IMMW20
International Magnetic Measurement Workshop

A Laser-Compass Magnet Probe for Field Measurements in Solenoids

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Outline

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- ✓ Motivation
- ✓ Laser-Compass principle
- ✓ Bench setup
- ✓ Error sources
- ✓ Calibration & Alignment
- ✓ Outlook
- ✓ Conclusions

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Motivation

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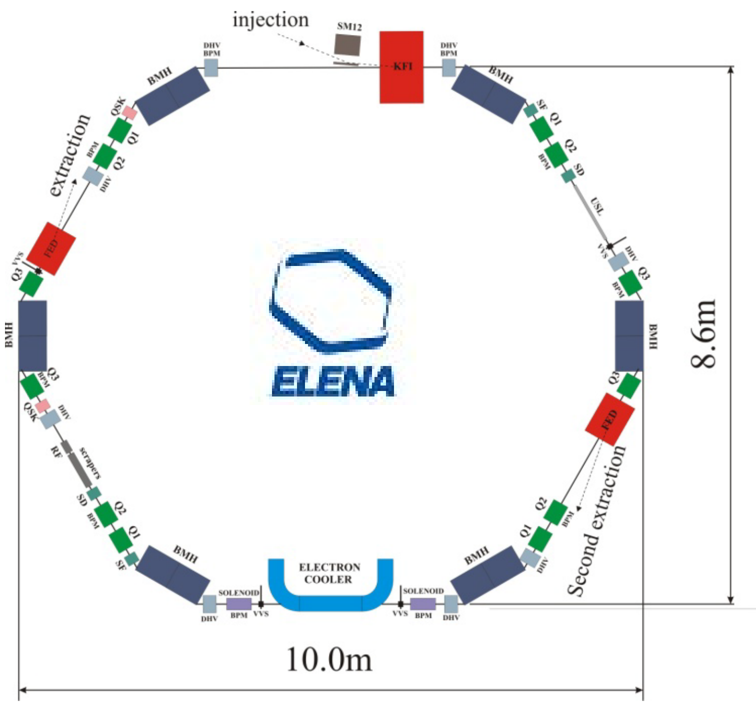
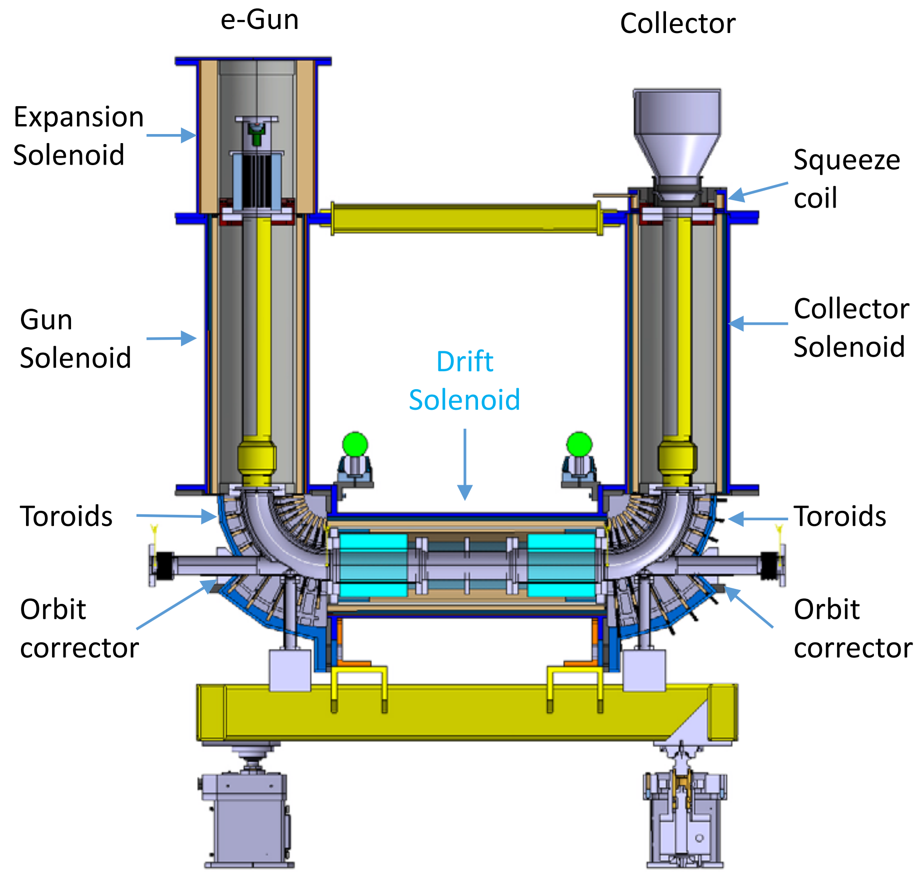
ELENA (Extra Low Energy Antiprotons) is a 30 m circumference ring for cooling and deceleration of 5.3 MeV antiprotons delivered by the CERN Antiproton Decelerator (AD) down to 100 keV, where the physics programme consists of trapping antiprotons to create anti-hydrogen atoms after recombination with positrons.





Electron cooling is essential in order to obtain the small emittance beams needed for deceleration and extraction to the experiments.

Motivation

The transverse component of the magnetic field in the drift solenoid must be kept small to ensure a minimal perturbation to the electron beam transverse temperature.

Parameter	Value	Unit
Nominal field B_z	100	Gauss
Aperture diameter	260	mm
Solenoid length	1000	mm
GFR diameter	60	mm
GFR length	650	mm
Field straightness (B⊥/B//)	$<5\cdot10^{-4}$	

ELENA ecool Solenoid V4 (T. Zickler)
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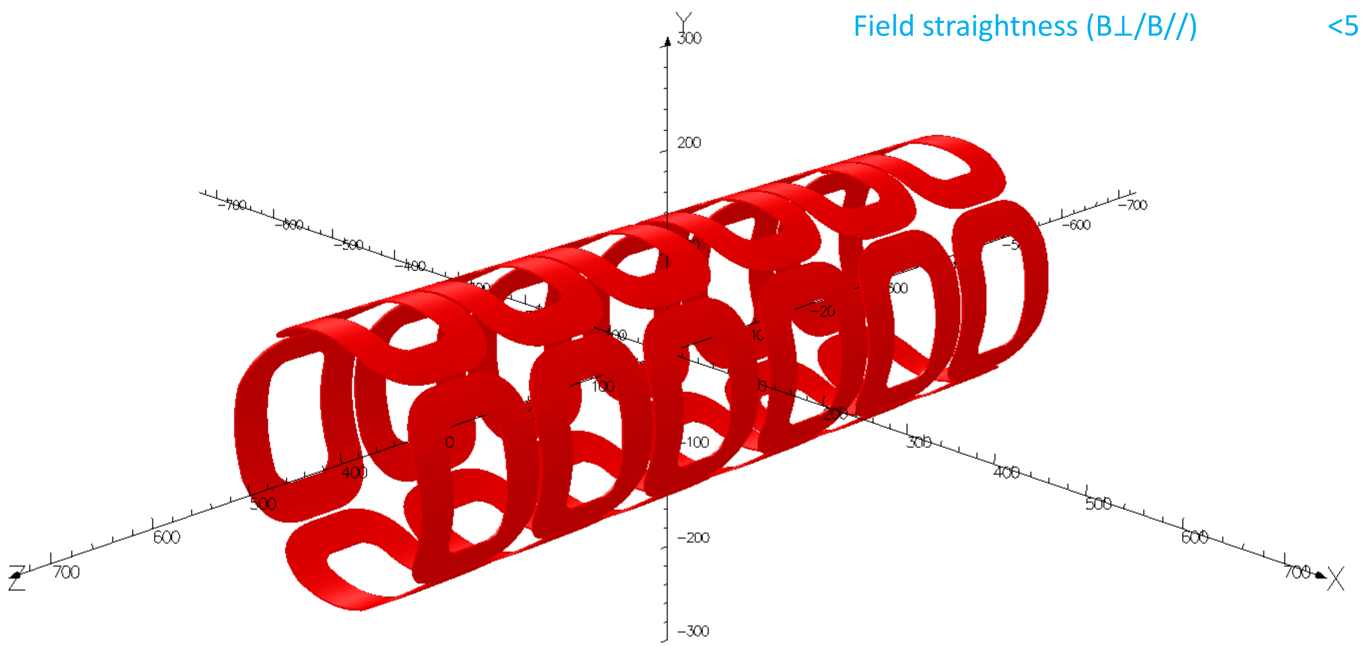


Requires precise magnetic measurements of the field straightness to characterize the solenoid and to define a correction scheme!

opera simulation software

Motivation

Measurement challenge: measuring very low levels of transverse field (0.05 Gauss) in the presence of a very strong axial field (100 Gauss) and the earth magnetic field (~0.5 Gauss)

"Classical" measurement techniques:

Hall probe (mapping):

Main sources of systematic errors:

- Transverse hall effect: can be cancelled out by taking measurements with both field directions
- Hall plate misalignment: can be reduced through calibration procedure; see:

A. Wolf, L. Hütten, H. Poth, *Magnetic Field Measurements in the Electron Cooling Device for LEAR*, CERN Int. Report 84-01, CERN, 1984

Vibrating wire:

Limited experience; see:

A. Jain, *Plans for Measurement of Field Straightness in the Solenoids for the Electron Lens System for RHIC*, IMMW17, Barcelona, Spain, 2011

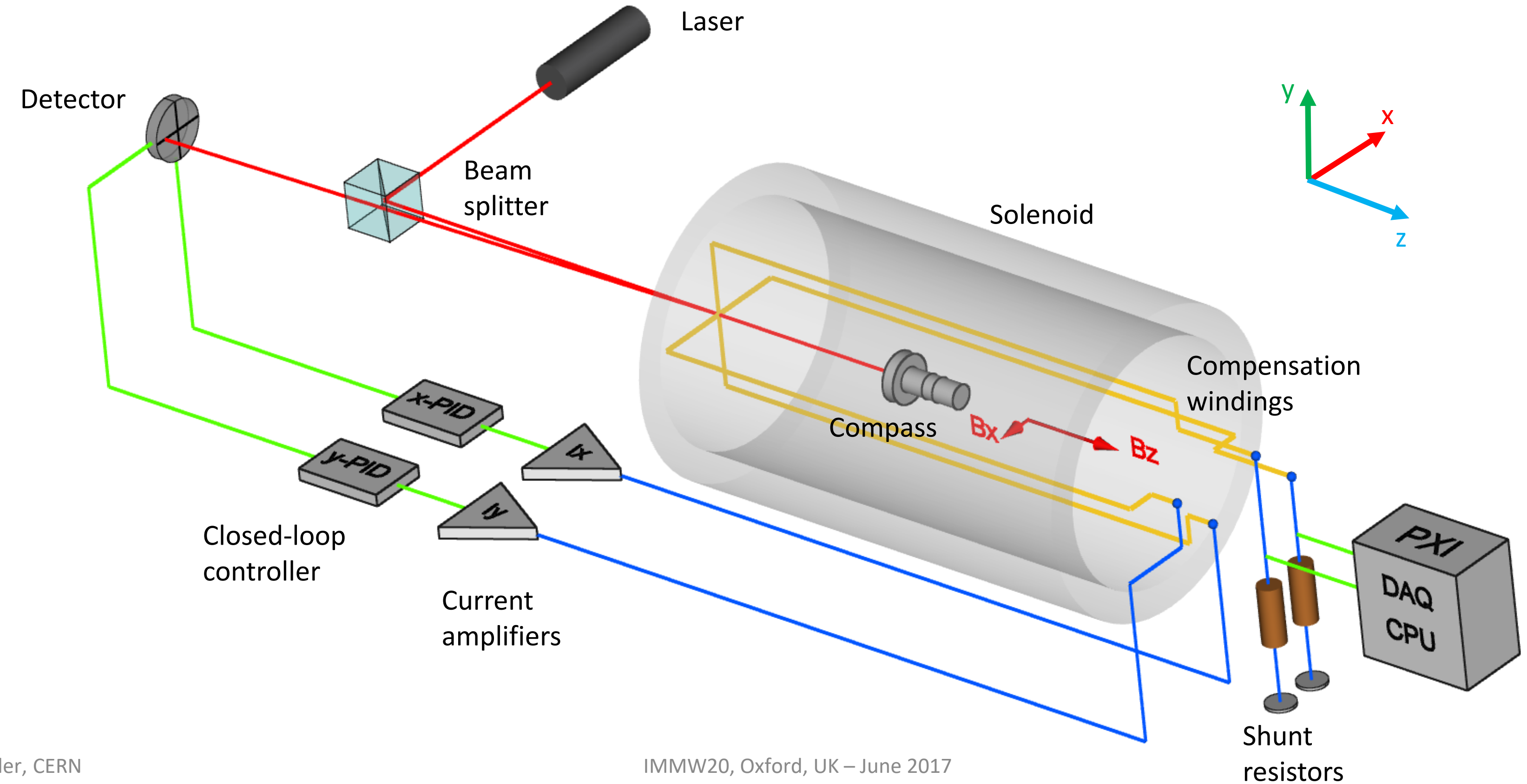
A. Jain, *Field Straightness Measurements in Electron Lens Solenoids for RHIC*, IMMW19, Hsinchu, Taiwan, 2015

CERN needs to develop a new dedicated measurement bench for Solenoids…

Laser-Compass Principle

Based on systems used at FNAL, BINP & BNL:

- C. Crawford et al., *Magnetic Field Alignment in the Beam-Beam Compensation Device*, Proc. PAC'99, p. 3221-3223
- V. V. Parkhomchuk et al., *Precision Measurement and Compensation for the Transverse Components of the Solenoids' Magnetic Field*, Instruments and Experimental Techniques, Vol. 48, No. 6, 2005, p.772-779
- A. Jain, *Field Straightness Measurements in Electron Lens Solenoids for RHIC*, IMMW19, Hsinchu, Taiwan, 2015



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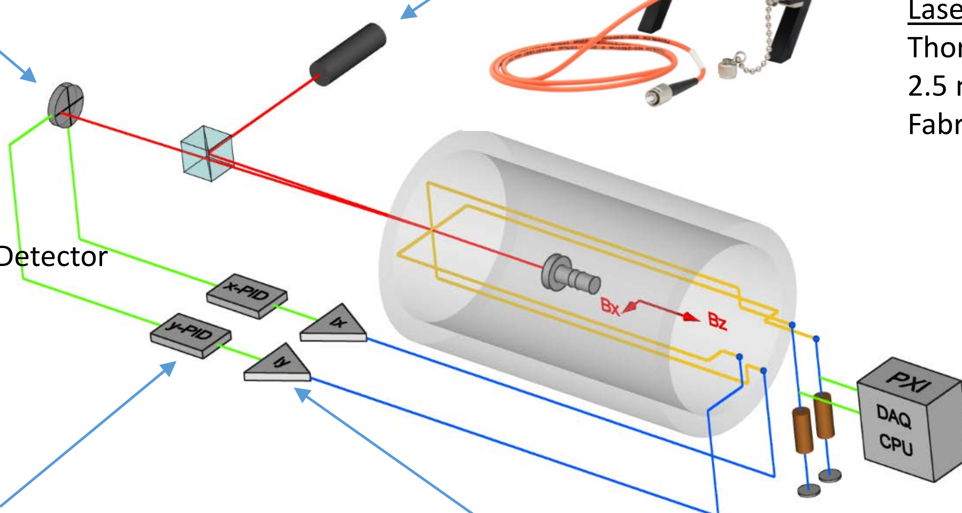
Bench Setup

Detector:
Thorlabs PDP90A
2D Lateral Effect Position Sensing Detector
0.75 µm resolution
9 mm x 9 mm active area

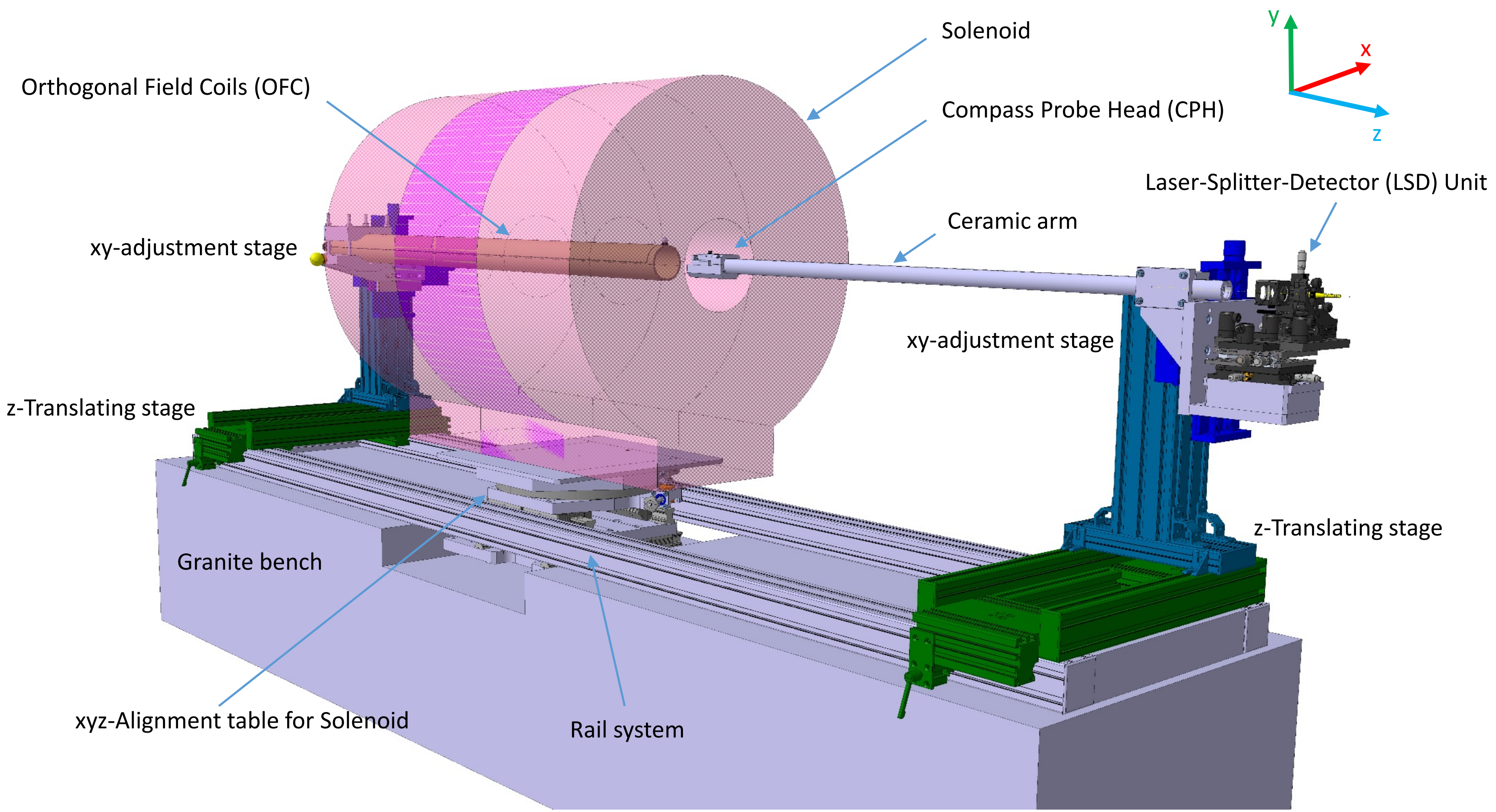
Laser:
Thorlabs S1FC635
2.5 mW, 635 nm Single-Mode
Fabry Perot Laser



Controller:
Thorlabs TPA101
2-axis (x/y) Closed-loop PID controller
± 10 V analogue output (2 ch + sum)
USB interface with GUI
Compatible with C++/LabView IDEs

Current amplifiers:
Kepco BOP 36-12M-802E
400 W, ± 12 A, ± 36 V
Voltage controlled

Bench Setup



Solenoid
Orthogonal Field Coils (OFC)
Compass Probe Head (CPH)
y
x
z
Laser-Splitter-Detector (LSD) Unit
Ceramic arm
xy-adjustment stage
xy-adjustment stage
z-Translating stage
z-Translating stage
Granite bench
xyz-Alignment table for Solenoid
Rail system

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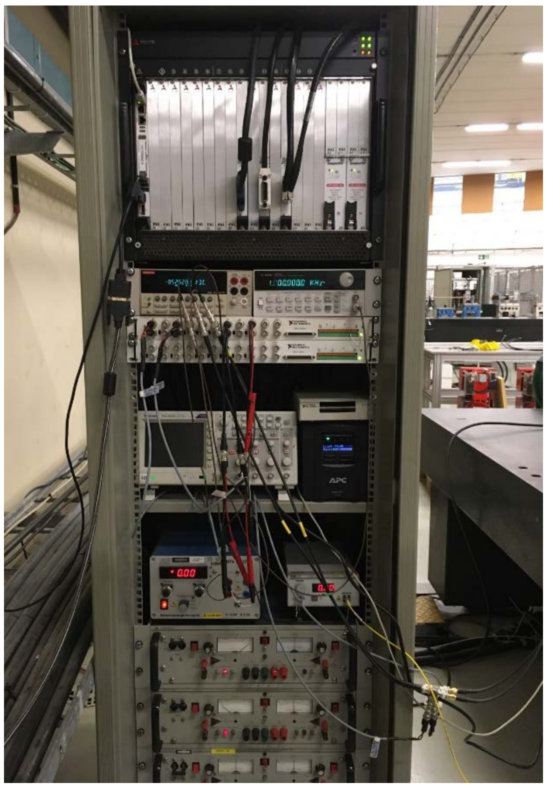
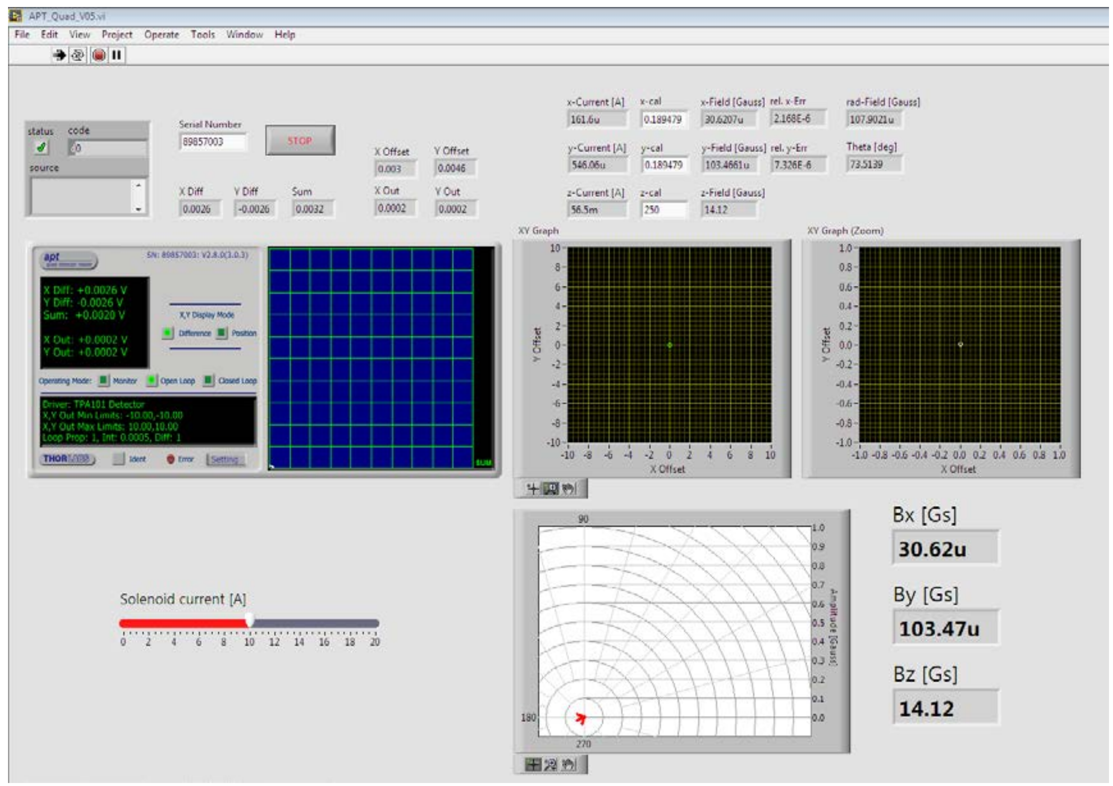
Bench Setup

CERN

Device control, data acquisition and analysis:

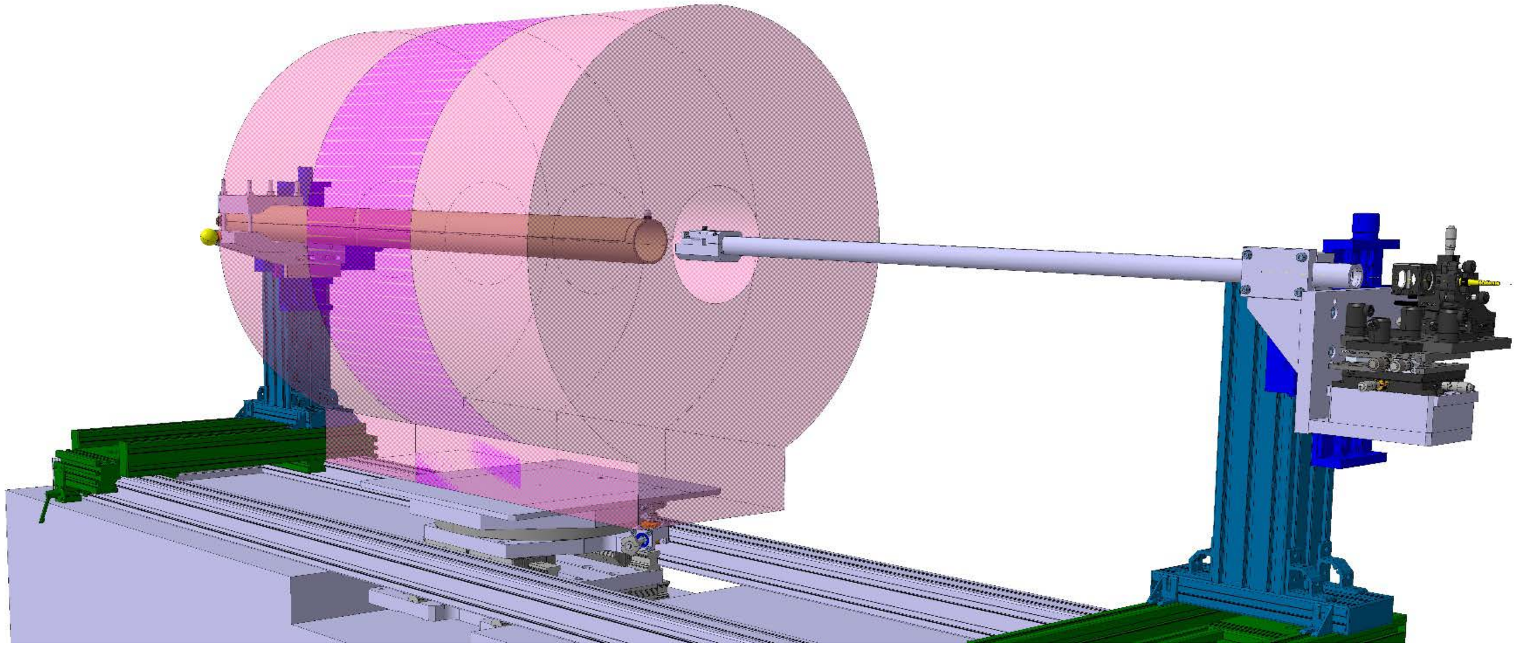
- ✓ PXI with NI-DAQ
- ✓ LabView® software (integration into CERN's FFMM for final version)





Error Sources

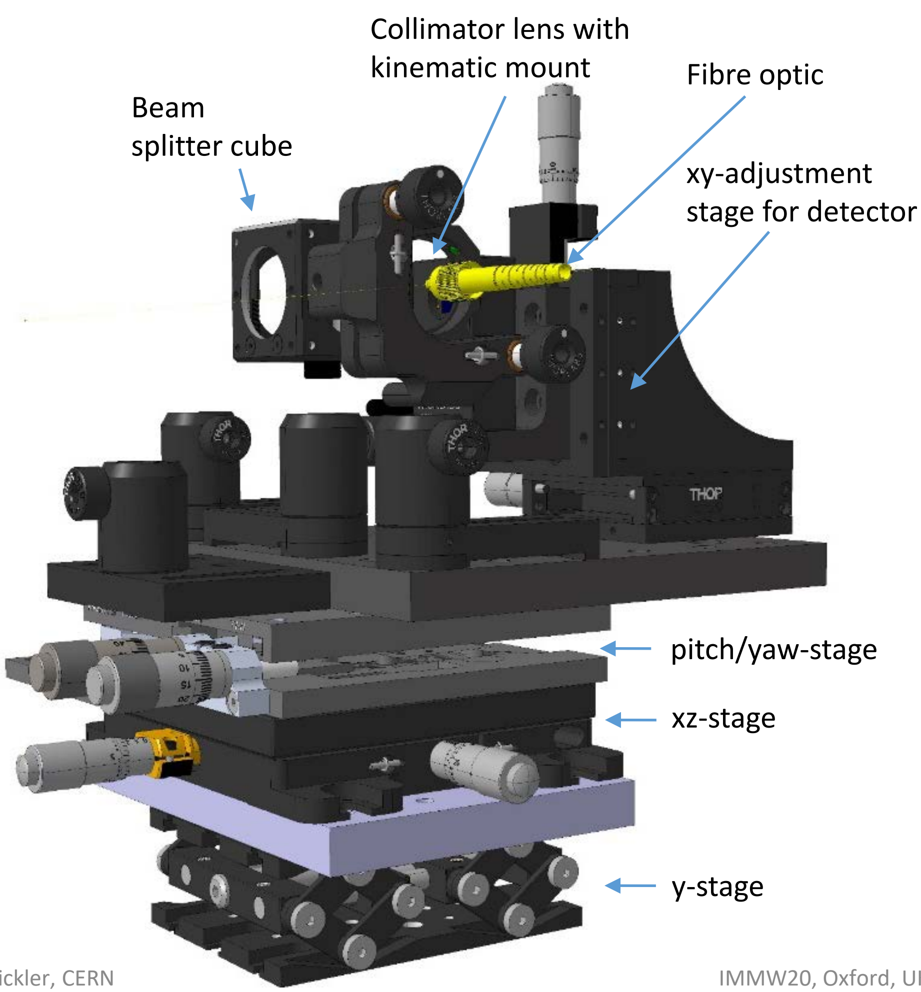
- Misalignment between LSD components
- OFC geometry
- Magnetic moment of compass deviates from z-axis
- Compass assembly errors
- Misalignment between solenoid axis, LSD and OFC
- Shunt precision?
- Others, not yet identified…

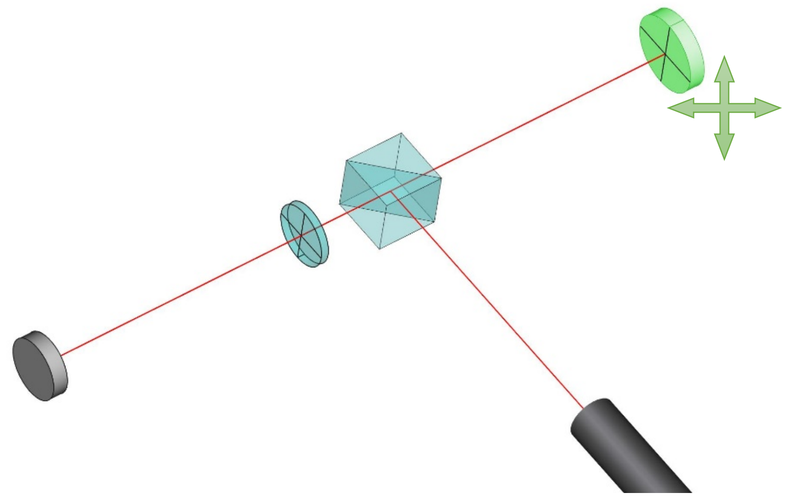


Calibration & Alignment

LSD unit:

- Alignment of laser, splitter and detector with mirror and recticles

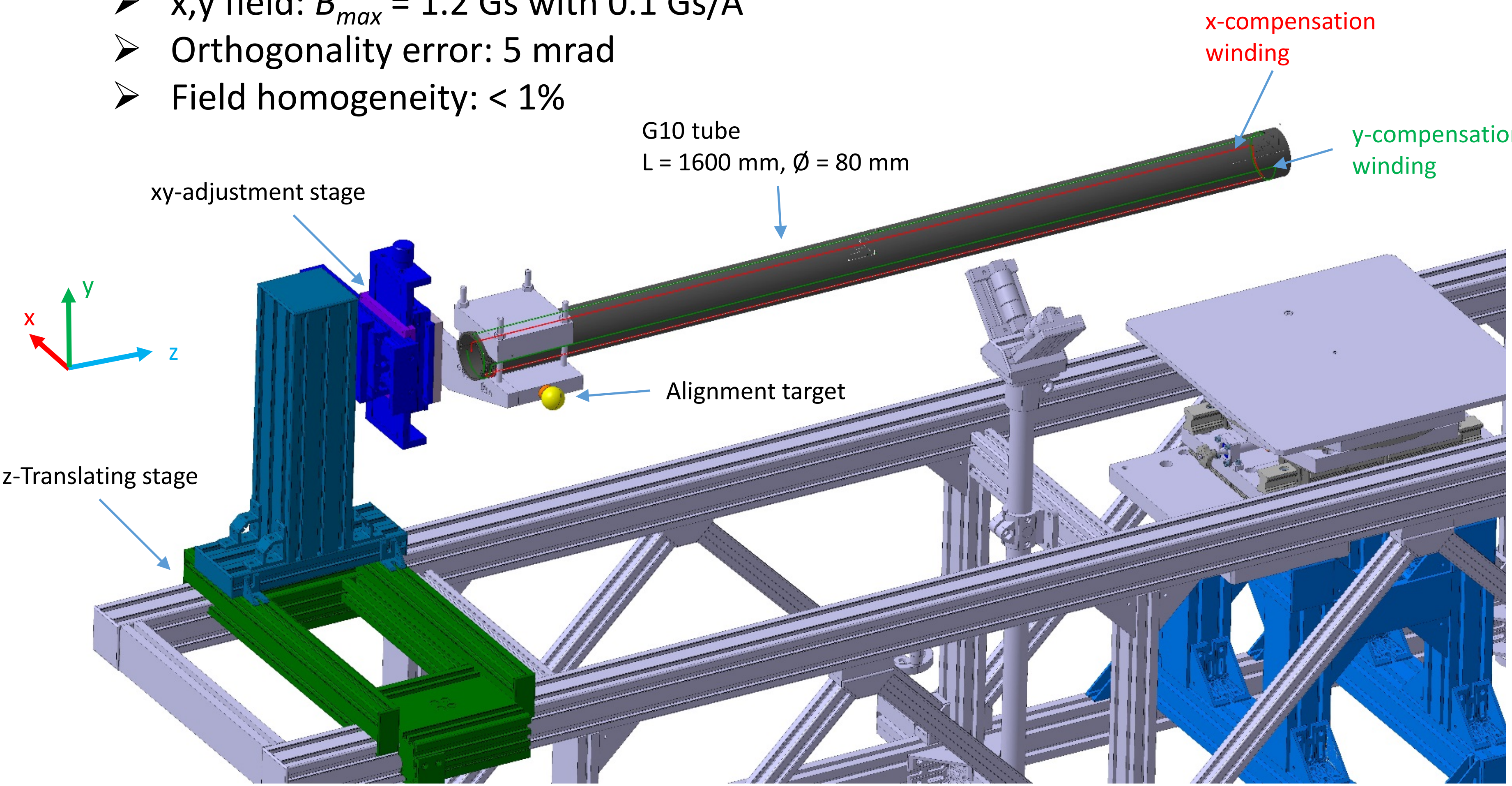




Calibration & Alignment

OFC geometry:

- Characterization with rotating coil system
- x,y field: B_{max} = 1.2 Gs with 0.1 Gs/A
- Orthogonality error: 5 mrad
- Field homogeneity: < 1%



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Calibration & Alignment

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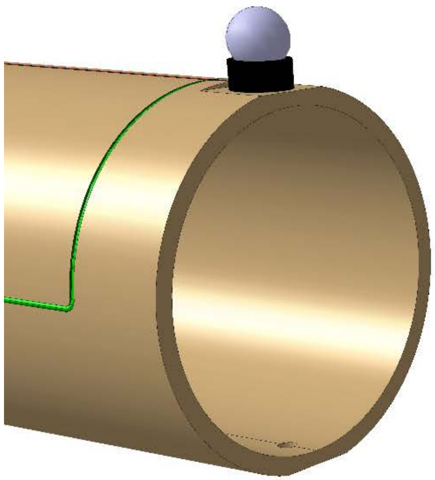
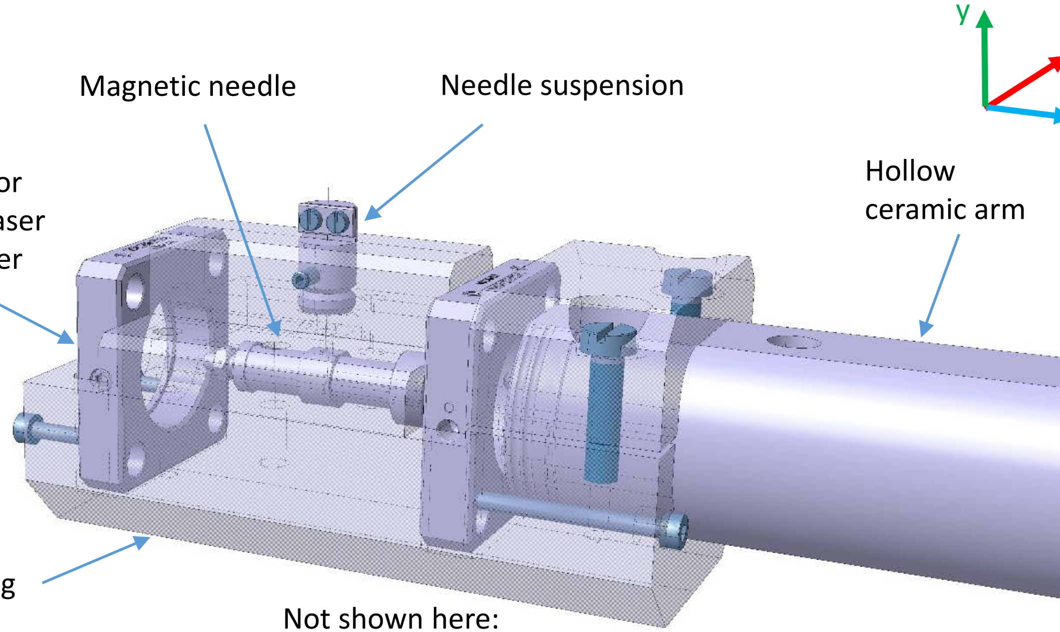
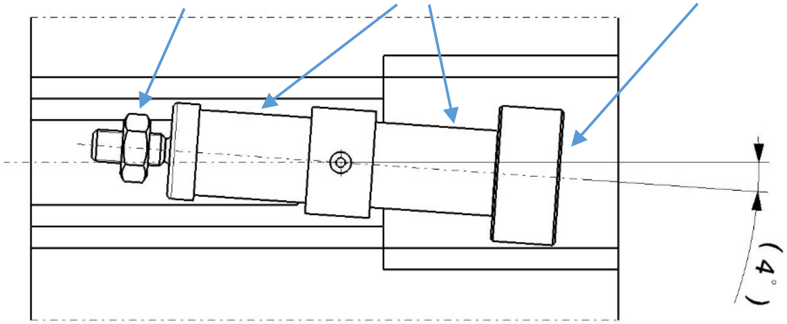
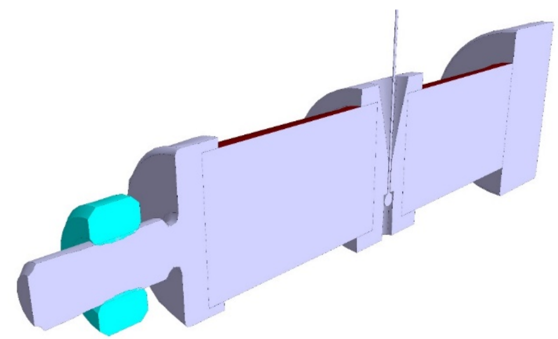




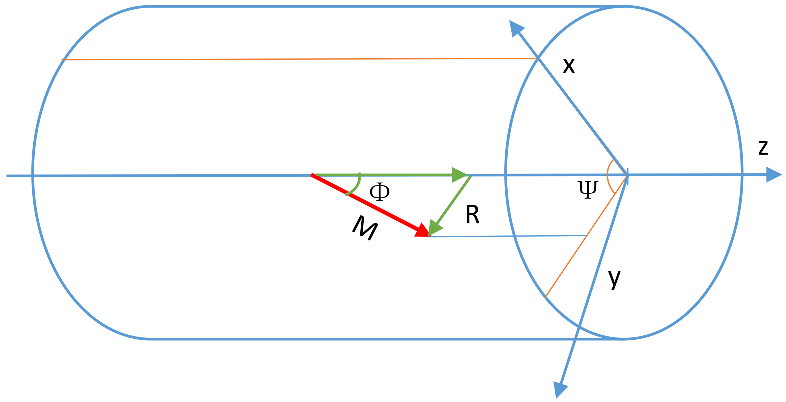


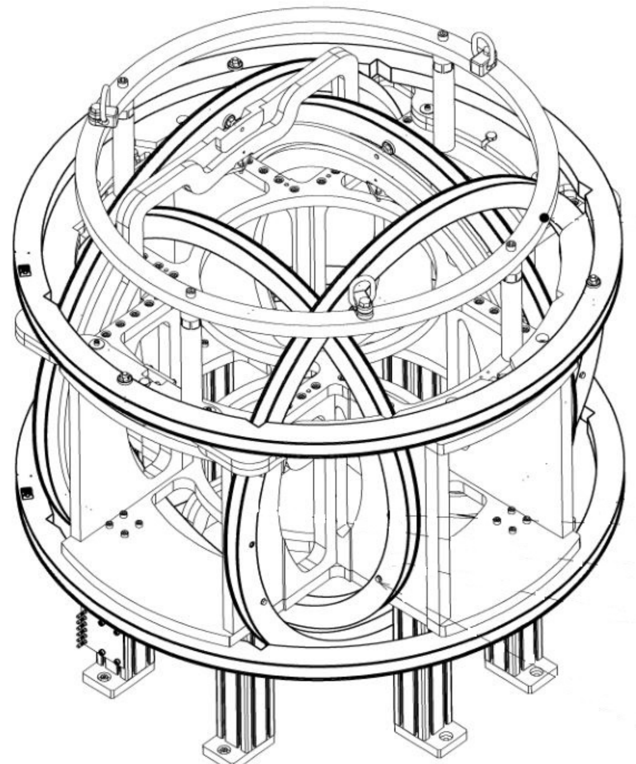


Calibration & Alignment

Deviation of magnetic moment *M* from z-axis of NdFeB-magnets

- Characterization in Helmholtz System (see presentation O. Dunkel, IMMW20)
- Measurement of > 25 samples: up to 40 mrad angular error *Φ* and 2% std.dev of |*M*|
- Sorting: find corresponding magnet pairs with similar angular error *Φ*
- Alignment: orient magnets that errors cancel out

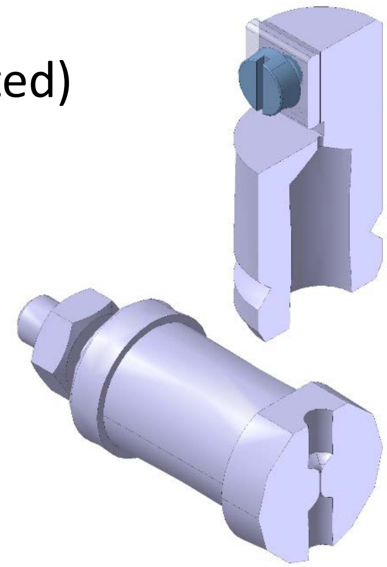




Calibration & Alignment

Unbalanced compass:

- ✓ Torque τ_x (centre-of-mass off-centre) or torque τ_y (twist in nylon wire)
- ✓ Measurement error: $\varepsilon_{x,y} \propto \frac{1}{B_z}$
- ✓ Calibration in zero-field volume (earth field compensated)



Compass assembly errors:

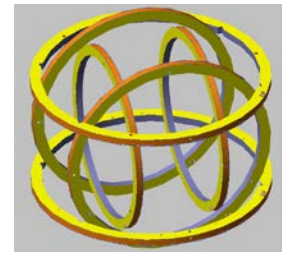
- ✓ Mirror plane not perpendicular to compass axis
- ✓ Measurement error: $\varepsilon_{x,y} = const.$
- ✓ Calibration in adjustable reference field B

→ requires device to provide reference field with independently adjustable field components B_x, B_y, B_z

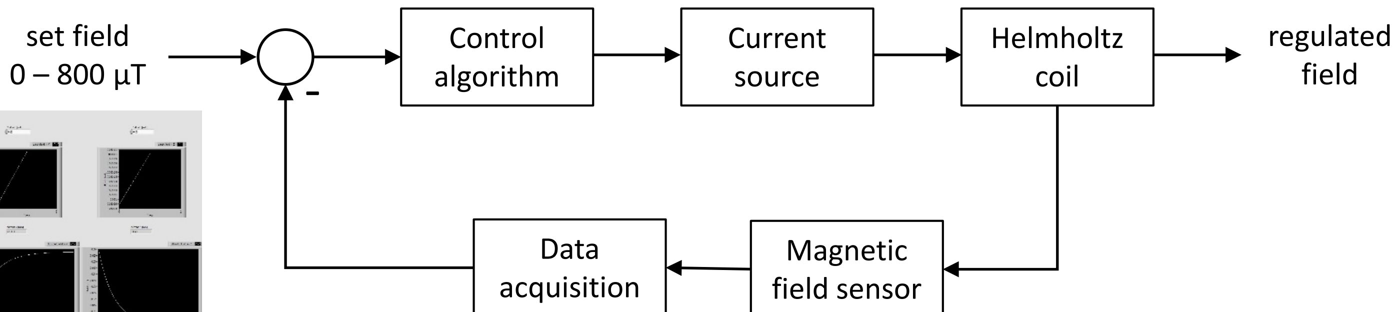
Calibration & Alignment

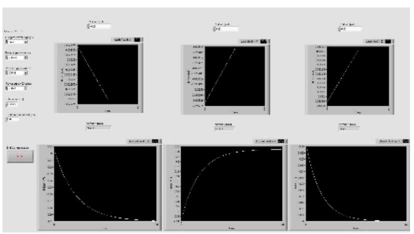
Control system for Helmholtz coils in active mode:

Current source:
FUG MCP 140-6500
0-1000 V, 0-200 mA
Setting range: 0.1% - 100%
with 20 bit resolution



Helmholtz coil:
Diameter: 436 – 563 mm
Windings: 1955 – 2522
Inductance: 8.3 – 17.8 H
Useful volume: r = 75 mm
Field uniformity: < 0.05 dB





Control software in LabVIEW/C++

Data acquisition:
NI PXI 6281
8-ch, 18 Bit, 500 kS/s

Field sensor:
Bartington Mag-03MS1000
3-axis Flux Gate
Measuring range: ±1 mT
Analogue output: 0 to ±10 V
Orthogonality error: 0.05°
Linearity error: < 0.0015%

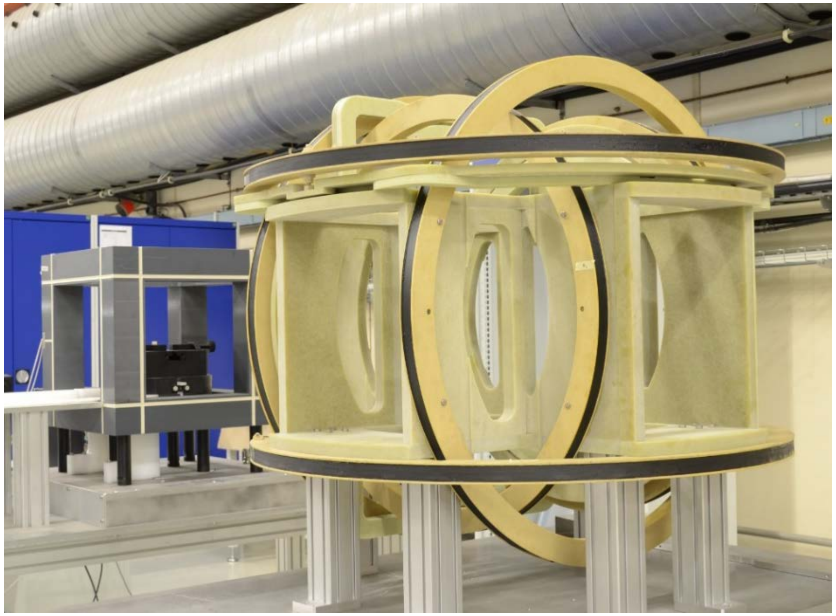
Calibration & Alignment

Helmholtz coil system

- ✓ passive mode: characterization of permanent magnets
- ✓ active mode: create zero-field or any arbitrary field vector *B*

Technical characteristics:

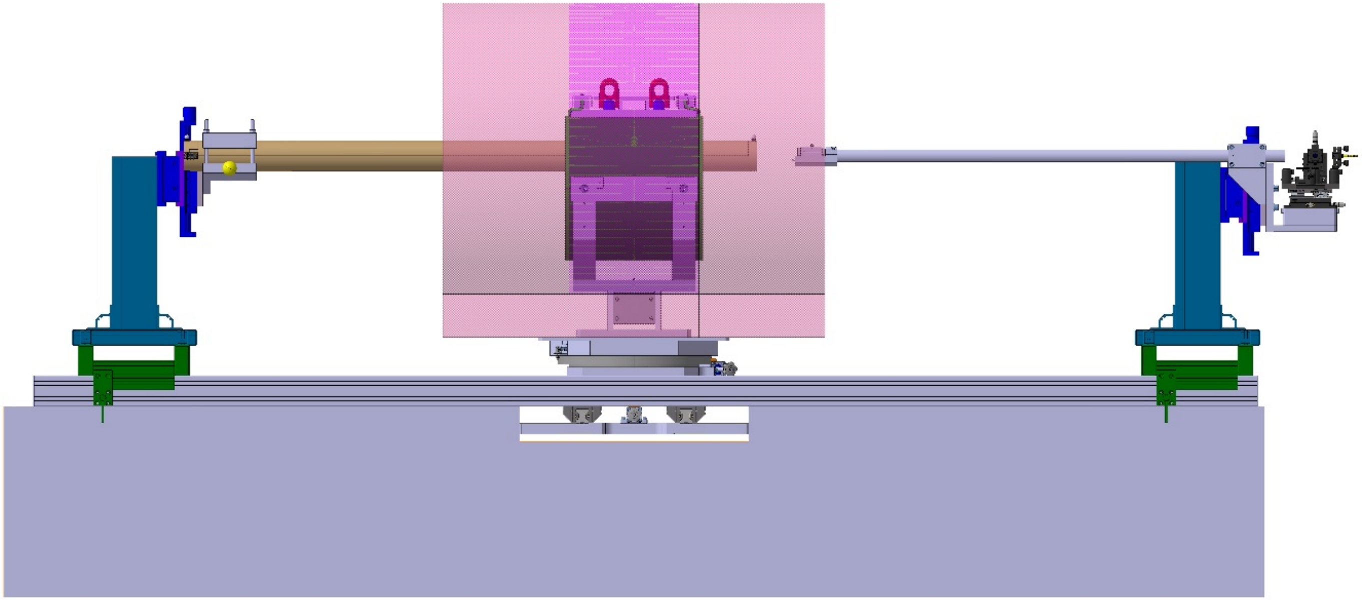
- Automatic earth-field compensation
- Max. zero-field offset: ± 51 nT
- Independently adjustable field components B_x, B_y, B_z between 0-800 µT
- 1 nT resolution
- Pos. and neg. polarity for each axis (switch)
- Automatic compensation for alignment errors between sensor axis and Helmholtz coil axis



Calibration & Alignment

Bench:

- Alignment of LSD unit wrt Solenoid with laser and recticles
- Alignment of OFC wrt Solenoid with cc-retro-reflectors and laser-tracker
- Setup is not sensitive to angular errors of the CPH and transversal (x,y) displacement error can be kept small



Note: in the latest version, LSD and compass head are mounted on separate stages in order to decouple the compass head motion from the LSD

Calibration & Alignment

Laser-Splitter-Detector (LSD) Unit:

- alignment between laser source, splitter and detector → Mirror / recticles

Orthogonal Field Coils (OFC):

- orthogonality between x- and y-coils
- coil geometry

→ Rotating coil

Compass Probe Head (CPH):

- sorting of NdFeB-magnets → Helmholtz coil
- balance compass
- correct compass assembly errors

→ Helmholtz coil

Bench:

- alignment between solenoid axis and LSD → Recticles
- alignment between solenoid axis and OFC (roll angle) → Laser Tracker

Outlook

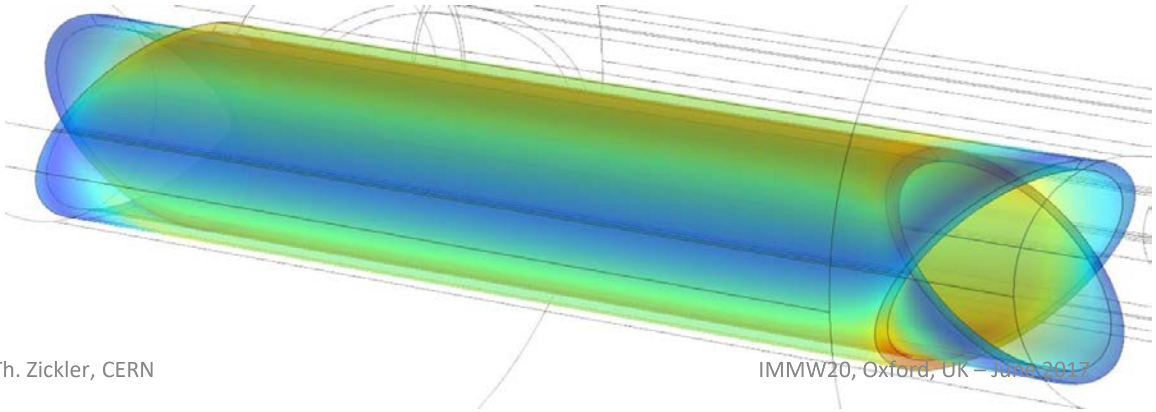
Next steps:

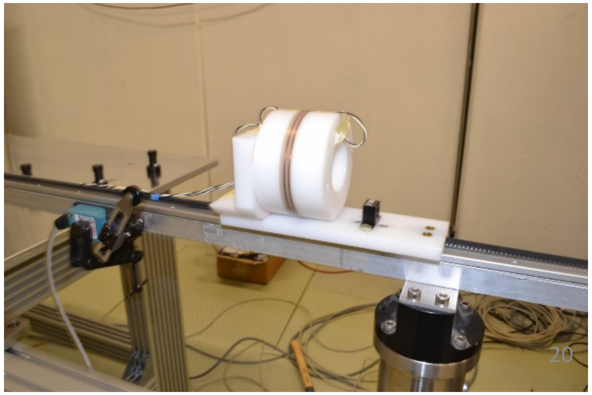
- ✓ Motorized motion unit with linear encoder and controller for CPH displacement
- ✓ Laser interferometer for precise z-position measurement of CPH
- ✓ Air cushion system to move Solenoid instead of CPH

Future extensions towards a multi-purpose solenoid bench:

- ✓ 3-axis hall probe complementary to laser-compass
- ✓ Translating coil magnetometer for axial field profile
- ✓ Adapt CPH to measure small axial components in a strong vertical field of a Canted Cos Theta (CCT) magnet

HE444 series 3D Analog Hall sensors (Asensor Technology SA)

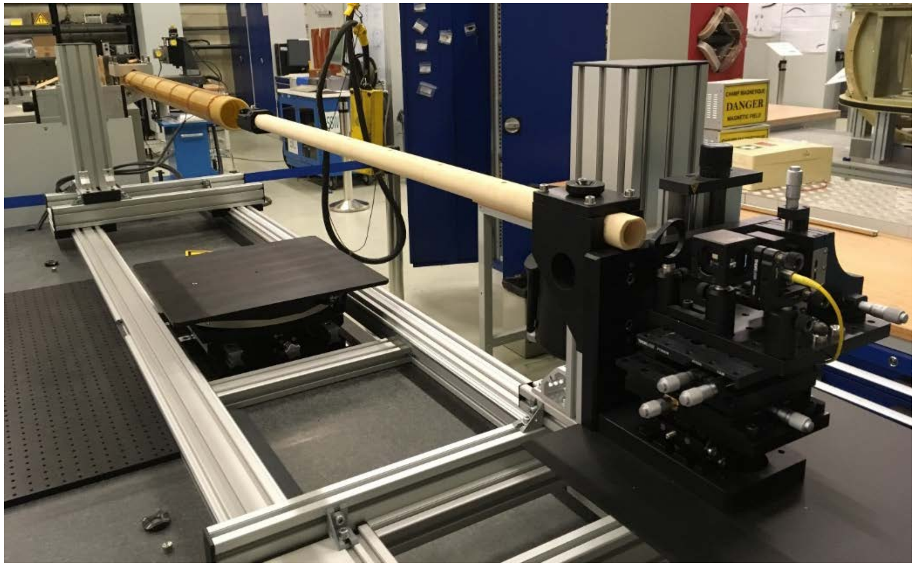


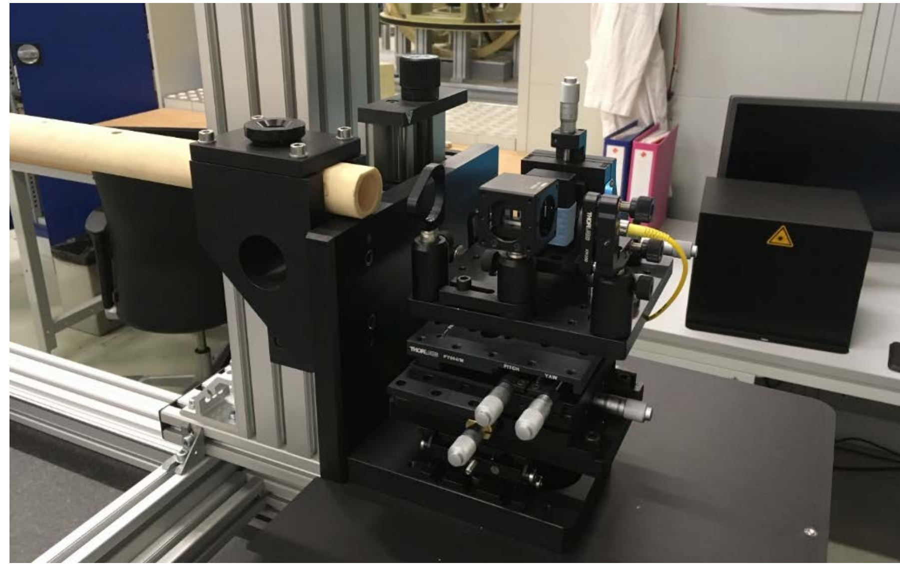


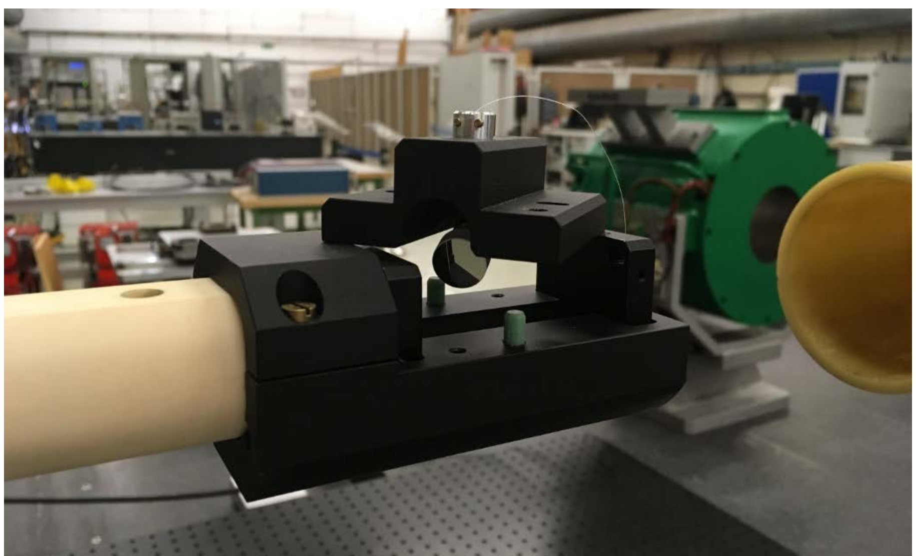
Conclusions

- ✓ System built mostly from recuperated or commercial standard components
- ✓ Detailed calibration & alignment procedure allows reaching required measurement accuracy
- ✓ Closed-loop feedback system solves common problems like:
  - ➢ limited acceptance range of detector
  - ➢ beam excursion depending on distance between mirror and detector
  - ➢ dependency on the axial field component
- ✓ First tests confirm that $B_{\perp}/B_{//}$ of a few 10^{-5} can be detected and we are confident to approach the 10^{-6} range
- ✓ Main challenge: stable movement of CPH (or Solenoid)
- ✓ Limitation: transversal field components larger than $1 \cdot 10^{-3}$ cannot be detected (out of range) → requires other technique (hall probes)

Thanks for your attention!







Questions…?

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