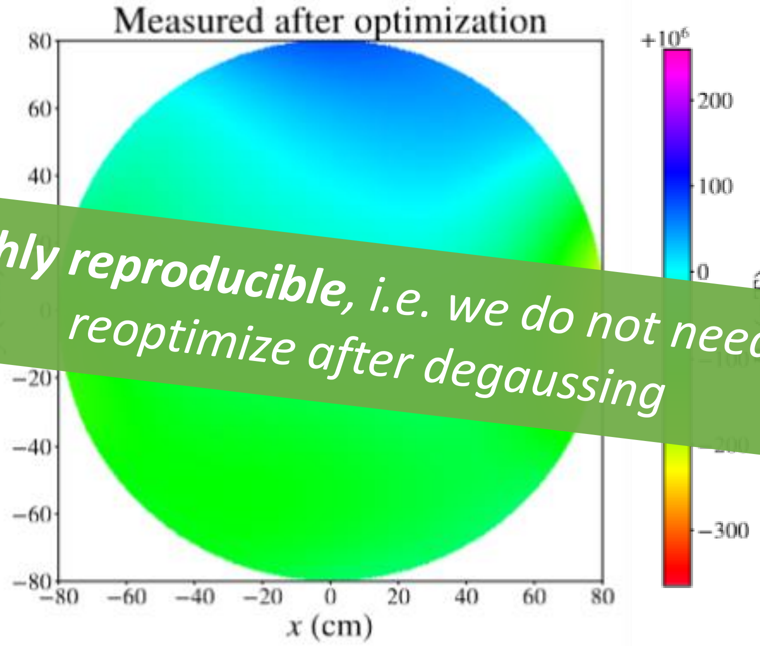
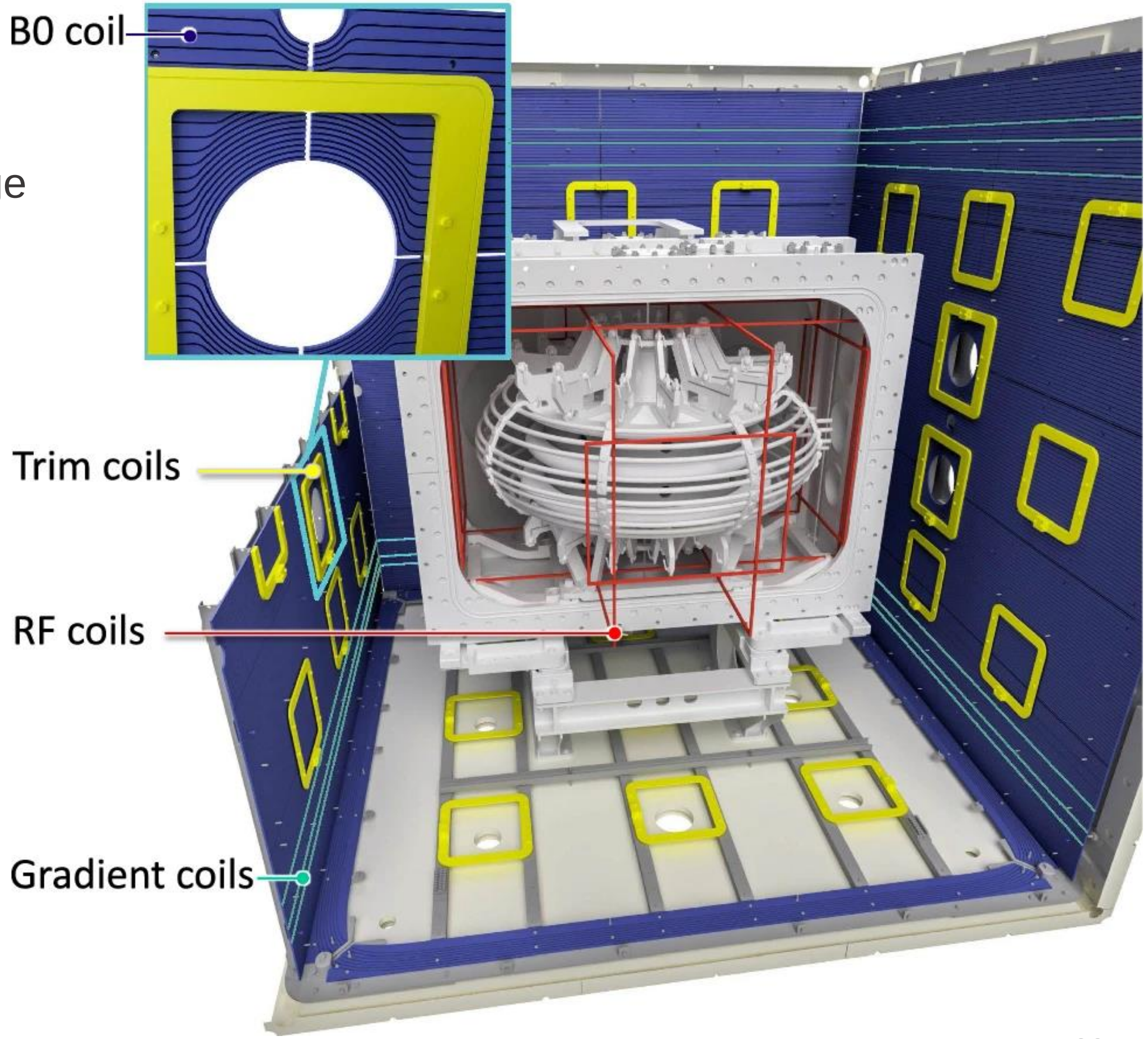
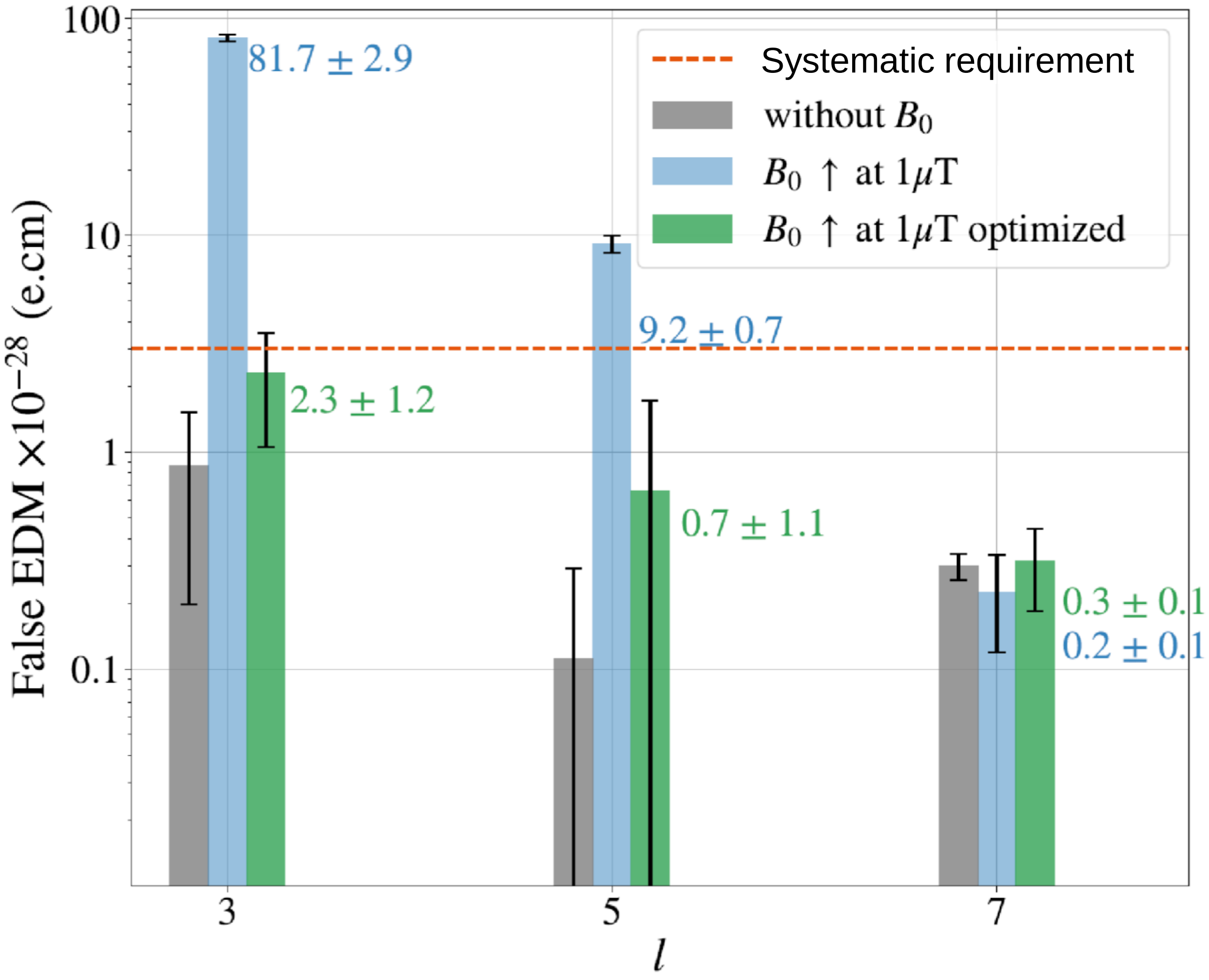


***Highly reproducible**, i.e. we do not need to reoptimize after degaussing*



How accurately can we shape the interior magnetic field?

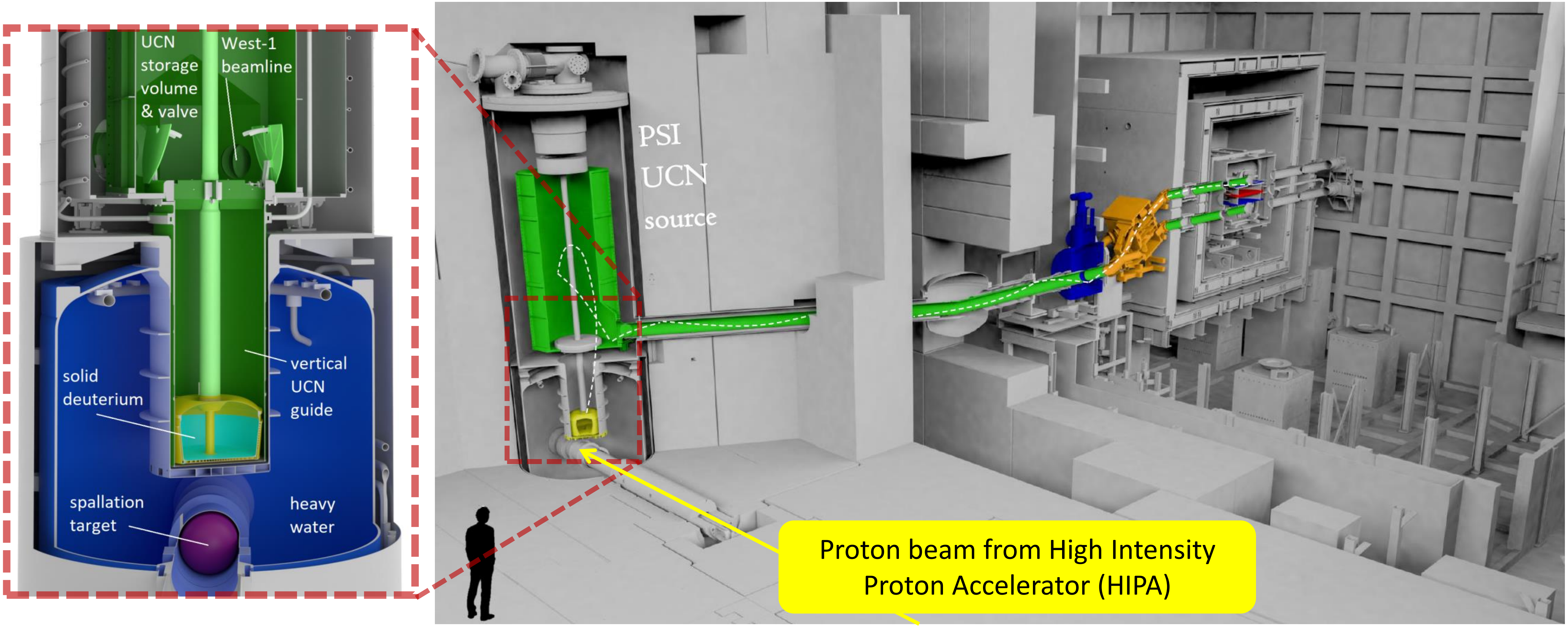


$3 \times 10^{-28}\ e$ cm

Magnetic field gradients, $G_{l,0}$

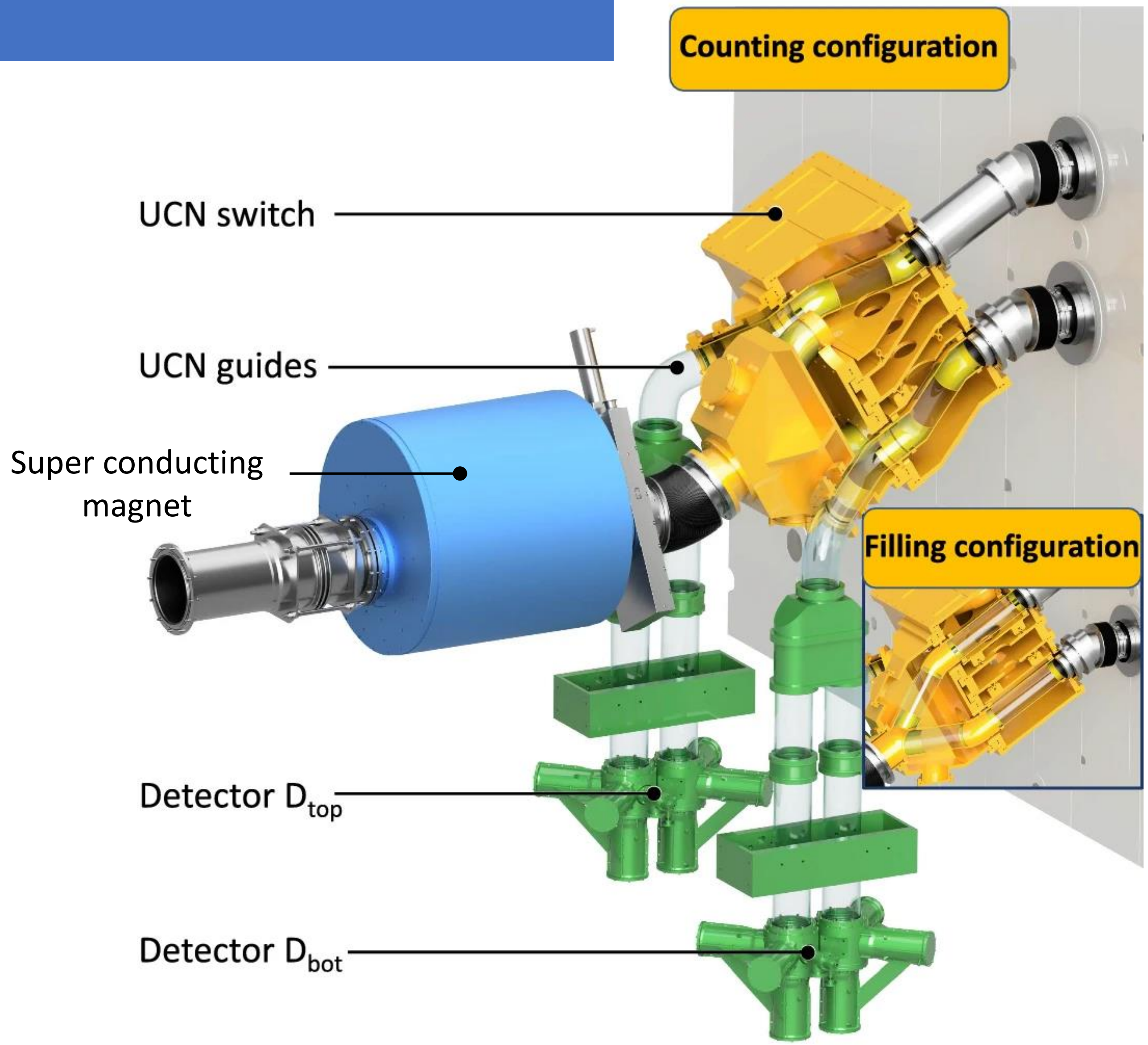
$G_{TB} = G_{1,0} - L_3^2 G_{3,0} + L_5^2 G_{5,0} - \cdots$

PSI Ultra cold neutron (UCN) source



[PSI UCN source] doi:10.3929/ethz-b-000579840 (2022)

How are polarised neutrons obtained and guided?



How to detect UCN polarisation spin state?

Ensemble of neutrons from each (Top/Bottom) chamber is released into separate polarisation spin state analyser

- *Gravitational potential,* $U_g = 1\text{neV/cm}$
- *Vertical arrangement allows for* U_g *at foils to be fine tuned*
- *Polarised neutron detection range: 90 neV to 330 neV*

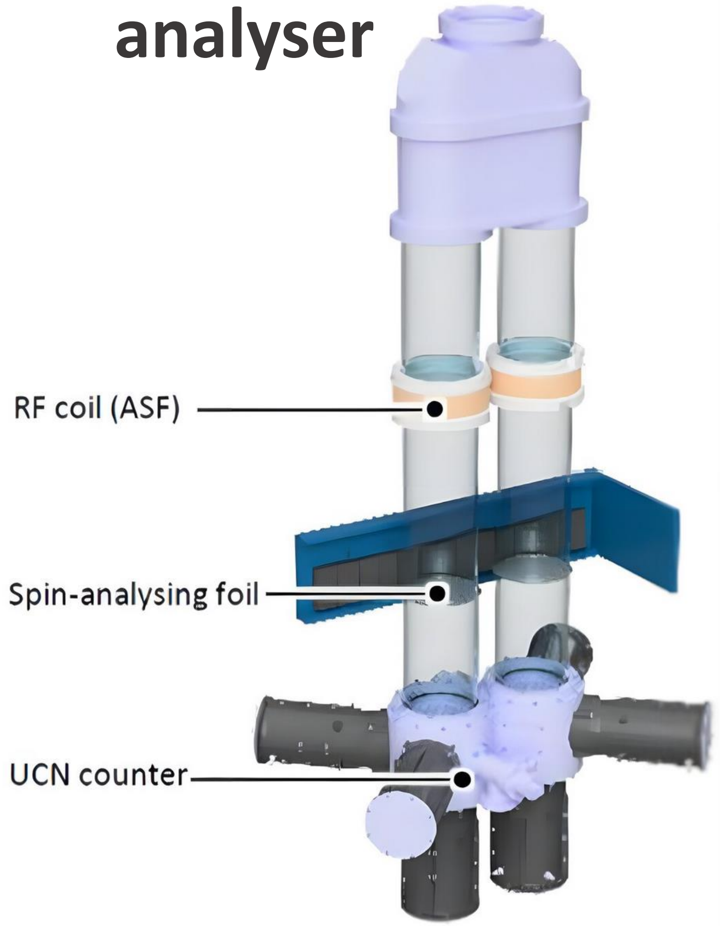
UCN counter: Gaseous detection of Helium-3 and Carbon-tetrafluoride mixture

Conversion to proton: $\mathrm{n} + {}^{3}He \rightarrow p + {}^{3}H$

Proton to scintillation: $p + {}^{3}H \rightarrow p + {}^{3}H + \gamma$ **and** $p + \mathrm{CF}_4 \rightarrow p + \mathrm{CF}_4 + \gamma$

Photo multiplier tubes detect scintillation

UCN Spin state analyser



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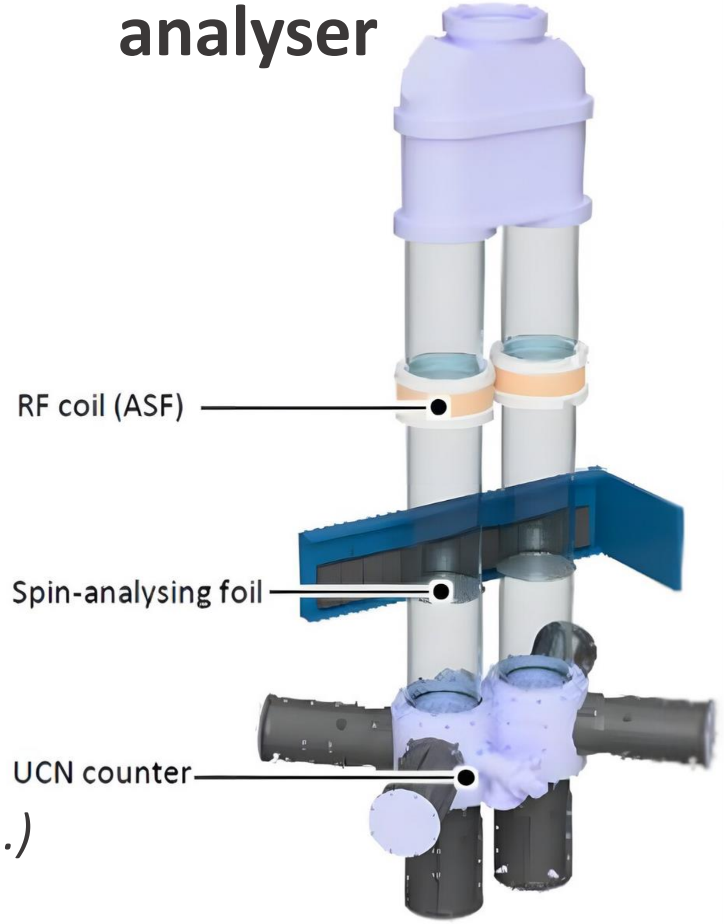
Asymmetry, $A_{\uparrow\downarrow} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$ (convolution of *initial neutron polarisation, neutron energies, detector efficiencies, polarisation loss mechanisms, …)*

UCN Spin state analyser

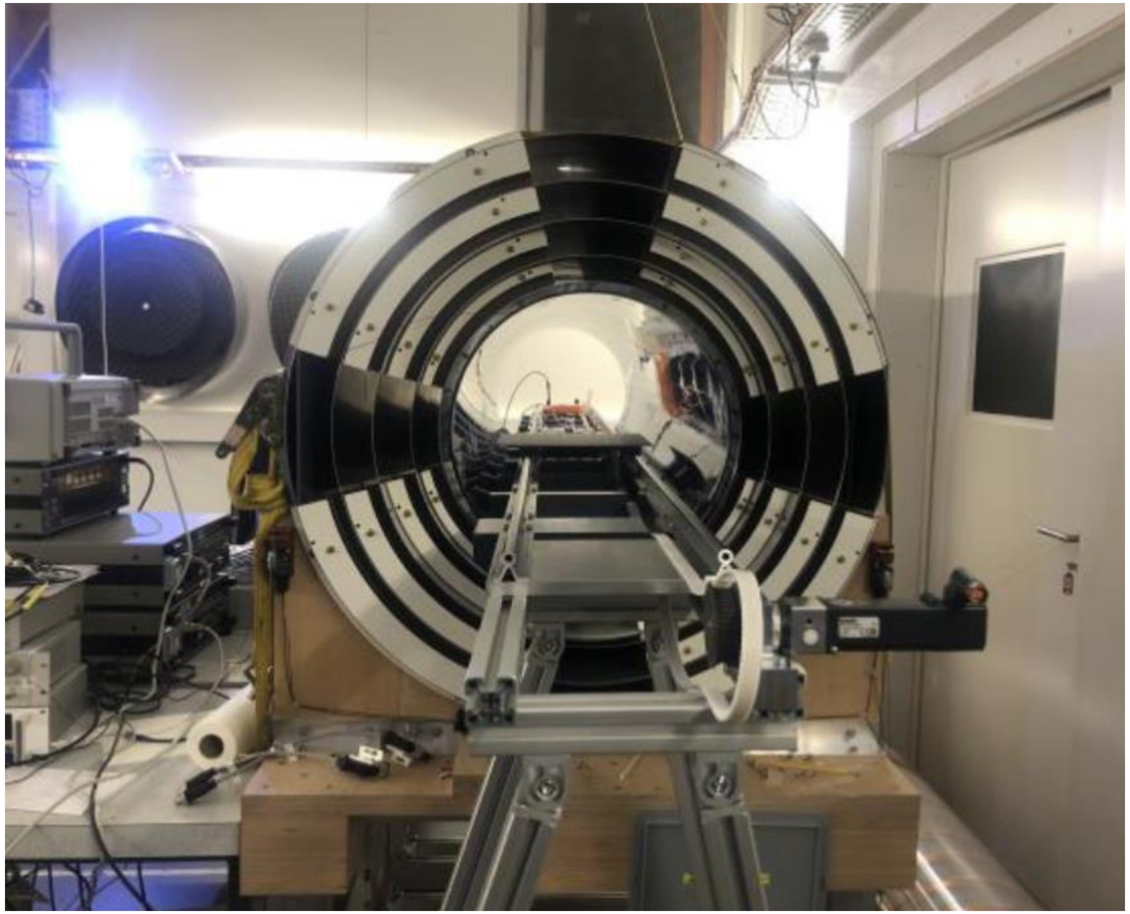


Dedicated setup to screen for magnetic contamination

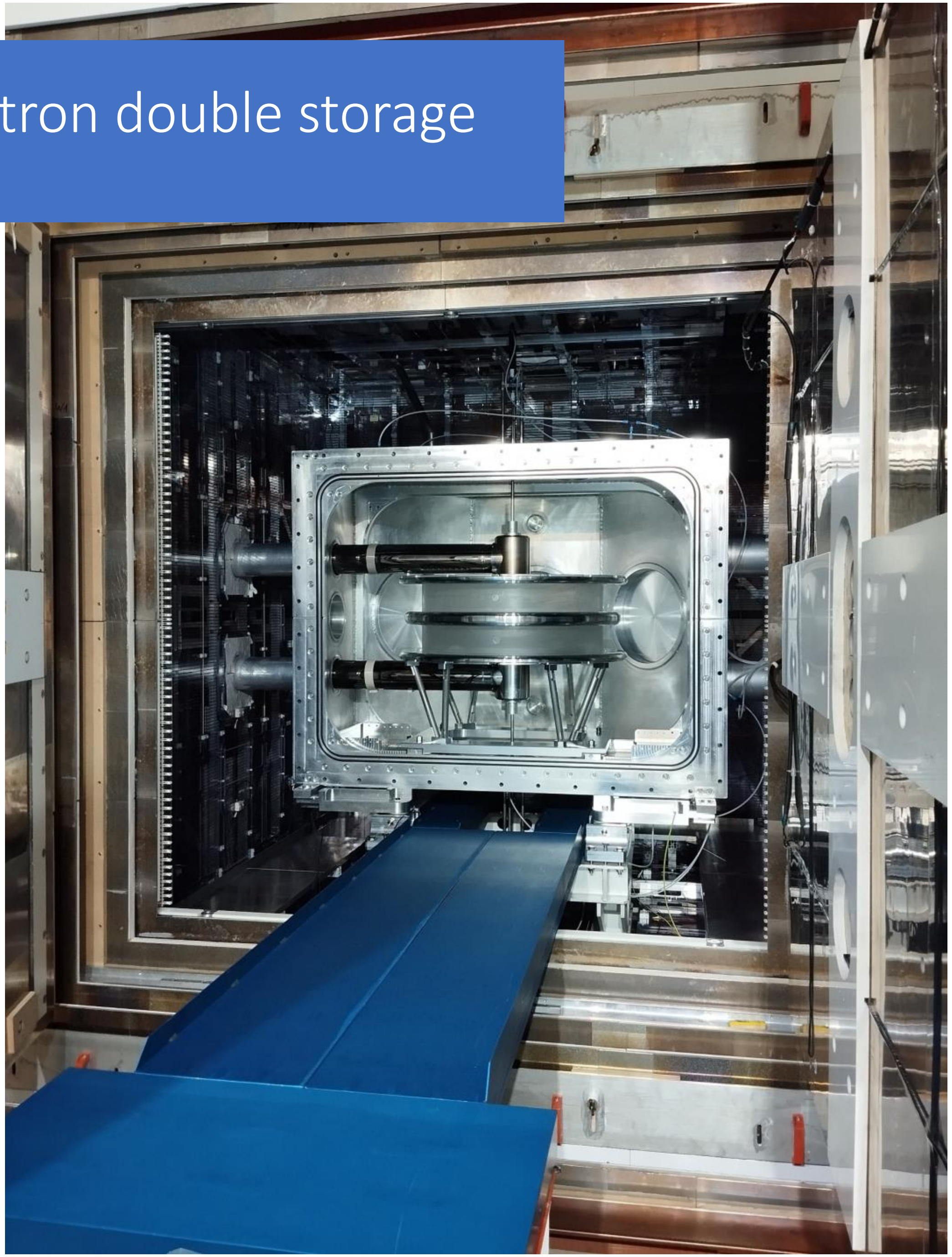
Gradiometer at PSI:

- *Fast scanning*
- *pT sensitivity for average measurements*

We need to check every single piece of the assembly that enters the vacuum vessel, i.e. thousands of screws



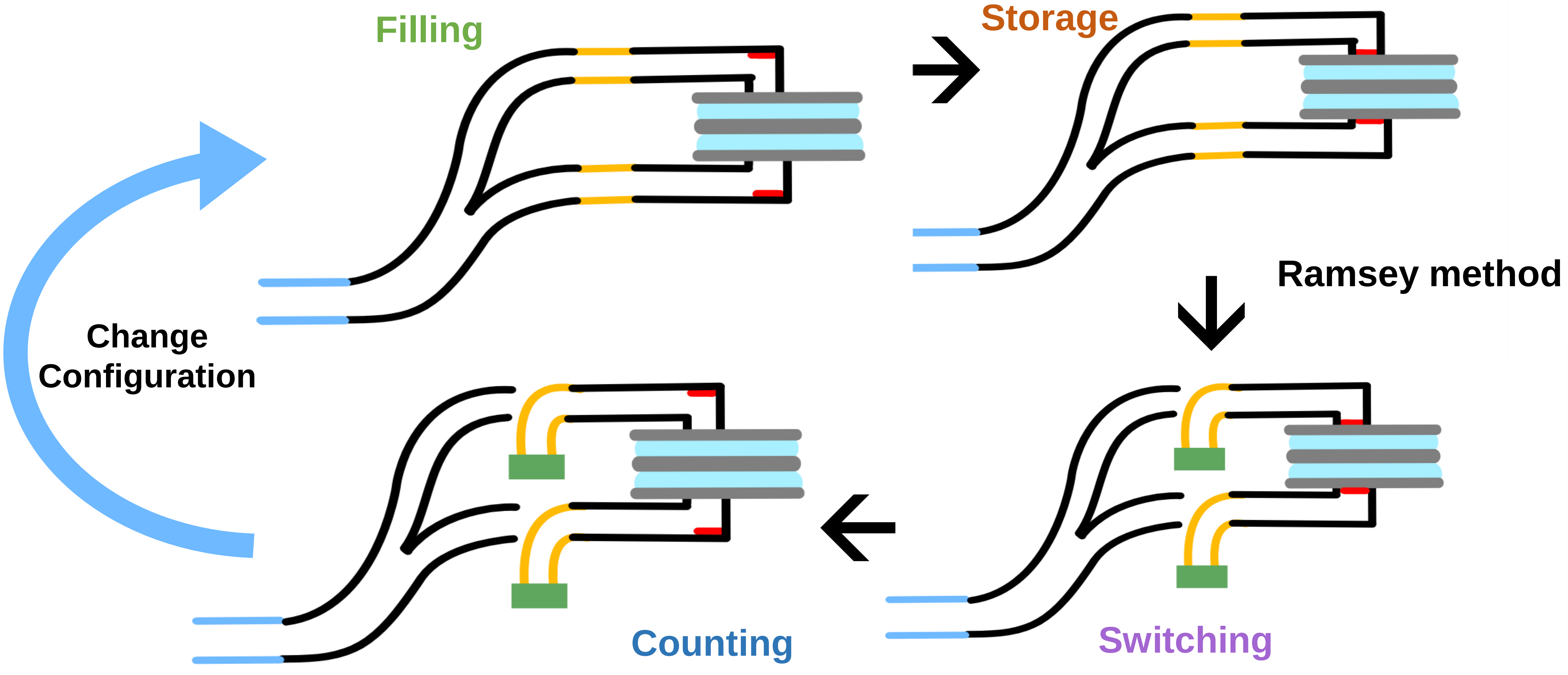
Assembly of neutron double storage chambers



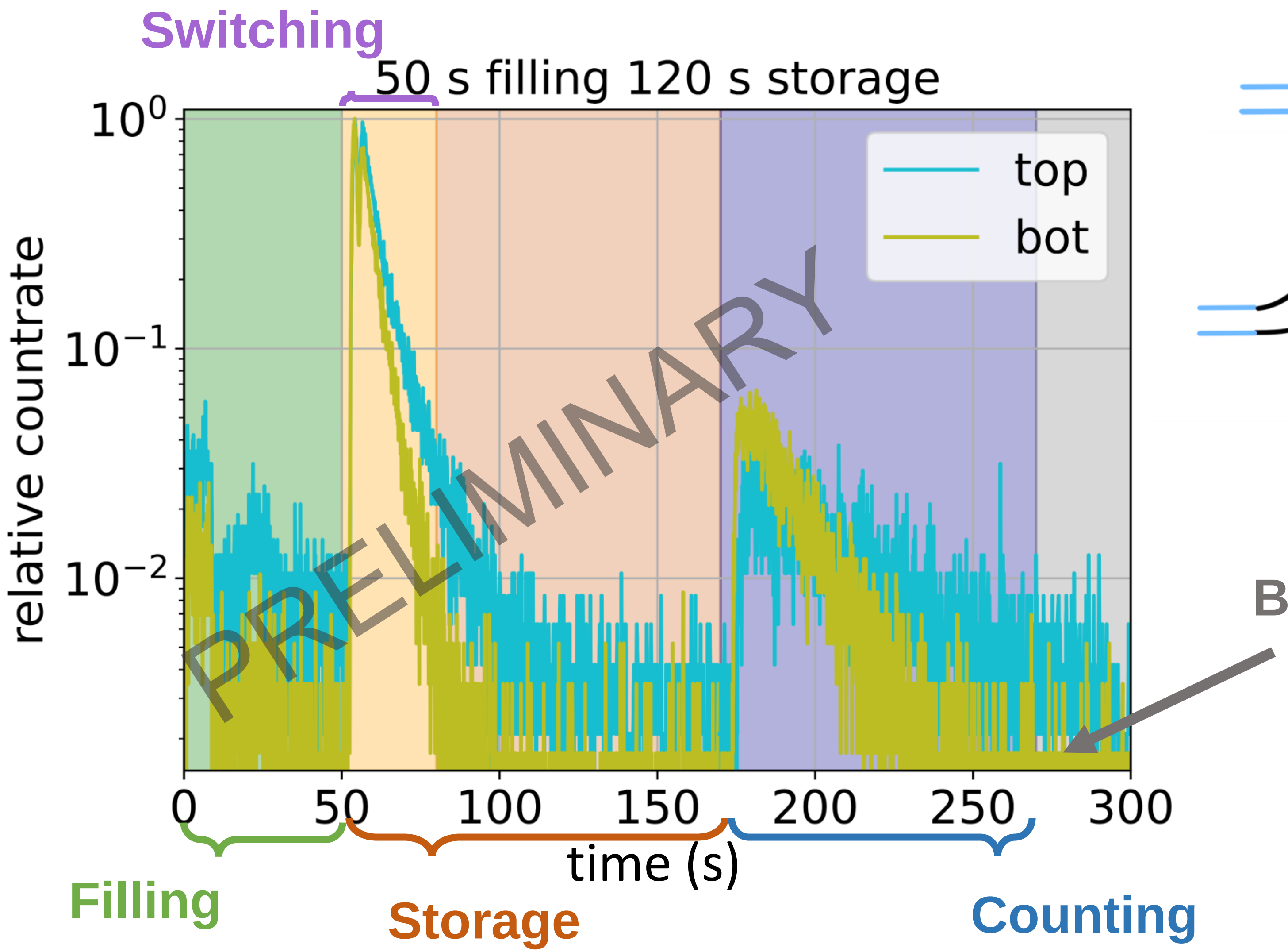
ETH zürich

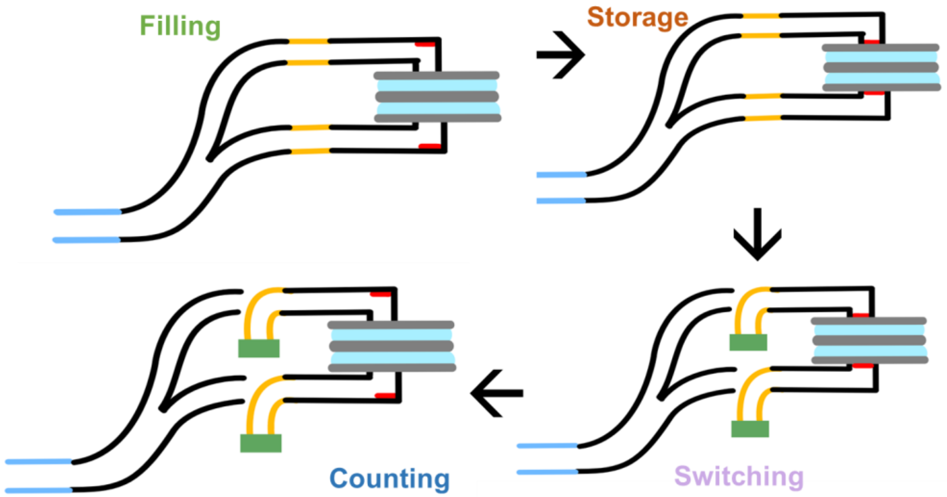
n2EDM

Sequence of measurements

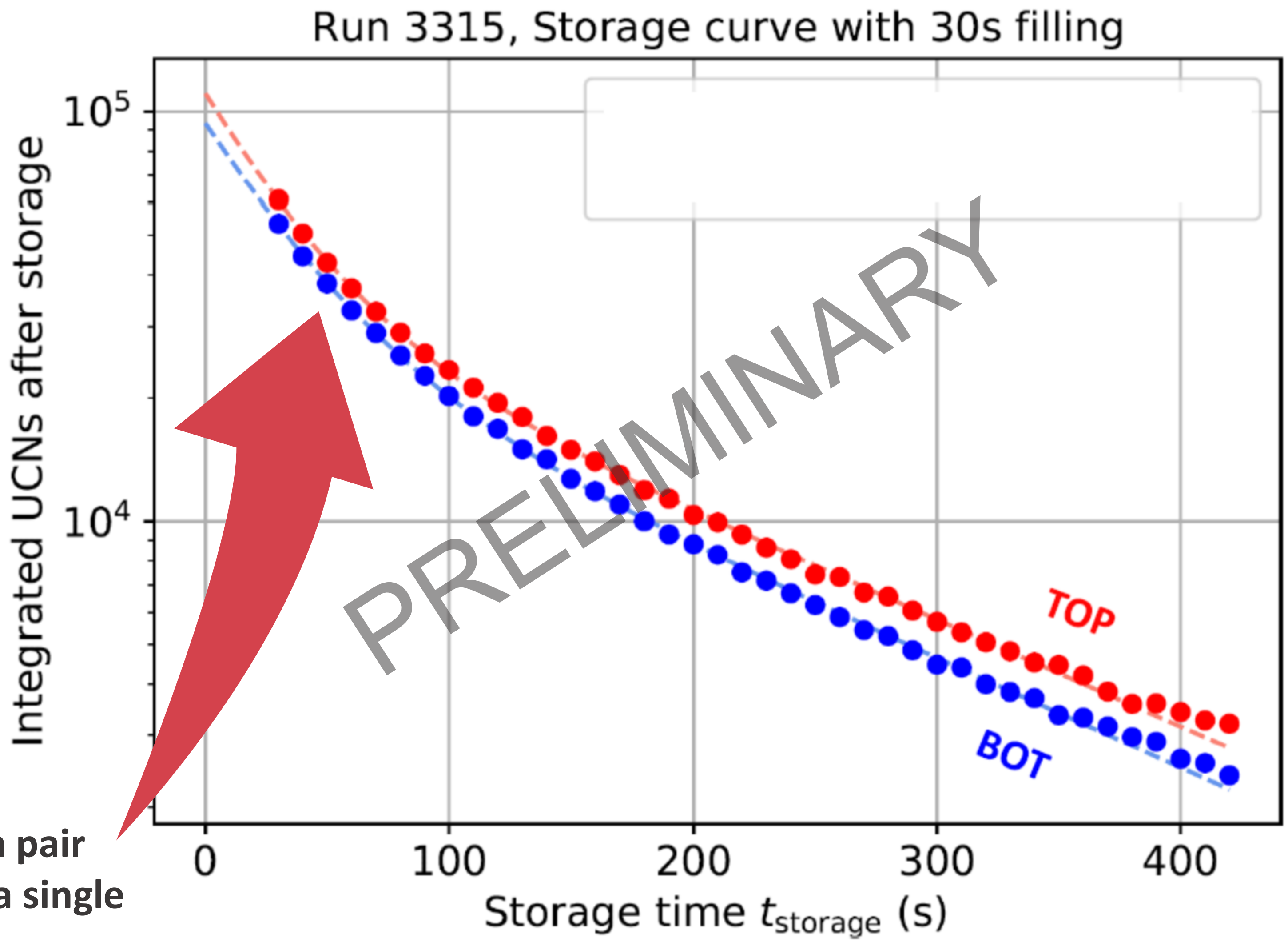


What do our neutron detectors see?





Can we store neutrons in the chambers?



Each Top/Bottom pair of data points is a single cycle of neutrons

Now for some results, Ramsey Curves

Ramsey method measurement

$\pi/2$ pulse, $t_{\pi/2} = 1.95\ s$

Precession duration, $T = 180\ s$

See Efrain Segarra's poster

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Precession duration, $T = 180\ s$

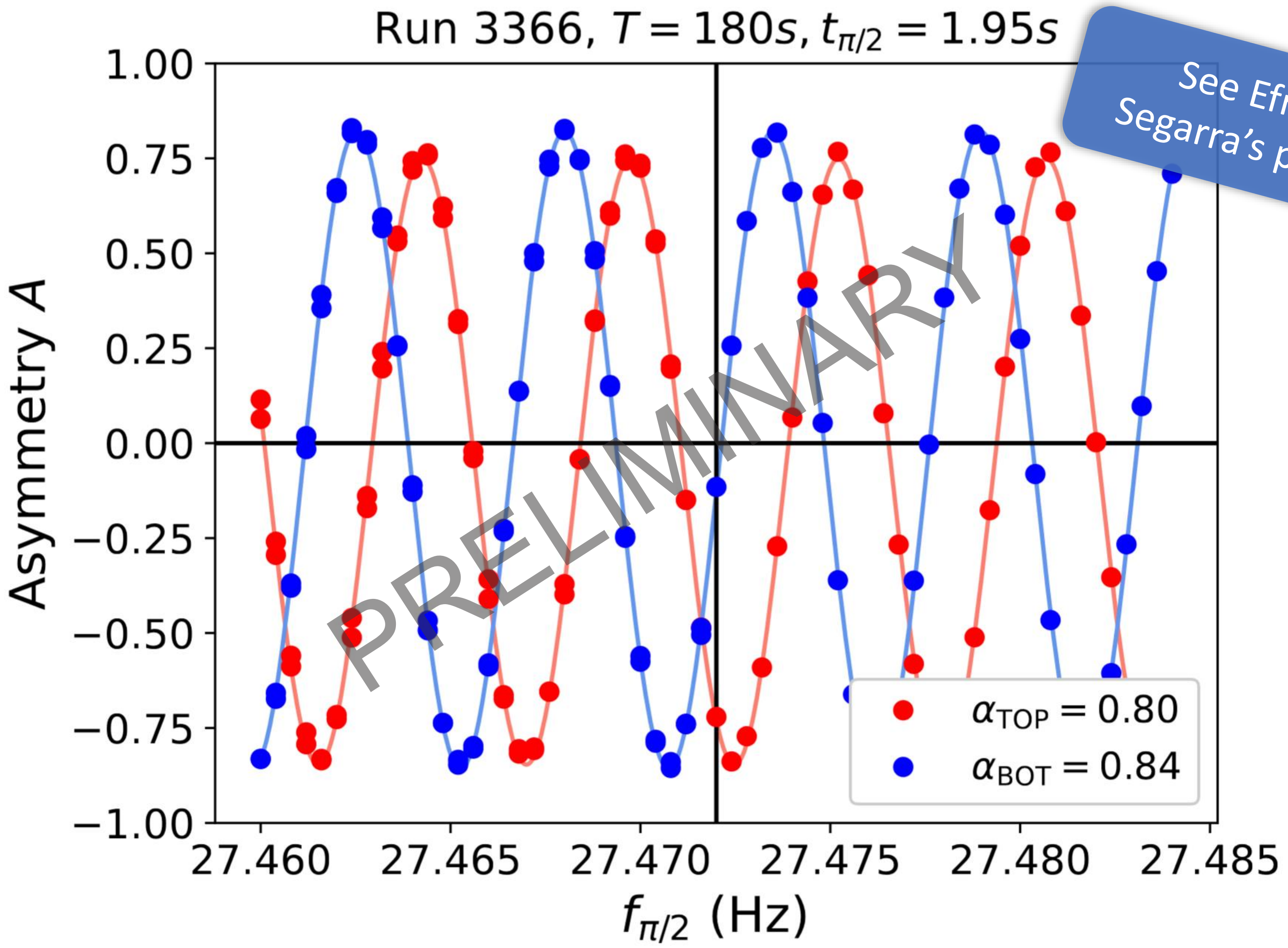
No comagnetometer!

Visibility, $\alpha \approx 80\%$
(Spin analysing detector efficiency $\sim 90\%$)

Is that an EDM?

$$A(f_{\pi/2}) = -\alpha \cos\left(\pi \frac{f_{\pi/2} - f_n - \delta}{\Delta\nu}\right)$$

$$\Delta\nu = \left(2T + 8\ t_{\pi/2}/\pi\right)^{-1}$$



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Is that an EDM?
No, the High Voltage hardware is yet to be installed and commissioned. This shift is too large. i.e. nEDM limit is at 70 nHz

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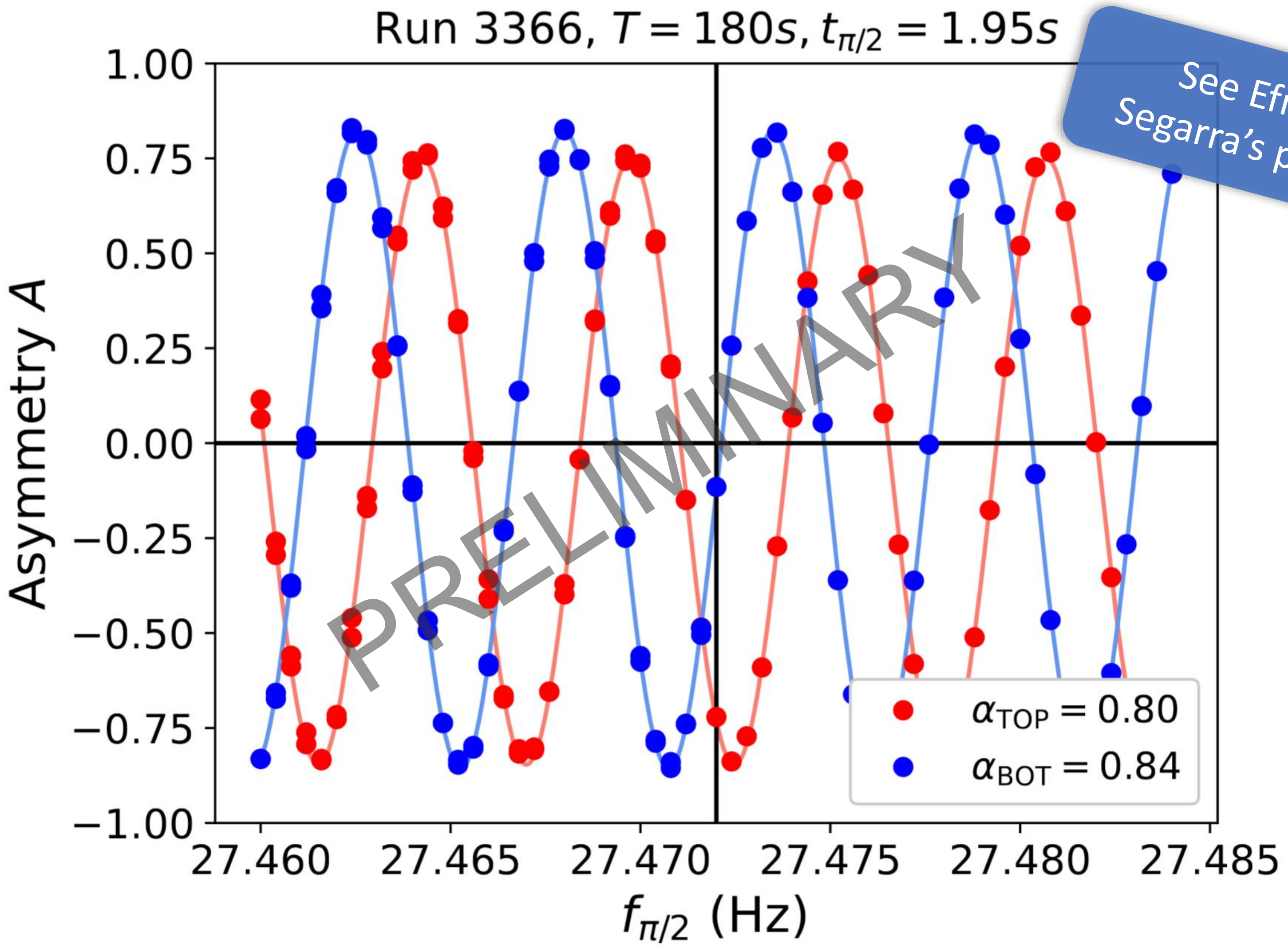

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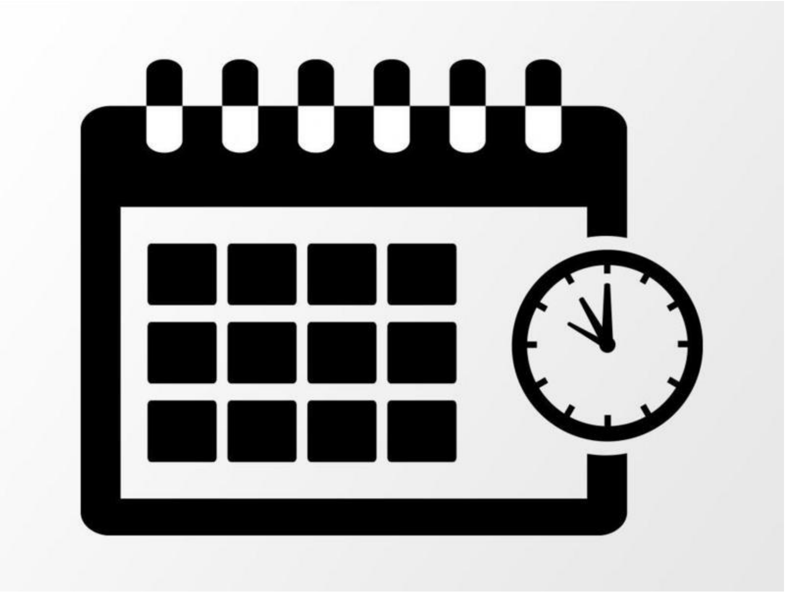
Plans for this year



1) Commissioning of Hg polarization cells
2) Installation and commissioning of high voltage
3) PSI neutron delivery starts in June, preliminary EDM measurements
4) At the end of this year, installation and testing of new electrodes and insulator rings

Thank you for your attention
Any questions?

[n2EDM design] doi:10.1140/epjc/s10052-021-09298-z (2021)
[MSR] doi:10.1063/5.0101391 (2022)
[PSI UCN source] doi:10.3929/ethz-b-000579840 (2022)
[Degaussing] arXiv:2309.16877 (2023)
[AMS] doi:10.1140/epjc/s10052-023-12225-z *(2023)*

pmullan@phys.ethz.ch