Improving the performance of a three-axes Hall probe mapper system

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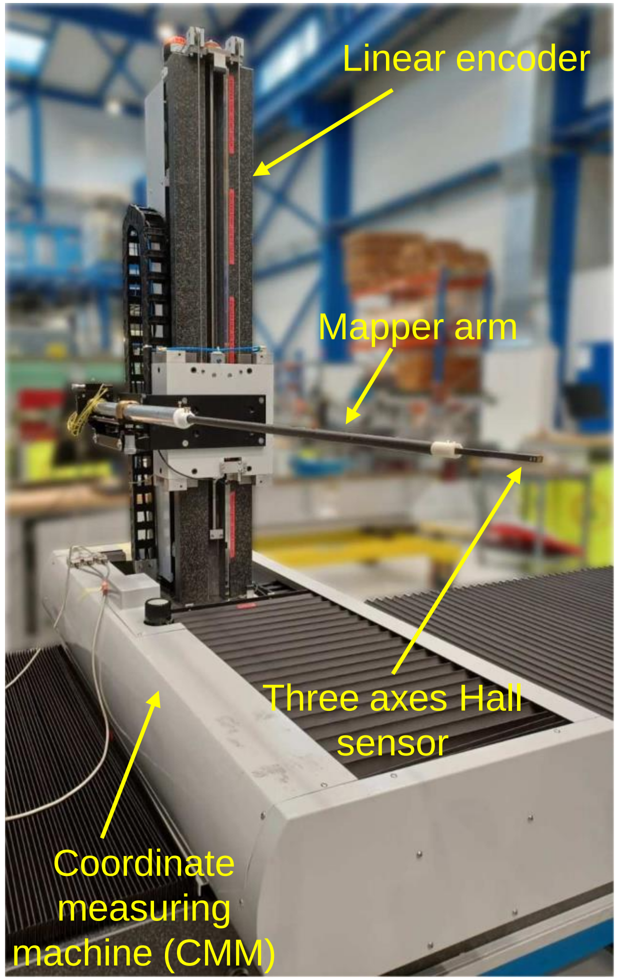
The new Hall probe mapper system at CERN



Some machine parameters	
Measurable volume	3 x 1 x 1 m^3
Resolution of the linear encoders	0.1 µm
Specified/validated positioning accuracy	0.1 mm
Maximum encoder trigger frequency	100 Hz
Nominal speed	20 mm/s

Some sensor parameters (currently equipped)	
Hall probe type	AS-3DC
Manufacturer	Projekt Elektronik
Sensor non-linearity error (calibrated)	< 0.01 % (|**B**| < 1 T)
Sensitivity	5 V/T
Hall sensor temperature coefficient	-0.411 mV/K
Diameter of Hall cube	2.2 mm
Sensor outer diameter	120 x 6 x 6 mm^3

Some features
Precision alignment for sag correction
Precision alignment for rotation around arm axis
Keysight 3458A Digital multimeters (8.5 digit) for Hall voltages
Measurements *“on-the-fly”*

Agenda

1. Sensor calibration
2. Fiducialization and alignment
3. Arm vibrations
4. Post processing
5. Outlook

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1. **Sensor calibration**
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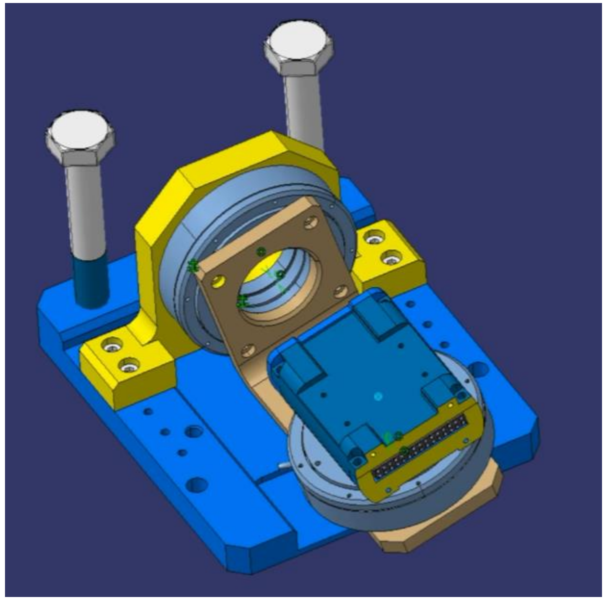
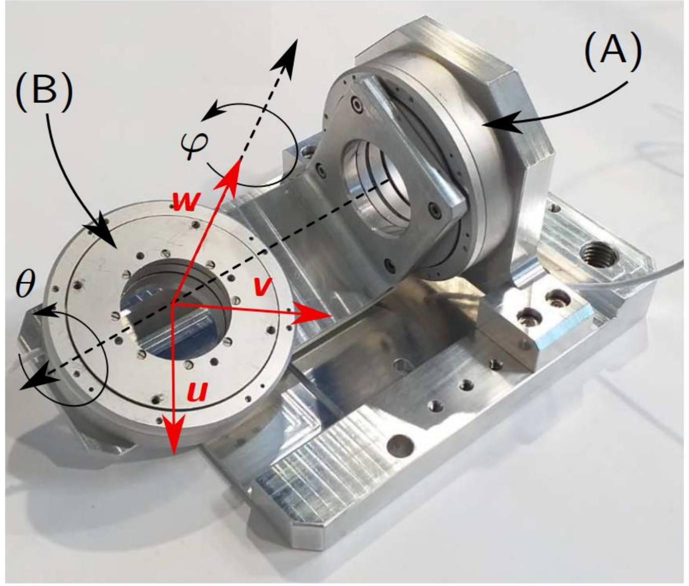
Sensor calibration

- The calibration of three axes Hall sensors is elaborate
- The new setup is designed for the calibration of

  → Non-linearity
  → Cross sensitivity (Orthogonality)
  → Planar Hall effects

- Two piezo-electric, non-magnetic rotary stages are used [1]
- Rotary encoder sensor accuracy is 25 μrad
- The assembly fits into a reference dipole of 80 mm gap height



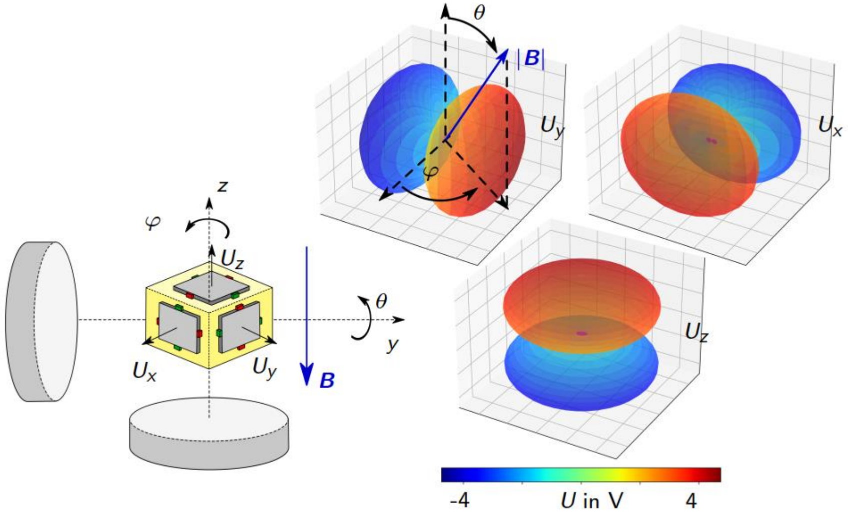


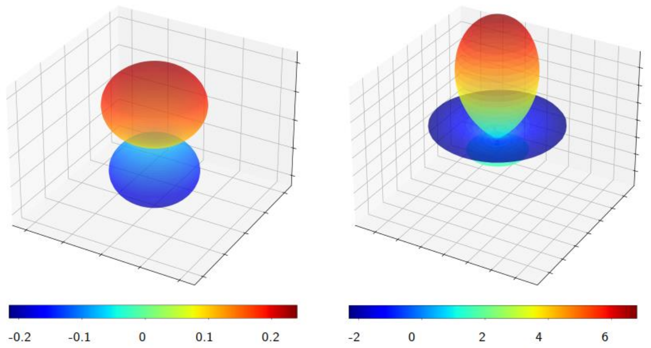
**Designed and manufactured by Olaf Dunkel (TE-MSC-TM)*

[1] *SmarAct* https://www.smaract.com/en

Sensor calibration

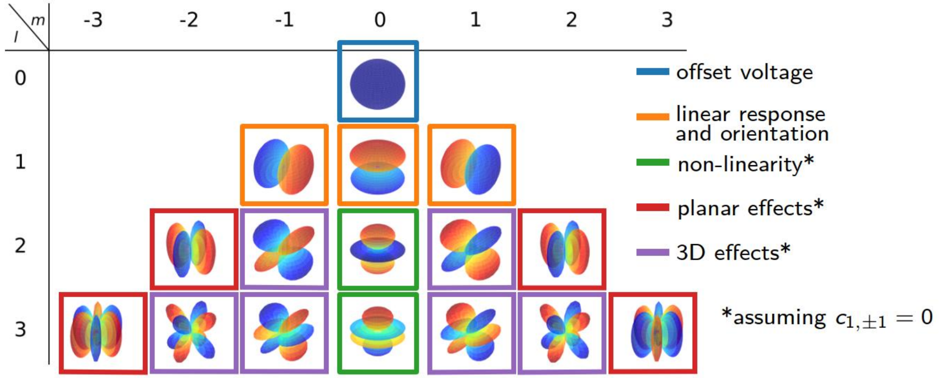
Sensor response surfaces for a full rotation





Response surface [V]   Imperfection in per-mille

The response surfaces can be expanded using the *solid harmonic functions* [2]



$$U(|\boldsymbol{B}|, \theta, \varphi) = \sum_{l=0}^{L} \sum_{m=-l}^{l} c_{l,m} \underbrace{|\boldsymbol{B}|^l Y_l^m(\theta, \varphi)}_{\text{solid harmonics}} .$$

The sensor orientation is encoded in the coefficients with $l = 1$

$$\varphi_{\max} = -\arg(c_{1,1}), \quad \theta_{\max} = \arg\left(c_{1,0} + j\sqrt{2}|c_{1,1}|\right) .$$

Higher order coefficients ($l > 1$) provide evidence for:

- Non-linearity
- Planar and 3D Hall effects

[2] F. Bergsma. *“Calibration of Hall sensors in three dimensions”*. In: IMMW13. 2003.

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2. **Fiducialization and alignment**
3. Arm vibrations
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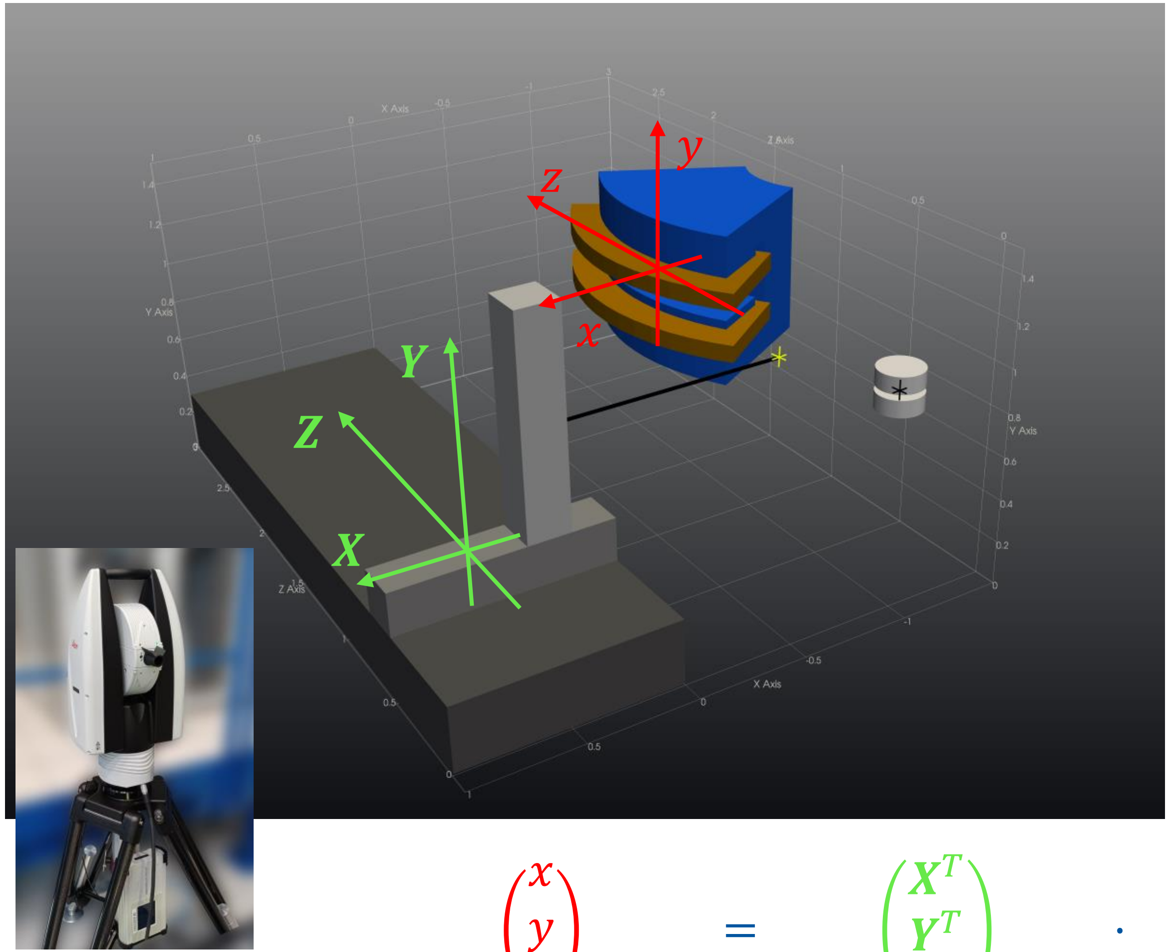
Fiducialization and alignment



Leica AT960 [3]

(1) A ***magnet coordinate system*** is constructed from optical measurements of the magnet geometry.

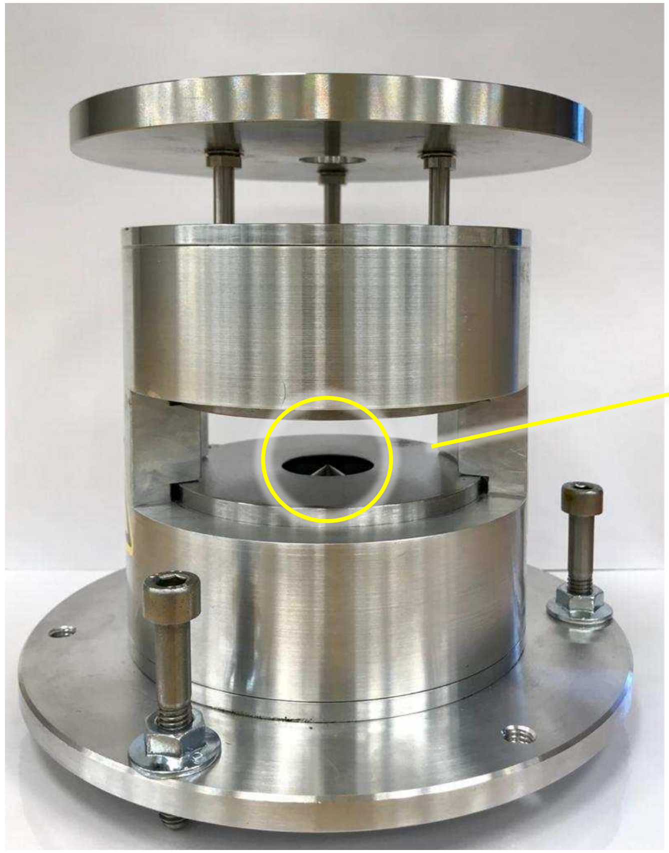
(2) The ***mapper orientation*** vectors $\boldsymbol{X}$,$\boldsymbol{Y}$ and $\boldsymbol{Z}$ are determined by measuring the stage movement along the three axes.

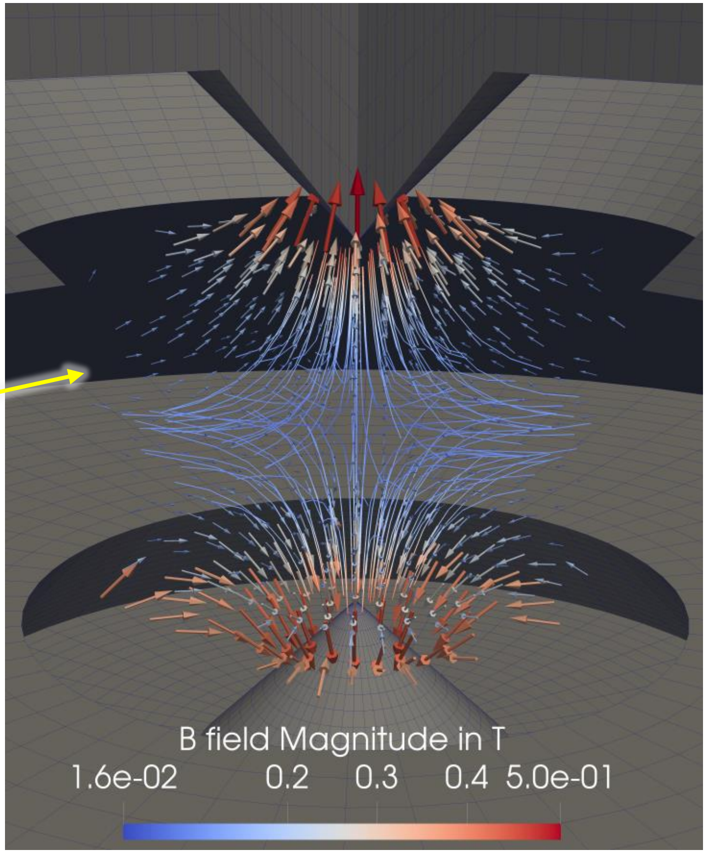
(3) The ***origin of the mapper coordinates*** $(x_0, y_0, z_0)^T$ can now be determined if the mapper coordinates are known for any point in the magnet coordinates.

$$\underbrace{\begin{pmatrix} x \\ y \\ z \end{pmatrix}}_{\text{magnet coordinates}} = \underbrace{\begin{pmatrix} \boldsymbol{X}^T \\ \boldsymbol{Y}^T \\ \boldsymbol{Z}^T \end{pmatrix}}_{\text{mapper orientation}} \cdot \underbrace{\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}}_{\text{mapper coordinates}} + \underbrace{\begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix}}_{\text{origin of the mapper coordoinates}}$$

[3] *Leica Absolute Tracker AT960*, https://www.hexagonmi.com/de-ch/products/laser-tracker-systems/leica-absolute-tracker-at960

Fiducialization and alignment



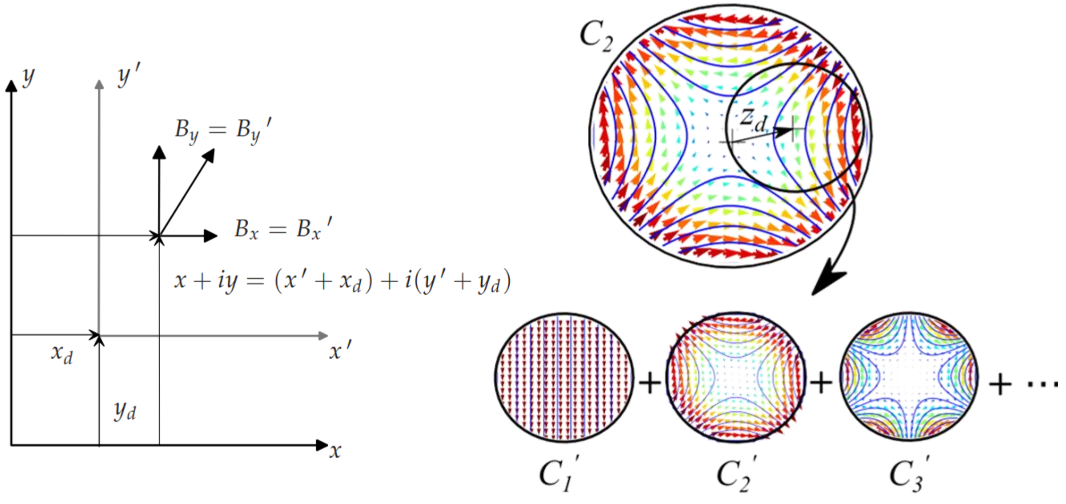


Designed and manufactured by Olaf Dunkel (TE-MSC-TM)

- Two permanent magnets and a yoke of electrical steel are used to shape a **rotationally symmetric *B*-field**
- The ***field is vanishing in the center*** of the magnet
- This ***central position is identifiable*** from the positions of three fiducialization targets on the top of the magnet
- The magnet center can be measured ***optically and magnetically***.
- In this way we can identify the ***origin of the mapper coordinates.***

Fiducialization and alignment

Remember: *Feed-down correction in rotating coil measurements*



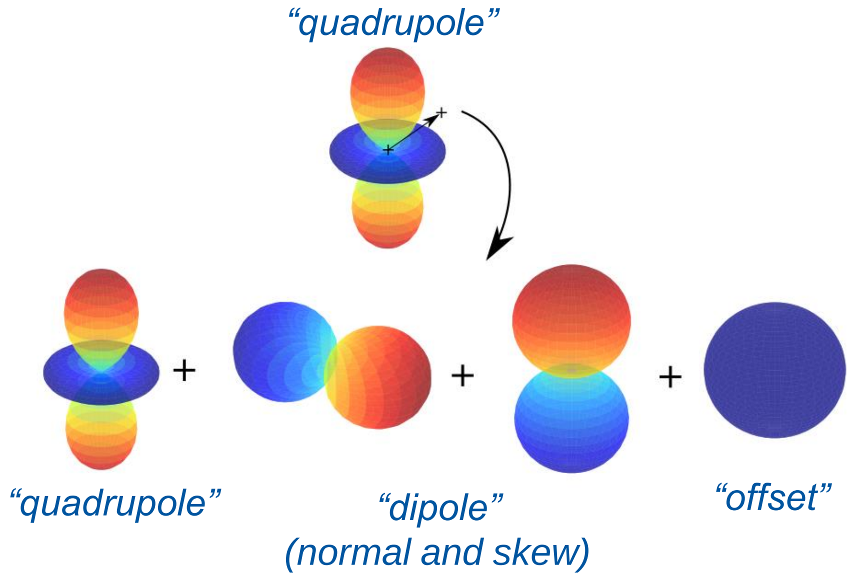
$$C_n' = \sum_{k=n}^{\infty} C_k \binom{k-1}{n-1} \left(\frac{z_d}{r_0}\right)^{k-n}$$

[4]

Implying $C_1 = 0$, the sensor position z_d can be determined.

In the 3D case: *The solid-harmonic expansion*

$$\phi_{\mathrm{m}}(r,\varphi,\theta) = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} \nu_{l,m} \underbrace{r^l Y_{l,m}(\theta,\varphi)}_{\text{solid harmonics}} .$$

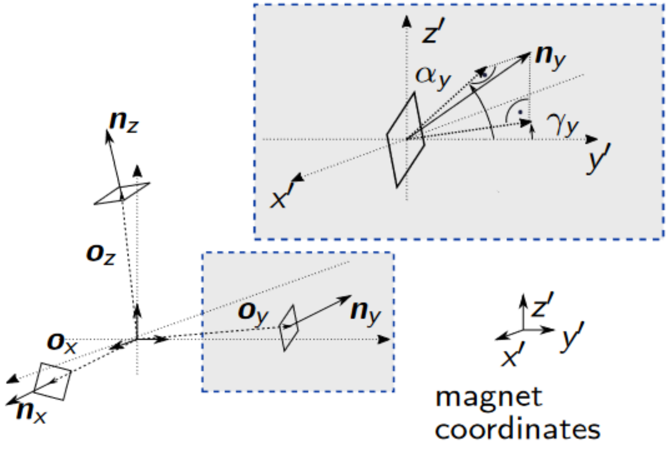


The same principle can be applied to identify the position of the Hall sensors in the cone magnet!

Fiducialization and alignment

In this way we can determine:

- Absolute sensor orientation (6 DoFs)
- Absolute sensor position (9 DoFs)



variable	mean[1]	design[1]	σ[1]
α_y	87.20	90	0.032
α_z	-92.25	-90	0.025
β_x	0.79	0	0.017
β_z	**75.44**	**0**	**0.456**
γ_x	178.70	180	0.030
γ_y	**-3.17**	**0**	**1.015**

orientation

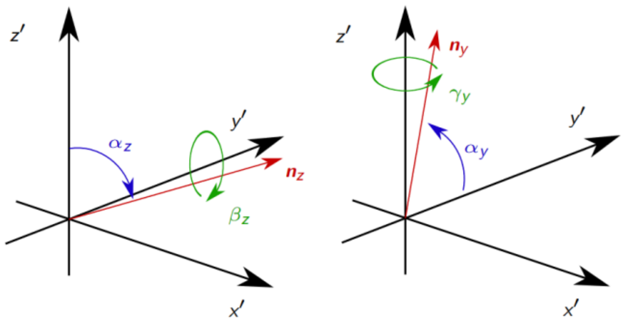
variable	mean[2]	design[2]	σ[2]
o^x_x	2.08	2	0.002
o^y_x	0.05	0	0.050
o^z_x	0.01	0	0.020
o^x_y	0.05	0	0.019
o^y_y	0.04	0	0.017
o^z_y	-2.09	-2	0.001
o^x_z	0.29	0	0.050
o^y_z	0.28	0.2	0.003
o^z_z	-0.25	0	0.023

position

[1] values given in deg.
[2] values given in mm.

rotation around parallel axis

magnets symmetry axis



The code is available in github [5]!

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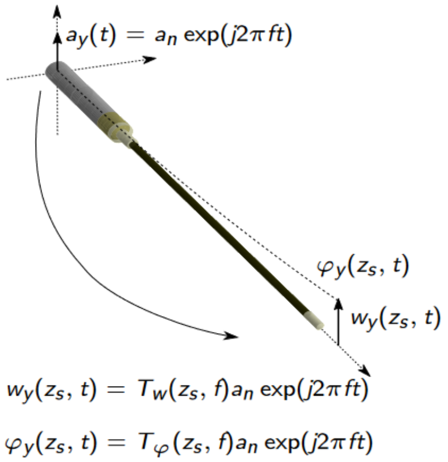
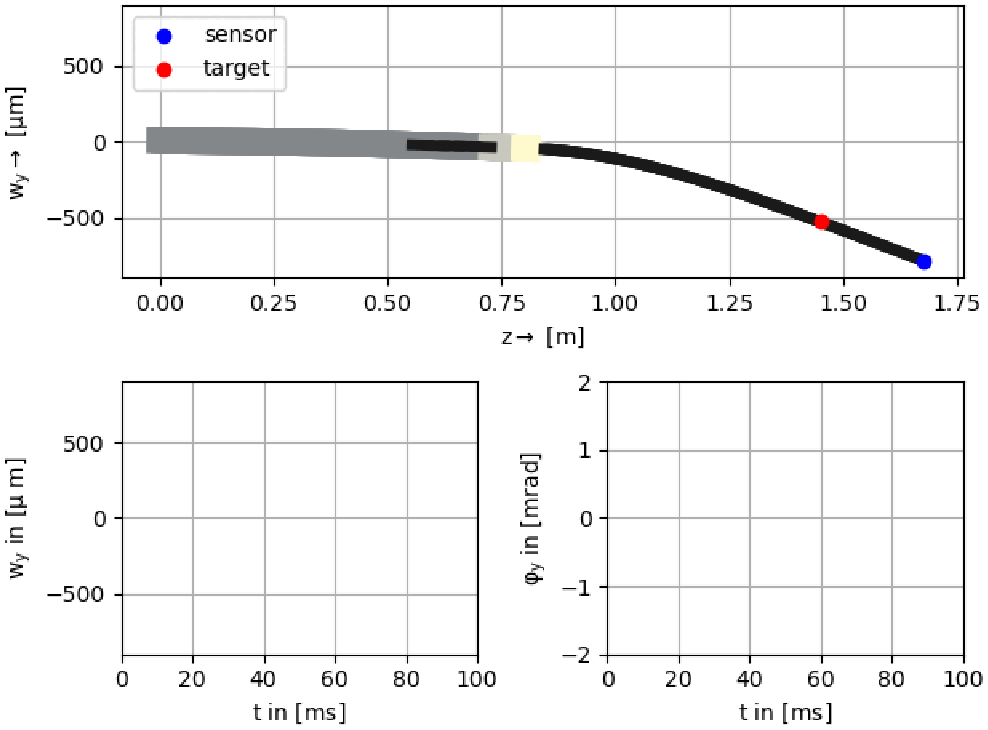
Arm vibrations

- Imperfections in the stage motion cause the ***mapper arm to vibrate***
- We have developed a FEM model of the mapper arm using ***Euler-Bernoulli beam theory***
- ***The Code is available in github! [6]***



What do we get from this?

- ***"Cheap" modal analysis***: Recover the vibration amplitudes and arm deformation at the sensor position from Leica measurements
- Improving the ***mapper arm design***.
- Develop a ***realistic noise model*** including the effect of arm vibration



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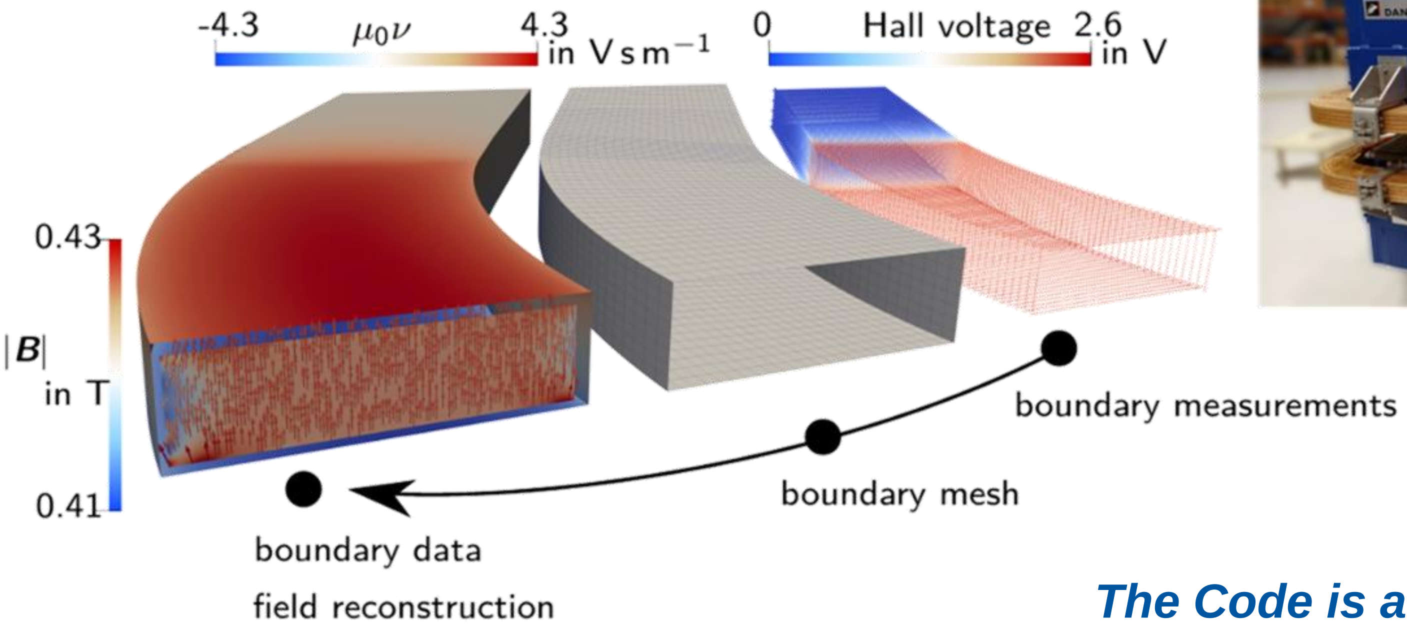
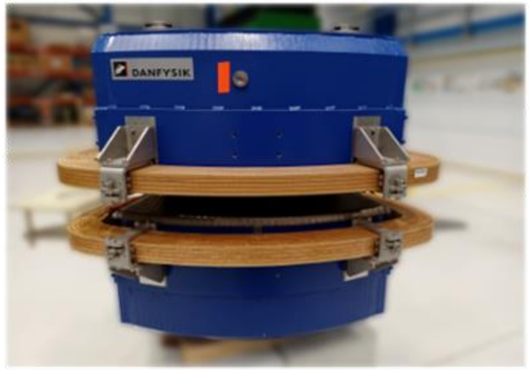
Post Processing

- Mapping the field along a ***domain boundary*** we acquire the boundary condition of a ***boundary value problem***.
- We make use of ***Kirchhoffs integral equation*** to reconstruct the field in the enclosed domain

$$\underbrace{\phi_{\mathrm{m}}(\boldsymbol{r})}_{\text{reconstructed}} = \int_{\partial\Omega} \frac{1}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|} \underbrace{\partial_{\boldsymbol{n}}\phi_{\mathrm{m}}(\boldsymbol{r}')}_{\text{measured}} \,\mathrm{d}\boldsymbol{r}' - \int_{\partial\Omega} \underbrace{\phi_{\mathrm{m}}(\boldsymbol{r}')}_{\text{reconstructed}} \,\partial_{\boldsymbol{n}} \frac{1}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|} \,\mathrm{d}\boldsymbol{r}', \qquad \boldsymbol{r} \in \Omega$$



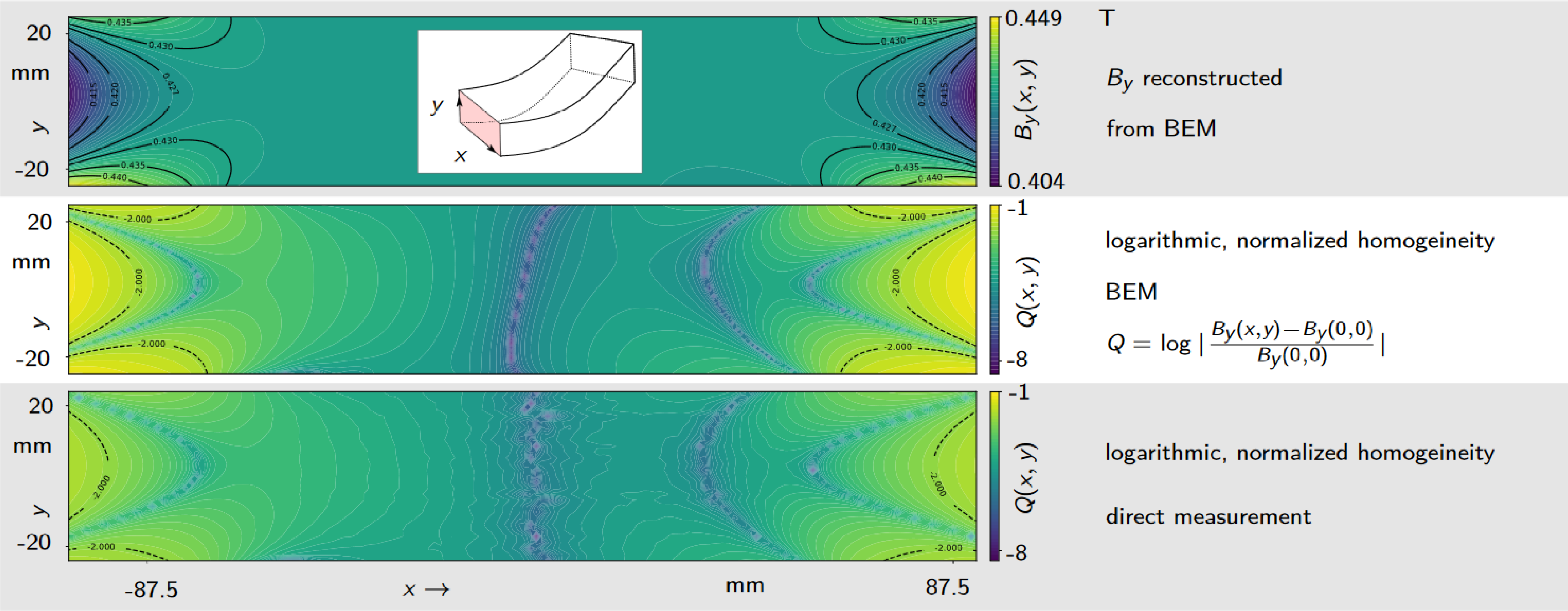


The Code is available in github! [7]

[7] https://github.com/MelvinLie/BEMMM

Post Processing

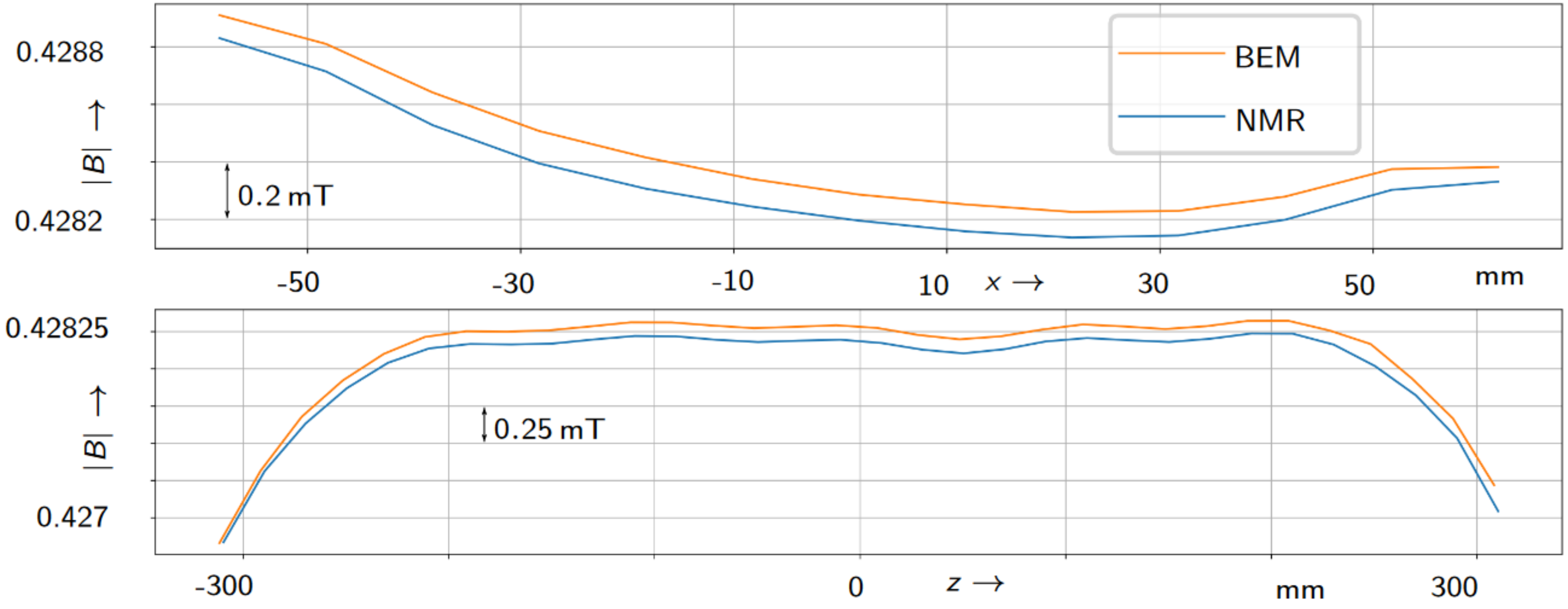
Example



No measurements inside the domain are needed!

Post Processing

Validation by NMR measurements



*A **systematic difference*** of ***2 units*** in 10 000 was found

The ***temperature dependency*** of the Hall voltage affects the measurements in this range

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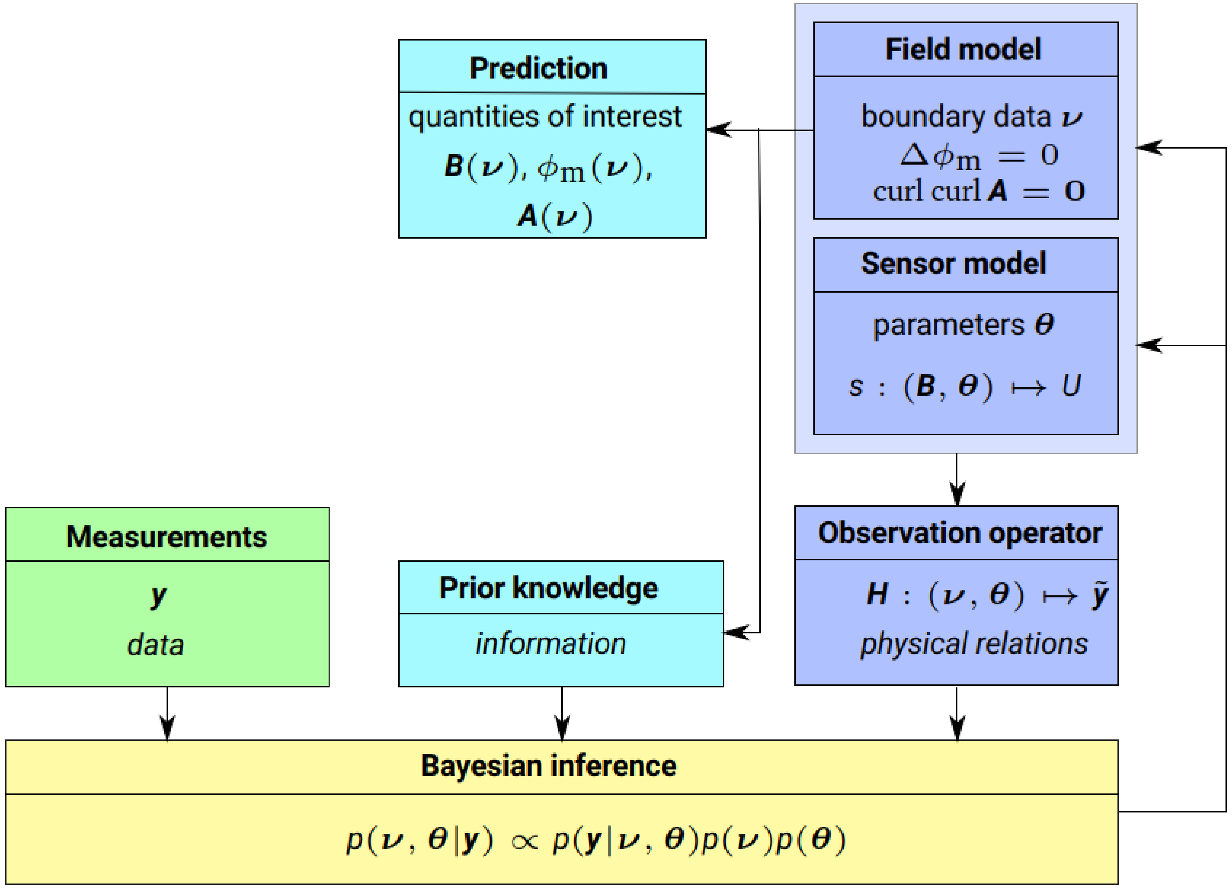
Outlook

Model based field reconstruction



See [8], [9].

Advantages:

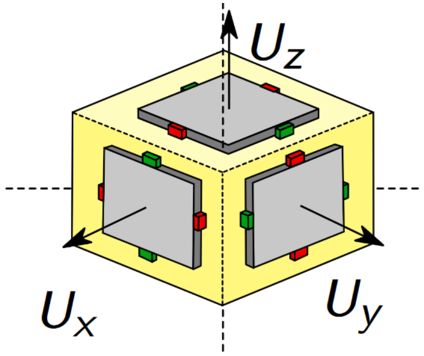
- ***Implying Maxwells equations*** *in the field reconstruction*
- ***Non-linear and complicated sensor models*** *are handled* ***without approximation***
- ***Multiphysical sensor modelling:*** *Examples: Uncertain sensor* ***position****, sensor* ***temperature****,* ***velocity***
- ***Realistic noise modelling*** *from the coupling of the physical parameters*

[8] S. Kurz, M. Liebsch et al. *"Hybrid modeling: towards the next level of scientific computing in engineering".* In: (Mar. 2022). DOI: 10.1186/s13362-022-00123-0.
[9] M. Liebsch, *"Inference of Boundary Data from Magnetic Measurements of Accelerator Magnets"*, https://tuprints.ulb.tu-darmstadt.de/21144/

Thank You for Your attention!

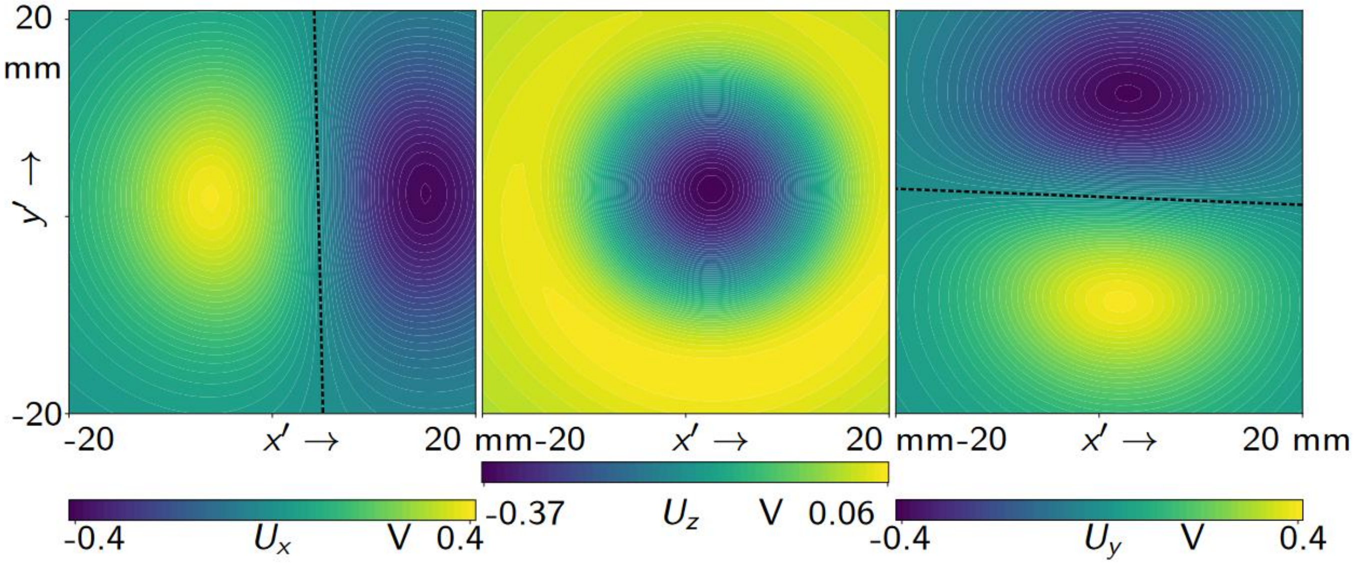
Backup slides

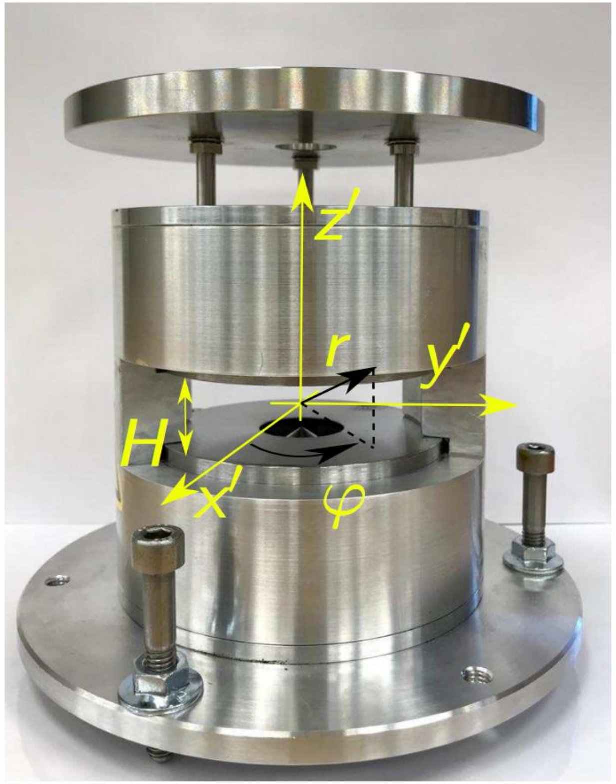
Fiducialization and alignment



Problem: The three Hall probes do not really measure the three components of the vector $\boldsymbol{B}$!

In fact: We measure three Hall voltages related to $\boldsymbol{n} \cdot \boldsymbol{B}$ at three different positions!





The Hall voltages are zero along three "zero-planes" where $\boldsymbol{n} \cdot \boldsymbol{B} = 0$.

We cannot uniquely identify the positions of the Hall sensors on the zero planes!