Construction & Commissioning of a 3D Hall probe bench for Insertion Devices measurements at ALBA Synchrotron Light Source

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IMMW15

August 21-24, 2007

Outline

- Introduction
- Magnetic measurements laboratory
- Upgrade of Hall probe bench
  - 3D Hall probe
  - 3D field calibration method
  - Offset determination (zero magnetic field chamber)
  - Determination of relative positions between sensors
  - New TANGO control software and on-the-fly measurement mode
- Some results

Introduction

- **ALBA** is a 3rd generation Synchrotron Light Source being built in Cerdanyola del Vallès, close to Barcelona (Spain)
- **ALBA** is being constructed and will be operated by the public consortium **CELLS** (*consortium for the Construction and Exploitation of the Synchrotron Light Laboratory*), which is co-financed by Catalan (local) and Spanish governments
- Energy of the electron beam ⇒ **E=3 GeV**
- Phase I → **7 beamlines** (BLs): 1 bending magnet BL + 6 ID BLs

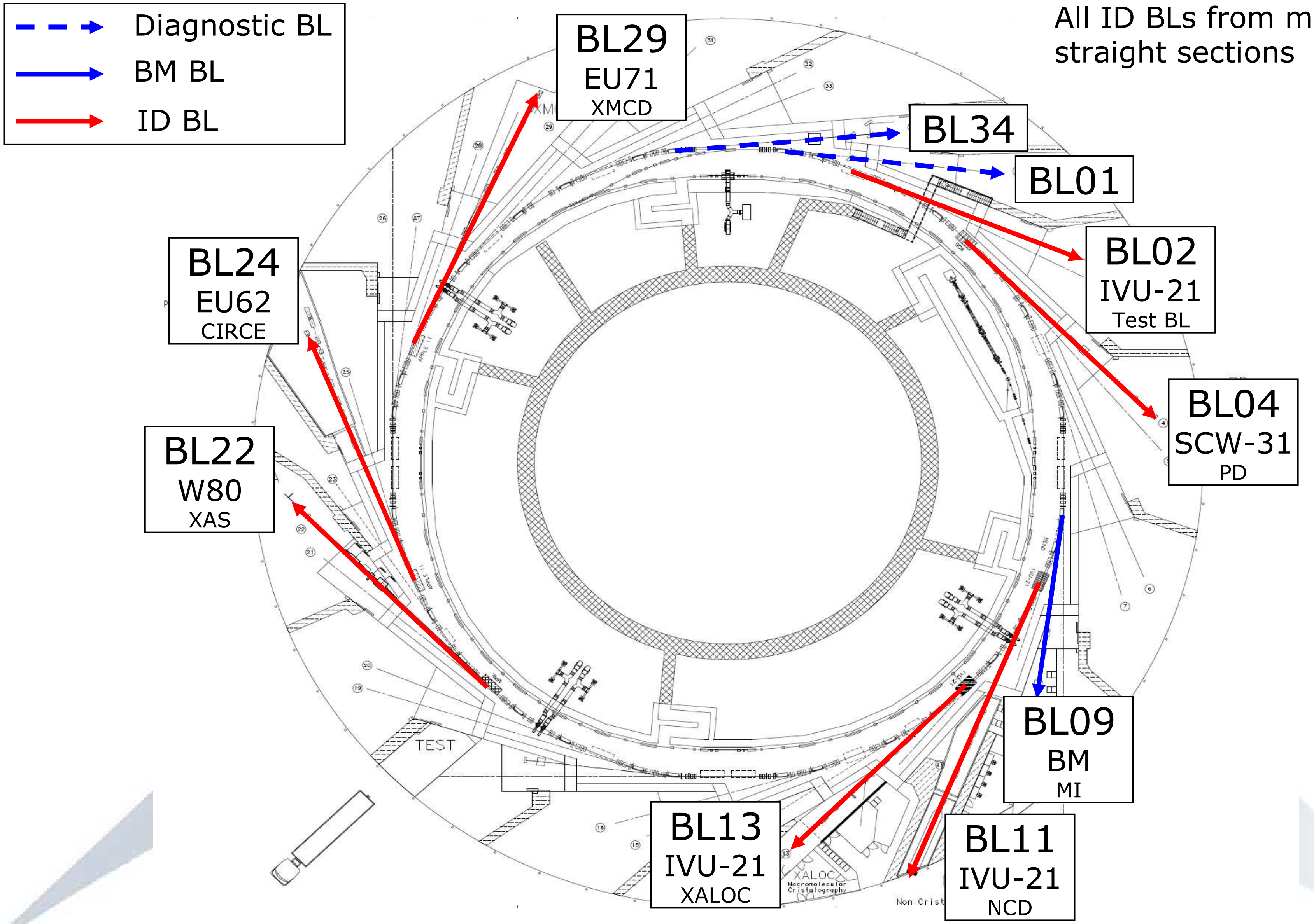
Introduction

Construction & commissioning schedule:

- end 2007: installation and commissioning of Linac
- 2008: installation of Booster and Storage Ring
- 2009: commissioning of accelerator
- 2010: Users operation with 7 Beamlines

Introduction

All ID BLs from medium straight sections



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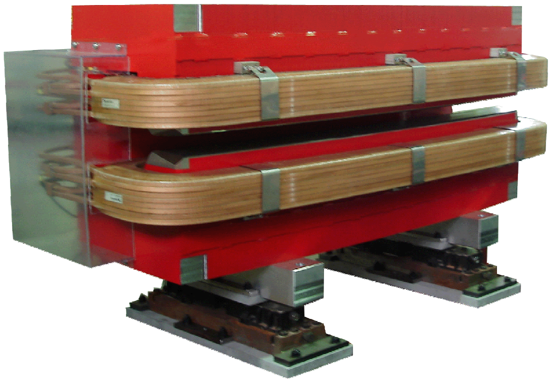
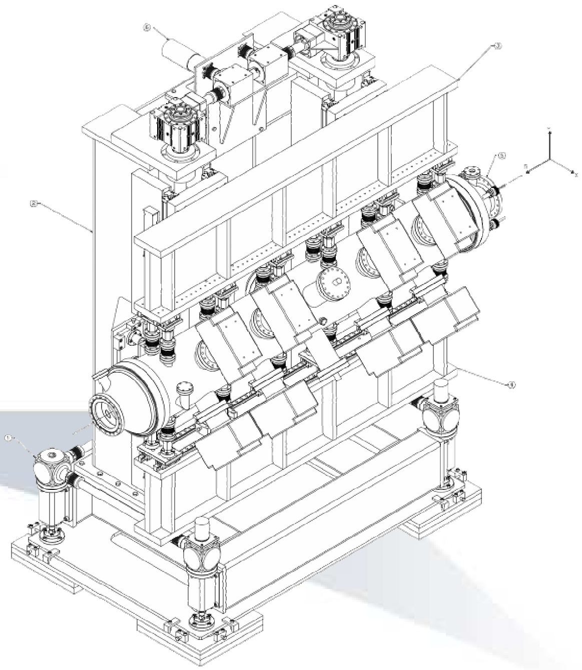
Magnetic Measurements Laboratory

Main aims of the laboratory:



1. Measurement of Storage Ring Bending Magnets
   - ⇒ Instrument for measuring magnetic field maps
     - → ***Hall probe bench***

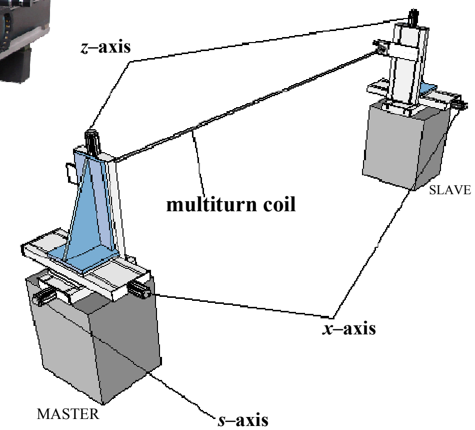


2. Construction and measurement of IDs
   - ⇒ Instruments for permanent magnet blocks characterisation
     - → *Helmholtz coils & Fixed Stretched wire*
   - ⇒ Instrument for measuring magnetic field maps
     - → ***Hall probe bench***
   - ⇒ Instrument for measuring field integrals
     - → *Flipping coil bench*

Magnetic Measurements Laboratory

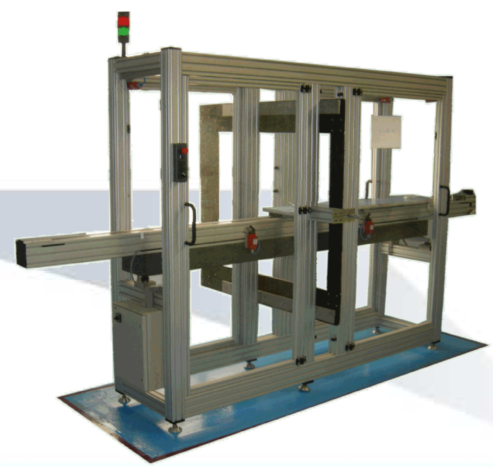
Measurement benches

1. Hall probe bench
   – Previously existing system



2. Flipping coil bench
   – Purchased from ESRF
3. Helmholtz coils
   – Purchased from Elettra

4. Fixed stretched wire
   – Designed and built in-house



Magnetic Measurements Laboratory

General view of the laboratory:

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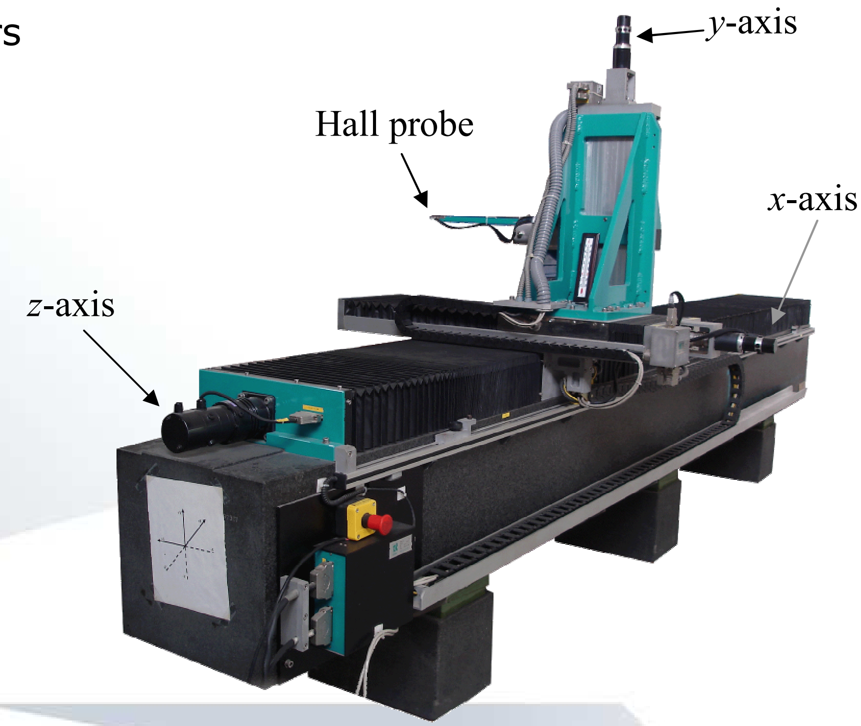
Hall probe bench

Characteristics of previously existing bench:

- Longitudinal scanning range: 3 meters
- 2D Hall probe (only two Hall sensors)
- EPICS control system
- Point-to-point measurement mode

Improvements implemented:

- 3D Hall probe (three Hall sensors)
- New probe calibration scheme
- Offset determination system
- Accurate determination of relative distances between sensors
- TANGO control system
- On-the-fly measurement mode



Scanning volume:

$(\Delta x \times \Delta y \times \Delta z) = 500 \times 250 \times 3000$ mm^3

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3D Hall probe

F.W. Bell Hall sensors

Model GH-700

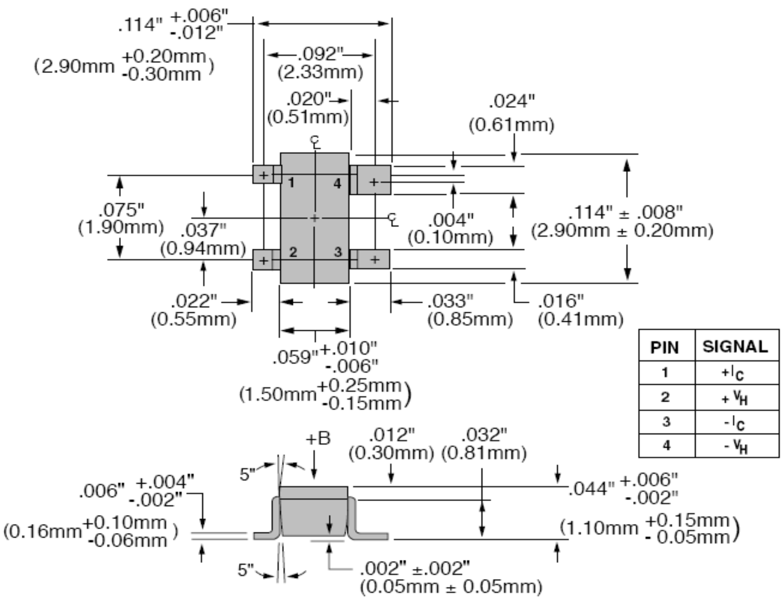
Gallium Arsenide

Nominal current: I_{nom} =5 mA

Magnetic Sensitivity ~ 1 V/Tesla

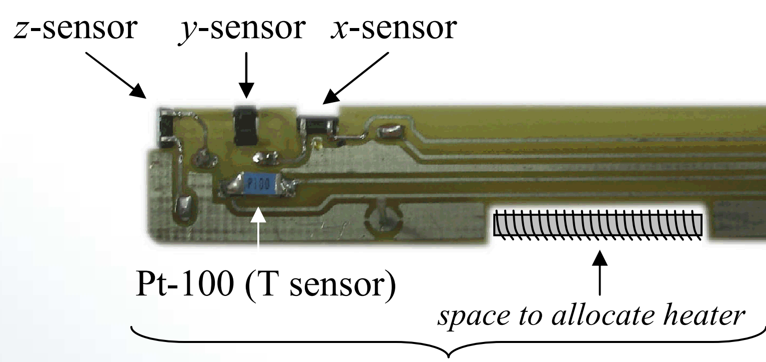
Max. linearity error (±1 Tesla): ±2%

Temperature coefficient: -0.07%/ºC



PIN	SIGNAL
1	$+I_C$
2	$+V_H$
3	$-I_C$
4	$-V_H$

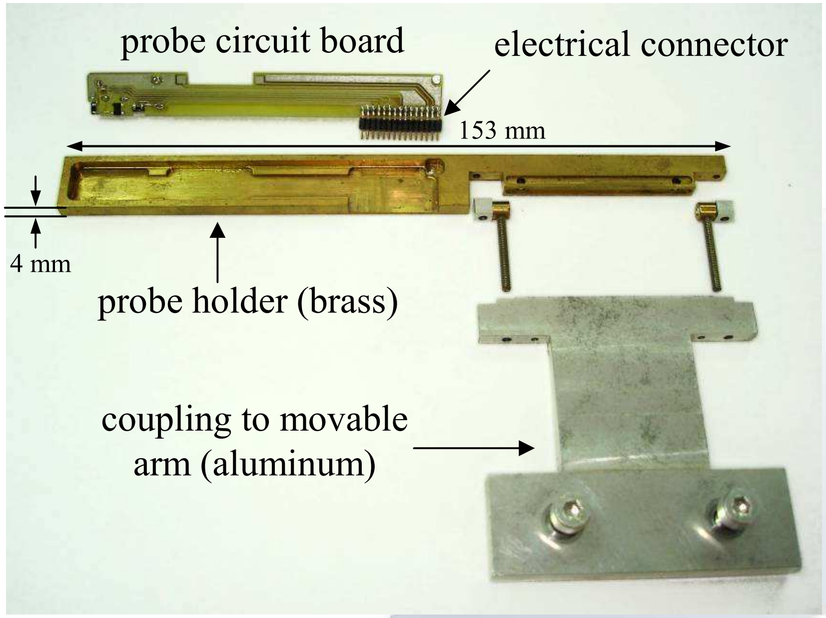
Detail of Hall probe circuit board:



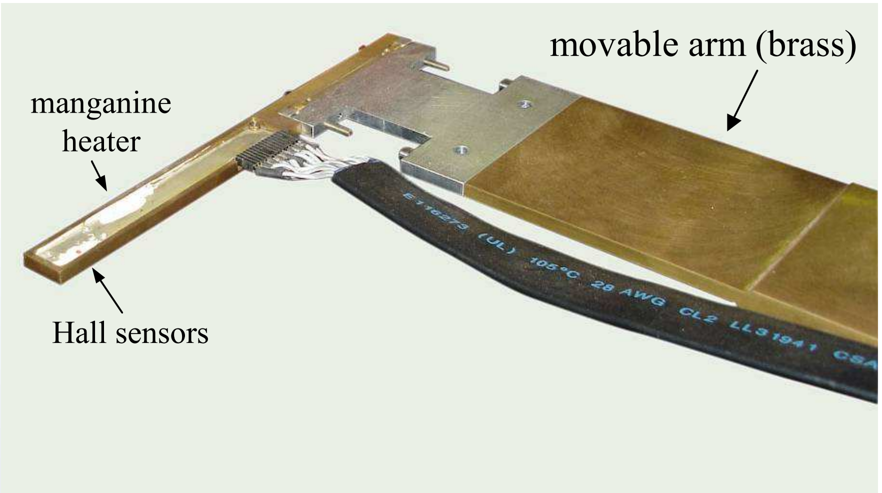
the temperature sensor and the manganine heater, in combination with a PID controller (*Eurotherm 3508*) allow to control the temperature of the probe within ±0.05ºC

3D Hall probe

Piece breakdown of Hall probe Holder:



Finished probe attached to movable arm:



- Brass holder improves mechanical rigidity and temperature homogeneity of the probe
- Probe holder thickness (4 mm) allows to measure all IDs at ALBA (5 mm of minimum gap)
- Circuit board bonded to probe holder using good thermal conductivity & electrical insulator adhesive (Arctic Alumina™ from Arctic Silver ®)

Arctic Alumina™
Premium Ceramic Thermal Adhesive

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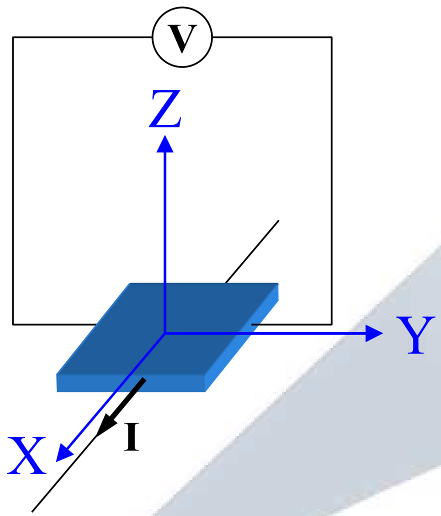
3D field calibration method

Modeling of the response of the probe to an external field taking into account the approach and results in:

- F. Bergsma (2003), *"Calibration of hall sensors in three dimensions"*, presented at 13th International Magnetic Measurement Workshop, May 19-22, 2003, Stanford, California
- F. Bergsma (2005), *"Progress on the 3D calibration of hall probes"*, presented at 14th International Magnetic Measurement Workshop, Sep 26-29, 2005, Geneva, Switzerland

Reference system of a Hall sensor:



Magnetic field components in the reference system of the Hall sensor:

$$(B_X, B_Y, B_Z) = (B \cos\Phi \sin\Theta, B \sin\Phi \sin\Theta, B \cos\Theta)$$

where Θ and Φ are the polar and azimuthal angles of the magnetic field relative to the Hall sensor

Response of the Hall sensor to the applied field:

$$V(B,\Theta,\Phi,T) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} c_{lm}(B,T)\, B^l\, Y_{lm}(\Theta,\Phi)$$

where $Y_{lm}(\Theta, \Phi)$ are spherical harmonics

However, according to the work of Bergsma, only some of the terms c_{lm} have a significant contribution…

3D field calibration method

We have determined that the terms needed to have errors <1 Gauss for B ≤1.7 Tesla are:

$$\boxed{V(B_X, B_Y, B_Z, T) = V_{00} + V_{10} + V_{20} + V_{22} + V_{30} + V_{32} + V_{50} + V_{52}}$$

where...

$V_{00} = c_{00}$	**Voltage offset**
$V_{10} = c_{10}(B,T)\, B_Z$	**Linear term – main component**
$V_{20} = c_{20}\left[2{B_Z}^2 - ({B_X}^2 + {B_Y}^2)\right]$	Non-reversible non-linearity
$V_{22} = c_{22}\, B_X\, B_Y + c^*_{22}({B_X}^2 - {B_Y}^2)$	**Planar Hall effect**
$V_{30} = c_{30}\left[2{B_Z}^3 - 3B_Z\left({B_X}^2 + {B_Y}^2\right)\right]$	Reversible non-linearity
$V_{32} = c_{32}\, B_X\, B_Y\, B_Z + c^*_{32} B_Z({B_X}^2 - {B_Y}^2)$	3D Hall effect
$V_{50} = c_{50}\left[8{B_Z}^5 - 40{B_Z}^3({B_X}^2+{B_Y}^2) + 15B_Z\,({B_X}^2+{B_Y}^2)^2\right]$	Reversible non-linearity
$V_{52} = c_{52}\, B_X\, B_Y\, B_Z[2{B_Z}^2 - ({B_X}^2+{B_Y}^2)] + c^*_{52}\, B_Z({B_X}^2 - {B_Y}^2)[2{B_Z}^2 - ({B_X}^2+{B_Y}^2)]$	

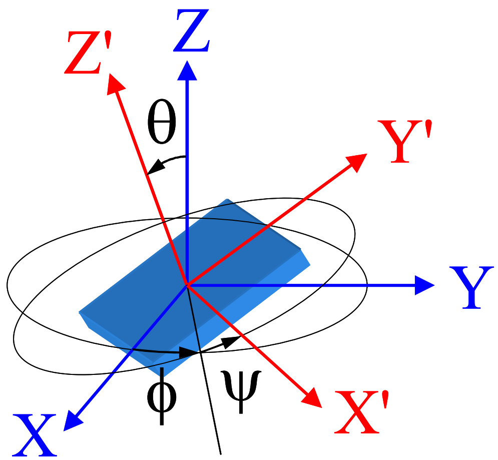
All c_{lm} coefficients unless the main one (c_{10}) are assumed to be B independent, and all the thermal dependence is assumed to be contained in the linear term c_{10}:

$$\boxed{c_{10}(B,T) = c_{10}(1 + c_{101}\, B + c_{102}\, B^2 + c_{103}\, B^3 + c_{104}\, B^4 + \ldots)[1 + \alpha_T\,(T - T_0)]}$$

where T_0 is the calibration temperature.

3D field calibration method

It shall be taken into account that the Hall sensors are not perfectly aligned with respect to the reference frame of the laboratory:



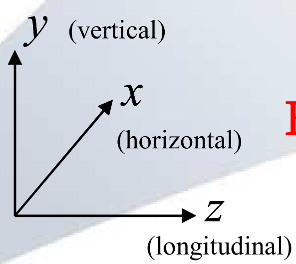
$$\begin{pmatrix} B_X' \\ B_Y' \\ B_Z' \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} B_X \\ B_Y \\ B_Z \end{pmatrix}$$

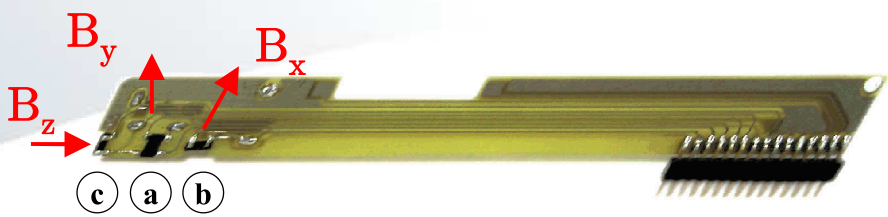
where ϕ, θ and ψ are Euler angles defining the misalignment of the Hall sensor relative to the component of the magnetic field to be measured.

Therefore the response of the Hall sensor to an external field in terms of the lab. frame components:

$$\boxed{V\left[B_X'(B_X, B_Y, B_Z), B_Y'(B_X, B_Y, B_Z), B_Z'(B_X, B_Y, B_Z), T\right]}$$

Lab. Reference frame:





vertical probe	a	$(X_a, Y_a, Z_a) \leftrightarrow (z, x, y)$
horizontal probe	b	$(X_b, Y_b, Z_b) \leftrightarrow (y, z, x)$
long. probe	c	$(X_c, Y_c, Z_c) \leftrightarrow (x, y, z)$

$$V_a(B_x, \mathbf{B_y}, B_z, T)$$
$$V_b(\mathbf{B_x}, B_y, B_z, T)$$
$$V_c(B_x, B_y, \mathbf{B_z}, T)$$

$$V_a(B_x,B_y,B_z,T) = c^a_{00} + c^a_{10}(1 + c^a_{101}B + c^a_{102}B^2 + c^a_{103}B^3 + c^a_{104}B^4)(1+\alpha^a_T\Delta T)\mathbf{B^a_y} + c^a_{20}[2B^{a\,2}_y - (B^{a\,2}_x + B^{a\,2}_z)] + c^a_{22}B^a_zB^a_x + c^{*a}_{22}(B^{a\,2}_z - B^{a\,2}_x) + c^a_{30}[2B^{a\,3}_y - 3B^a_y(B^{a\,2}_x + B^{a\,2}_z)] + c^a_{32}B^a_yB^a_zB^a_x + c^{*a}_{32}B^a_y(B^{a\,2}_z - B^{a\,2}_x) + o(B^5)$$

$$V_b(B_x,B_y,B_z,T) = c^b_{00} + c^b_{10}(1 + c^b_{101}B + c^b_{102}B^2 + c^b_{103}B^3 + c^b_{104}B^4)(1+\alpha^b_T\Delta T)\mathbf{B^b_x} + c^b_{20}[2B^{b\,2}_x - (B^{b\,2}_z + B^{b\,2}_y)] + c^b_{22}B^b_yB^b_z + c^{*b}_{22}(B^{b\,2}_y - B^{b\,2}_z) + c^b_{30}[2B^{b\,3}_x - 3B^b_x(B^{b\,2}_z + B^{b\,2}_y)] + c^b_{32}B^b_xB^b_yB^b_z + c^{*b}_{32}B^b_x(B^{b\,2}_y - B^{b\,2}_z) + o(B^5)$$

$$V_c(B_x,B_y,B_z,T) = c^c_{00} + c^c_{10}(1 + c^c_{101}B + c^c_{102}B^2 + c^c_{103}B^3 + c^c_{104}B^4)(1+\alpha^c_T\Delta T)\mathbf{B^c_z} + c^c_{20}[2B^{c\,2}_z - (B^{c\,2}_y + B^{c\,2}_x)] + c^c_{22}B^c_xB^c_y + c^{*c}_{22}(B^{c\,2}_x - B^{c\,2}_y) + c^c_{30}[2B^{c\,3}_z - 3B^c_z(B^{c\,2}_y + B^{c\,2}_x)] + c^c_{32}B^c_zB^c_xB^c_y + c^{*c}_{32}B^c_z(B^{c\,2}_x - B^{c\,2}_y) + o(B^5)$$

a
$$\begin{cases} B^a_y = B_y\cos\theta_a + B_z\sin\phi_a\sin\theta_a - B_x\cos\phi_a\sin\theta_a \\ B^a_z = B_y\sin\psi_a\sin\theta_a + B_z(\cos\phi_a\cos\psi_a - \sin\phi_a\sin\psi_a\cos\theta_a) + B_x(\sin\phi_a\cos\psi_a + \cos\phi_a\sin\psi_a\cos\theta_a) \\ B^a_x = B_y\cos\psi_a\sin\theta_a - B_z(\cos\phi_a\sin\psi_a + \sin\phi_a\cos\psi_a\cos\theta_a) + B_x(\cos\phi_a\cos\psi_a\cos\theta_a - \sin\phi_a\sin\psi_a) \end{cases}$$

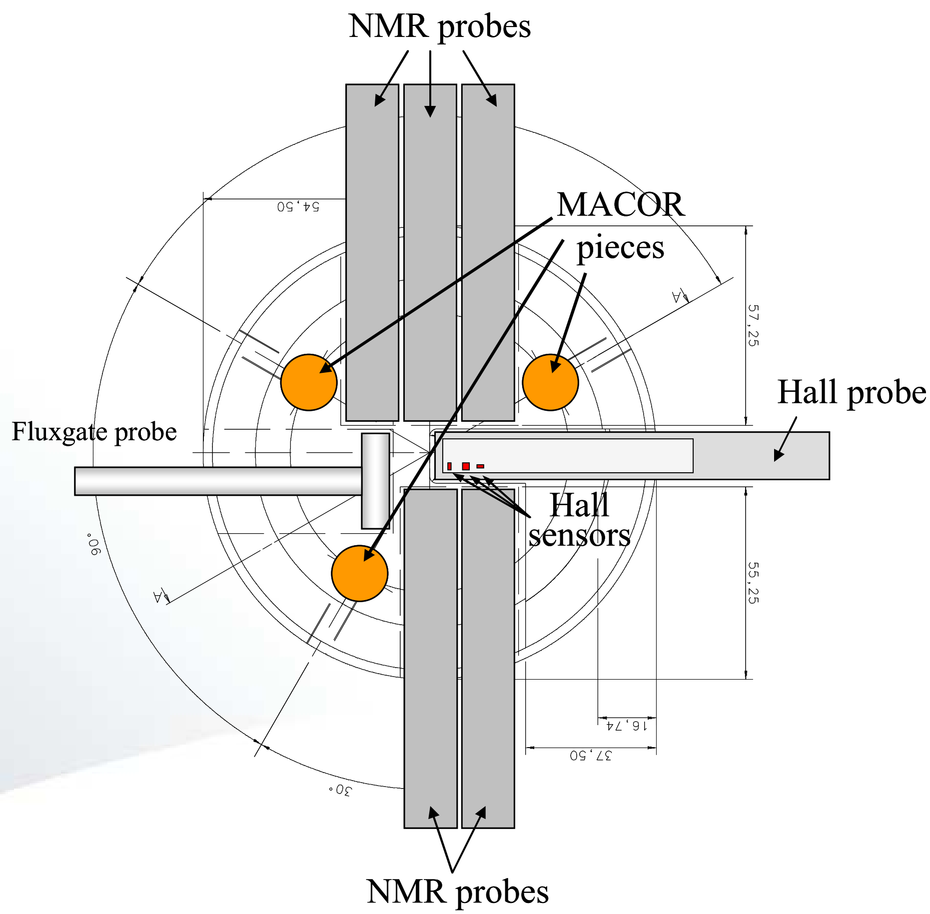
b
$$\begin{cases} B^b_x = B_x\cos\theta_b + B_y\sin\phi_b\sin\theta_b - B_z\cos\phi_b\sin\theta_b \\ B^b_y = B_x\sin\psi_b\sin\theta_b + B_y(\cos\phi_b\cos\psi_b - \sin\phi_b\sin\psi_b\cos\theta_b) + B_z(\sin\phi_b\cos\psi_b + \cos\phi_b\sin\psi_b\cos\theta_b) \\ B^b_z = B_x\cos\psi_b\sin\theta_b - B_y(\cos\phi_b\sin\psi_b + \sin\phi_b\cos\psi_b\cos\theta_b) + B_z(\cos\phi_b\cos\psi_b\cos\theta_b - \sin\phi_b\sin\psi_b) \end{cases}$$

c
$$\begin{cases} B^c_z = B_z\cos\theta_c + B_x\sin\phi_c\sin\theta_c - B_y\cos\phi_c\sin\theta_c \\ B^c_x = B_z\sin\psi_c\sin\theta_c + B_x(\cos\phi_c\cos\psi_c - \sin\phi_c\sin\psi_c\cos\theta_c) + B_y(\sin\phi_c\cos\psi_c + \cos\phi_c\sin\psi_c\cos\theta_c) \\ B^c_y = B_z\cos\psi_c\sin\theta_c - B_x(\cos\phi_c\sin\psi_c + \sin\phi_c\cos\psi_c\cos\theta_c) + B_y(\cos\phi_c\cos\psi_c\cos\theta_c - \sin\phi_c\sin\psi_c) \end{cases}$$

3D field calibration method

Calibration system:

- Dipole Magnet *GMW 3473-50 150 MM*
- Power supply *Danfysik 858*
- RMN magnetometer *Metrolab PT 2025*
- Fluxgate magnetometer *Bartington Mag-01*



Magnet’s air gap: 15mm

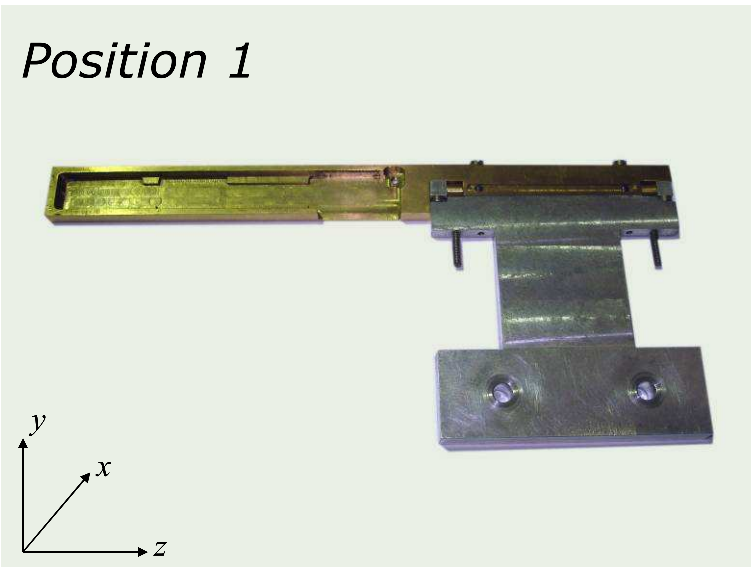
5 NMR probes: |B|= 500 Gauss–2.1 Tesla

Fluxgate probe: |B|< 150 Gauss

3D field calibration method

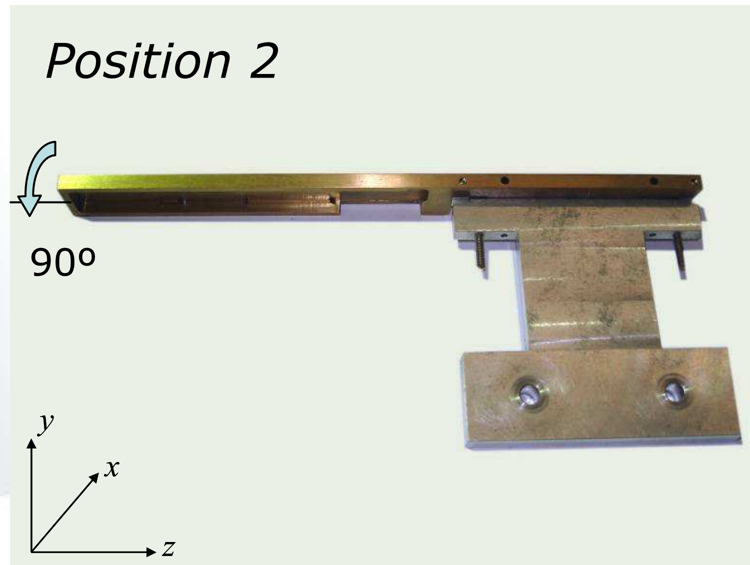
Field calibration carried out at four predefined positions:

At positions 1 and 2 the probe is attached to the moving arm



magnetic field along vertical (y) direction

$$(B_x, B_y, B_z)_{\text{pos 1}} = (0, B, 0)$$

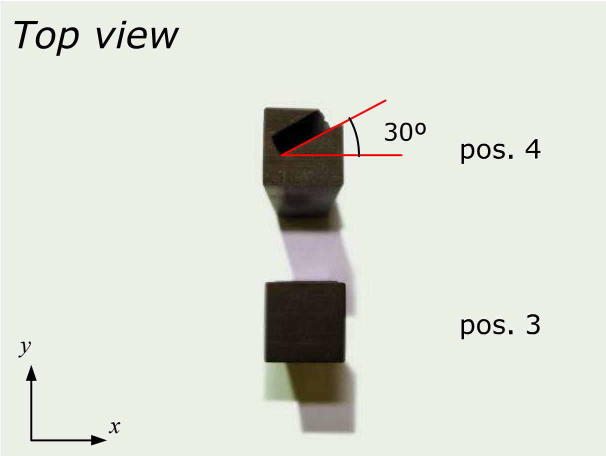


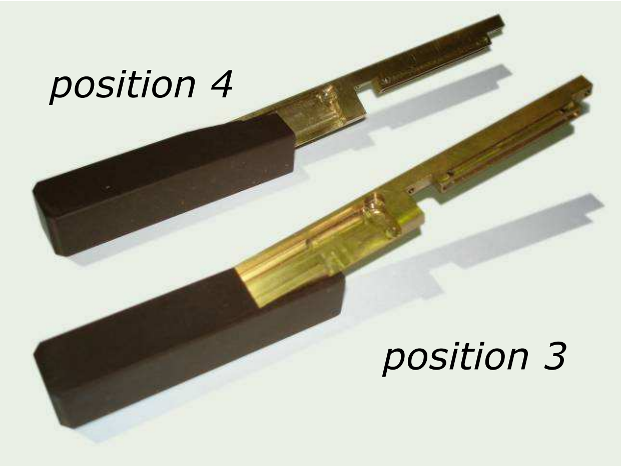
magnetic field along horizontal (x) direction

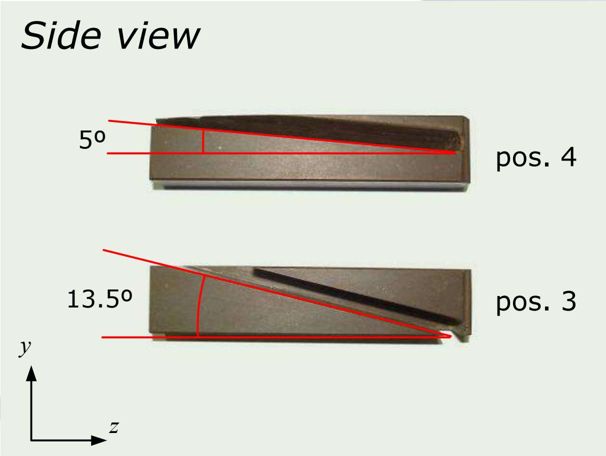
$$(B_x, B_y, B_z)_{\text{pos 2}} = (B, 0, 0)$$

Field calibration carried out at four predefined positions:

Positions 3 and 4 are defined using to auxiliary Bakelite pieces that are inserted into the gap of the calibration dipole







Position 3:

magnetic field along vertical and longitudinal (y and z) directions

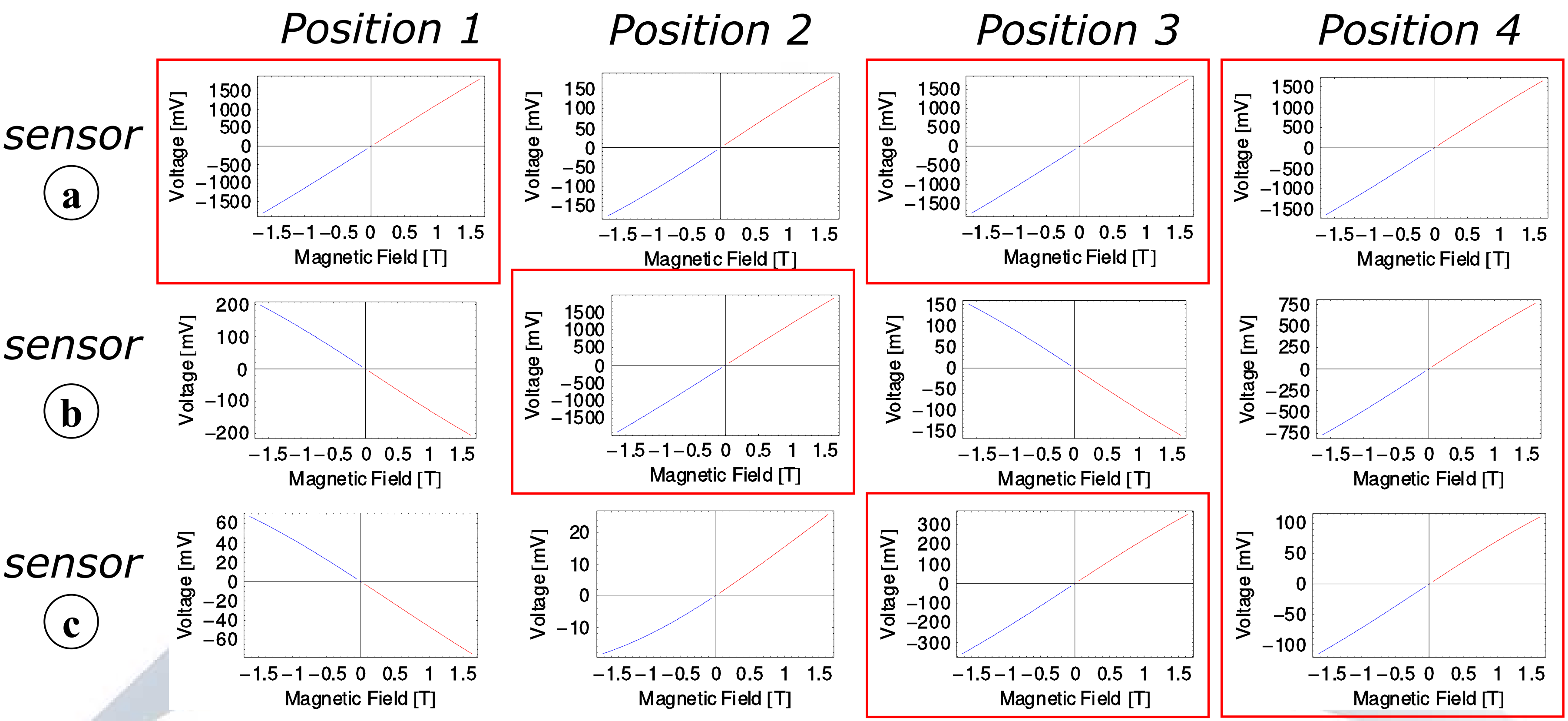
$$(B_x, B_y, B_z)_{\text{pos } 3} = (0, B\ \cos 13.5^\circ, B\ \sin 13.5^\circ)$$

Position 4:

all three components (x, y and z) non-zero

$$(B_x, B_y, B_z)_{\text{pos } 4}$$

Calibration curves obtained at constant temperature (T_o=30ºC) in the range ±1.7 Tesla:



3D field calibration method

Least squares fitting in order to determine c_{lm} and ϕ, θ and ψ parameters for each sensor:

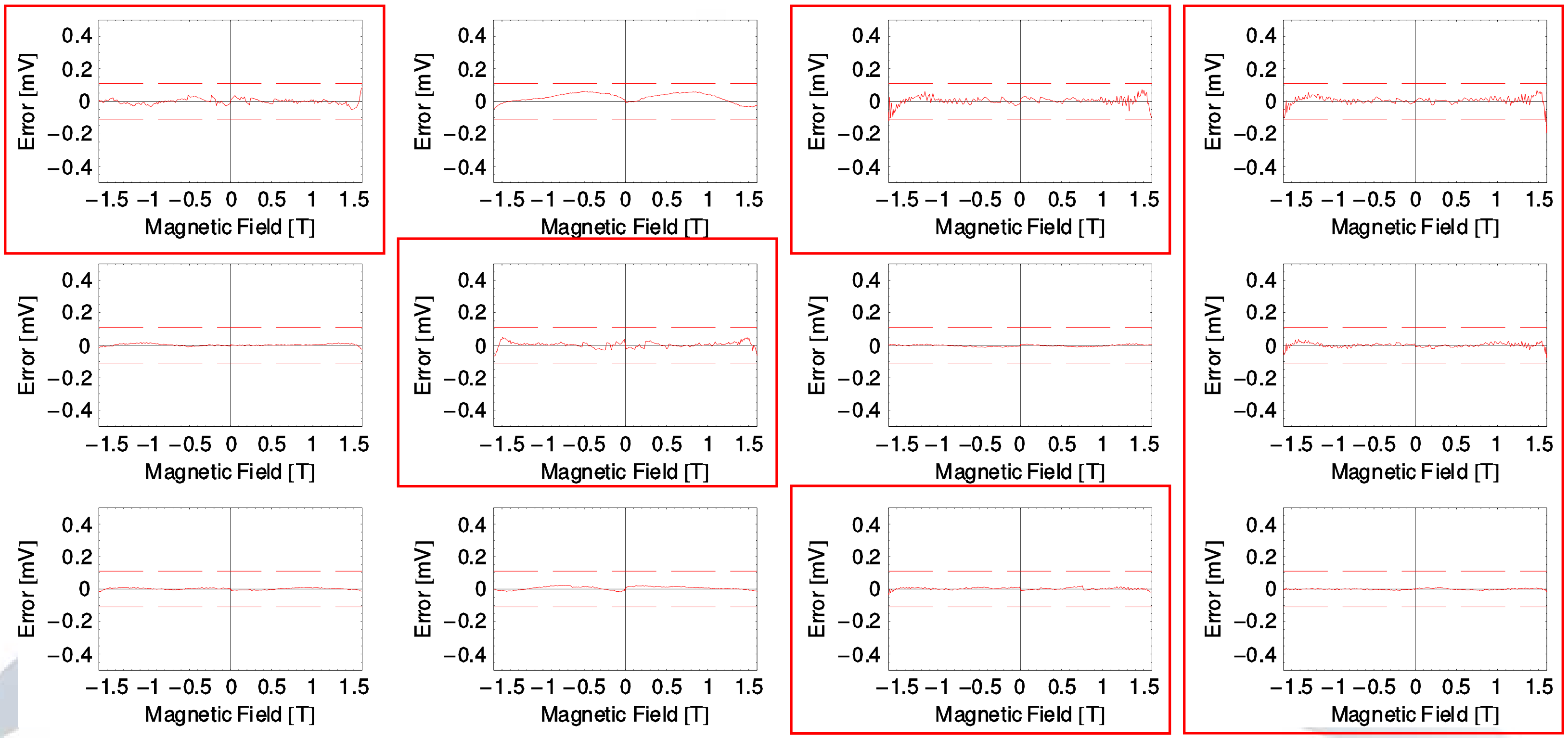
Simultaneous fit of $\begin{cases} V_a = V_a(B_x, B_y, B_z, T_0) \\ V_b = V_b(B_x, B_y, B_z, T_0) \\ V_c = V_c(B_x, B_y, B_z, T_0) \end{cases}$ at each calibration position

Position 1 *Position 2* *Position 3* *Position 4*

sensor a

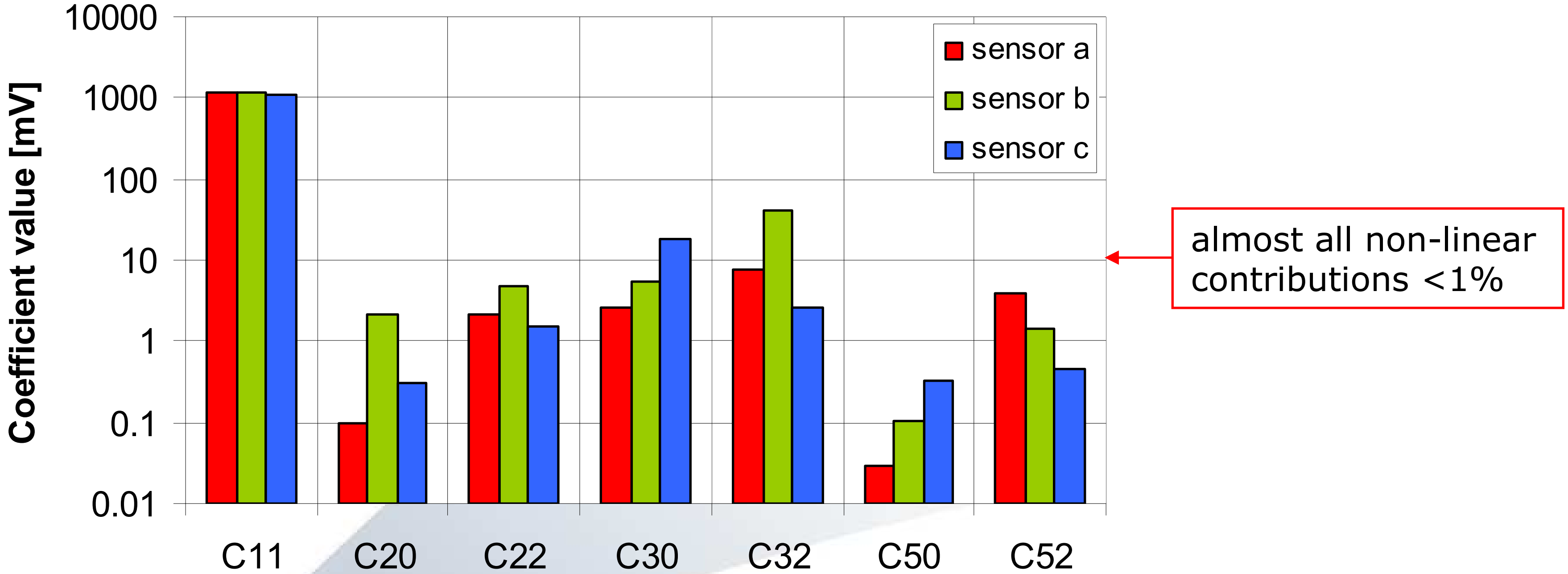
sensor b

sensor c



The residual *rms* error is 0.02 mV, which corresponds to **0.2 Gauss**

Obtained results



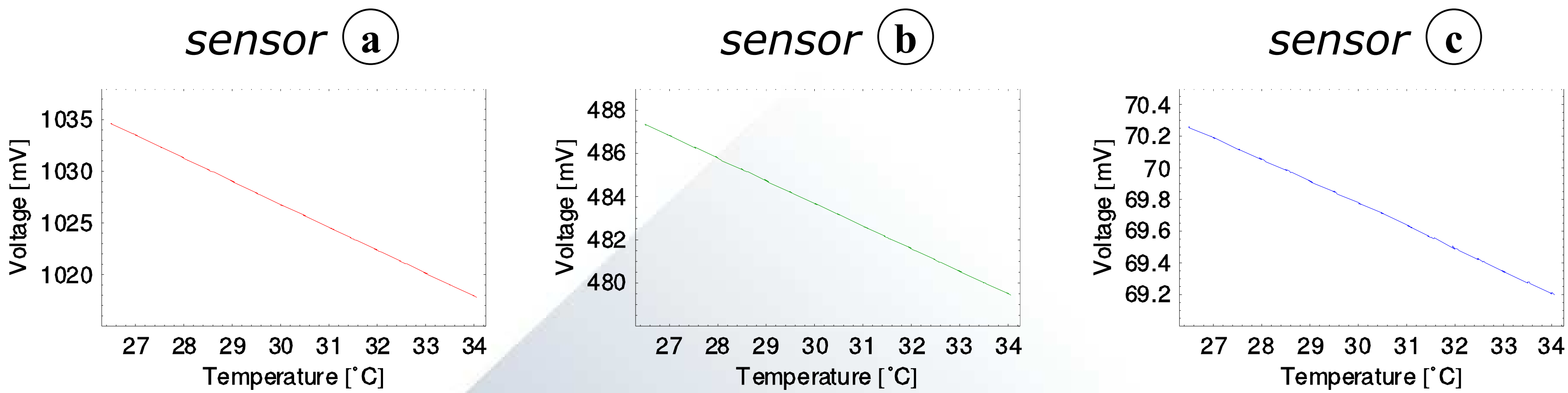
Misalignment angles: $\theta_a = 5.8^\circ$

$$\theta_b = 7.9^\circ$$

$$\theta_c = 2.3^\circ$$

Determination of temperature coefficients:

measurement at constant magnetic field in position 4 (all field components ≠0) with changing temperature



The temperature coefficients are:

$$\boxed{\begin{aligned} \alpha_T^a &= -0.217\%/^\circ C \\ \alpha_T^b &= -0.212\%/^\circ C \\ \alpha_T^c &= -0.209\%/^\circ C \end{aligned}}$$

Reconstruction of the magnetic field

Given the signals of the three sensors (V_a, V_b and V_c) and the temperature of the probe (T), the three components of the magnetic field are determined by inverting the non-linear system (it is done by means of a C routine implementing Broydn method):

$$\begin{cases} V_a = V_a(B_x, B_y, B_z, T) \\ V_b = V_b(B_x, B_y, B_z, T) \\ V_c = V_c(B_x, B_y, B_z, T) \end{cases} \Longrightarrow (B_x, B_y, B_z)$$

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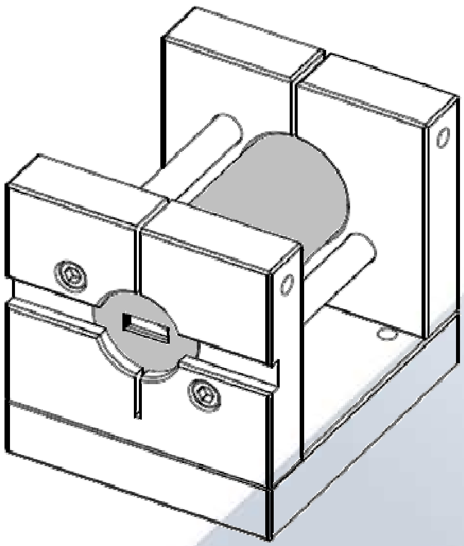
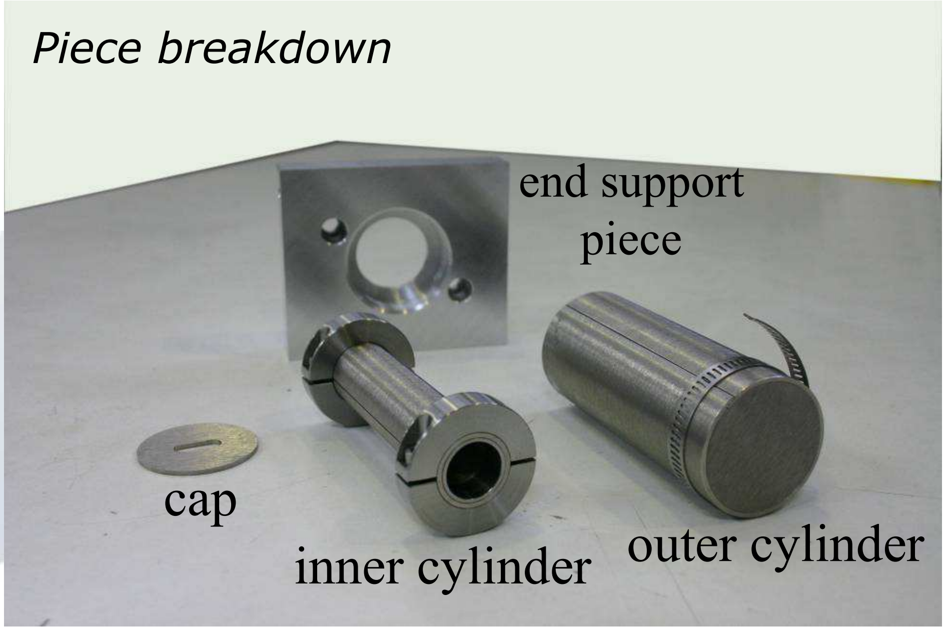
Determination of offsets

A double layer μ-metal chamber has been designed and constructed in order to measure the offsets of Hall sensors

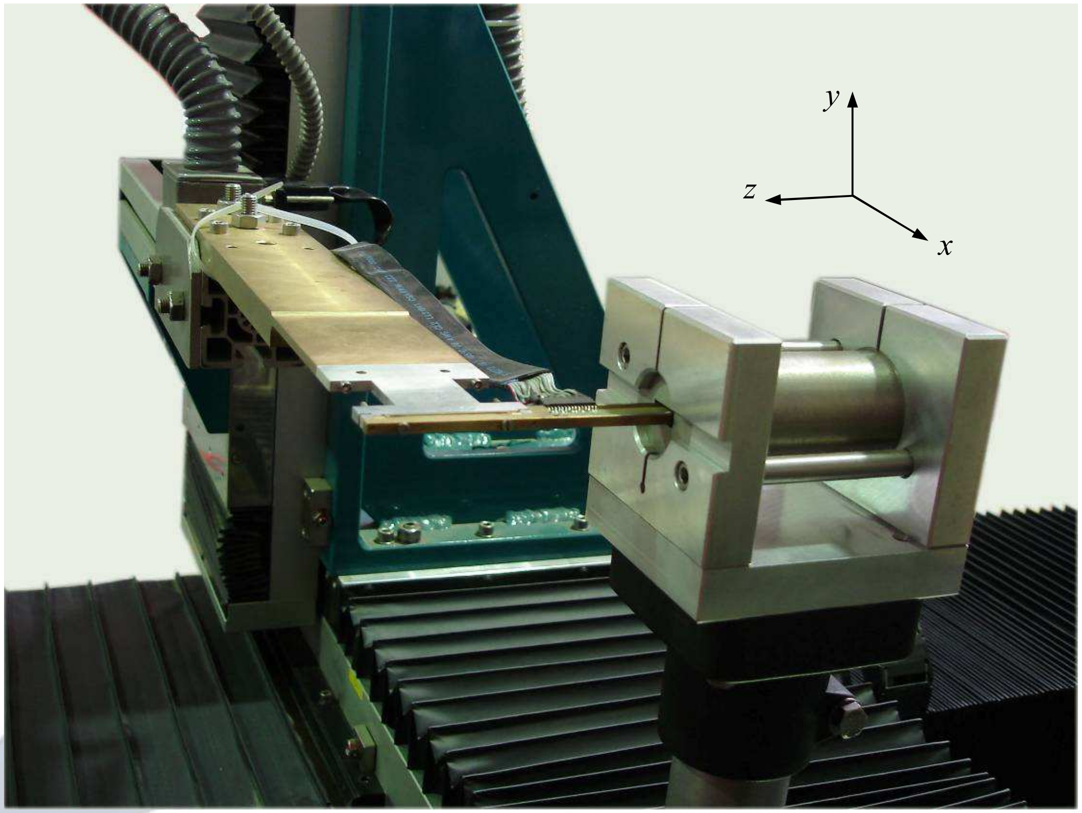




Selected material:

80%Ni-Fe μ-metal from ***Amuneal Manufacturing Corp.*** in the form of 0.062''=1.575 mm thickness sheets

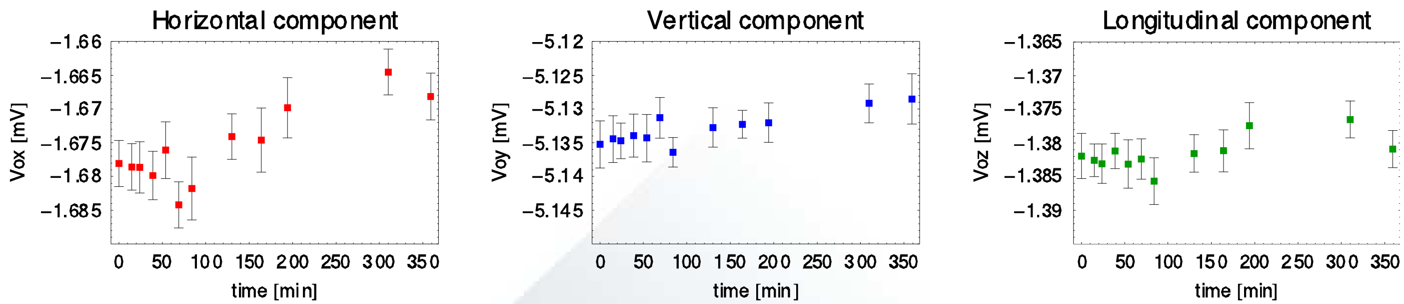
Determination of offsets



Shielding factor: $\eta = \frac{B_{\text{ext}}}{B_{\text{in}}}$ $\begin{cases} \text{Field along } x \text{ or } y\text{: } \eta \sim 1500 \\ \text{Field along } z\text{: } \eta \sim 700 \end{cases}$

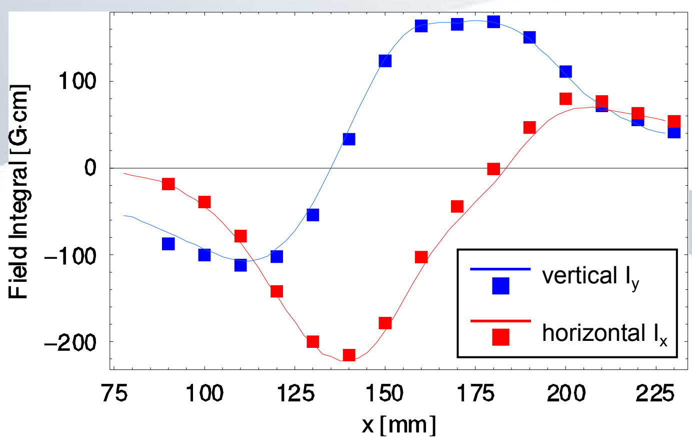
Determination of offsets

Evolution of offsets: drifts of ~10 μV observed within one session and up to ~50 μV from one day to another → systematic errors up to ~ 0.5 Gauss



Offsets have to be determined for each measurement!!

Comparison of field integral measured using flipping coil and determined using Hall probe



rms difference ~10 G·cm

Outline

- Introduction
- Magnetic measurements laboratory
- Upgrade of Hall probe bench
  - 3D Hall probe
  - 3D field calibration method
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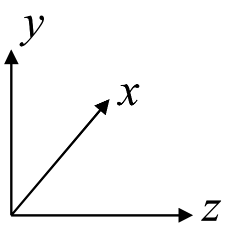
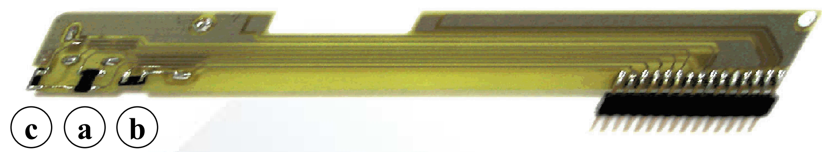
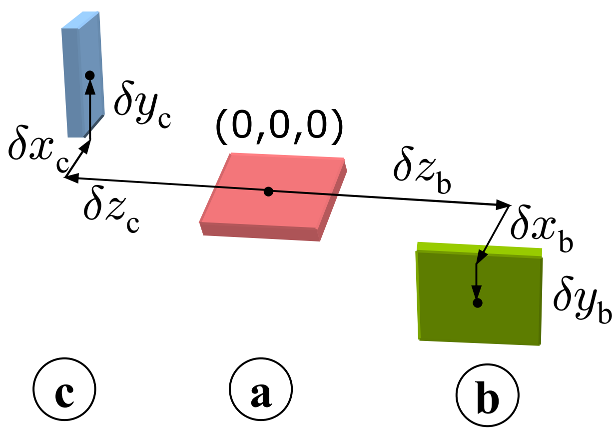
- Some results

Relative position between Hall sensors

Refinement of the relative positioning between the sensitive areas of the three sensors







Reference sensor

Ideal values by construction:

$$\begin{cases} \delta z_b = -\delta z_c = 5.5\,\mathrm{mm} \\ \delta x_b, \delta x_c = 0 \\ \delta y_b, \delta y_c = 0 \end{cases}$$

Relative position between Hall sensors

Determination of δx_{b}, δy_{b}, δz_{b}, δx_{c}, δy_{c} and δz_{c} using Maxwell equations:

Any magnetic field measured with the probe must fulfill:

$$\begin{cases} \vec{\nabla} \cdot \vec{B}(\vec{r}) = 0 \\ \vec{\nabla} \times \vec{B}(\vec{r}) = 0 \end{cases}$$

$$\Rightarrow \begin{cases} f_1(\vec{r}) = \partial_x B_x(\vec{r}) + \partial_y B_y(\vec{r}) + \partial_z B_z(\vec{r}) = 0 \\ f_2(\vec{r}) = \partial_y B_z(\vec{r}) - \partial_z B_y(\vec{r}) = 0 \\ f_3(\vec{r}) = \partial_z B_x(\vec{r}) - \partial_x B_z(\vec{r}) = 0 \\ f_4(\vec{r}) = \partial_x B_y(\vec{r}) - \partial_y B_x(\vec{r}) = 0 \end{cases}$$

$$\Rightarrow g(\vec{r})^2 \equiv f_1(\vec{r})^2 + f_2(\vec{r})^2 + f_3(\vec{r})^2 + f_4(\vec{r})^2 = 0$$

We define the “Maxwellness” of the measured field over a volume v as:

$$\boxed{\xi = \sqrt{\frac{1}{v} \int_v g(\vec{r})^2 \, \mathrm{d}v} = 0}$$

Relative position between Hall sensors

Measurement of a magnetic field with strong gradients in all three directions —all $(\partial B_i/\partial x_j)\neq 0$— within a given volume (15 × 15 × 15 mm^3) and optimization of $\delta x_{\rm b}$, $\delta y_{\rm b}$, $\delta z_{\rm b}$, $\delta x_{\rm c}$, $\delta y_{\rm c}$ and $\delta z_{\rm c}$ in order to minimize "Maxwellness" (ξ):

Correction of distances between sensors:

Sensor b

$$\Delta\delta x_{\rm b} = (-0.08 \pm 0.1)\,\mathrm{mm}$$
$$\Delta\delta y_{\rm b} = (-0.43 \pm 0.1)\,\mathrm{mm}$$
$$\Delta\delta z_{\rm b} = (-0.04 \pm 0.05)\,\mathrm{mm}$$

Sensor c

$$\Delta\delta x_{\rm c} = (+0.28 \pm 0.05)\,\mathrm{mm}$$
$$\Delta\delta y_{\rm c} = (+0.02 \pm 0.05)\,\mathrm{mm}$$
$$\Delta\delta z_{\rm c} = (+0.05 \pm 0.05)\,\mathrm{mm}$$

After optimization, "Maxwellness" reduced from ~ 1 Gauss/mm down to 0.1 Gauss/mm

Relative position of Hall sensors determined with an accuracy of ~50—100 µm

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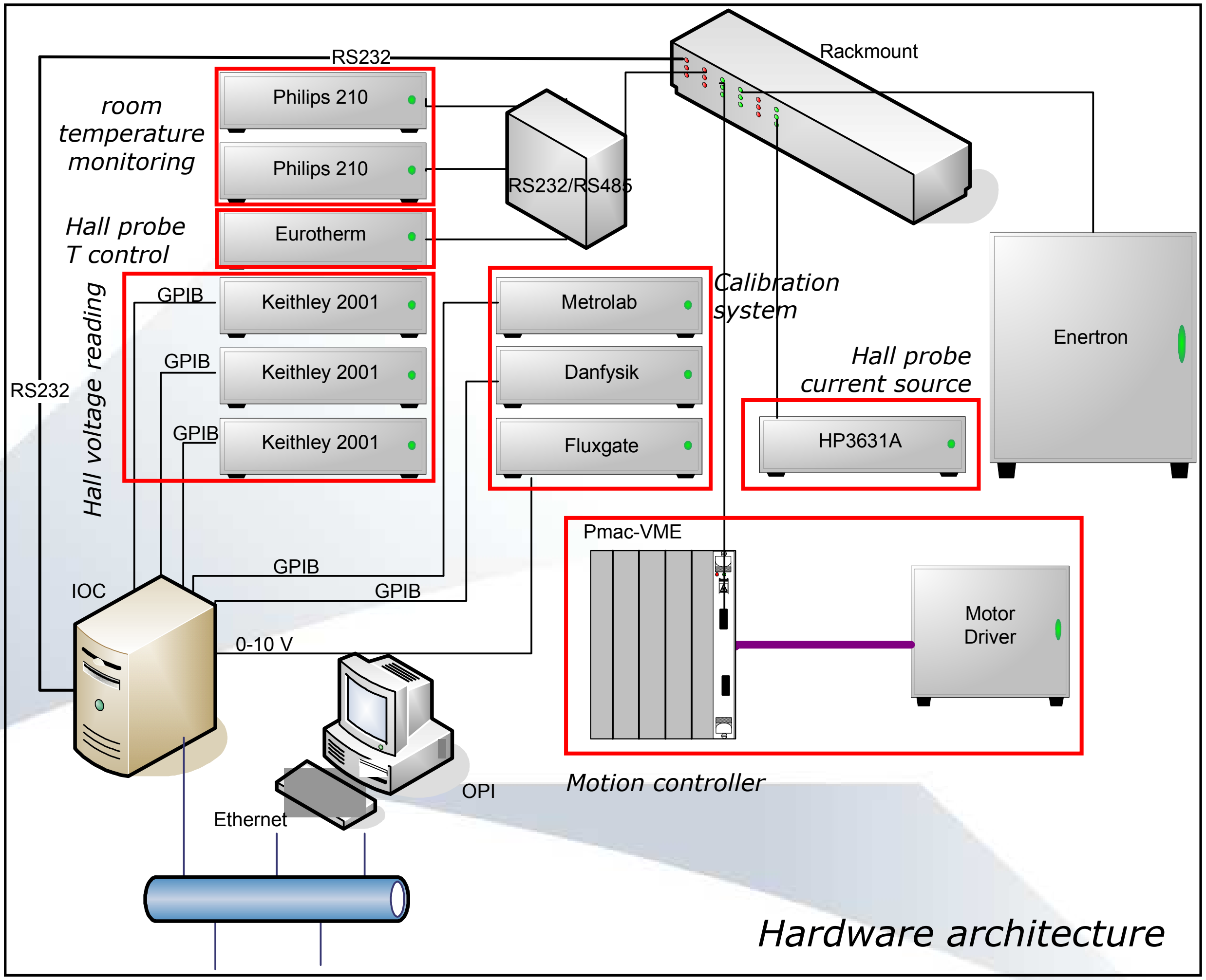
New TANGO control system

- Control system has been migrated from EPICS to TANGO
- New devices have been included (additional voltmeter for 3rd Hall sensor, fluxgate magnetometer…)
- On-the-fly measurement mode has been implemented

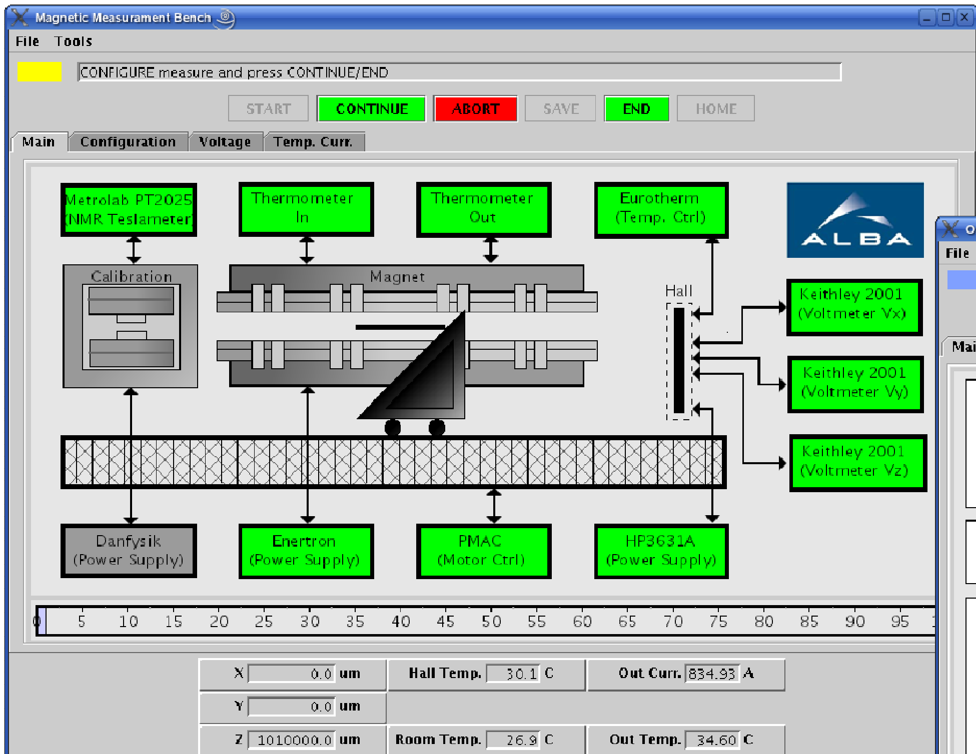


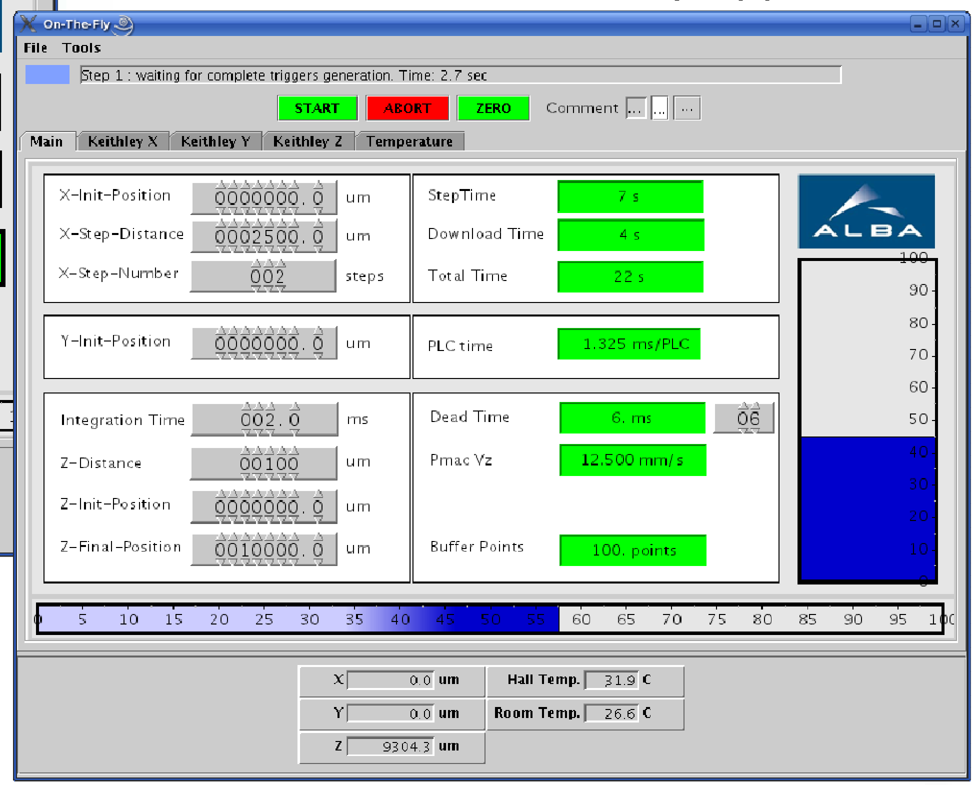
Hardware architecture

New TANGO control system

GUI screenshots

on-the-fly application





point-to-point application

On-the-fly measurement mode

Characteristics of on-the-fly measurement mode:

- Maximum velocity v_z= 16 mm/sec
- Minimum step size δz= 20 µm
- Min. "dead time" between acquisitions $\delta\tau$=6 msec
- Max. number points/scan 30000

Performance of on-the-fly measurement mode:

(when measuring a periodic device with 10^3 Gauss peak field)

- Repeatability between different scans **~0.5 Gauss *rms***
- Agreement between point-to-point and on-the-fly measurement **~0.5 Gauss *rms***

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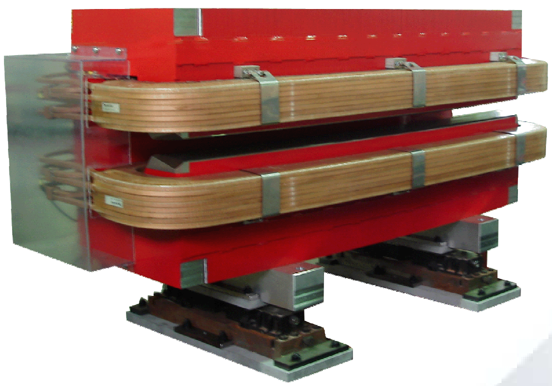
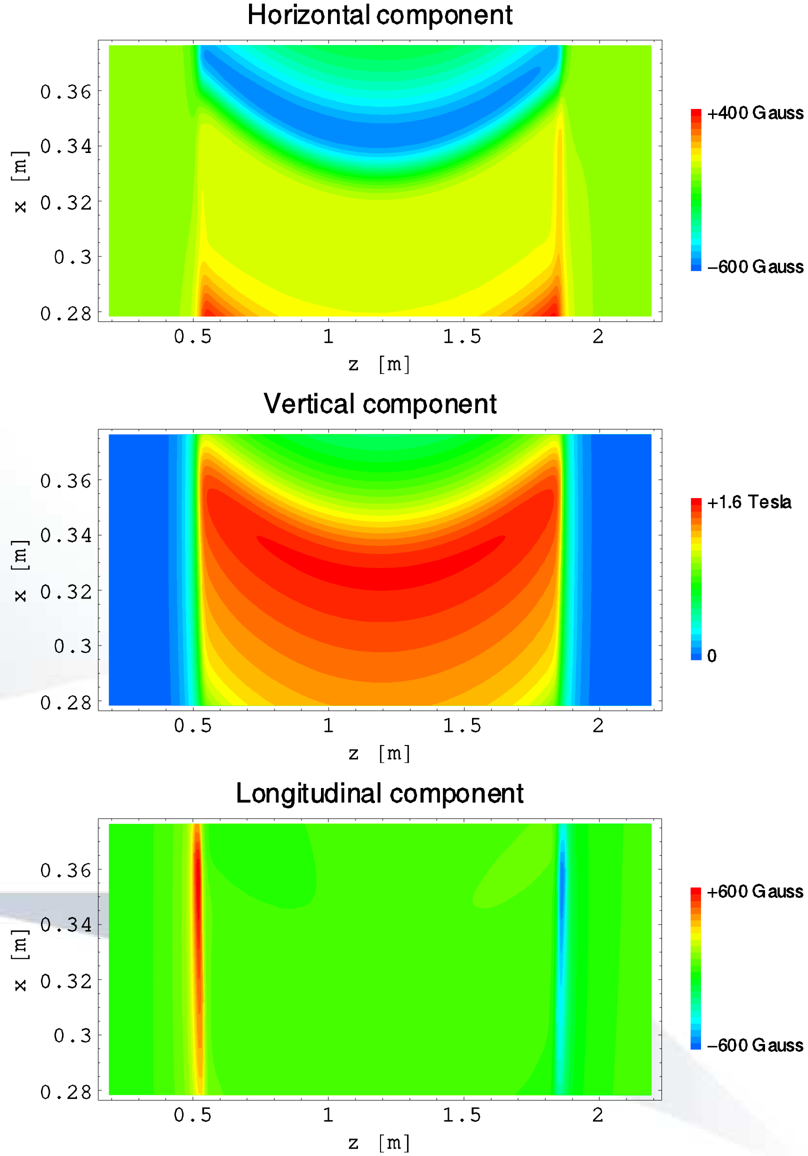
Measurement of pre-series Storage Ring Bending Magnet
(combined function magnet produced by Danfysik)



Measurement parameters:
- Scan range: $\Delta x \times \Delta z$ = 98mm $\times$ 2000mm
- Scan grid: $\delta x \times \delta z$ =2mm $\times$ 1mm
- # of points/map: 98000 points
- measurement time ~2 hours

Measurement at y=+2mm above mid-plane:



Measurement of pre-series Storage Ring Bending Magnet

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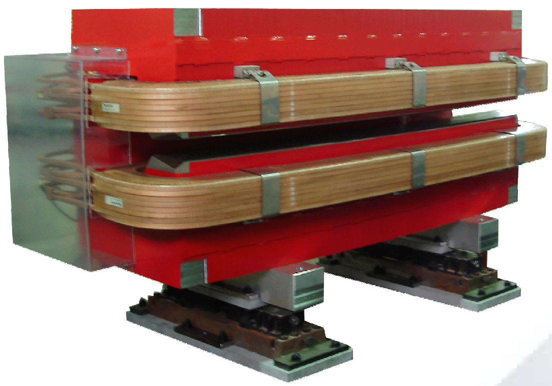
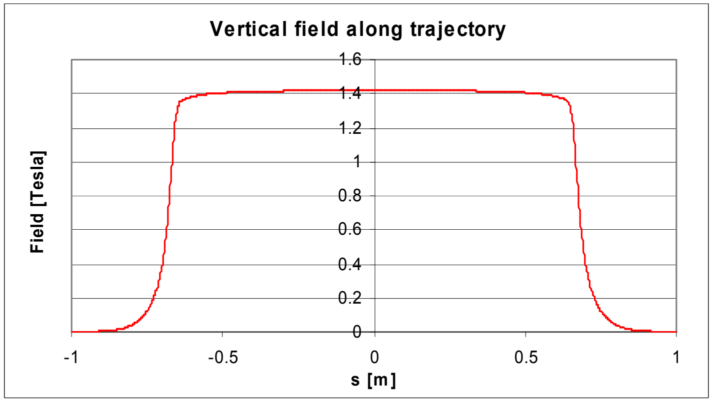
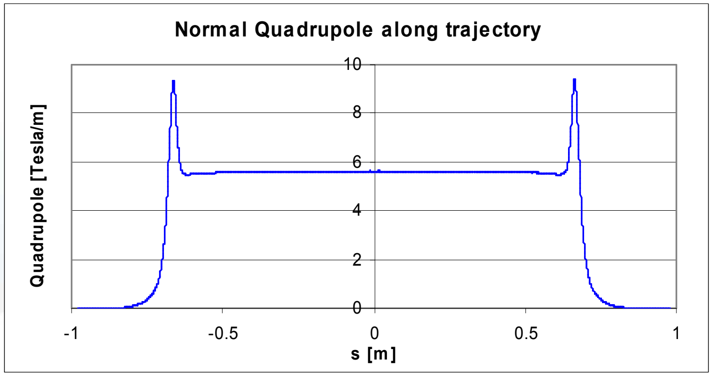
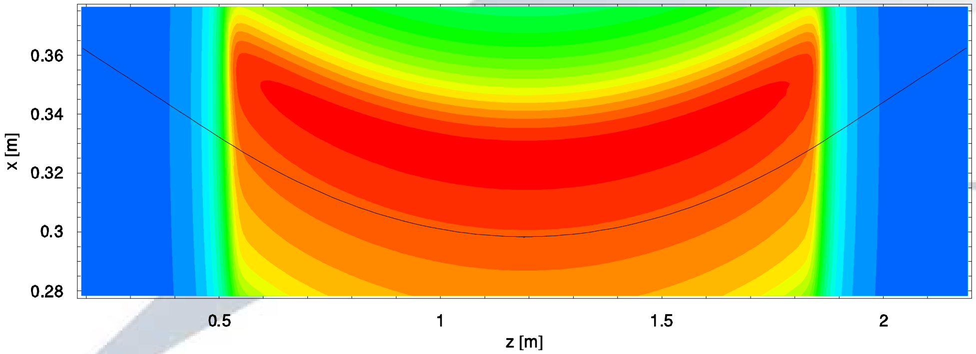
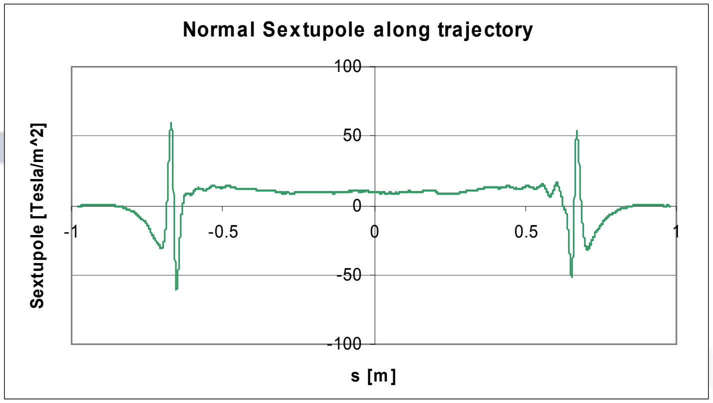






Measurement at y=0 (mid-plane):





Thanks for your attention