Paola La Marca :: PhD Program in Mechanical Engineering :: Paul Scherrer Institut

paola.lamarca@psi.ch

Compact field mapper for LGB magnets

International Magnetic Measurement Workshop 21 - ESRF

Outline

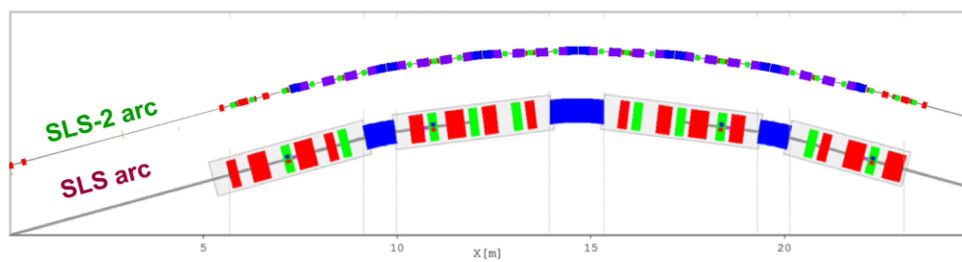
1. Introduction

Context

- SLS: Swiss Light Source
- Photon beams of high brightness for research in materials science, biology and chemistry

Constraints:

- Same ring diameter
- Same energy (2.4 GeV)
- Move as few beamlines as possible

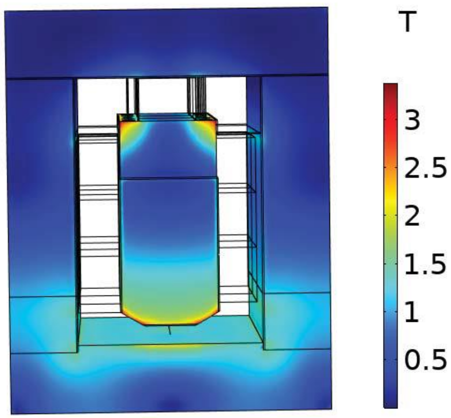


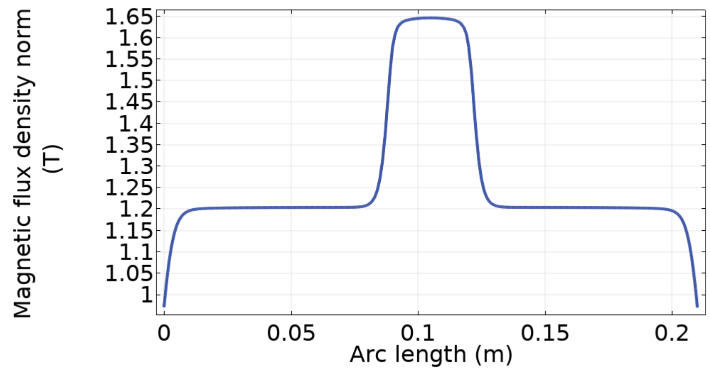
Reduction of emittance 5000 pm →140 pm

Context

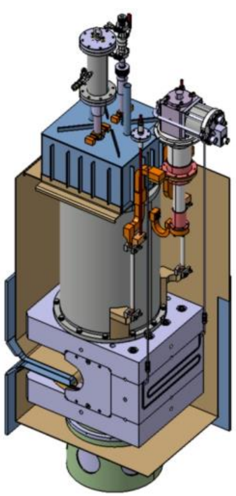
Designed <u>Longitudinal</u> Gradient Bending (LGB) magnets:

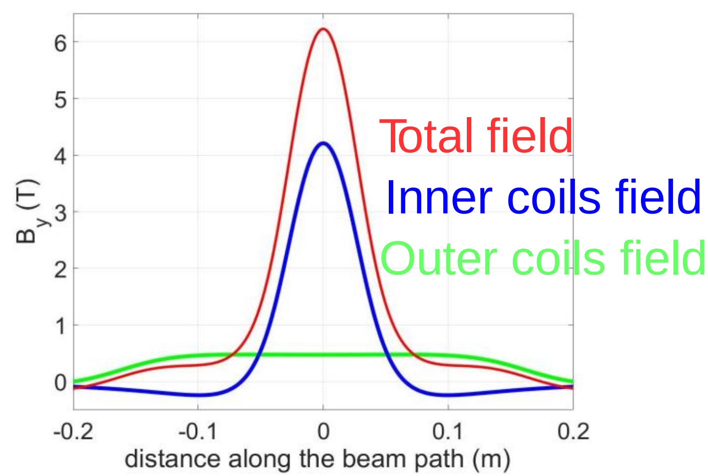
- Permanent magnets bending dipoles - 1.6T



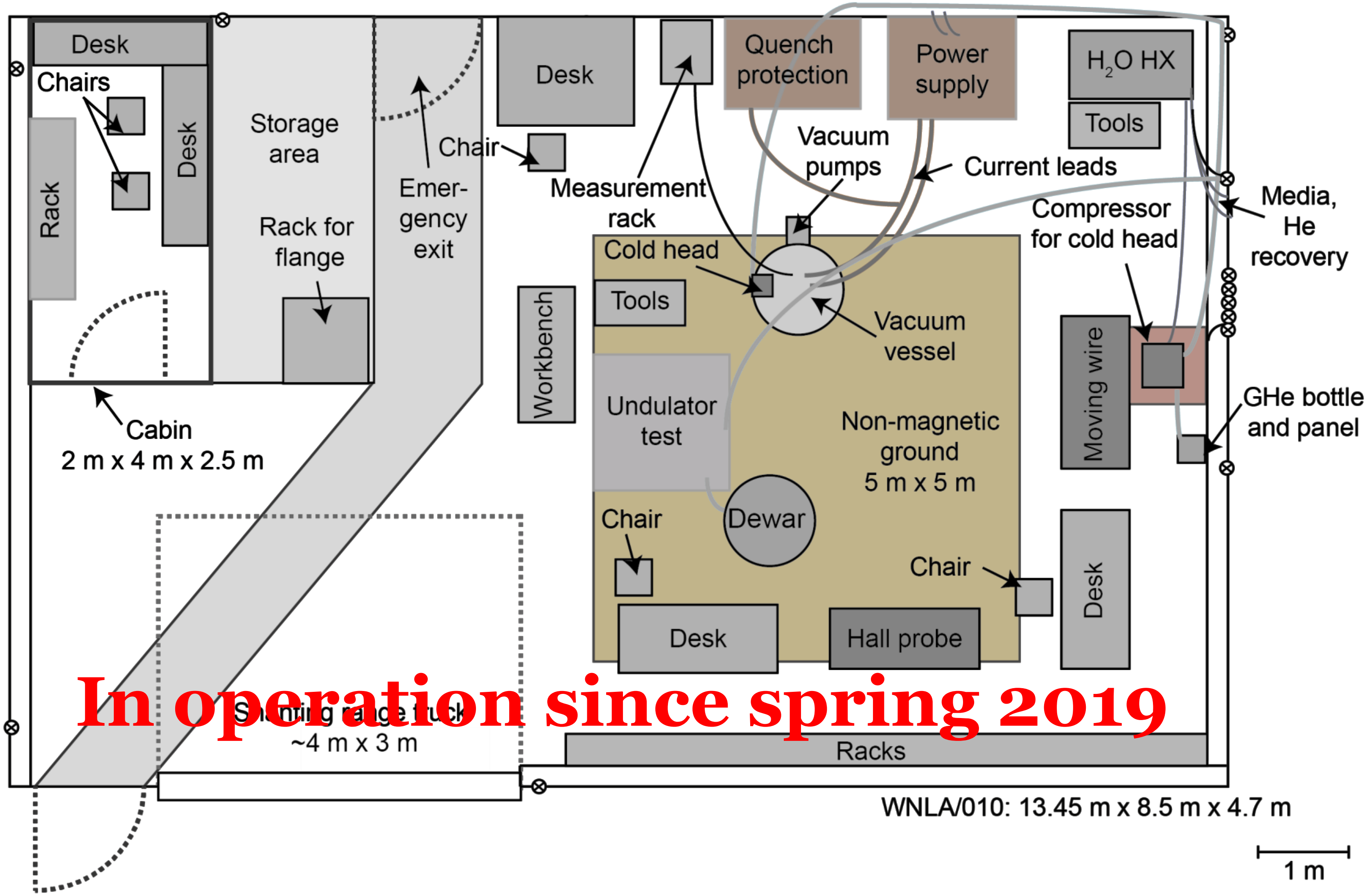


- Three superconducting bending dipoles reaching minimum 4T





Test stand for SLS2.0 magnet



In operation since spring 2019

Measurement challenges

Realization of a measurement bench for the magnetic characterization of SLS2.0 magnets

- Compactness
- Flexibility - adaptable to different magnets
- 3D profiles to be scanned

Mechanical

- Space restrictions (gap < 20mm)
- Materials
- Actuators and sensors
- Survey

Magnetic

- Accurate 3D probe
- Peak location assessment
- 10 units accuracy along 3 axis
- Access to GFR – anti-chamber

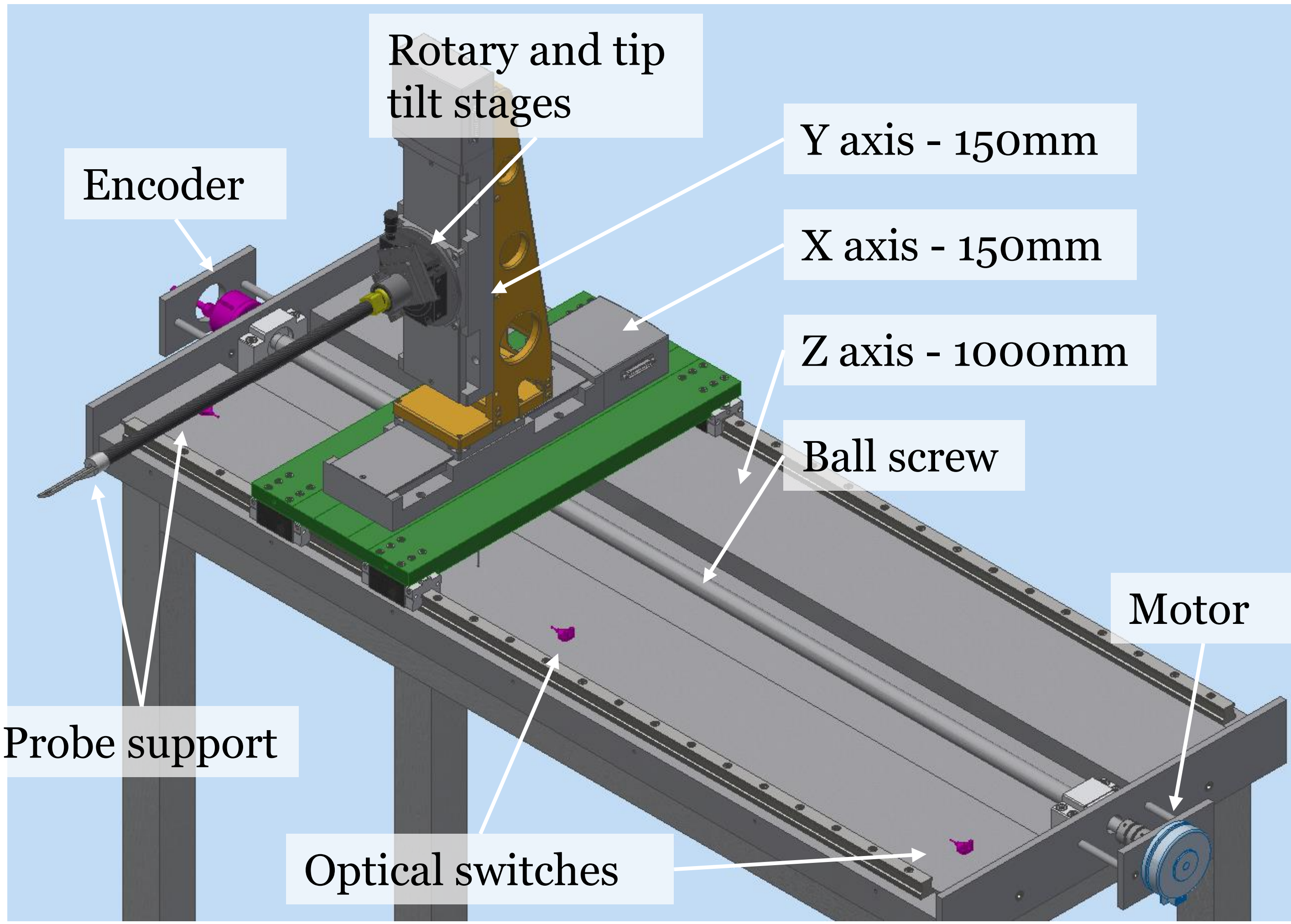
Mechanical → Target accuracy ← Magnetic

Target accuracy

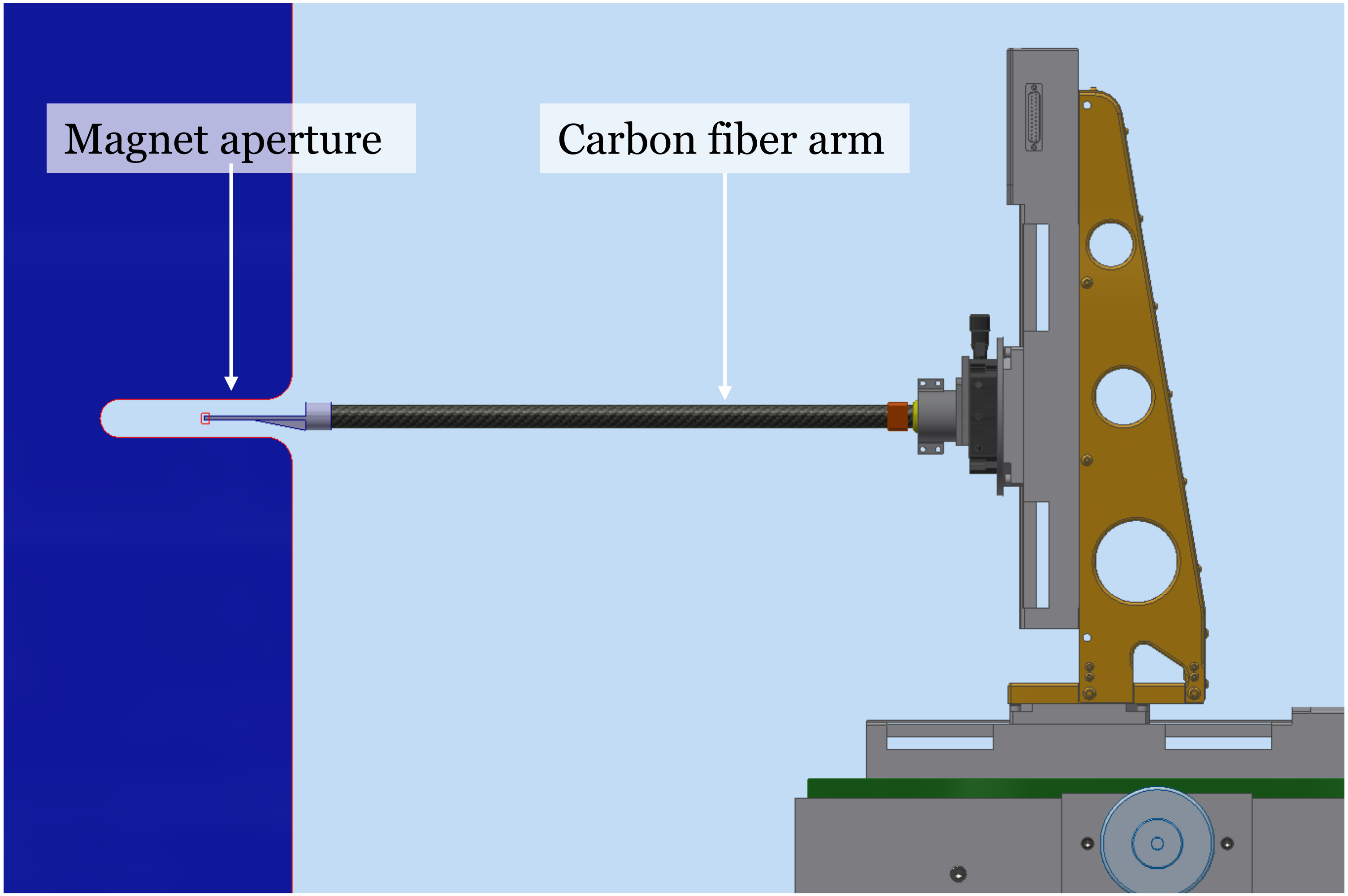
0.1% - 0.5% of B_{max}

2. Field mapper design

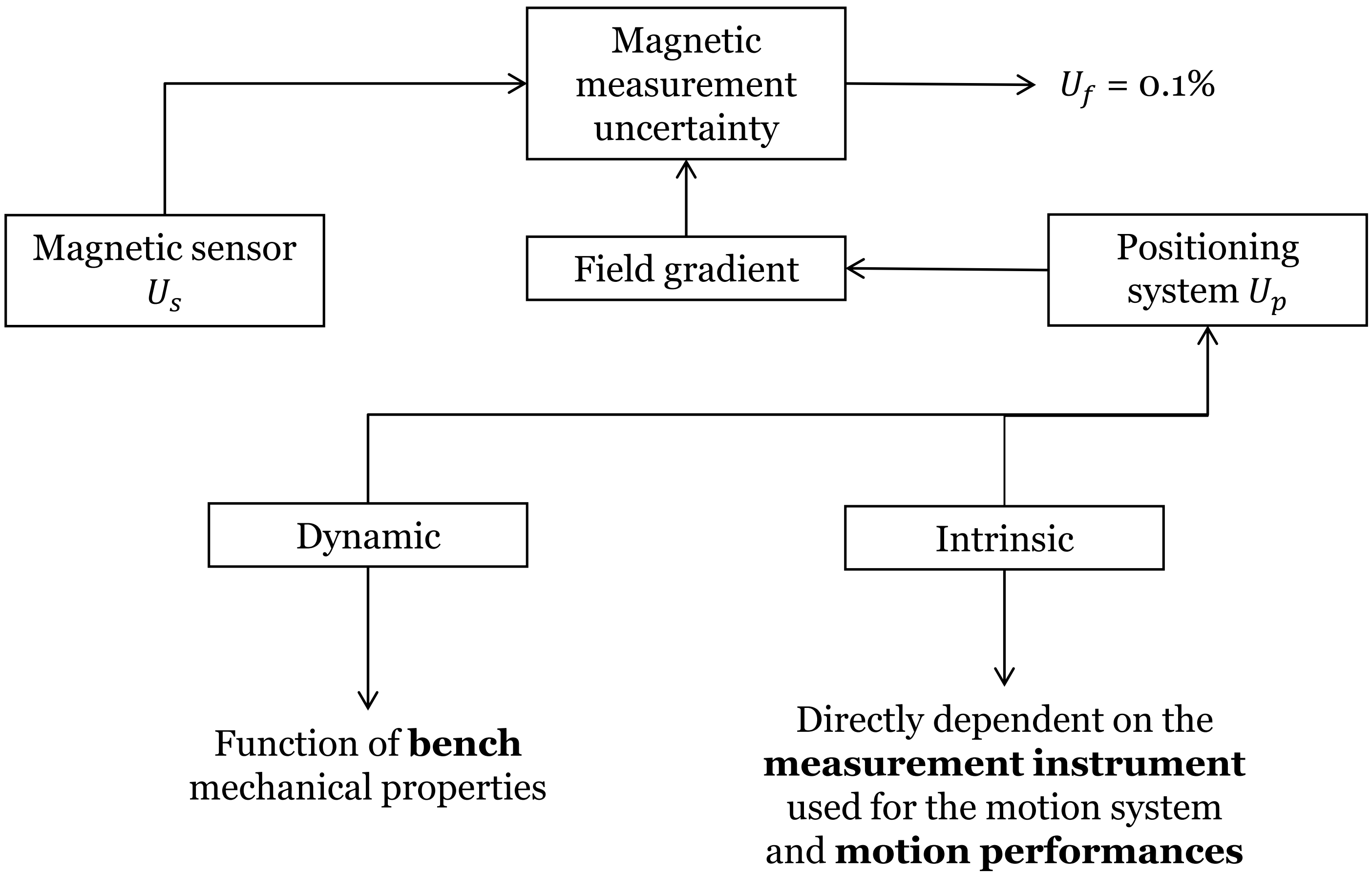
Motion system - CFM



Motion system - CFM



Uncertainty budget



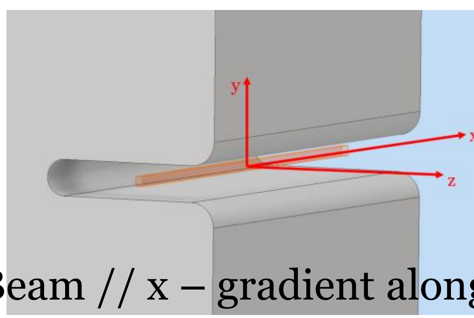
Positioning accuracy

Propagation of the sensor positioning uncertainty U_p to the magnetic measurement

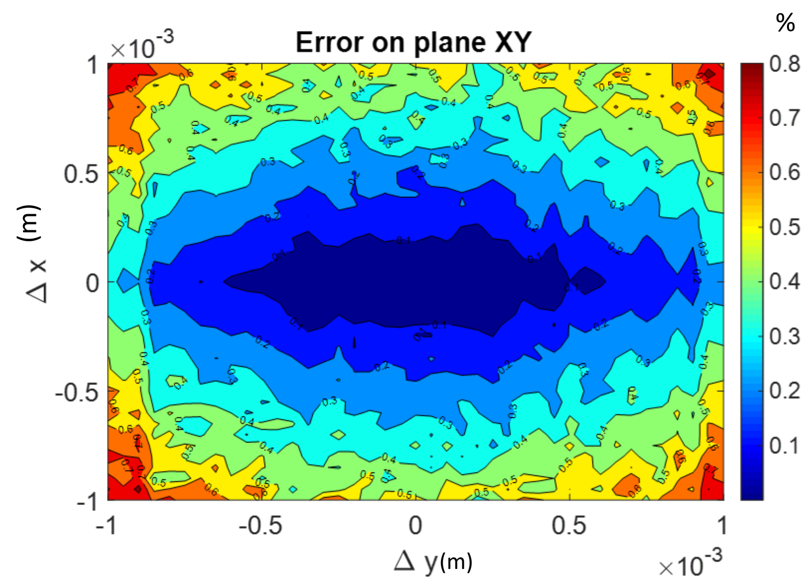
Uncertainty on position U_p → Magnetic field model → Field measurement uncertainty

Triangulation of field maps obtained by FEM --> Nodal interpolation to get the simulated measurement value

$$E = \frac{\Delta B}{B_{nom}}\% = \frac{B_{meas} - B_{nom}}{B_{nom}}\%$$



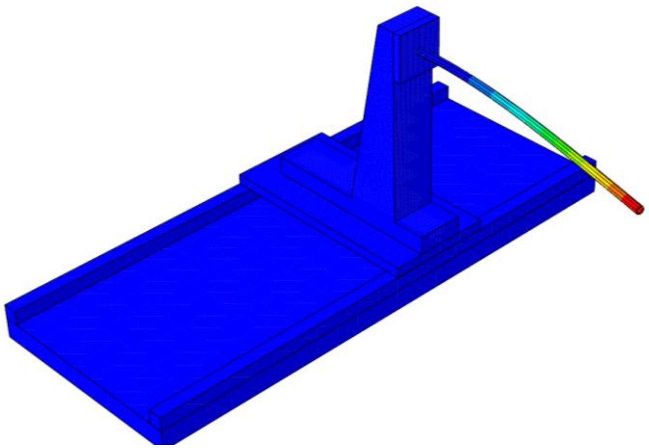
Beam // x – gradient along x

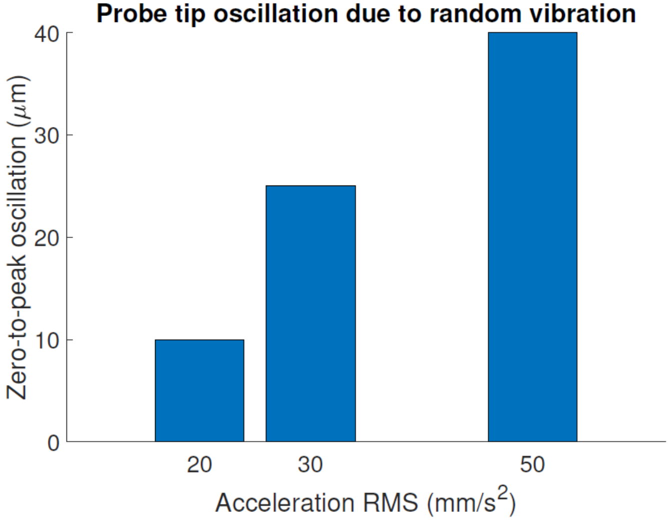


Dynamic effects

Positioning system U_p → Dynamic U_{dyn}

Positioning system U_p → Intrinsic U_{int}





Mechanical FEM model implemented to study the structure dynamic properties:

- Natural frequencies and modes
- Random vibration analysis

$U_{p,T}$ positioning uncertainty expressed in magnetic field units

$$U_{p,T} = \sqrt{U_{int,T}^2 + U_{dyn,T}^2}$$

Vibration level $[\frac{mm}{s^2}]$	$U_{p,T}$ $[\mu T]$	u_p $[ppm]$
20	± 48	± 48
30	± 138	± 138
50	± 203	± 203

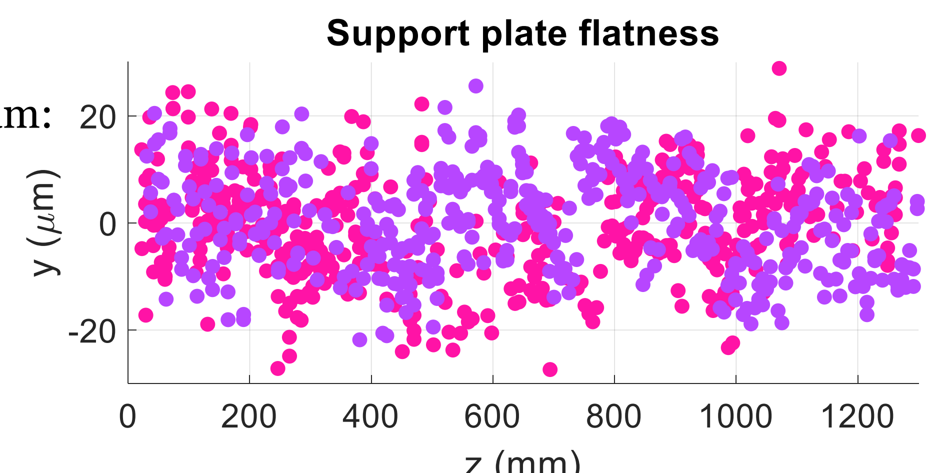
3. Assembly

Mechanical assembly

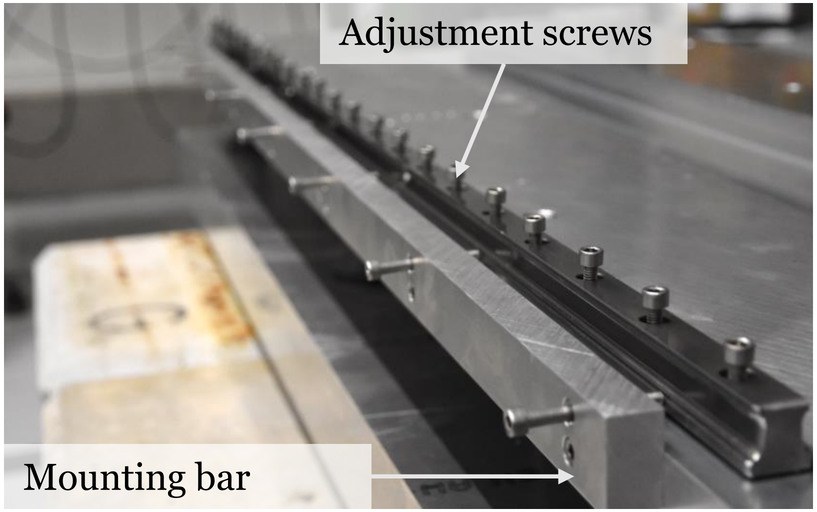
Linear stage assembly started with the support plate adjustment using the Laser tracker.

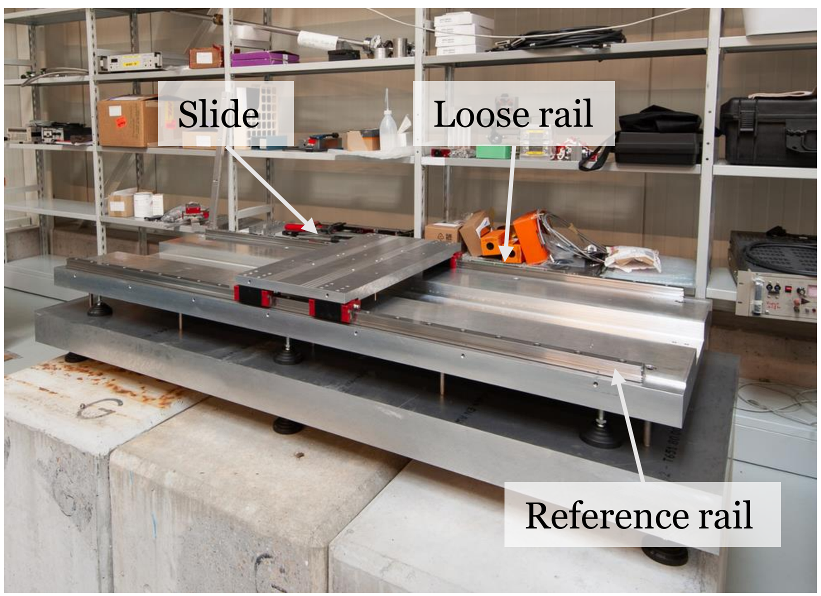
Flatness of grooves for profiled guideways ±30µm:

- Within mechanical specifications
- Comparable to laser tracker accuracy



Mechanical assembly





- Mounting bar → Horizontal straightness in motion

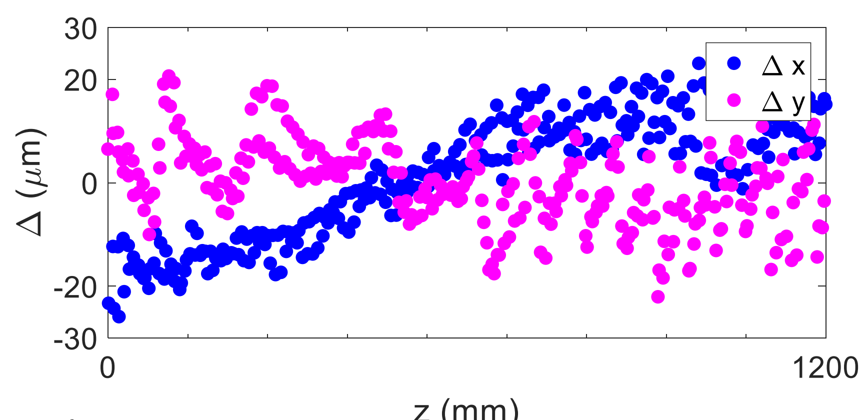
- Adjustment screws → Vertical straightness in motion

  → **Installation of reference rail**

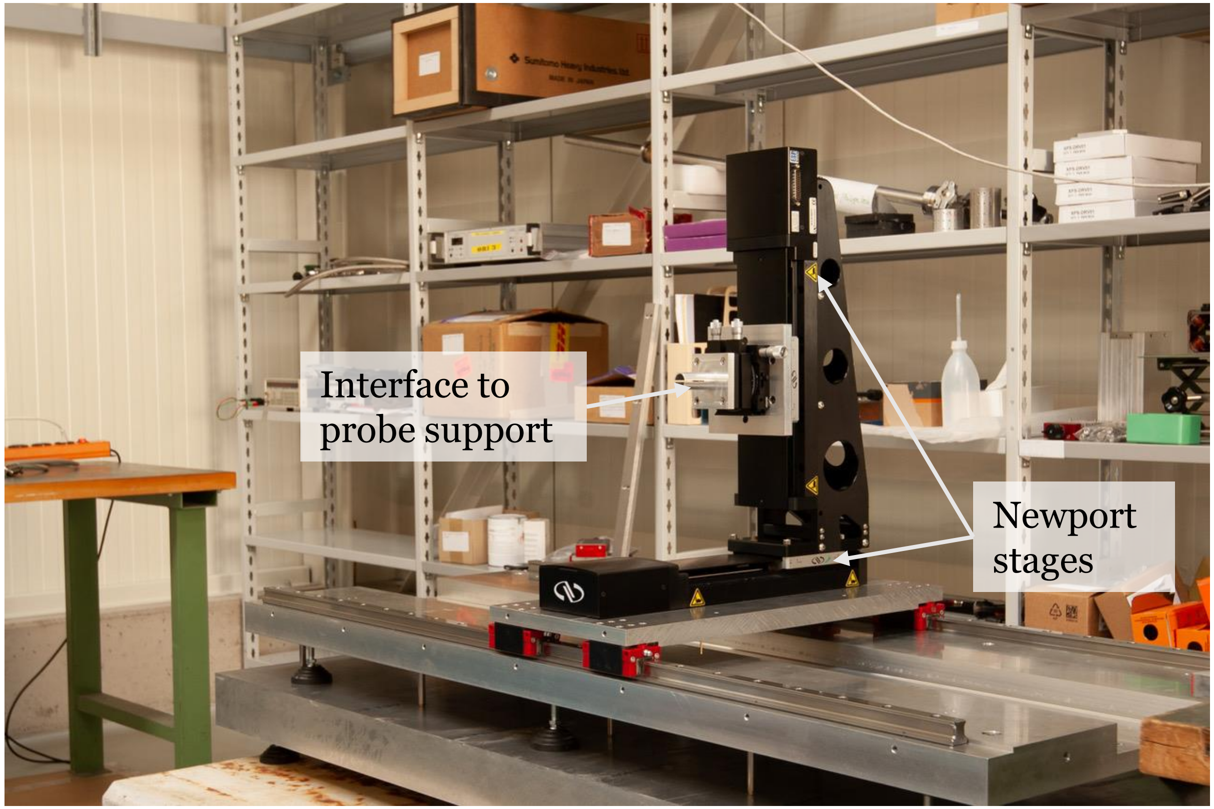
  → **Second rail left loose**

- Installation of the slide with mounting bars on the reference rail

- Stepwise installation of loose rail to force it to be parallel to the reference rail



Mechanical assembly



Vertical stage double mounting

→ Arm parallel to x-axis

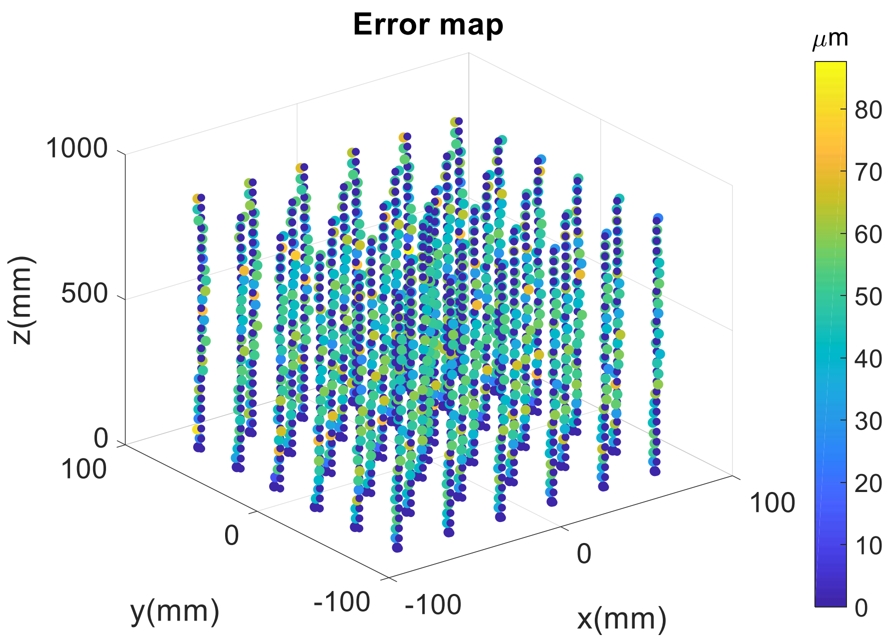
→ Arm parallel to z-axis

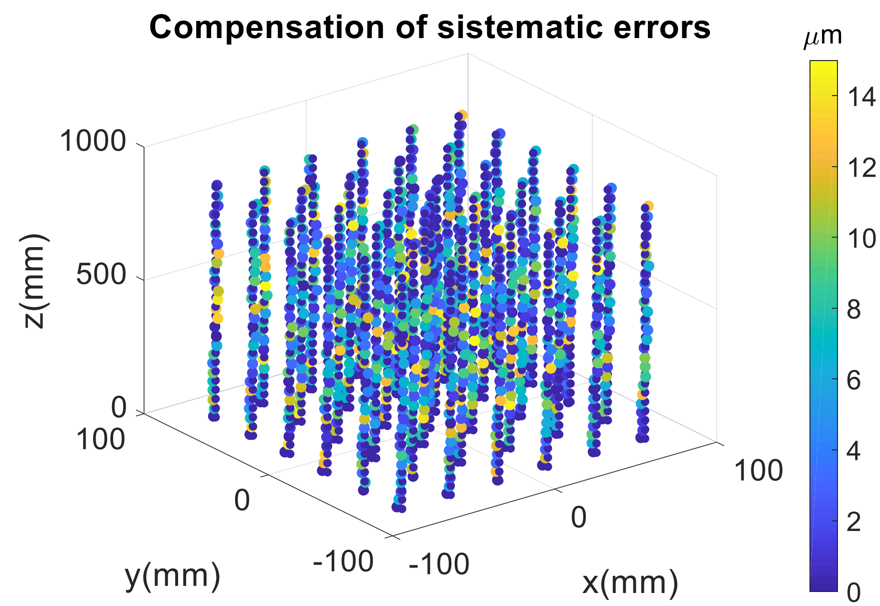
Positioning error

Verification of positioning accuracy with Laser tracker

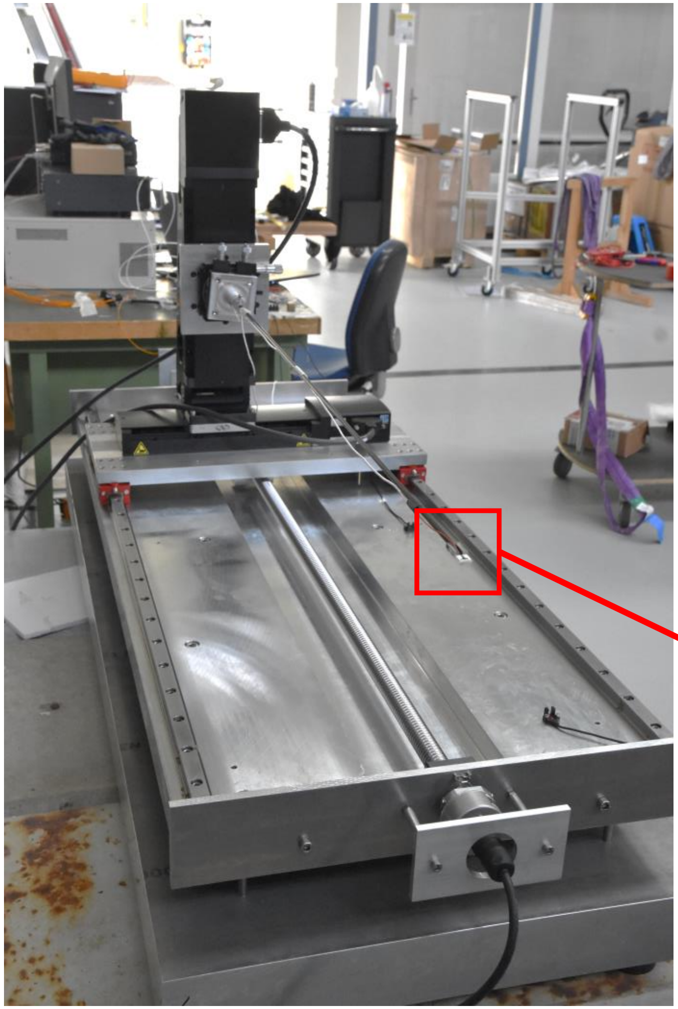
- Comparison of encoder readings and Laser measurements
- Correction of linear errors introduced by the ball screw
- Correction of systematic errors and implementation of error map in motion controller

$$\rightarrow U_{\text{position}} = \pm 40\ \mu\text{m} \quad (\text{coverage factor} = 3)$$

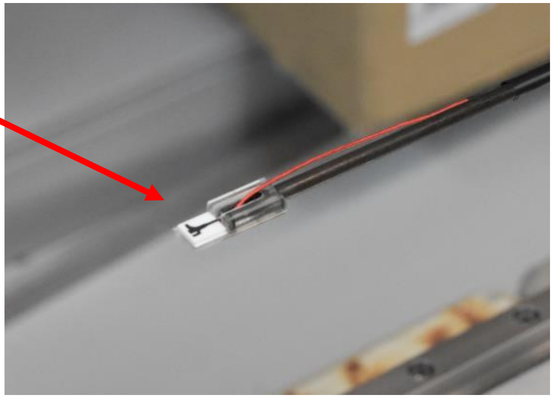




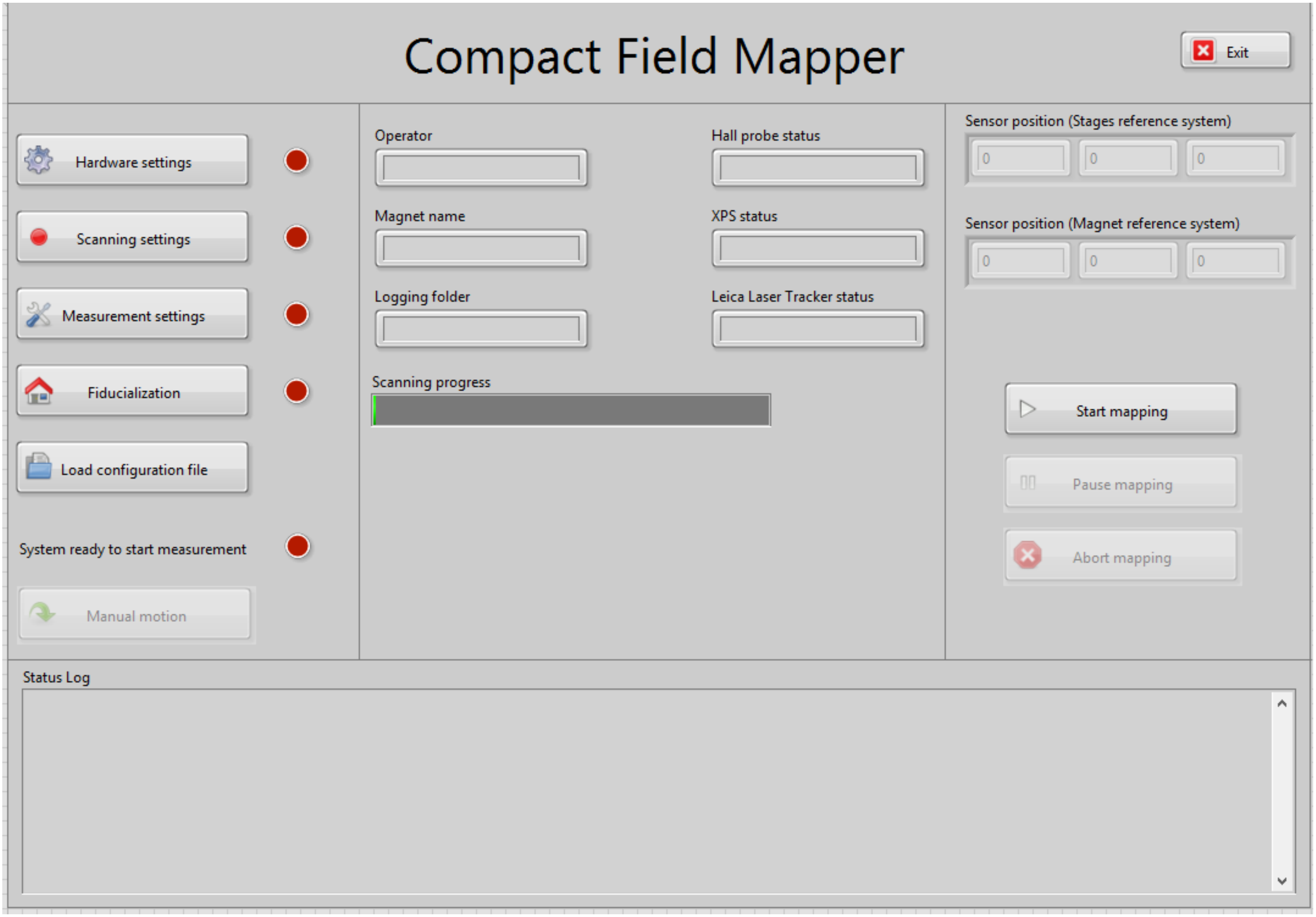
Hall probe specifications



SENIS 3-axis H3A	
Measurement range	±2T
Sensitivity	5V/T
Accuracy	±0.1% of B_{max}
Resolution	100μT
Offset	5mV (1mT)
Temperature sensitivity	±25ppm/°C
Planar Hall voltage	<0.05% of V_{normal}



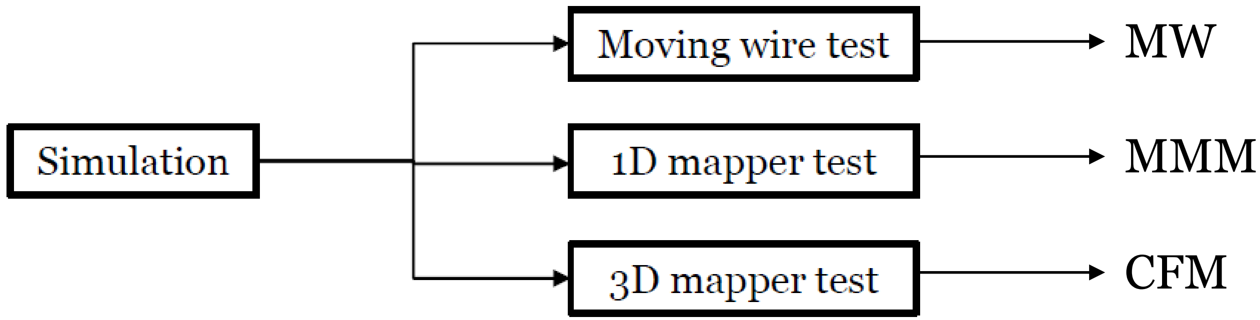
Software


Compact Field Mapper
Exit
Hardware settings
Scanning settings
Measurement settings
Fiducialization
Load configuration file
System ready to start measurement
Manual motion
Operator
Magnet name
Logging folder
Hall probe status
XPS status
Leica Laser Tracker status
Scanning progress
Sensor position (Stages reference system)
0
0
0
Sensor position (Magnet reference system)
0
0
0
Start mapping
Pause mapping
Abort mapping
Status Log

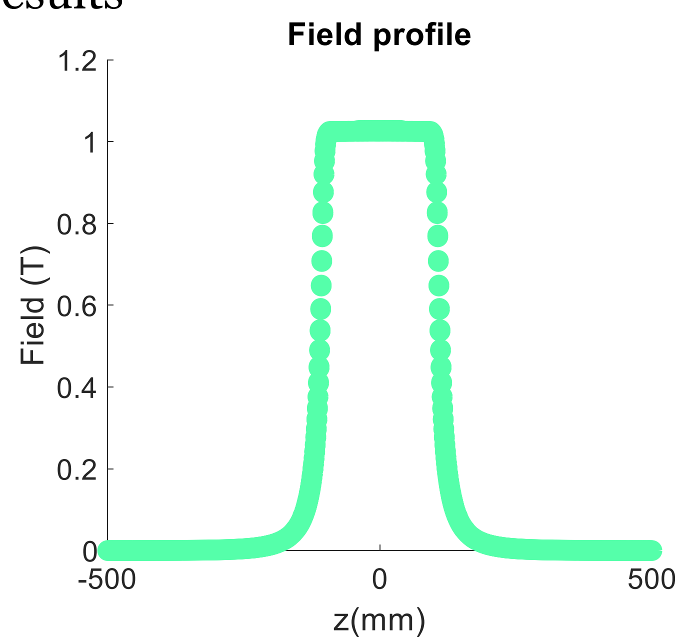
3.3 Measurements

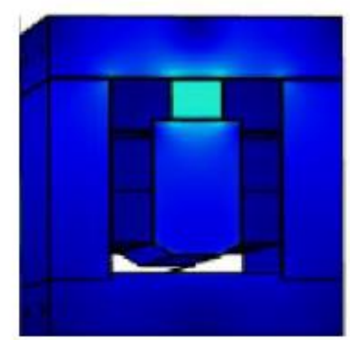
HD13-210 (Half dipole)

The first test is performed on a half dipole pre-prototype magnet (permanent magnet) reaching 1T along its axis

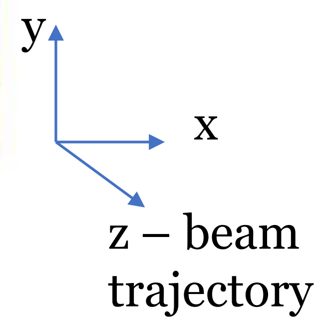


Simulation results



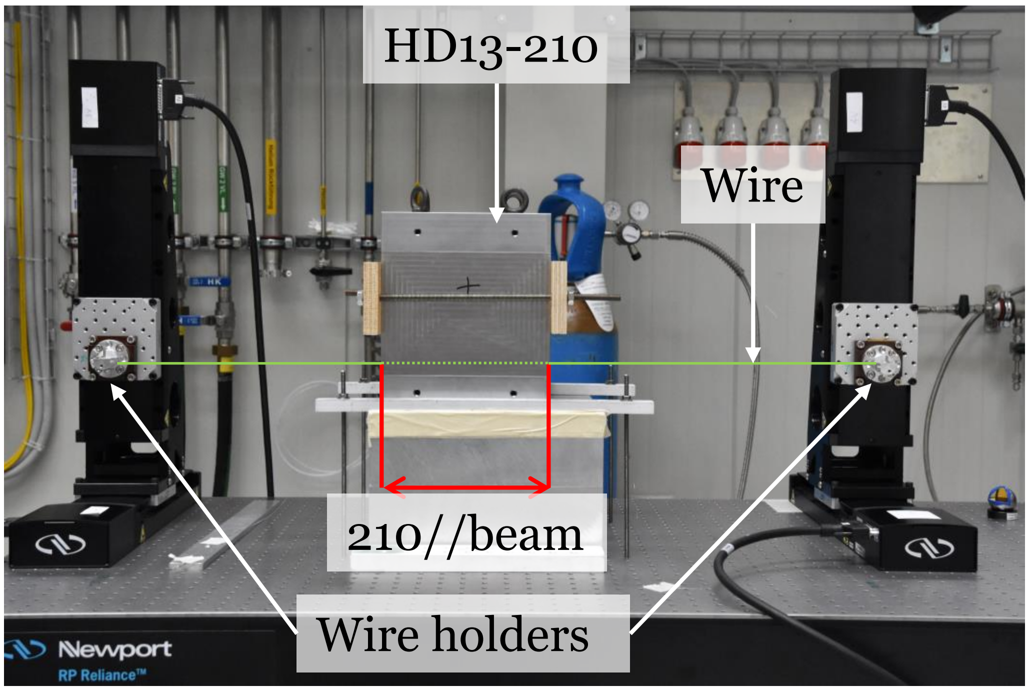


13 mm gap



Moving Wire measurements

Moving wire setup under construction – preliminary tests have been performed



Newport Linear stages

- Stroke = 200mm
- Positioning accuracy = 0.5μm
- Velocity = 28mm/s
- Orthogonality adjustment with Laser tracker

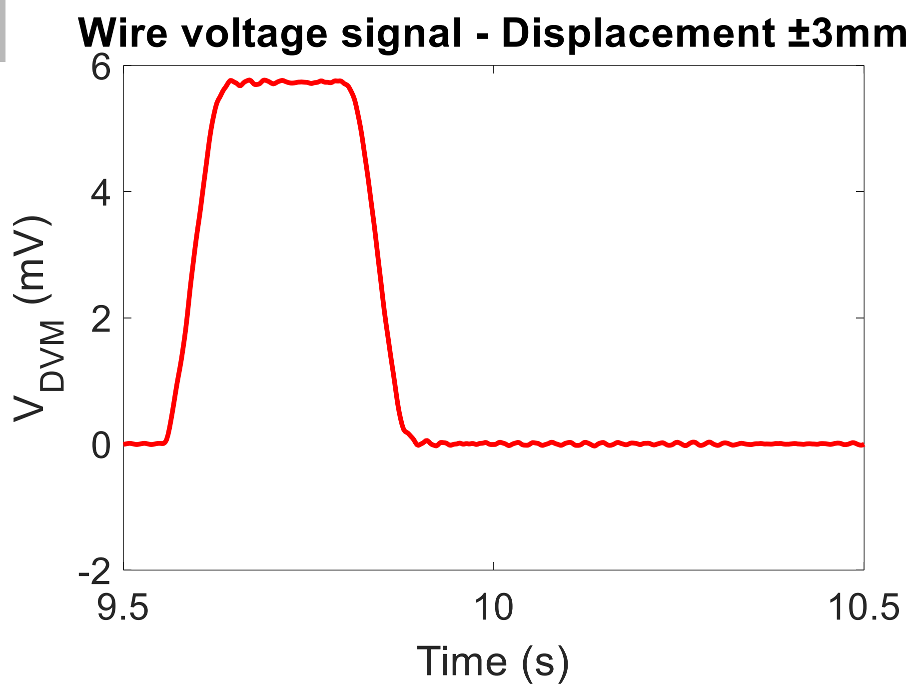
Wire diameter 125μm

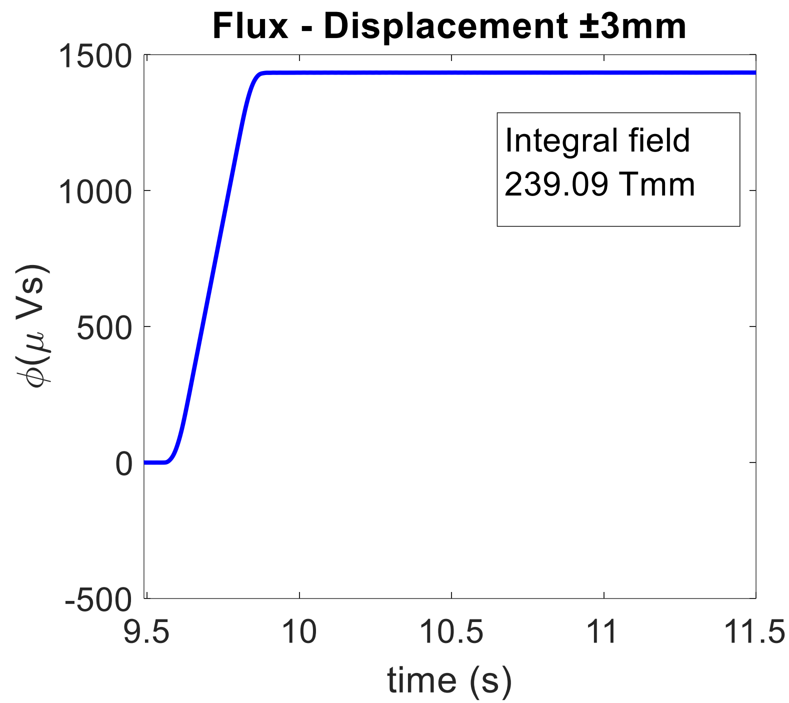
Acquisition by DVM

- Sampling frequency = 50 kHz
- Externally triggered by Newport controller

Moving Wire measurements

Measurements results: field integral measurement of HD13-210



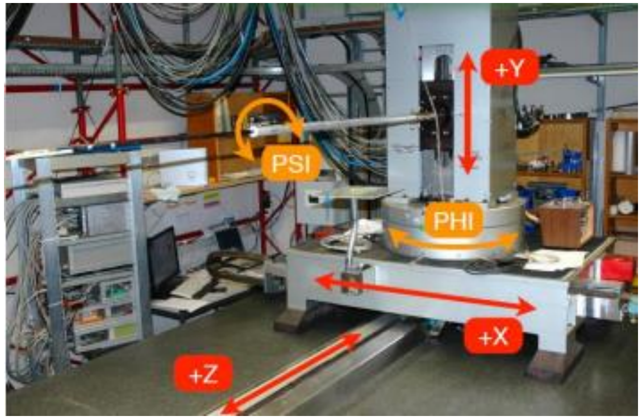


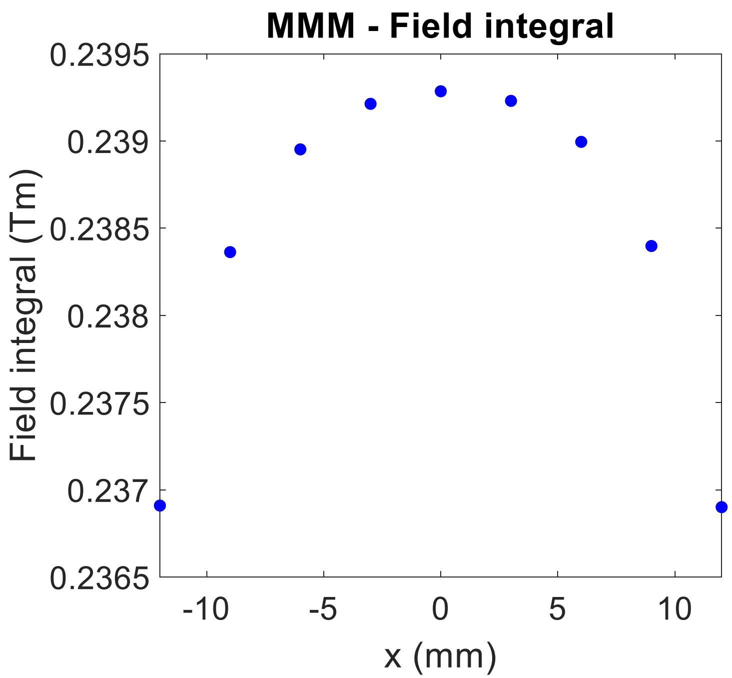
1-σ repetability - 1.5 units

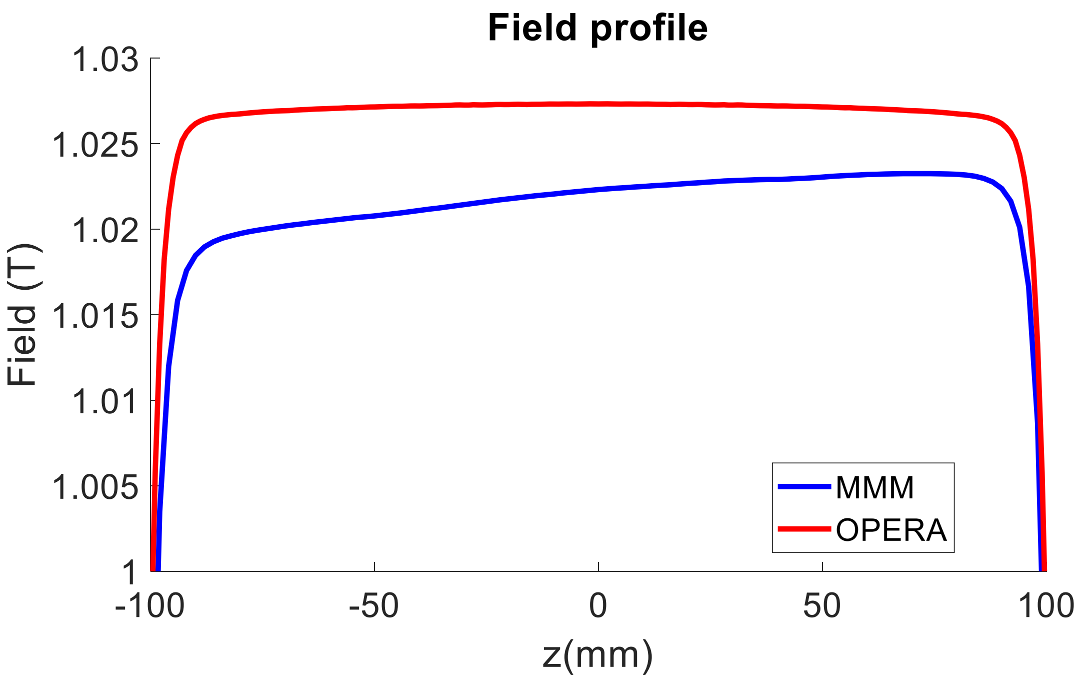
MMM - 1D Hall probe measurements

MMM setup

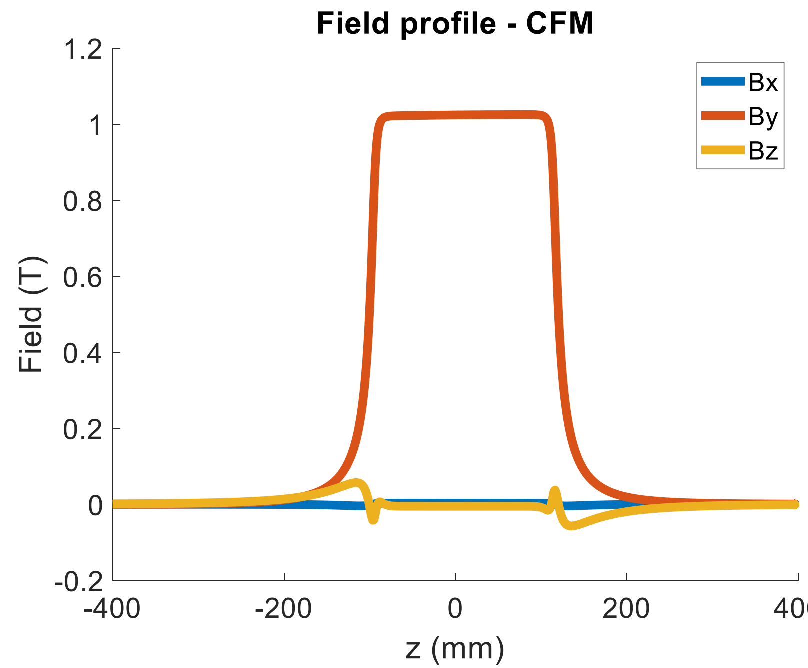
- 5 axis machine
- Air bearings
- Equipped with 1D Hall probe
- Long probe holder

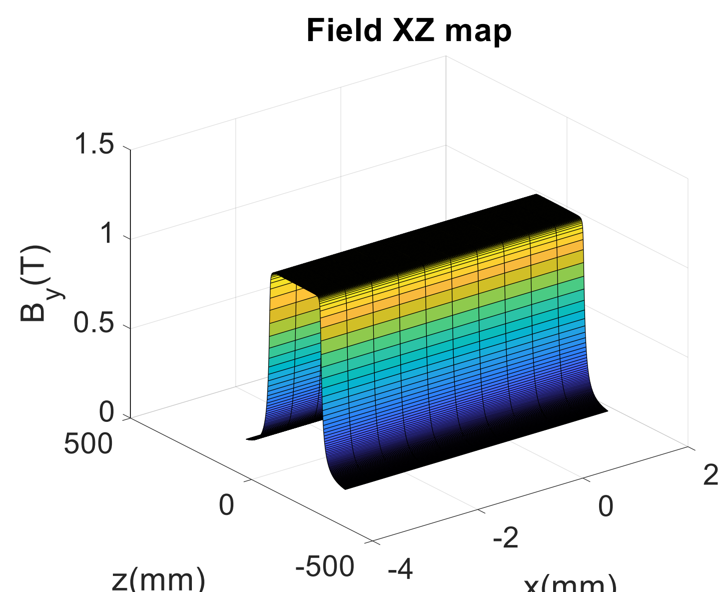






CFM - 3D Hall probe measurements

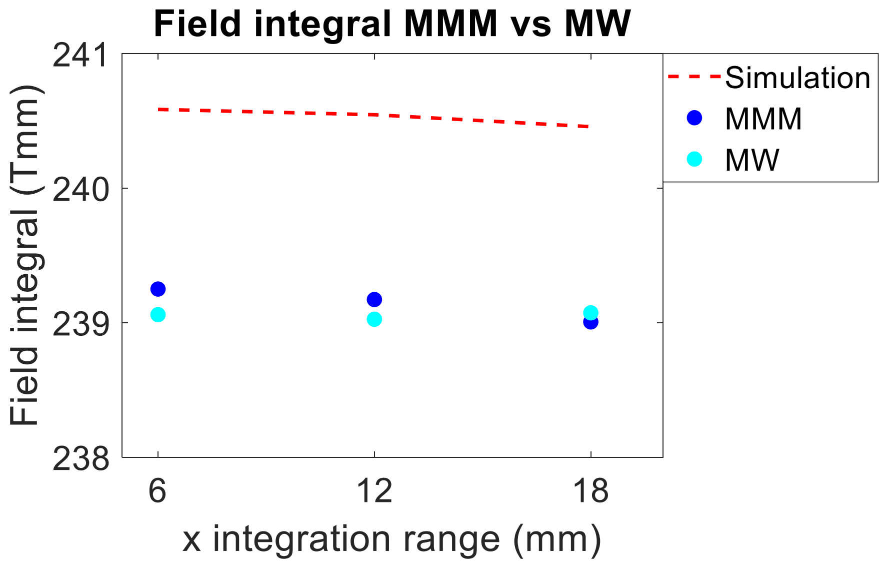




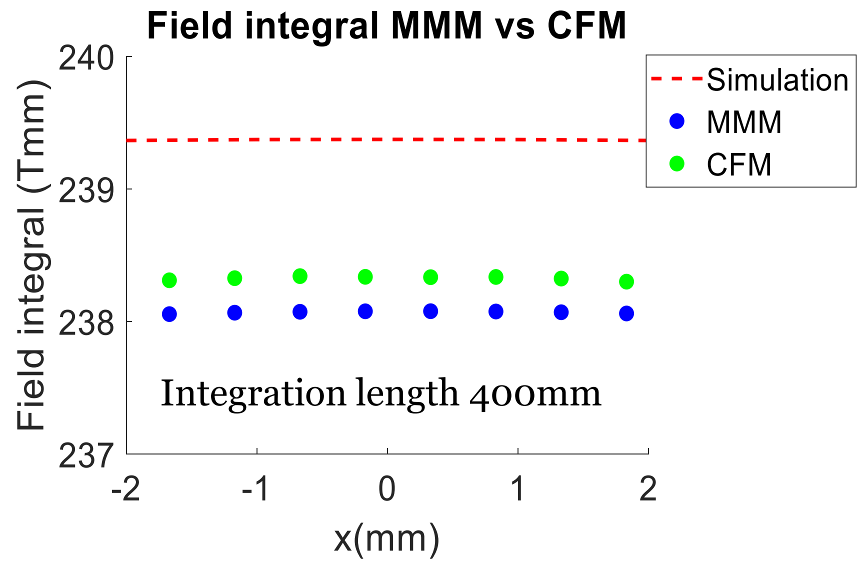
1-σ repetability = 2.5 units

(referred to measurement range $\pm$ 1T)

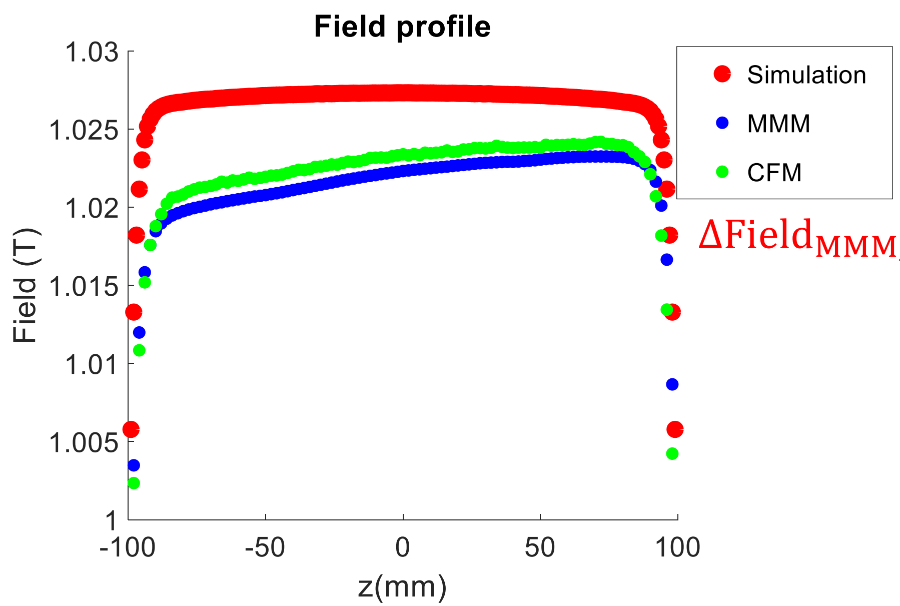
Measurements comparison



$\Delta \mathrm{Int}_{\mathrm{MMM,MW}} = 8\mathrm{units}$

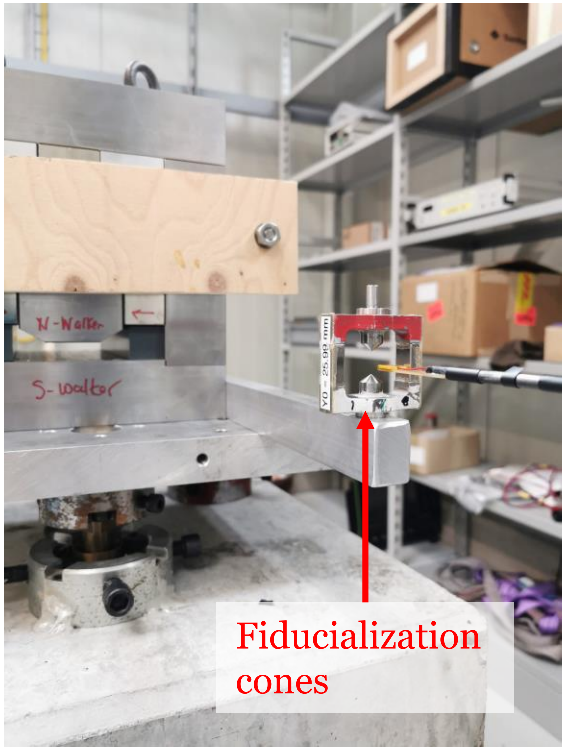


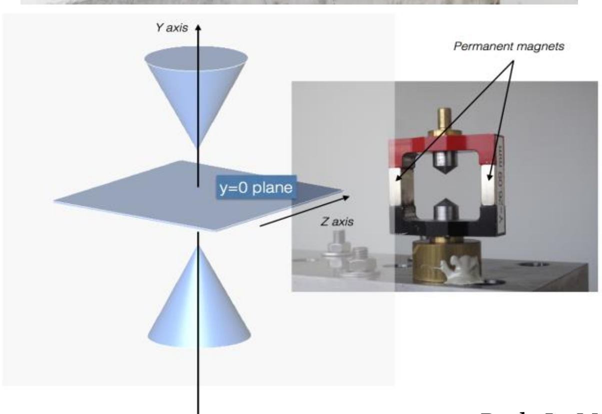
$\Delta \mathrm{Int}_{\mathrm{MMM,CFM}} = 11\mathrm{units}$

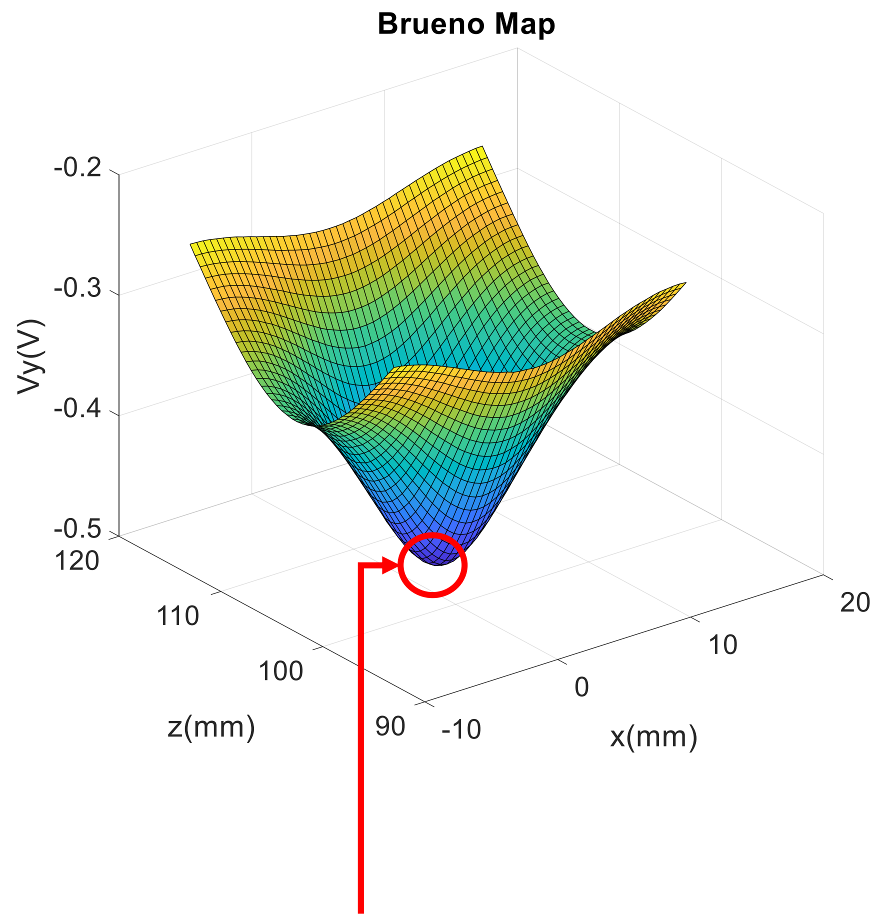


$\Delta \mathrm{Field}_{\mathrm{MMM,CFM}} = 12\mathrm{units}$

Fiducialization procedure



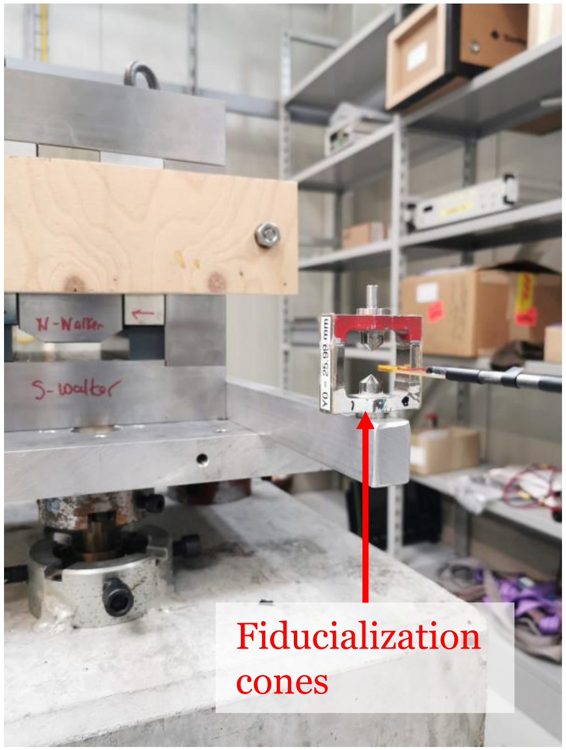


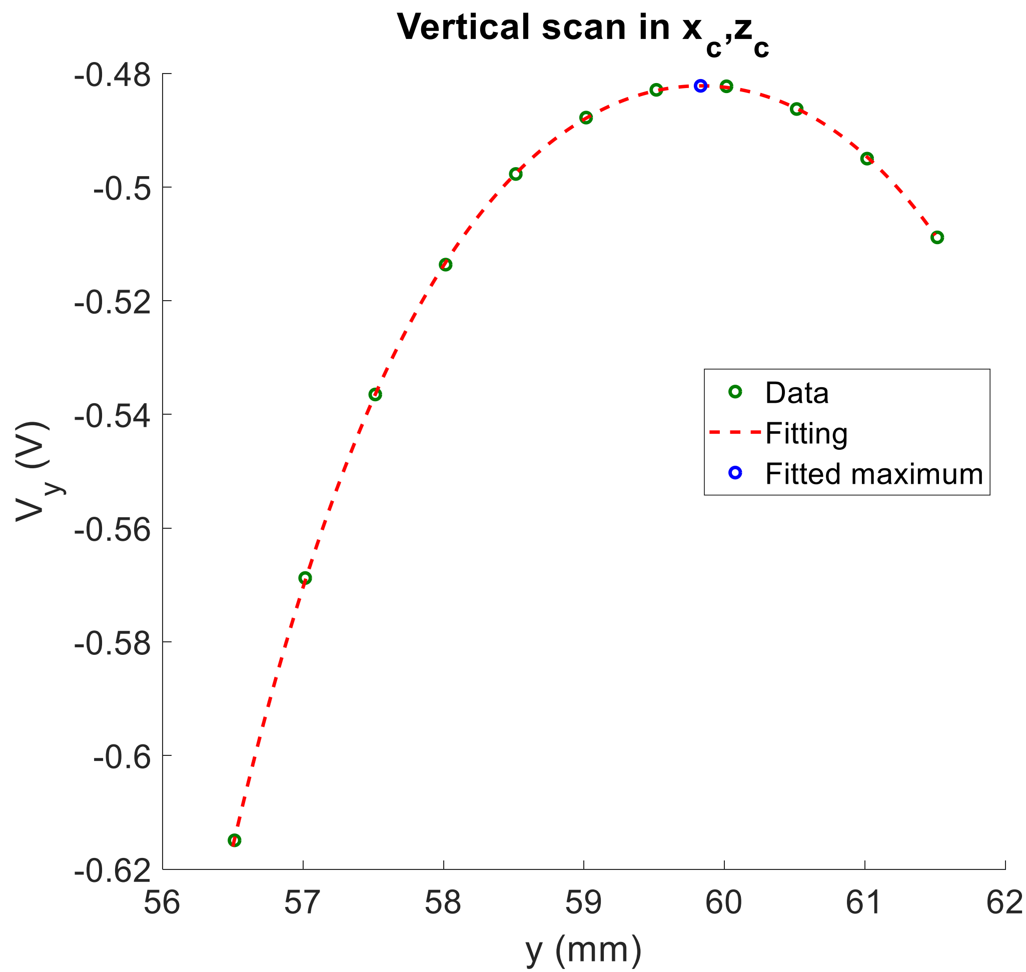


Field fitting around the minimum with quadratic function

$$f(x,y) = b_0 + b_1 x + b_2 x^2 + b_3 y + b_4 y^2 + b_5 xy$$

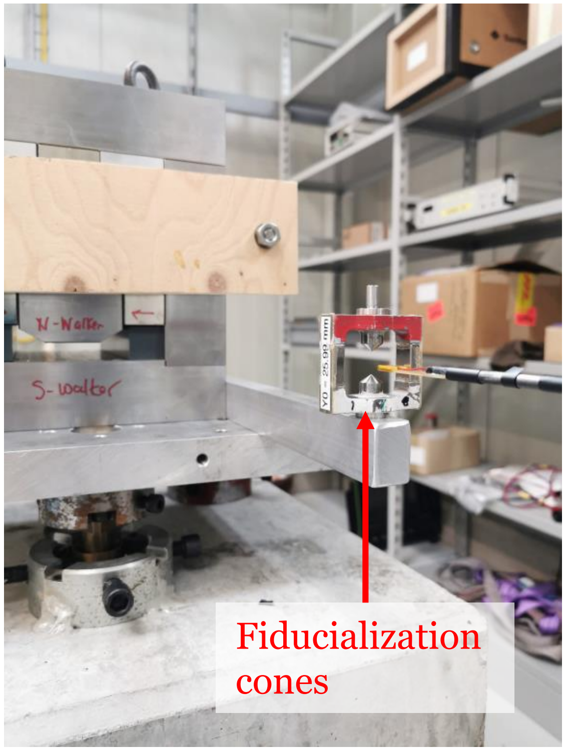
Fiducialization procedure

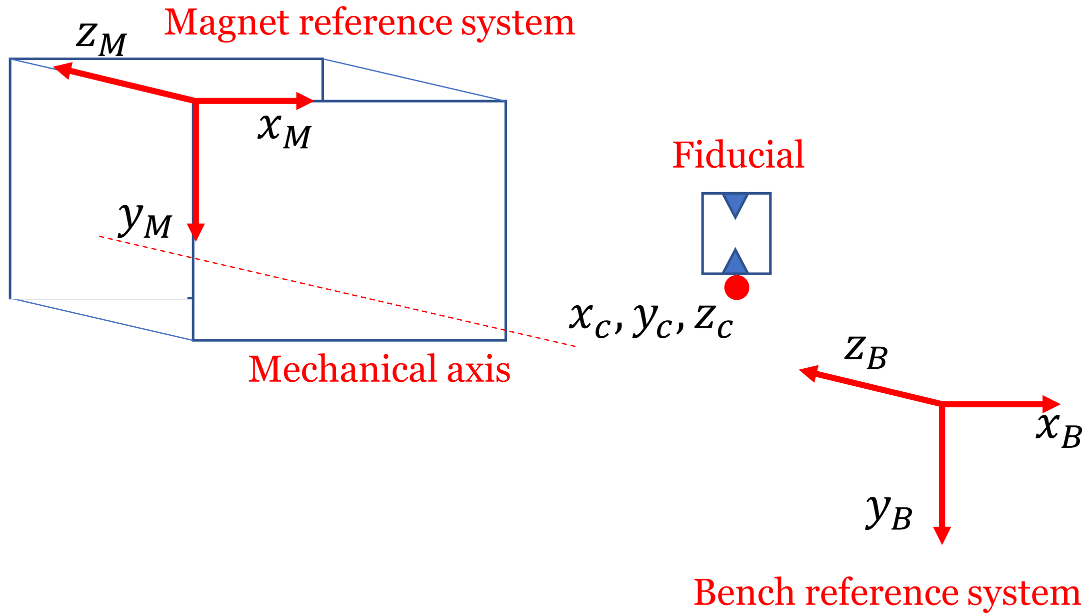




The cones position is also measured with the laser tracker

Fiducialization procedure





Coordinate transformation

$$x_{ax,B} = x_{ax,M} + \Delta x_{B,M}$$
$$y_{ax,B} = y_{ax,M} + \Delta y_{B,M}$$
$$z_{ax,B} = z_{ax,M} + \Delta z_{B,M}$$

Definition of bench – magnet offsets

$$\Delta x_{B,M} = x_{c,B} - x_{c,M}$$
$$\Delta y_{B,M} = y_{c,B} - y_{c,M}$$
$$\Delta z_{B,M} = z_{c,B} - z_{c,M}$$

4. Conclusions and future work

Conclusions and future work

- Uncertainty driven bench design
- Assembly and mechanical commissioning
- Measurement of LGB permanent magnet pre-prototype

Future work:

- Finalization of the measurement and control software
- Optimization of fiducialization procedure
- Investigation on vibration and temperature effects
- Test of prototype permanent magnets
- Probe geometrical characterization and calibration to measure higher fields (>4T)

Thank you for your attention!

Many thanks to Prof. Marco Tarabini from Politecnico di Milano and
PSI Magnet Section, in particular to S. Sanfilippo, Ph. Lerch, A. Gabard, G. Montenero,
C. Calzolaio, C. Zoller and M. Calvi (ID group)

Backup slides

Bench control and data acquisition

Measurement bench

Motion control

Linear stages controllers

Encoders

Limit and home sensors

Temperature

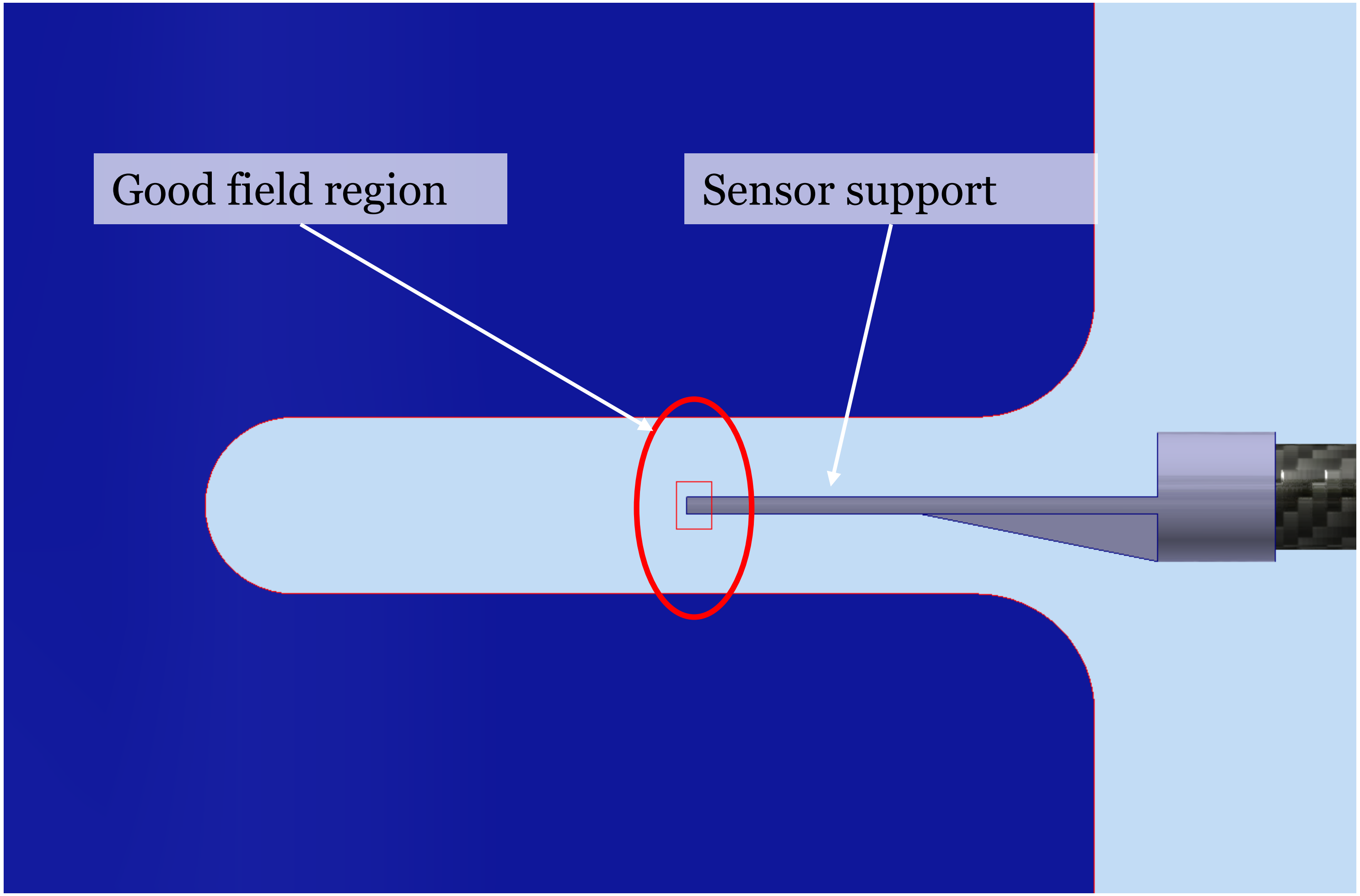
Magnetic measurement

Hall probe electronics

DAQ

Field maps

Motion system



Positioning accuracy and resolution

Field maps x, y, z, B_x, B_y, B_z by FEM

Positioning accuracy

Simulation of positioning error on x, y, z

Estimation of the magnetic field by linear interpolation in **mis-placed mesh nodes**

Calculation of the error as

$$E = \frac{\Delta B}{B_{\mathrm{nom}}}\% = \frac{B_{\mathrm{meas}} - B_{\mathrm{nom}}}{B_{\mathrm{nom}}}\%$$

Maximum error E—› **maximum** admissible positioning error

Positioning resolution

Mesh points iterative reduction

Estimation of magnetic field by linear interpolation in **removed nodes**

Calculation of the error as

$$E = \frac{\Delta B}{B_{\mathrm{nom}}}\% = \frac{B_{\mathrm{meas}} - B_{\mathrm{nom}}}{B_{\mathrm{nom}}}\%$$

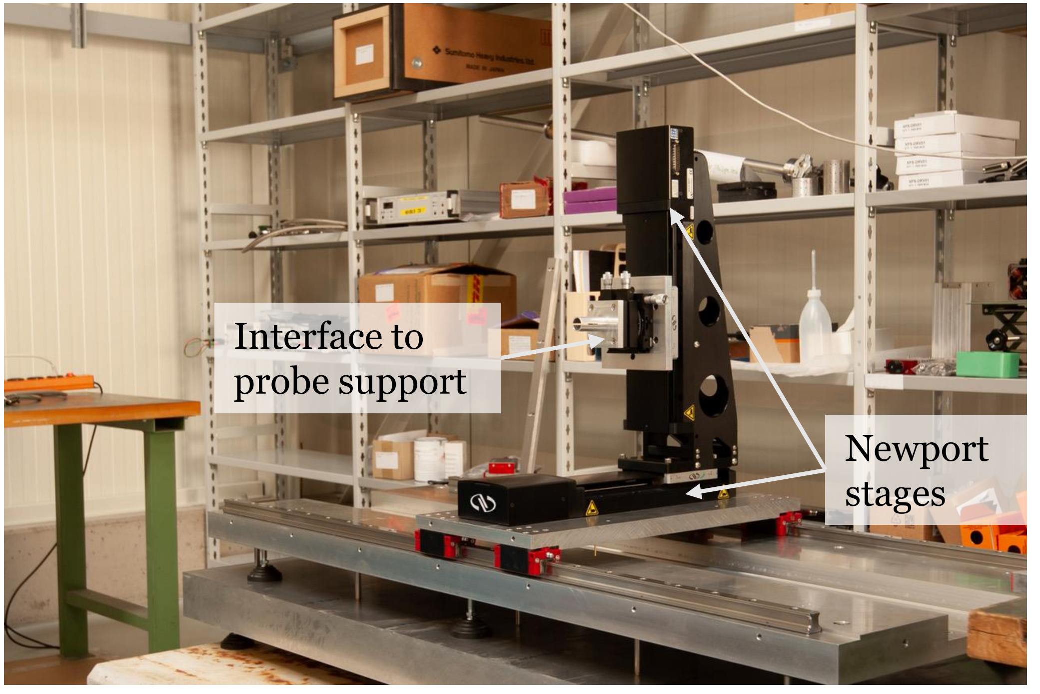
Maximum error E—› **minimum** number of mesh points

Superconducting magnet results

Positioning accuracy U_p ±200 μm

Positioning resolution 500 μm

Mechanical assembly



Vertical stage double mounting

→ Arm parallel to x-axis

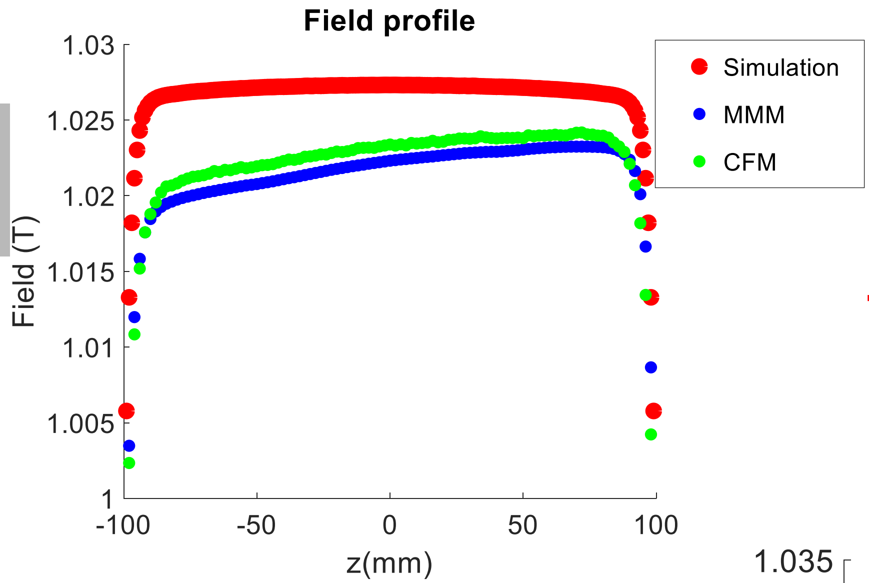
→ Arm parallel to z-axis

Verification of the orthogonality with Laser tracker

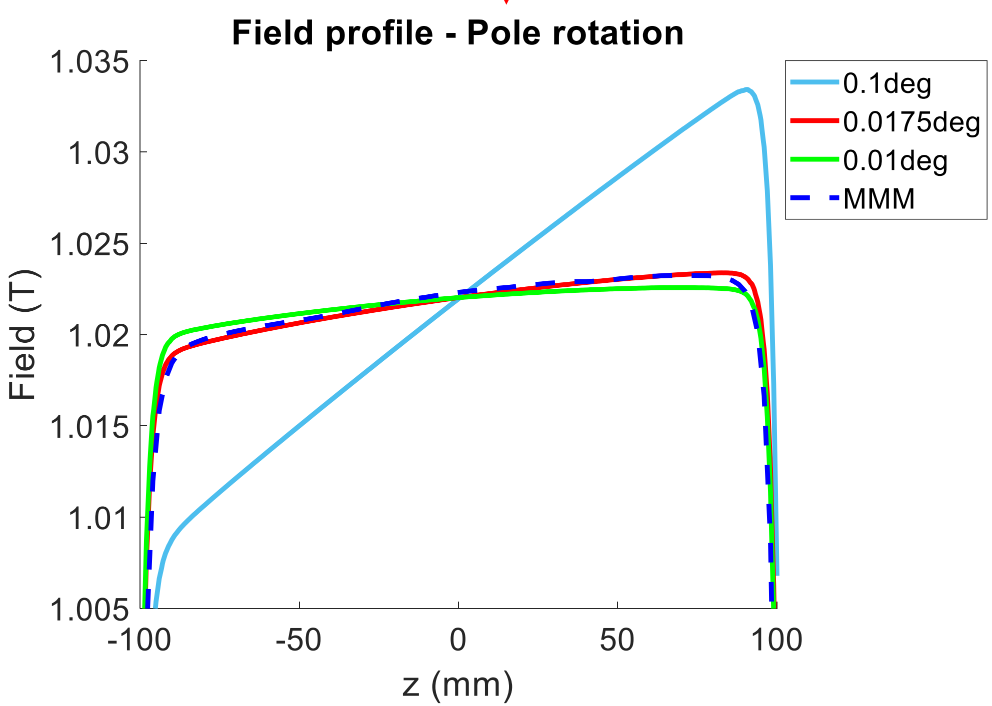
	Δx (μm)	Δy (μm)	Δz (μm)
X-axis	-	15	30
Y-axis	10	-	15
Z-axis	30	35	-

Longer stroke

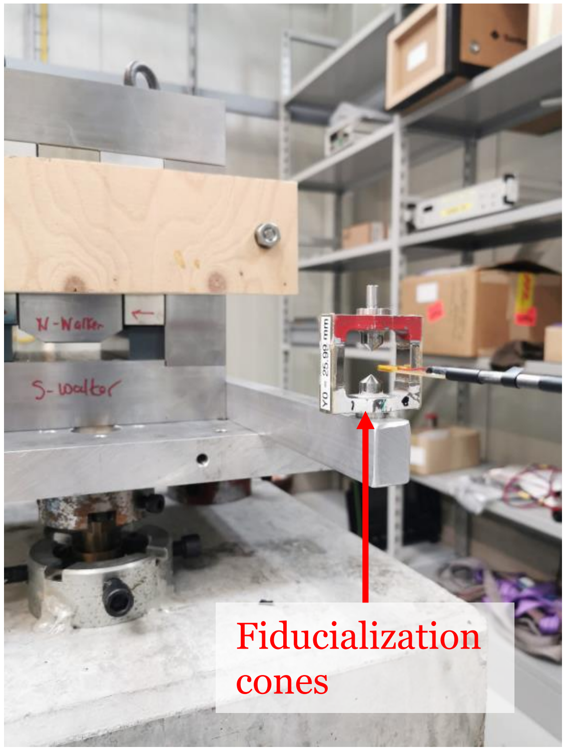
HD13-210 – Field profile

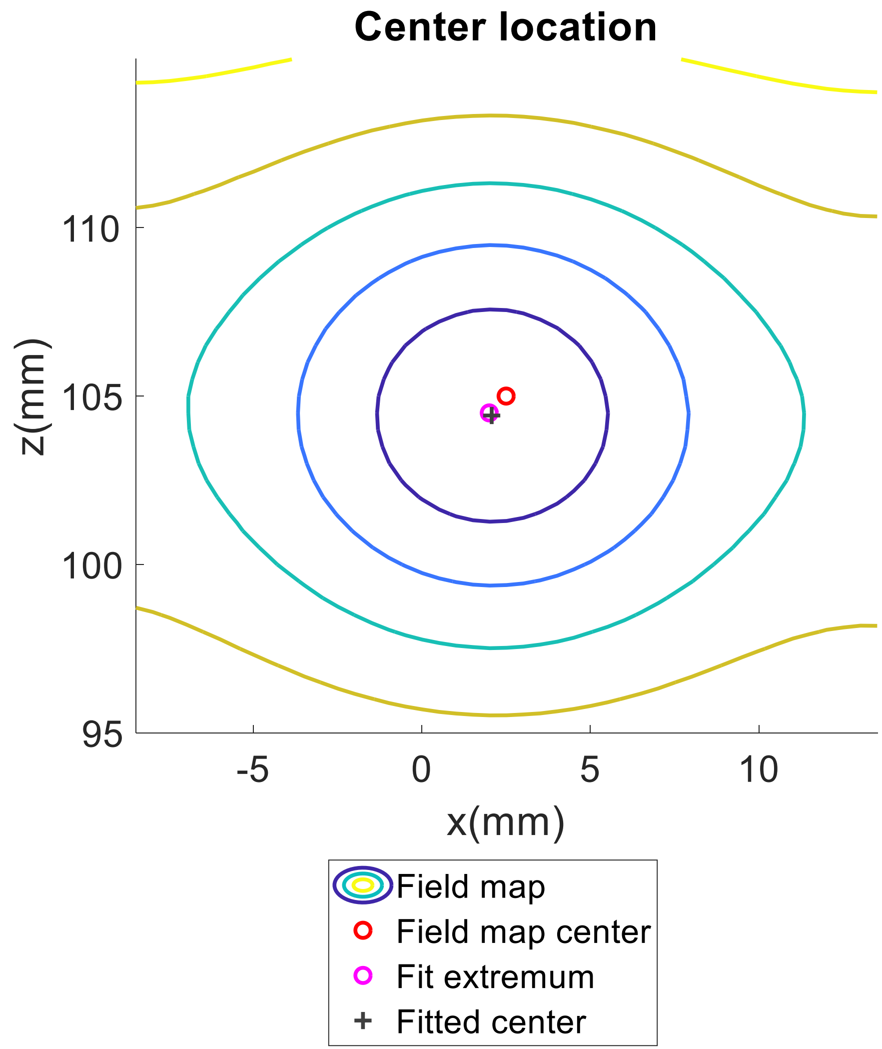


COMSOL Simulation of rotation of the pole around x-axis



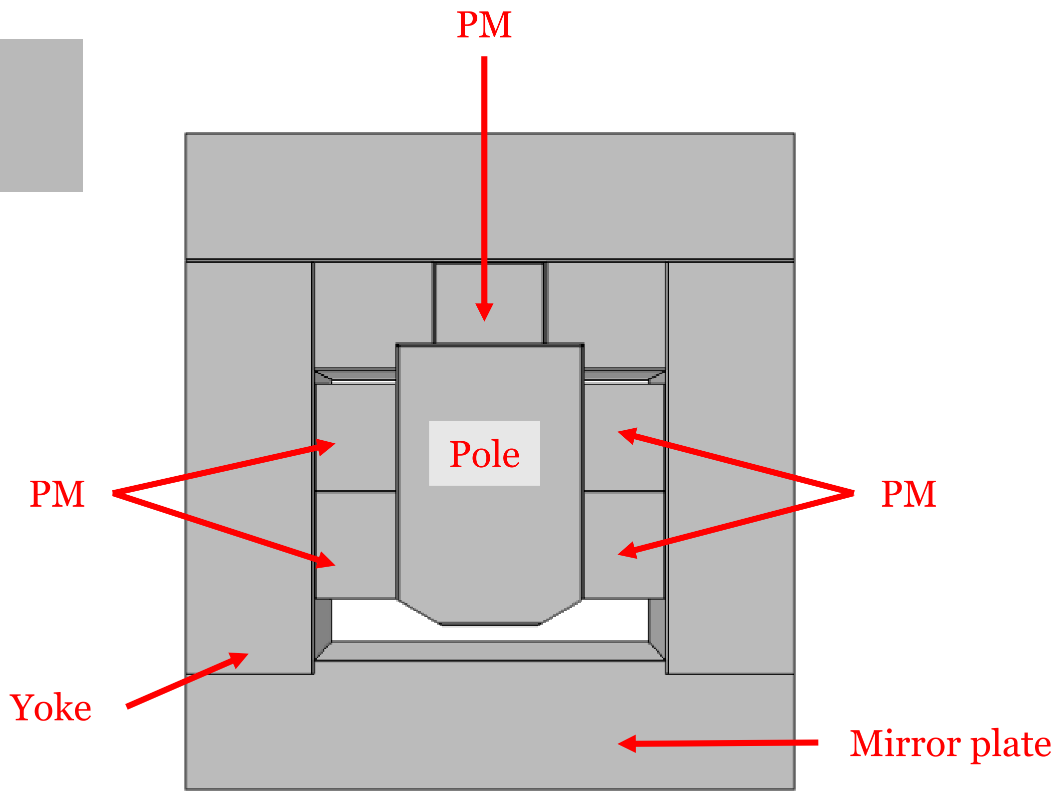
Fiducialization procedure





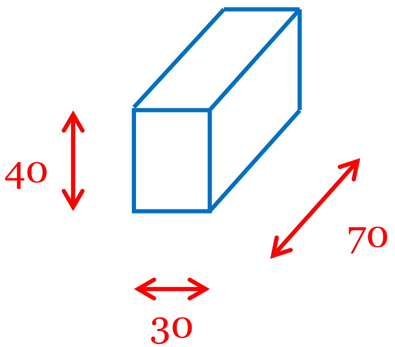
Probe positioned in x_c, z_c to find y_c - In bench reference system!

HD13-210



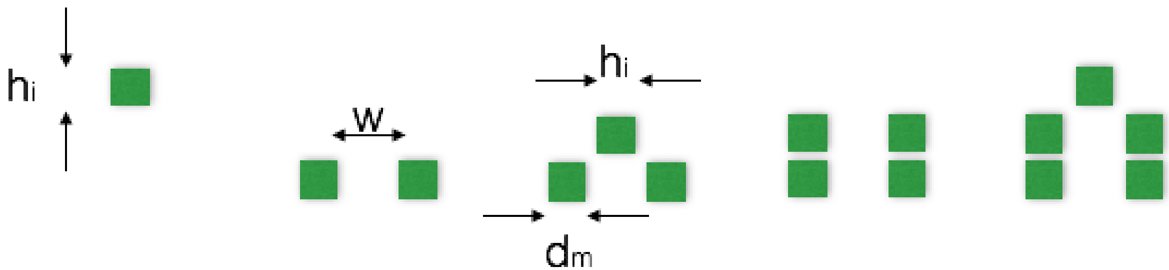
13 mm gap

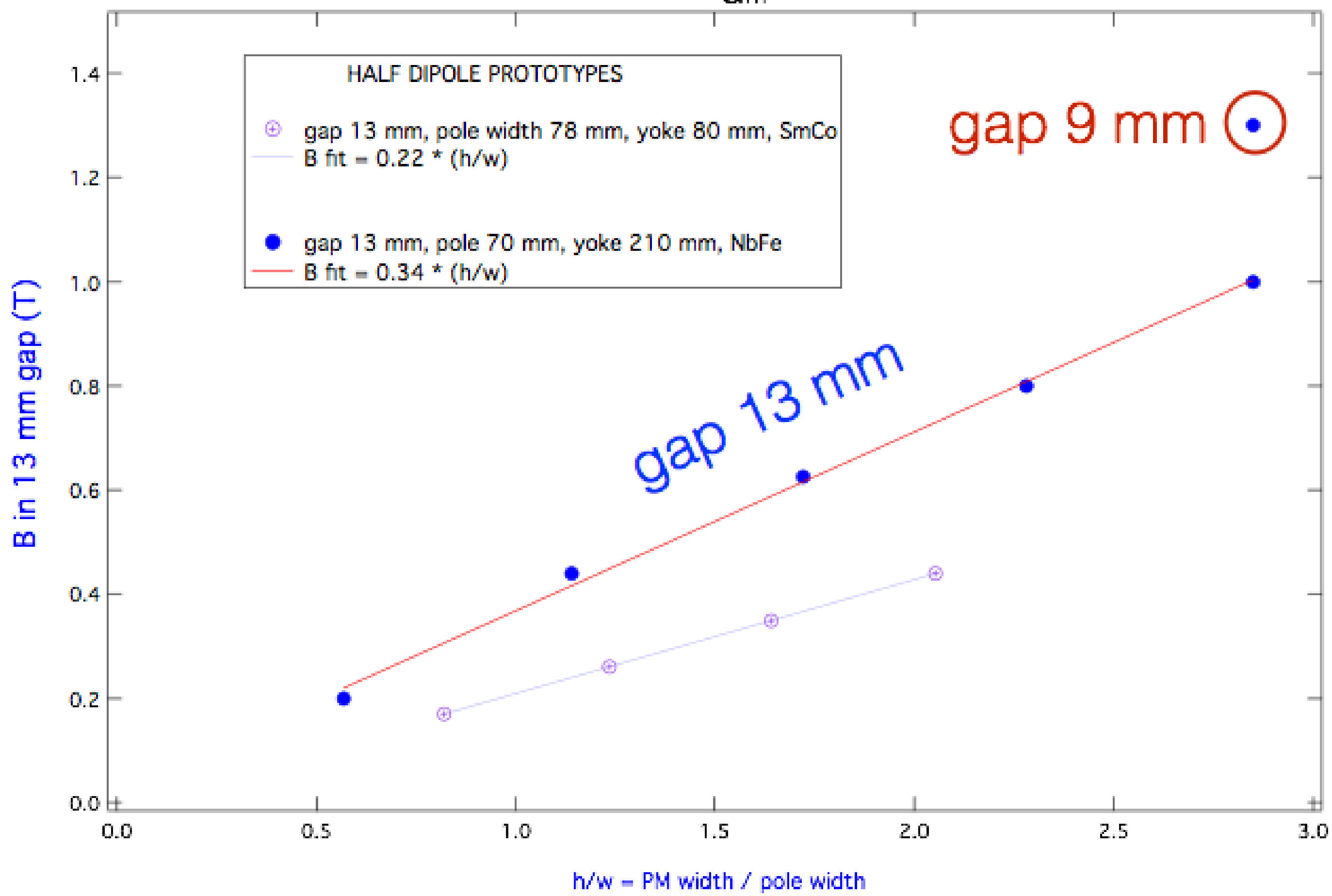
PM block - NdFeB



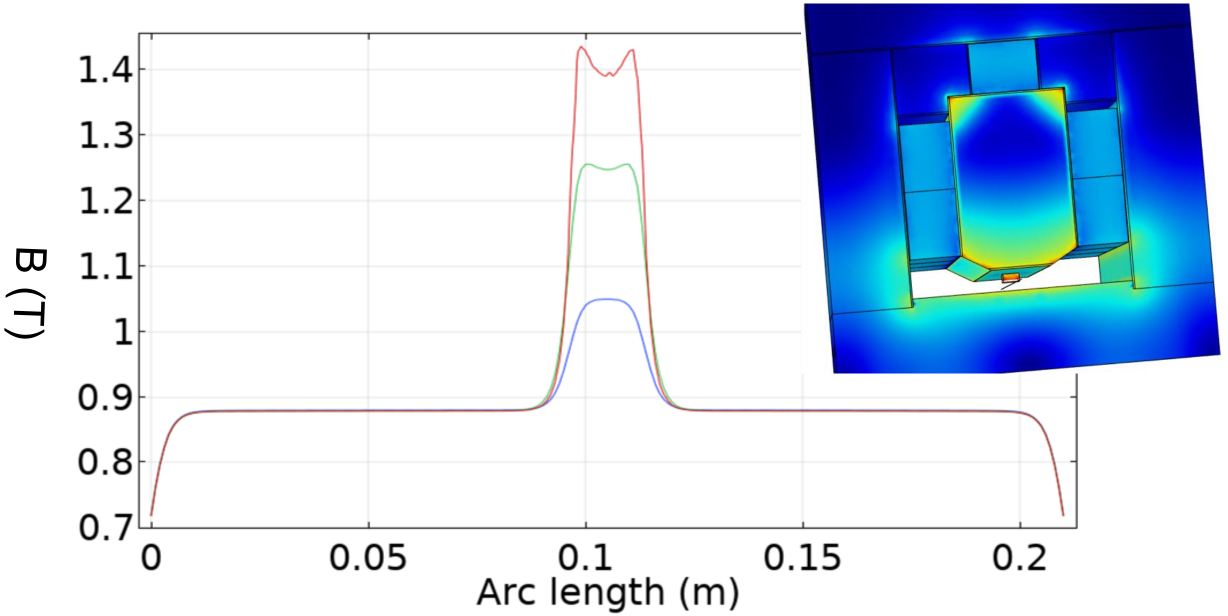
$B_r = 1.26\text{T}$

Geometrical optimization HD





Fe plate insertion in HD13_210



t_p=5.0 mm

t_p=3.5 mm

t_p=2.0 mm