# Achieving ultra-low and -uniform magnetic fields with n2EDM

Efrain Segarra @ Paul Scherrer Institut

nEDM2023,

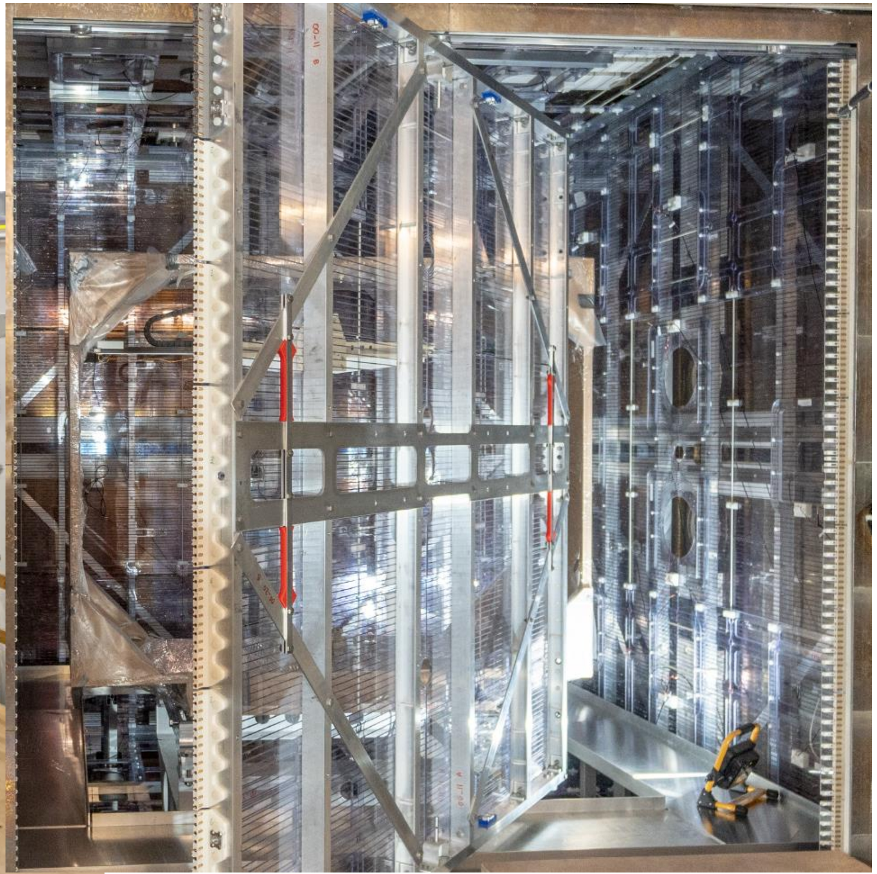
Nov 8, 2023

# Magnetic field control for n2EDM

Active magnetic shield

Magnetically shielded room

$B_0$ field



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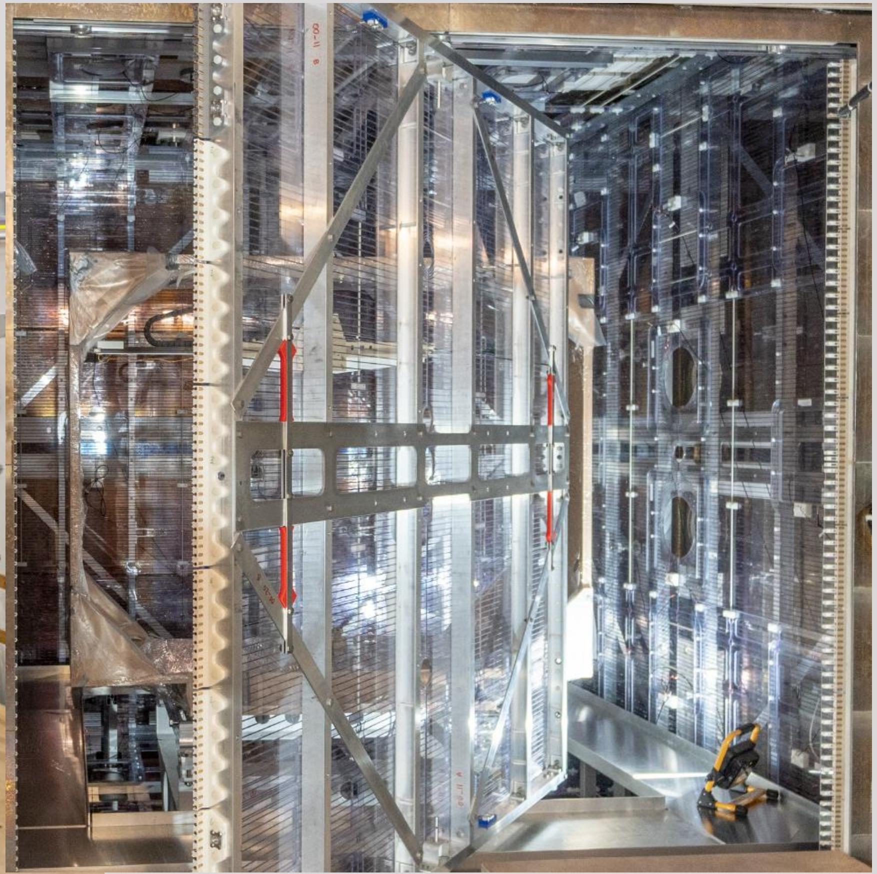
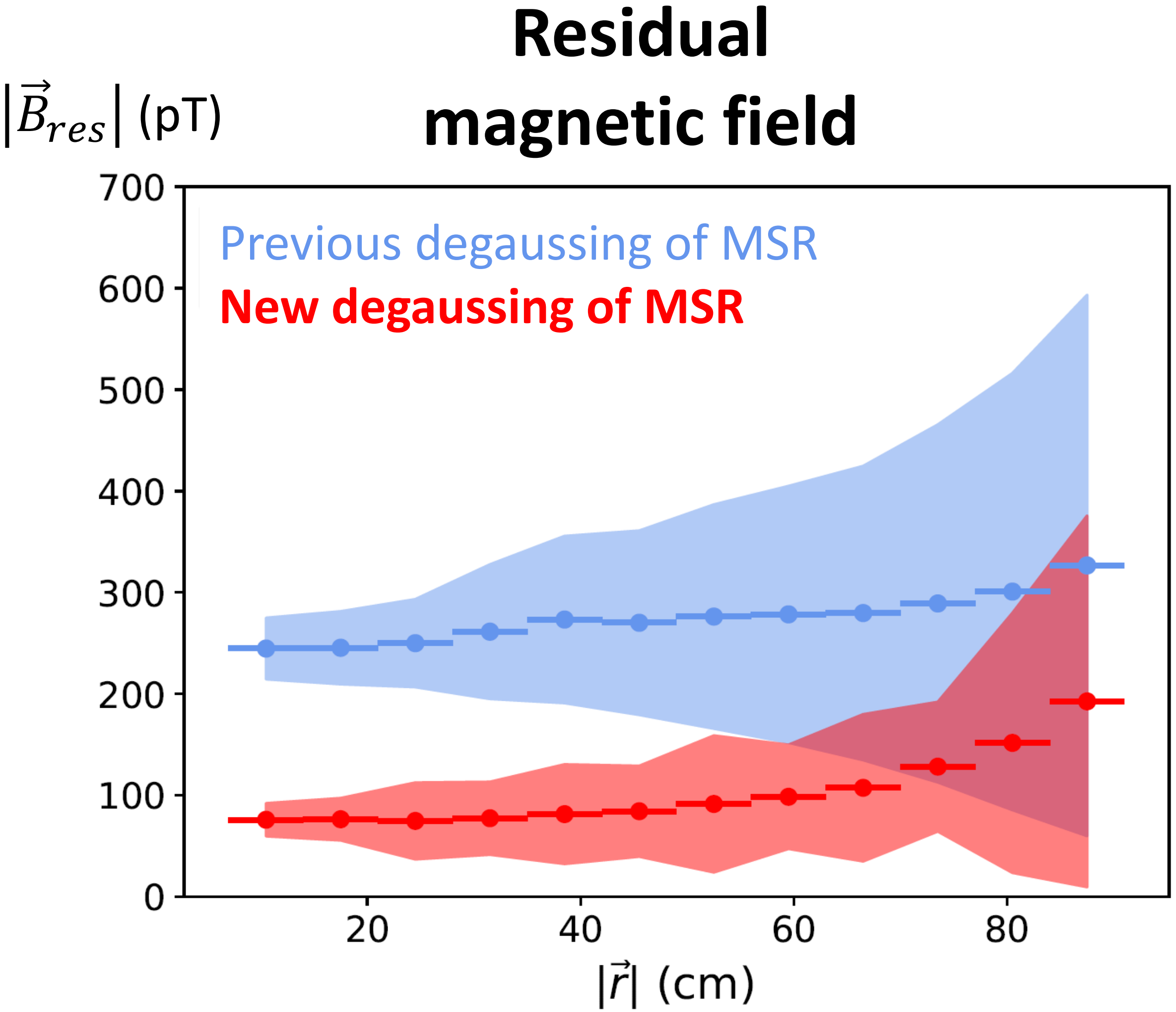
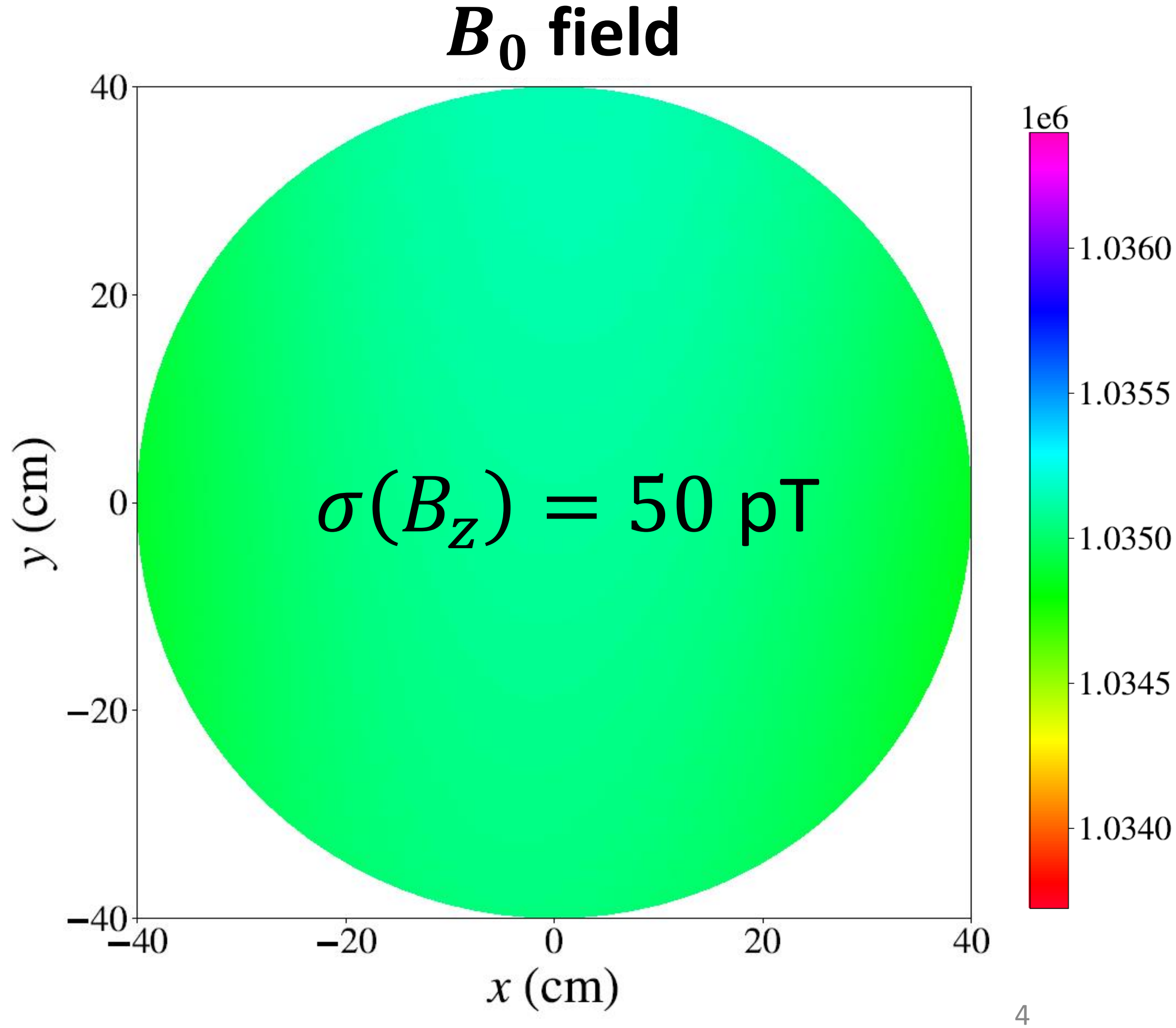


# Today: magnetic environment ready for UCNs





The nEDM Collaboration, arXiv:2309.16877 (submitted)

# The Magnetically Shielded Room (MSR)

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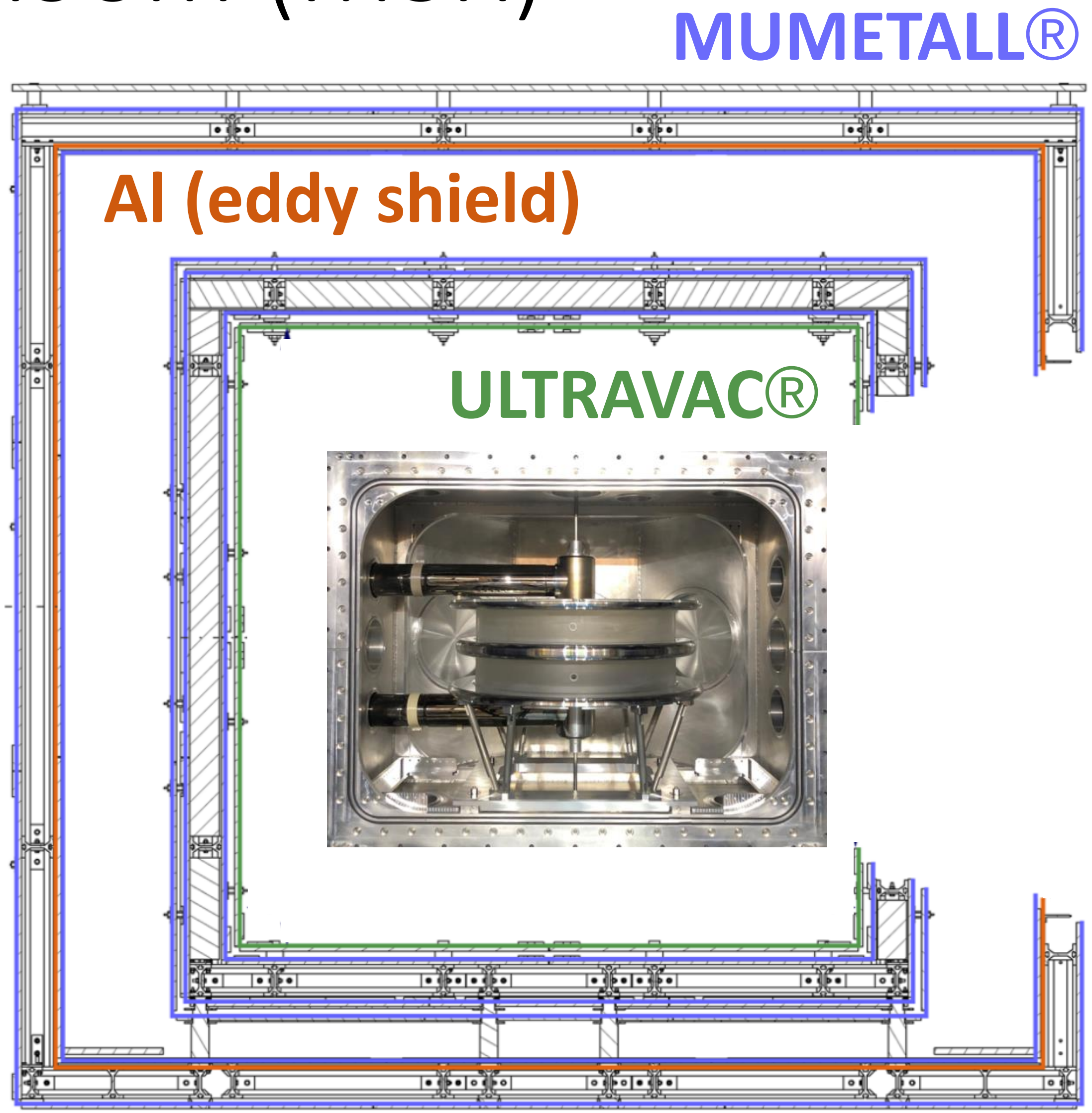
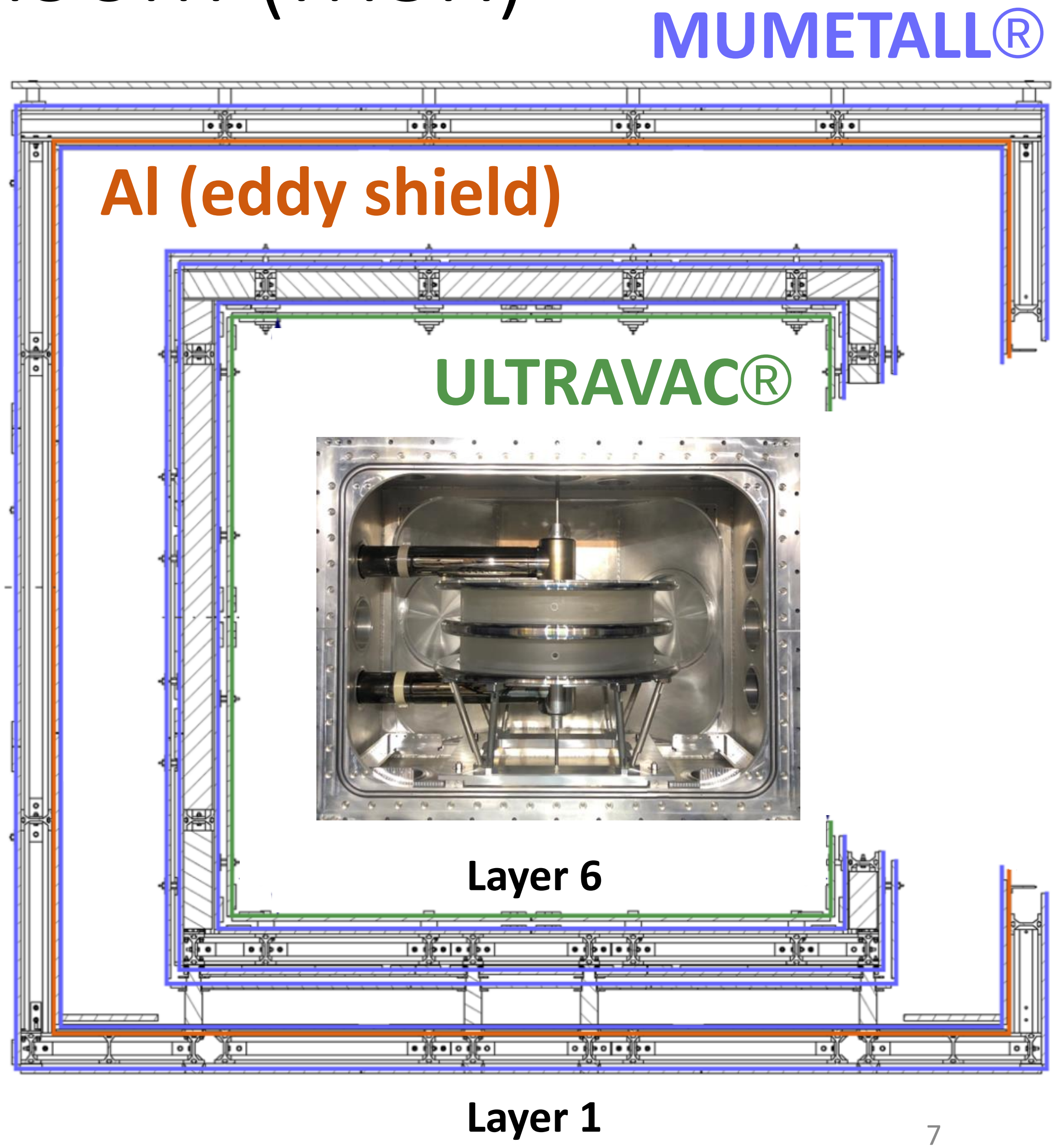


# The Magnetically Shielded Room (MSR)

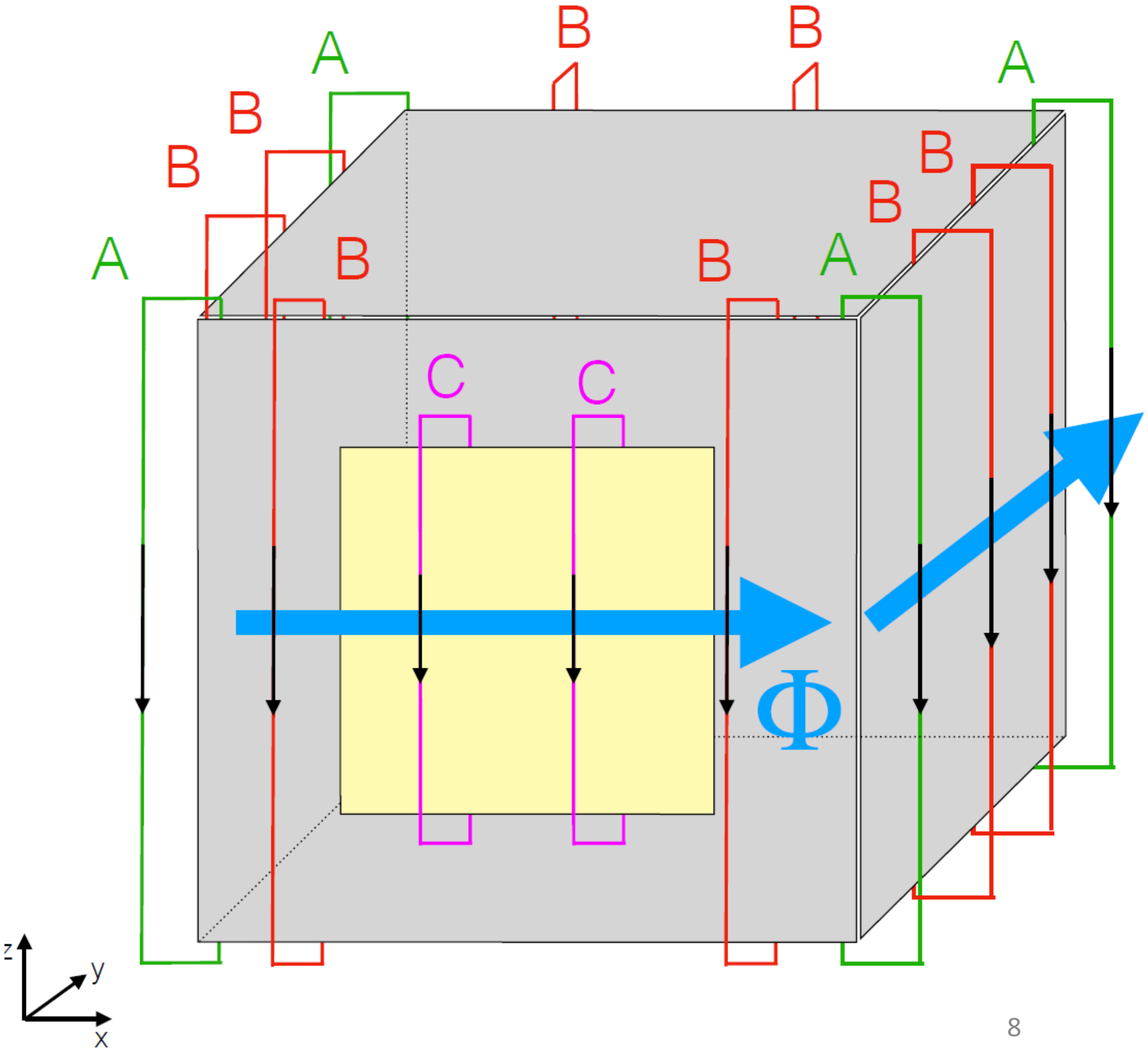
- 6 permeable layers
- Shielding factor $10^5$ at 0.01 Hz ($1\mu\text{T} \rightarrow 10\text{pT}$)
- Excitation coils to degauss permeable layers



The nEDM Collaboration, *Rev. Sci. Intrum. (2022)*

# Degaussing coils of MSR

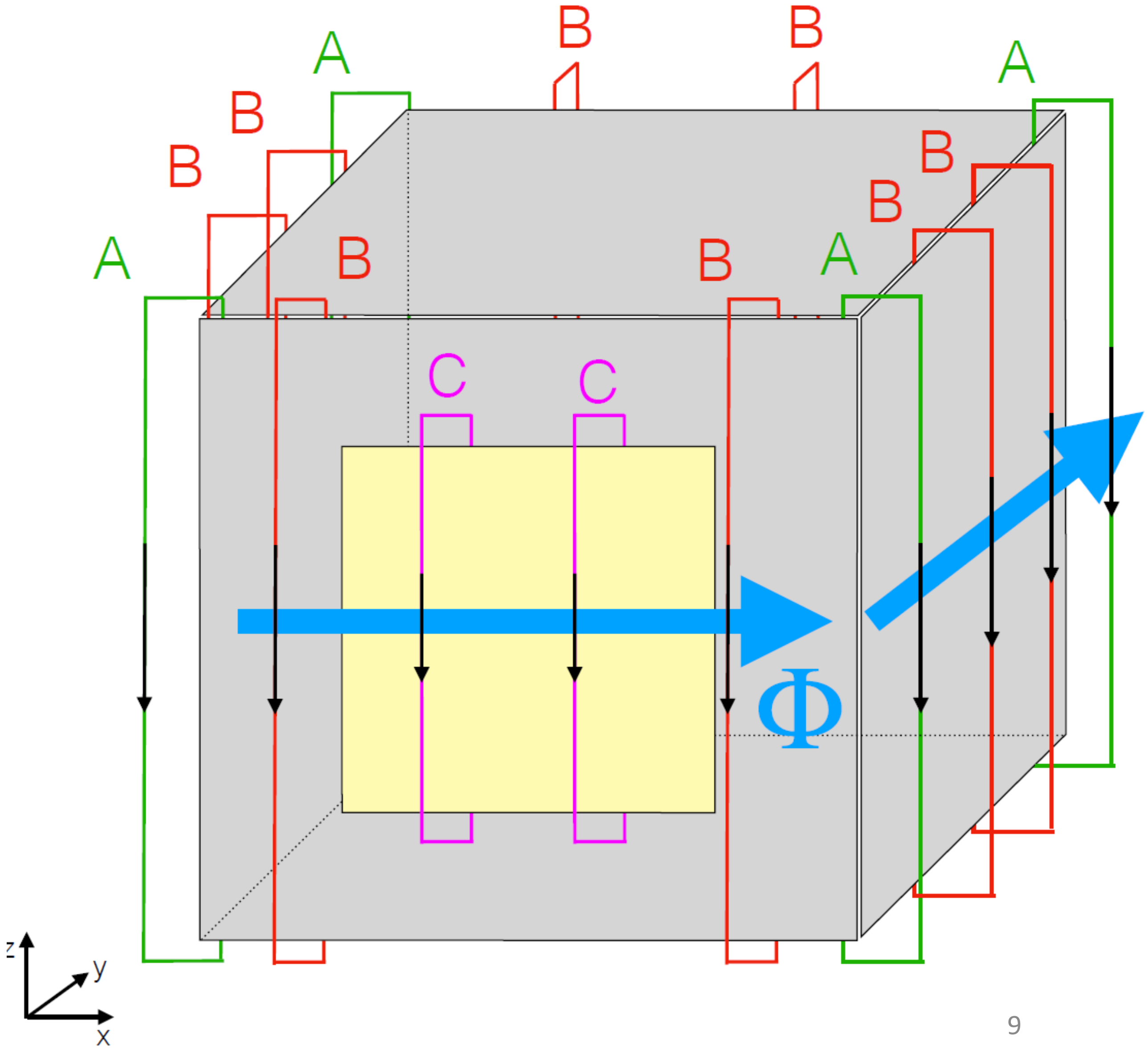
- Layers 1-5 uses corner coils for each spatial direction



The nEDM Collaboration, arXiv:2309.16877 (submitted)

# Degaussing coils of MSR

- Layers 1-5 uses corner coils for each spatial direction
- Layer 6 has distributed coils

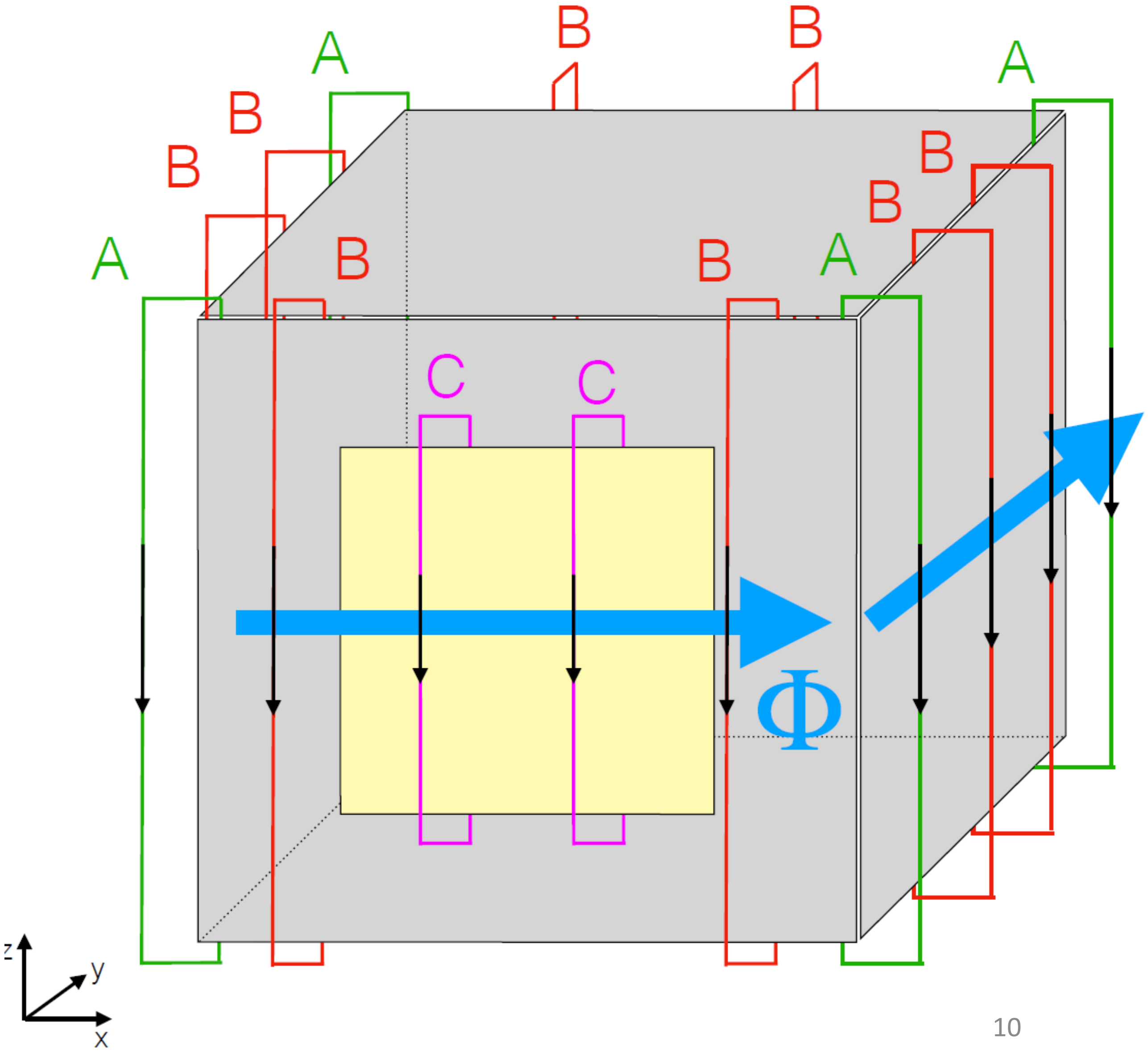


The nEDM Collaboration, arXiv:2309.16877 (submitted)

# Degaussing coils of MSR

- Layers 1-5 uses corner coils for each spatial direction
- Layer 6 has distributed coils
- Additional coils on the door

→ **100 coils in total**



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# Previous degaussing procedure

- From outside MSR to inside
- Flux around x-, then y-, then z-axis (***serial***)

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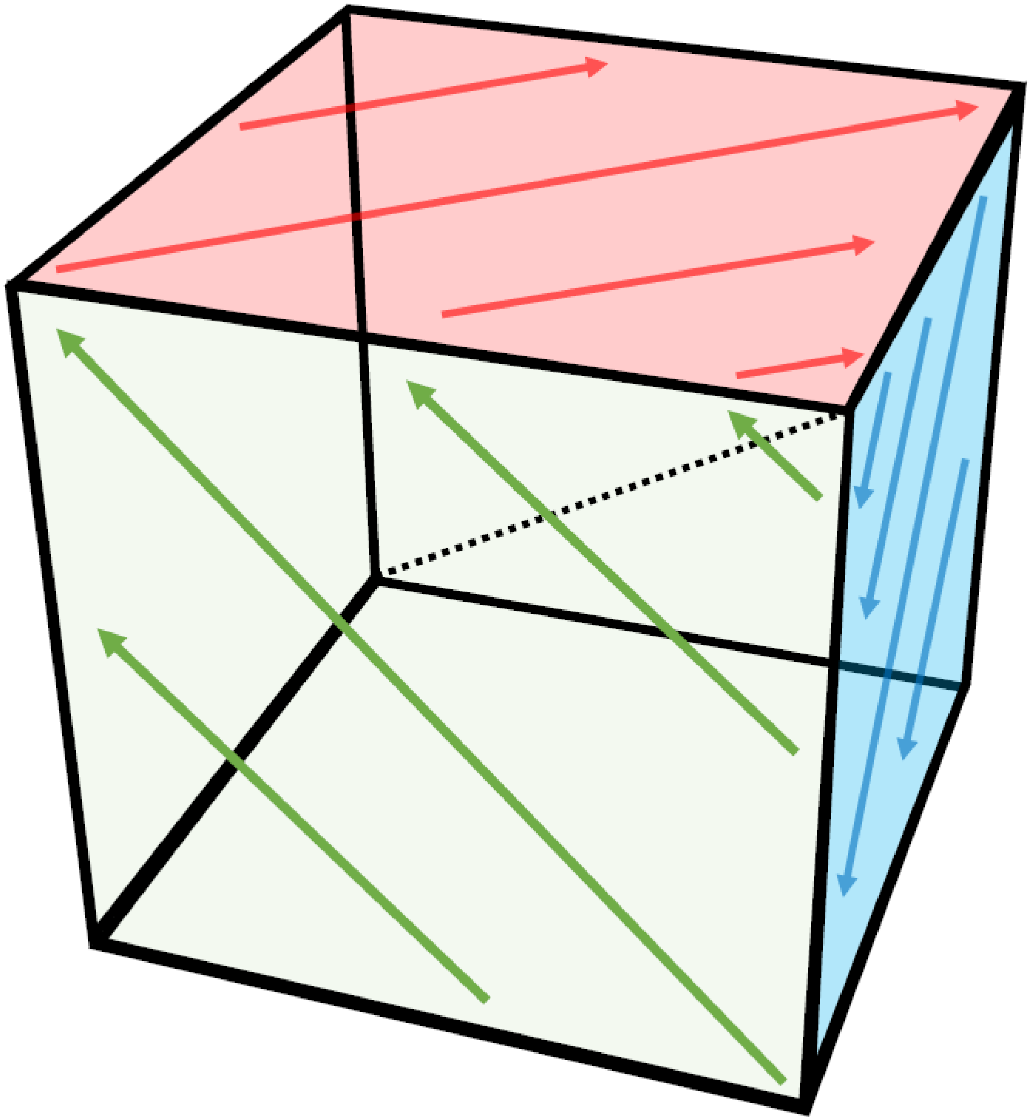
- From outside MSR to inside
- Flux around x-, then y-, then z-axis (***serial***)
- 3.5 hours to degauss + 12 hours for thermal stability
- Residual magnetic field up to 600 pT

# *Can we improve this?*

- From outside MSR to inside
- Flux around x-, then y-, then z-axis (***serial***)
- ***3.5 hours to degauss + 12 hours*** for thermal stability
- Residual magnetic field up to ***600 pT***

# Well we can generate flux simultaneously* in x-y-z

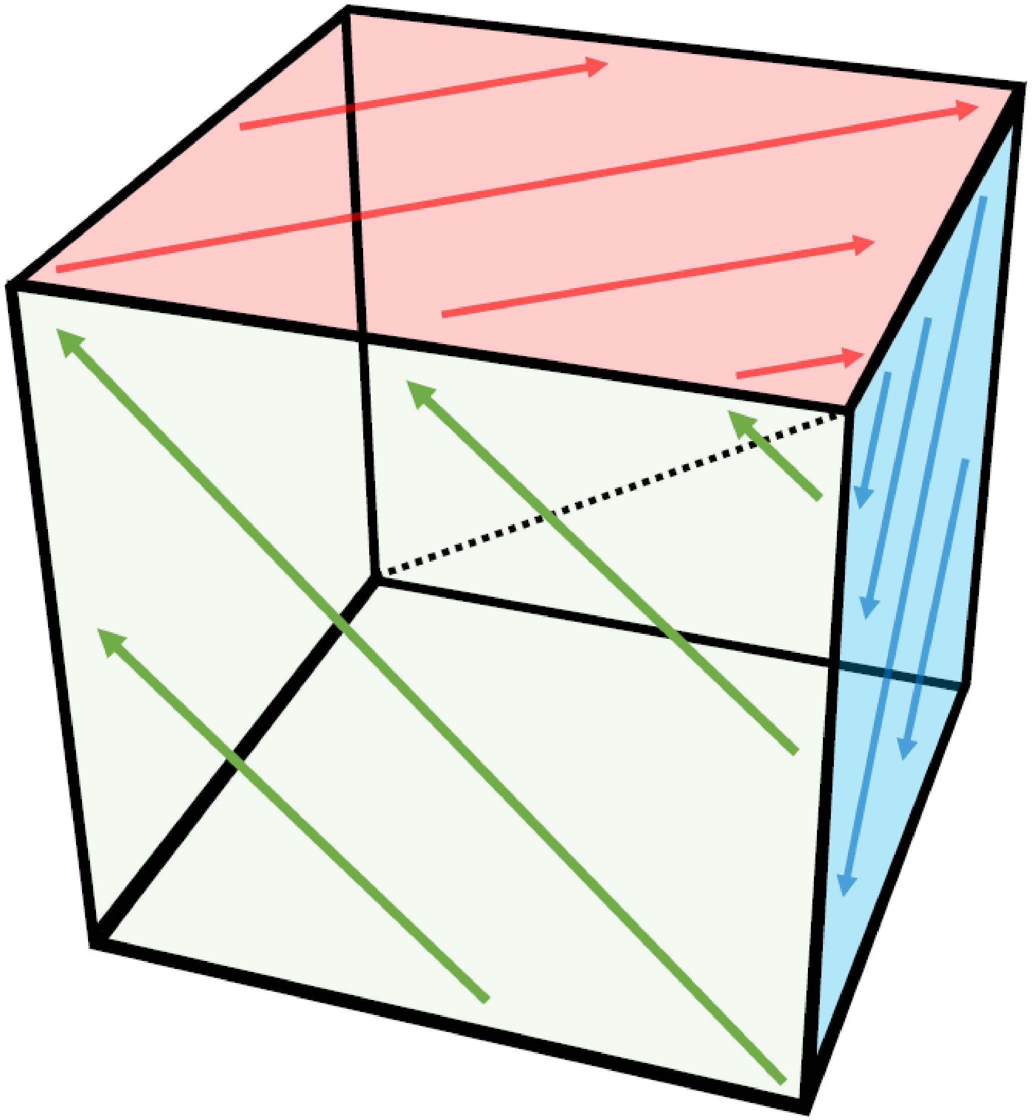


*In layer 6 (innermost) only

The nEDM Collaboration, [arXiv:2309.16877 (submitted)](https://arxiv.org/abs/2309.16877)

# We can achieve huge improvements

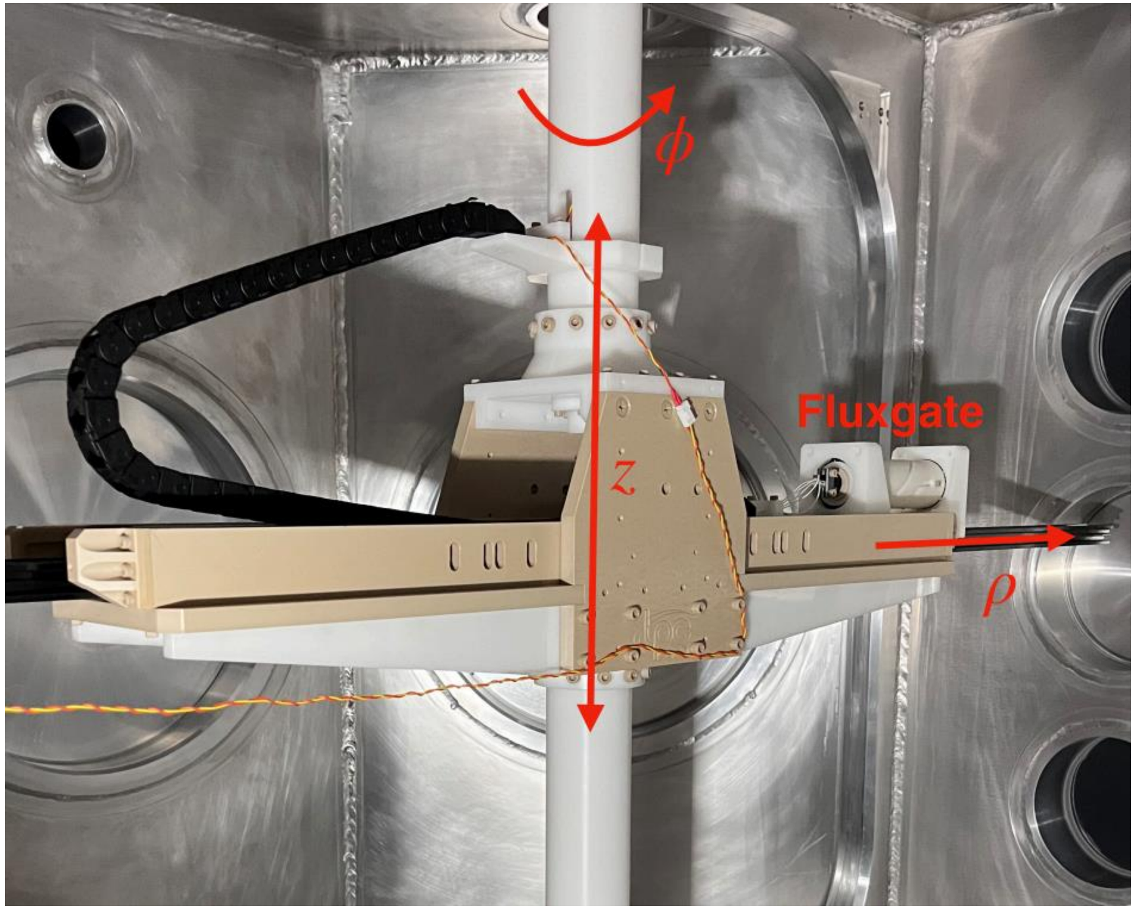
- Reduces time to degauss (2.4 hours)
- Reduces equilibrium time (1.5 hours)
- Reduces residual field (< 300 pT)

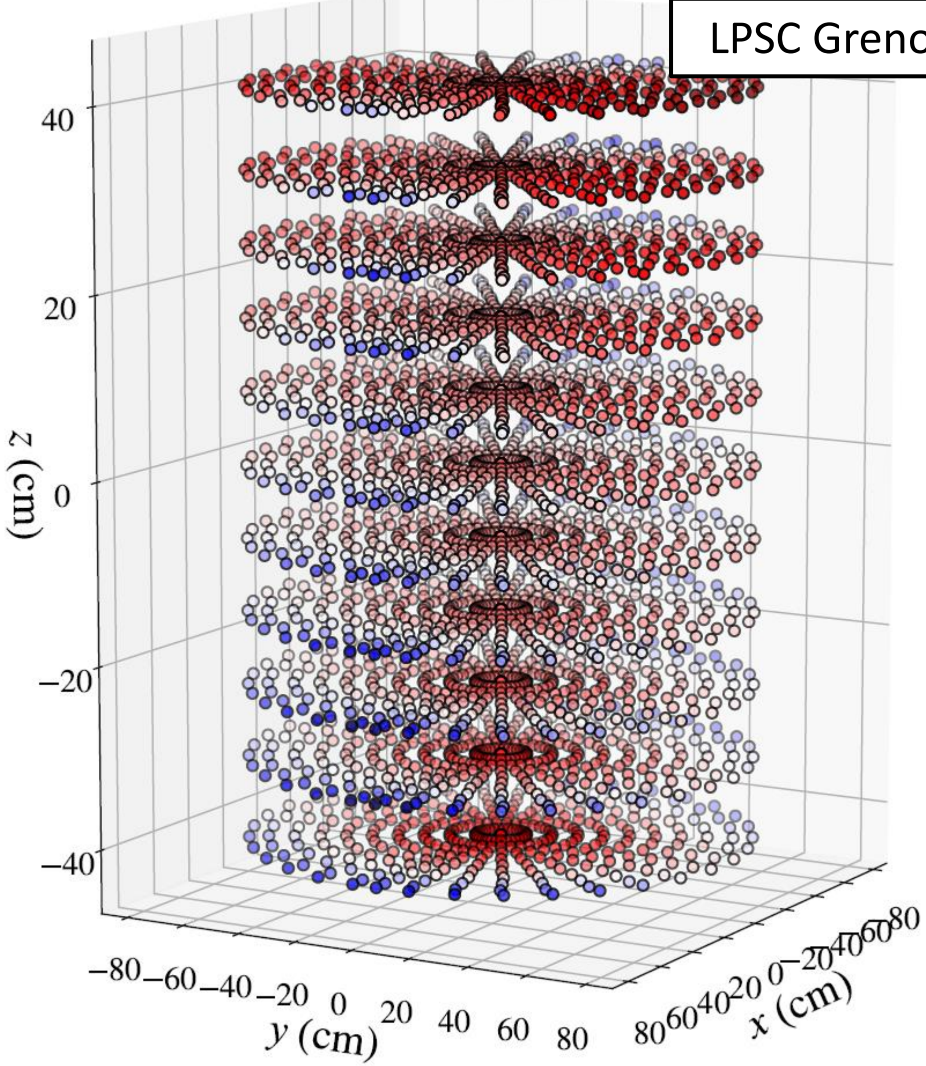


The nEDM Collaboration, [arXiv:2309.16877 (submitted)]()

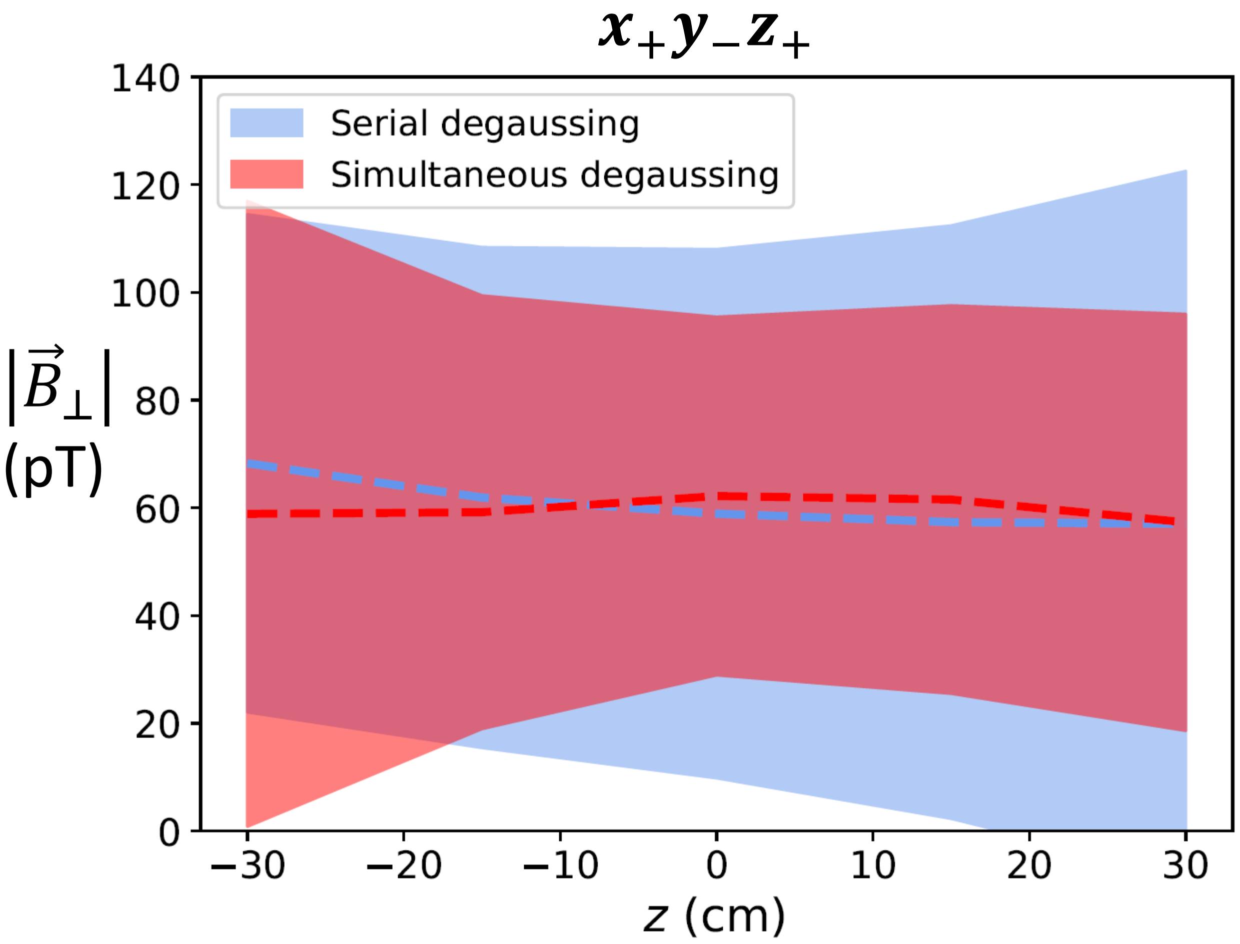
# Mapping the magnetic environment

LPSC Grenoble





# Residual field after simultaneous degaussing



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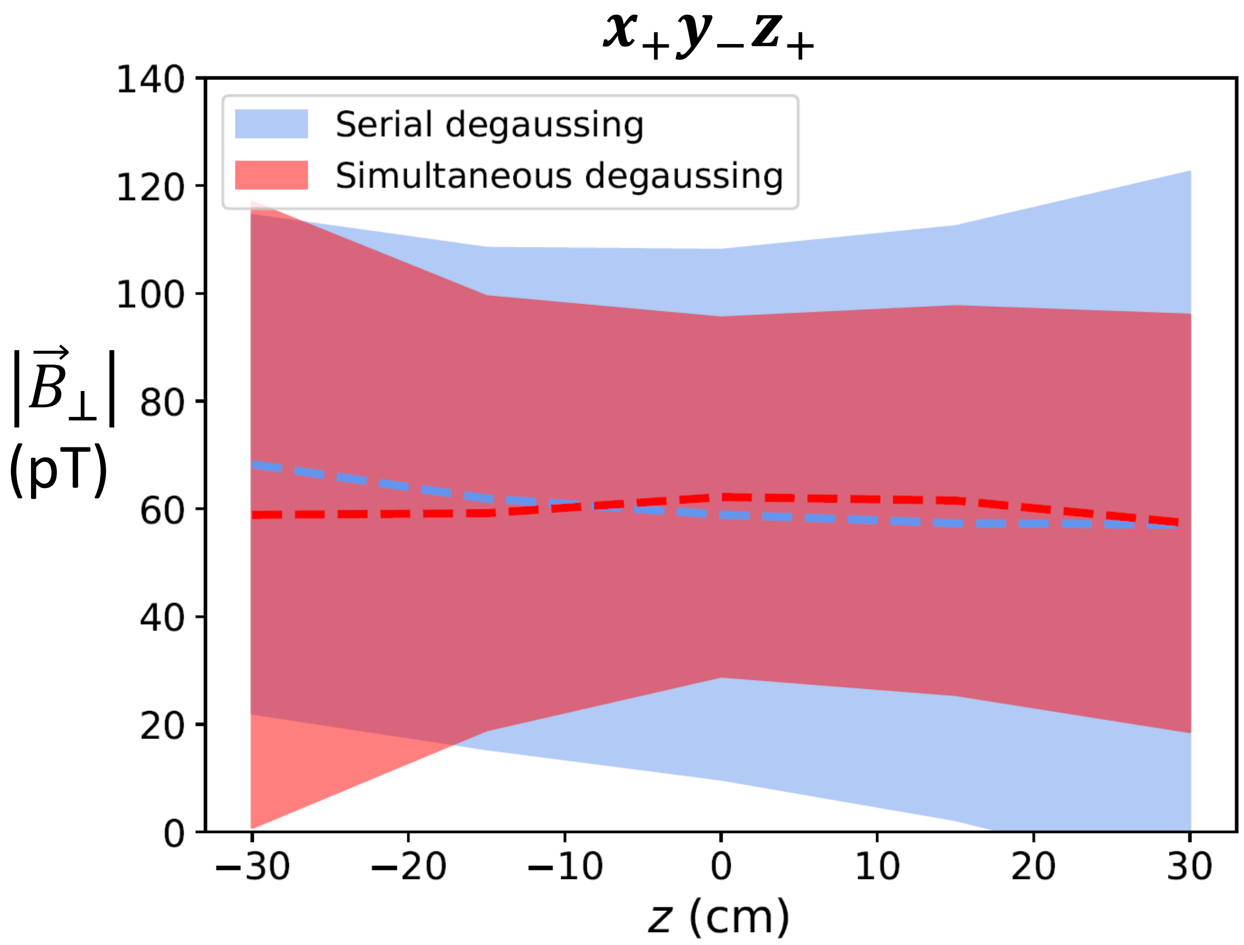
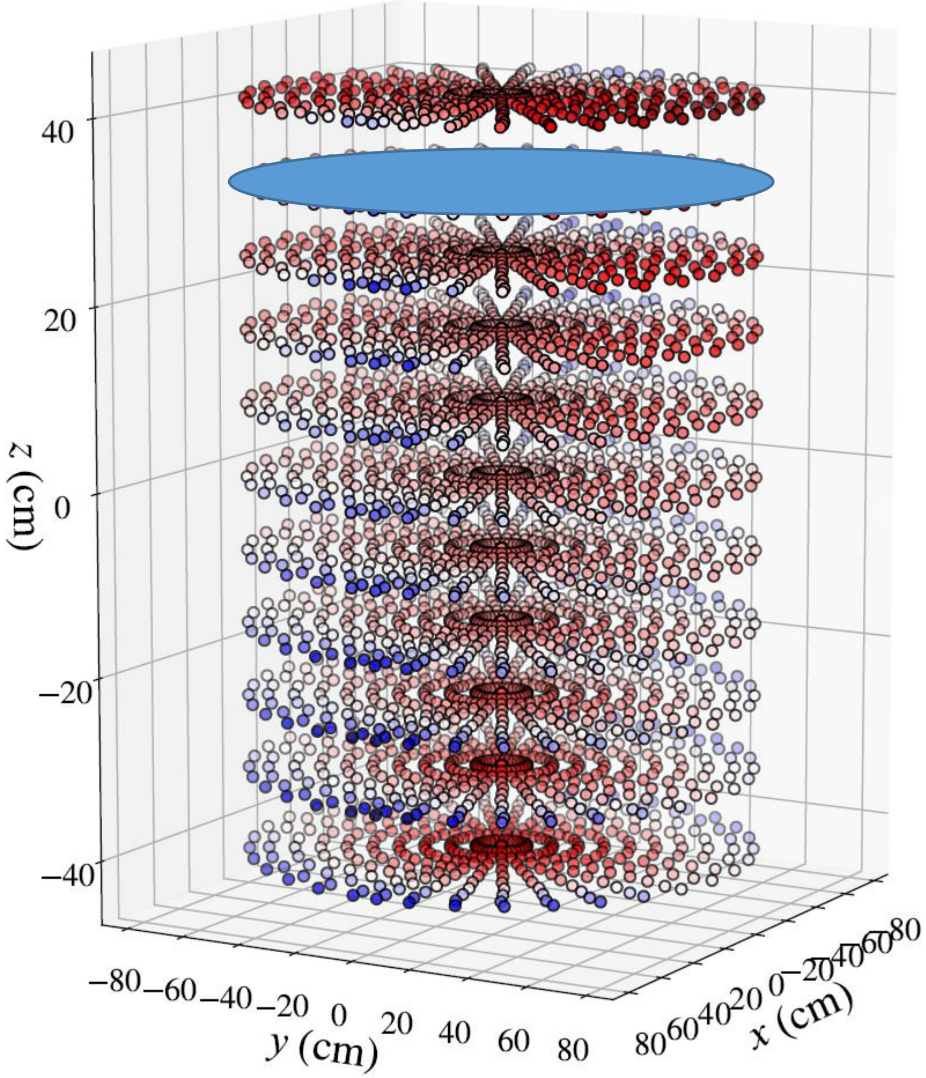


$|\vec{B}_\perp|$: Average transverse field in each disk



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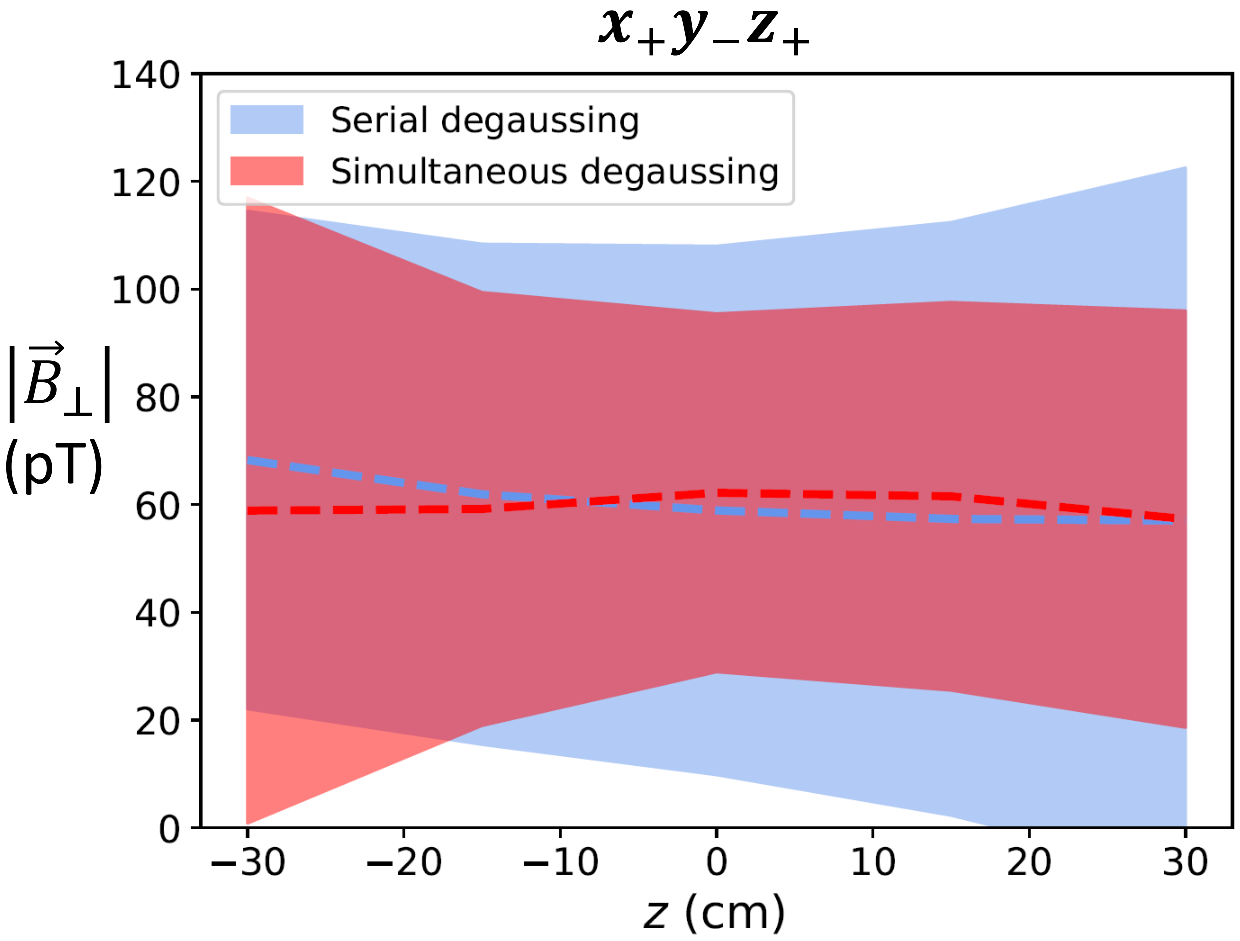
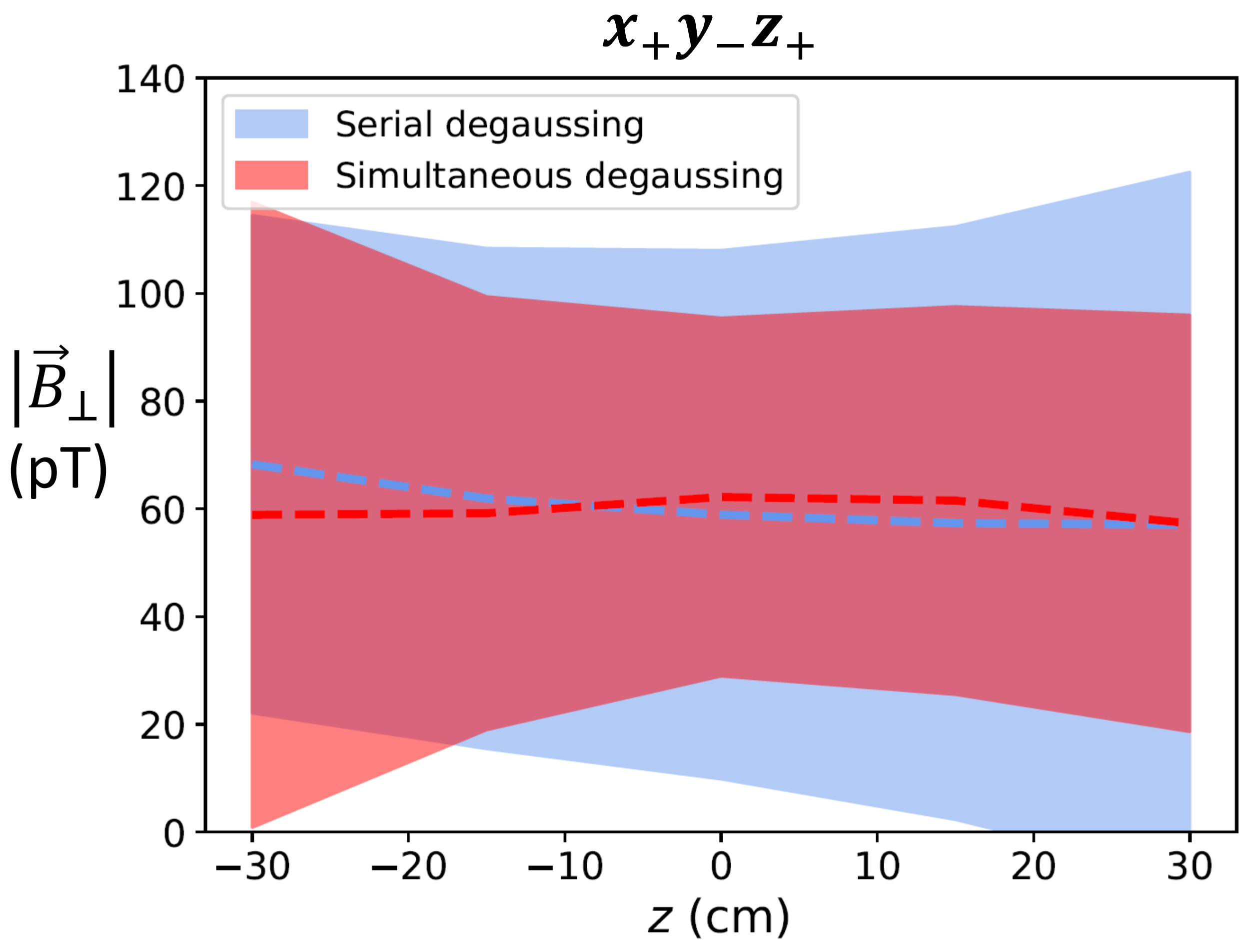
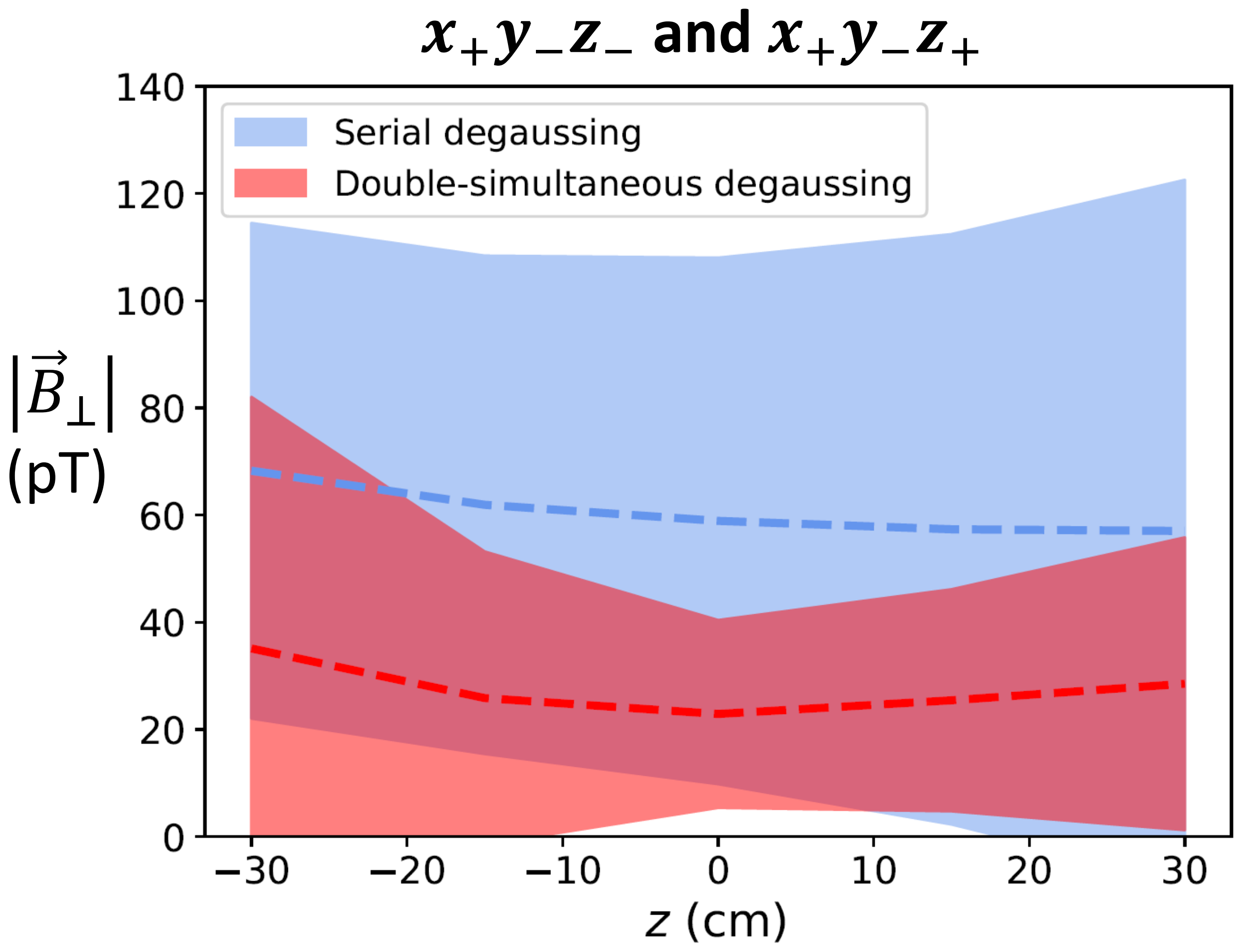


- Faster
- Less heat
- Bit more uniform
- Just as low residual

The nEDM Collaboration, arXiv:2309.16877 (submitted)

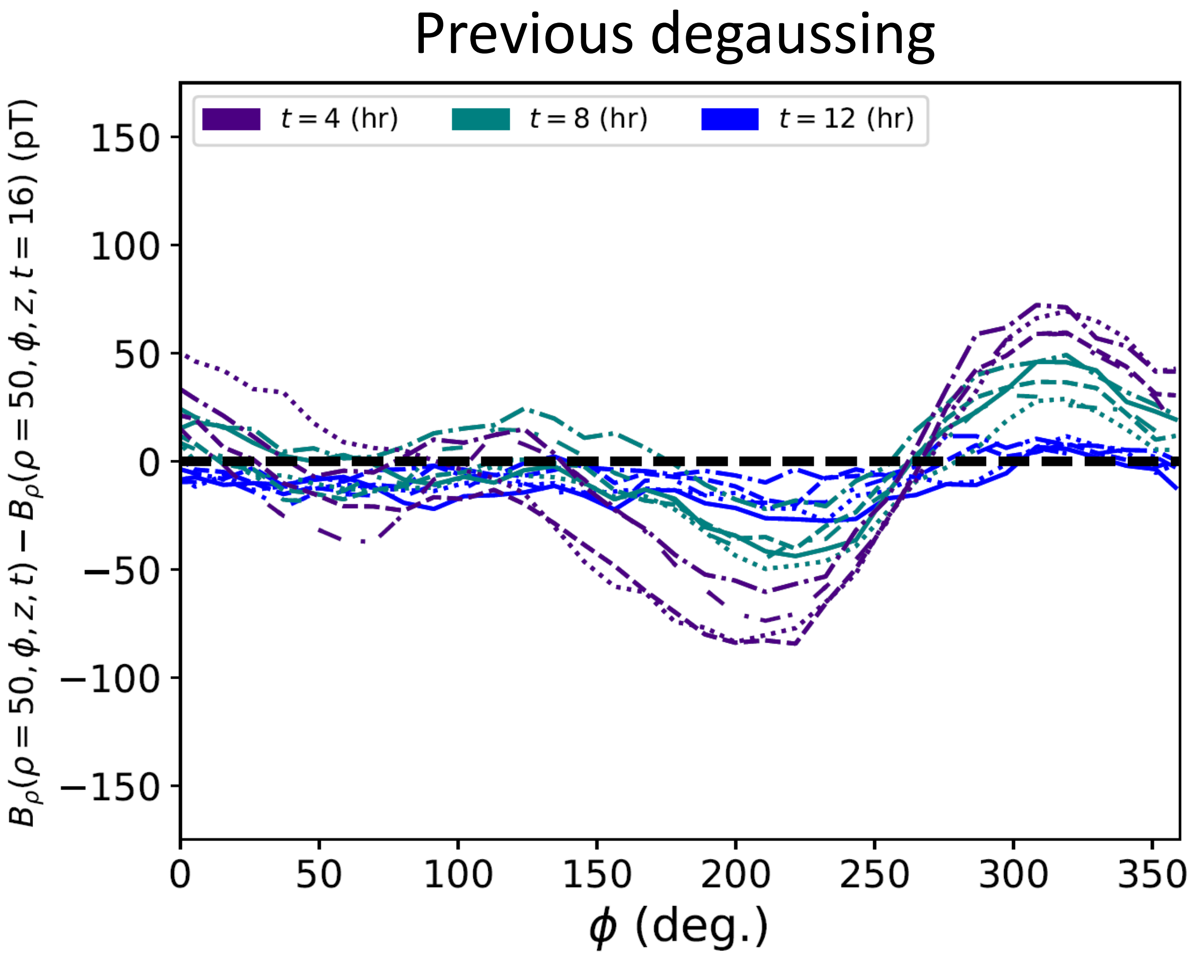
# Do it twice: lower and more uniform residual field





The nEDM Collaboration, [arXiv:2309.16877 (submitted)]

# Previous degaussing took 12 hours to relax



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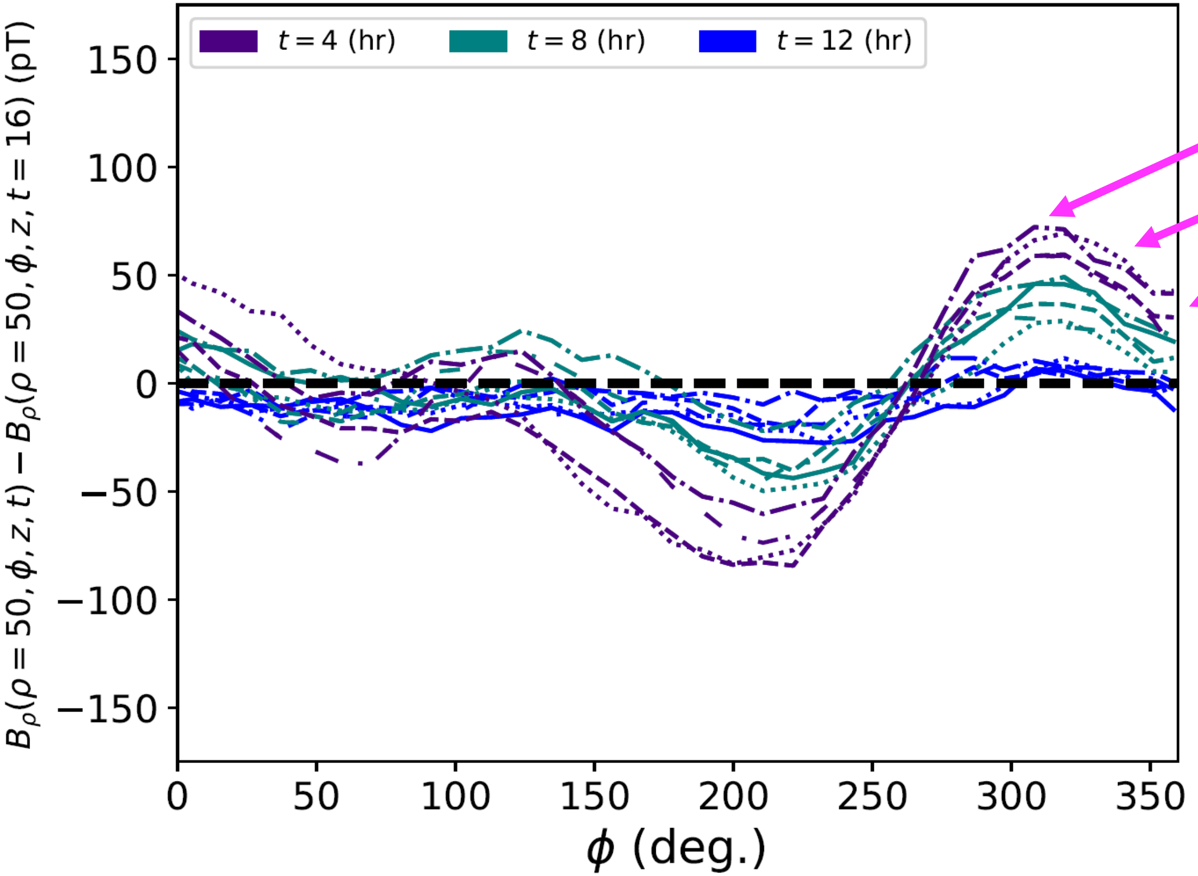
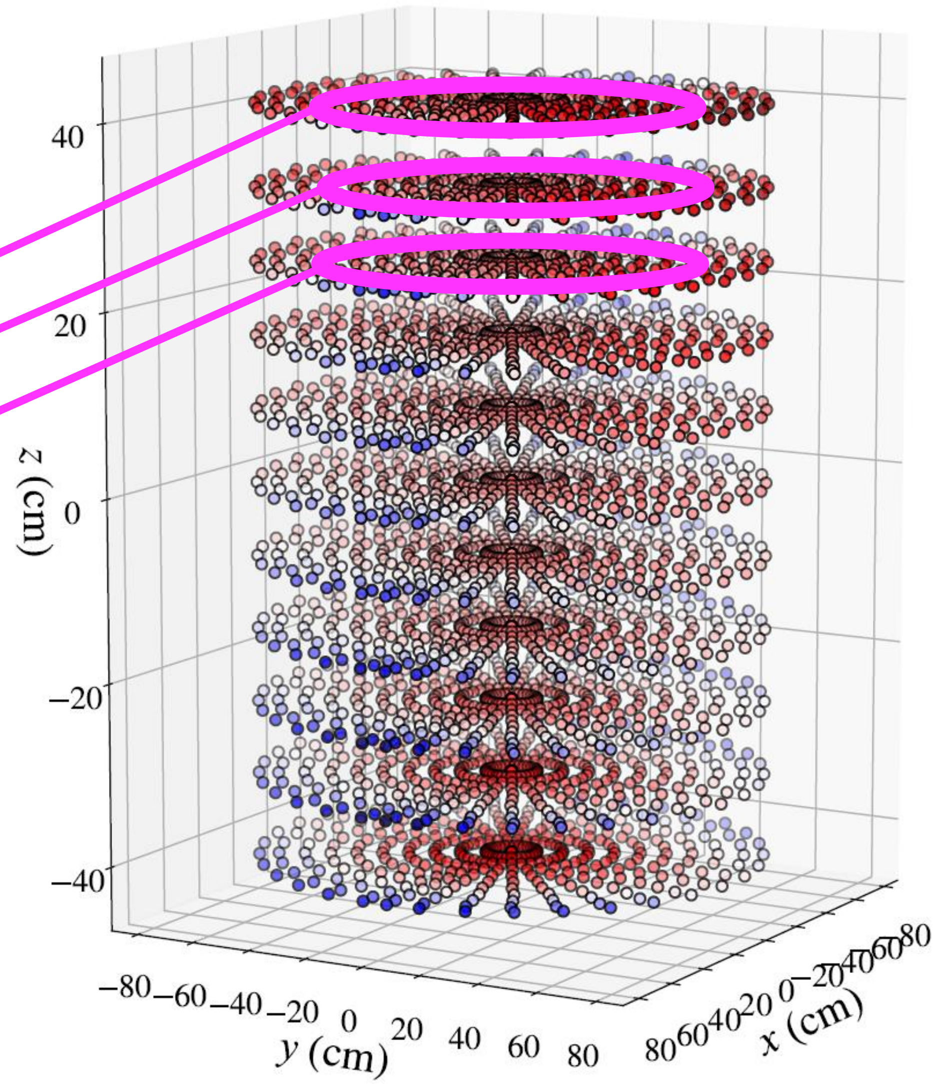


$B_\rho(\phi)$ at fixed $z, \rho$ at different $t$



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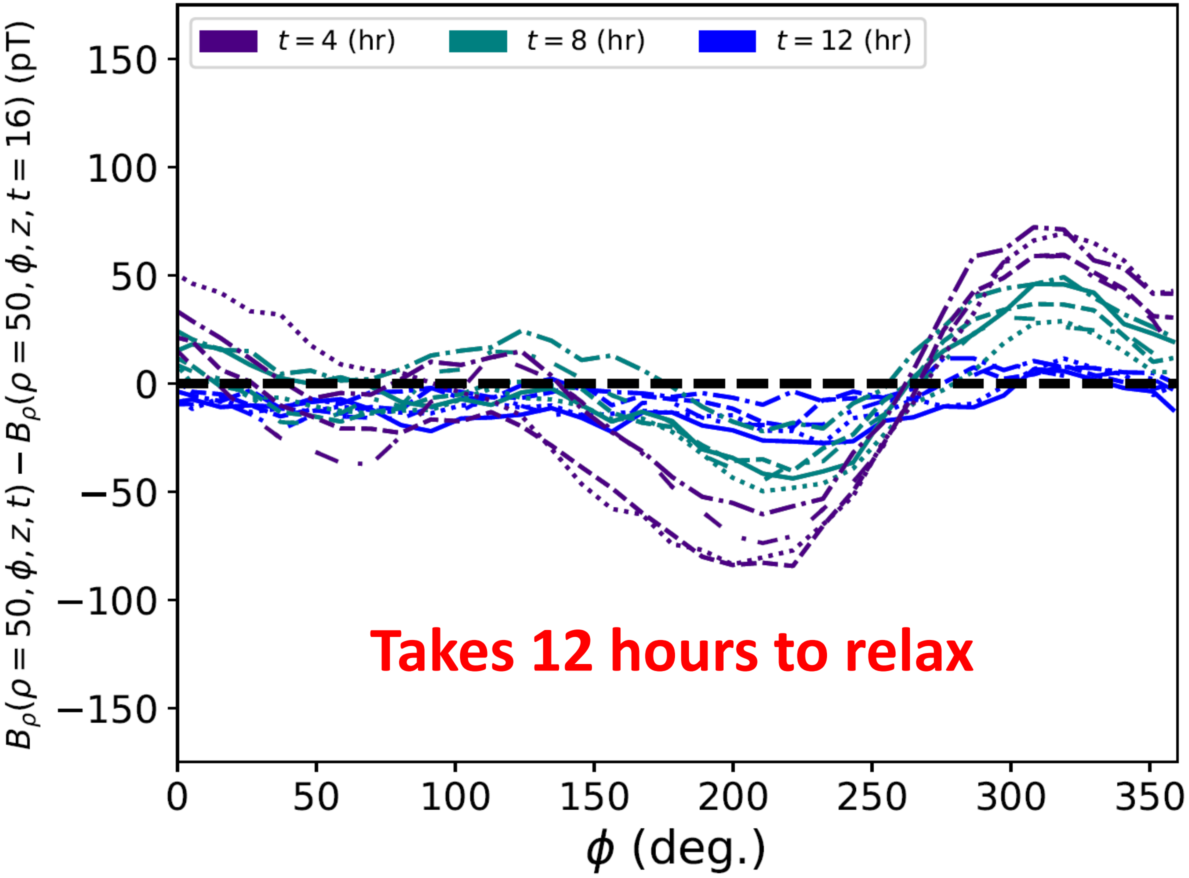
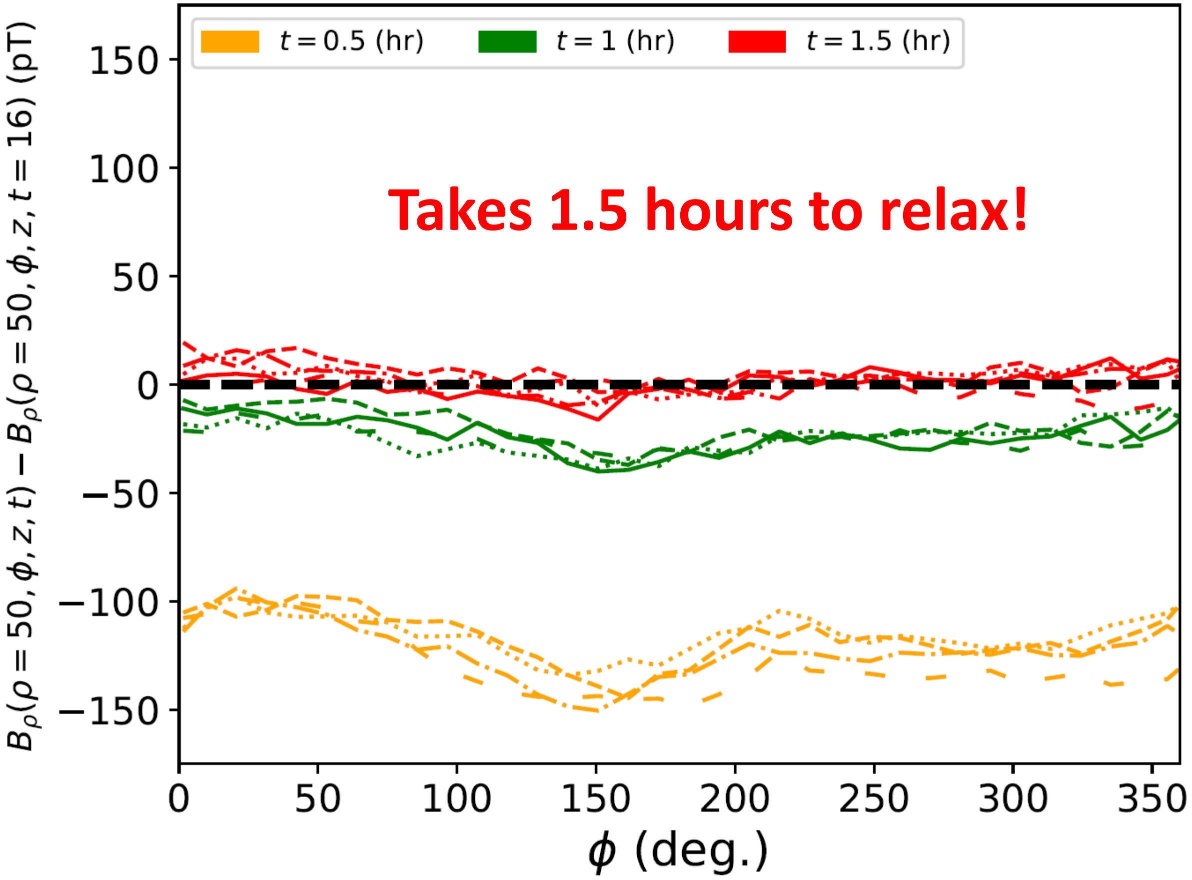
# Double-simultaneous degaussing relaxes faster

## Previous degaussing



**Takes 12 hours to relax**

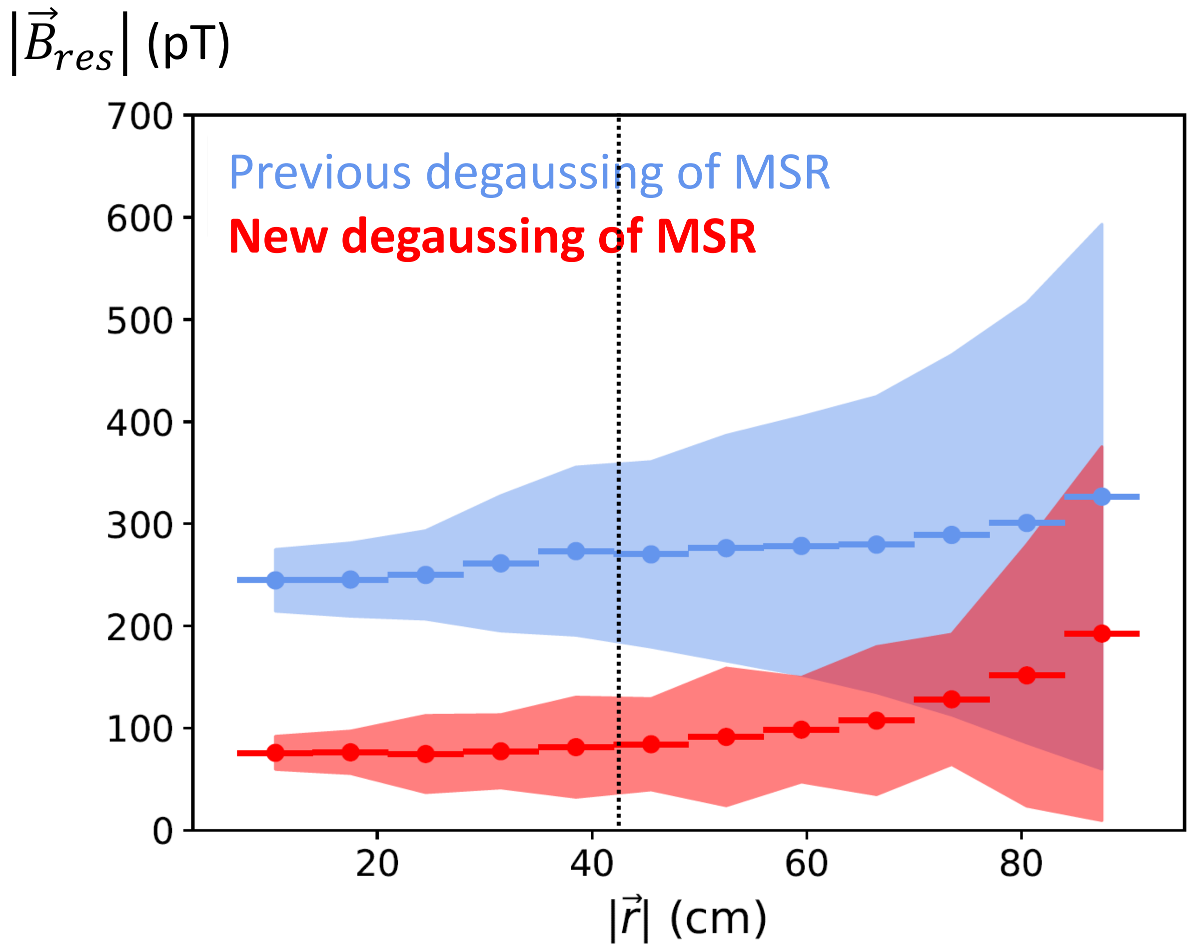
## New degaussing



**Takes 1.5 hours to relax!**

The nEDM Collaboration, arXiv:2309.16877 (submitted)

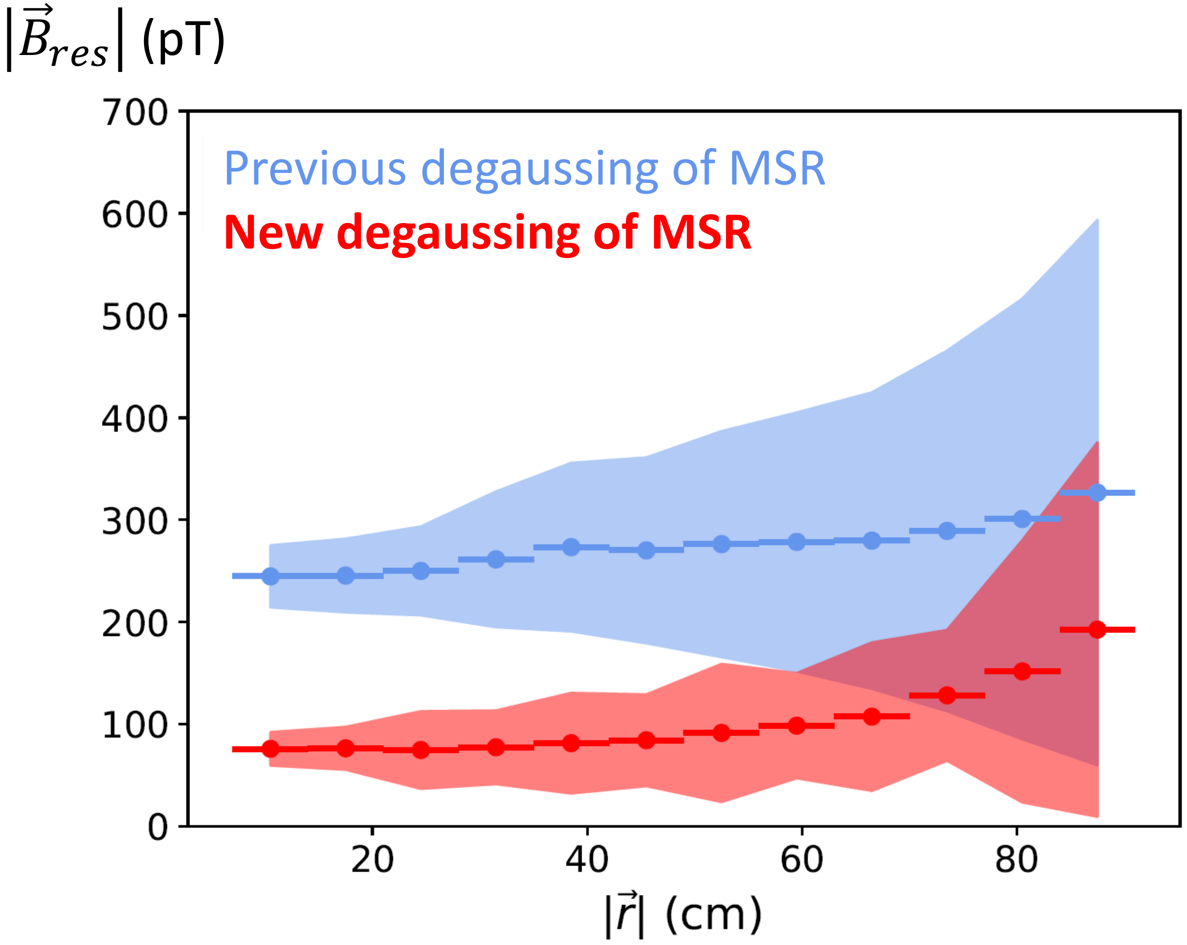
# Total residual field is more uniform and lower



The nEDM Collaboration, arXiv:2309.16877 (submitted)

# Huge improvements with residual field in MSR

- Reduces time to degauss
- Reduces equilibrium time
- Lower residual field
- More uniform



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# How does $B_0$ look in this environment?

LPSC Grenoble

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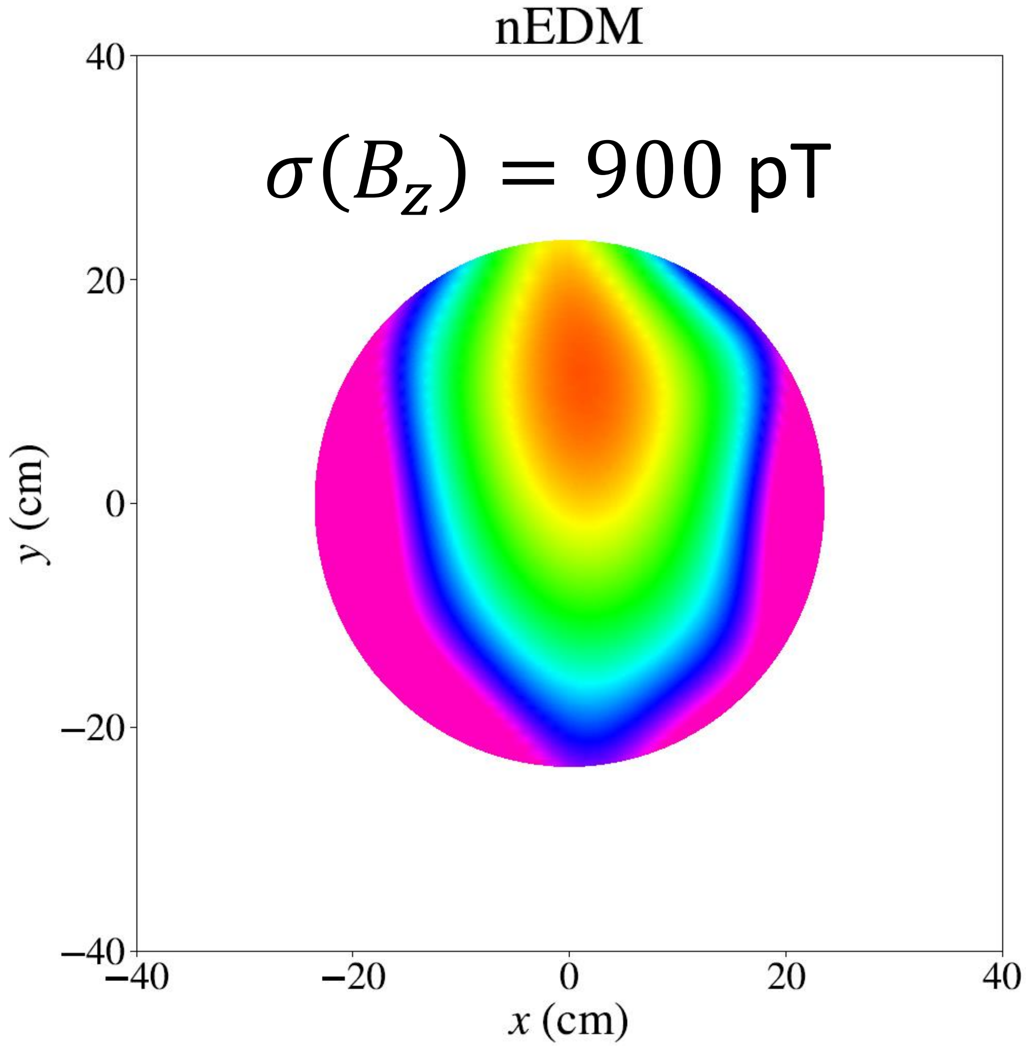
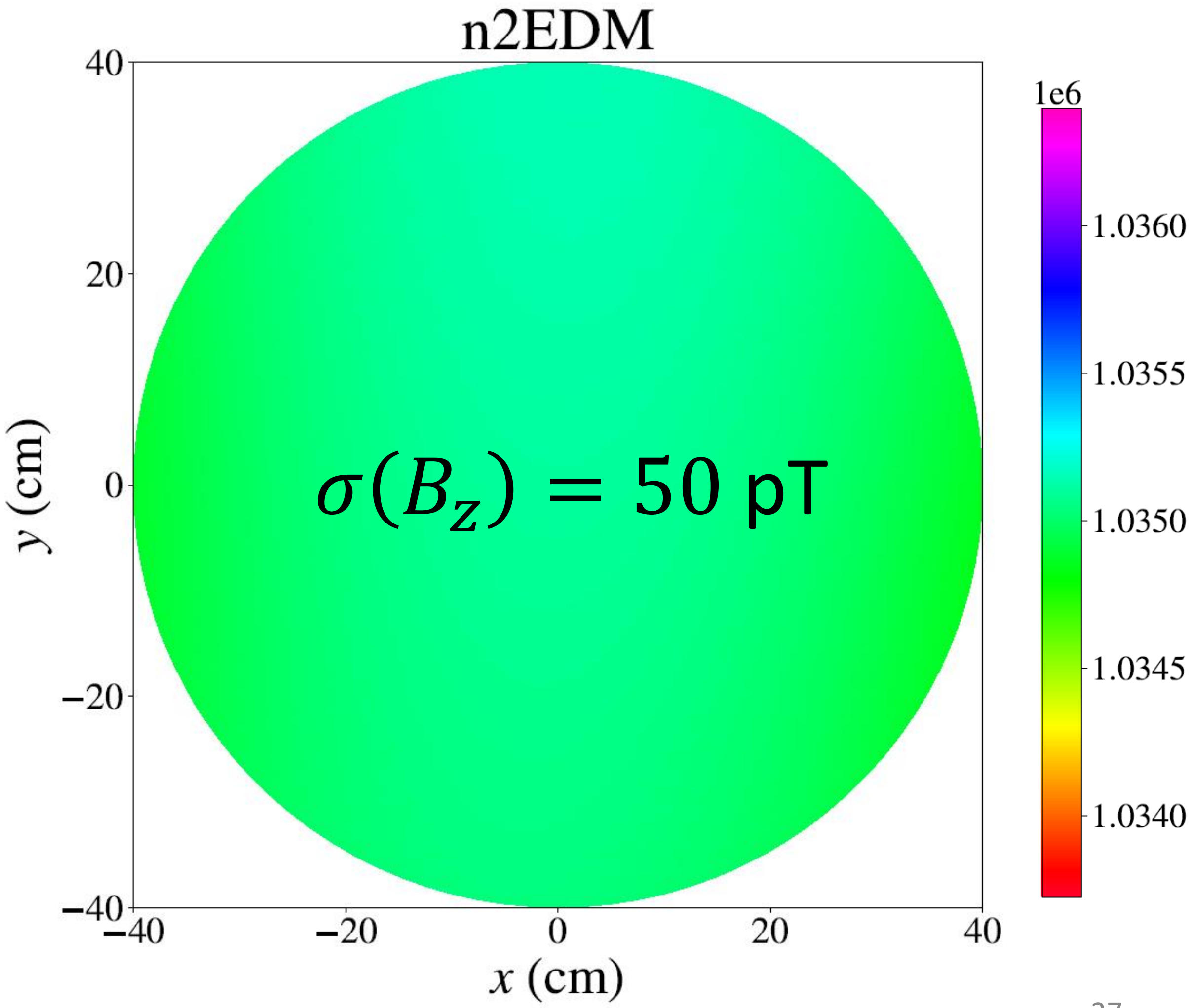


$\sigma(B_z) = 900$ pT

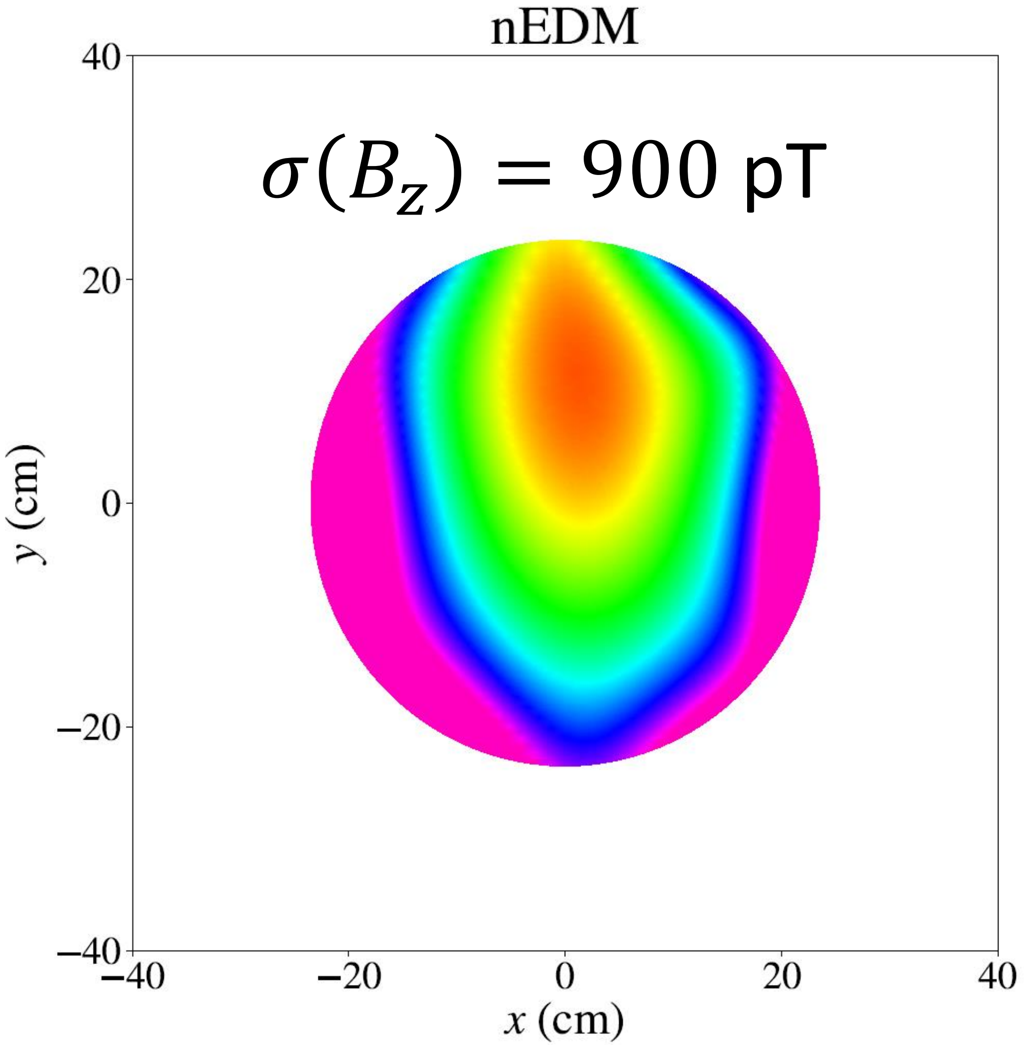


$\sigma(B_z) = 50$ pT

# Requirement for UCN depolarization

$\sigma(B_z) < 170$ pT ✓

LPSC Grenoble



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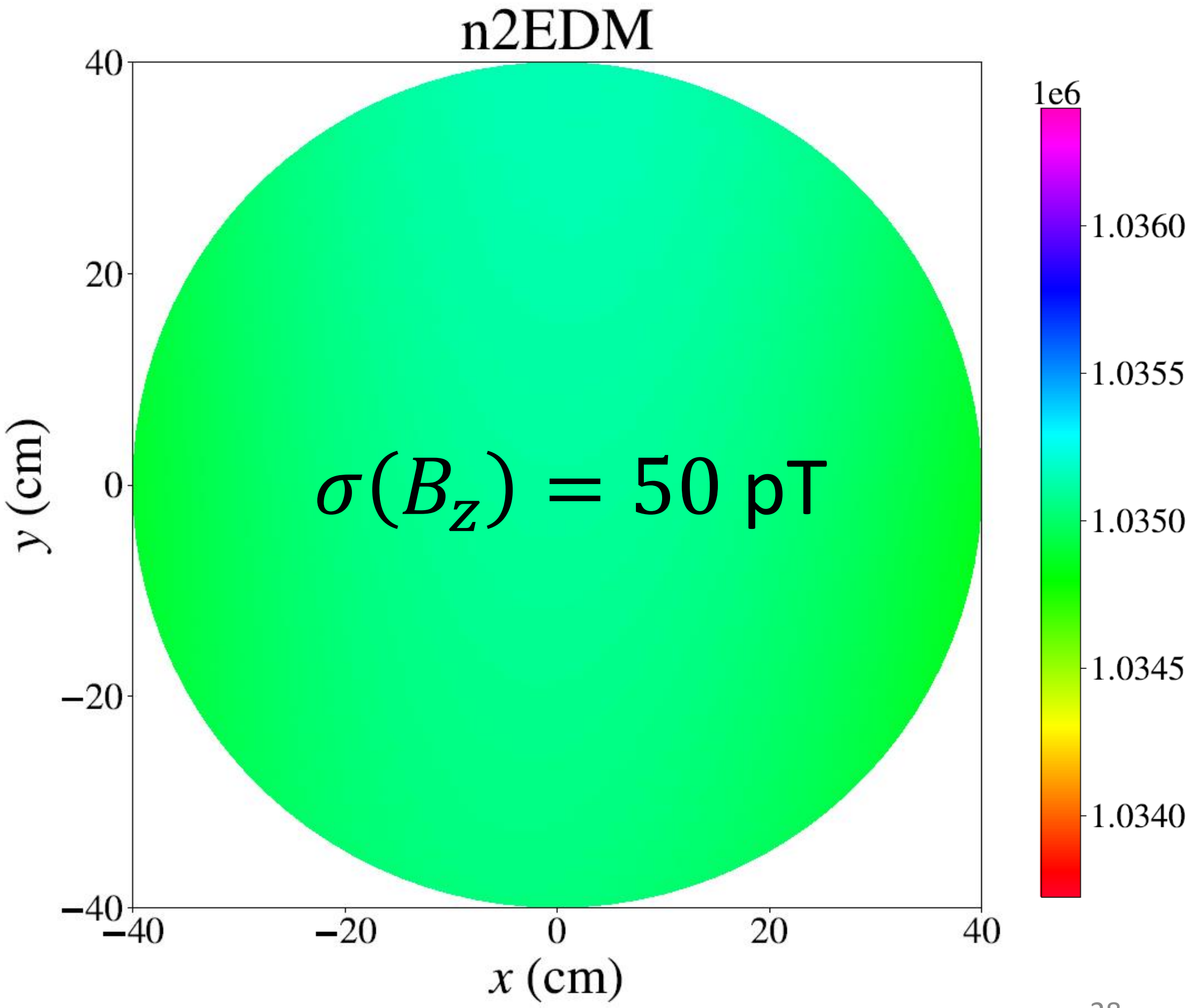

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# Mercury-induced false nEDM

LPSC Grenoble

$$d_{n\leftarrow \mathrm{Hg}}^{\mathrm{false}} = \mathrm{Const} \cdot \langle \rho B_{\rho} \rangle$$

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$$\vec{B}(\vec{r}) = \sum_{l\geq 0}\sum_{m=-l}^{l} G_{l,m}\Pi_{l,m}(\vec{r})$$

$$d_{n\leftarrow\mathrm{Hg}}^{\mathrm{false}} \propto G_3' + G_5' + \cdots$$

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**Two approaches:**

- Reproducible-enough field that we can correct offline
- Uniform-enough field that it’s small without correction

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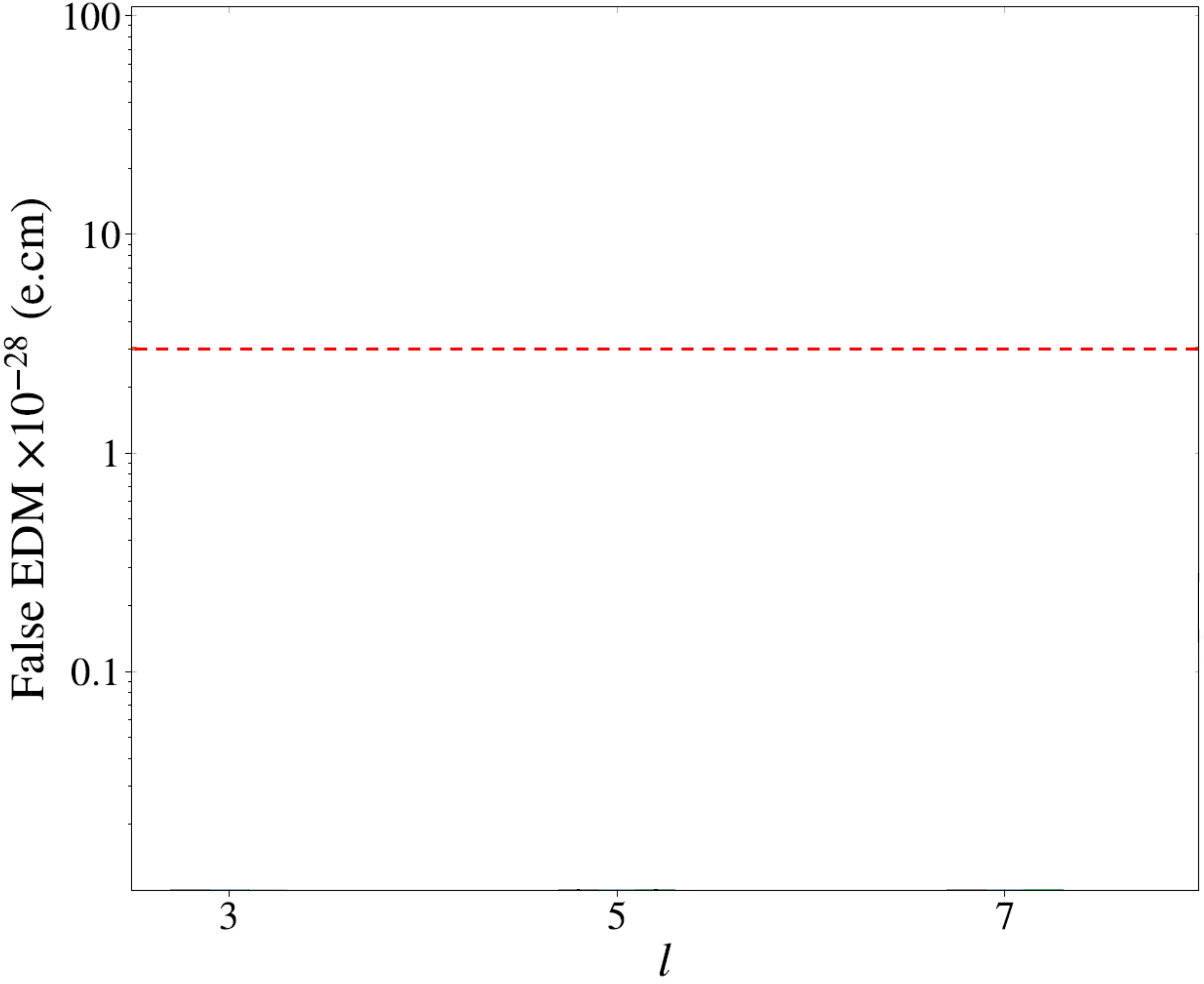
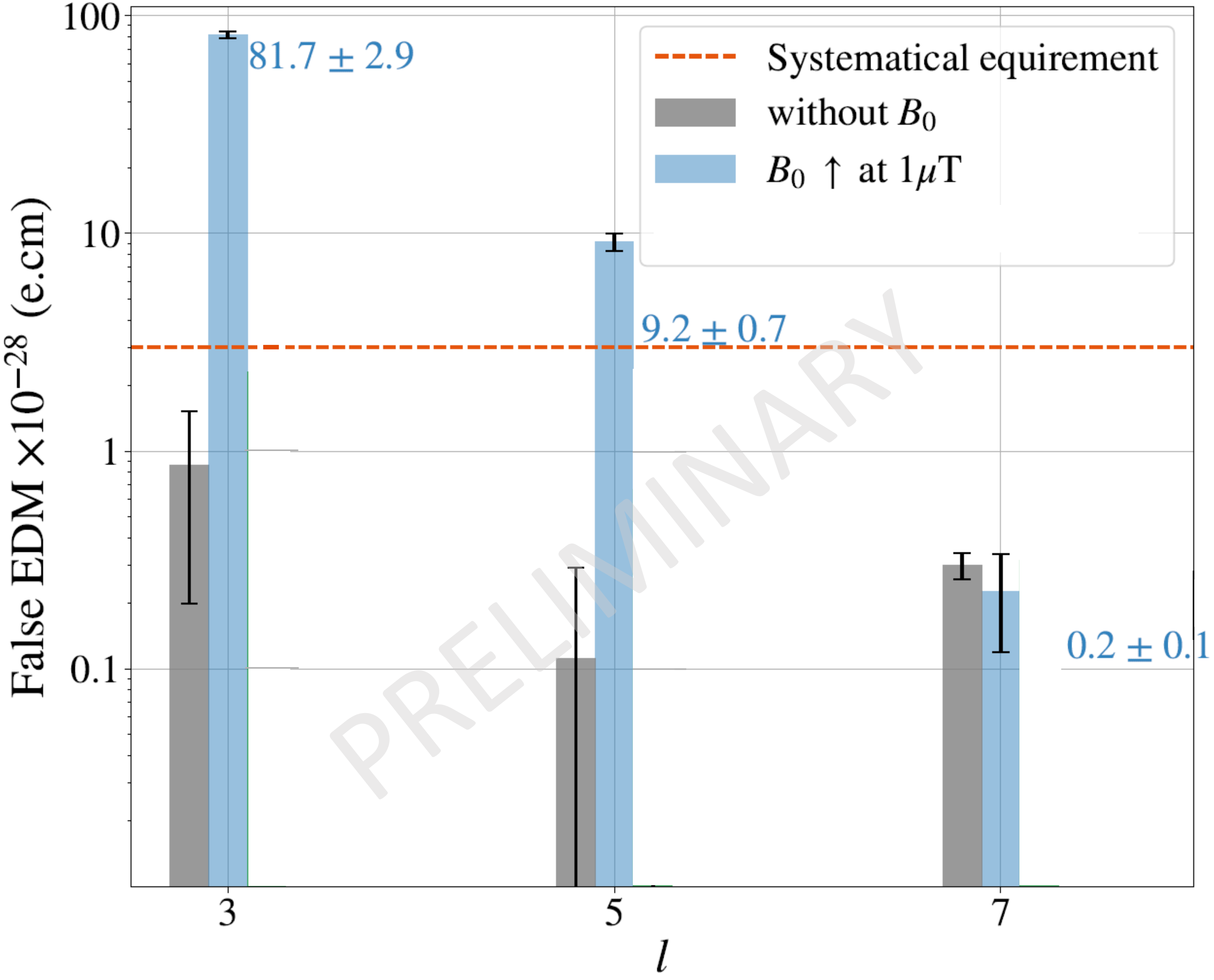
**Two approaches:**

- ✓ Reproducible-enough field that we can correct offline
- ✓ Uniform-enough field that it's small without correction



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

LPSC Grenoble



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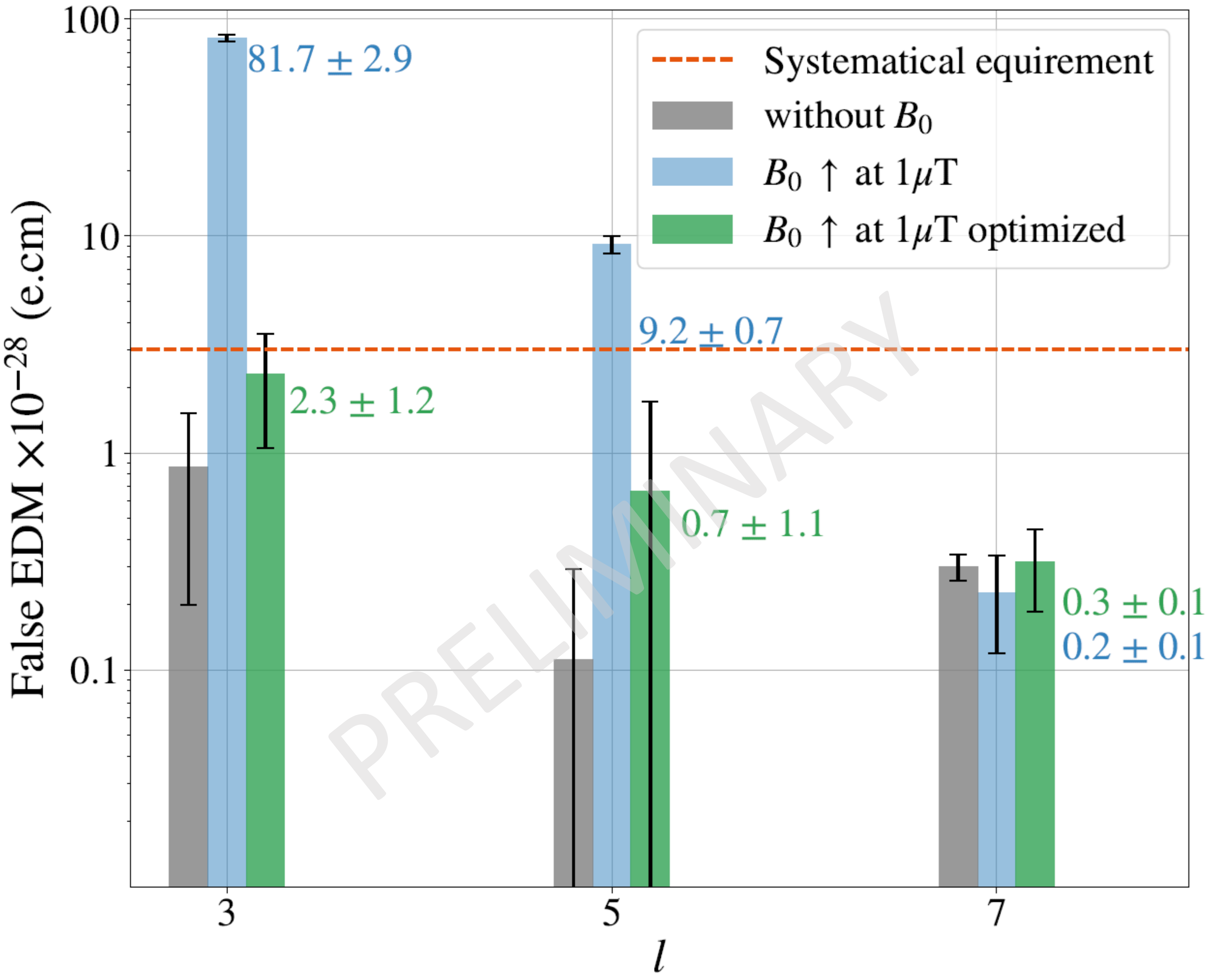
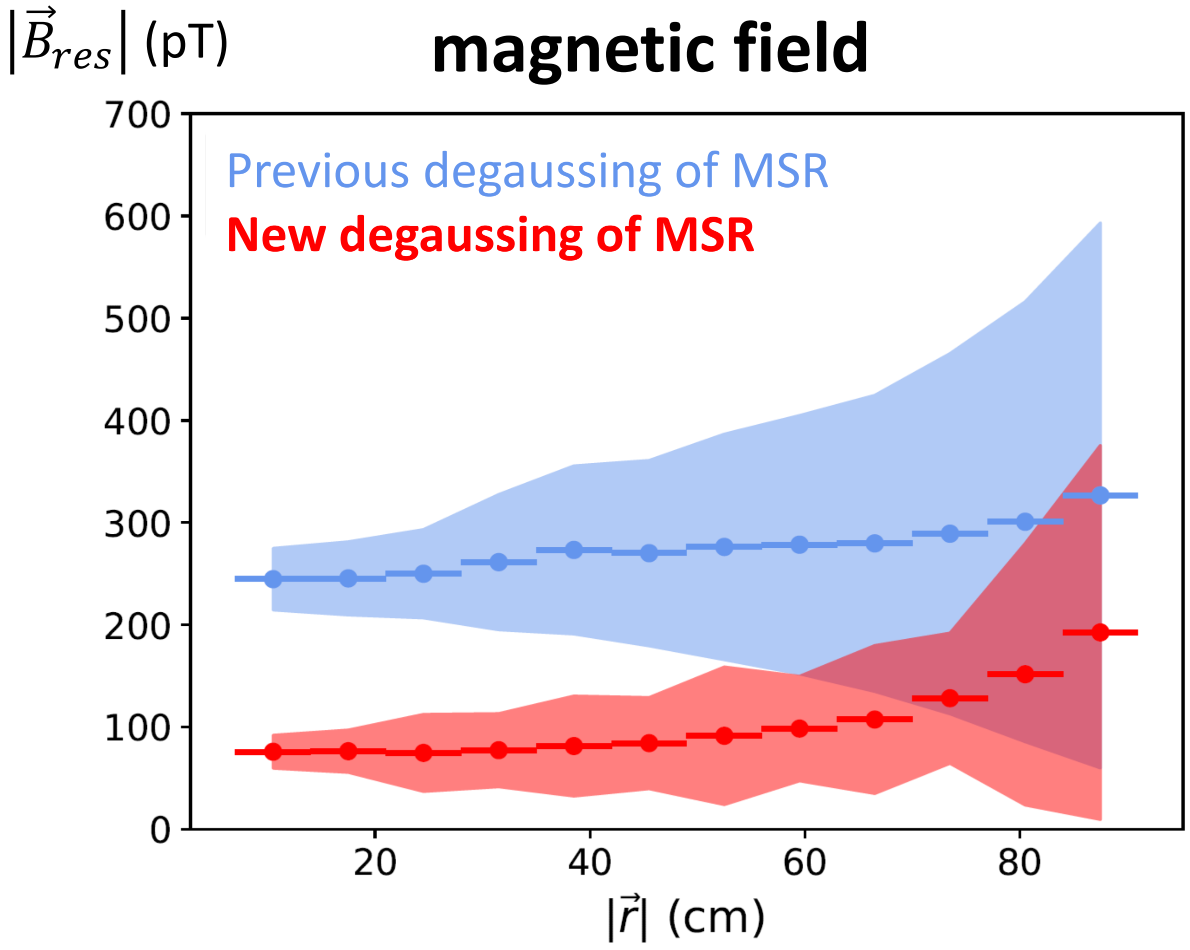


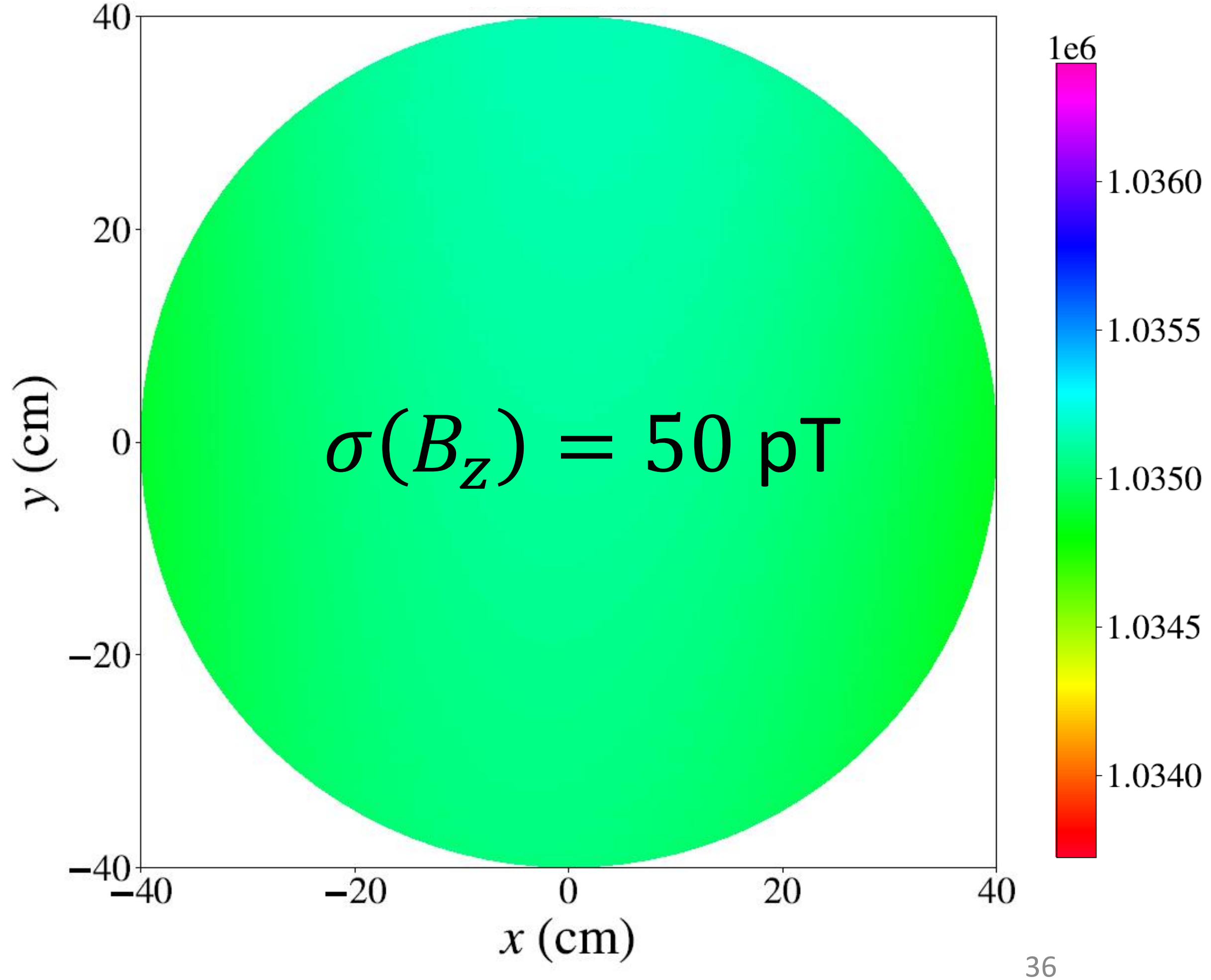
$3 \times 10^{-28}\ e$ cm

LPSC Grenoble

# n2EDM has satisfied our B-field requirements



**Residual magnetic field**



**$B_0$ field**

$\sigma(B_z) = 50$ pT

The nEDM Collaboration, arXiv:2309.16877 (submitted)

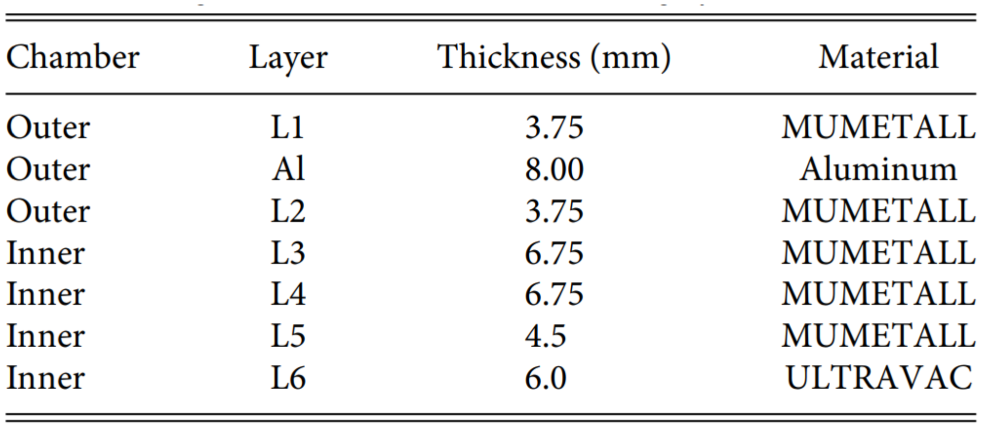
# Thanks!

Efrain Segarra

PSI Fellow III-3i

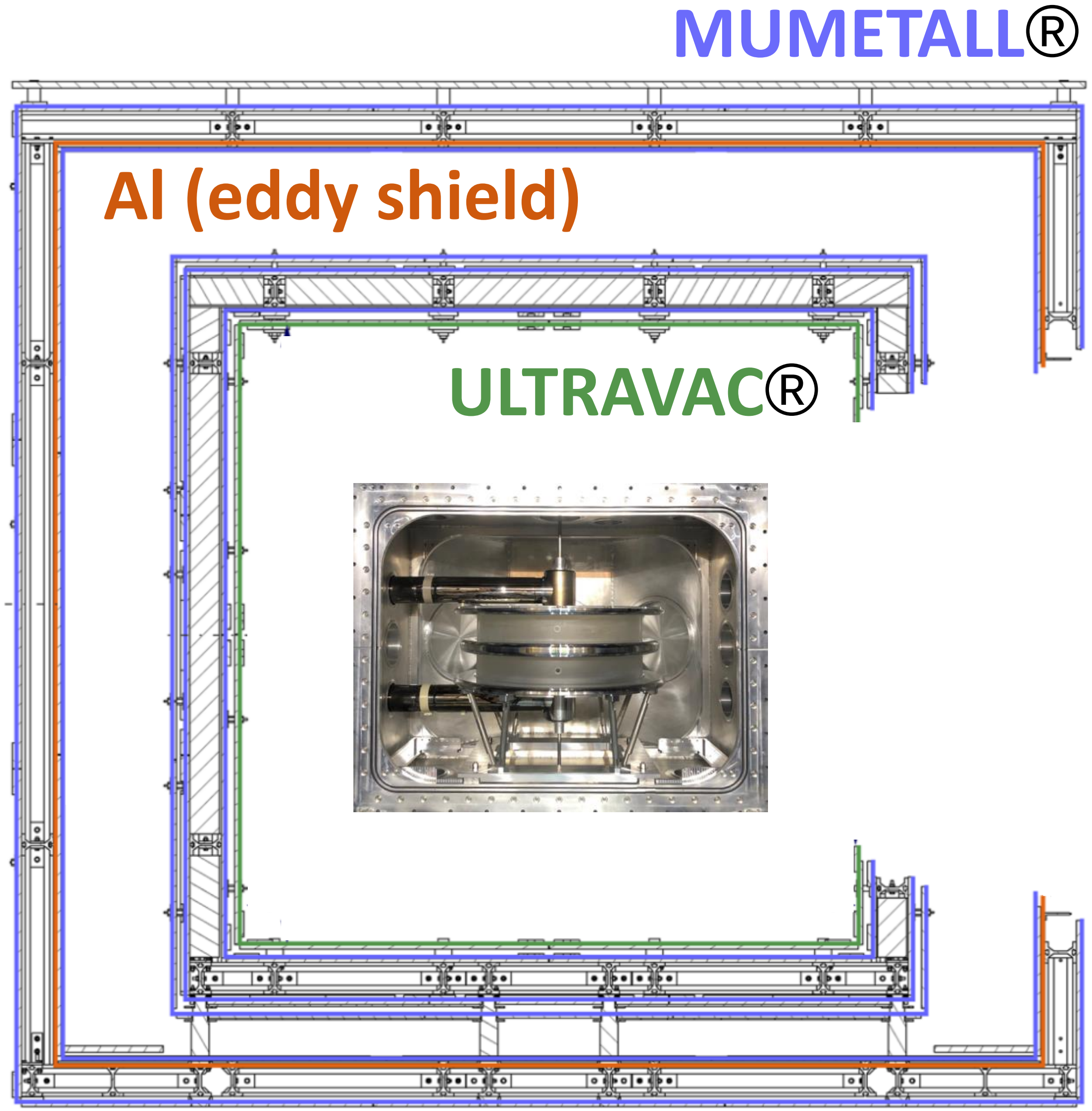
*This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 884104*

# MSR layers



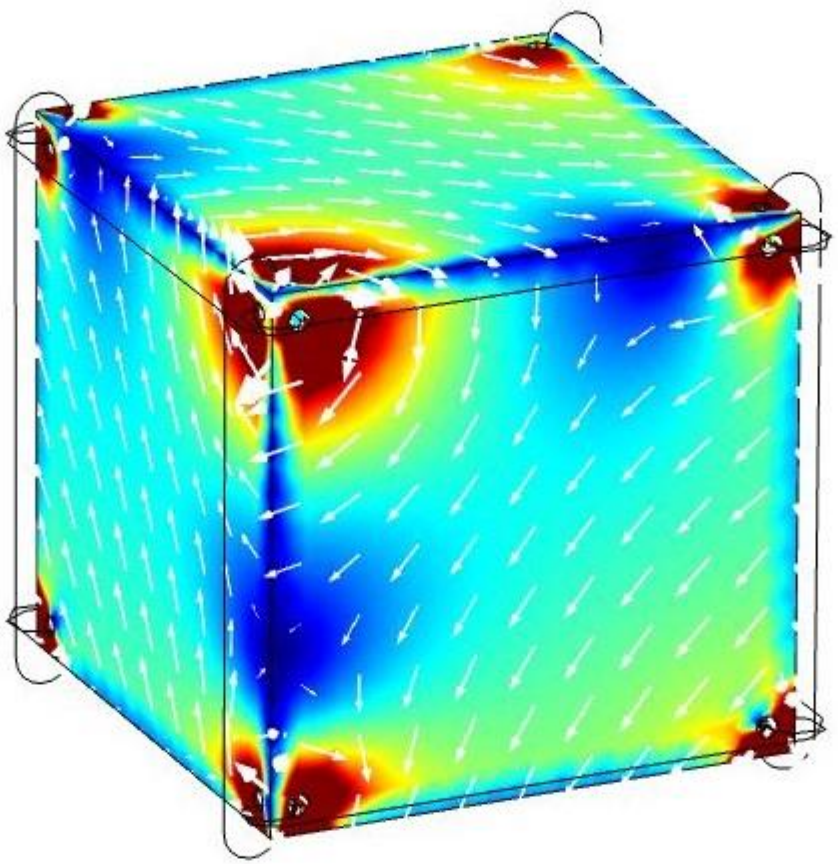
| Chamber | Layer | Thickness (mm) | Material |
|---|---|---|---|
| Outer | L1 | 3.75 | MUMETALL |
| Outer | Al | 8.00 | Aluminum |
| Outer | L2 | 3.75 | MUMETALL |
| Inner | L3 | 6.75 | MUMETALL |
| Inner | L4 | 6.75 | MUMETALL |
| Inner | L5 | 4.5 | MUMETALL |
| Inner | L6 | 6.0 | ULTRAVAC |

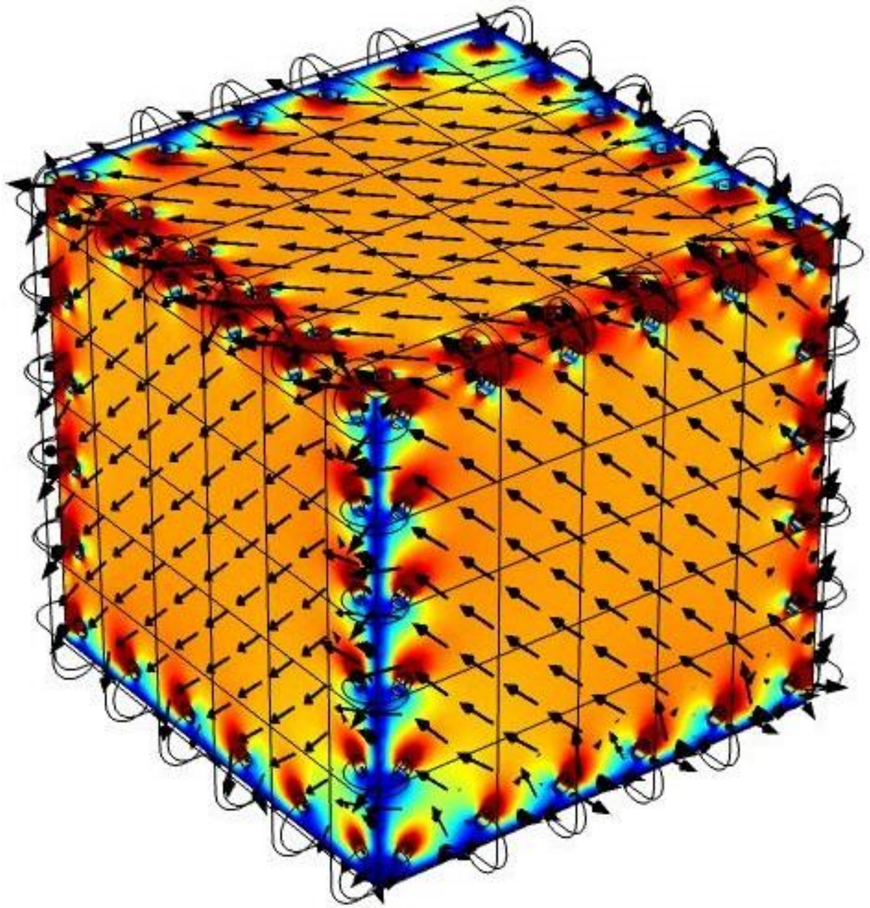
MUMETALL: Ni 77%, Cu 4.5%, Mo 3.3%, Fe balance
ULTRAVAC: Ni 81%, Mo 6%, Fe balance



The nEDM Collaboration, *Rev. Sci. Intrum. (2022)*

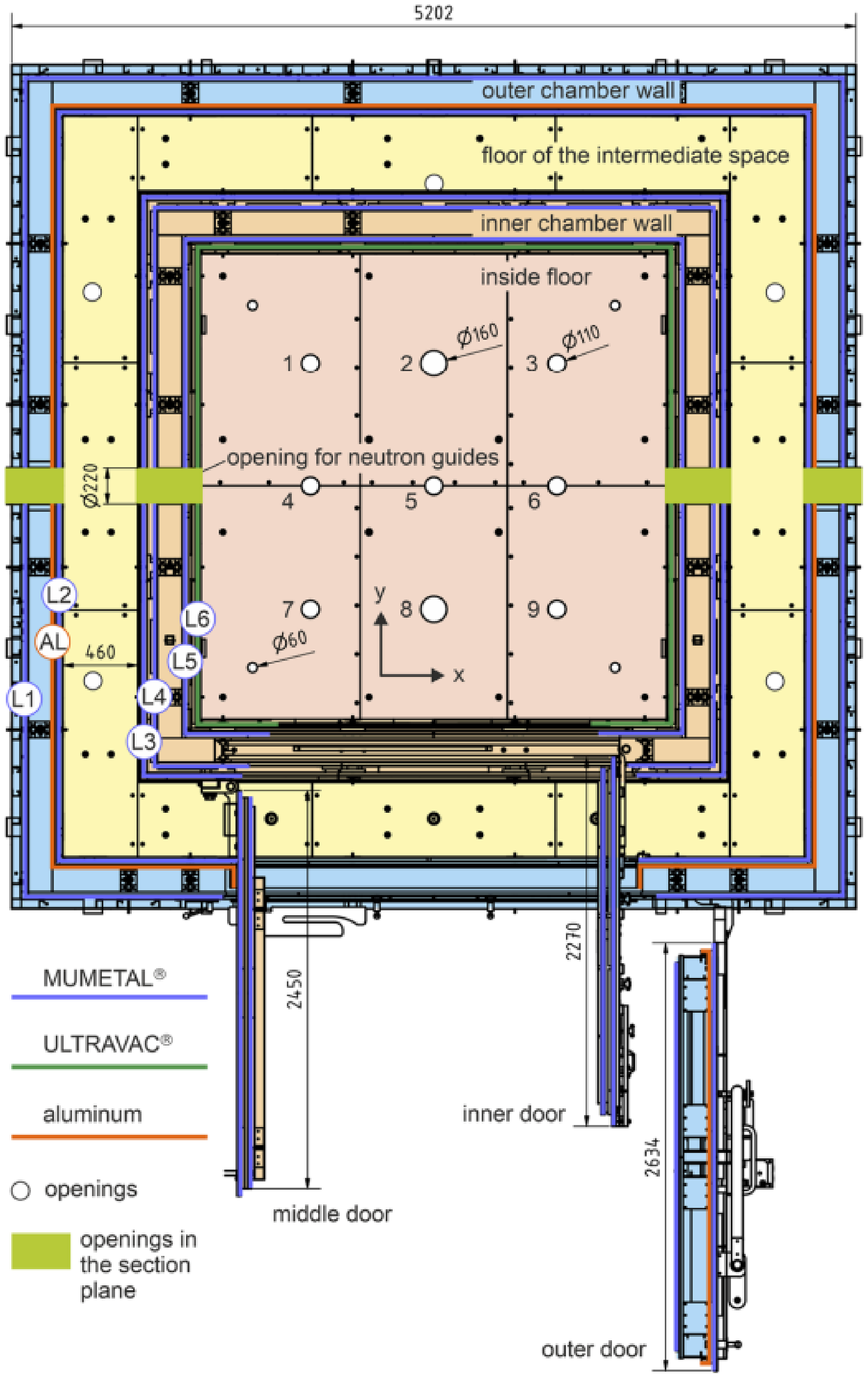
# Distributed coils





# MSR door & holes

- Holes on top
- Side holes for guides & pumping
- Many inner holes



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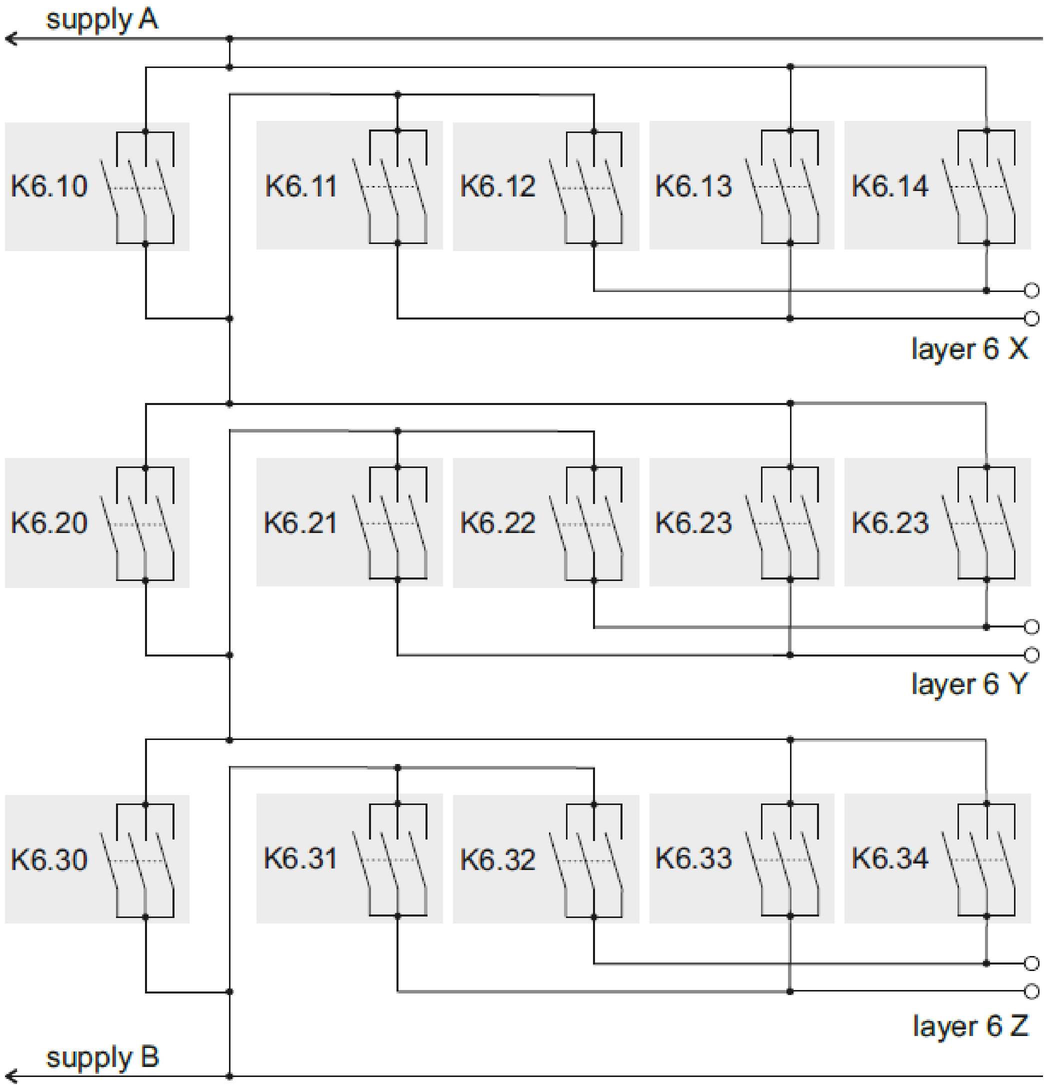
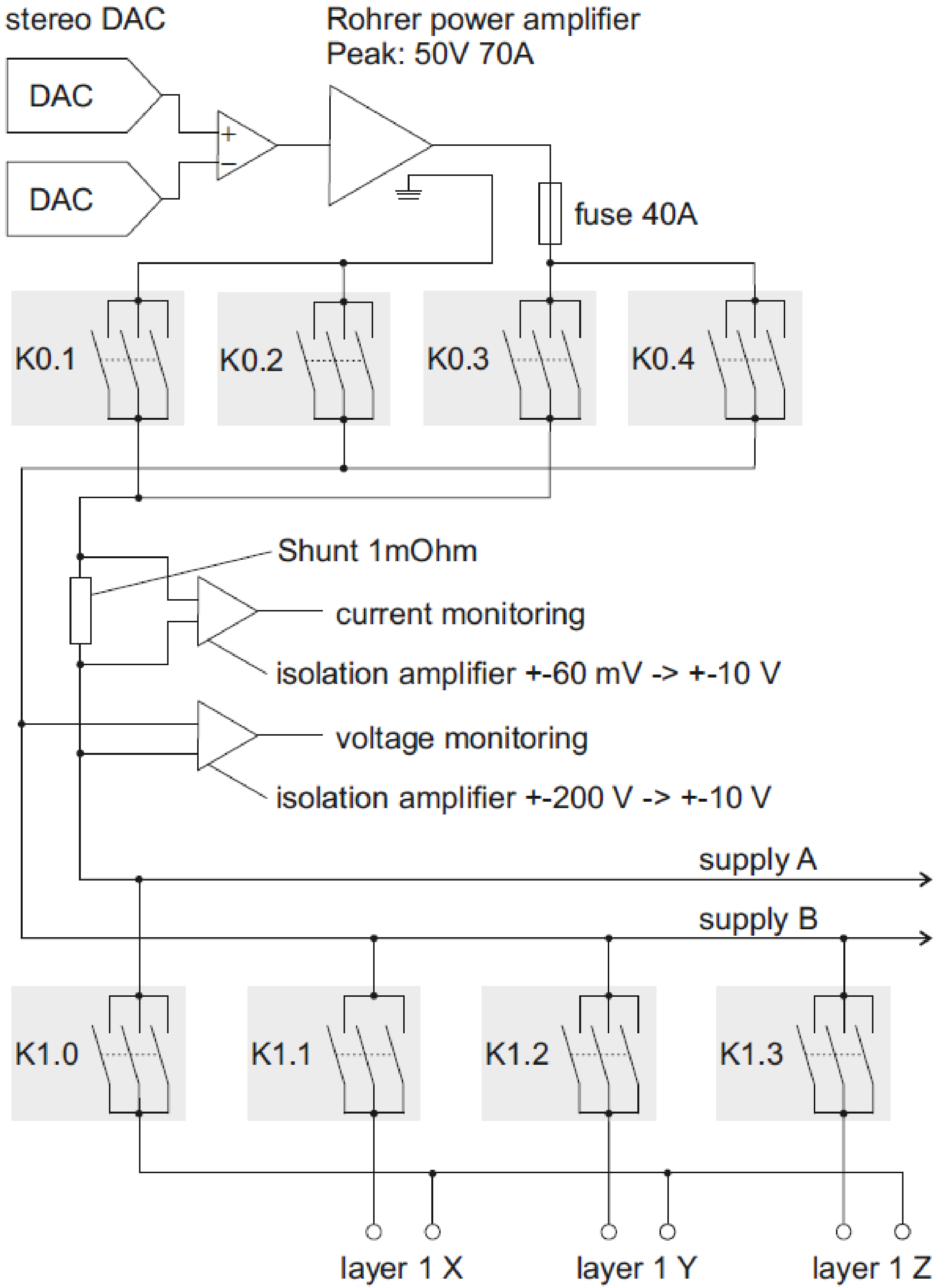
# Coil electrical scheme

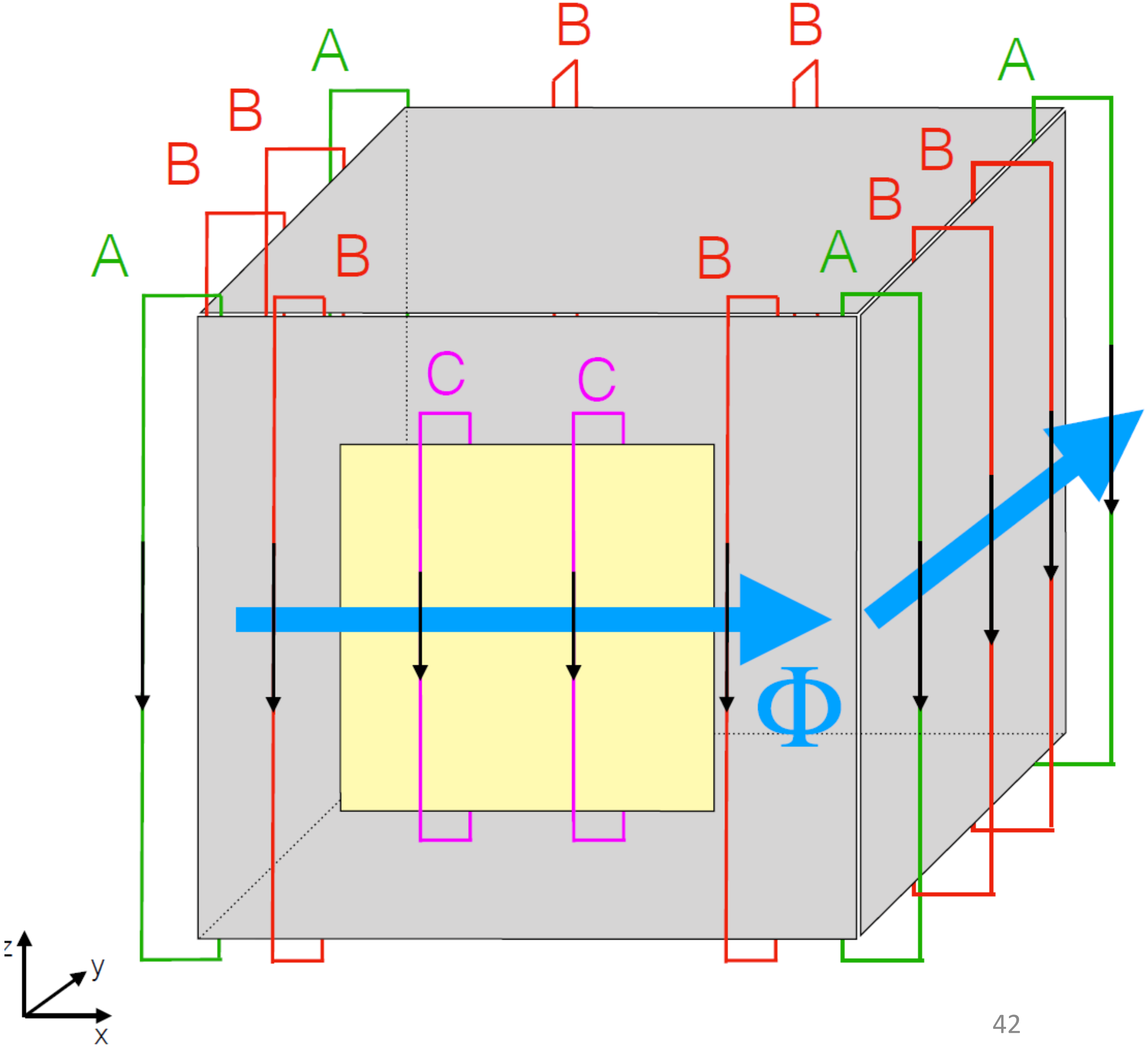




The nEDM Collaboration, arXiv:2309.16877 (submitted)

# Degaussing the permeable material

- Rohrer amplifier (50V / 70A)
- AC magnetic field
- Saturate material
- Decrease amplitude to zero



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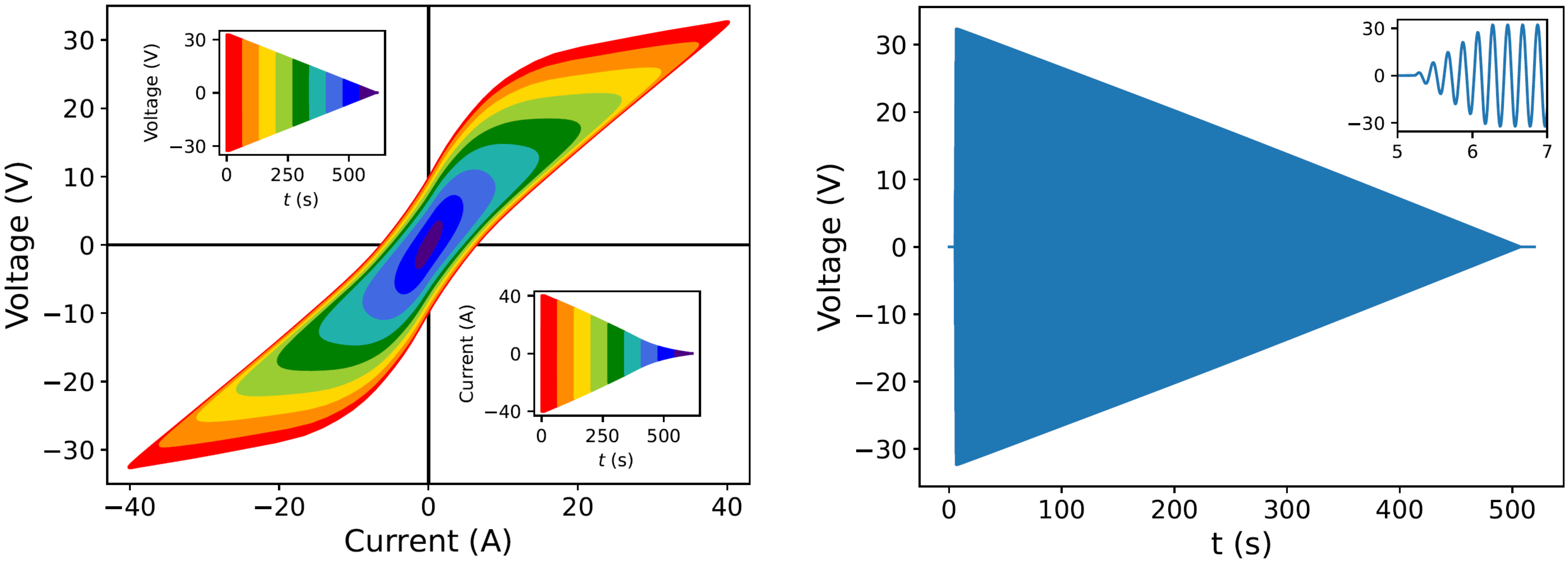
# Reaching saturation



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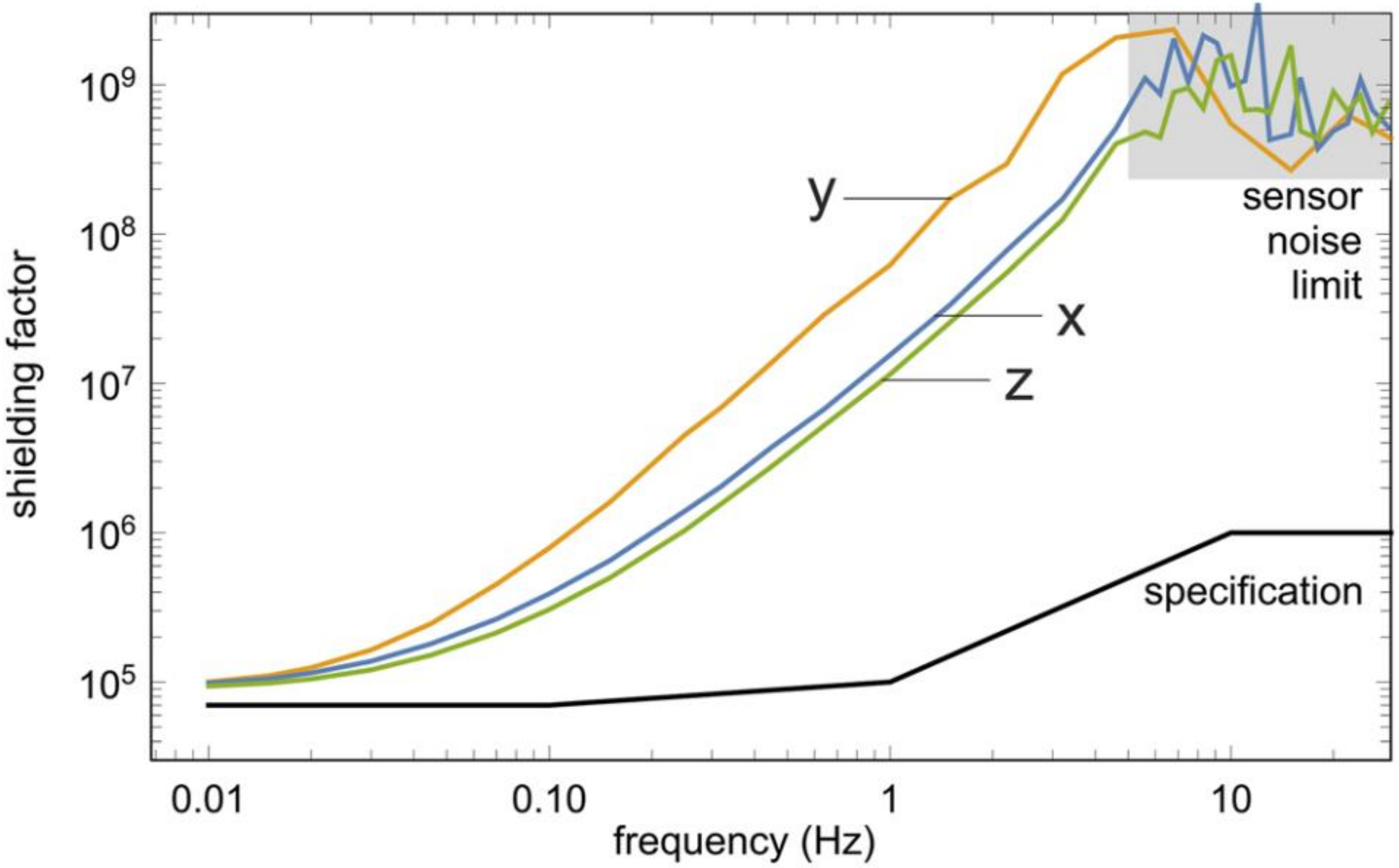
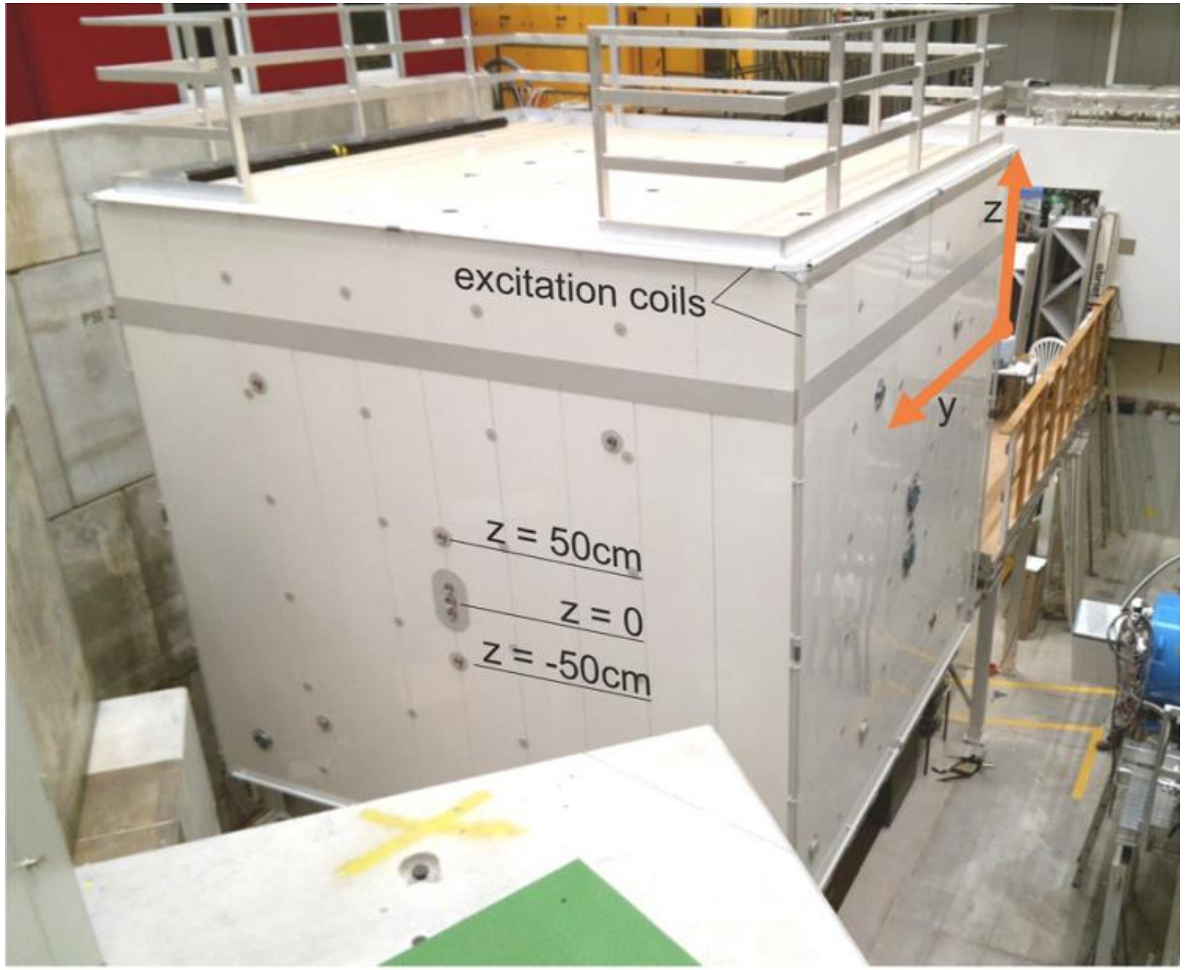
# Shielding factor

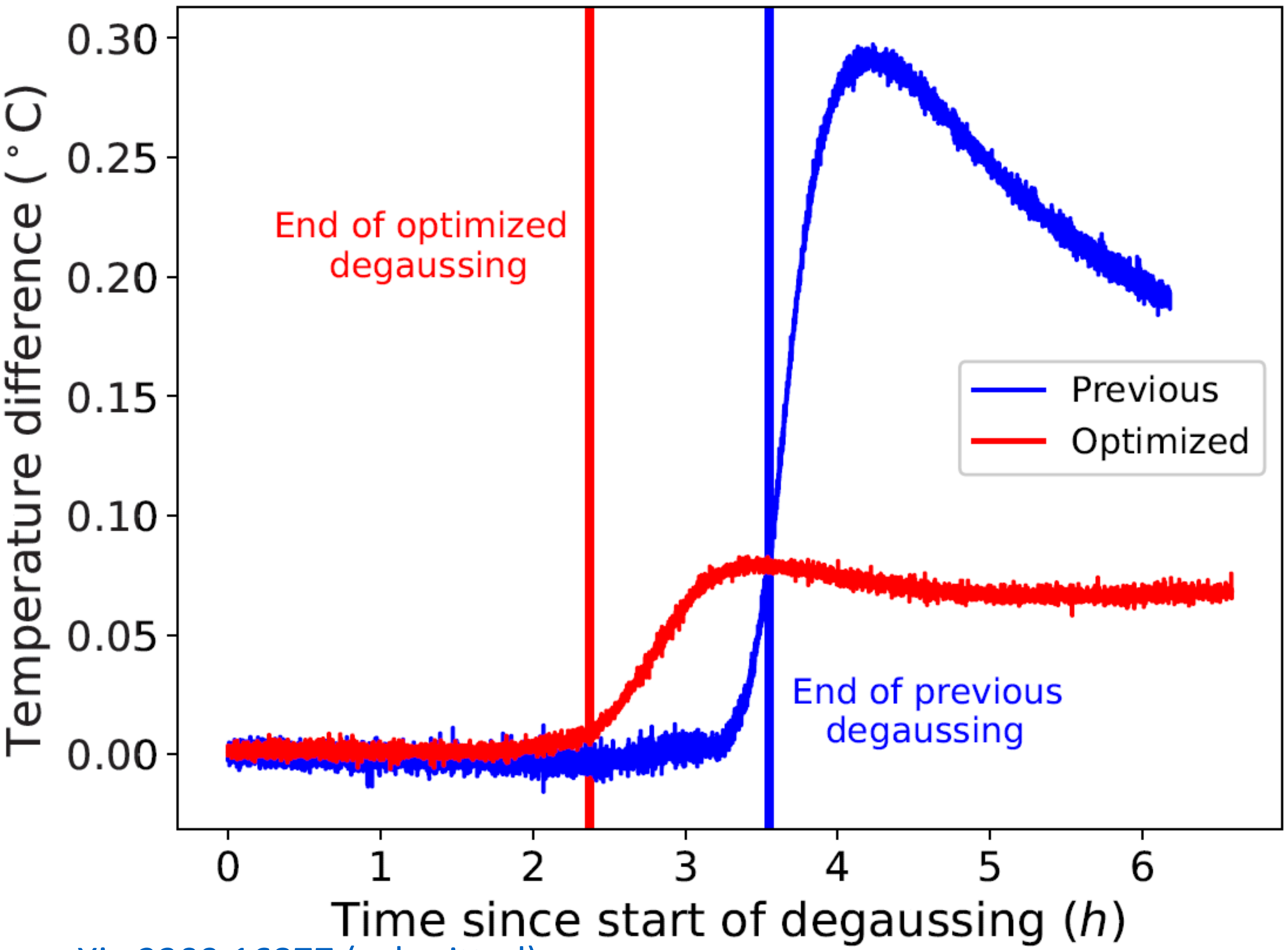


# Shielding factor extraction



- Excitation coils produce sin-like field with 2 muT peak-to-peak amp @ MSR center
- Pickup by QuSpin

# Thermal relaxation inside MSR



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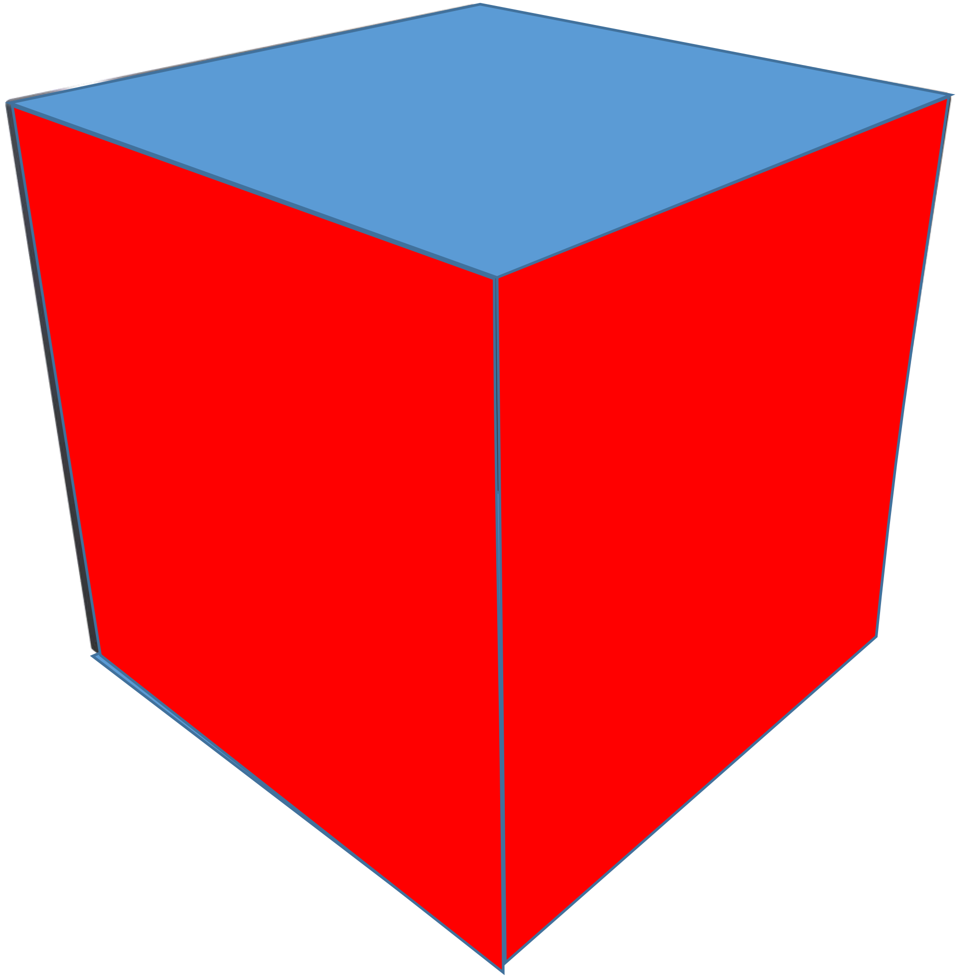
# Simultaneous degaussing improvement



- Serial degaussing: 4/6 faces are degaussed at once
- 2 faces can produce background field for the 4

# n2EDM field requirements

## *Statistical requirements*

1. **Vertical uniformity.**

   Minimize neutron spin depolarization ($\propto \gamma_n \tau_c \sigma^2(B_z)$):

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

2. **Top-bottom resonance matching condition.**

   Keep Ramsey $f_{RF}$ optimal for the two chambers:

$$|G_{10}| < 0.6\ pT/cm$$

Goal of magnetic field mapping:

Measure problematic $G_{lm}$ and their reproducibility, to allow for either calculation or cancellation of generated errors.

## *Systematical requirements*

**Hg-induced false neutron EDM.**

Minimize the error on $d_n$ extraction:

$$d_{n\leftarrow Hg}^{\text{false}} < 3 \times 10^{-28} e.cm$$

Non-uniform fields lead to a shift $\delta f_{Hg}$ which affects $d_n$ through $\mathcal{R} = f_n / f_{\text{Hg}}$. This effect scales with chamber size and magnetic gradients:

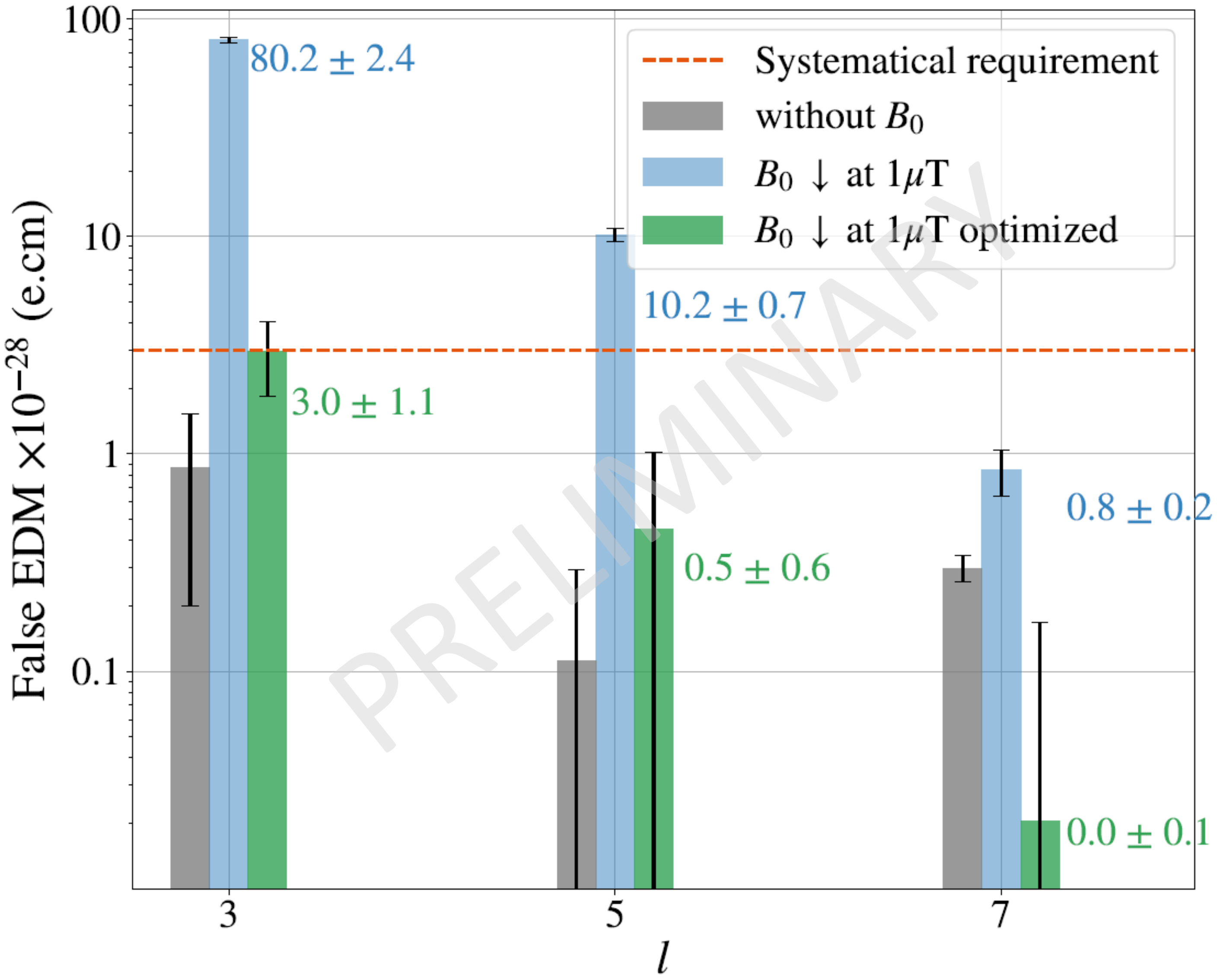
$$d_{n\leftarrow Hg}^{\text{false}} = \frac{\hbar|\gamma_n \gamma_{Hg}|}{2c^2} \langle \rho B_\rho \rangle$$

$$= -\frac{\hbar|\gamma_n \gamma_{Hg}|}{8c^2} R^2 (G_{\text{TB}} + \acute{G}_3 + \acute{G}_5 + \acute{G}_7)$$

*Monitored online*

*Offline mapping*

# $B_0$-down uniformity



# Magnetic mapper details

- low-noise Bartington MAG13 three-axis
- $\phi \in [-30,380]_{\circ}$
- $\rho \in [-5,76]$ cm
- $z \in [-39.6,50]$ cm