Simulation and Optimization of the Active Magnetic Shield for n2EDM

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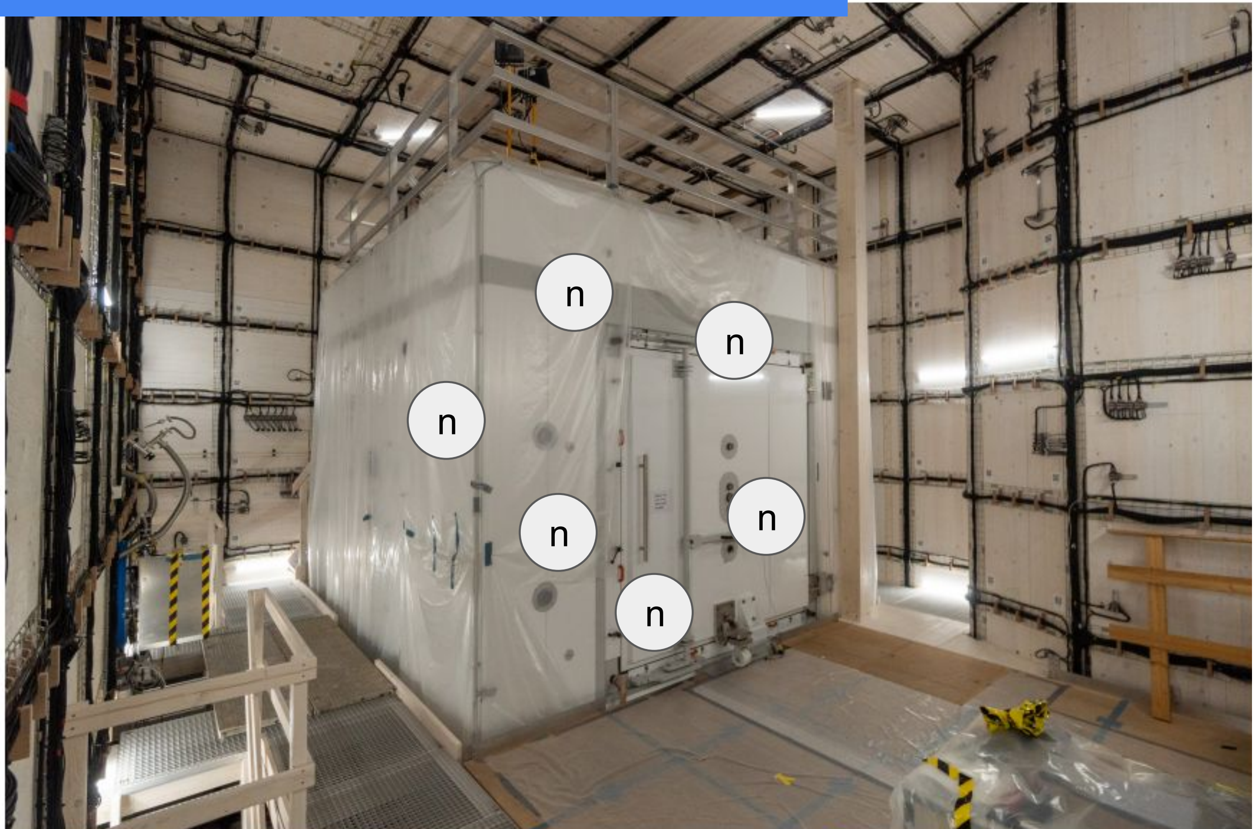
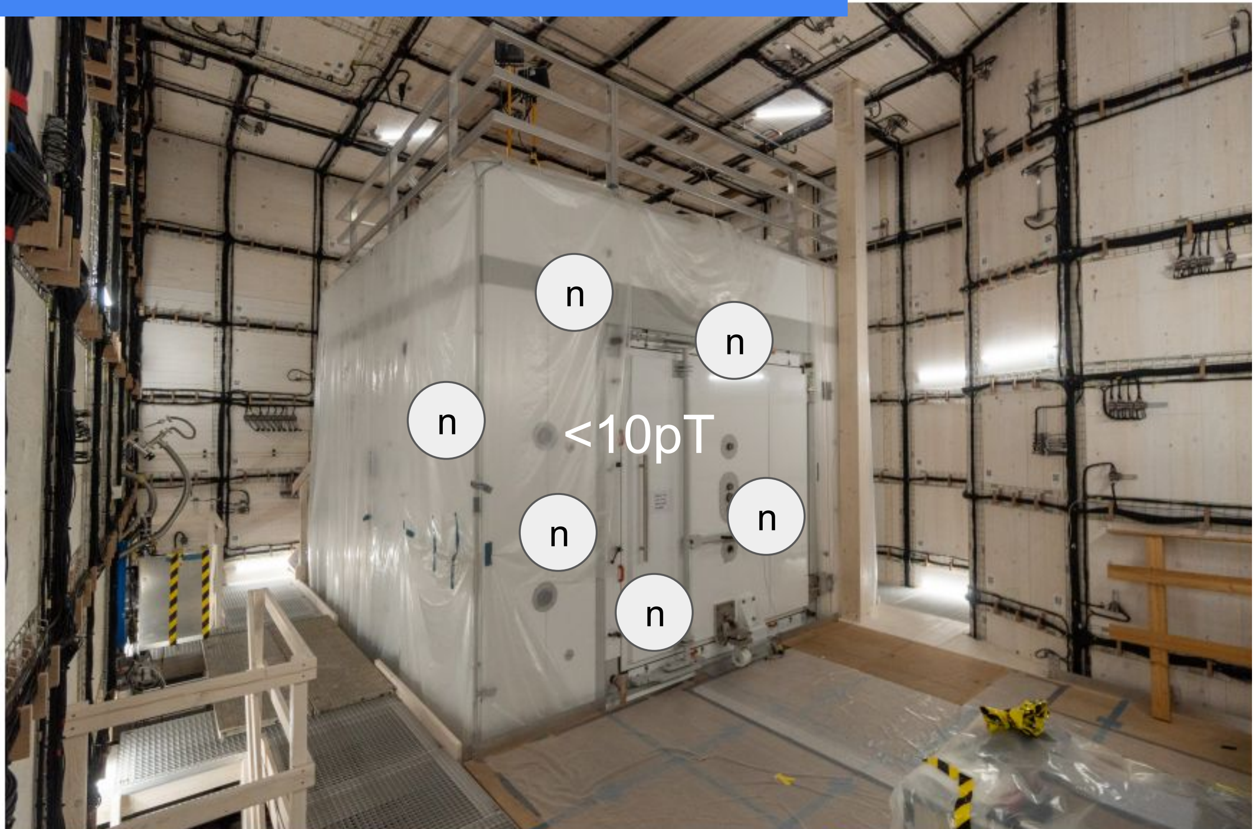
On behalf of the n2edm collaboration at PSI
ETH Zürich
11th September 2024, Zürich

The n2EDM Experiment

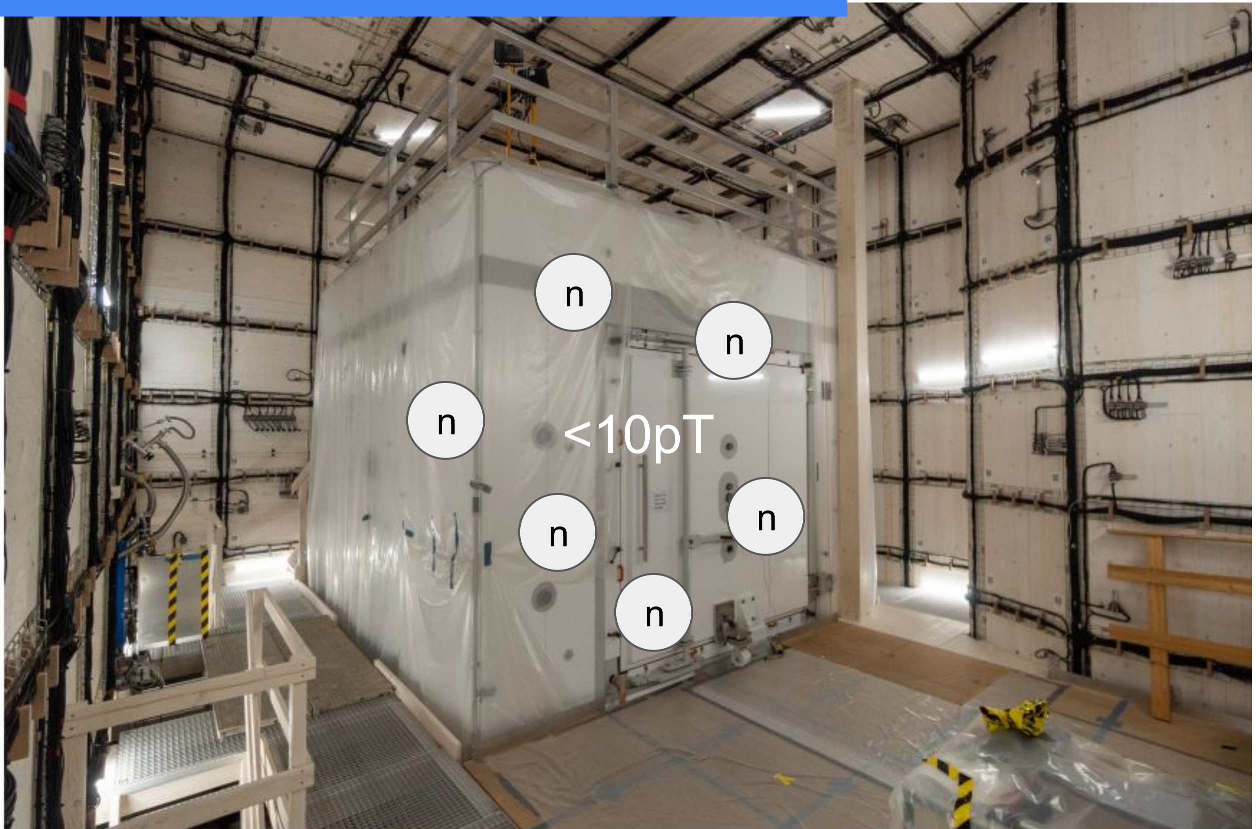


The n2EDM Experiment



The n2EDM Experiment

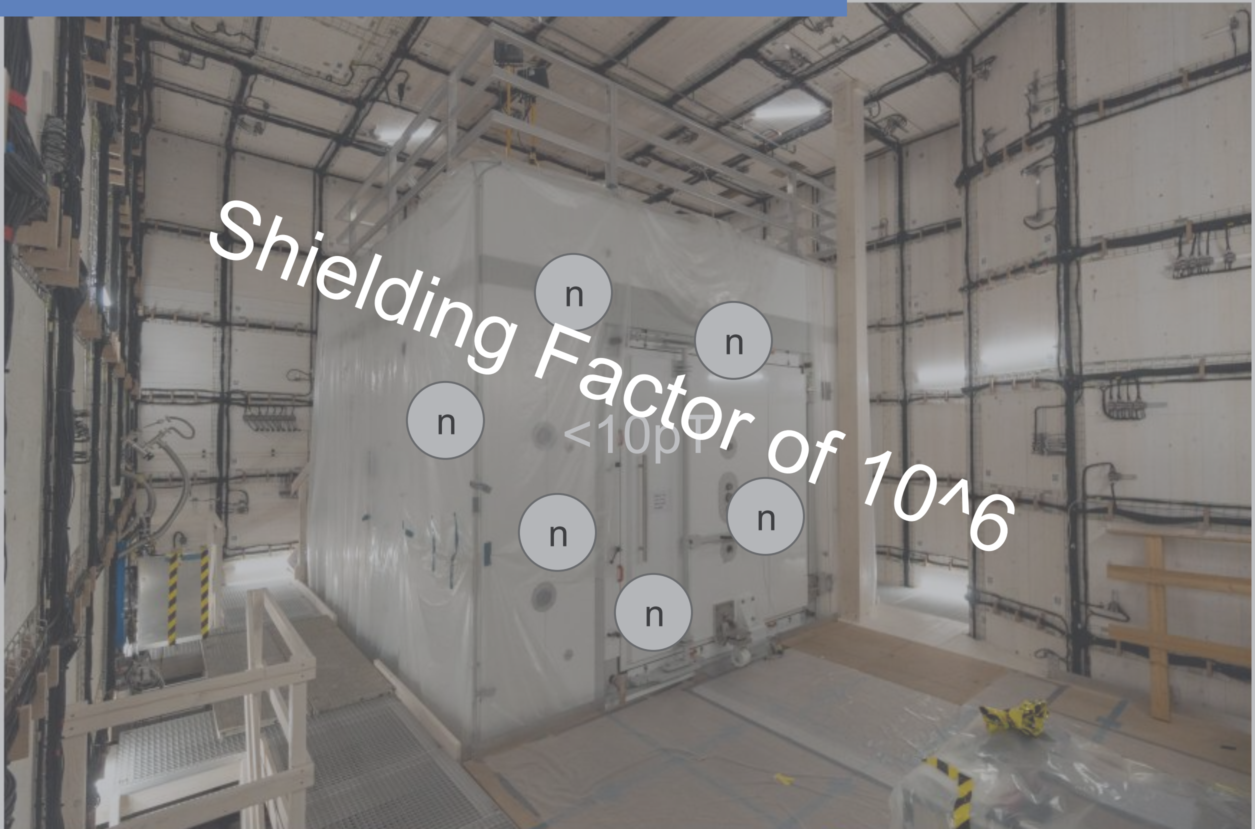
100μT



100μT

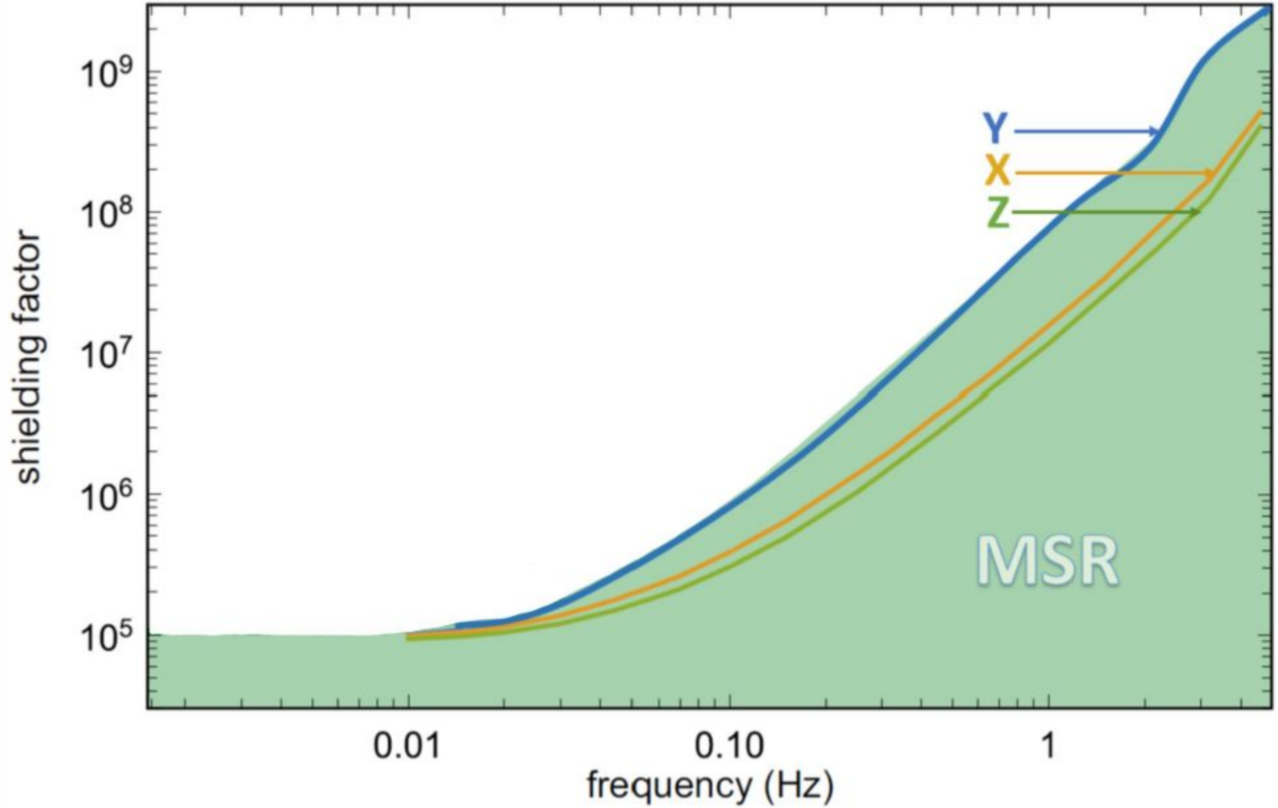
The n2EDM Experiment

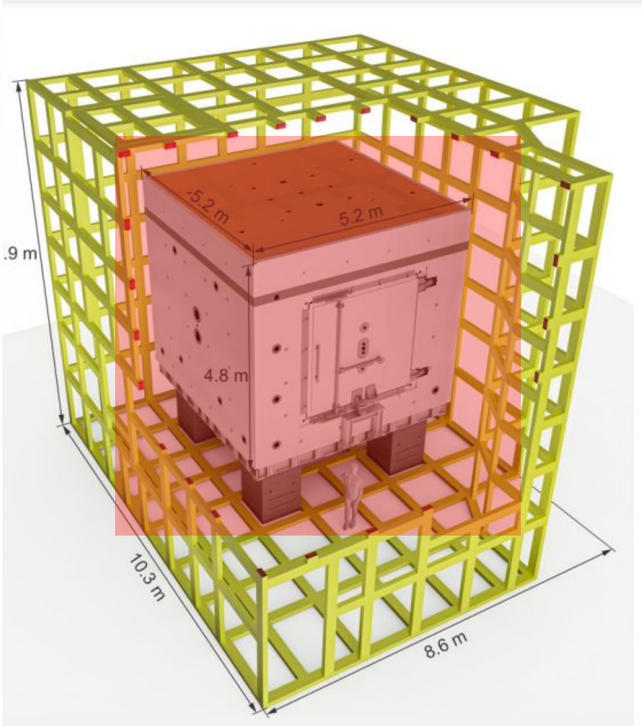
100μT



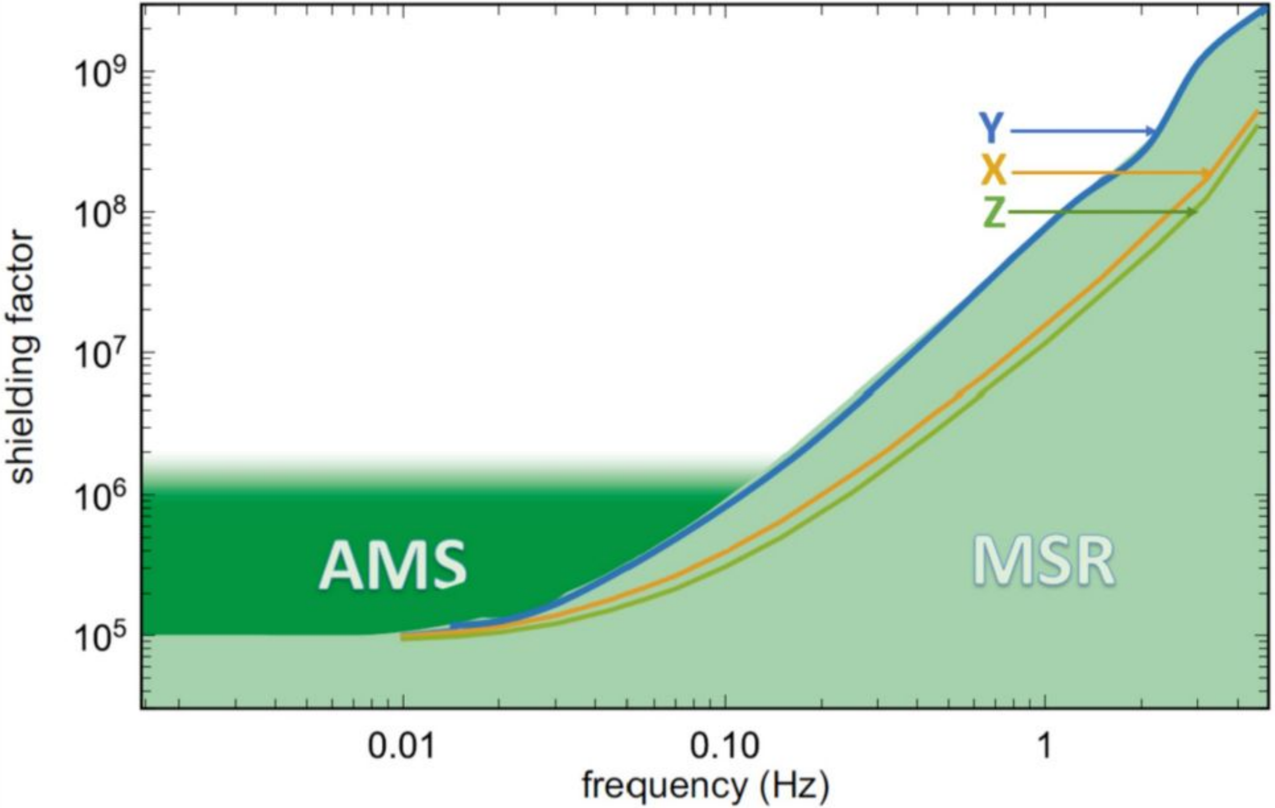
100μT

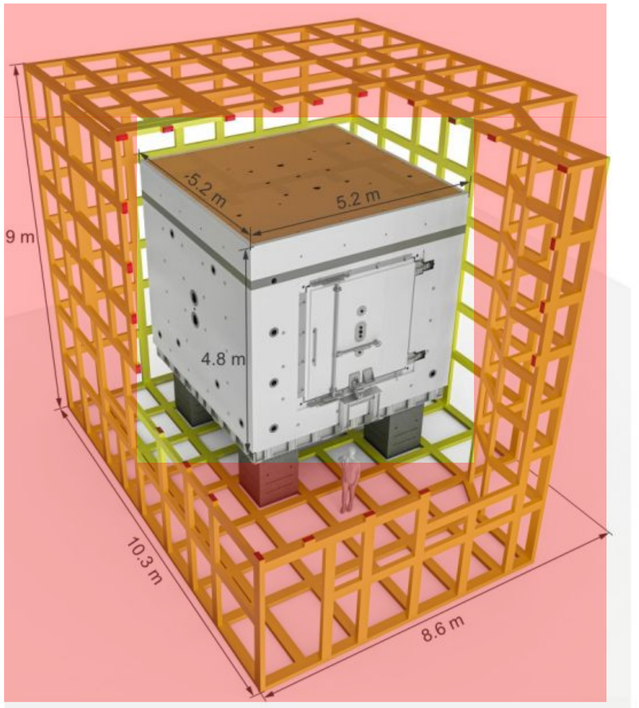
Magnetic Shielding





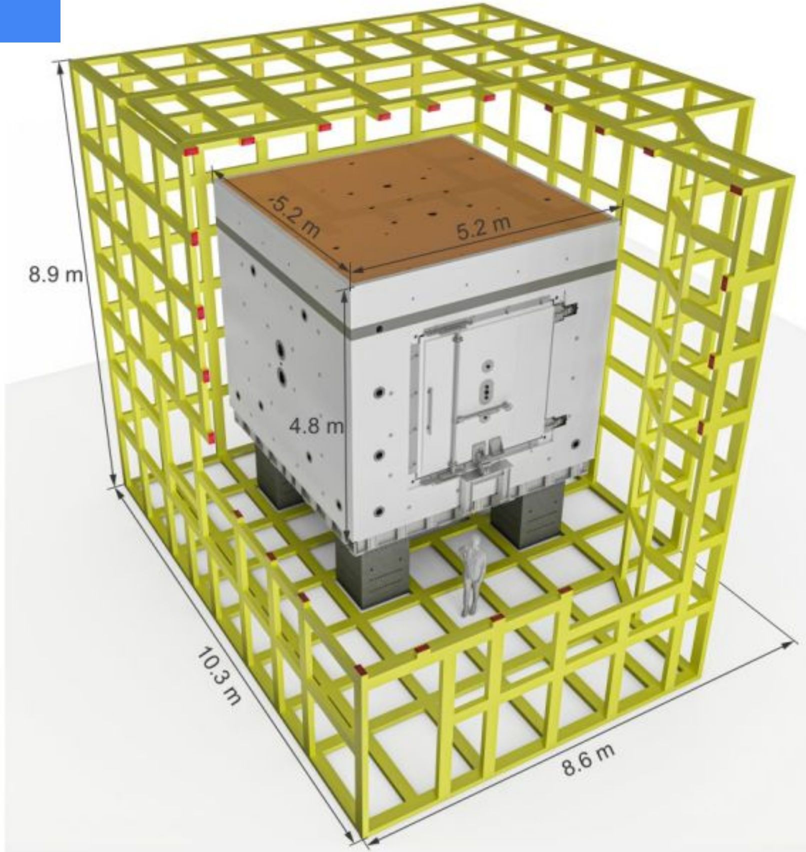
Magnetic Shielding



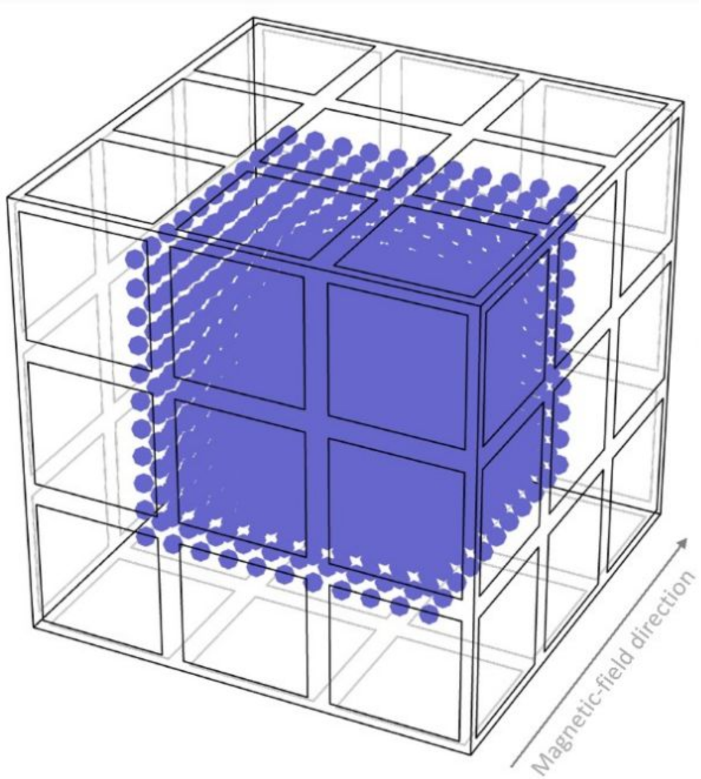


Active Magnetic Shielding

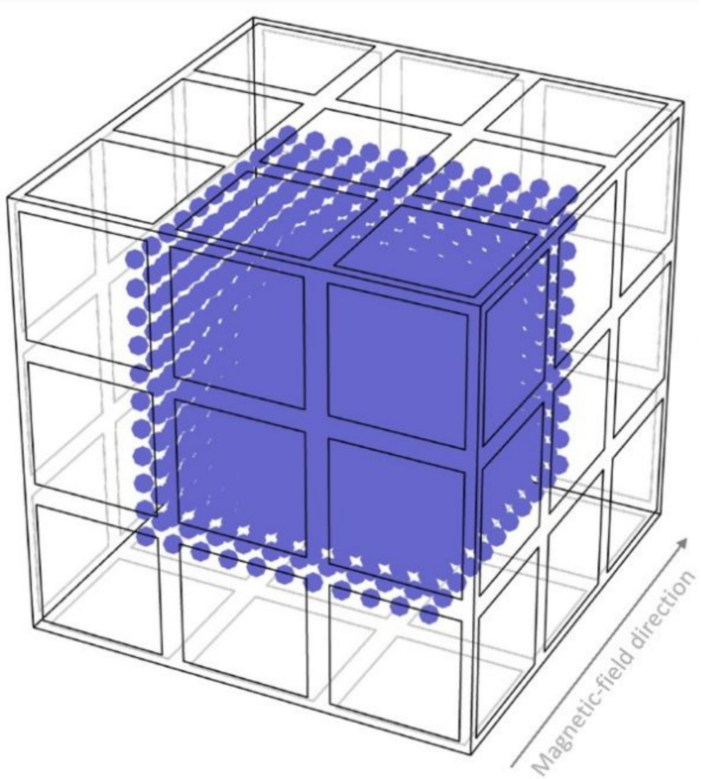
- Based on sensors around the experiment
- Coils generate a magnetic field
- To dynamically compensate for external disturbances

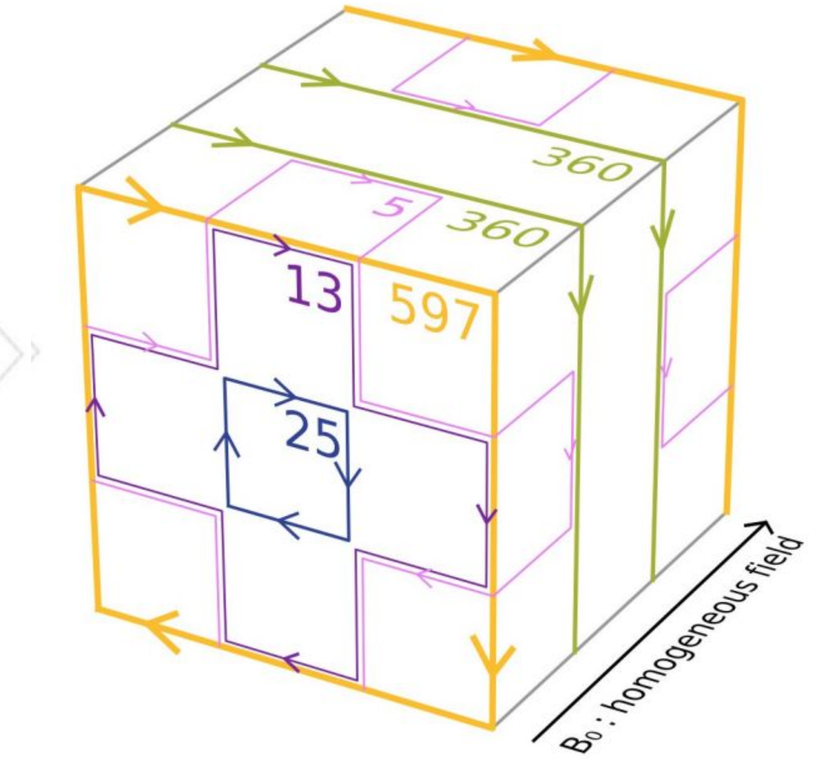


Intricate Coil System



Intricate Coil System





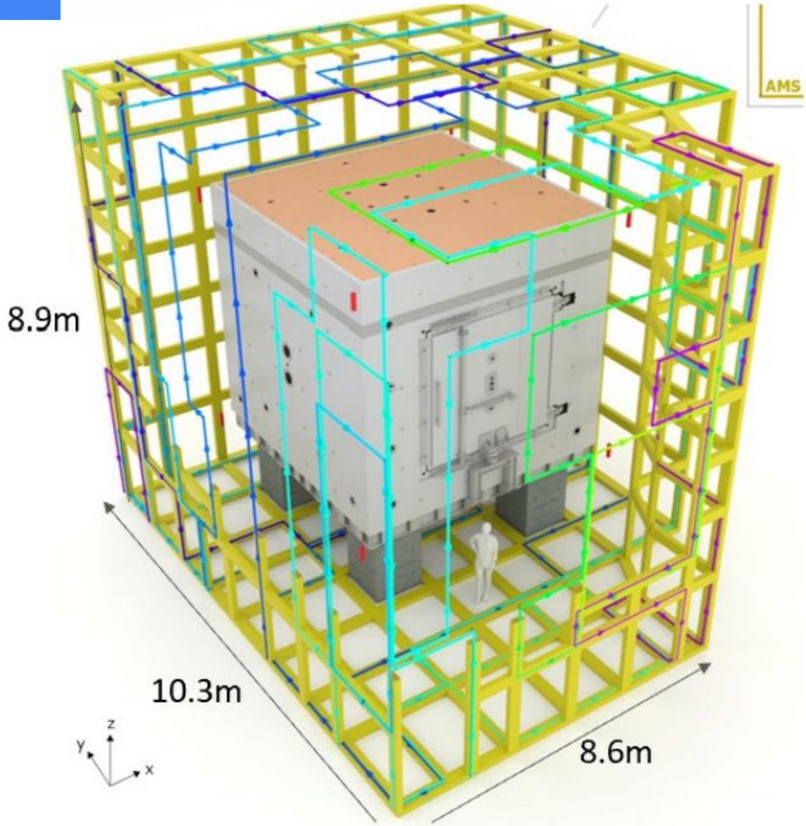
Active Magnetic Shielding

- 8 coils:
  → 3 homogeneous
  → 5 higher order

- ±50μT

- **<u>1μT compensation</u>**

- 3-axis Fluxgates



Compensation Algorithm

$$B = B_0 + MI$$

Compensation Algorithm

$$B = B_0 + MI$$

$$\begin{pmatrix} B_{0,1\text{x}} \\ B_{0,1\text{y}} \\ B_{0,1\text{z}} \\ \vdots \\ B_{0,8\text{z}} \end{pmatrix}$$

Background Magnetic Field

Compensation Algorithm

$$B = B_0 + MI$$

$$\begin{pmatrix} B_{0,1x} \\ B_{0,1y} \\ B_{0,1z} \\ \vdots \\ B_{0,8z} \end{pmatrix} + \begin{pmatrix} M_{11x} & M_{21x} & \cdots & M_{81x} \\ M_{11y} & M_{21y} & \cdots & M_{81y} \\ M_{11z} & M_{21z} & \cdots & M_{81z} \\ \vdots & \vdots & \ddots & \vdots \\ M_{18z} & M_{28z} & \cdots & M_{88z} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_8 \end{pmatrix}$$

Background Magnetic Field → B_0

AMS Generated Magnetic Field → MI

Compensation Algorithm

$$B = B_0 + MI$$

$$\begin{pmatrix} B_{1x} \\ B_{1y} \\ B_{1z} \\ \vdots \\ B_{8z} \end{pmatrix} = \begin{pmatrix} B_{0,1x} \\ B_{0,1y} \\ B_{0,1z} \\ \vdots \\ B_{0,8z} \end{pmatrix} + \begin{pmatrix} M_{11x} & M_{21x} & \cdots & M_{81x} \\ M_{11y} & M_{21y} & \cdots & M_{81y} \\ M_{11z} & M_{21z} & \cdots & M_{81z} \\ \vdots & \vdots & \ddots & \vdots \\ M_{18z} & M_{28z} & \cdots & M_{88z} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_8 \end{pmatrix}$$

Measured Magnetic Field

Background Magnetic Field

AMS Generated Magnetic Field

Compensation Algorithm

$$B = B_0 + MI$$ → Least Squares

$$\begin{pmatrix} B_{1x} \\ B_{1y} \\ B_{1z} \\ \vdots \\ B_{8z} \end{pmatrix} = \begin{pmatrix} B_{0,1x} \\ B_{0,1y} \\ B_{0,1z} \\ \vdots \\ B_{0,8z} \end{pmatrix} + \begin{pmatrix} M_{11x} & M_{21x} & \cdots & M_{81x} \\ M_{11y} & M_{21y} & \cdots & M_{81y} \\ M_{11z} & M_{21z} & \cdots & M_{81z} \\ \vdots & \vdots & \ddots & \vdots \\ M_{18z} & M_{28z} & \cdots & M_{88z} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_8 \end{pmatrix}$$

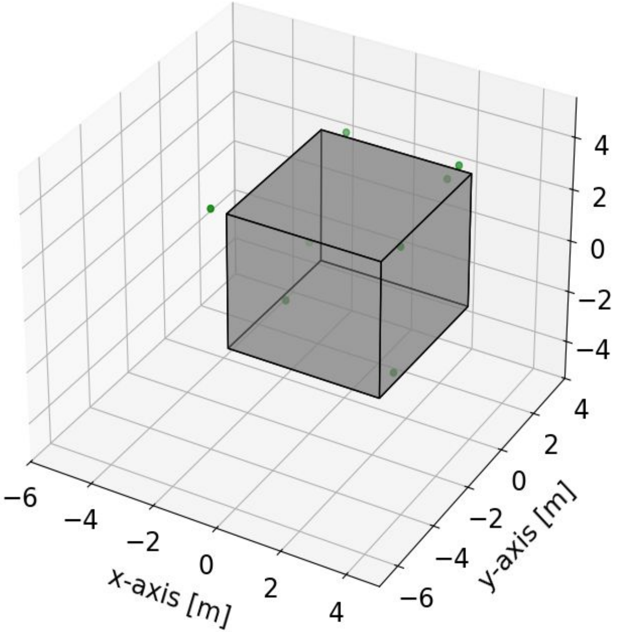
Measured Magnetic Field → B

Background Magnetic Field → B_0

AMS Generated Magnetic Field → MI

Response Matrix

$$\begin{pmatrix} M_{11\mathrm{x}} & M_{21\mathrm{x}} & \cdots & M_{81\mathrm{x}} \\ M_{11\mathrm{y}} & M_{21\mathrm{y}} & \cdots & M_{81\mathrm{y}} \\ M_{11\mathrm{z}} & M_{21\mathrm{z}} & \cdots & M_{81\mathrm{z}} \\ \vdots & \vdots & \ddots & \vdots \\ M_{18\mathrm{z}} & M_{28\mathrm{z}} & \cdots & M_{88\mathrm{z}} \end{pmatrix}$$



Response Matrix

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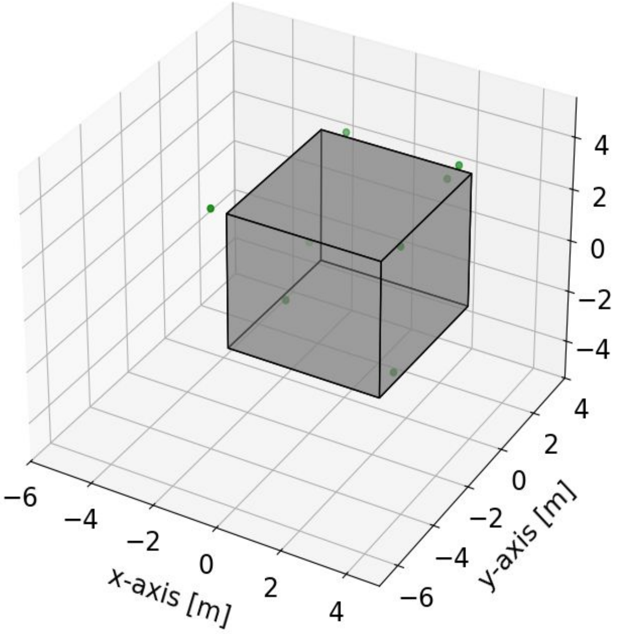


Condition Number

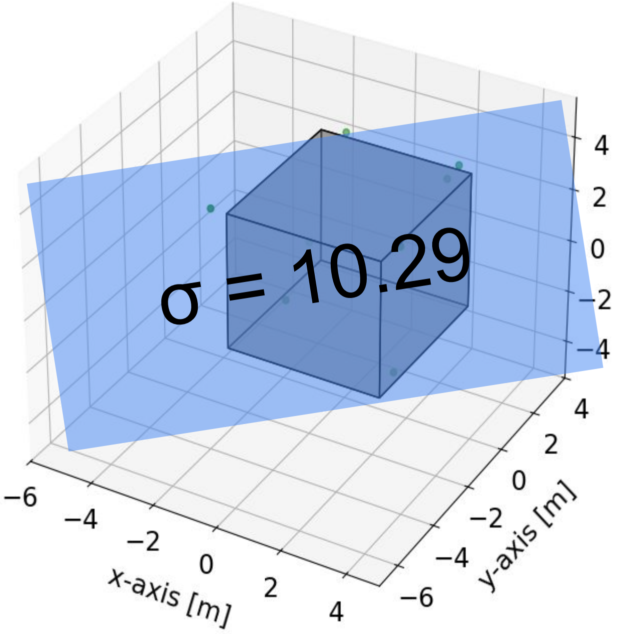
$\sigma \in [1,\infty)$

Lower σ,

Lower Numerical Error

Response Matrix

$$\begin{pmatrix} M_{11x} & M_{21x} & \cdots & M_{81x} \\ M_{11y} & M_{21y} & \cdots & M_{81y} \\ M_{11z} & M_{21z} & \cdots & M_{81z} \\ \vdots & \vdots & \ddots & \vdots \\ M_{18z} & M_{28z} & \cdots & M_{88z} \end{pmatrix}$$



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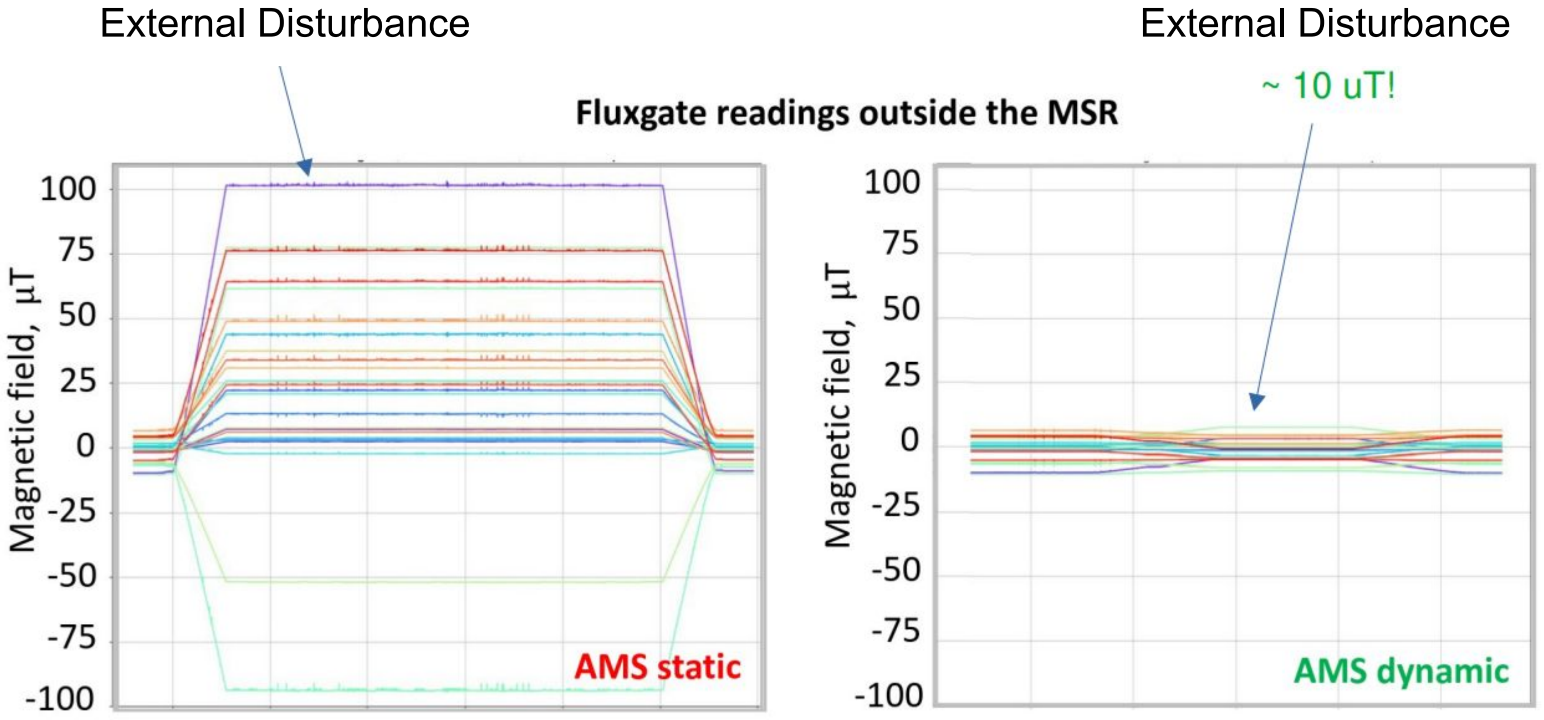
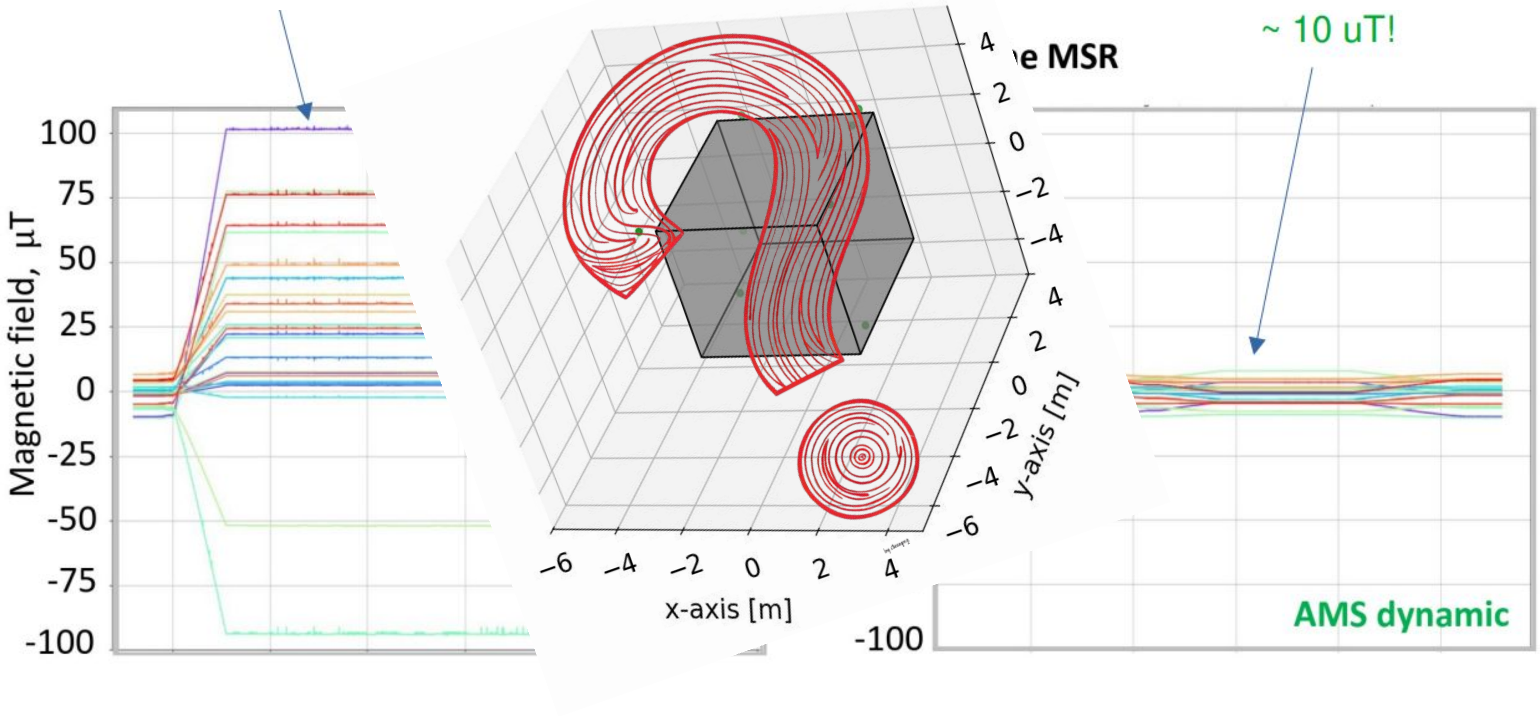
Compensation Example



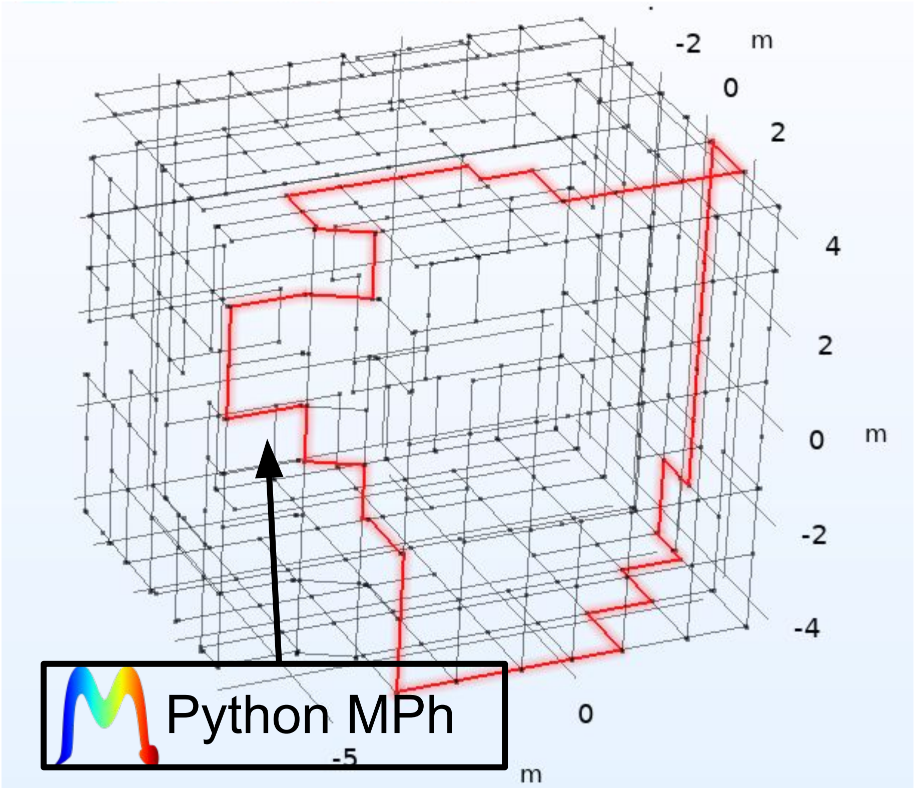
Compensation Example

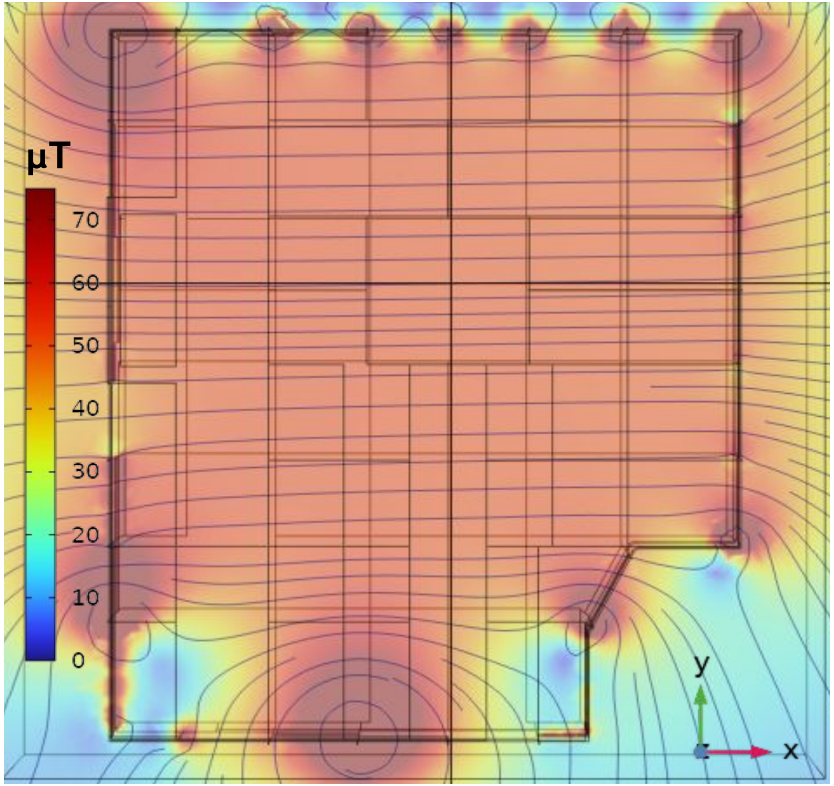
External Disturbance

External Disturbance



COMSOL Implementation





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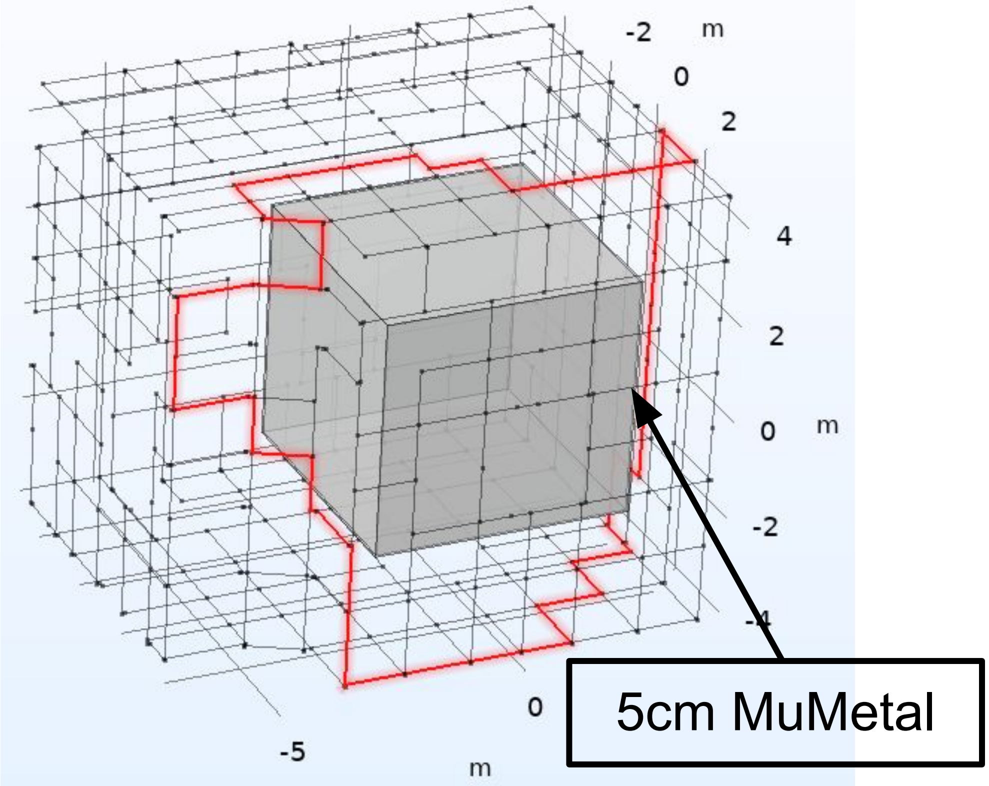

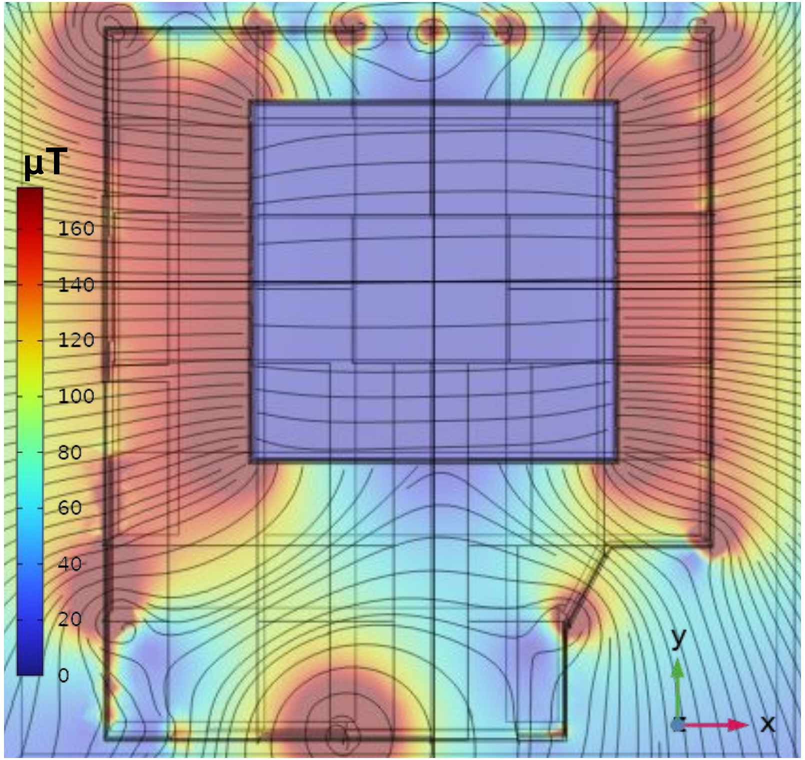

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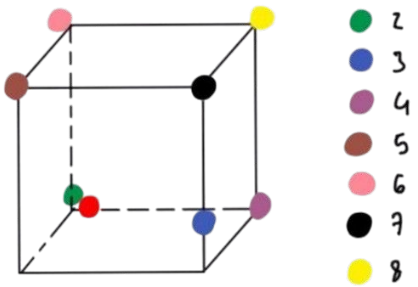
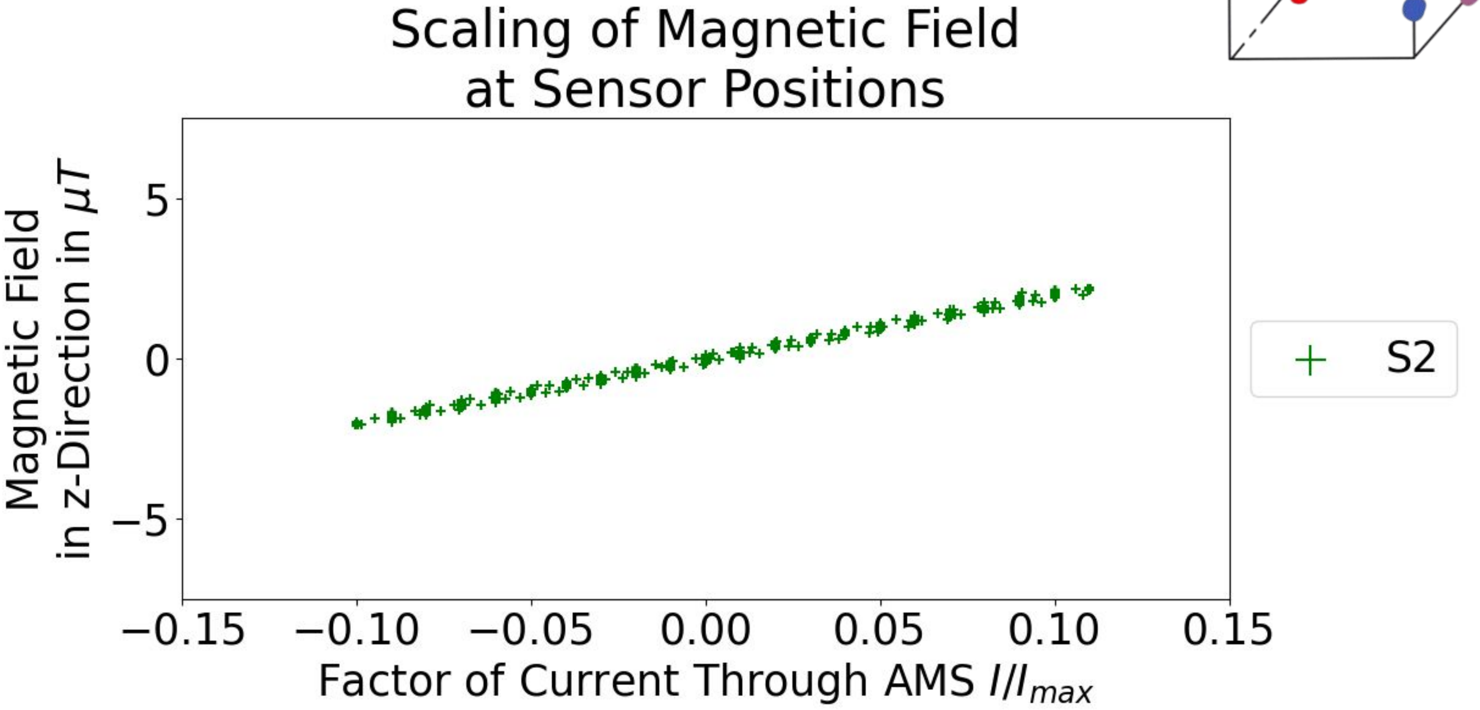
Verification of Simulation





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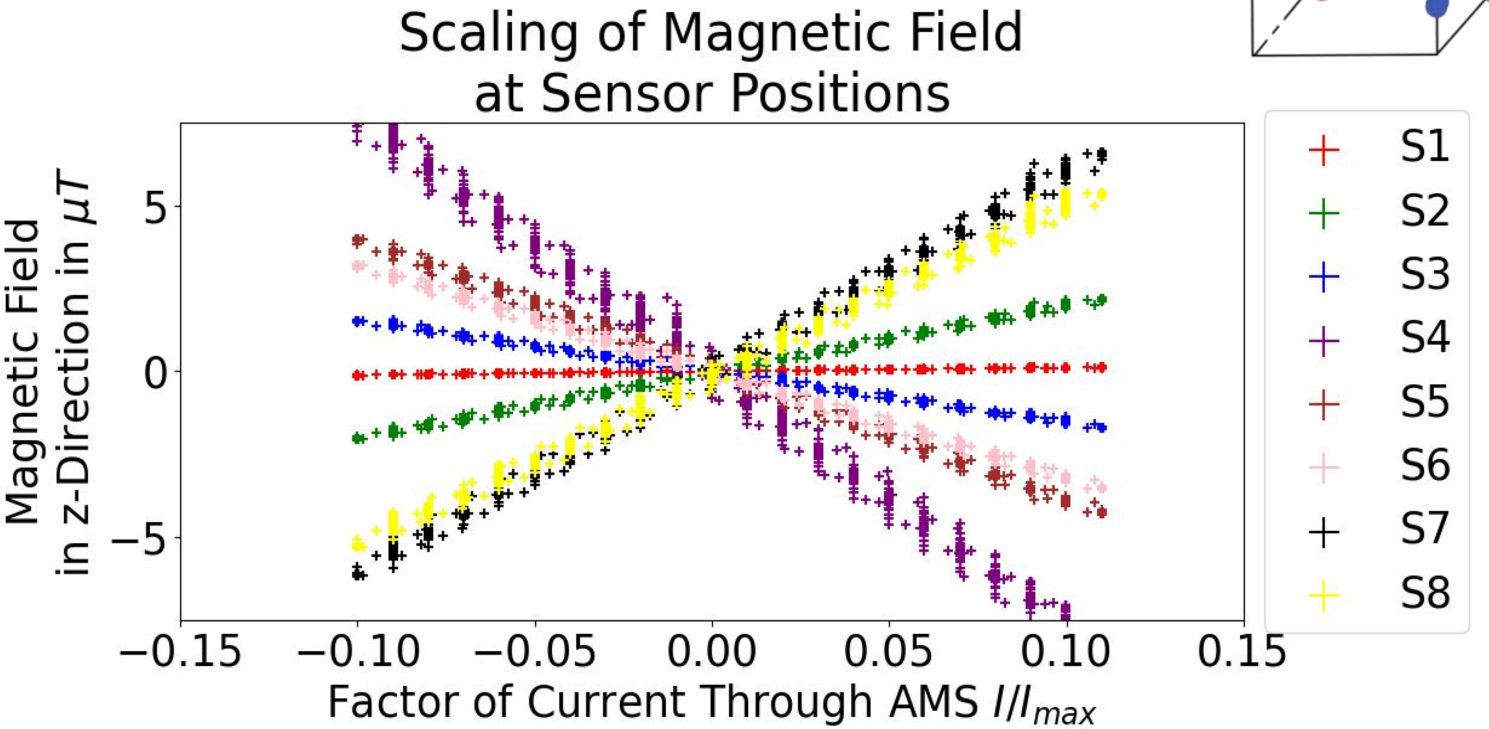

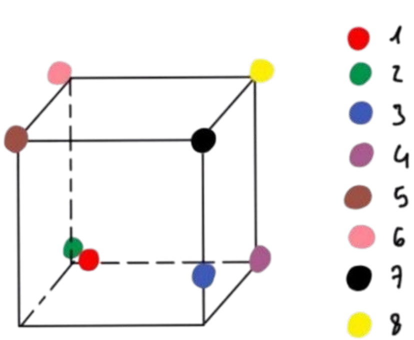

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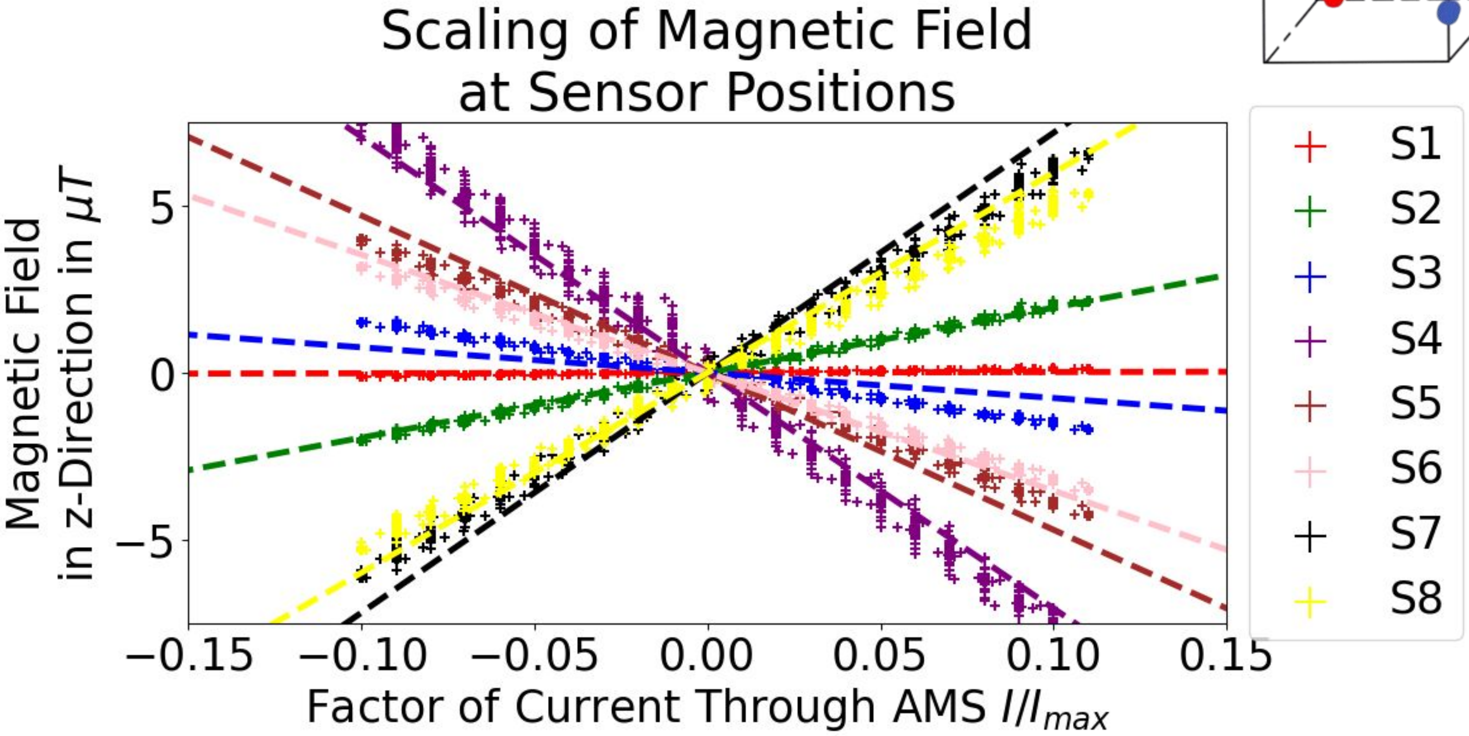

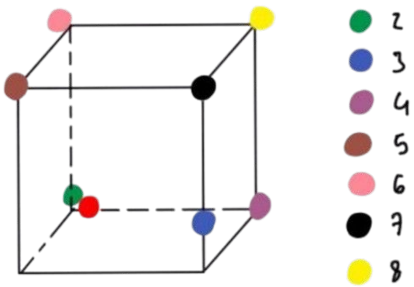

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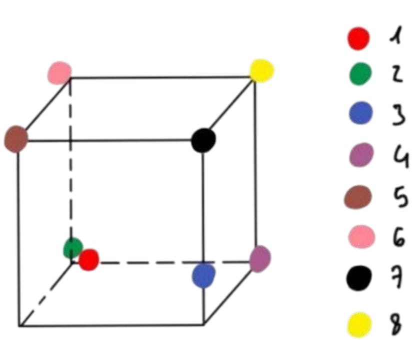

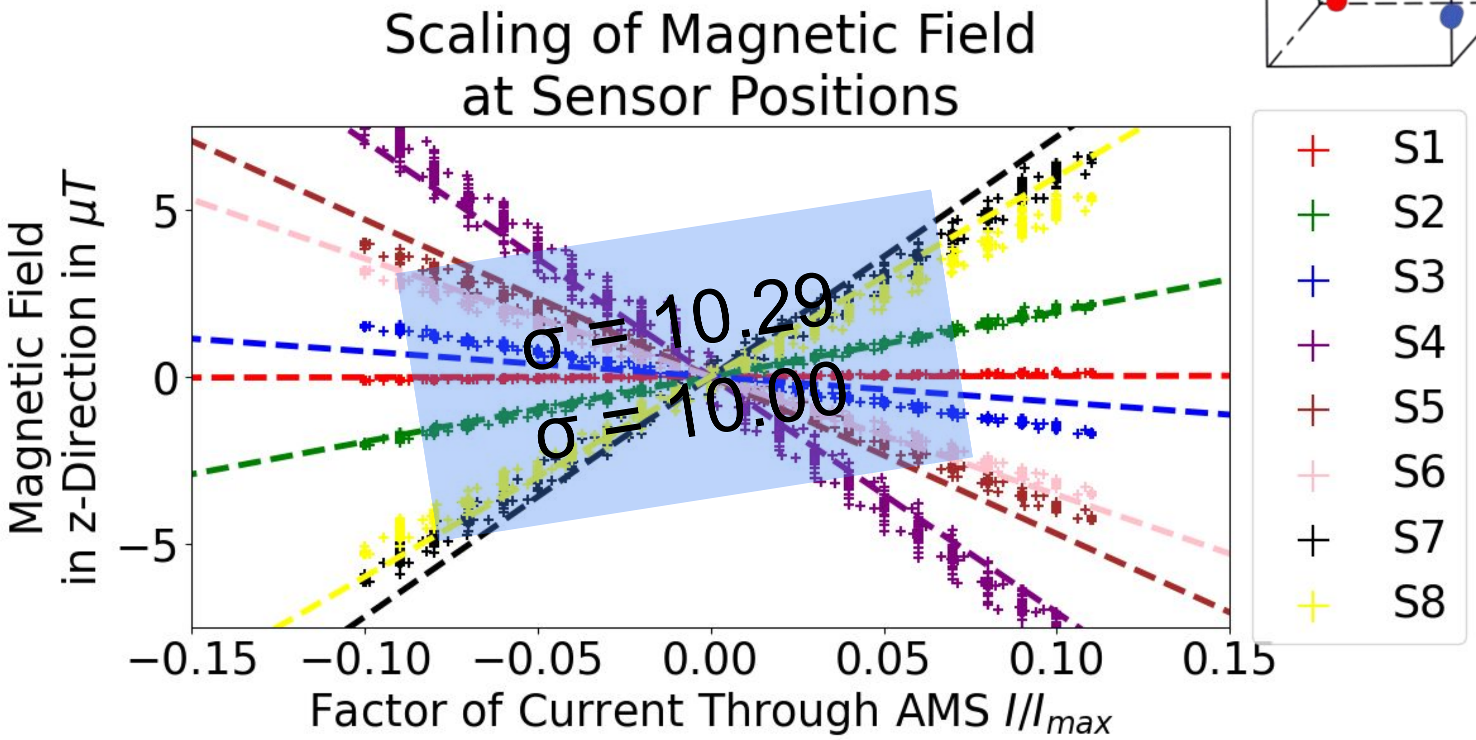

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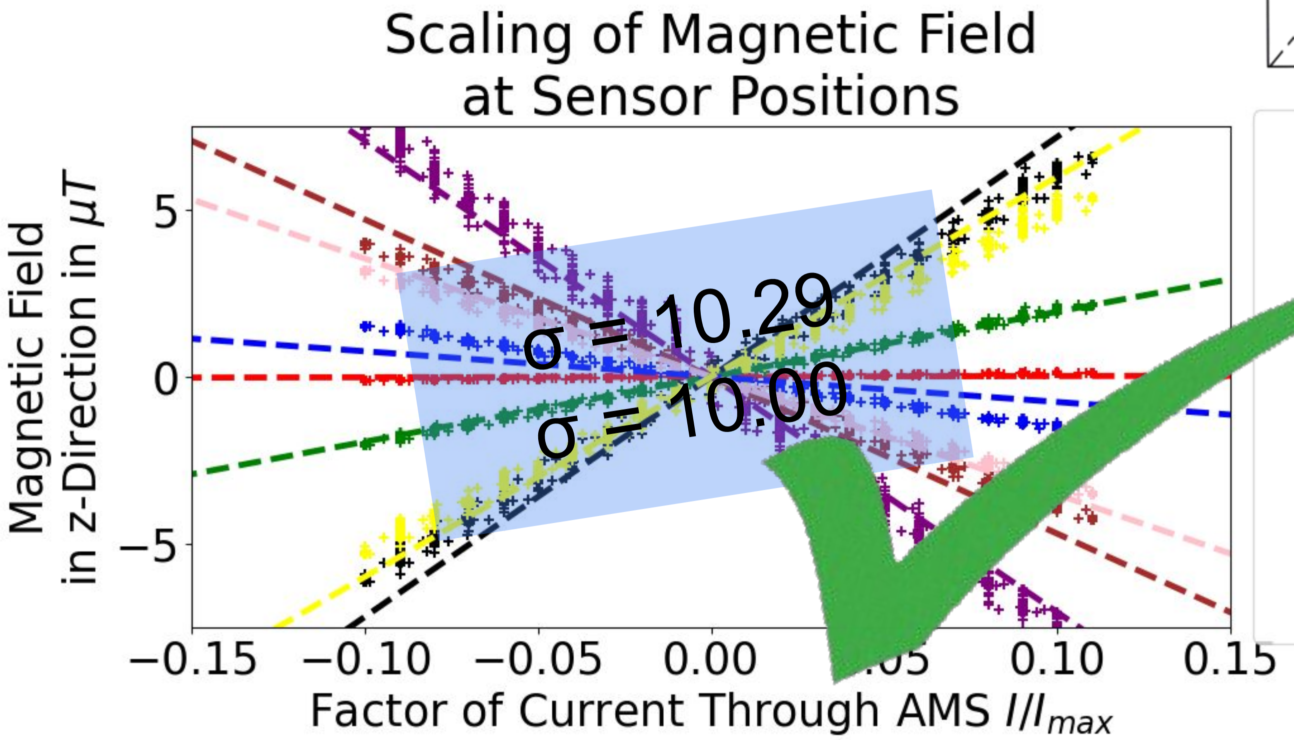
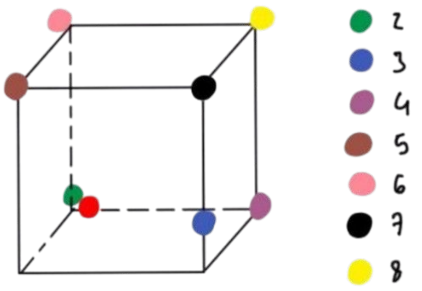
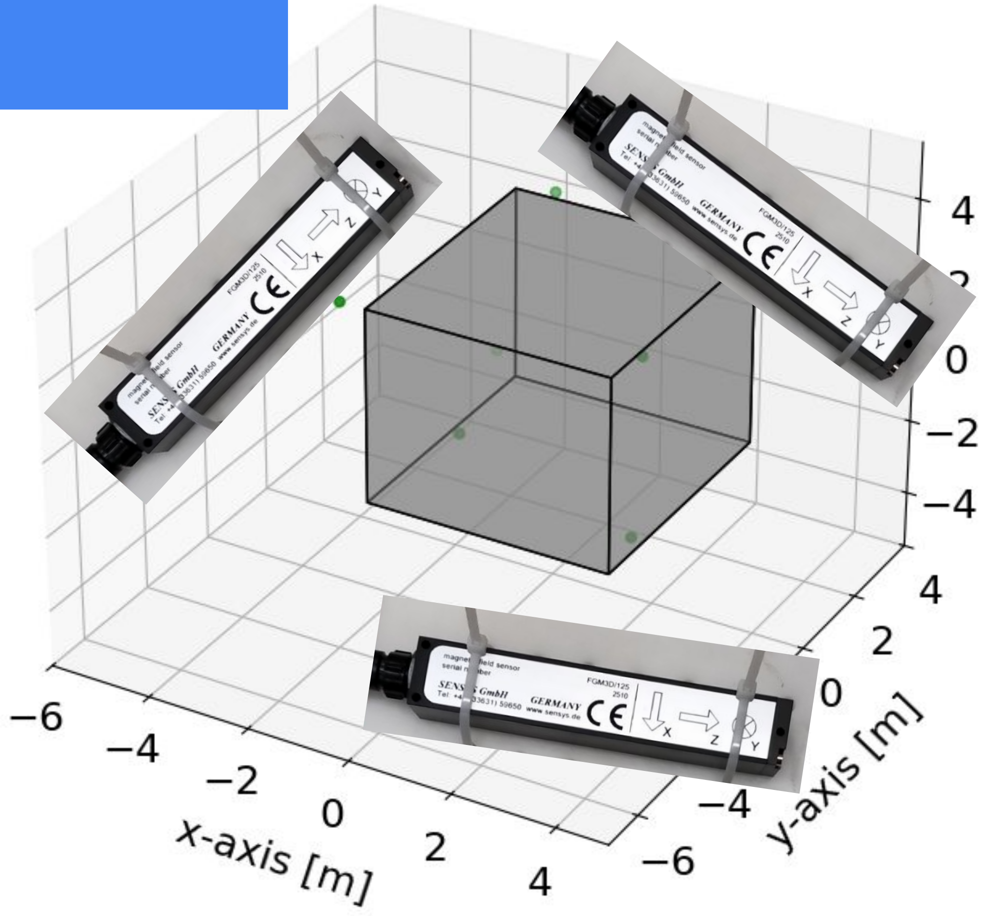




Optimization Targets

- Target:
  1) Condition Number
  2) Average Distance to MSR corners



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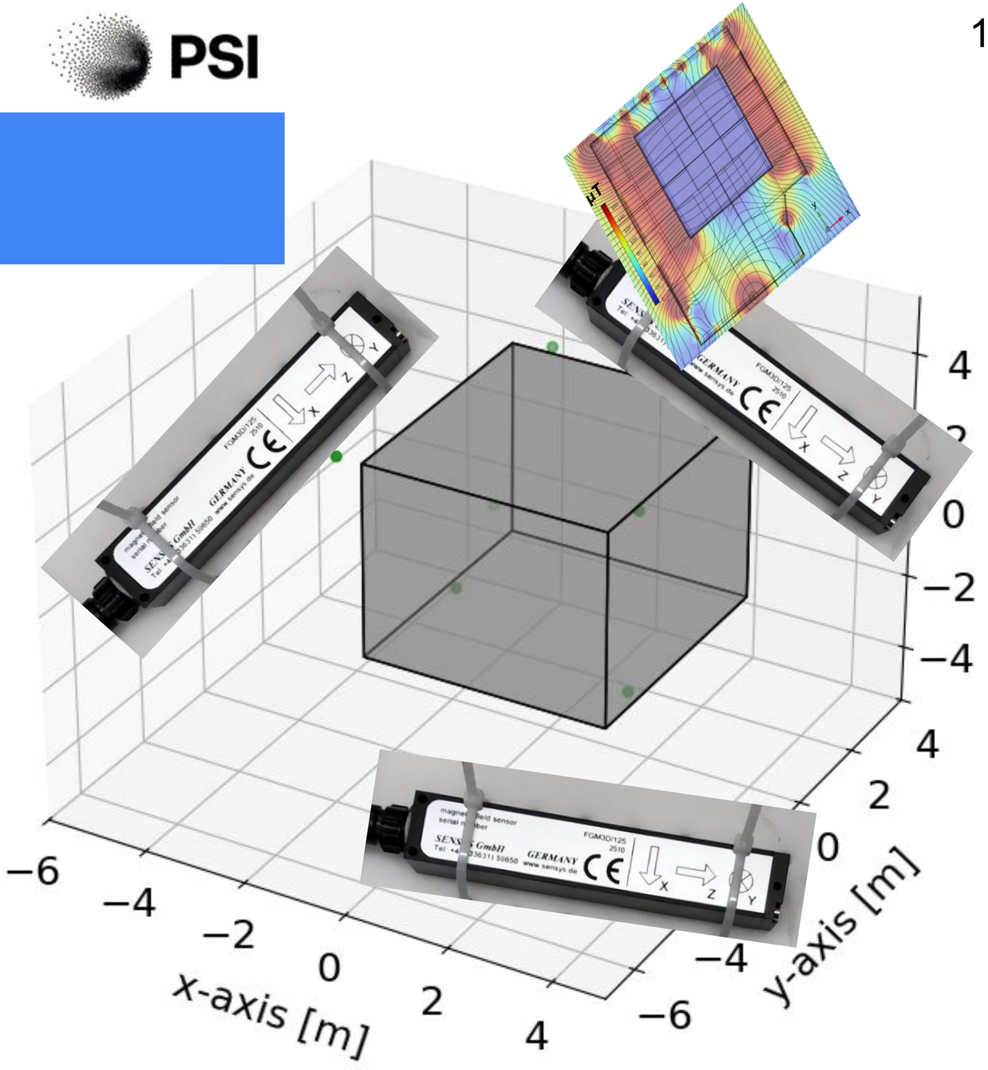

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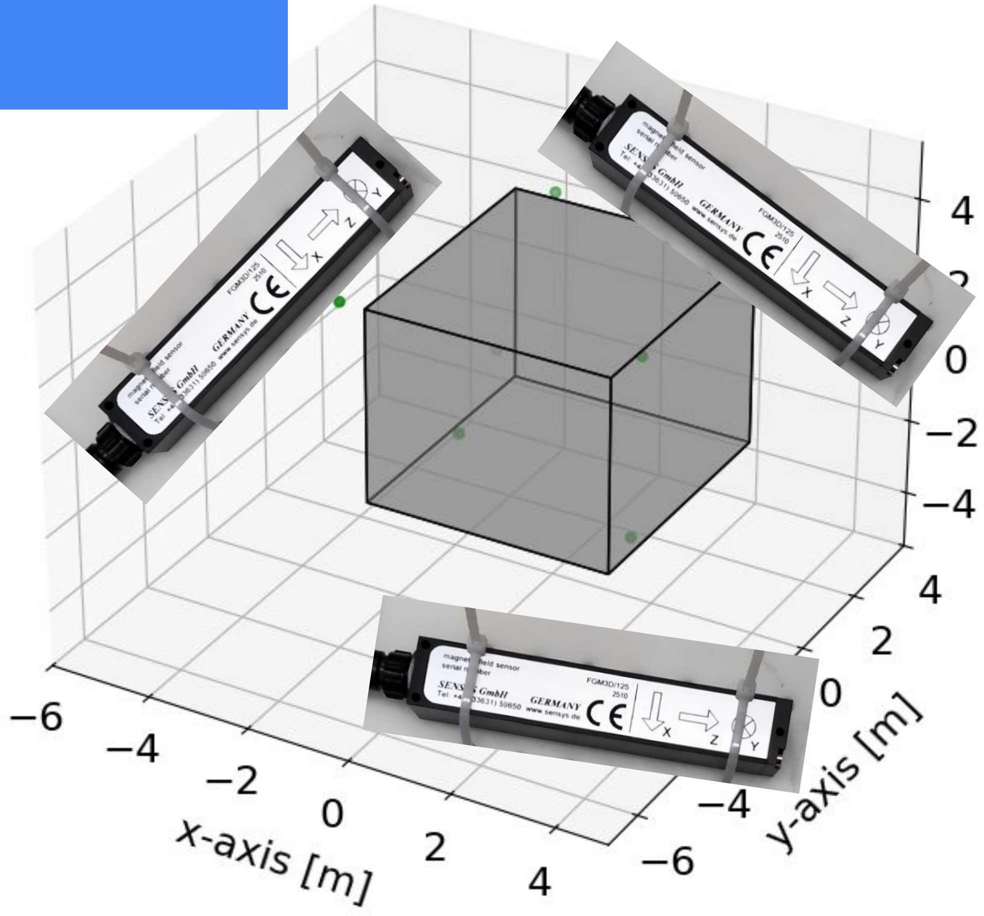

Optimization Targets

- Target:
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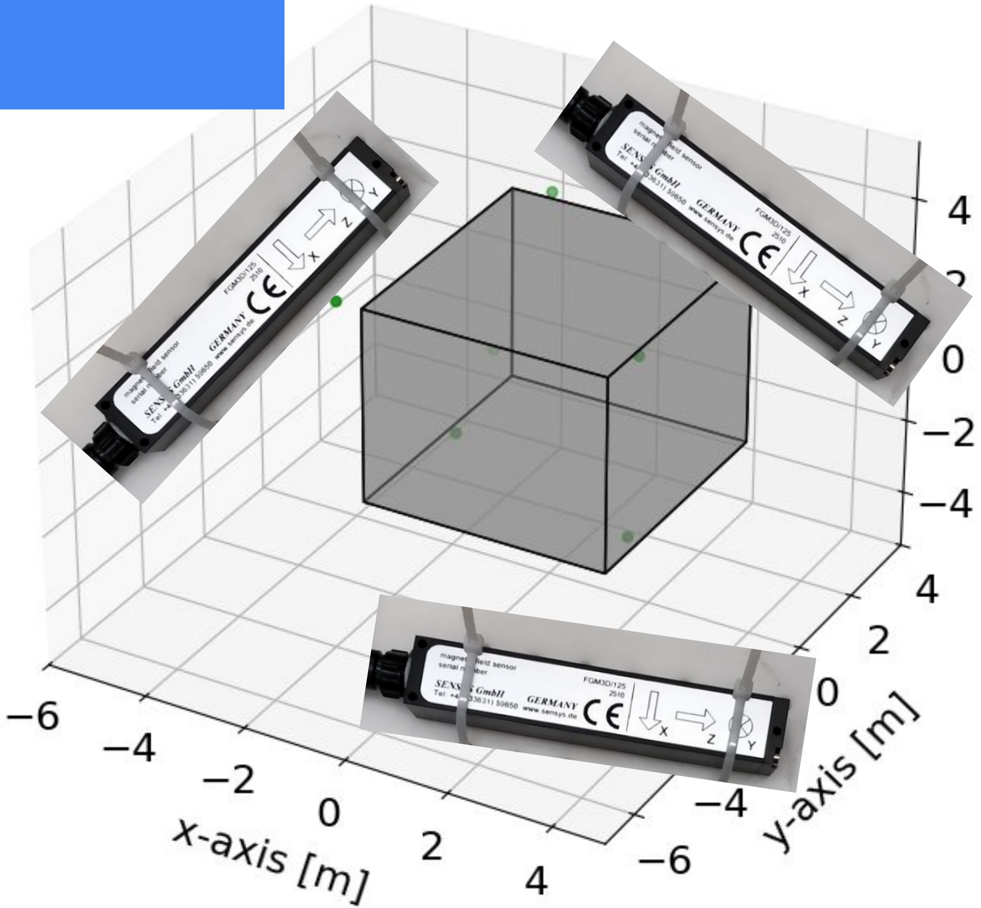
- Vary:
  1) # Fluxgates



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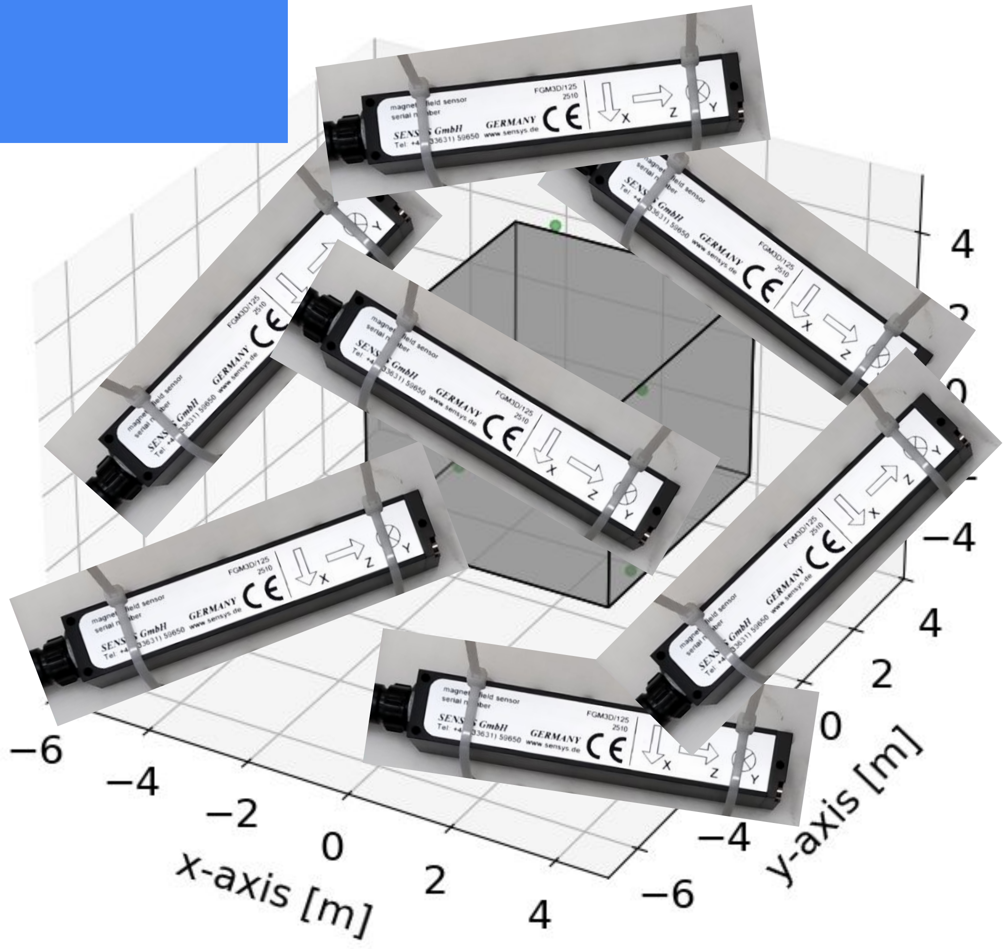

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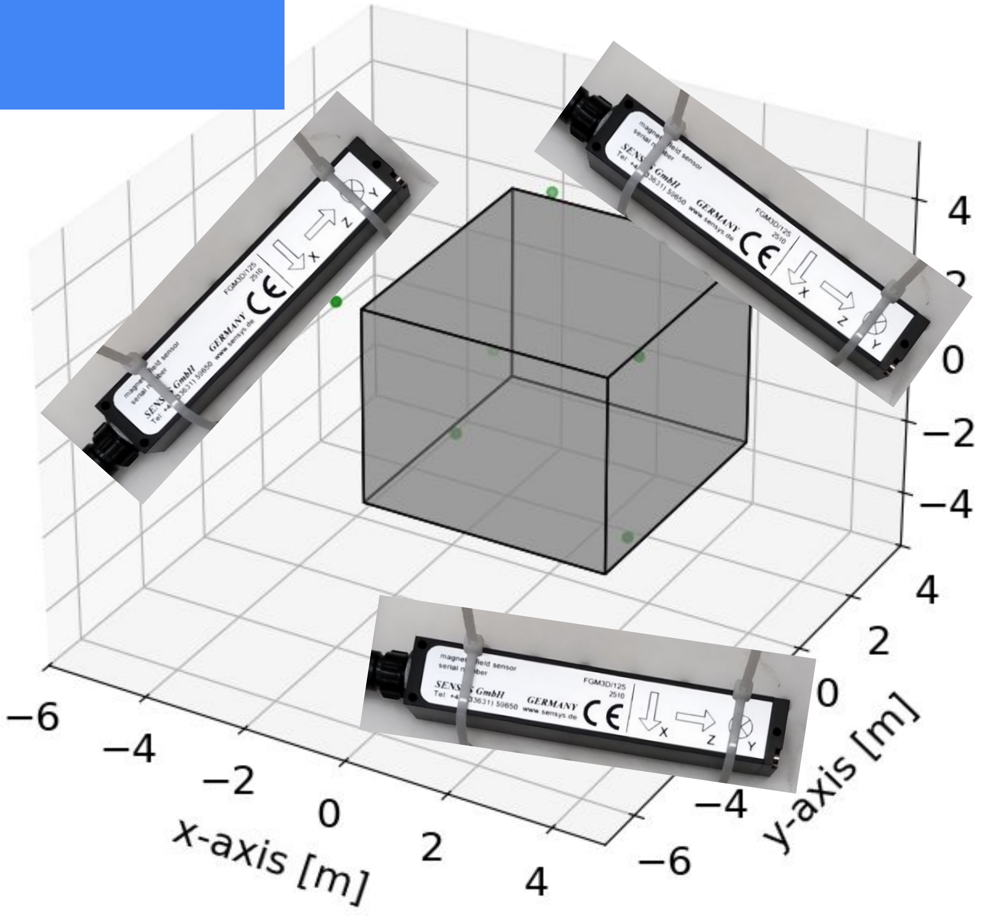

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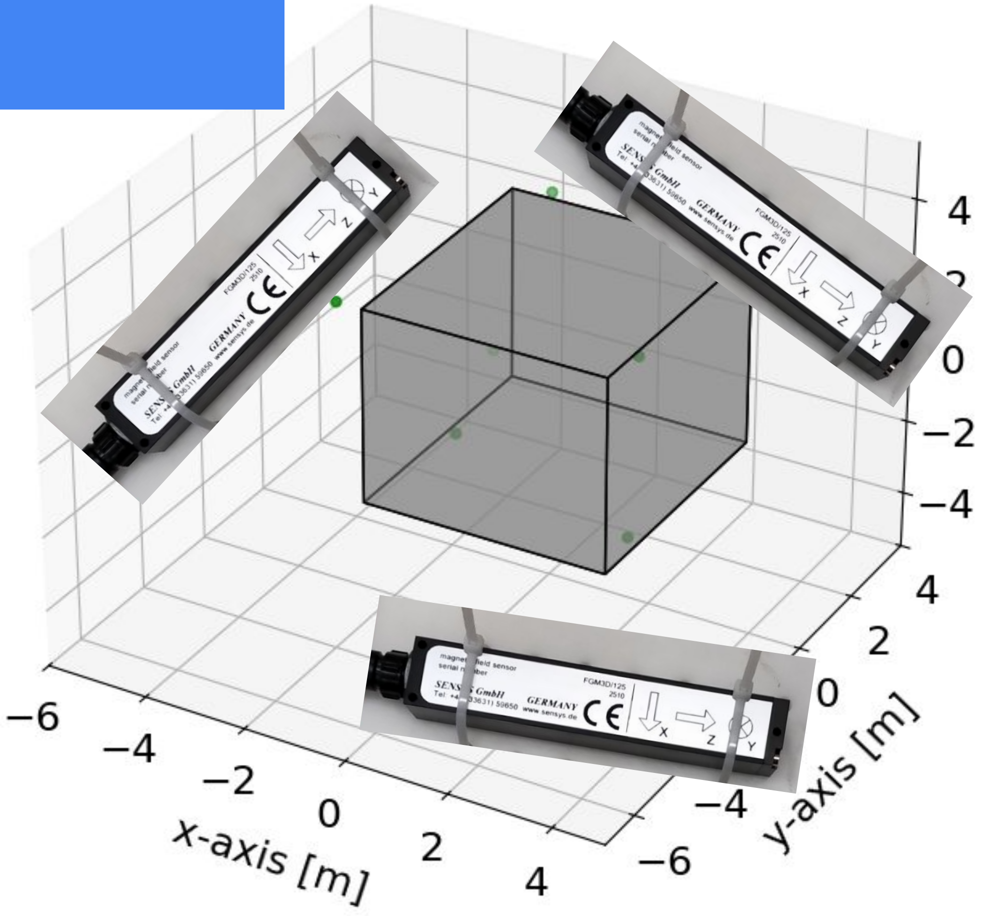

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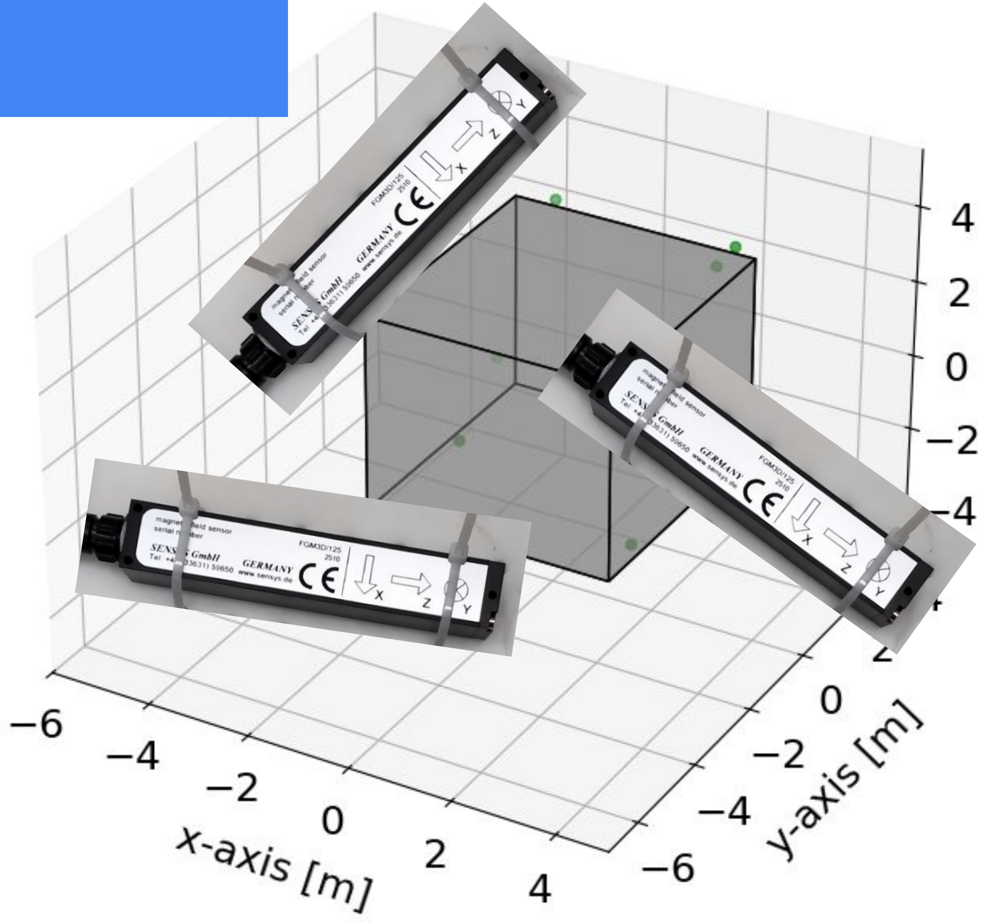

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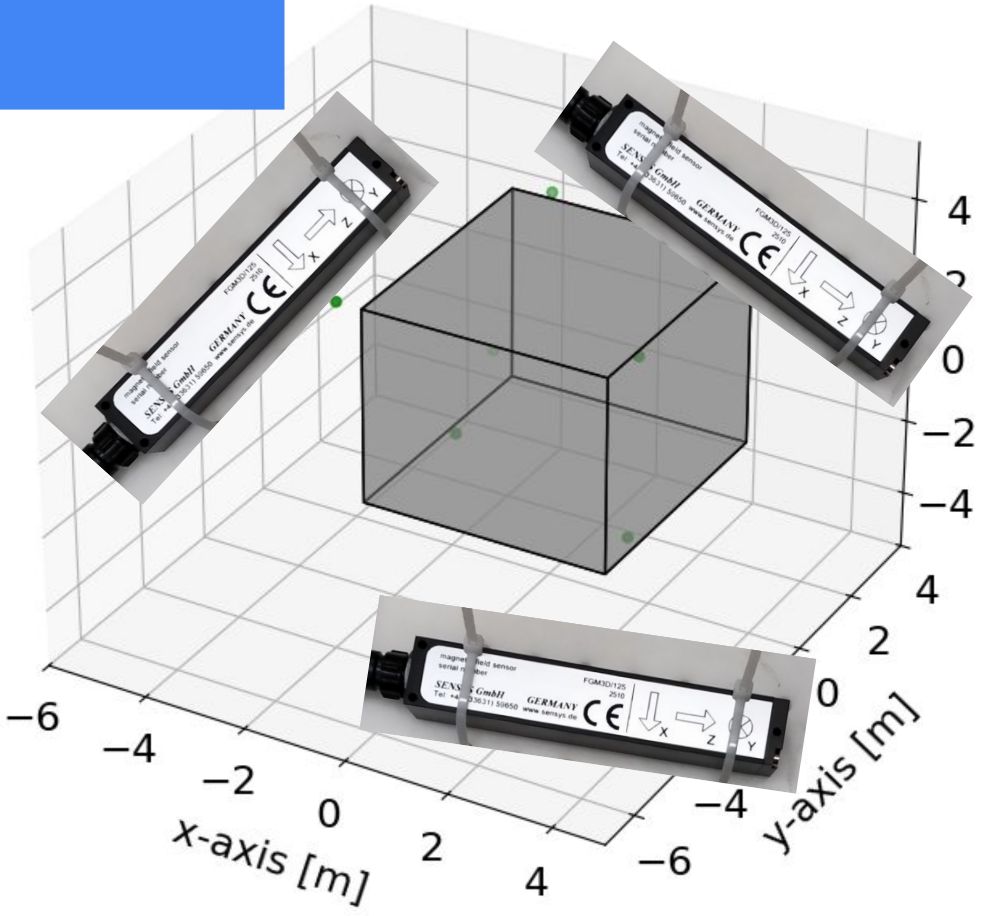

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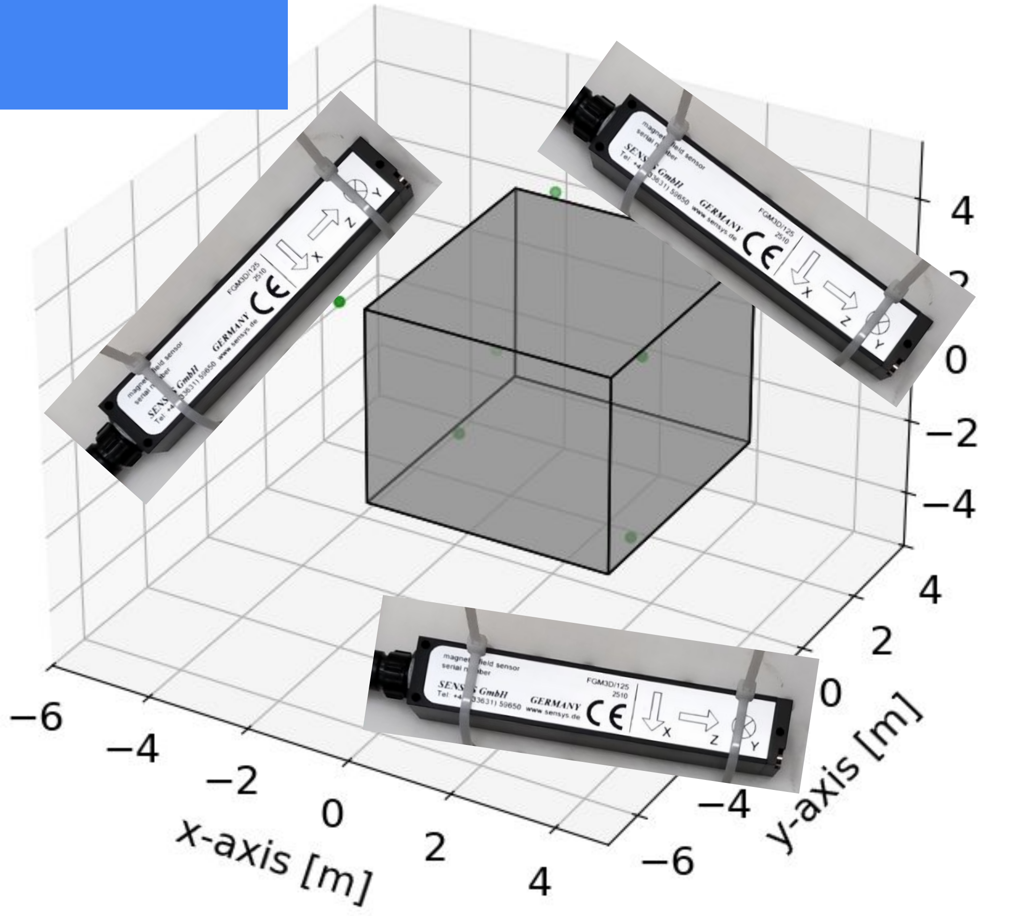

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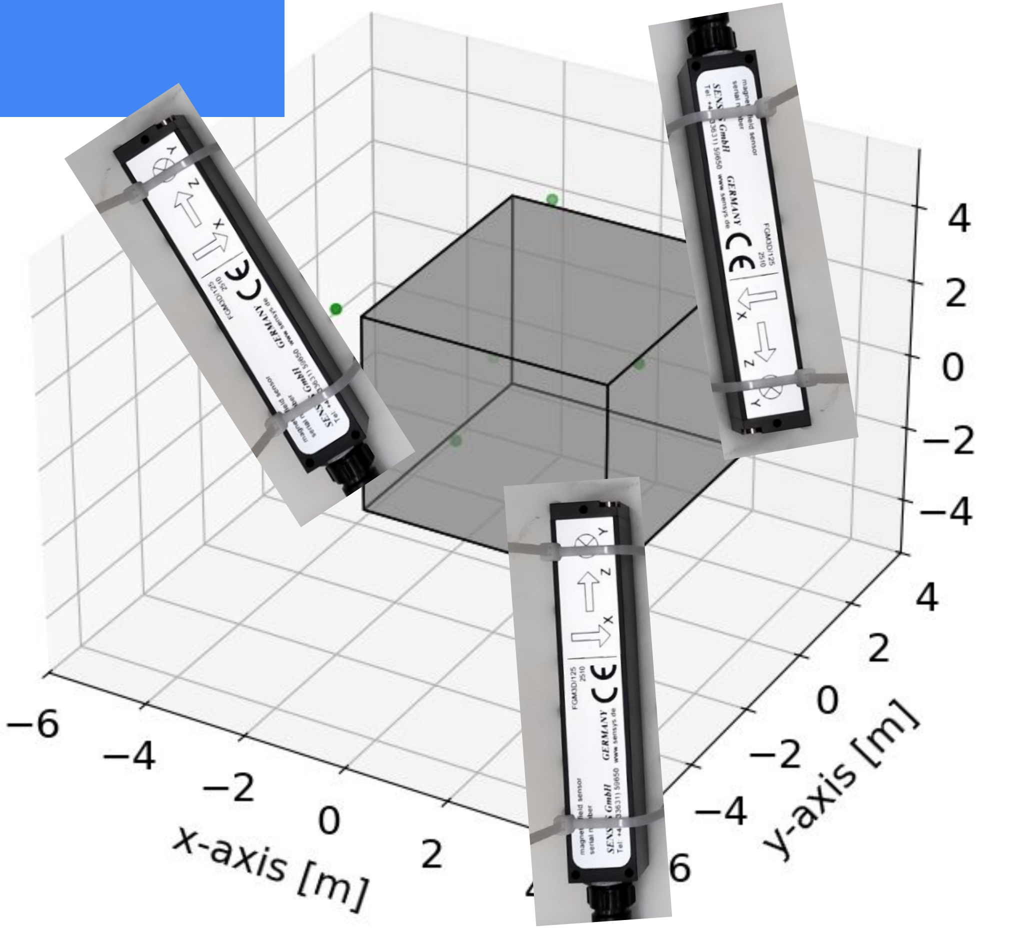

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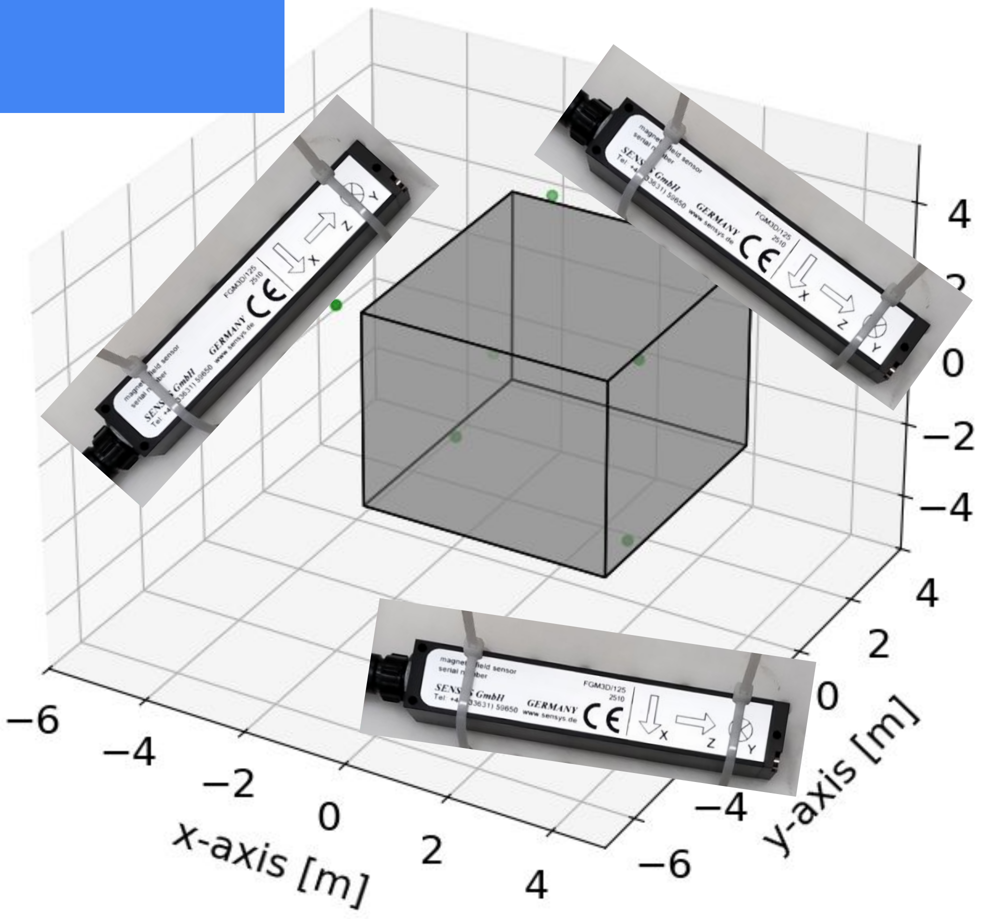
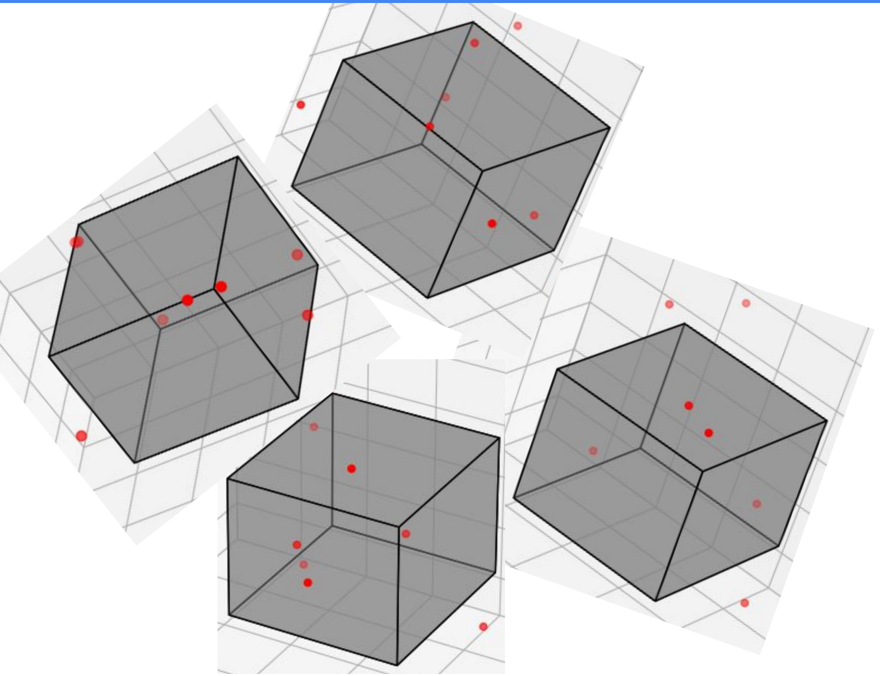


Genetic Algorithms



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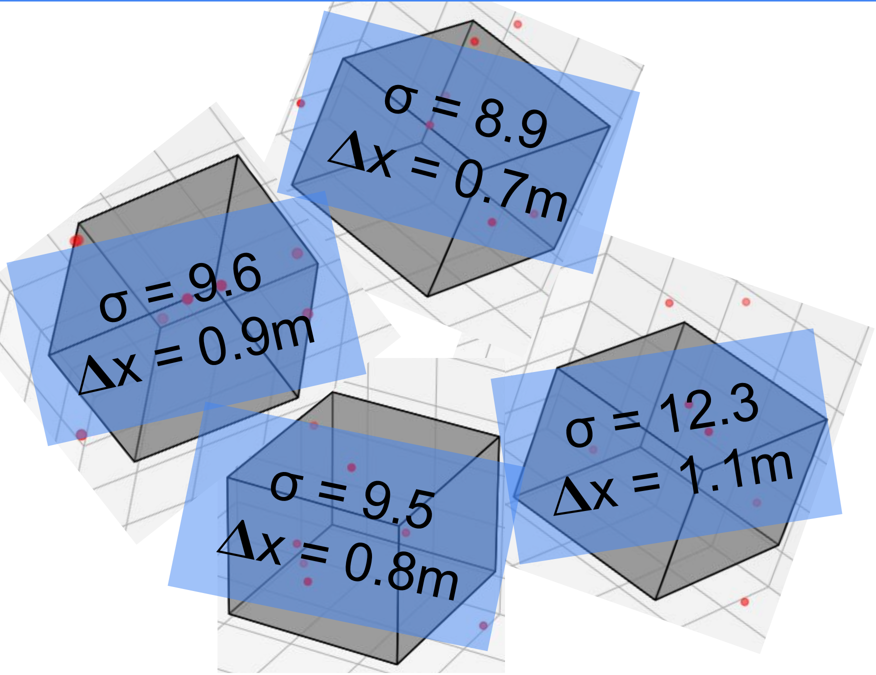

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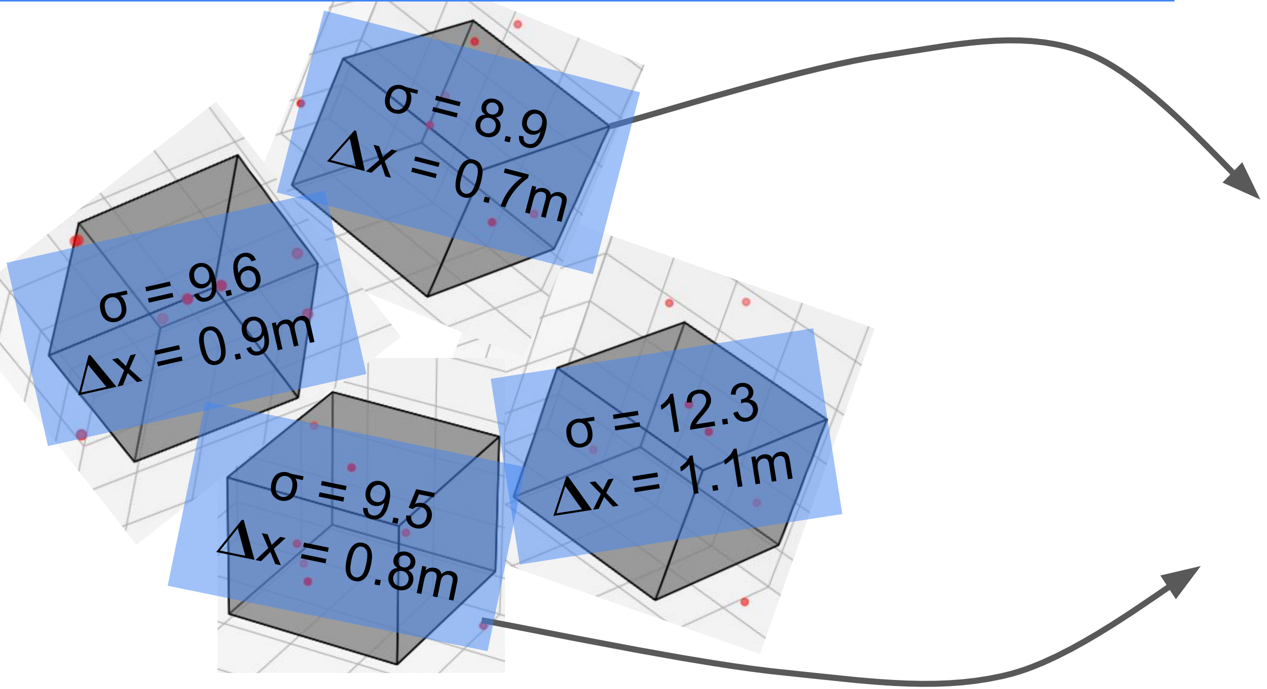

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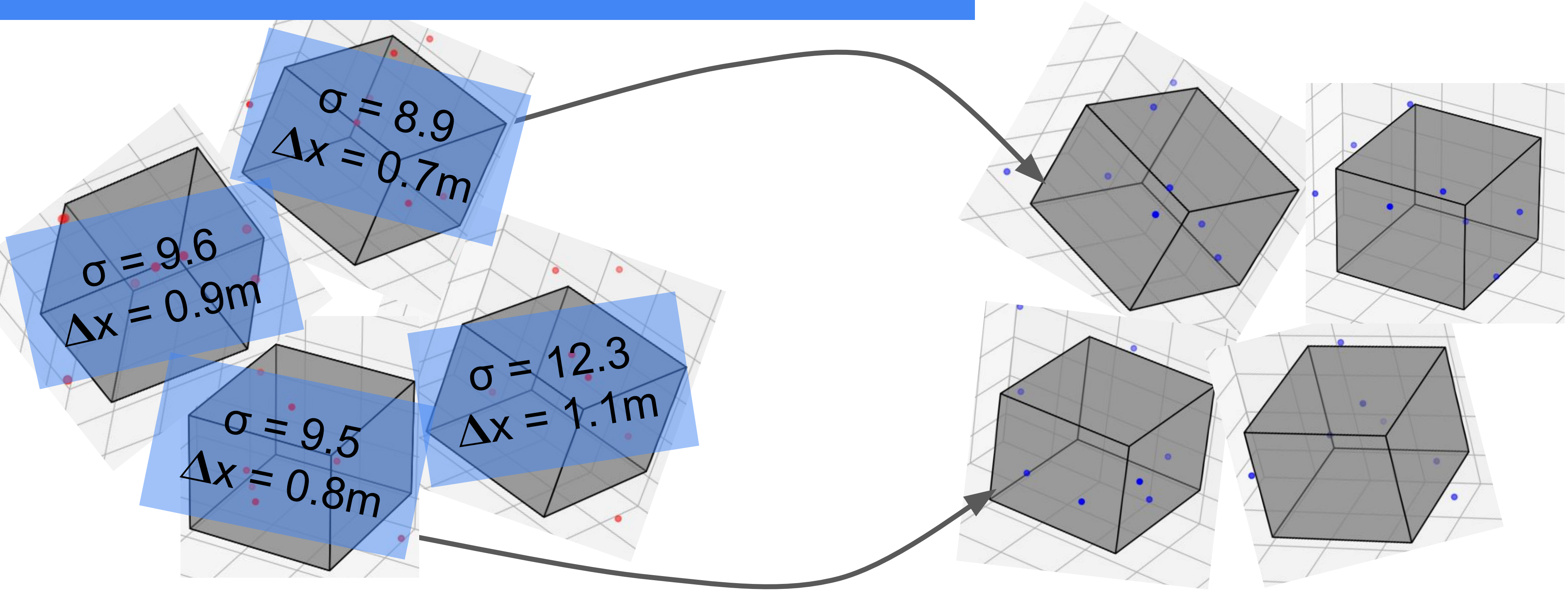

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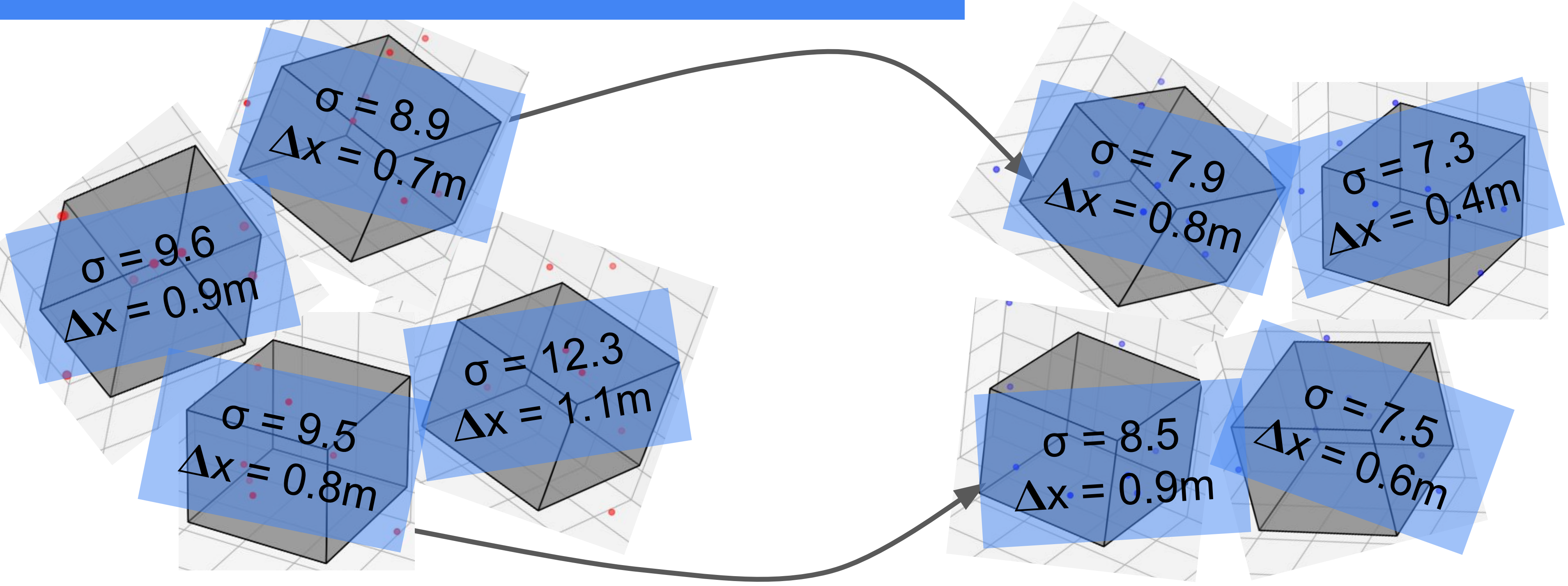

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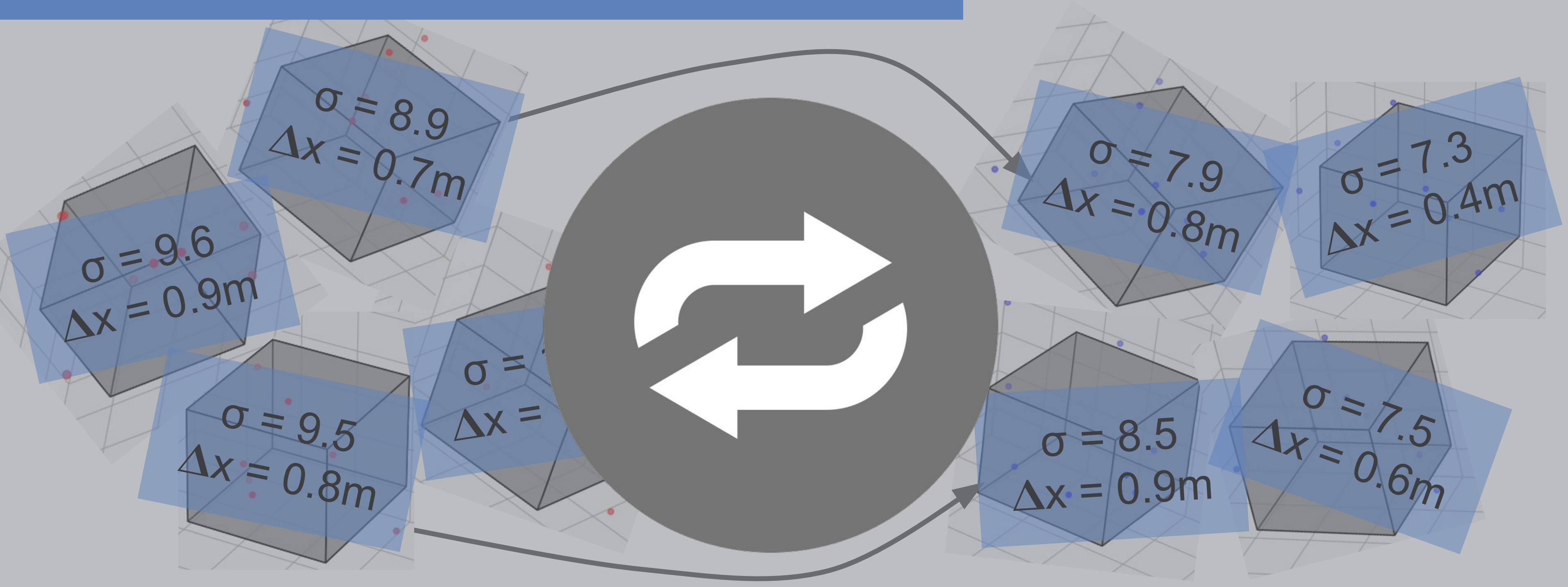
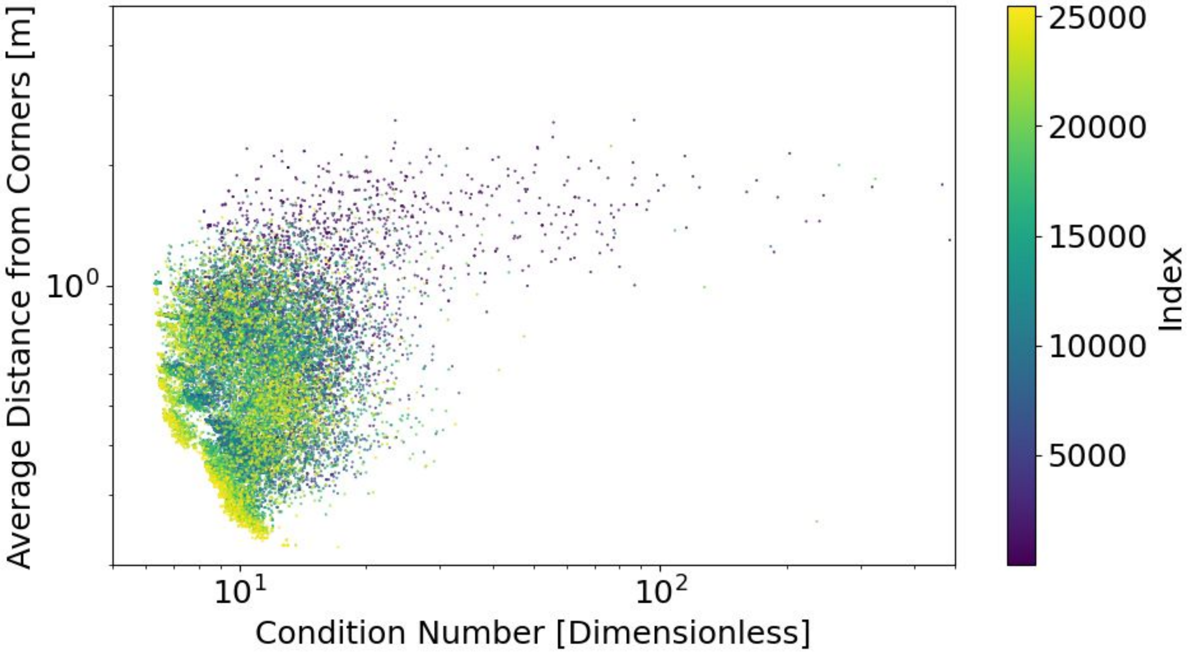
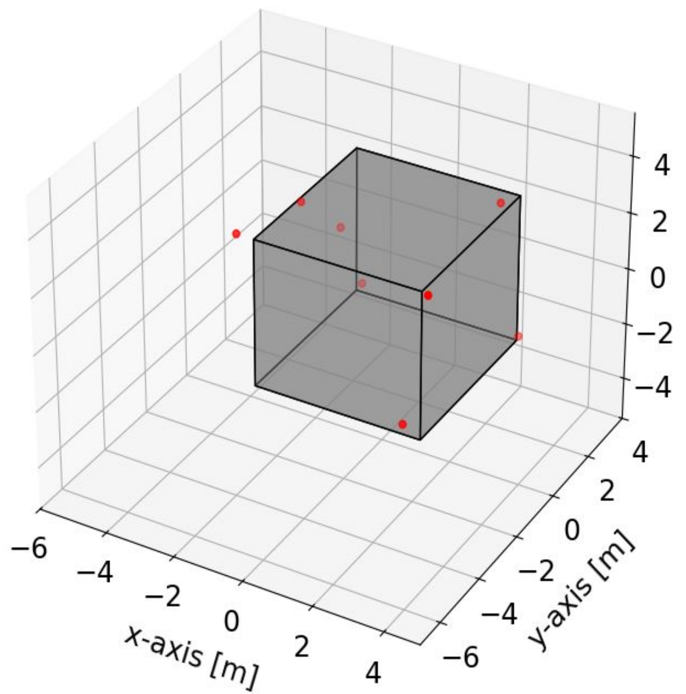


Optuna - Results



Optimal Condition Number $\sigma = 7.85$



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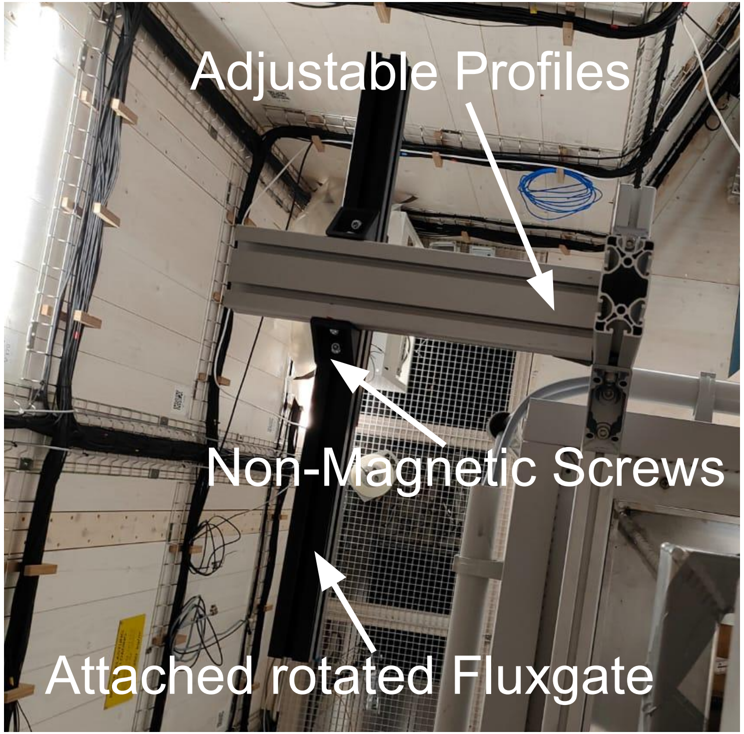
Implementation in System



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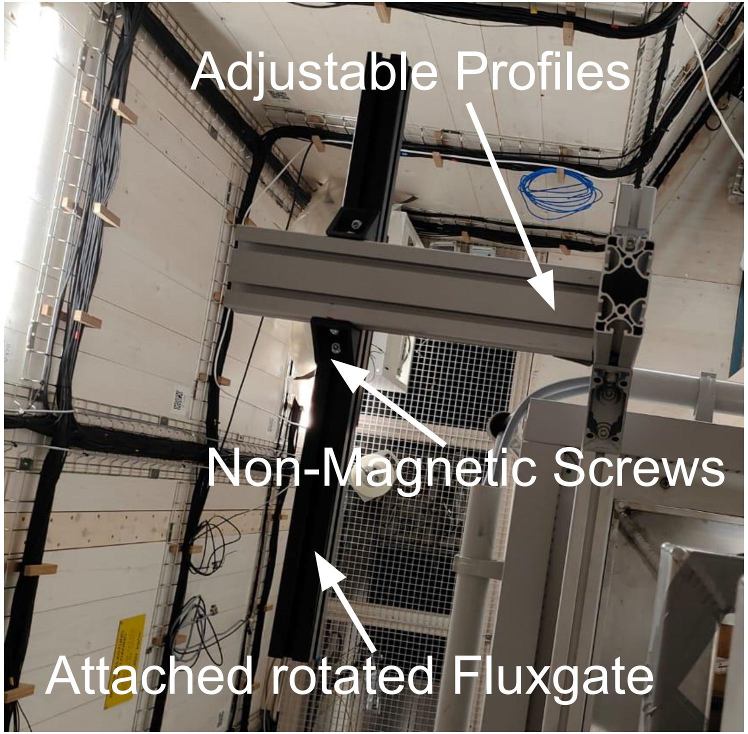
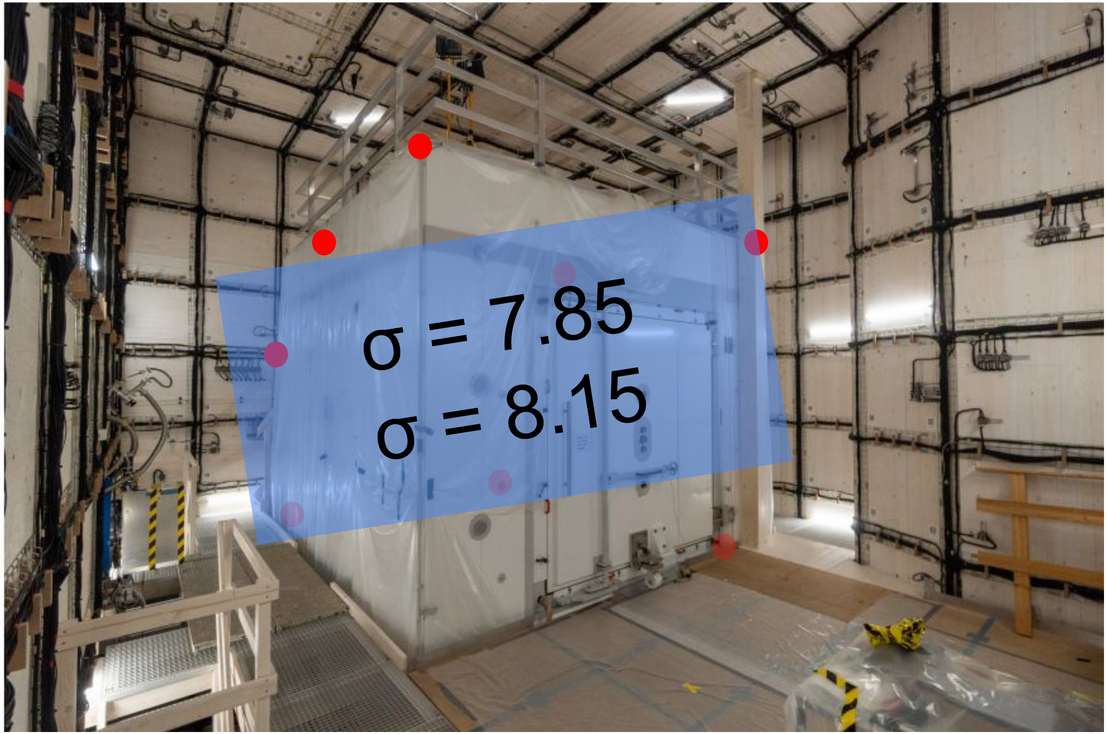
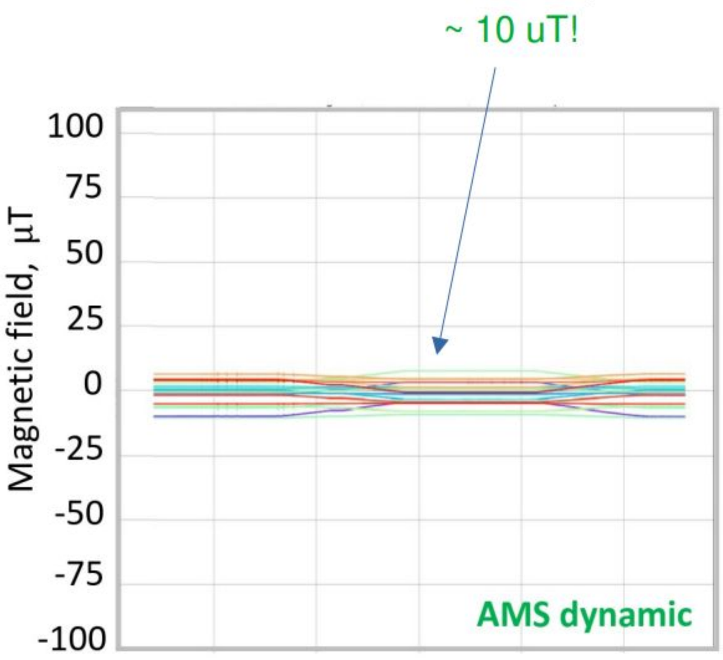
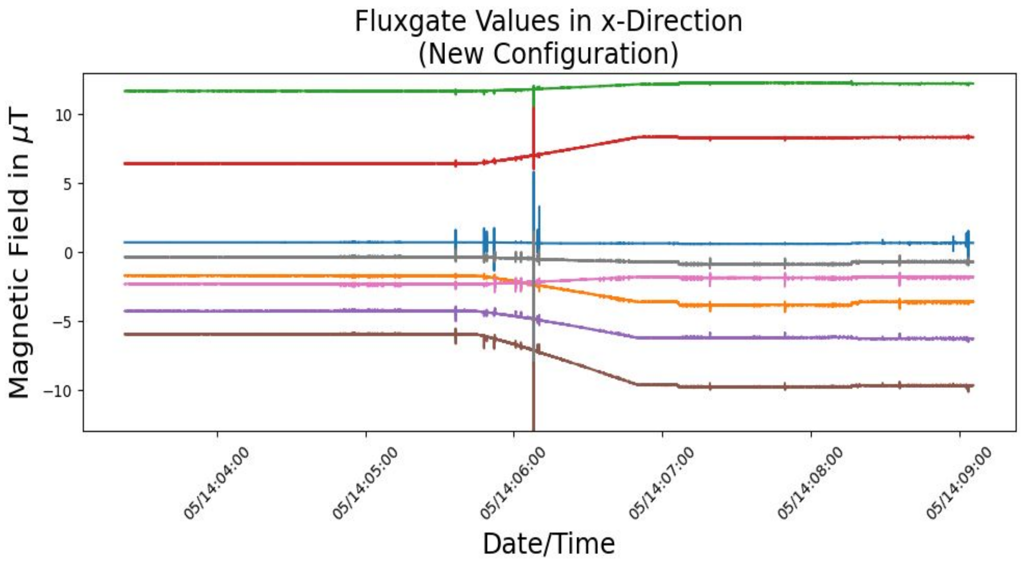




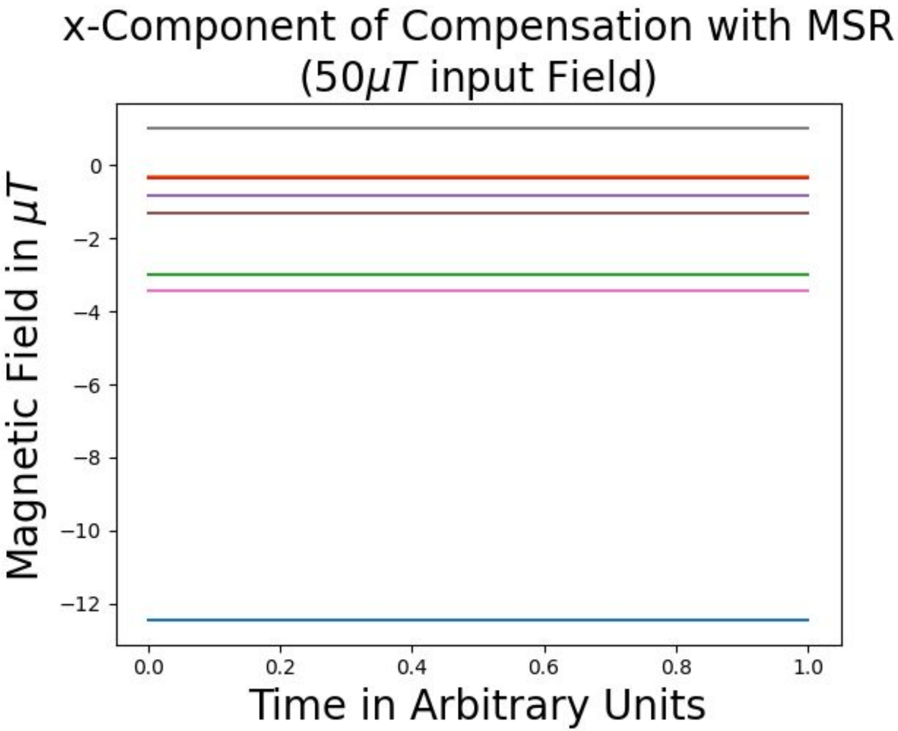
Performance Test

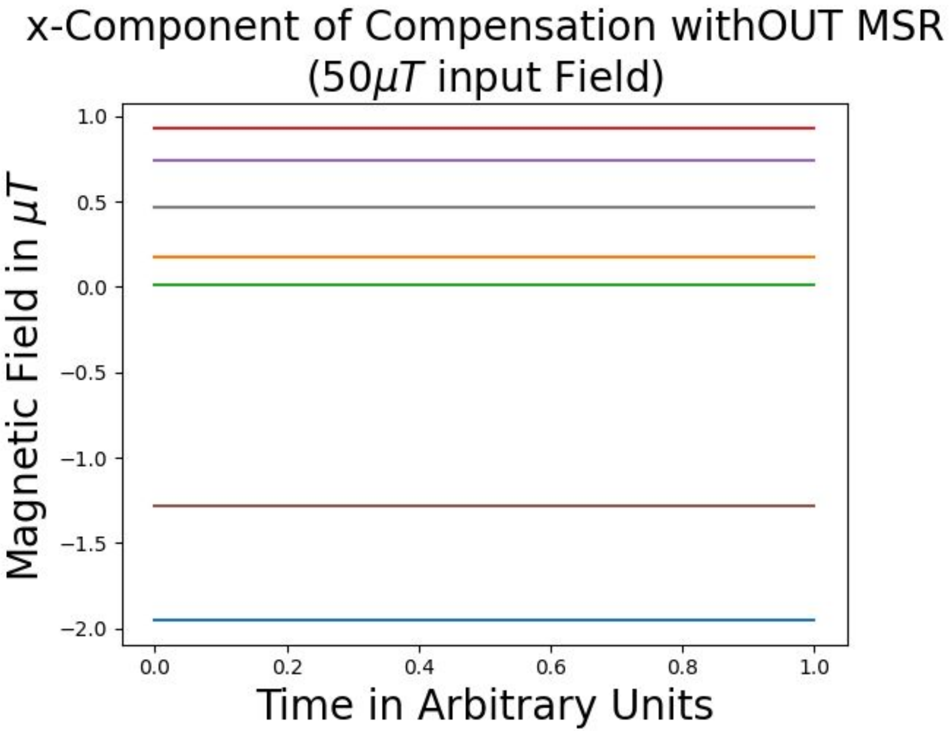
External Disturbance





Simulated Residual Field





Conclusion and Outlook

- Successful Optimization for Condition Number
- Spread unchanged
  → Why?
- Applicable to many more systems!
- C. Abel et. al., arXiv:2307.07588v1 (2023)

Conclusio

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Poster No. 388

Questions?