

## Simulation and Optimization of the Active Magnetic Shield for n2EDM

Sergey Konstantin Ermakov

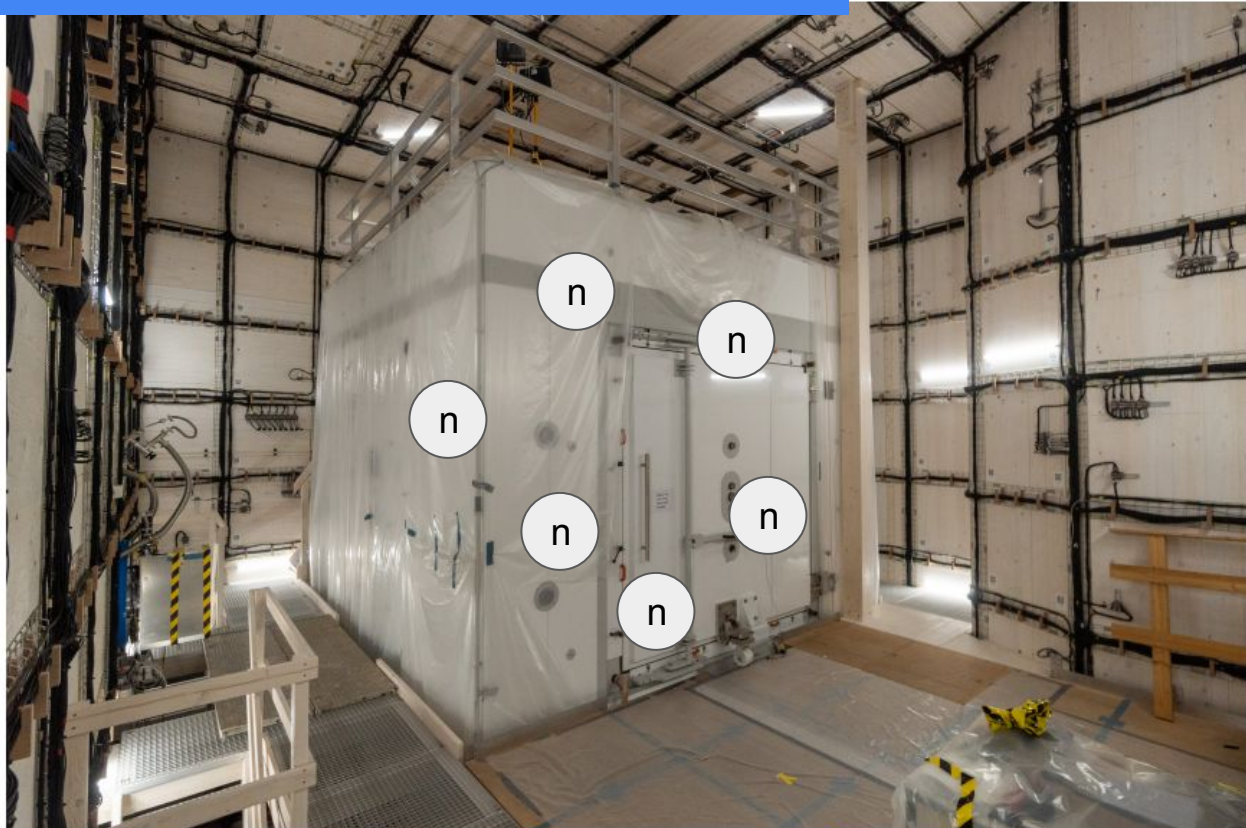
On behalf of the n2edm collaboration at PSI

ETH Zürich

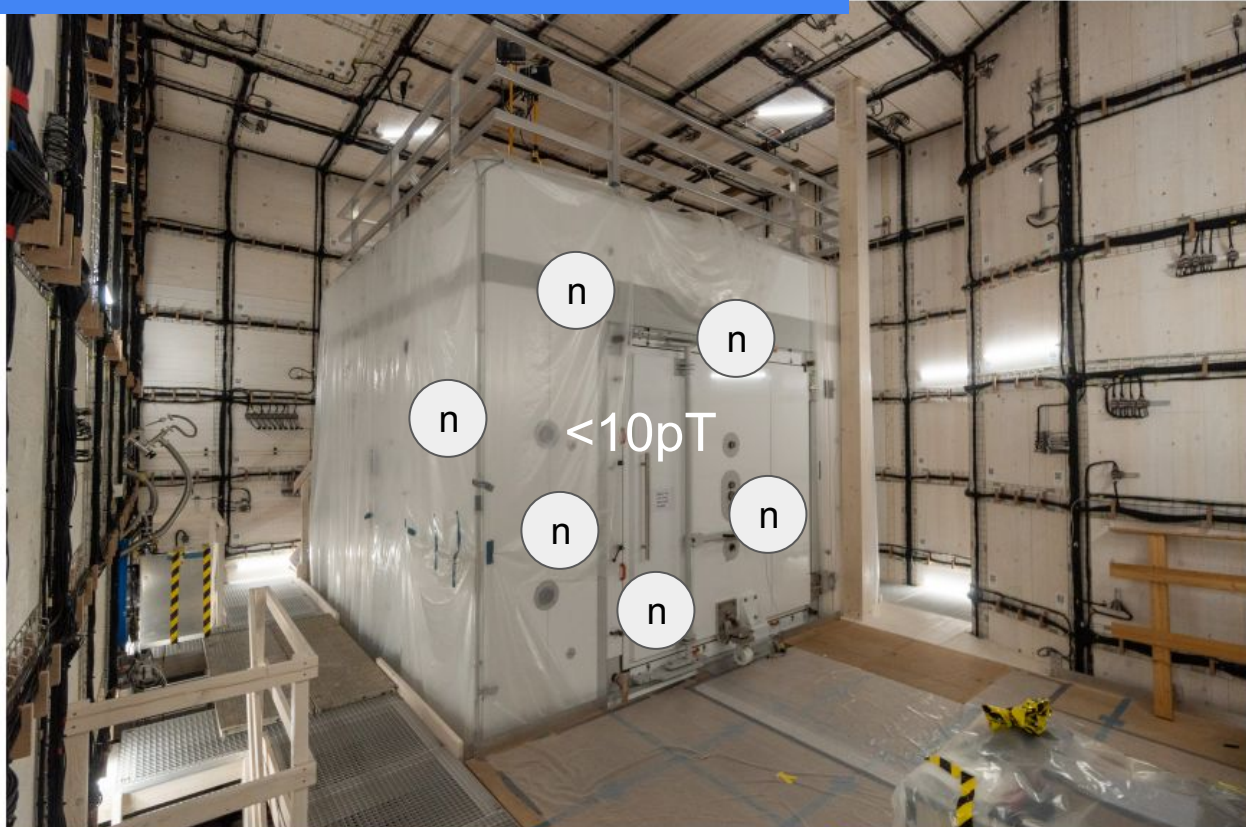
11th September 2024, Zürich



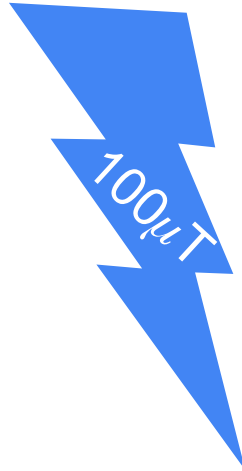
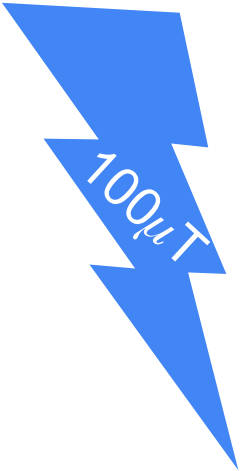
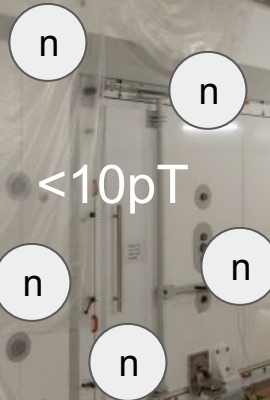
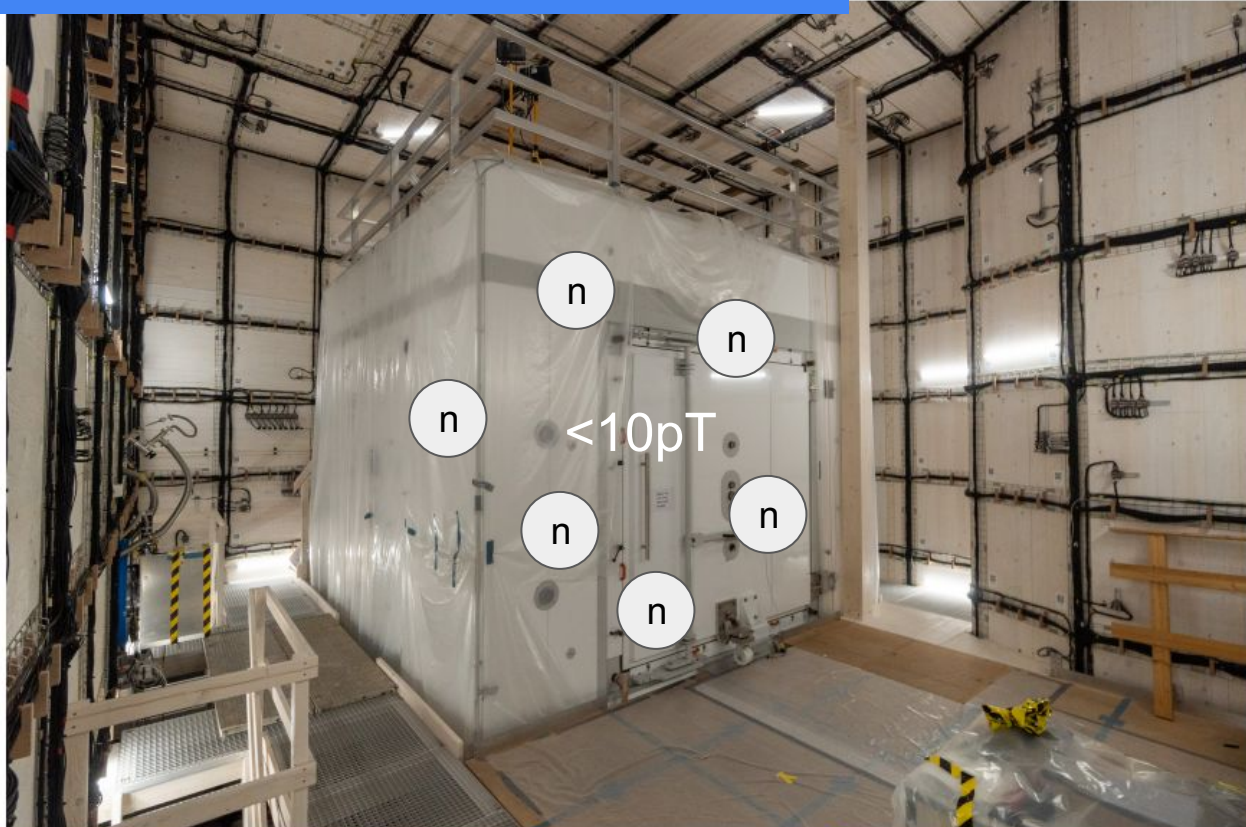
# The n2EDM Experiment



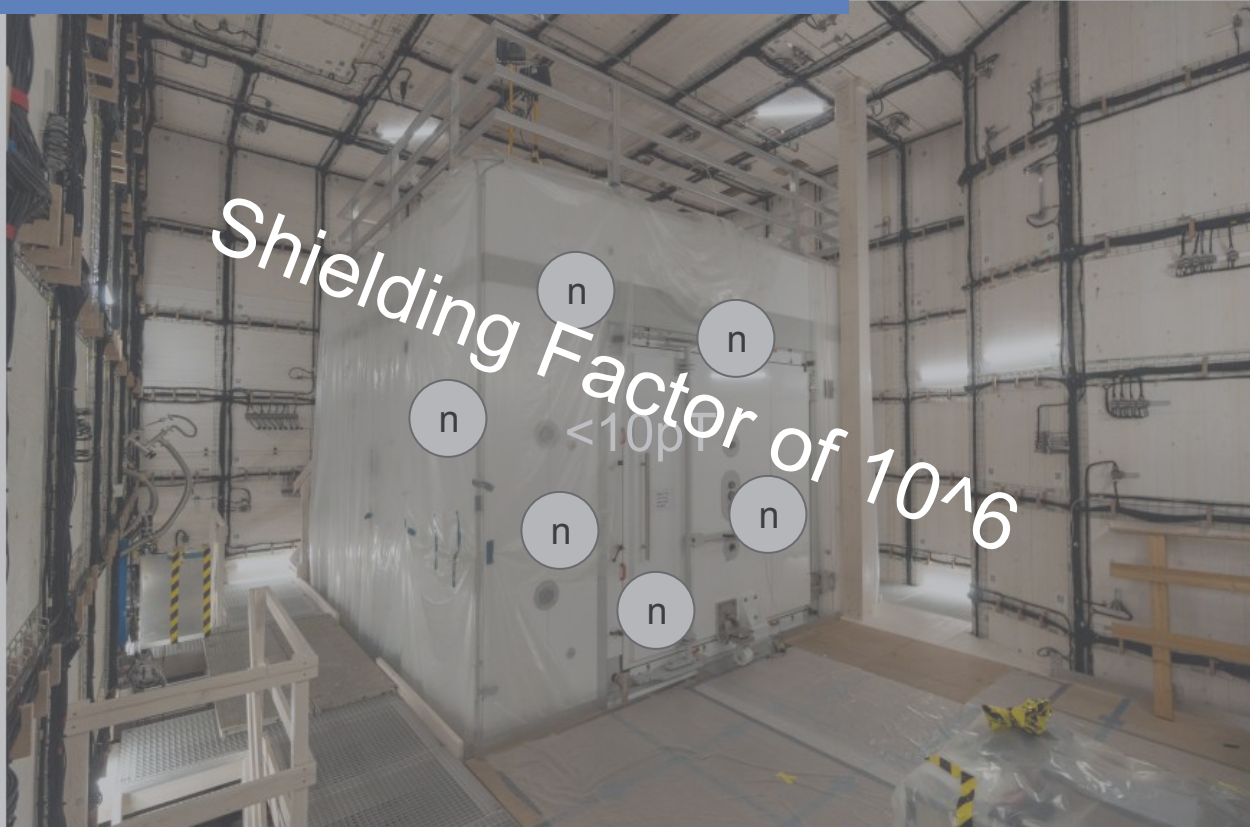
# The n2EDM Experiment



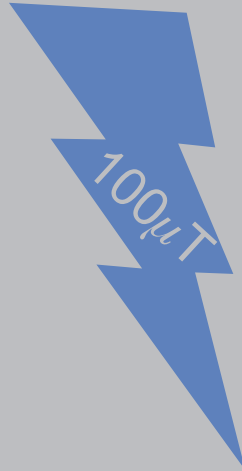
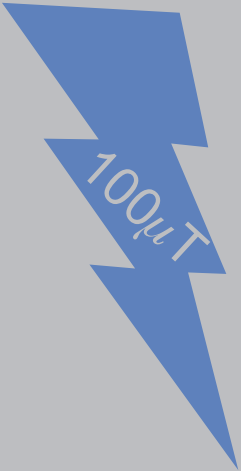
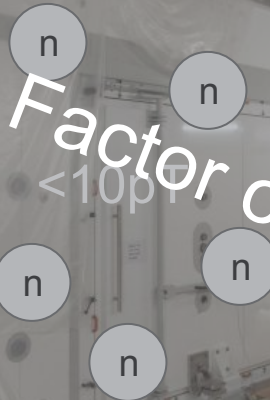
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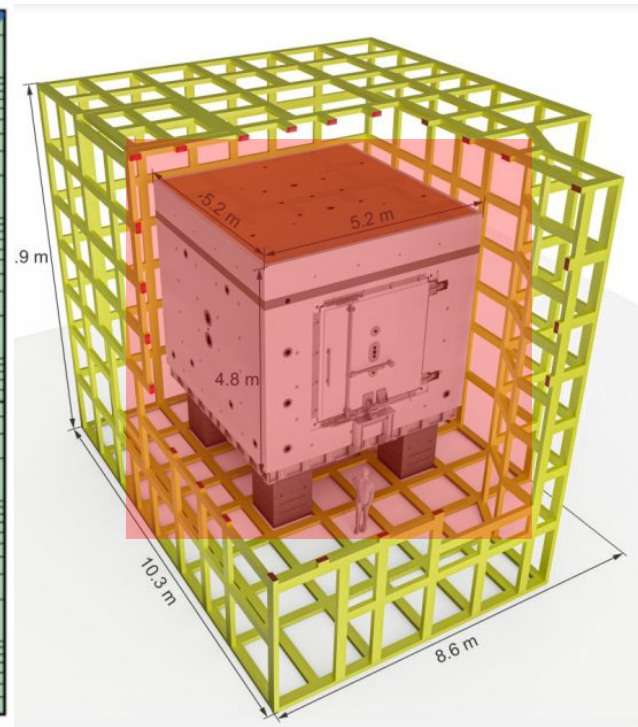
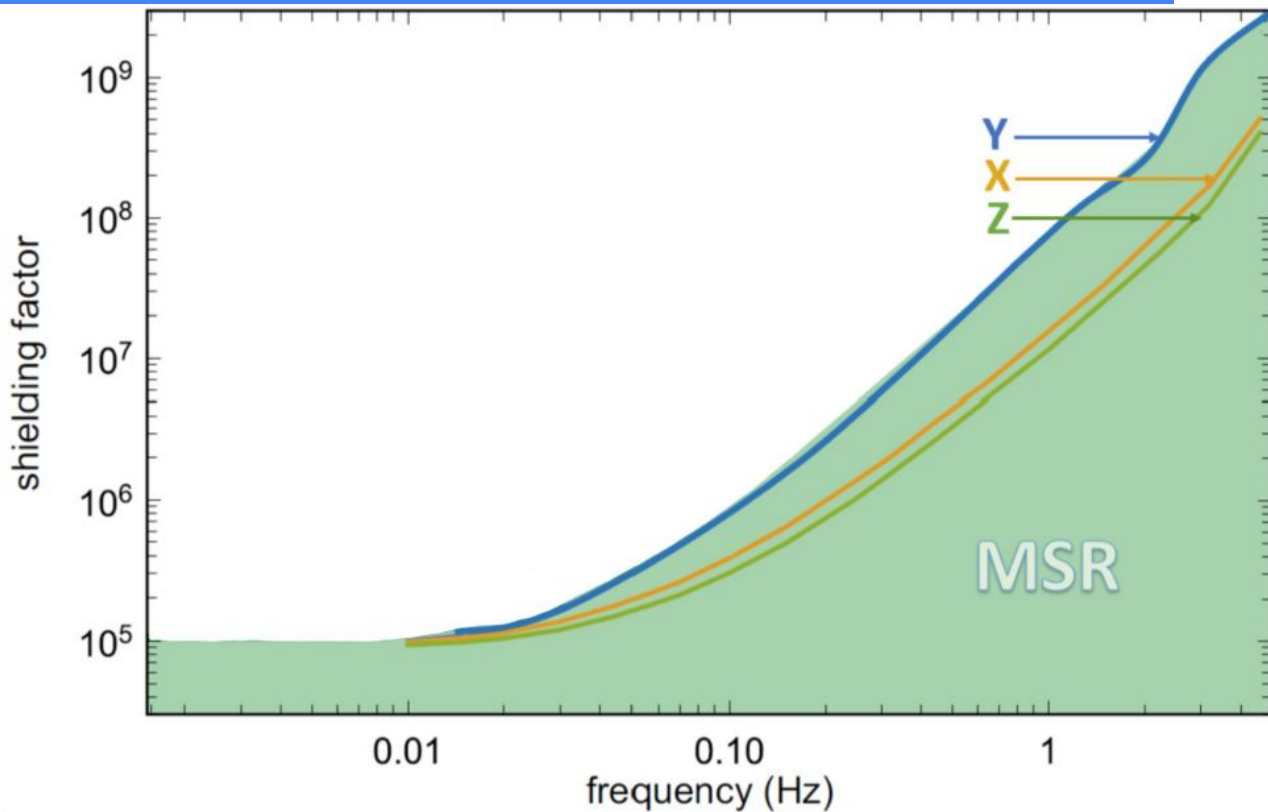
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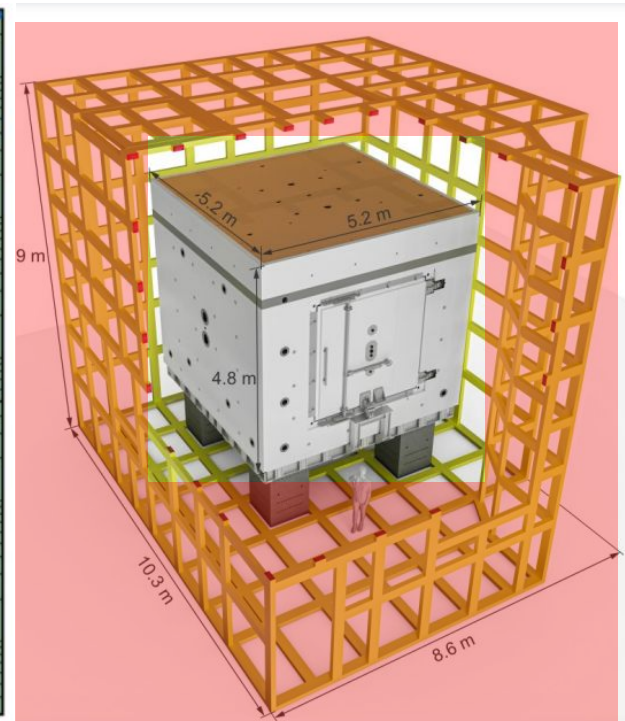
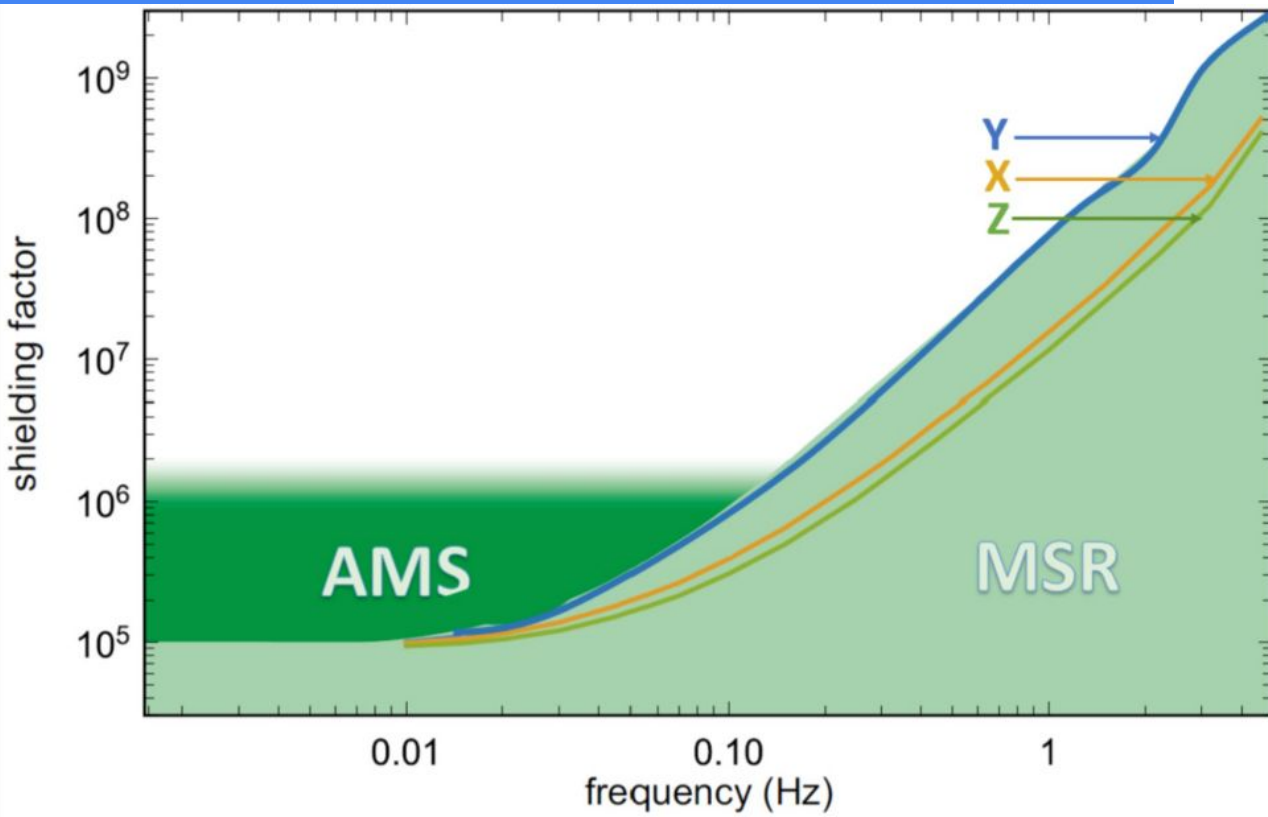
Shielding Factor of  $10^{16}$   
< 10 pT



# Magnetic Shielding

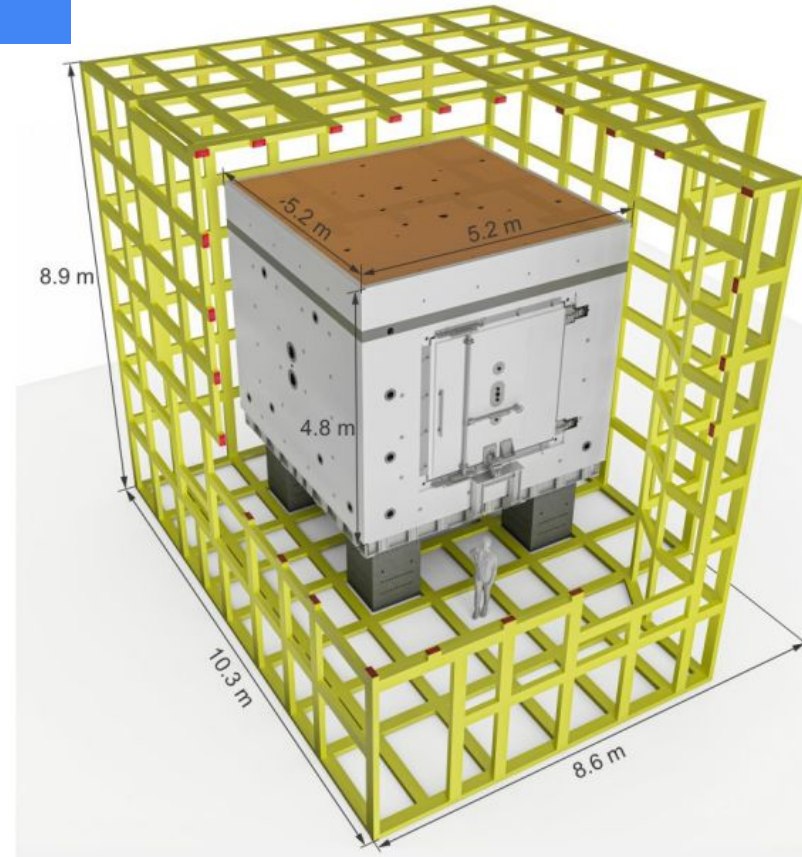


# Magnetic Shielding



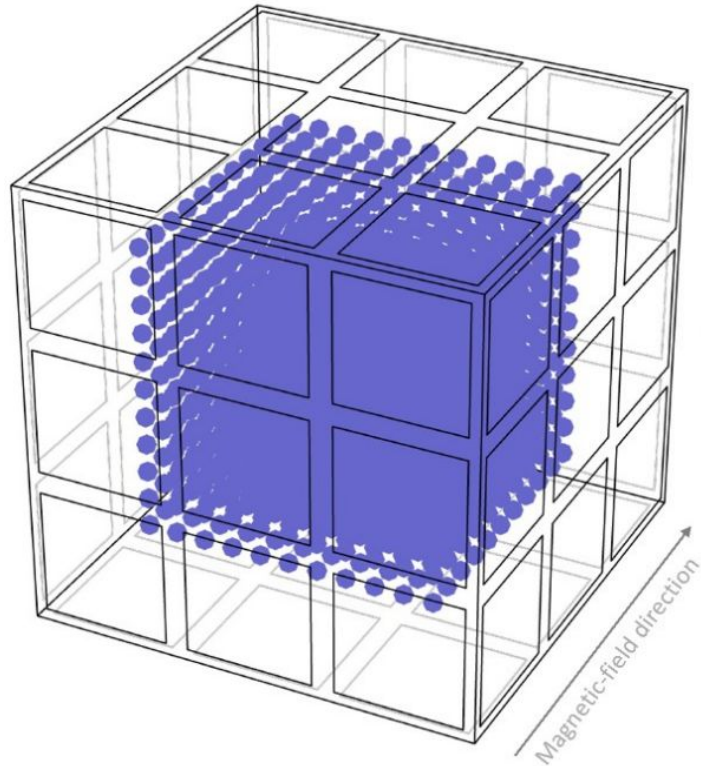
# Active Magnetic Shielding

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

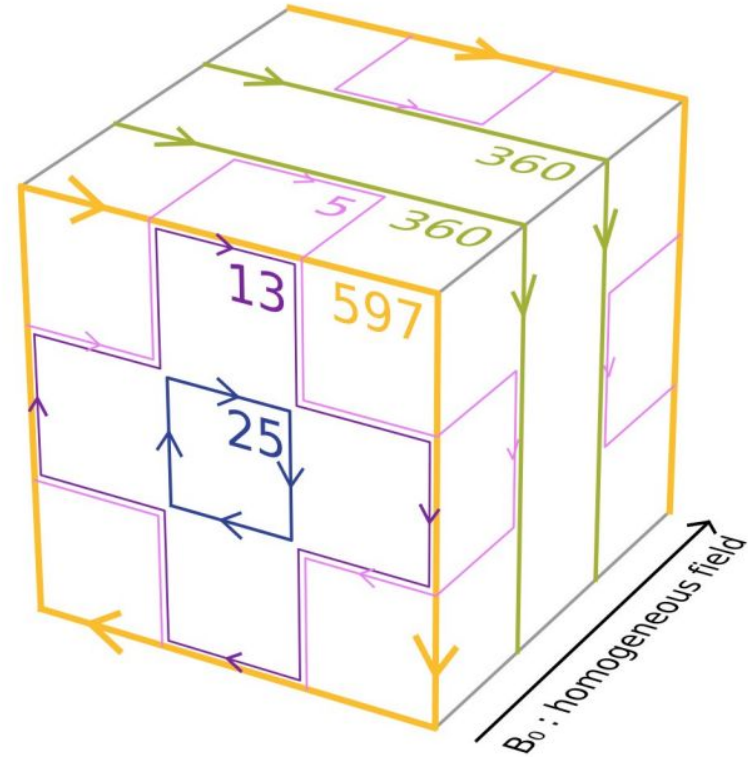
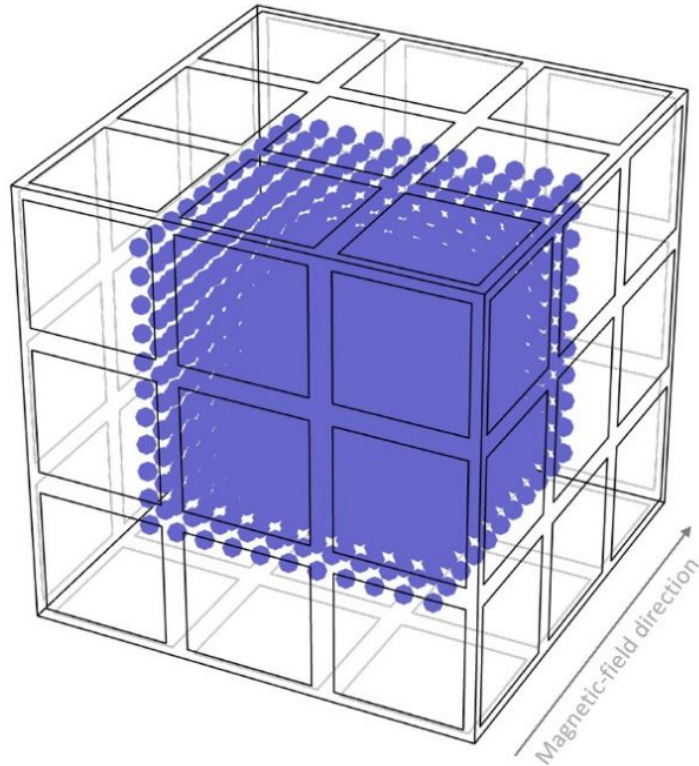




# Intricate Coil System

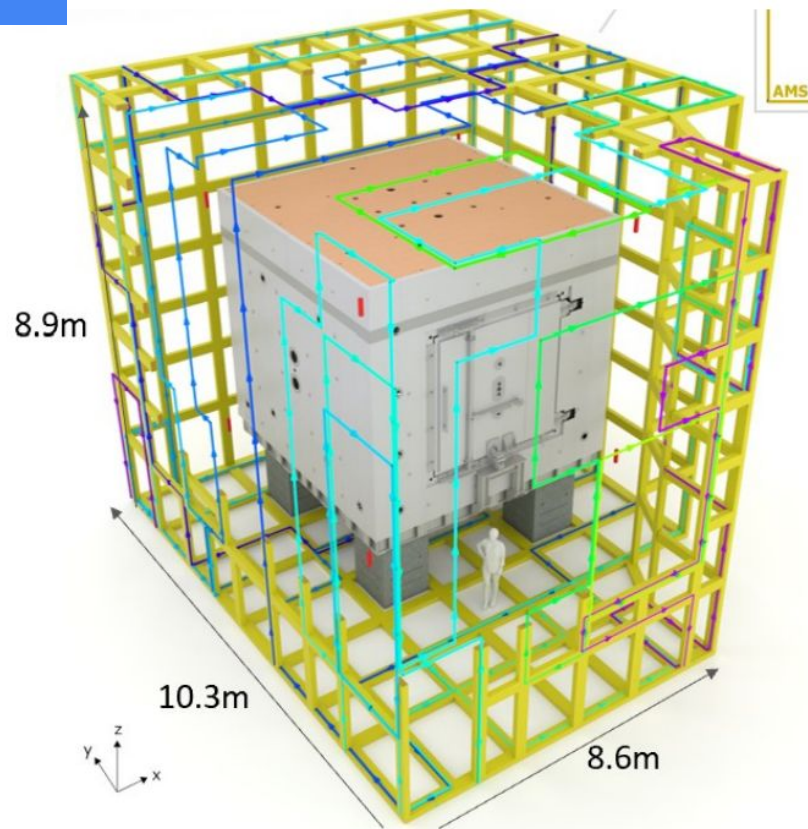


# Intricate Coil System



# Active Magnetic Shielding

- 8 coils:
  - 3 homogeneous
  - 5 higher order
- $\pm 50 \mu\text{T}$
- $1 \mu\text{T}$  compensation
- 3-axis Fluxgates




# Compensation Algorithm

$$B = B_0 + MI$$

# Compensation Algorithm

$$B = B_0 + MI$$


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

Background  
Magnetic Field

# Compensation Algorithm

$$B = B_0 + MI$$

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

Background  
Magnetic Field

AMS Generated  
Magnetic Field

# Compensation Algorithm

$$B = B_0 + MI$$

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

Measured

Magnetic Field

Background

Magnetic Field

AMS Generated

Magnetic Field

# Compensation Algorithm

$$B = B_0 + MI \rightarrow \text{Least Squares}$$

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

Measured

Magnetic Field

Background

Magnetic Field

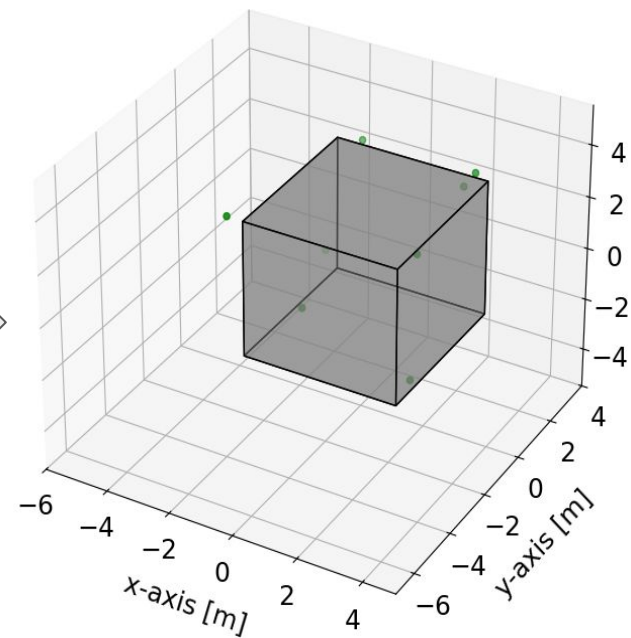
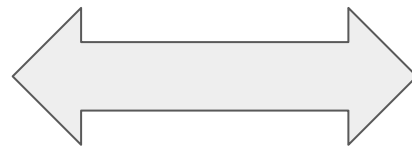
AMS Generated

Magnetic Field



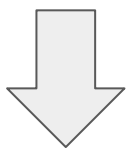
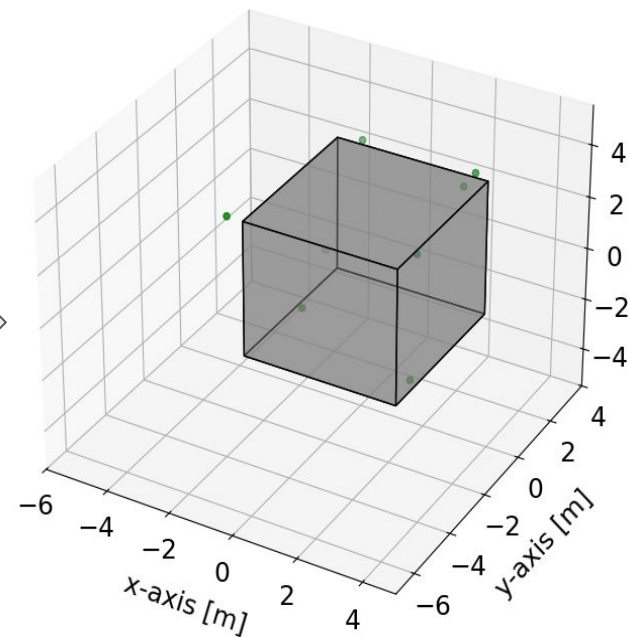
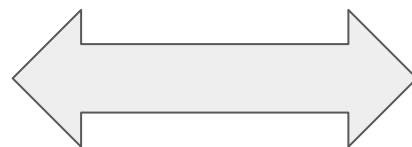
# Response Matrix

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



# Response Matrix

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



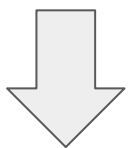
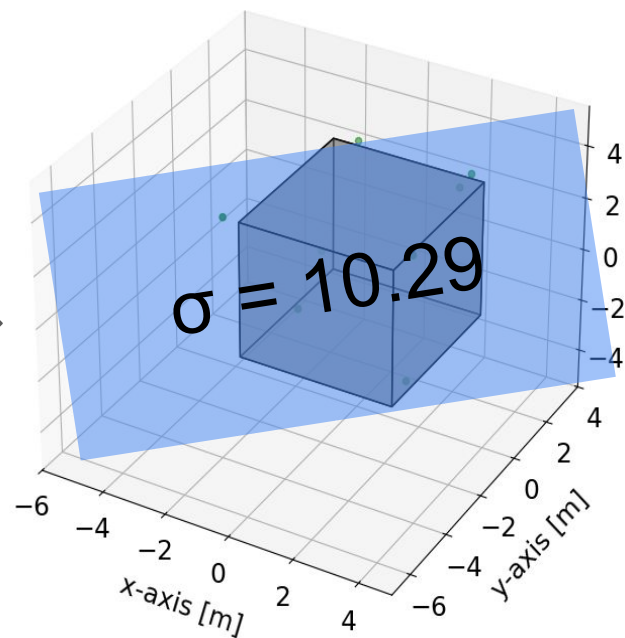
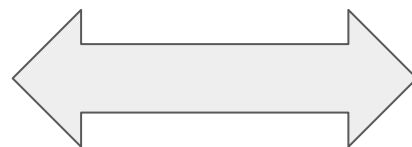
Condition Number  
 $\sigma \in [1, \infty)$



Lower  $\sigma$ ,  
Lower Numerical Error

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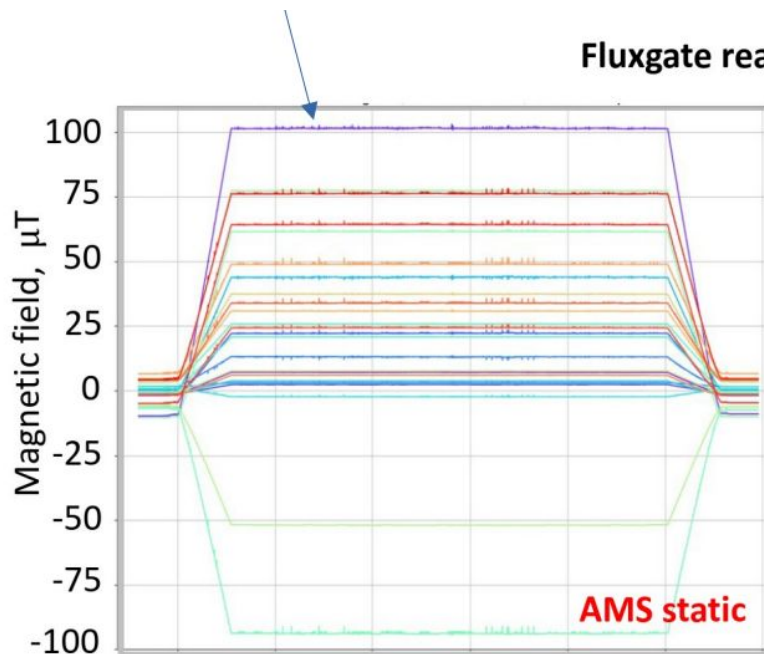
Condition Number  
 $\sigma \in [1, \infty)$



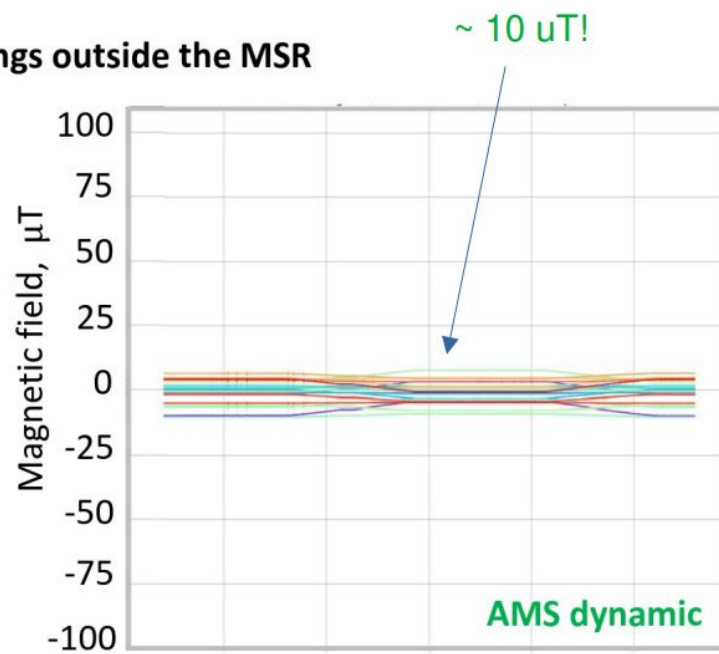
Lower  $\sigma$ ,  
Lower Numerical Error

# Compensation Example

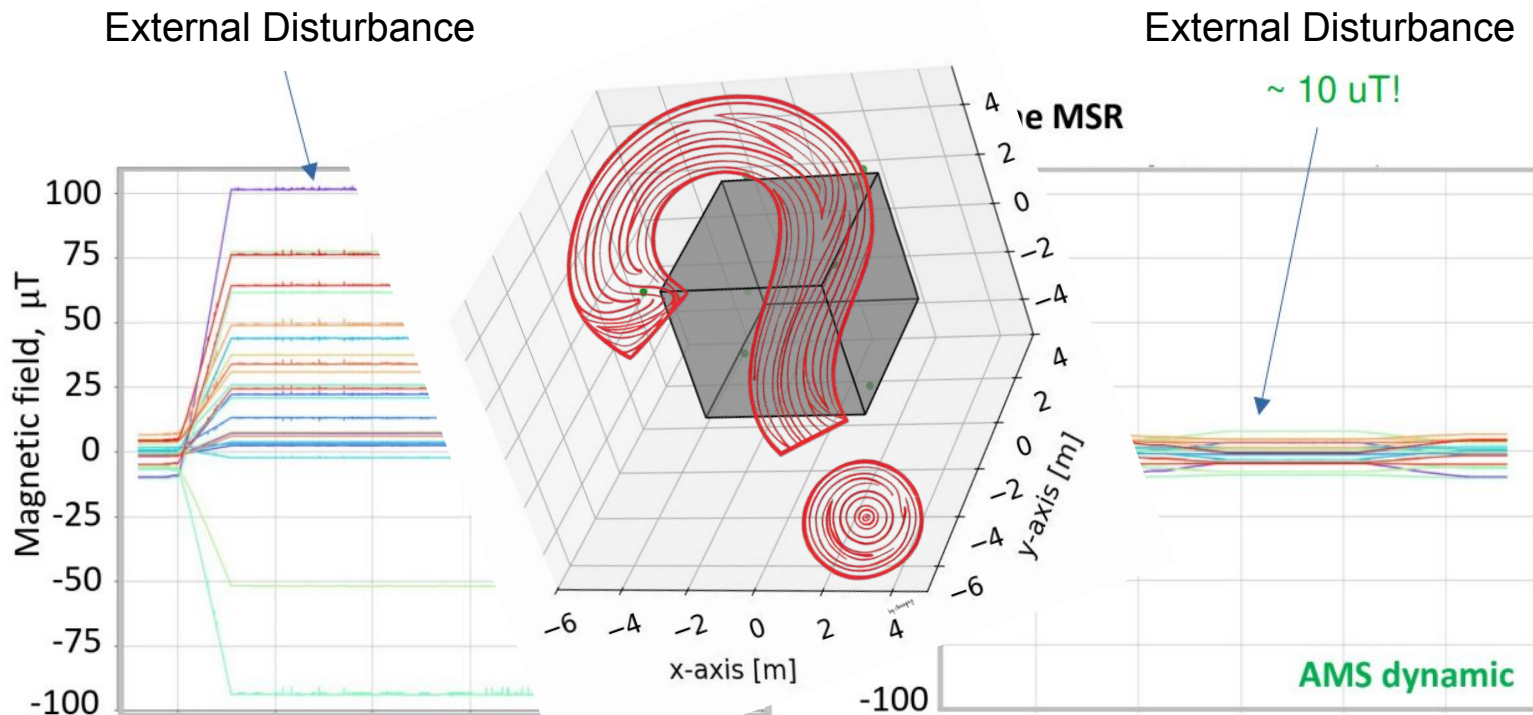
External Disturbance



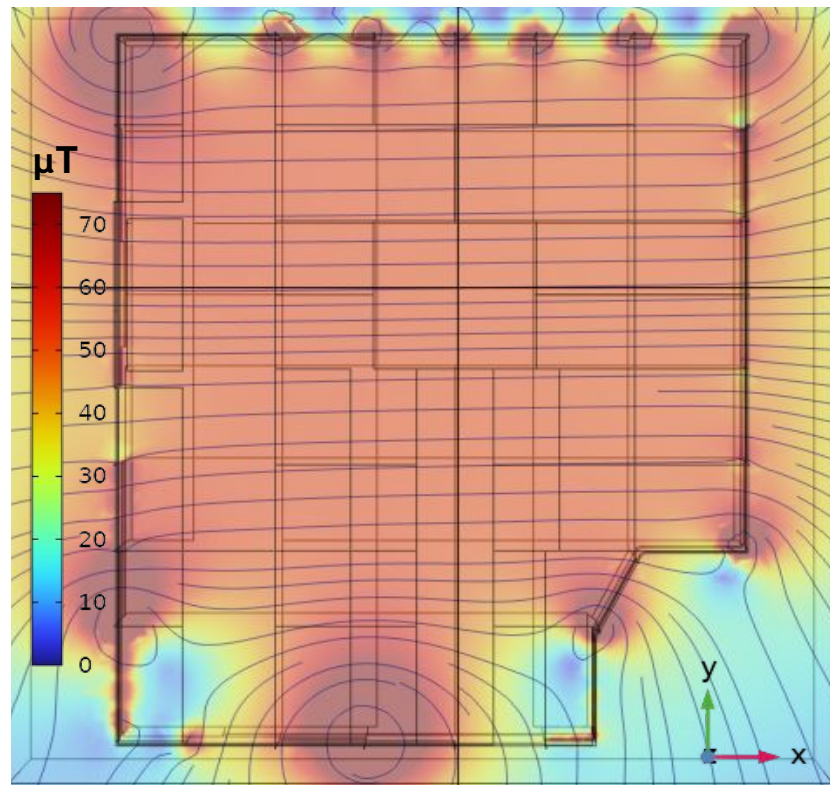
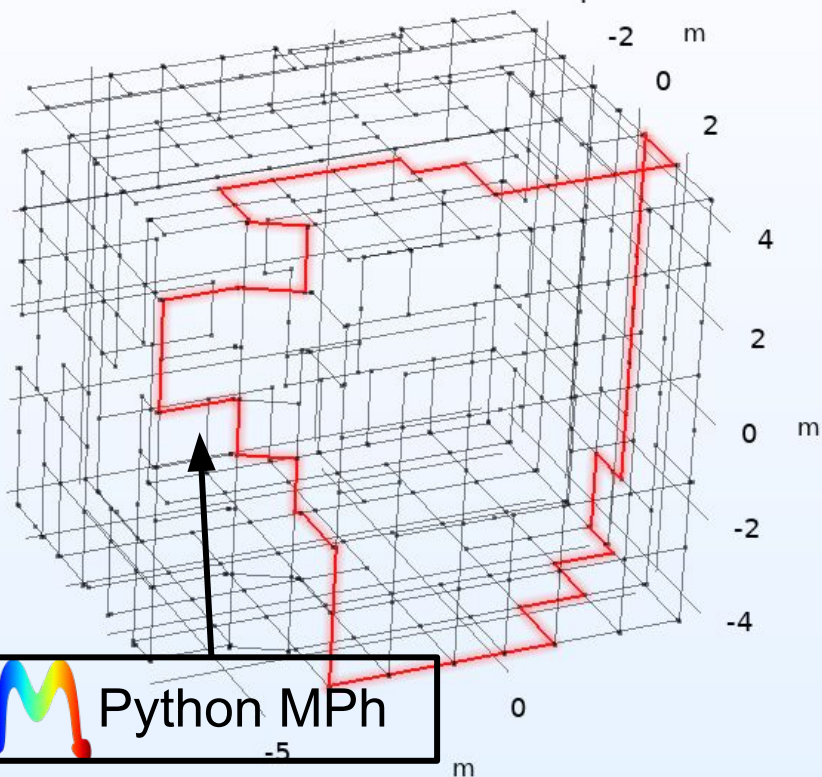
External Disturbance



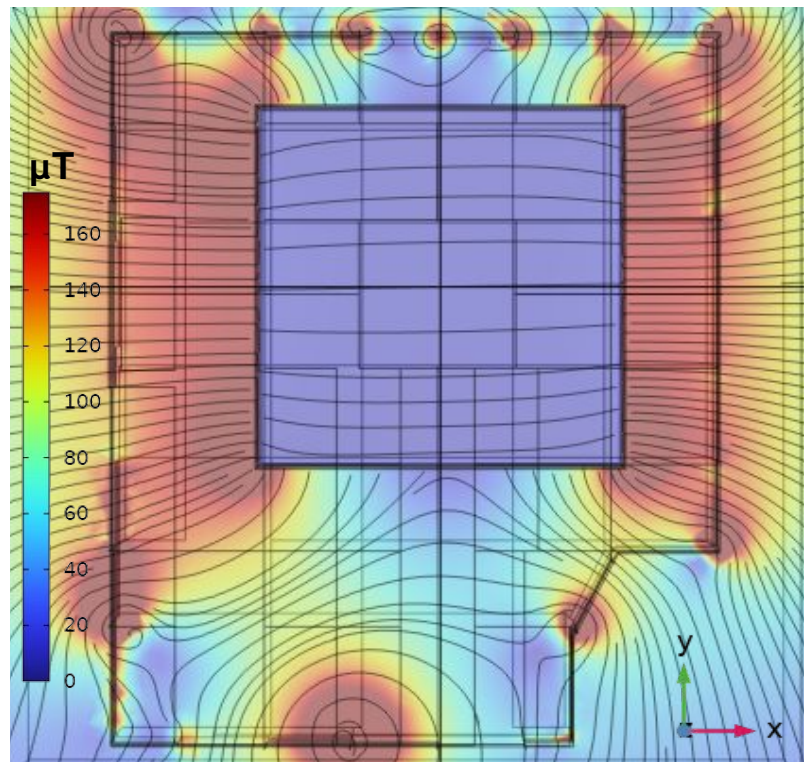
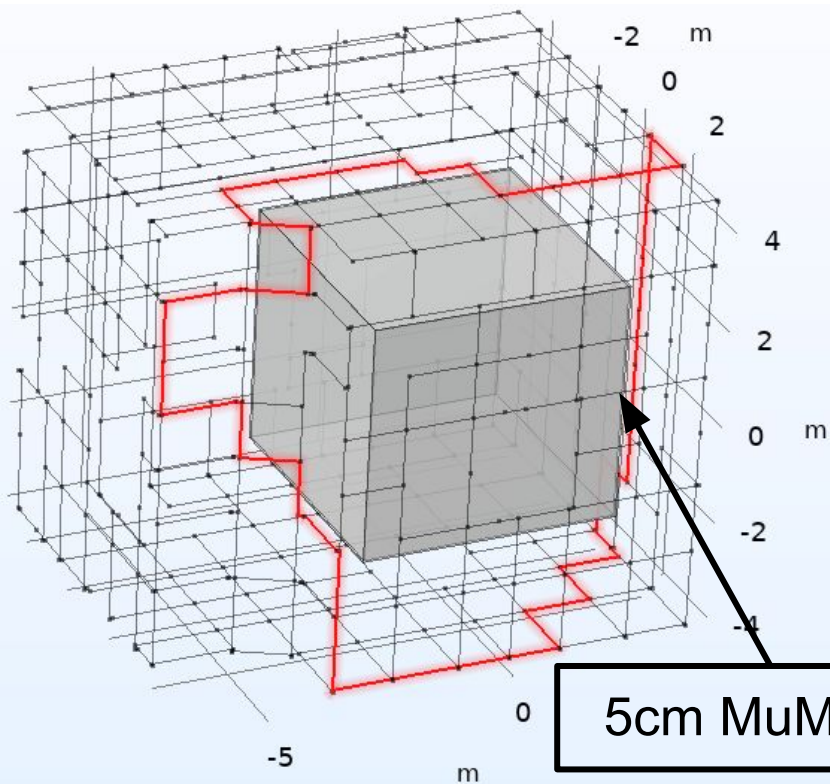
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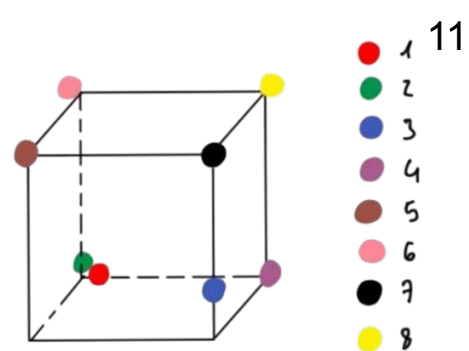
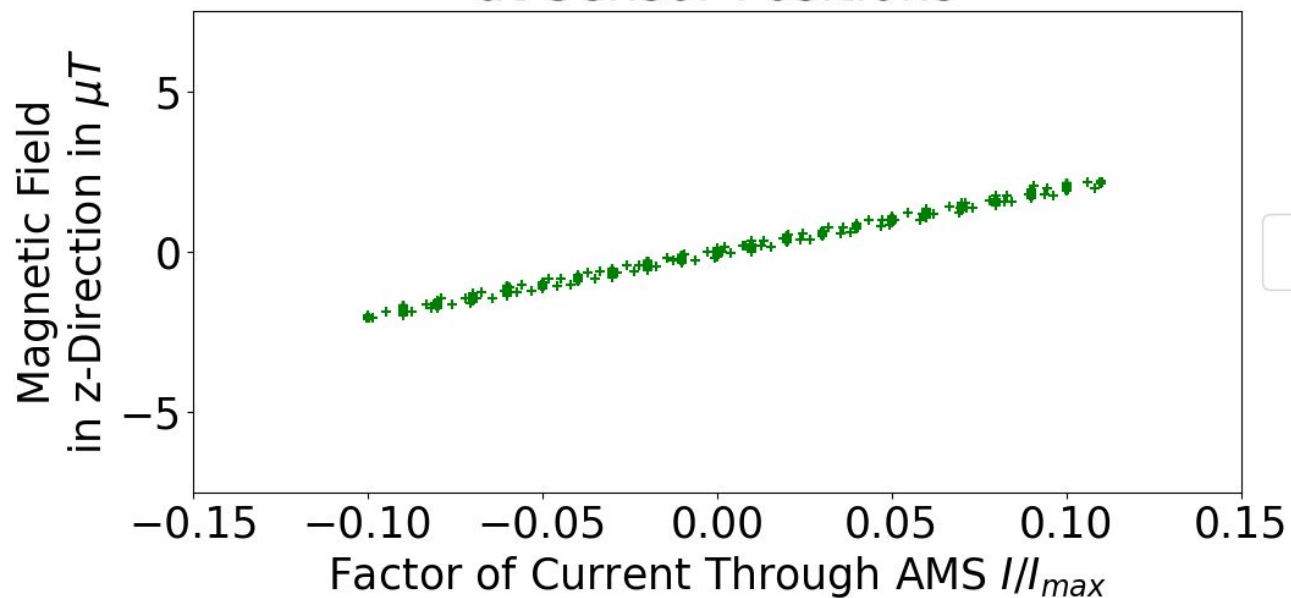
# COMSOL Implementation



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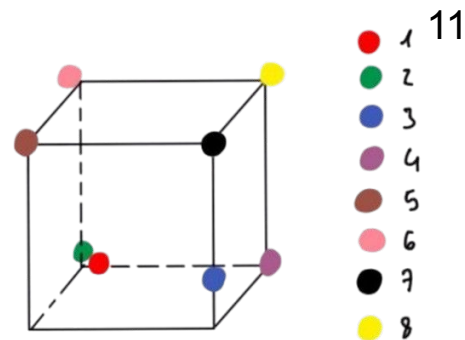


## Verification of Simulation

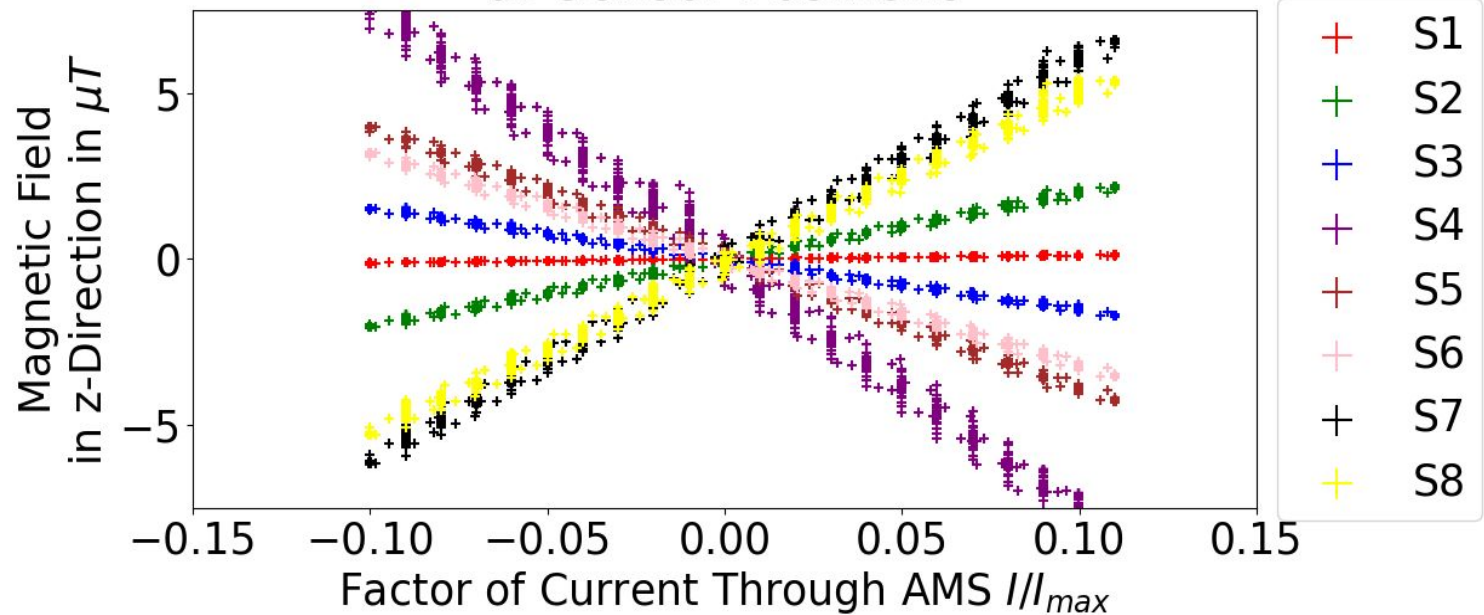
Scaling of Magnetic Field  
at Sensor Positions



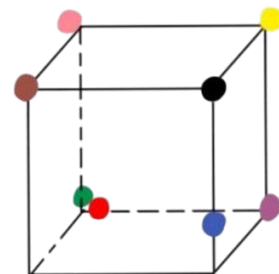
# Verification of Simulation



## Scaling of Magnetic Field at Sensor Positions

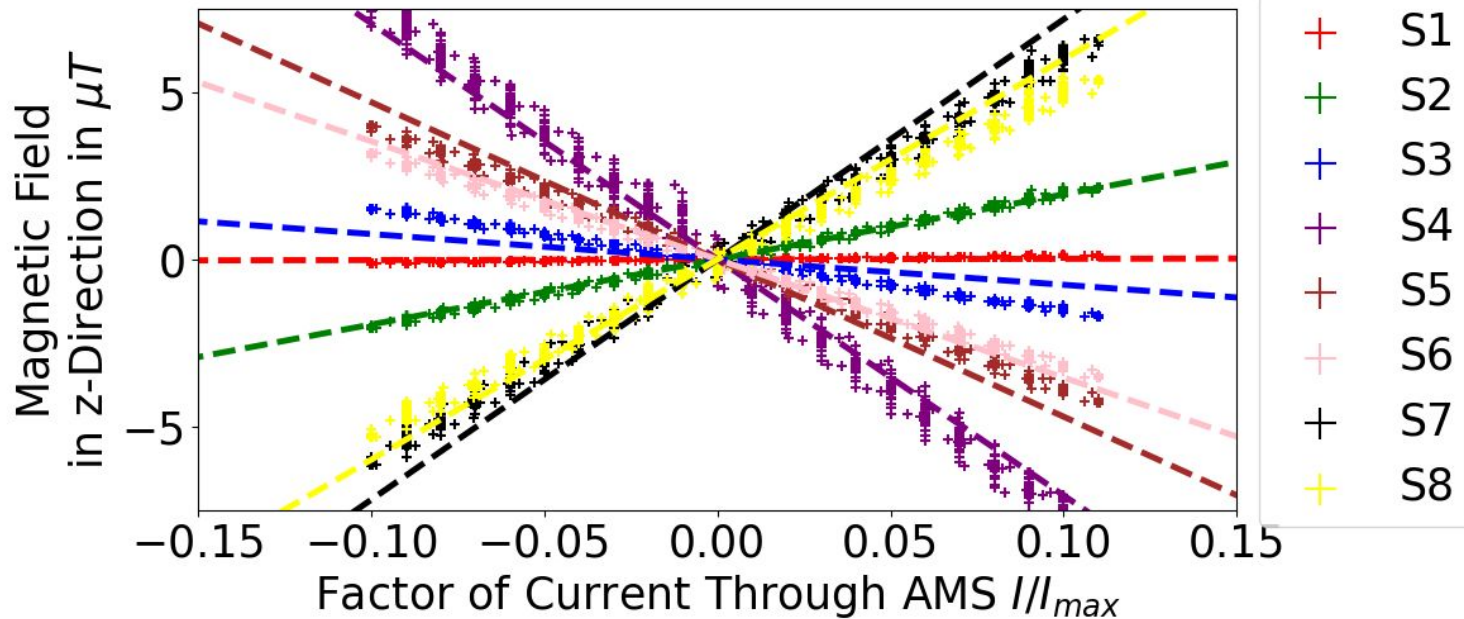


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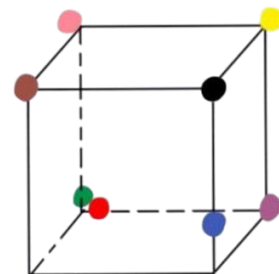


- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Scaling of Magnetic Field at Sensor Positions

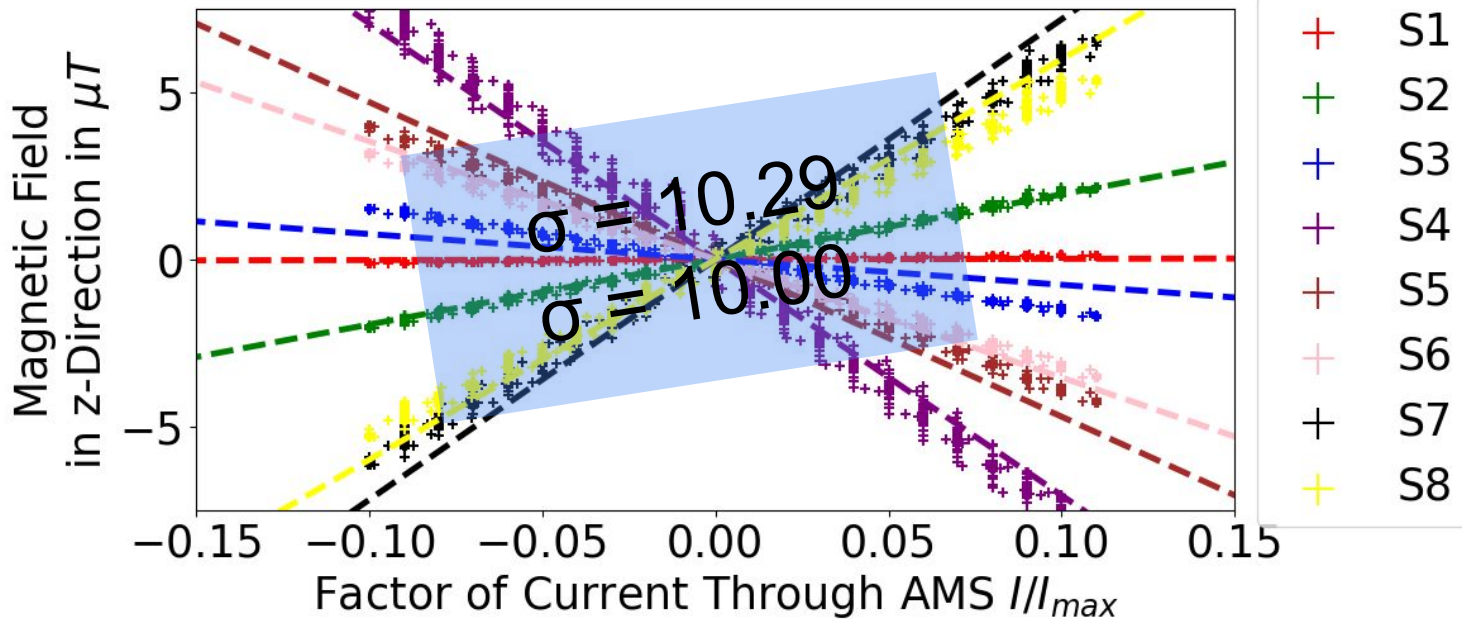


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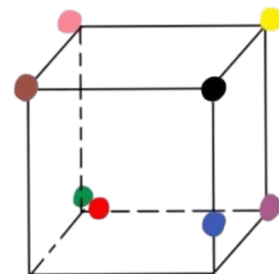


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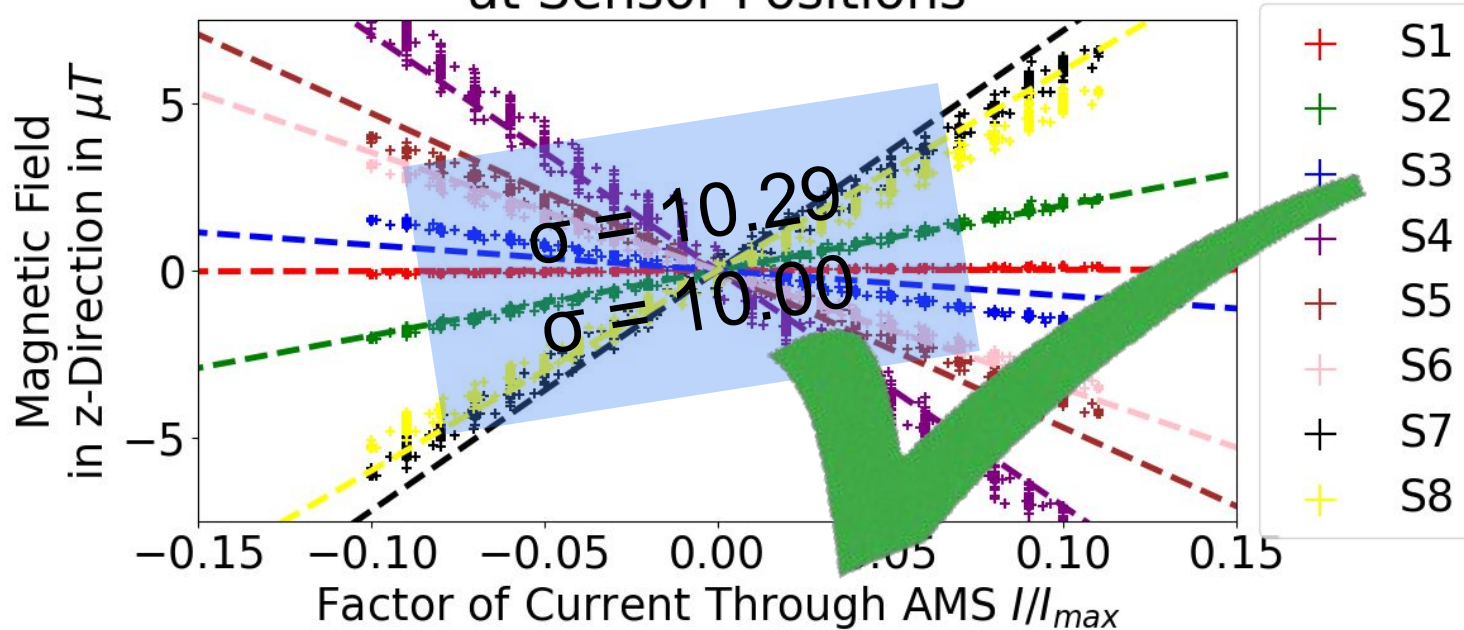


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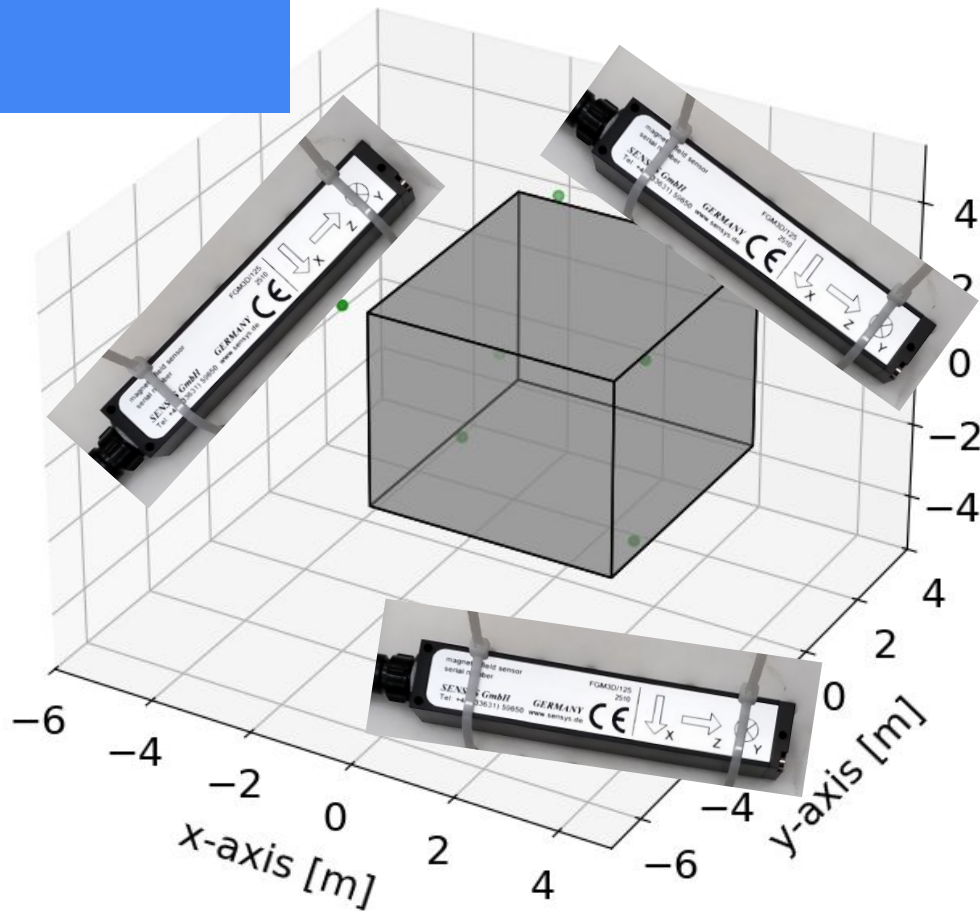
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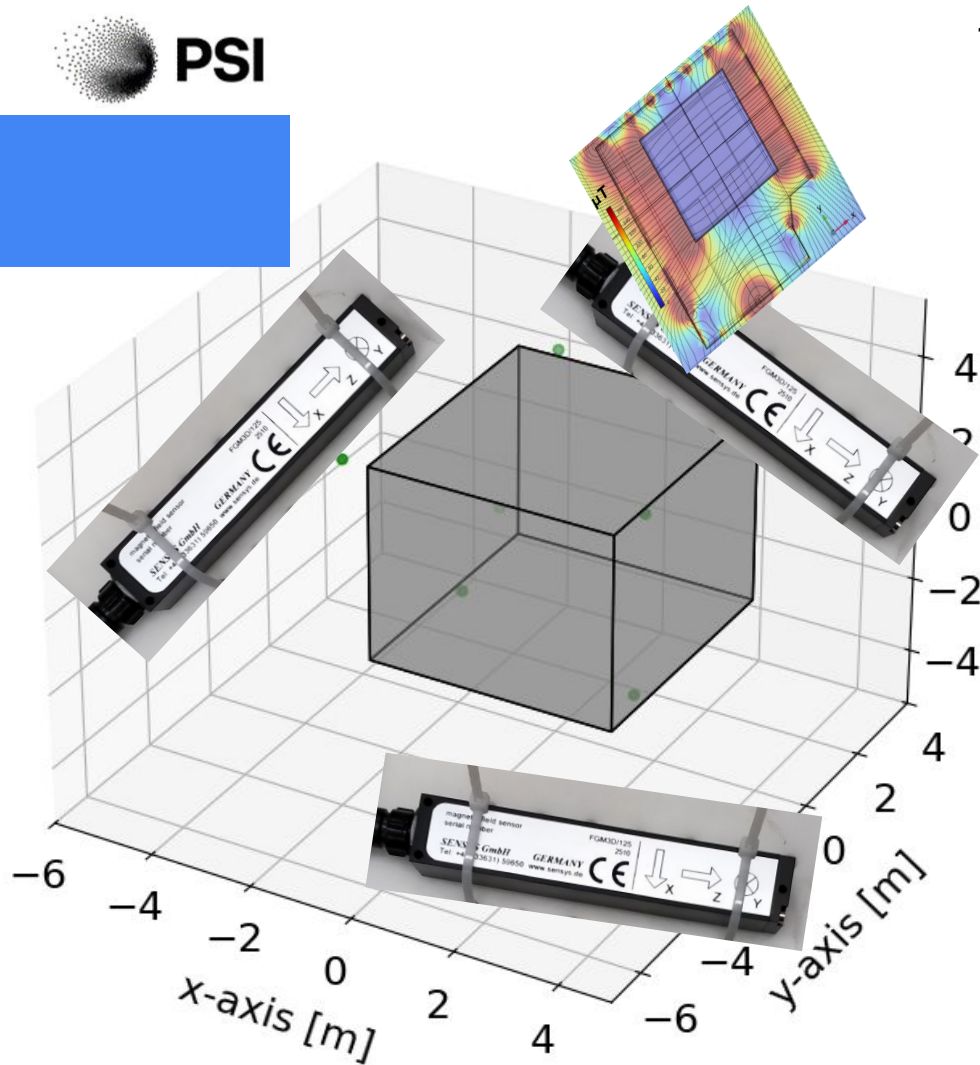
# Optimization Targets

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



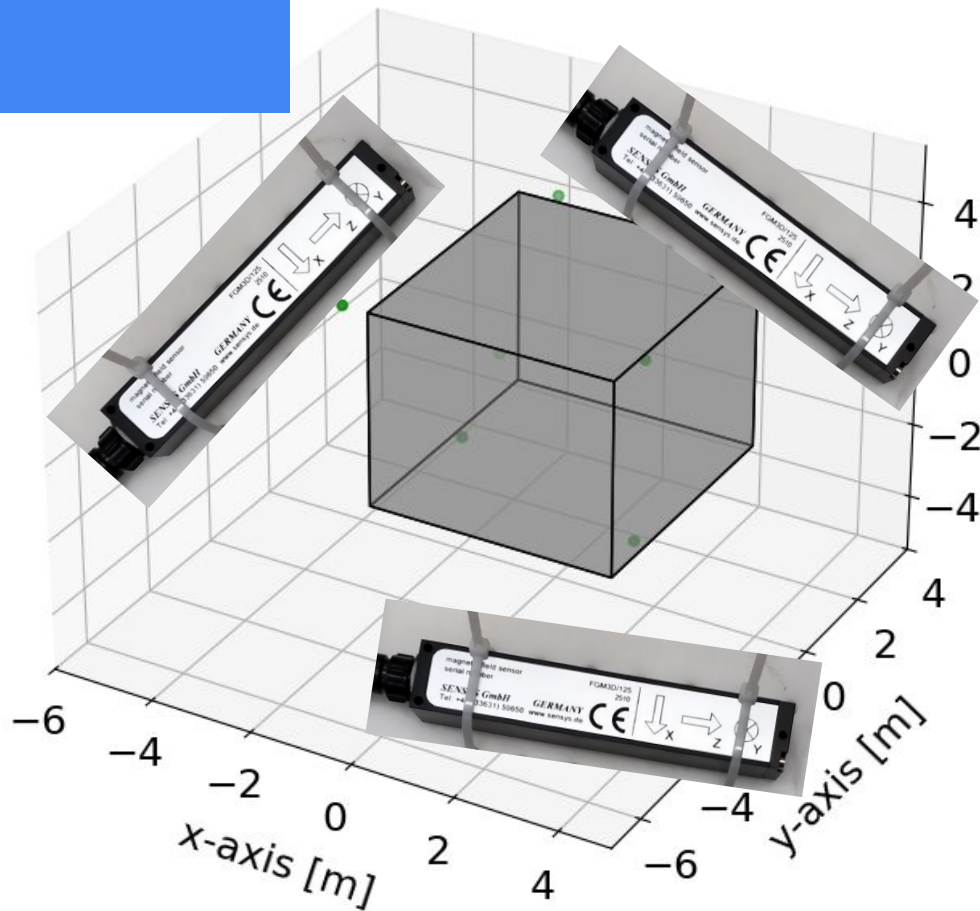
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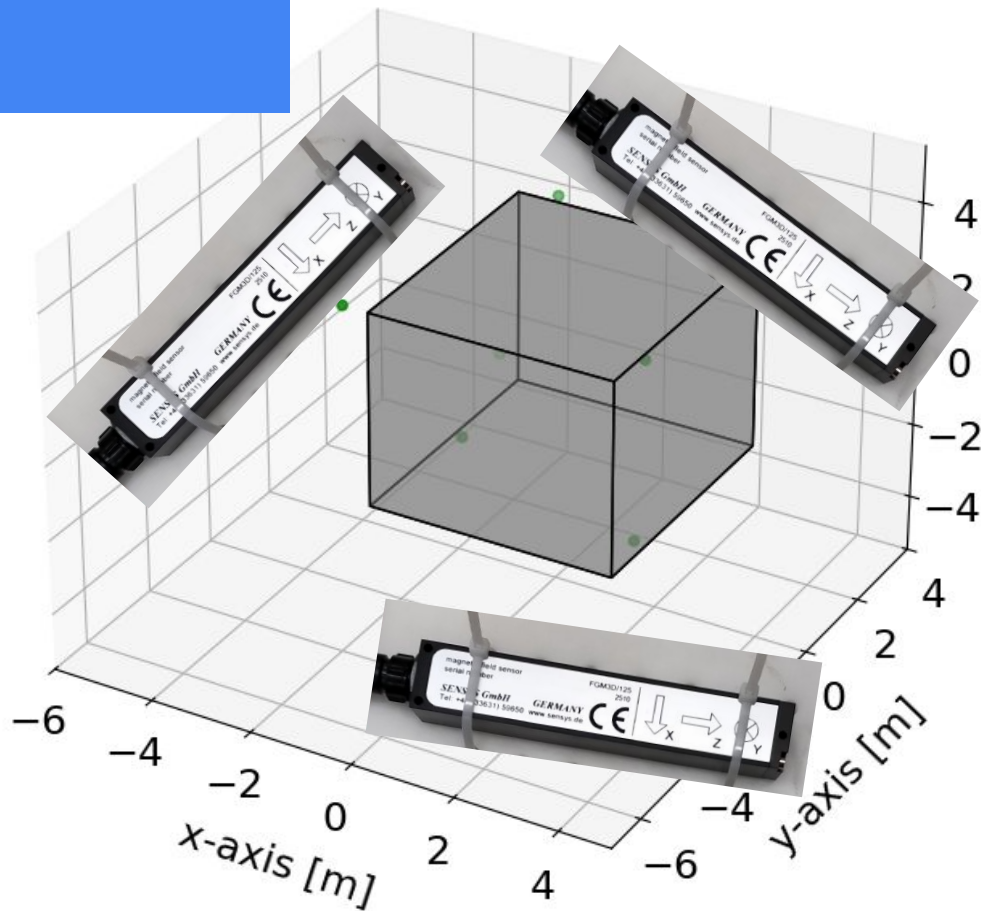
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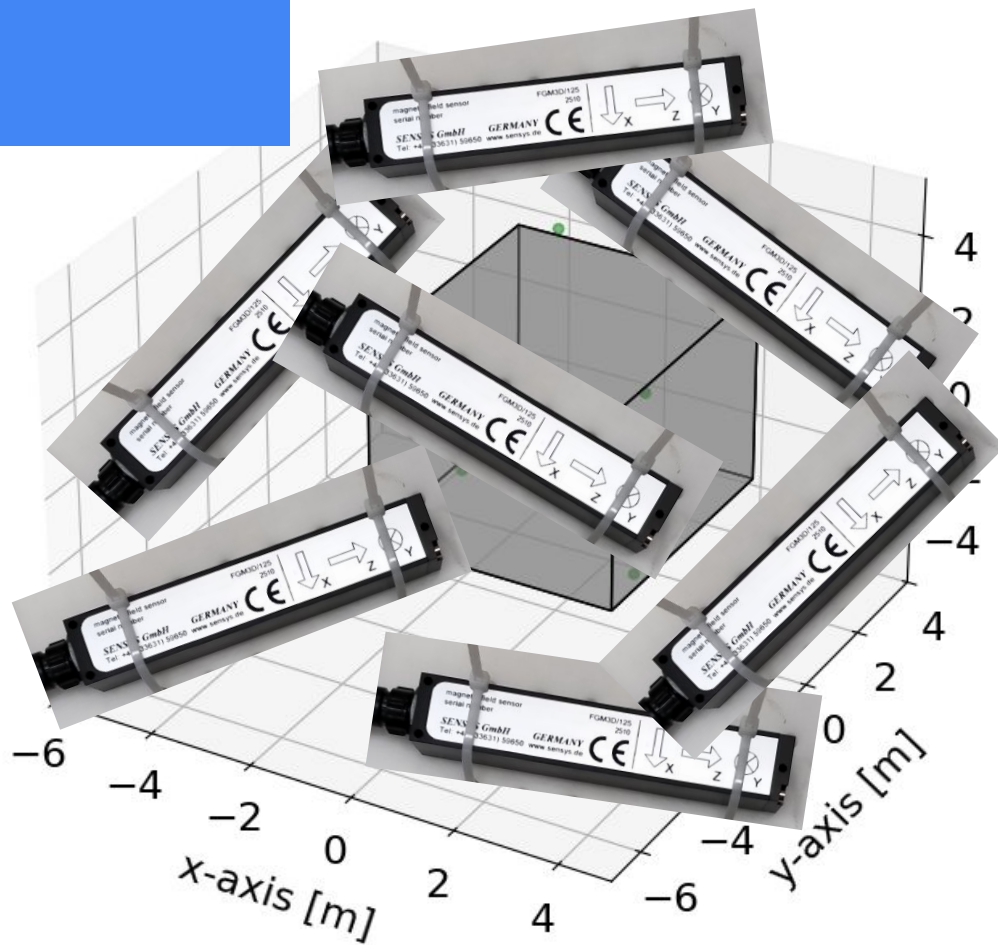
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  - 1) # Fluxgates





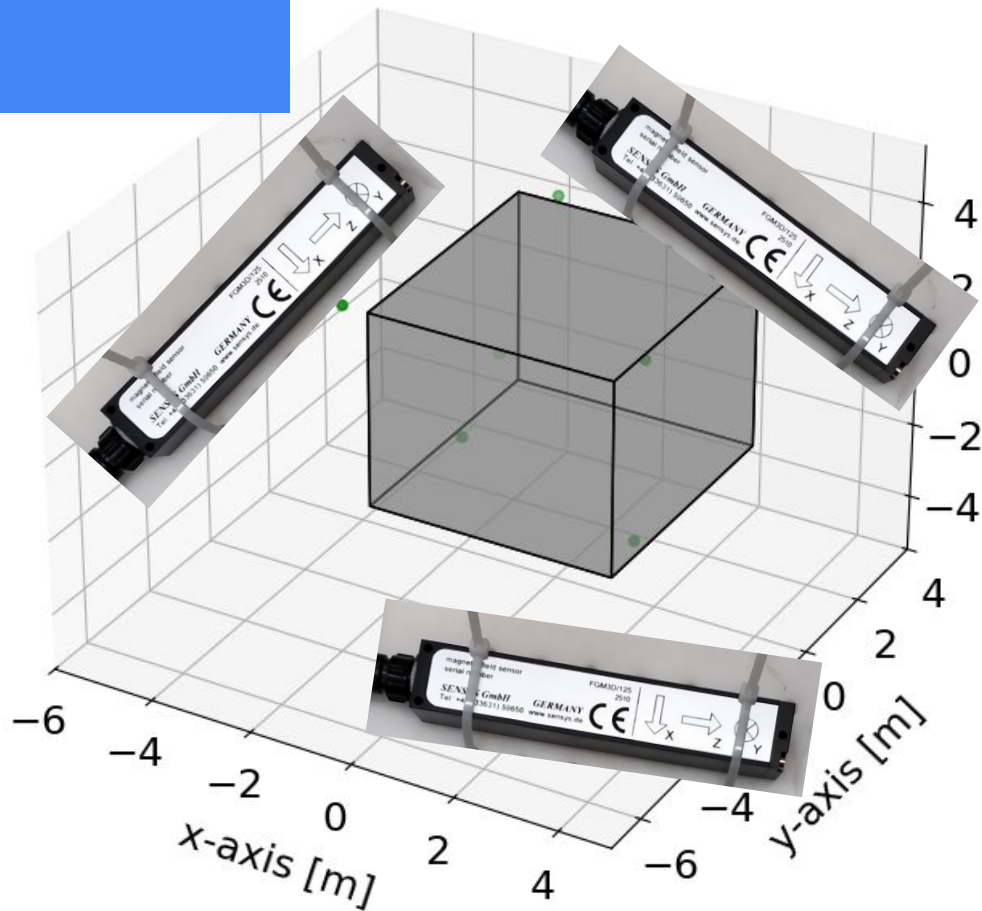
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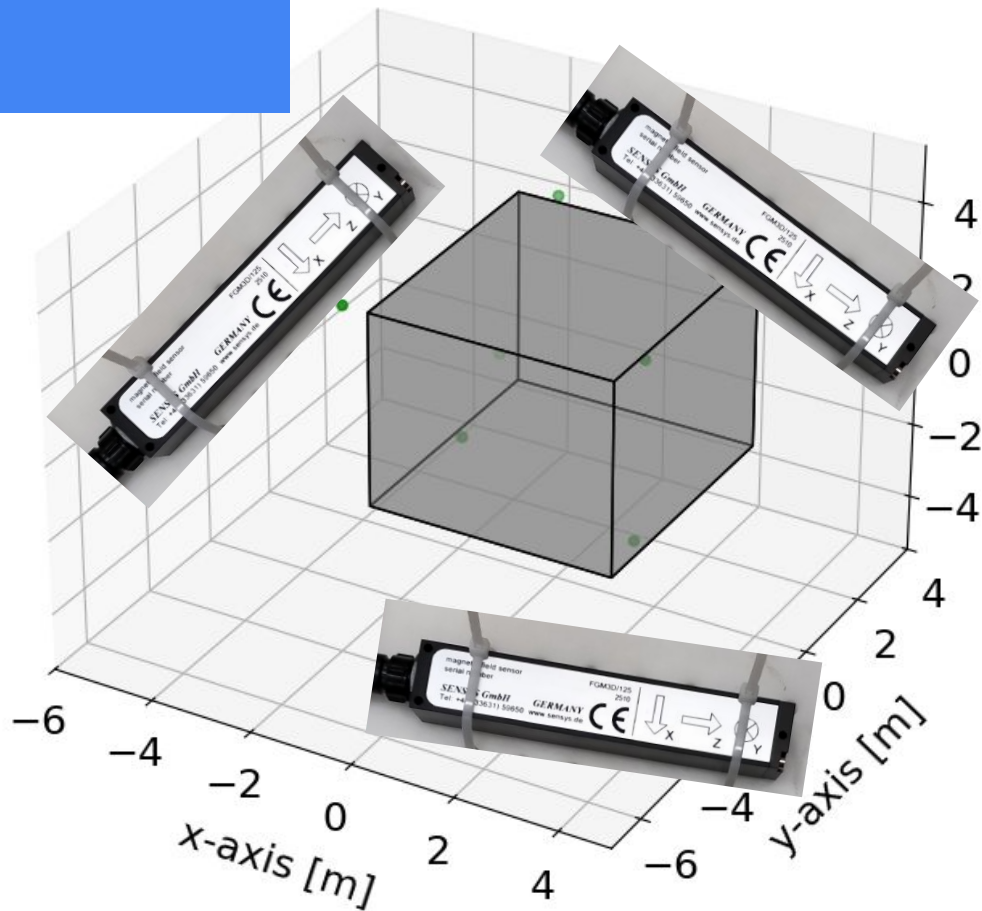
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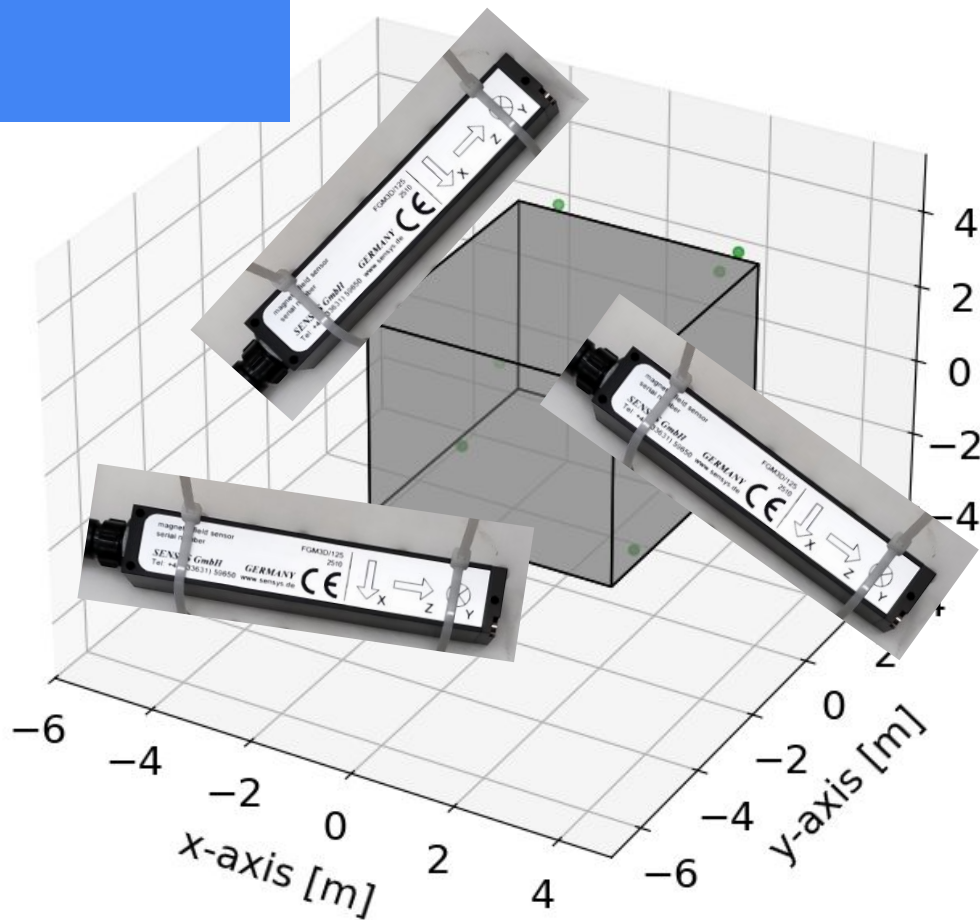
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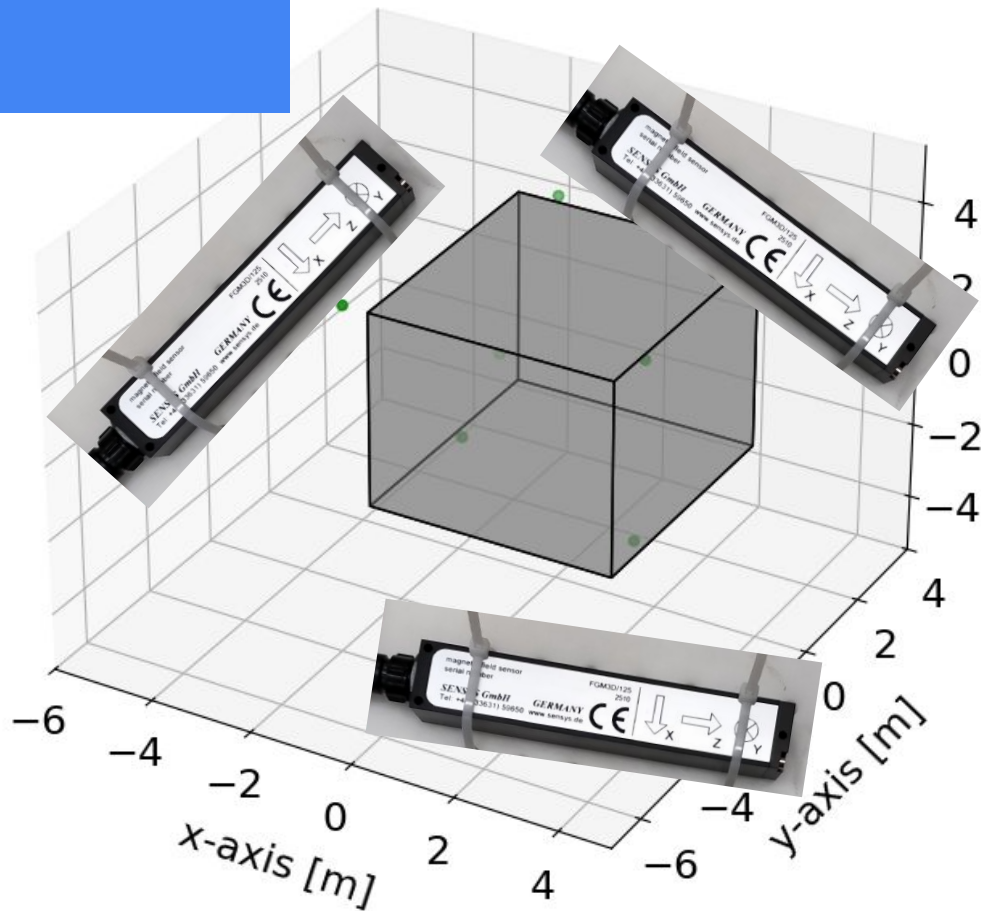
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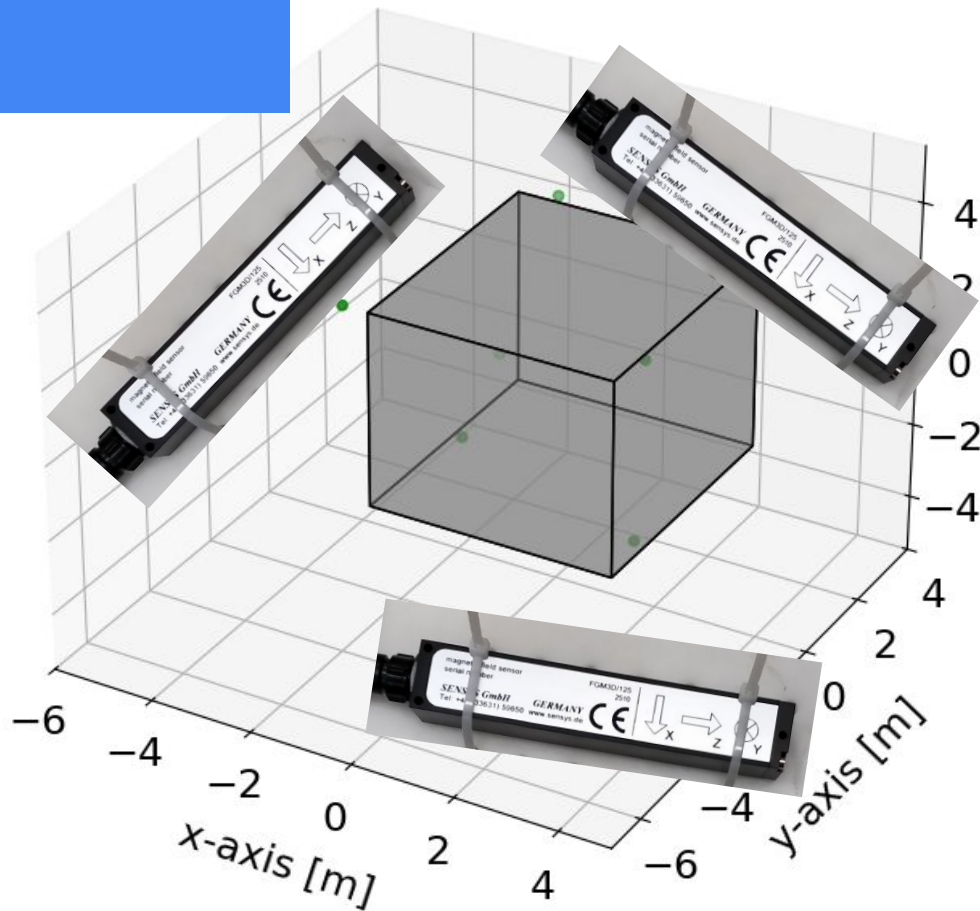
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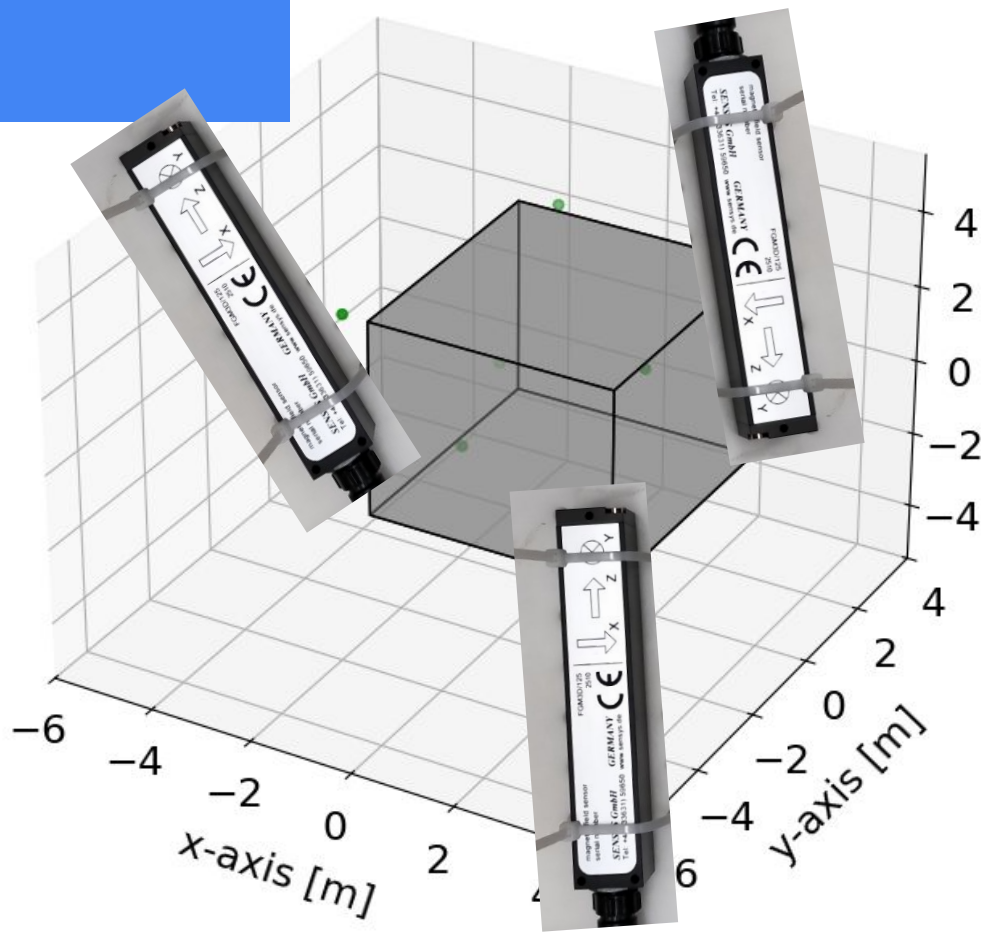
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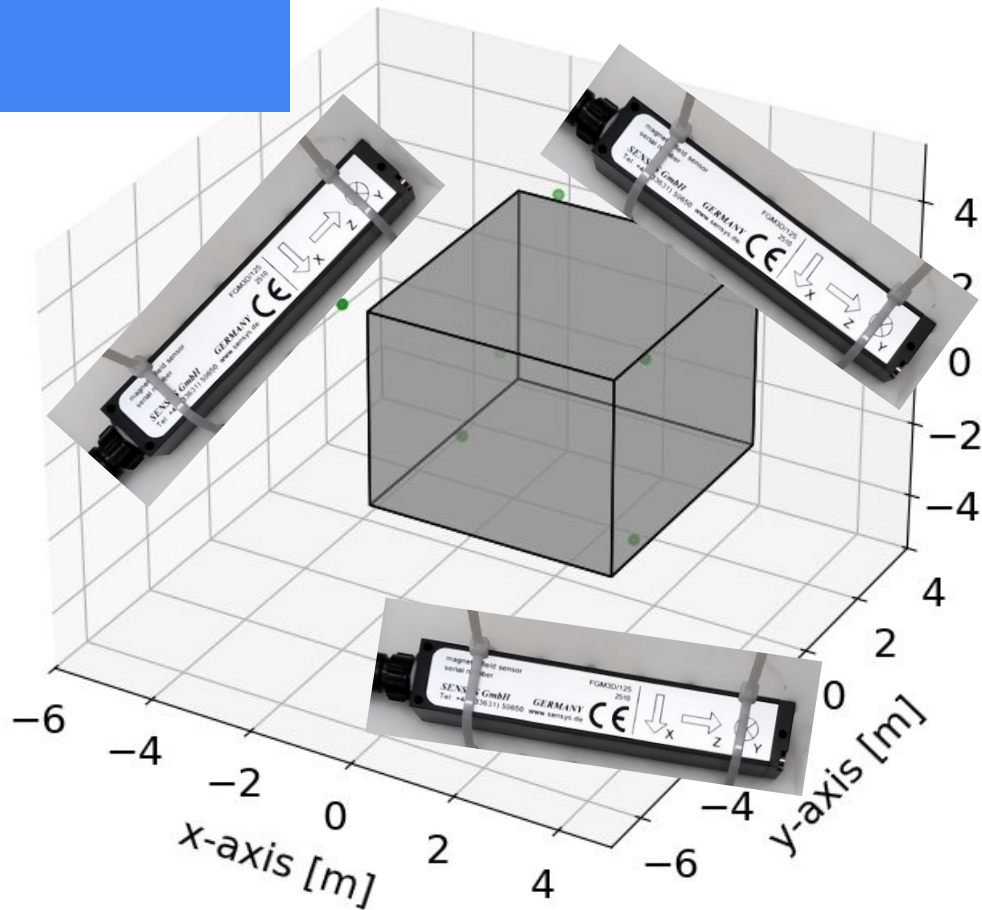
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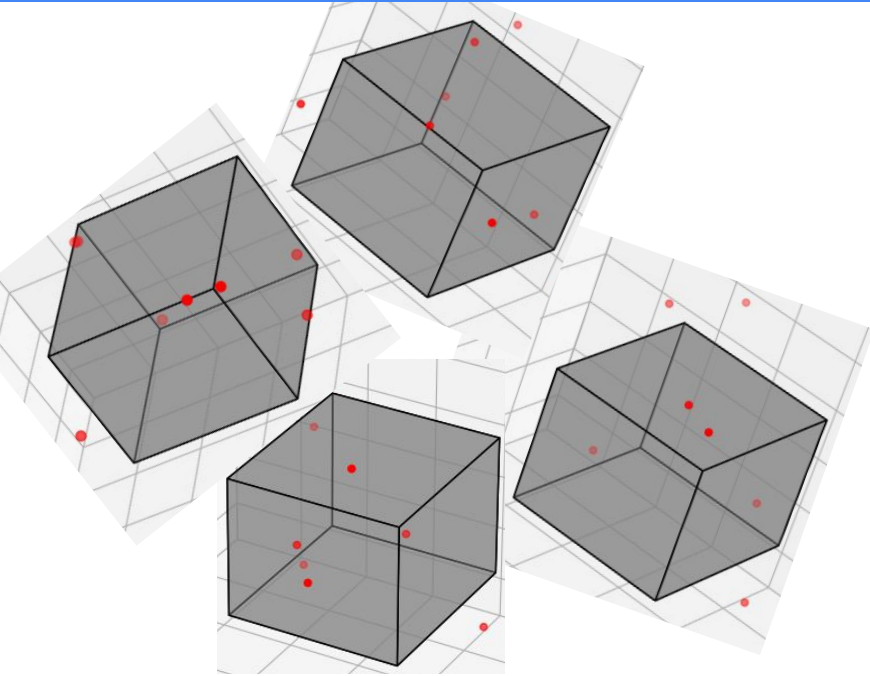
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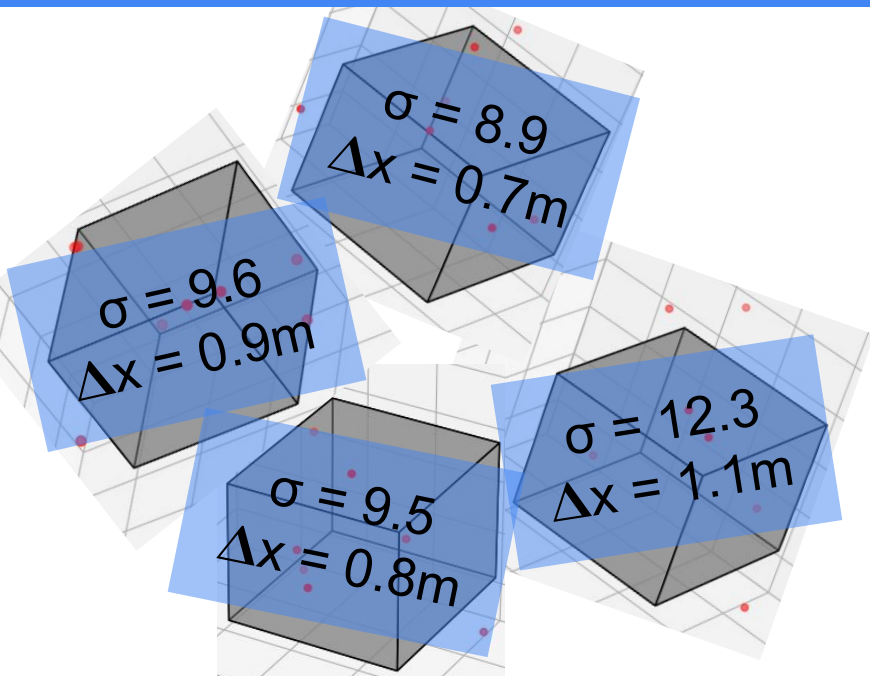




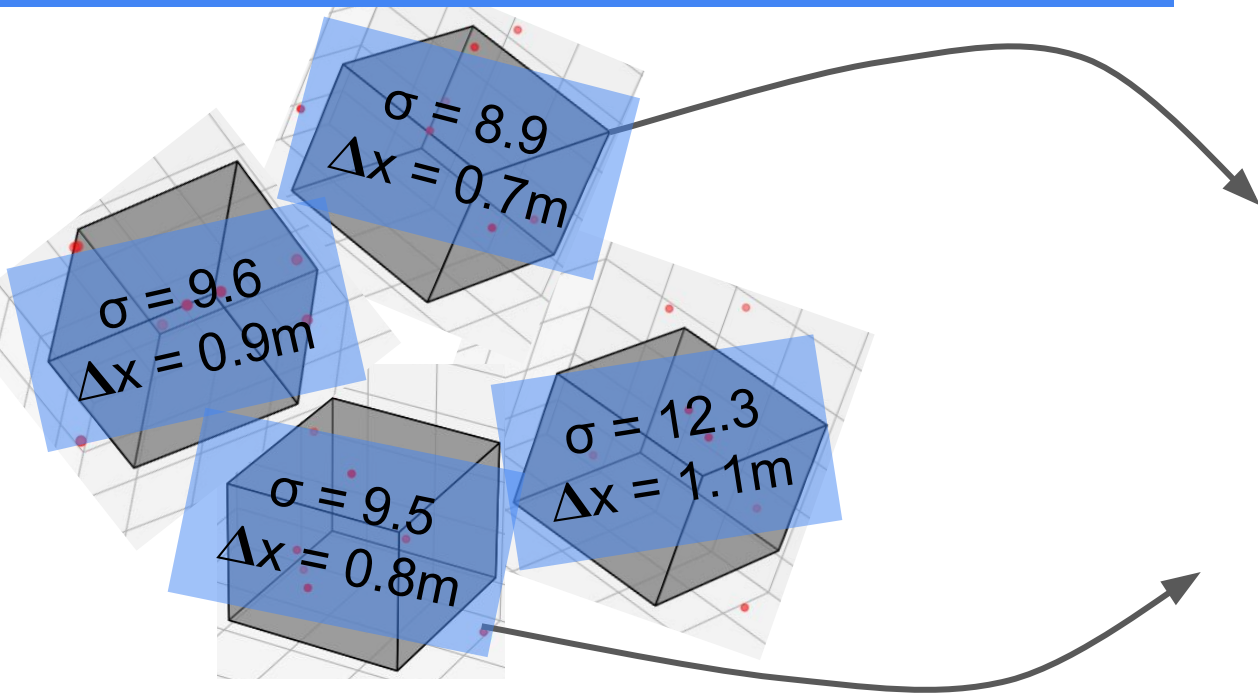
# Genetic Algorithms



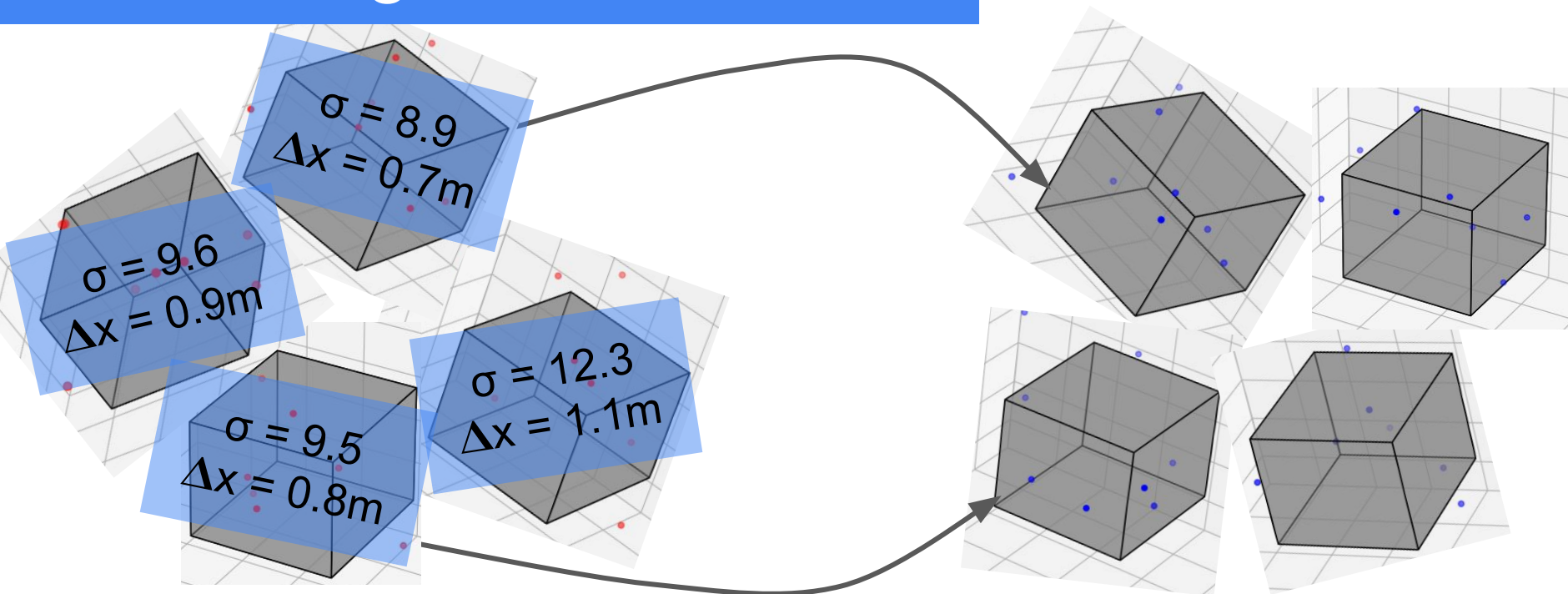
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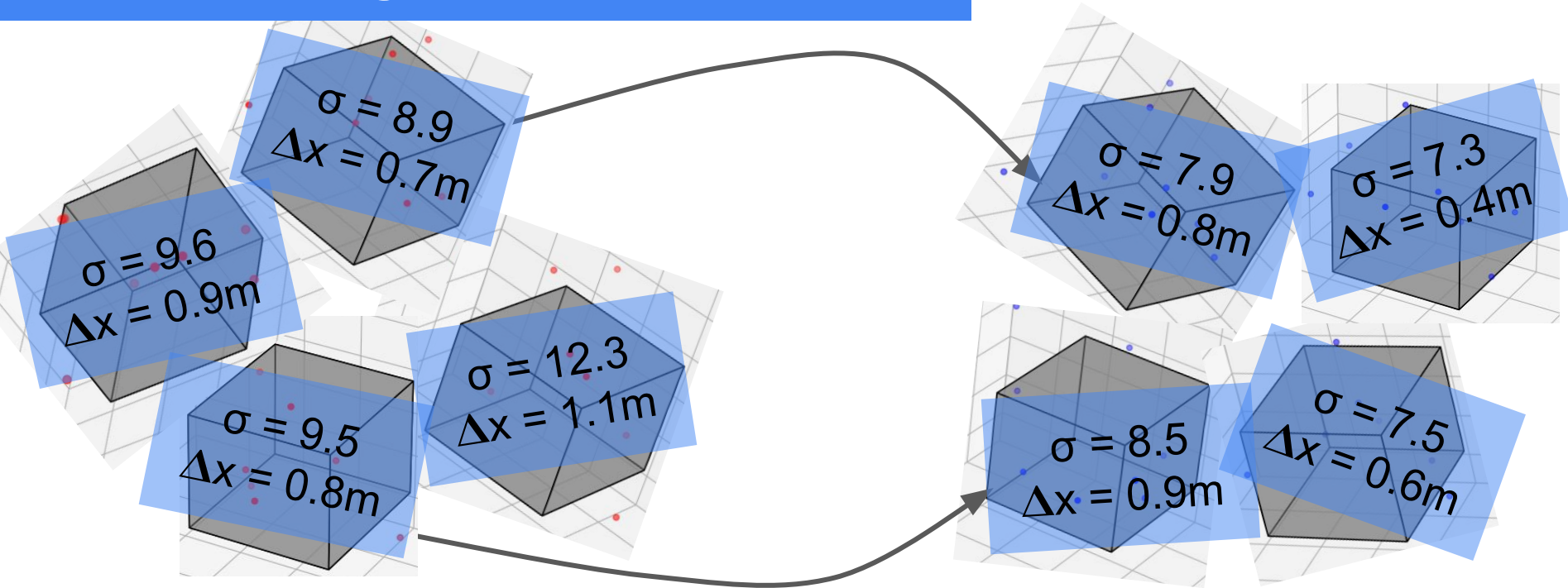
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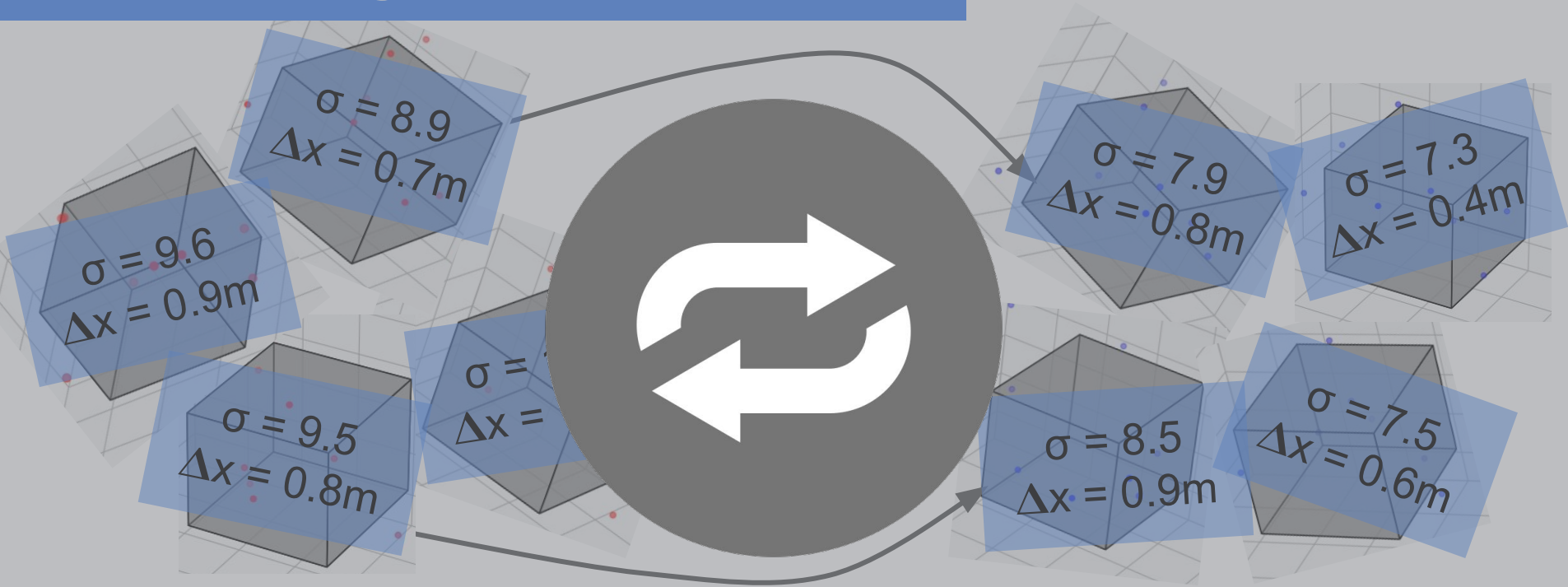
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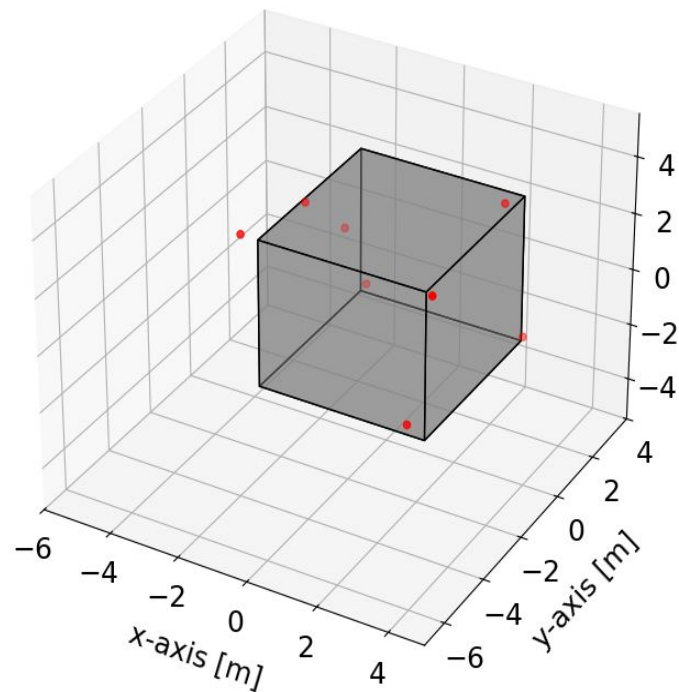
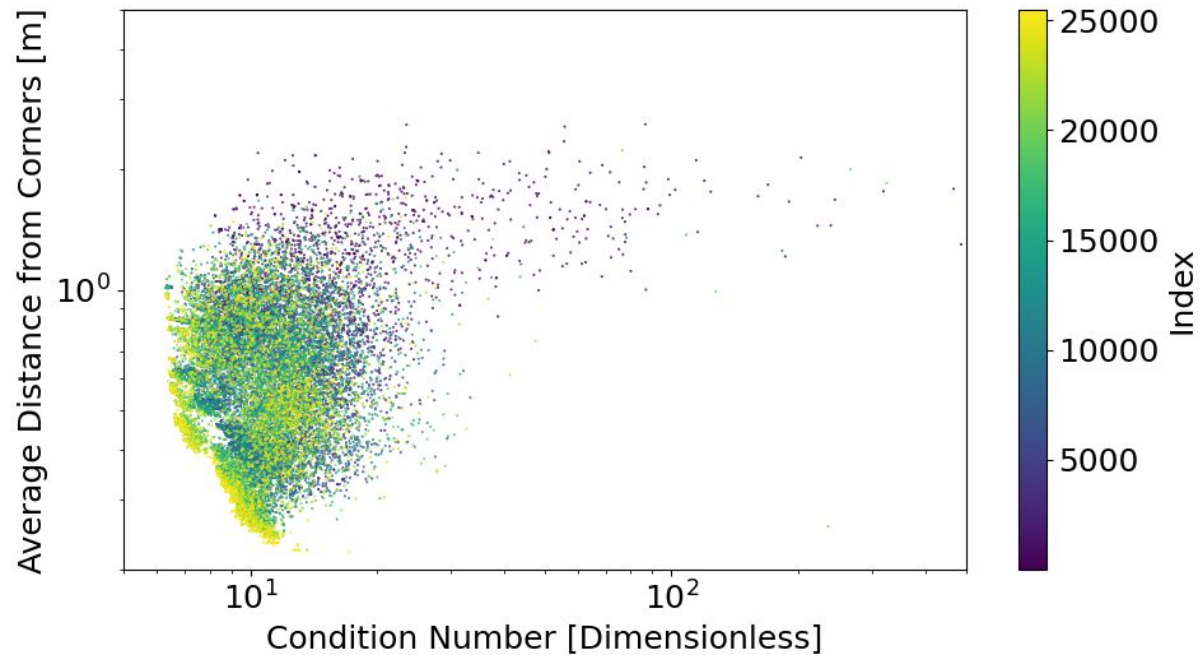
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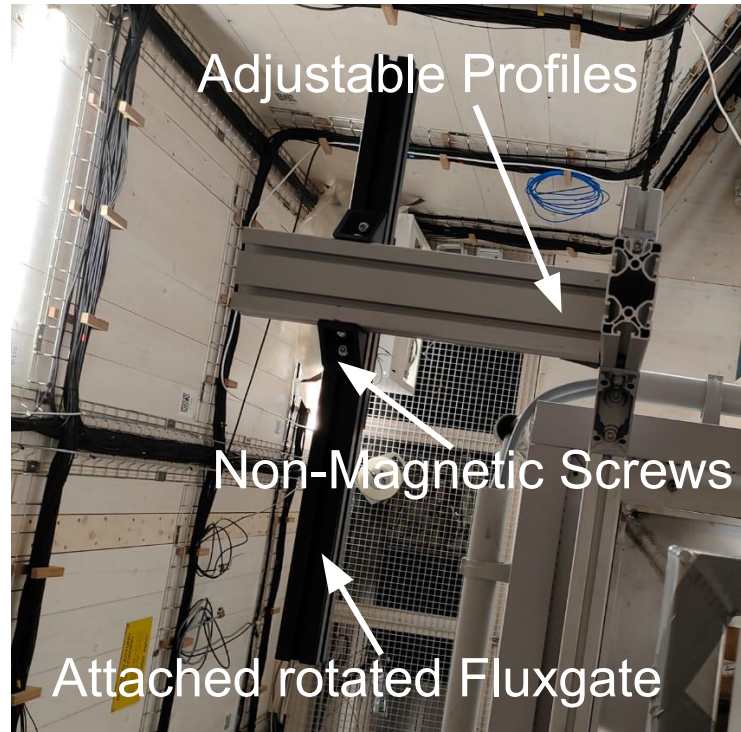
## Optuna - Results



OPTUNA

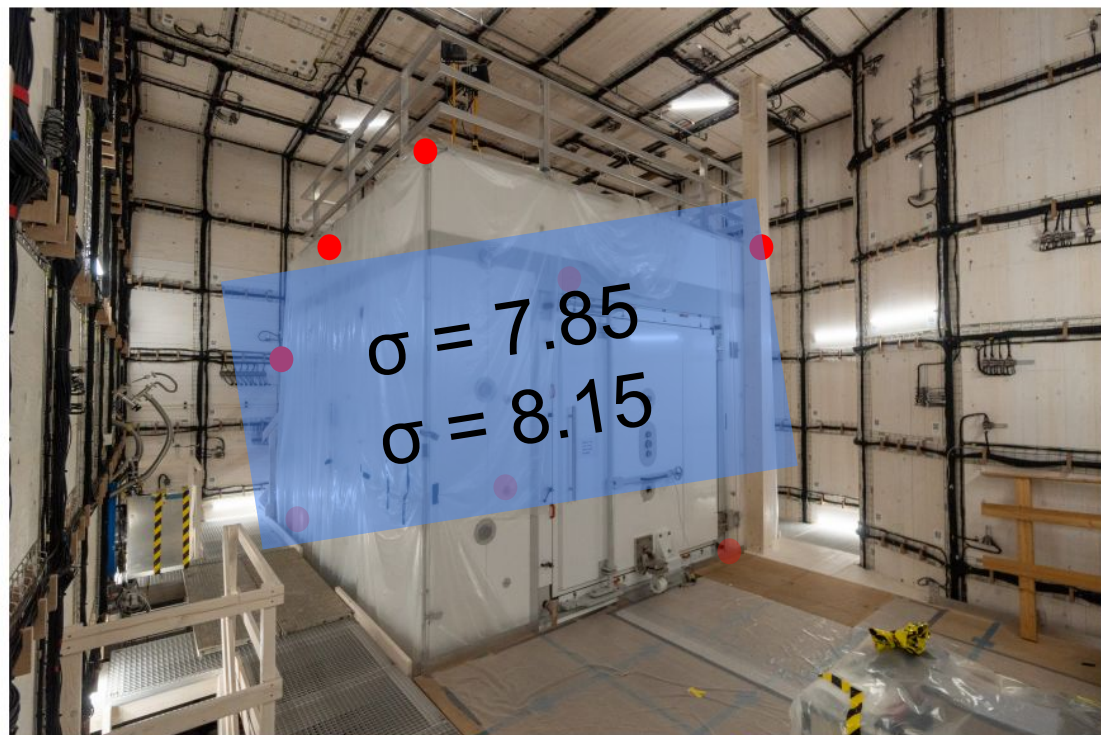
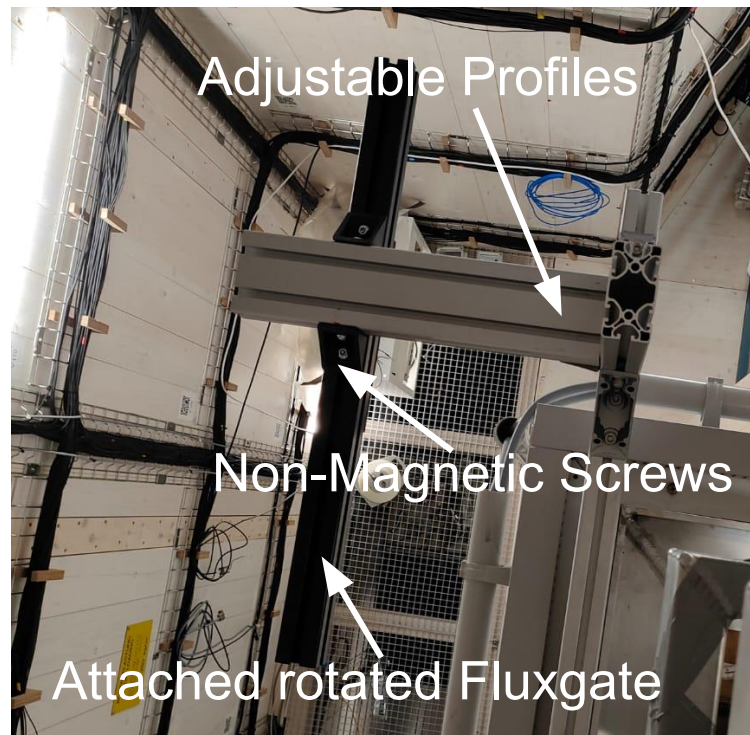
Optimal Condition Number  $\sigma = 7.85$ 

# Implementation in System





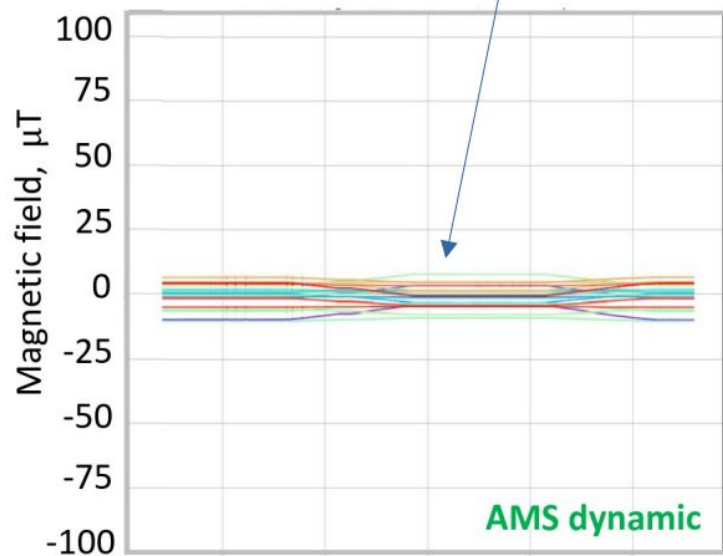
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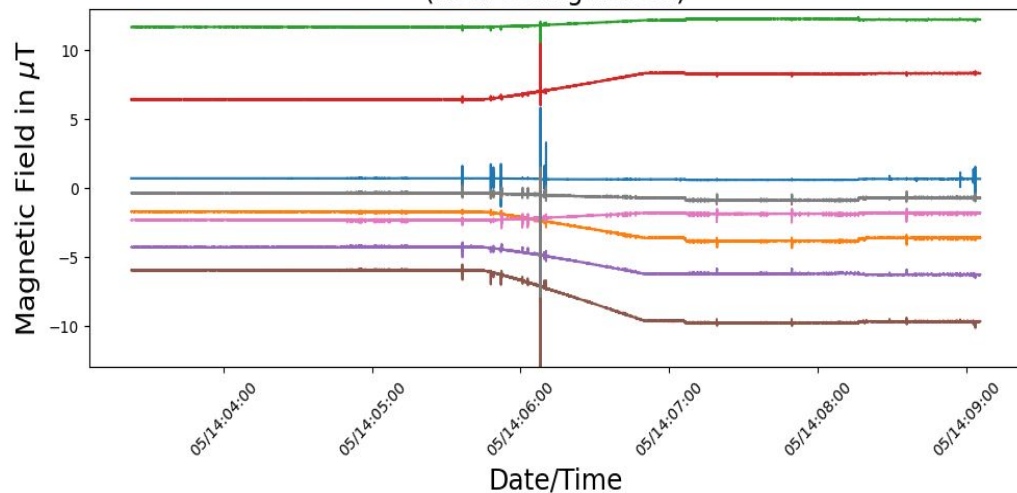
# Performance Test

External Disturbance

~ 10  $\mu\text{T}$ !

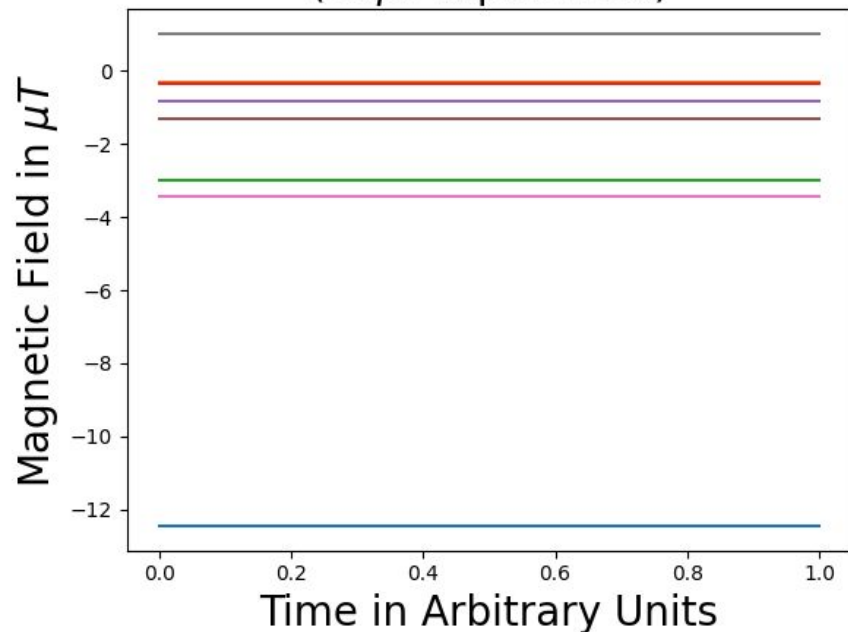


Fluxgate Values in x-Direction  
(New Configuration)

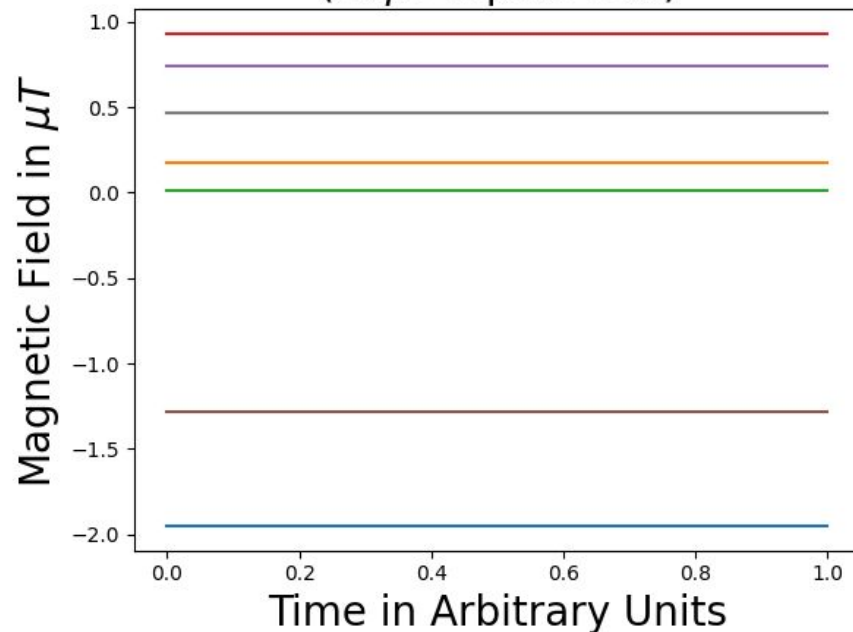


# Simulated Residual Field

x-Component of Compensation with MSR  
( $50\mu T$  input Field)



x-Component of Compensation withOUT MSR  
( $50\mu T$  input 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

**ETH zürich**

### An external array of remote magnetometers for the n2EDM experiment

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 On behalf of the n2EDM collaboration at PSI. <https://www.psi.ch/en/n2edm>

**Context**

The n2EDM experiment aims to improve the most accurate measurement of the neutron spin Hall shift (NSHS) using an external array of remote magnetometers.

**System architecture**

**Requirements:**

- Master computer remotely commands many Raspberry Pi slave computers
- All sensor data streamed to experiment's primary data acquisition computer
- Standardised commands (SCP)
- Reliability and Scalability

**Implementation**

- Asynchronous TCP communication (ZeroMQ) between master and slave computers
- Experiment-wide Master/slave communication handler streams data via TCP
- Standardised commands (SCP)
- Identical control code across all Raspberry Pi

**Outlook**

- Continuously collecting data from the external magnetometers
- Determine common trends that identify the external magnetometers that are changing their state
- Long term, the RMA sensors could be integrated into the n2EDM control algorithm to increase the ability to compensate for the inhomogeneities

**Sources and Acknowledgements**

- G. Jents, Bachelor thesis ETH Zurich (2015)
- H. Bertsch, Bachelor thesis ETH Zurich (2018)
- S. Ermakov, Summer thesis ETH Zurich (2022)
- The work is supported by SNF grant 200441.

**Towards magnetic source identification from known magnet system**

**Initial steps towards source identification:**

AMS is a well-known magnetic source to develop our analysis tools for identifying sources of magnetic disturbances.

- Use AMS (known magnetic fields) for initial development of analysis building materials
- Use Raspberry Pi to take measurements while AMS (known magnet system) changes coil currents

**Results:**

- Successful
- 

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Poster No. 388



WOW



WOW

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Questions?