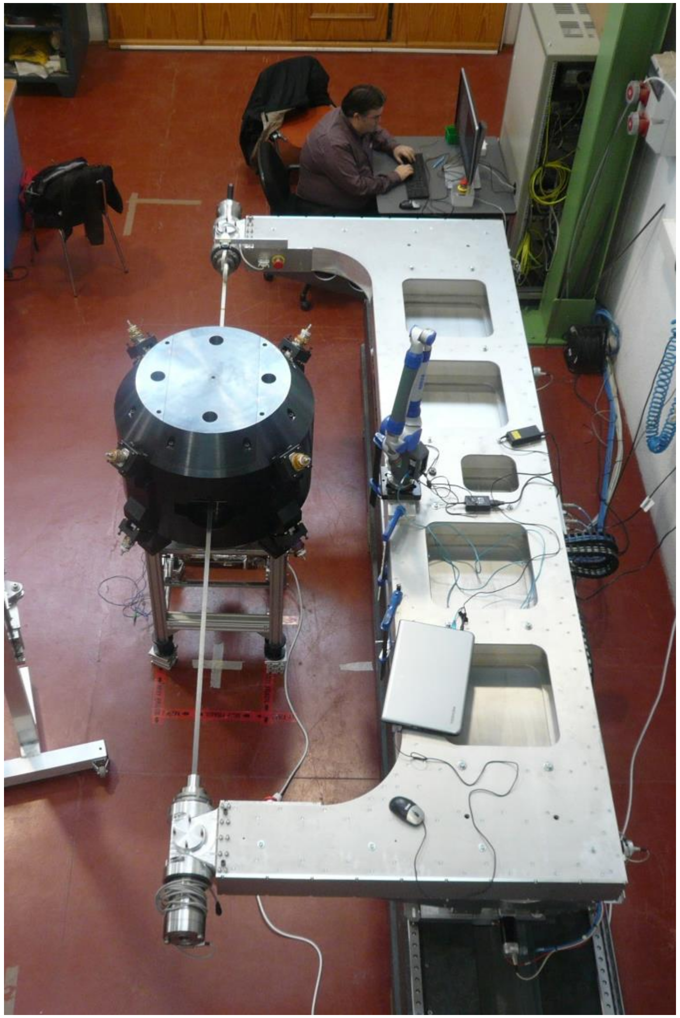
Last developments at ALBA magnetic measurements laboratory



J.Marcos on behalf of ID Section

Outline

1 Introduction	2 Hall probe system
3 Latest developments	4 Conclusions

Outline

1
Introduction

2
Hall probe system

3
Latest developments

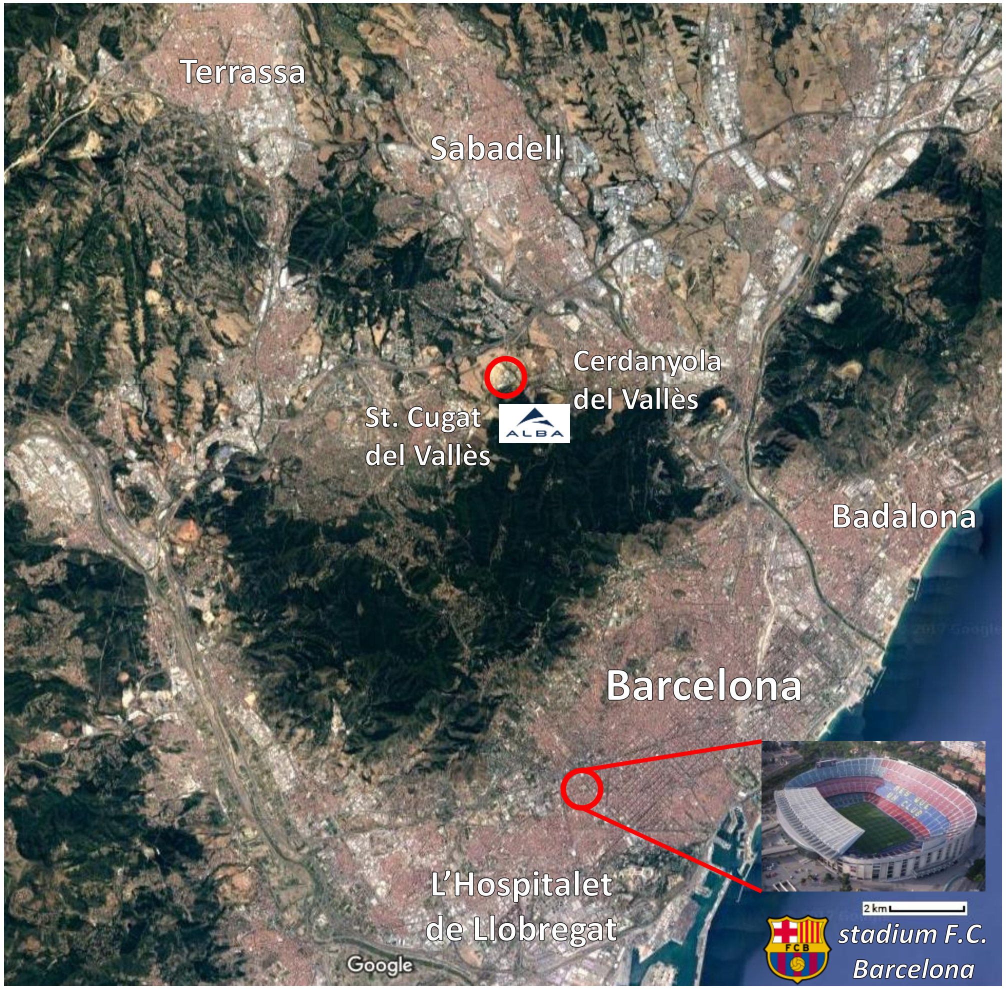
4
Conclusions

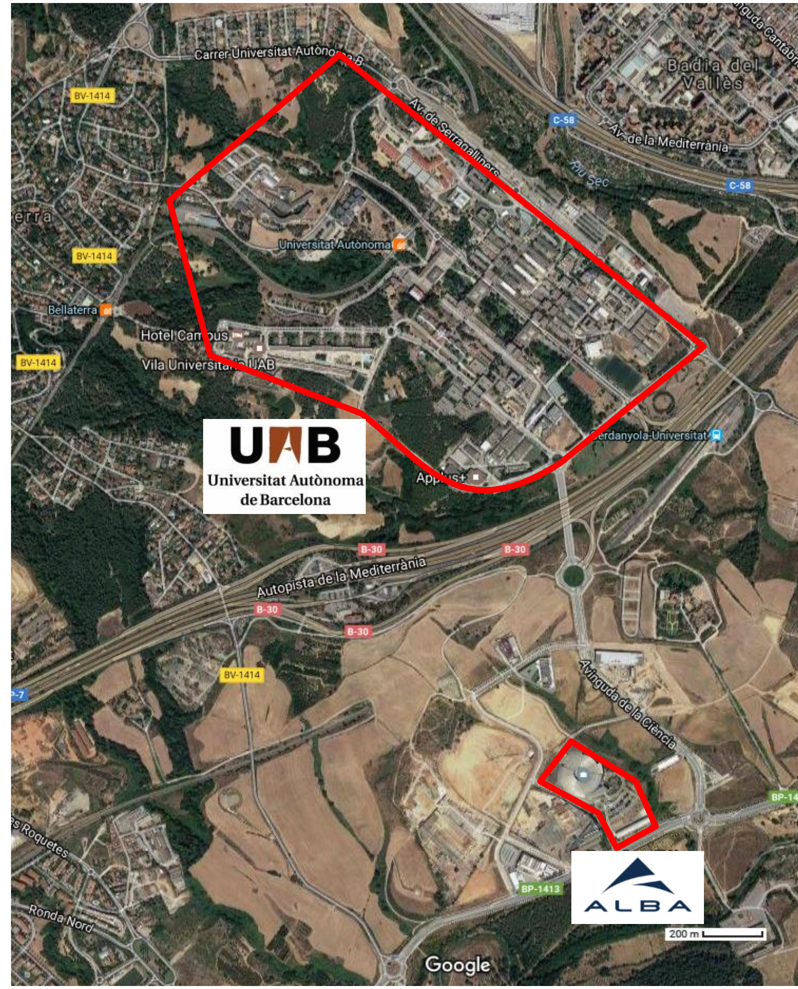
Who are we?

- **ALBA** is a 3rd generation Synchrotron Light Source open to users since **2012** in Cerdanyola del Vallès, close to Barcelona.
- ALBA operates at an electron beam energy of **3GeV**. It is currently running **8 Beamlines**, with an additional 1 under construction, and 2 more with their budget approved.
- The consortium in charge of building and operating ALBA, **CELLS**, was founded on **2003**.
- However, since **1996** some infrastructure already existed associated to the former consortium **LLS**, devoted to promoting the construction of a synchrotron light source in the Barcelona area.
- That infrastructure included a **laboratory for the testing and development of magnetic structures**, sited in the premises of Universitat Autònoma de Barcelona (UAB).
- This laboratory was afterwards moved to ALBA site on **2009**.

Introduction

Where are we?





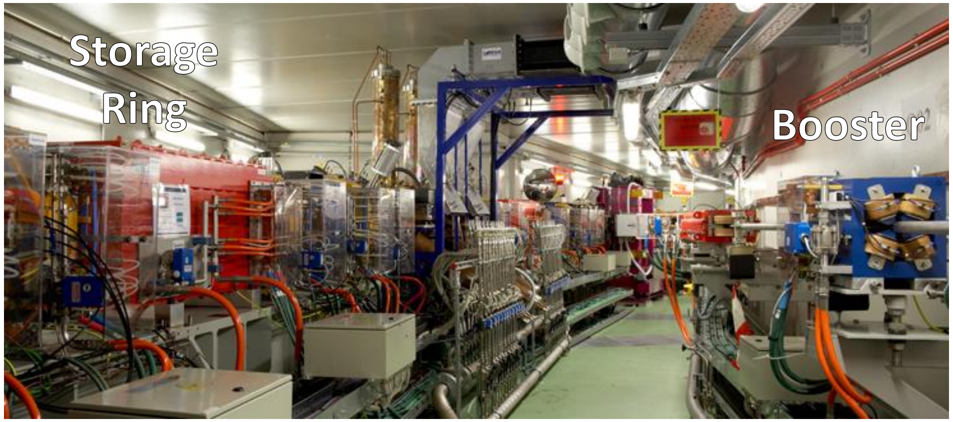
Introduction

The ALBA site

Aerial view of ALBA site

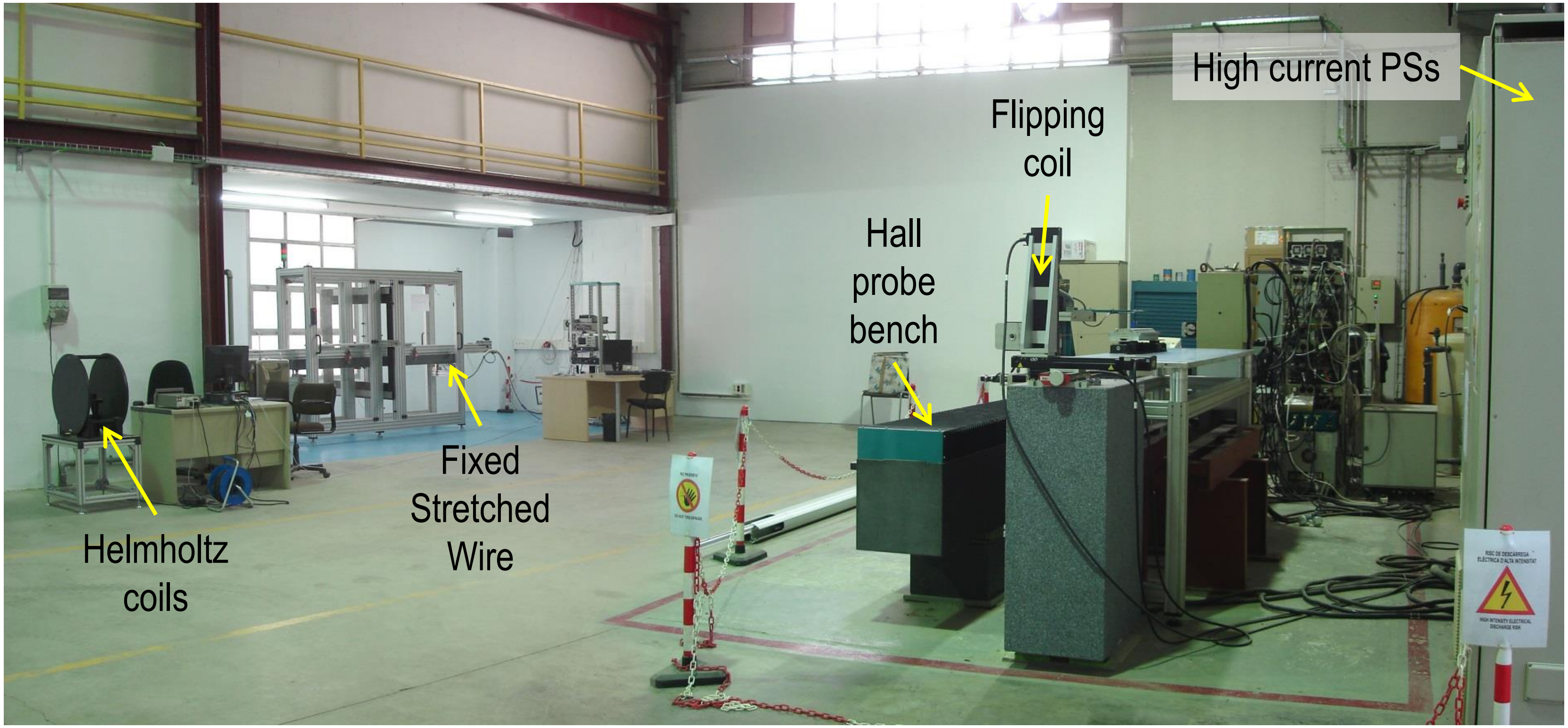
Inside Main Building

Inside accelerator tunnel



Introduction

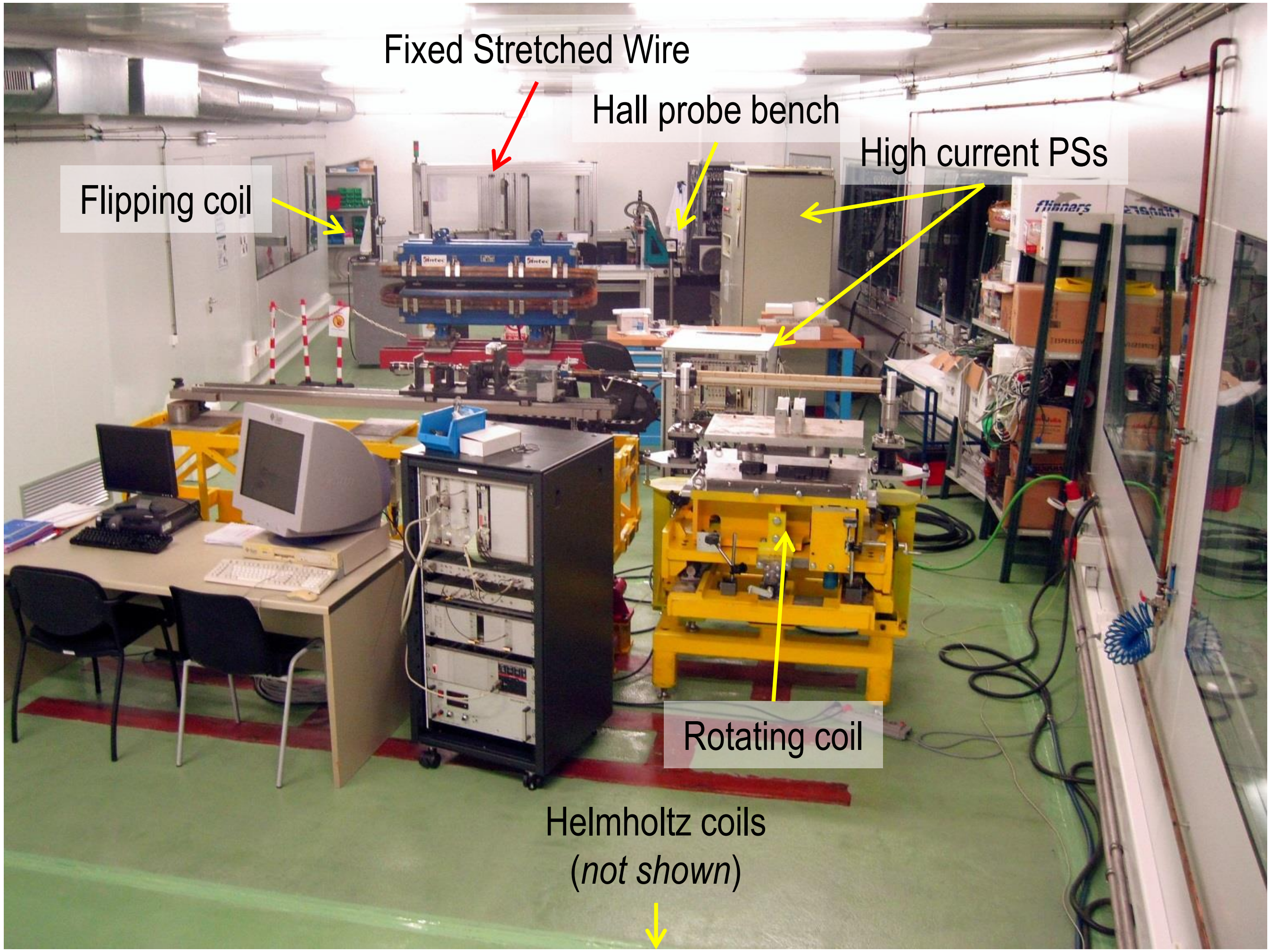
Magnetic measurements laboratory at UAB (1998-2009)



- 160m^2 area
- High ceiling "industrial unit"-type structure without temperature control
- Up to 5° thermal drift within a single day, up to 10° over the whole year

Introduction

Magnetic measurements laboratory at ALBA site (2009-)



- 150 m² laboratory
- Enclosed space inside service area with removable roof and independent AC system
- **Temp. controlled ±0.1ºC**

Introduction

Available systems in the laboratory

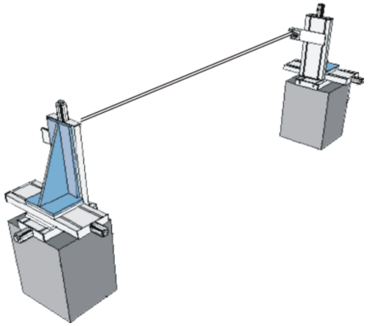
Hall probe bench

- Produced by Ramem (1997)
- General purpose bench
- 3D field mapping with a longitudinal range of 3 m

Rotating coil bench

- Purchased 2nd hand from CERN (2008)
- General purpose bench
- Determination of integrated field harmonics of magnets with lengths up to 0.5 m

Flipping coil bench



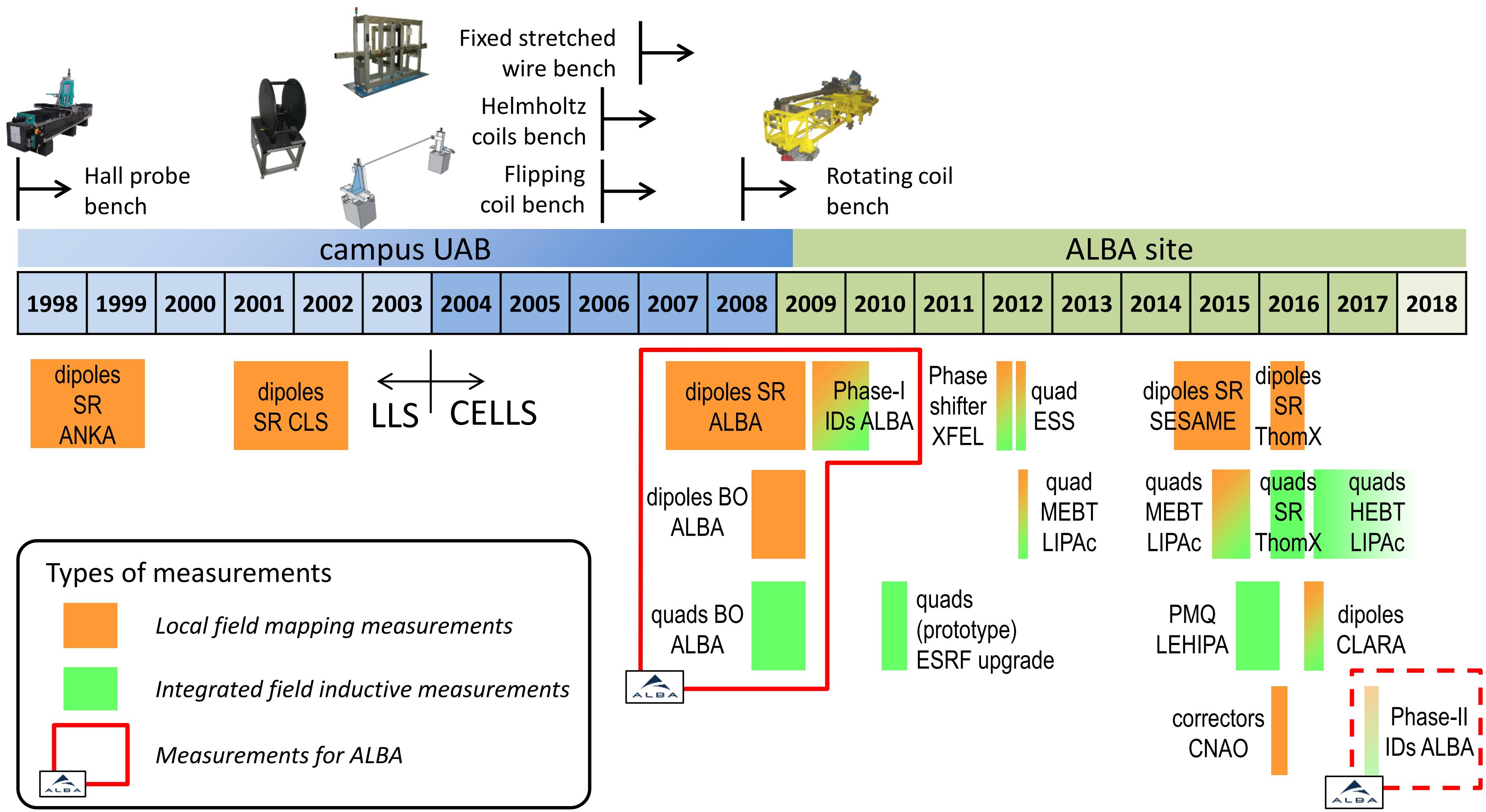
- Produced by ESRF (2006)
- Determination of low-value field integrals from small gap devices
- Insertion Device-oriented bench

Helmholtz coils & Fixed Stretched Wire

- Helmholtz coils: produced by Elettra (2006)
- Fixed Stretched Wire: in-house development (2007)
- Characterization of magnet blocks for Insertion Devices (IDs)

Introduction

Magnetic measurements campaigns at LLS and ALBA: a quick overview



Introduction

Magnetic measurements campaigns in images

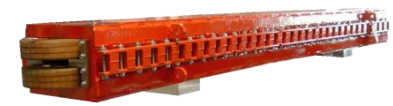
- ANKA SR dipoles (×16)
- Pure dipoles
- 1.5 Tesla, L_{eff}=2.18 m

- CLS SR dipoles (×24)
- Combined function dipoles
- 1.35 Tesla, L_{eff}=1.9 m

Canadian Light Source Centre canadien de rayonnement synchrotron

- ALBA SR dipoles (×32+1)
- Combined function dipoles
- 1.42 Tesla, L_{eff}=1.4 m

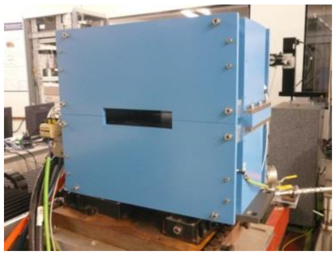
- ALBA BO dipoles (×32 + ×8)
- Combined function dipoles
- 0.87 Tesla, 2 m / 1 m
- Only characterization of edges



- SESAME SR dipoles (×16+1)
- Combined function dipoles
- 1.46 Tesla, L_{eff}=2.25 m

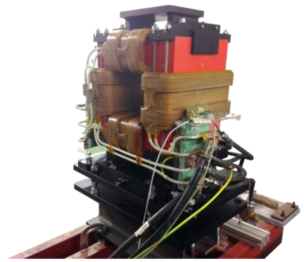
- ThomX SR dipoles (×15)
- Pure dipoles
- 0.63 Tesla, L_{eff}=0.3 m

- CLARA bunch compressor dipoles (×4)
- Pure dipoles
- 0.5 Tesla, L_{eff}=0.23 m



Science & Technology Facilities Council

- CNAO correctors (×2)
- Frame corrector
- 0.06 Tesla, L_{eff}=0.5 m

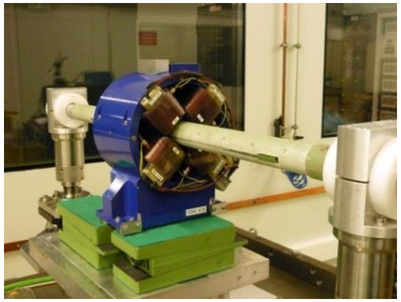


Introduction

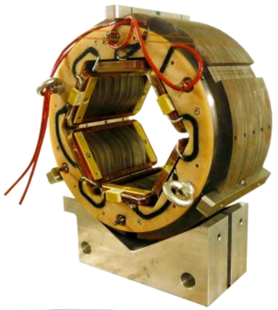
Magnetic measurements campaigns in images

- Prototype phase shifter for E-XFEL

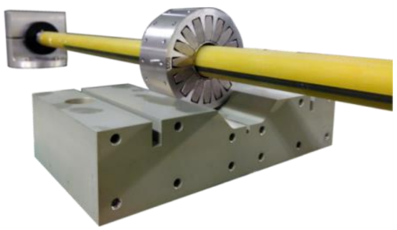
- ThomX SR quadrupoles (×34) and sextupoles (2 tested)



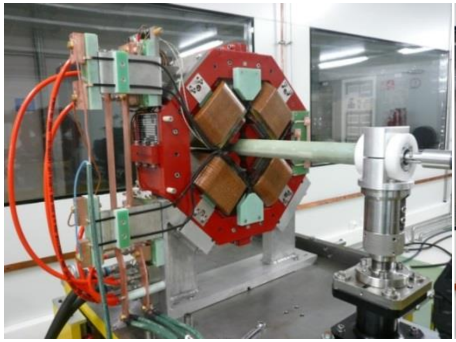
- Superferric sextupole for LHC upgrade

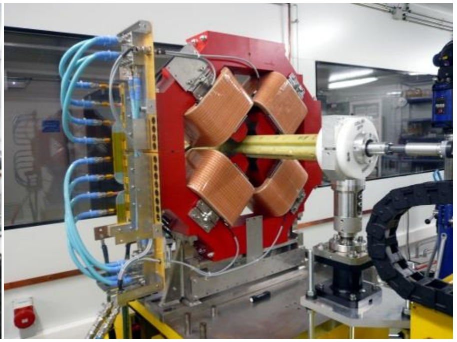


- Permanent magnet quadrupoles for DTL of LEHIPA accelerator in BARC (India)



- Quadrupoles+steerers for MEBT (×5) and HEBT (×8) of LIPAc accelerator (IFMIF project)



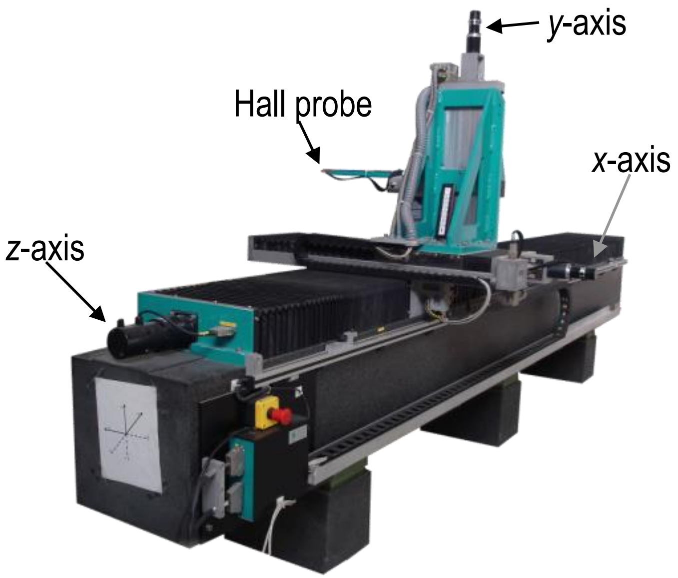


Outline

1 Introduction	2 Hall probe system
3 Latest developments	4 Conclusions

Hall probe system

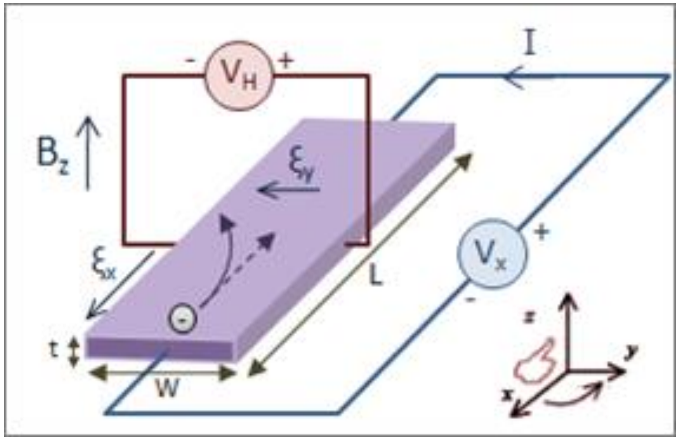
Characteristics of Hall probe bench at ALBA



- Scanning volume ($\Delta x \times \Delta y \times \Delta z$)=500×250×3000 mm^3
- DC motors for all 3 axes with PMAC controller
- Maximum velocity: v_z= 16 mm/sec
- 3-axis Hall probe with temperature control
- Hall voltages recorded using Keithley 2001 voltmeters
- Magnetic field absolute accuracy ~50µT
- TANGO control system
- **point-to-point** and **on-the-fly** measurement modes

Hall effect

Definition: production of a voltage difference across an electrical conductor transverse to an electric current in the conductor and a magnetic field perpendicular to the current



Ideal (linear) Hall effect:

$$V_H(B_z) = I_c \frac{R_H}{t} B_z = c_1 \, B_z$$

I_c: control current
t: plate thickness
R_H: Hall coefficient
B_z: field component ⊥ to the plate
c_1: magnetic sensitivity

Real Hall effect:

$$V_H(B_x, B_y, B_z, T) = \underbrace{V_{\text{offset}}}_{\text{Offset voltage}} + \underbrace{c_1(T)}_{\text{Thermal dependence}} B_z + \underbrace{c_p \, B_x B_y}_{\text{Planar Hall effect}} + \underbrace{o(B^2)}_{\text{Non-linearities and higher order cross-terms}}$$

Hall probe system

Issues with Hall probe systems

Issue	Solution
Non-linearities and cross-terms between field components (planar Hall effect and higher order terms)	Calibration against a precise reference (NMR) involving all 3 field components to remove cross-terms
Thermal dependence of Hall coefficient	Proper calibration of thermal dependence and measurement of temperature and/or temperature stabilization of Hall sensor
Non-zero offset ($V_{Hall} \neq 0$ at B=0) drifting with time	Measurement of voltage offset using a zero gauss chamber before/after each measurement
Relative position of Hall sensors in case of using several uniaxial sensors mounted on a common board	Self-consistent determination of relative positions using Maxwell equations
Absolute position of the Hall probe with respect to the laboratory system of reference	Usage of a magnetic structure defining a singular point of the magnetic field (magnetic cones or similar)
Orientation of the Hall probe with respect to the laboratory system of reference	Usage of a magnetic structure generating a magnetic field with a well defined direction (reference dipole)

Hall probe system

3D Hall probe at ALBA

In-house circuit board with **3-orthogonally mounted 1-axis Hall** sensors from **F.W. Bell**, a **Pt-100 for temperature measurement**, and a **heater** to keep a constant probe temperature

F.W. Bell Hall sensors

Gallium Arsenide planar sensors

Nominal current: I_{nom} =5 mA (I_{max} =12 mA)

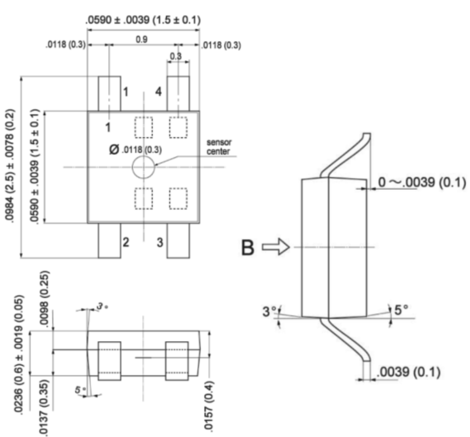
Magnetic Sensitivity ~ 1 V/Tesla

Max. linearity error (±1 Tesla): ±2%

Temperature coefficient: -0.07%/ºC

Sensitive area ∅: ~0.3mm

Cost: ~10€/sensor



Dimensions:

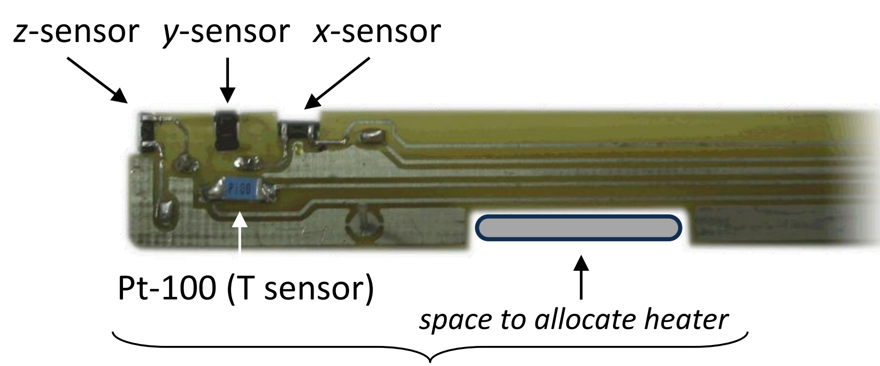
GH-700 (*discontinued*)

area	2.9×1.5mm²
thickness	1.1mm

GH-701

area	**1.5×1.5mm²**
thickness	**0.6mm**

Detail of Hall probe circuit board:



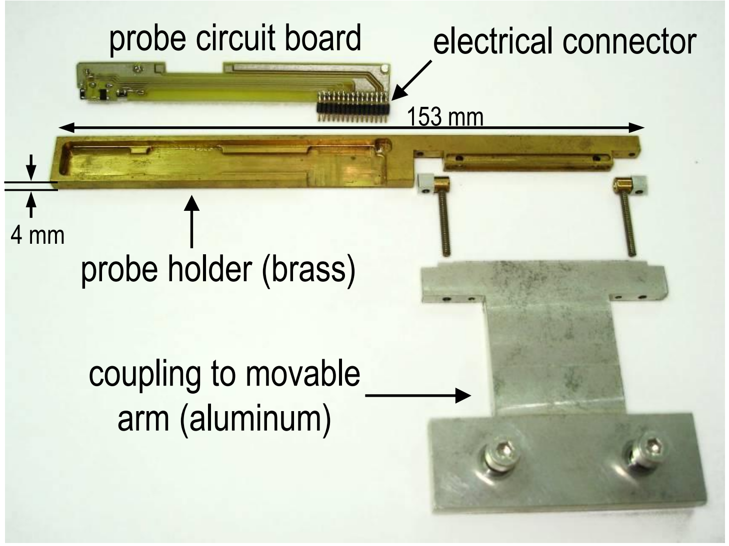
the temperature sensor and the heater, in combination with a PID controller (*Eurotherm 3508*) allow to **control the temperature of the probe within ±0.05ºC**

Hall probe system

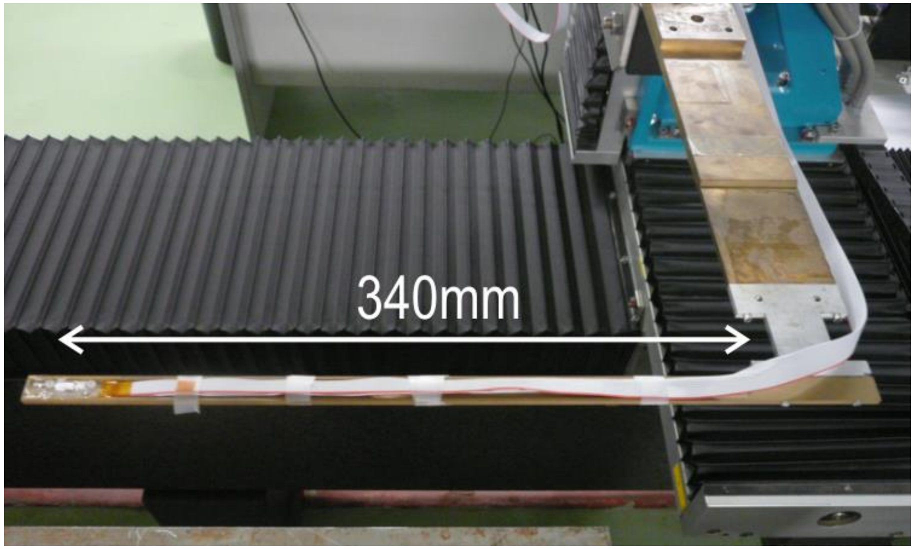
Probe mechanical assembly

- Circuit board with Hall sensors is mounted onto a **brass holder** in order to improve **mechanical rigidity** and **temperature homogeneity** of the probe.
- Circuit board is bounded to the probe holder using a **good thermal conductivity** & **electrically insulating** adhesive (Arctic Alumina™ from Arctic Silver).
- Probe holder **thickness** (**4mm**) allows measuring Insertion Devices at ALBA at minimum gap (5mm).
- Special probes with increased length have also been produced in order to get access to closed structures.

Piece breakdown of conventional probe



Special probe with increased length

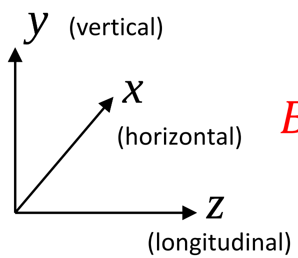


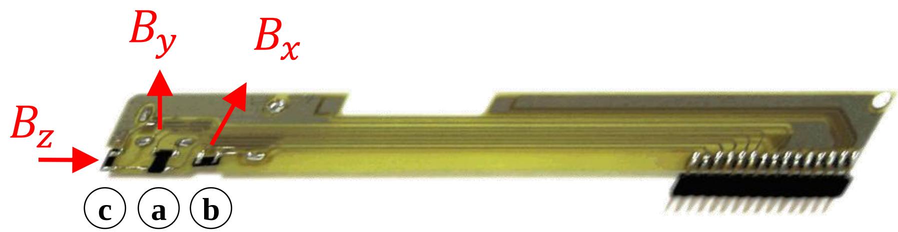
Hall probe system

Hall probe calibration

- To reproduce the response of the Hall probe to an arbitrary field, a model is used that takes into account **non-linearities**, **cross-terms** between different magnetic field components (planar Hall effect and others), and the **non-orthogonality** between the 3 Hall sensors mounted on the probe.
- More details of our approach can be found in:
  - J. Marcos *et al* (2007), "*Construction & Commissioning of a 3D Hall probe bench for Insertion Devices measurements at ALBA Synchrotron Light Source*", presented at 15th IMMW, Aug 21-24, 2007, Fermilab

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





- By applying magnetic fields of known intensity (NMR standard) inside a calibration magnet for **different orientations** of the Hall probe, it is possible to determine all the parameters characterizing the Hall probe.
- Afterwards, an arbitrary magnetic field can be **reconstructed from the measured voltages** (V_a, V_b, V_c) by solving a **non-linear system of equations**.

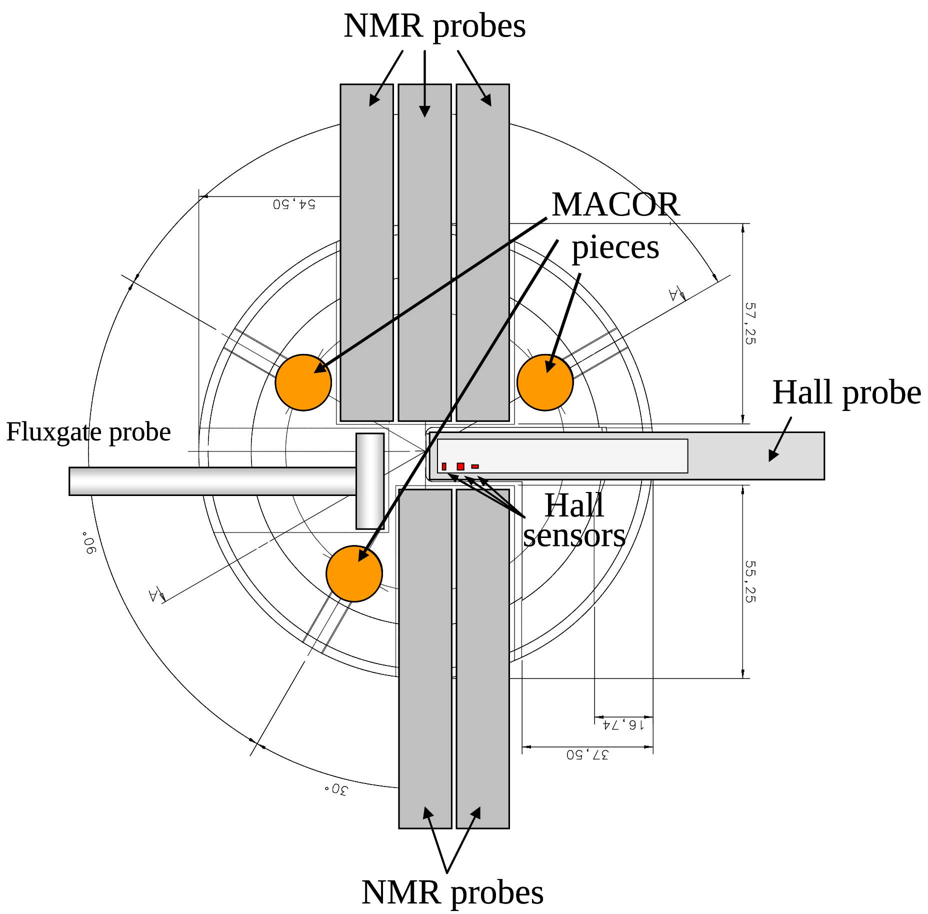
Hall probe system

Calibration system

- Dipole Magnet **GMW 3473-50 150 MM**
- Power supply **Danfysik 858**
- NMR 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

Typical residual *rms* error of the calibration data is **20 µTesla**

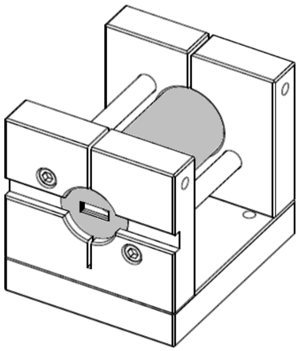


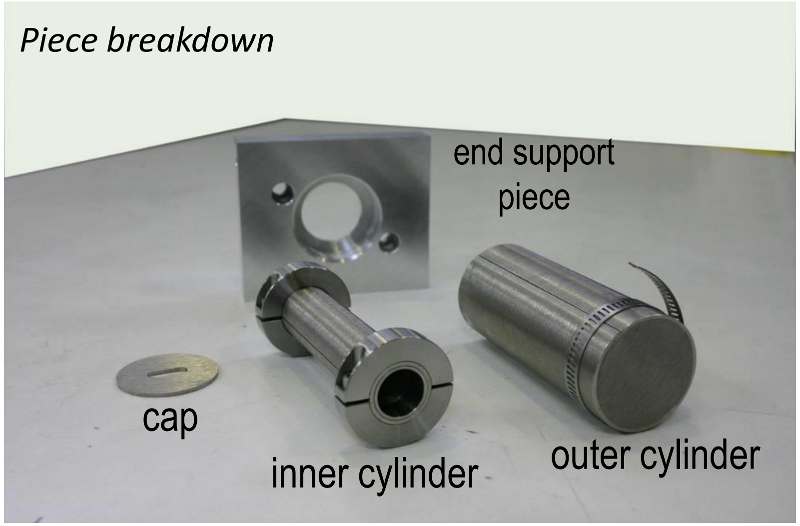
Hall probe system

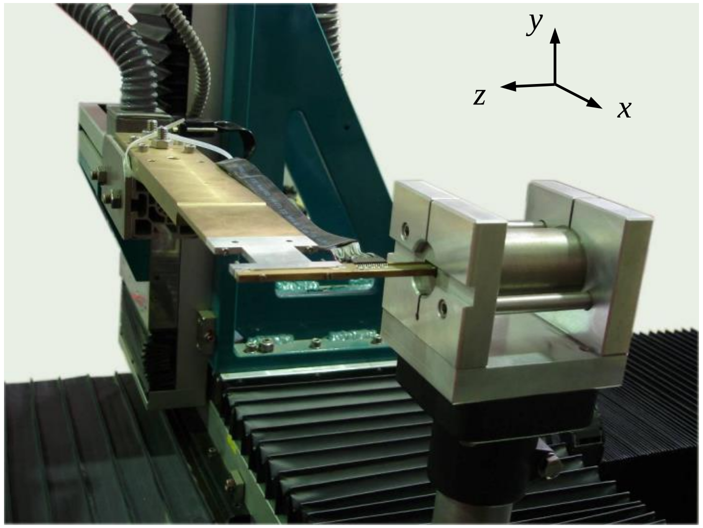
3rd PACMAN workshop

Offset voltage: Zero gauss chamber

- A **double layer µ-metal chamber** was designed and constructed in-house (2006) in order to measure the offsets of the Hall sensors.
- The selected material was 80%Ni-Fe µ-metal with a thickness of 1.575mm.







- The chamber provides a **shielding factor** of $\eta \sim 1500$ along the **radial direction** and $\eta \sim 700$ along the **axial direction**.
- It has been determined that the offset of Hall sensors drifts up to **~10 µTesla within a working day**, and up to **~50 µTesla from one day to the other**, making it advisable **to measure the probe offset before and after each long measurement**.

Relative distances between sensors

- A self-consistent method based on **Maxwell equations** is used in order to determine the **relative positioning between the sensitive areas** of the three Hall sensors
- Any magnetic field must fulfill:

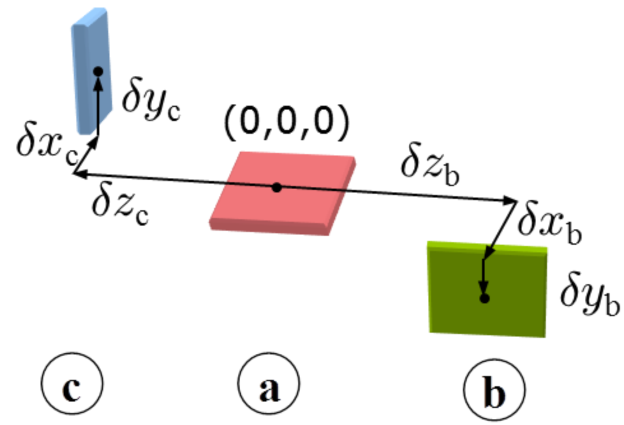
$$\begin{cases} \vec{\nabla}\cdot\vec{B} = 0 \\ \vec{\nabla}\times\vec{B} = 0 \end{cases}$$

- Therefore

$$\begin{cases} f_1(\vec{r}) = \partial_x B_x(\vec{r}) + \partial_y B_y(\vec{r}) + \partial_z B_Z(\vec{r}) = 0 \\ f_2(\vec{r}) = \partial_y B_z(\vec{r}) - \partial_z B_y(\vec{r}) = 0 \\ f_3(\vec{r}) = \partial_z B_x(\vec{r}) - \partial_x B_z(\vec{r}) = 0 \\ f_4(\vec{r}) = \partial_x B_y(\vec{r}) - \partial_y B_x(\vec{r}) = 0 \end{cases} \Rightarrow g(\vec{r})^2 \equiv f_1(\vec{r})^2 + f_2(\vec{r})^2 + f_3(\vec{r})^2 + f_4(\vec{r})^2 = 0$$

- Over a given volume v we can define:

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

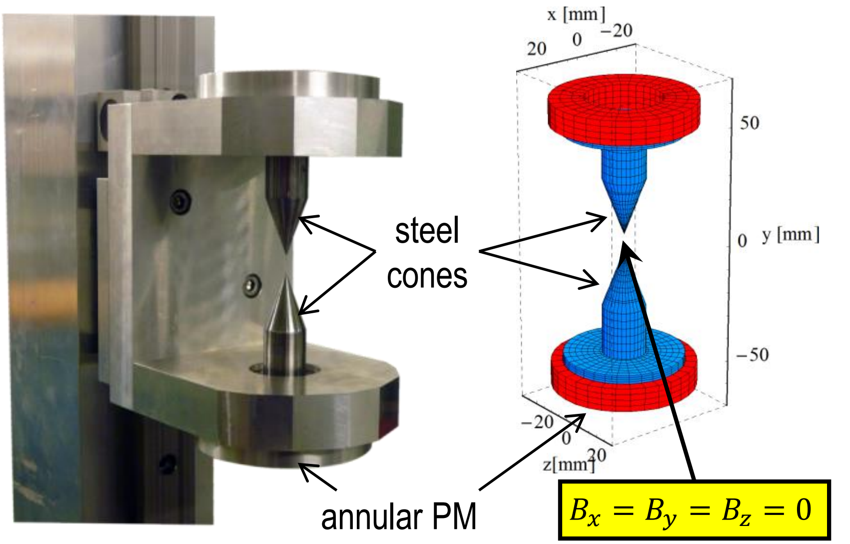


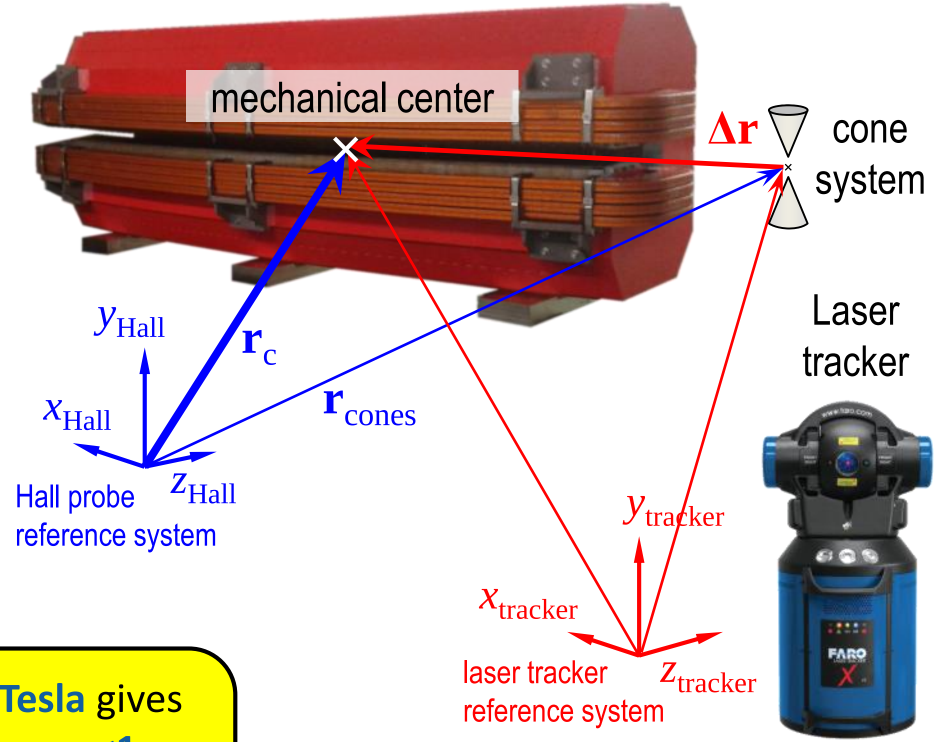
- By measuring a magnetic field with **strong gradients** in all three directions it is possible to determine the values $\delta x_b, \delta y_b, \delta z_b, \delta x_c, \delta y_c$ and δz_c with an accuracy of **50-100µm**

Hall probe system

Absolute positioning of Hall probe: magnetic cones

- A system of **magnetic cones** defining a **point of zero magnetic field** at their center is used as a reference to locate the **sensitive area of the Hall probe** in the system of reference of the laboratory





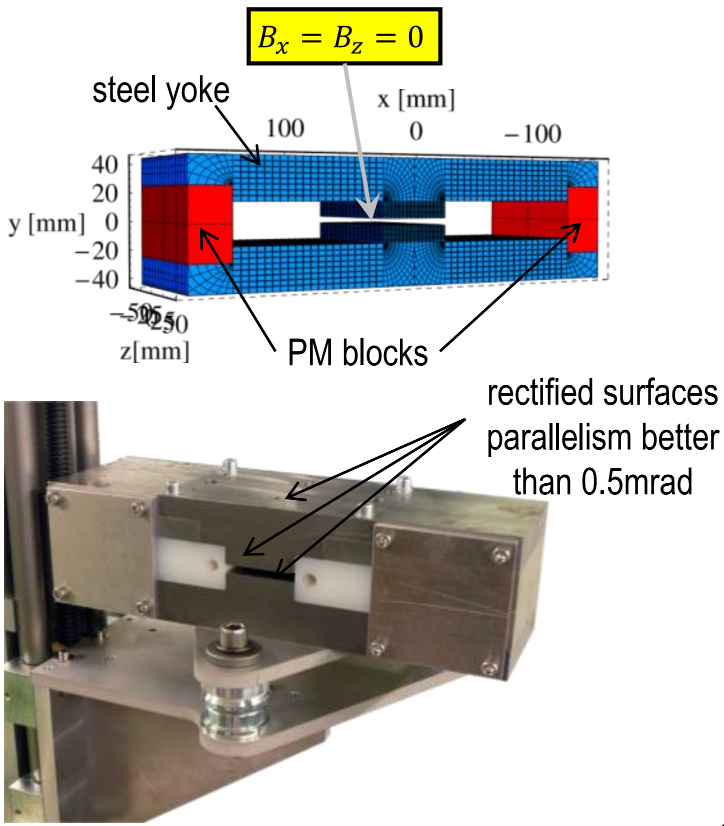
$$\frac{\partial B_x}{\partial x} = +14\ \mu\text{Tesla}/\mu\text{m}$$
$$\frac{\partial B_z}{\partial z} = +14\ \mu\text{Tesla}/\mu\text{m}$$
$$\frac{\partial B_y}{\partial y} = -28\ \mu\text{Tesla}/\mu\text{m}$$

a field error of **10µTesla** gives rise to positioning errors **<1µm**

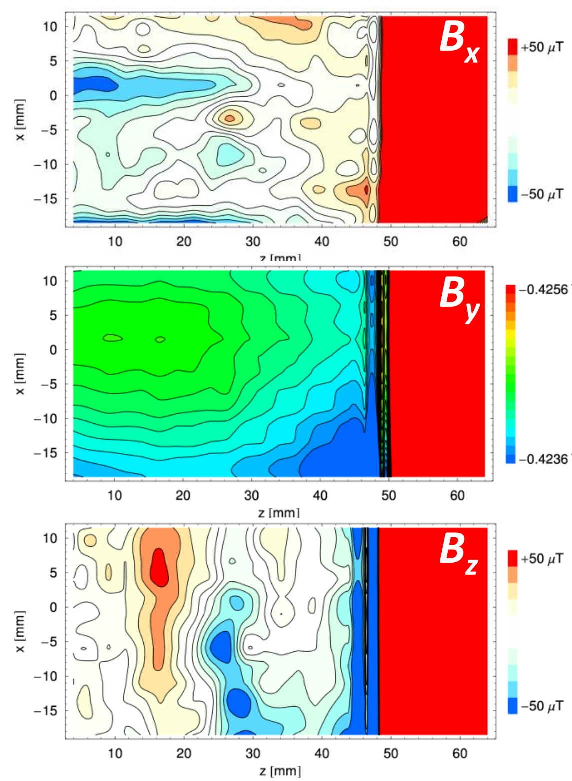
Hall probe system

Hall probe alignment: reference dipole

- In order to determine the **orientation of the Hall probe relative to gravity**, we use a **permanent dipole** generating a magnetic field perpendicular to its rectified top surface



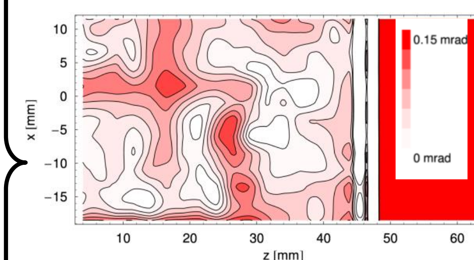
Fieldmap in the central region



Major component (B_y) homogeneous within **±0.5mT**

Minor components (B_x & B_z) smaller than **±0.05mT**

Polar angle of magnetic field vector



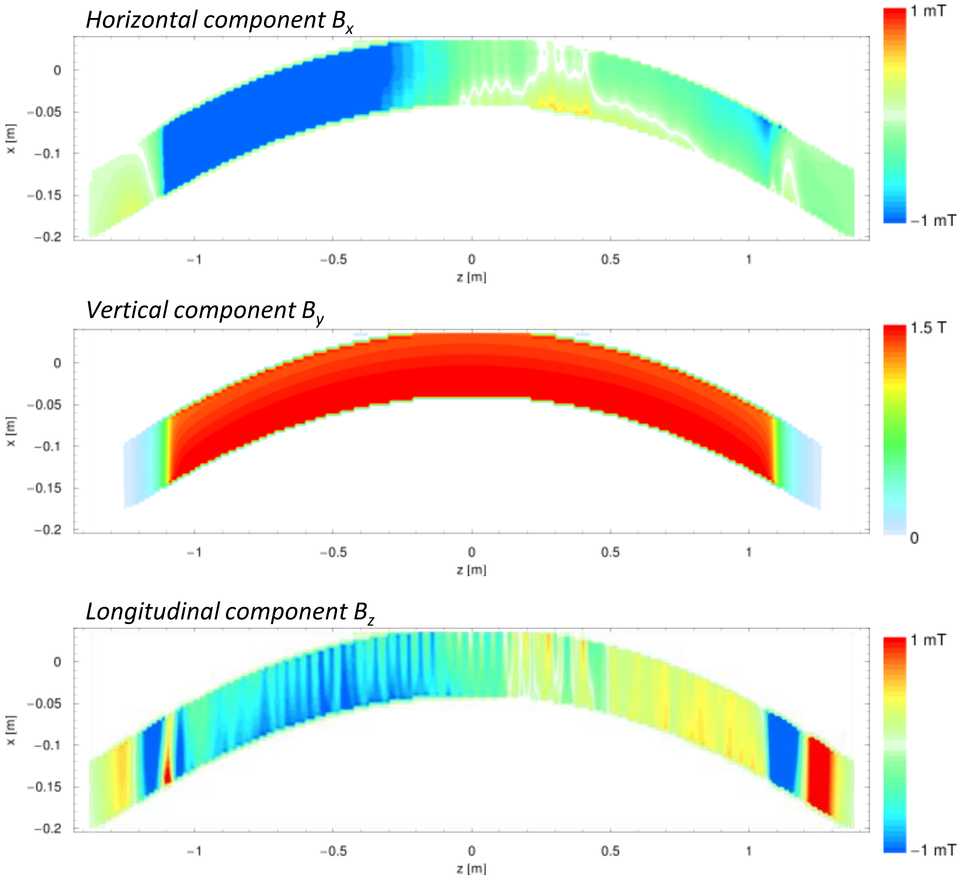
alignment accuracy of **0.20 mrad**

Hall probe system

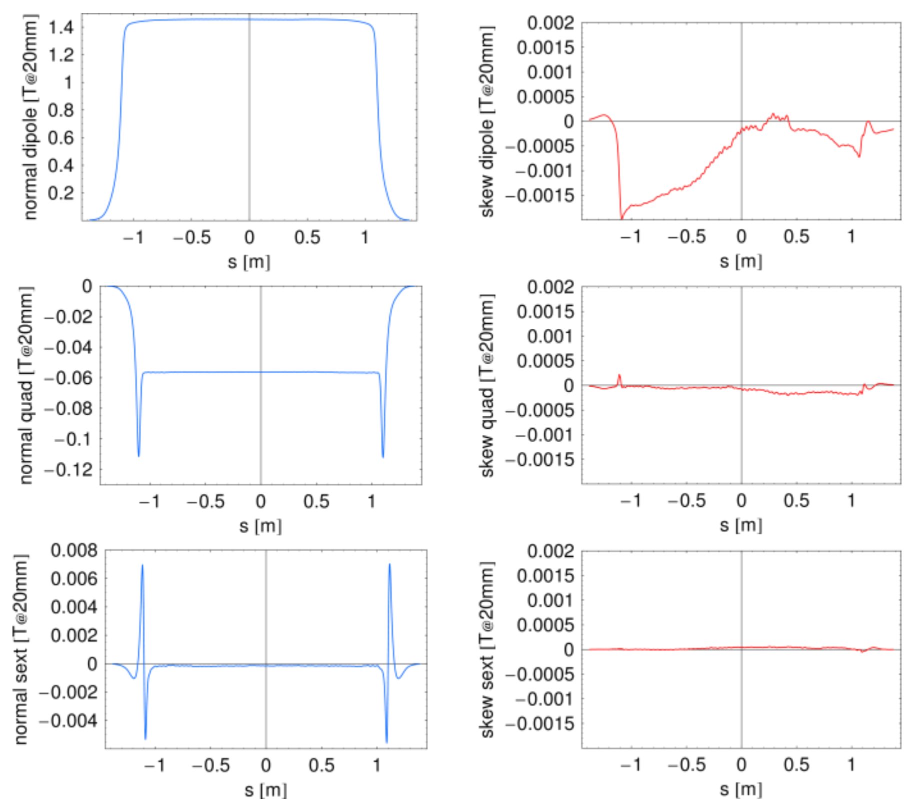
Example of measurement: SESAME SR dipole

Fieldmap at mechanical midplane at nominal current with a grid of 4mm×2mm ($\delta x \times \delta z$)

Magnetic field components



Multipoles along nominal trajectory



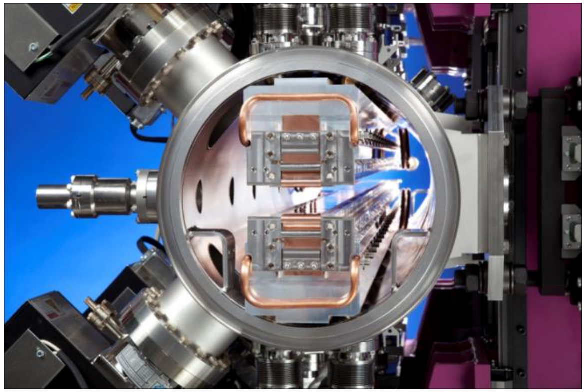
Outline

1 Introduction	2 Hall probe system
3 Latest developments	4 Conclusions

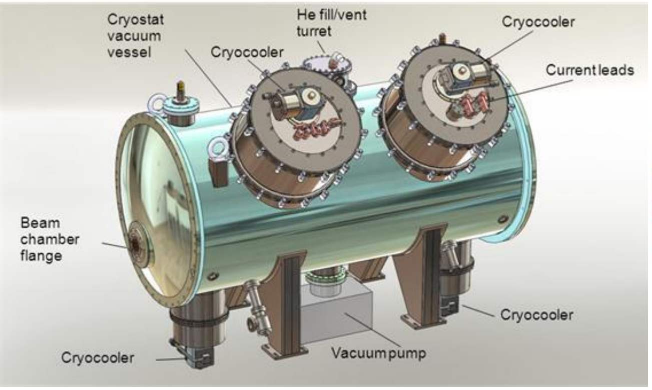
Latest developments

During the last years an interest has emerged in developing systems to measure **magnetic field inside "closed" structures**

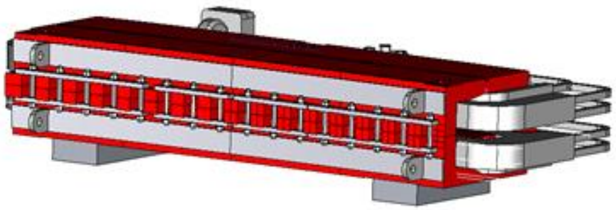
→ superconducting devices (either wigglers or undulators), in-vacuum devices (either cryogenic or RT), H-type long dipolar magnets…



in-vacuum ID



Superconducting device

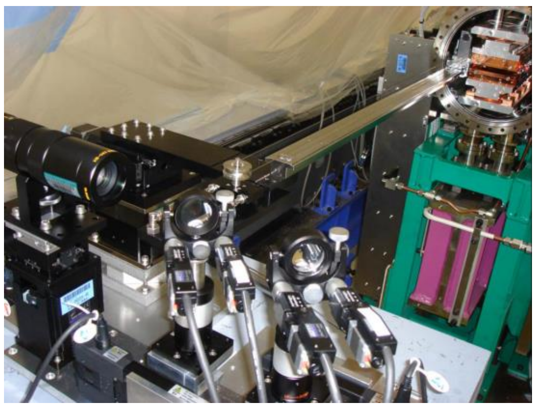


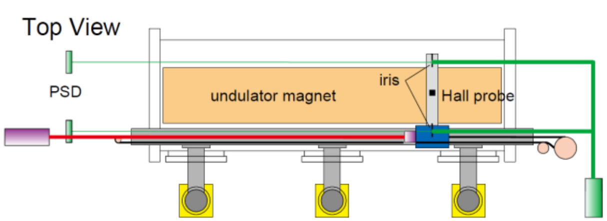
H-type dipole

Latest developments

Most of the implemented solutions involve **introducing the mechanics inside the vacuum chamber**, and are very specific for each case.

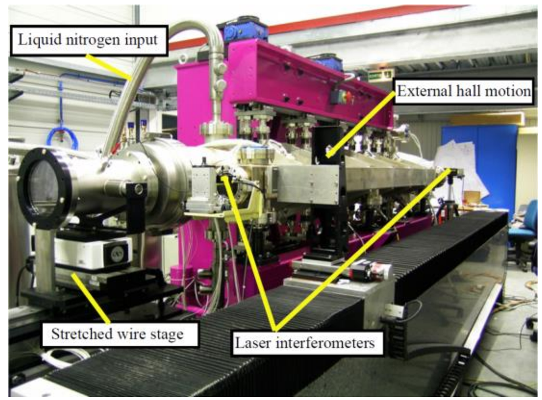
SAFALI system
Spring8 (2007)

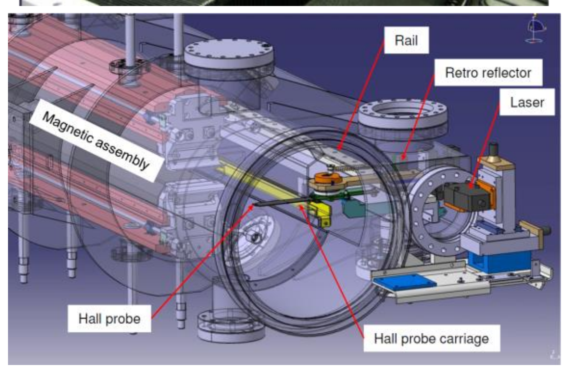




IN-SITU UNDULATOR FIELD MEASUREMENT WITH THE SAFALI SYSTEM
T. Tanaka *et al.*
Proceedings of FEL07, Novosibirsk, WEPPH052

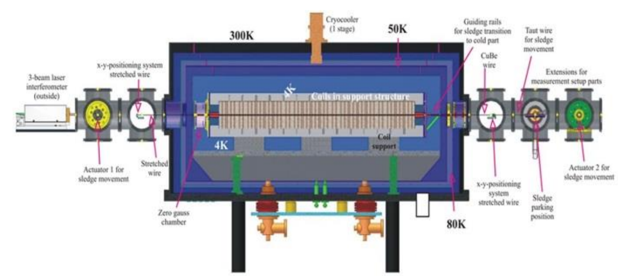
ESRF (2008)





CONSTRUCTION OF A CRYOGENIC PERMANENT MAGNET UNDULATOR AT THE ESRF
J.Chavanne *et al.*
Proceedings of EPAC08, Genoa, WEPC105

CASPER II system
ANKA (2011)

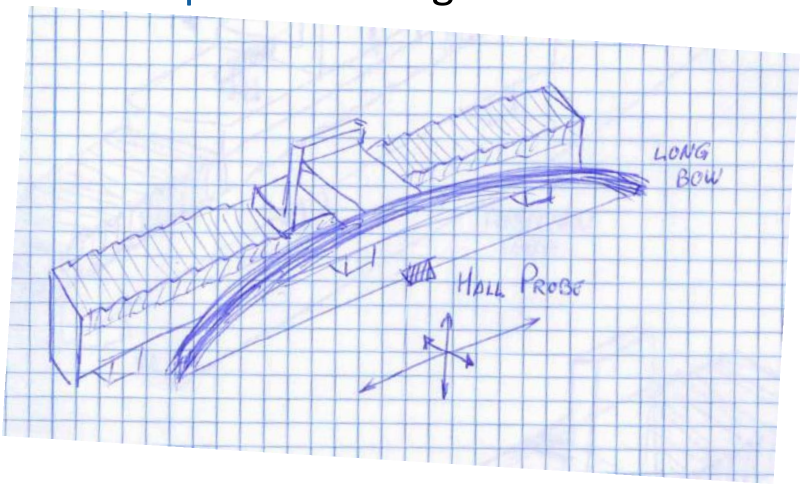


FIRST CHARACTERIZATION OF A SUPERCONDUCTING UNDULATOR MOCKUP WITH THE CASPER II MAGNETIC MEASUREMENT SYSTEM
S.Gerstl *et al.*
Proceedings of IPAC15, Richmond, WEPMA027

Latest developments

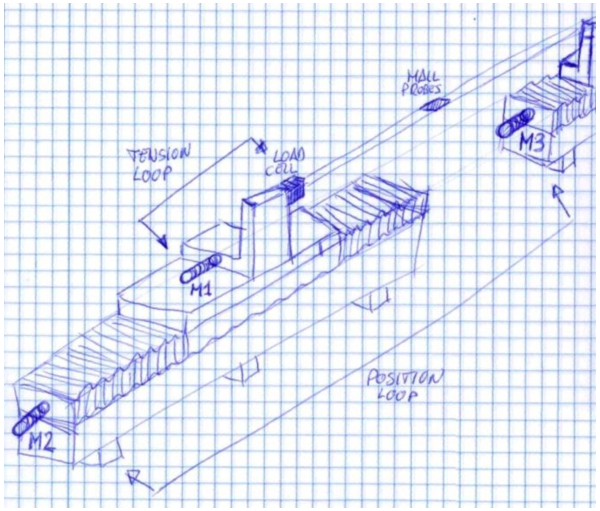
- At **ALBA** we have been looking for a more general approach, providing **more flexibility**.
- Two conceptual alternatives based on placing a **light Hall probe on top of a stretched flexible tape** were presented at IMMW18 Workshop (2013).
- **Main concern: vibrations**. But they depend on tension and f_0 can be shifted to high values (>100 Hz).

Option 1: «longbow»



- Using current existing bench with an attached **«longbow» arch**.
- **Main drawback**: an arch **~3 times longer** than the structure to be measured is required.

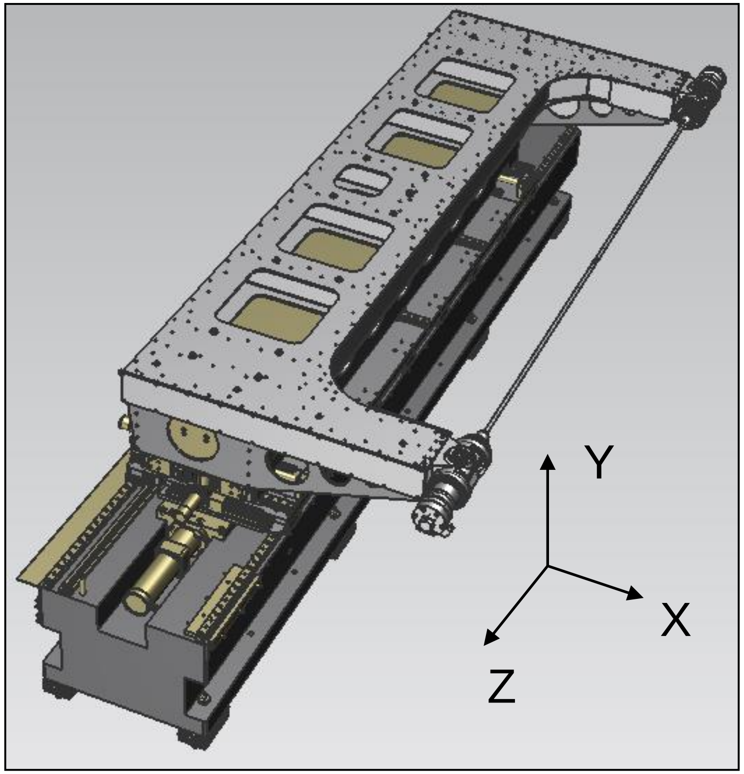
Option 2: double-bench



- M2 and M3 motors defining position.
- M1 motor controlled by a load cell at higher frequency.
- **More complicated solution** from a mechanical and control system point of view.

Latest developments

- It was decided to implement the **«longbow» option**, given that it was mechanically simpler.
- A prototype well suited to carry out an on-going **collaboration with CIEMAT** has been developed in-house.



Design specifications

Ranges

X → 230 mm
Y → 90 mm
Z → 1280 mm
Maximum speed **v_z = 13mm/sec**

Repeatability

X, Y, Z ≤ 0.03mm

Positioning errors

σ_X, σ_Y, $\sigma_Z \leq$ 0.05mm

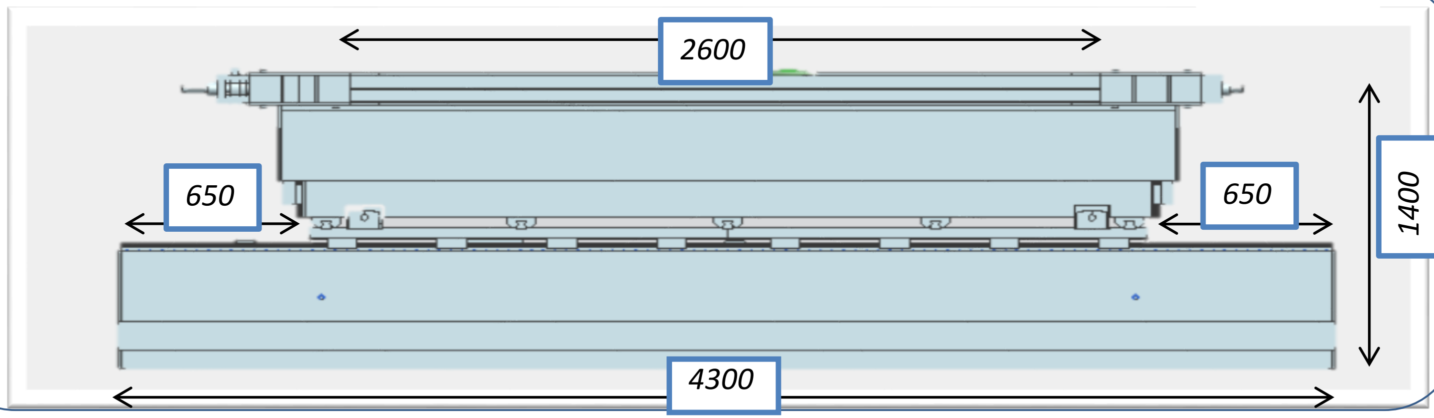
Angular errors

Roll, Pitch < 0.05mrad
Yaw <0.1mrad

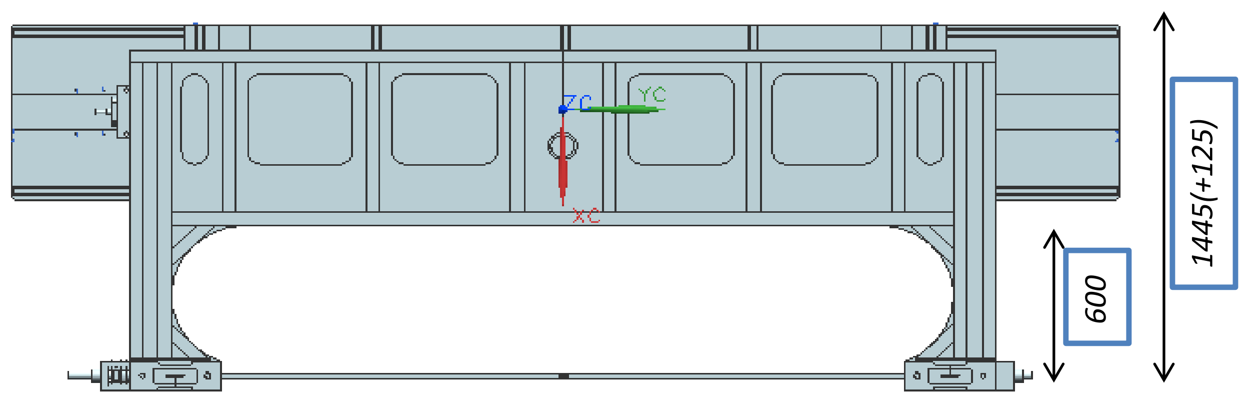
Latest developments

Prototype dimensions

Side View



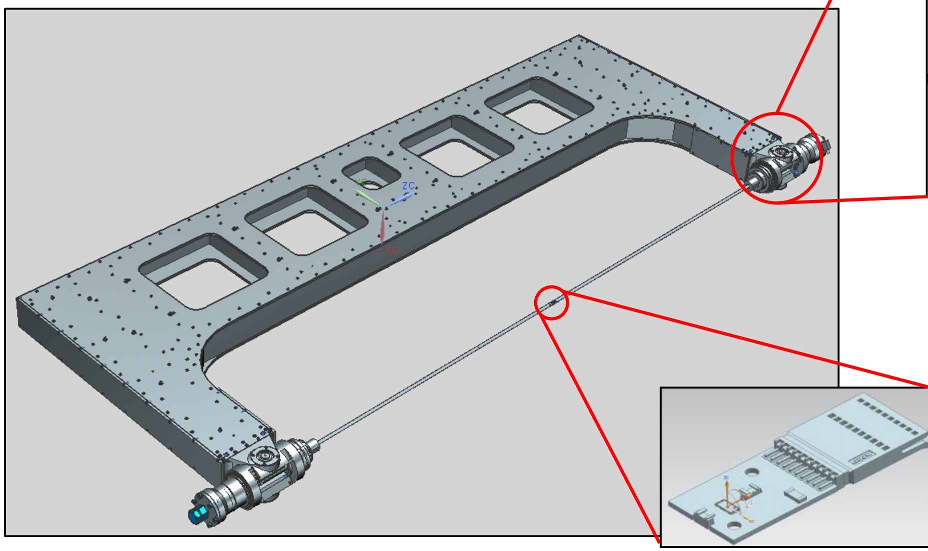
Top View

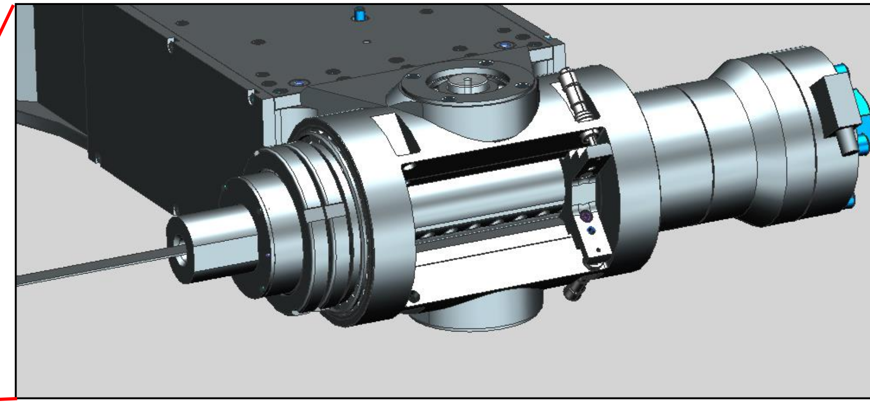


Latest developments

«Longbow» structure

- Aluminum profile structure
- Two tensioning blocks, one with stretch gauge
- **Mass ~400Kg**

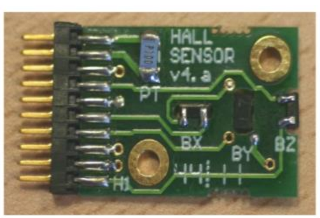




Carbon fiber strip

- **Cross section: 16×1.4 mm^2**
- **Vibrating length: 2600 mm**
- Density: 1600 Kg/m^3 (36 g/m)
- **Nominal tension: 5 kN** (max. 20 kN)

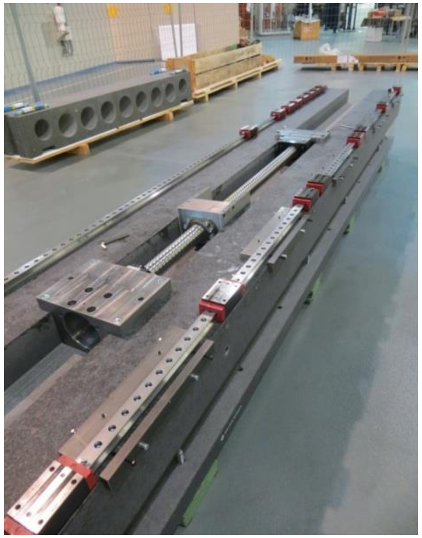
- Stress: 223 MPa
- Security factor: 13
- **f_0 = 71Hz**
- Elongation ~4mm



Hall probe

- **2mm-thick in-house 3D probe** using F.W.Bell sensors.
- Standard calibration against NMR probes.
- **Pt-100 sensor** for thermal correction.

Latest developments



Assembled bench in ALBA Experimental Hall

Latest developments

Mechanical system thoroughly characterized using **laser interferometer**

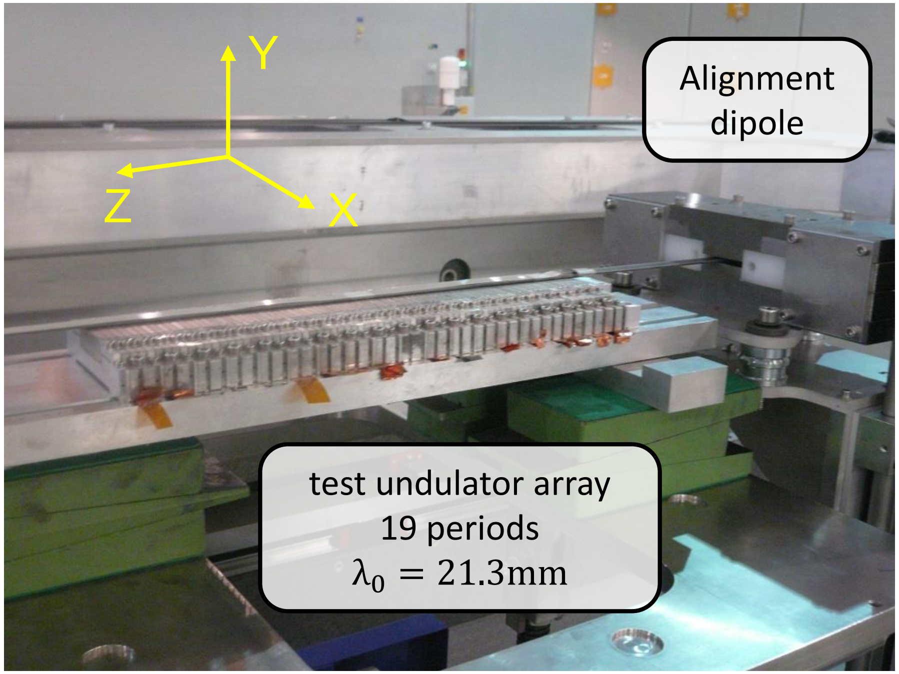
Interferometer Renishaw ML10

Resolution (linear)	1 nm
Resolution (angular)	41 nrad
Maximum sampling rate	5 kHz
Noise level	~0.1 nm RMS
Accuracy (linear)	±0.7p.p.m
Linearity (angular)	±0.5 µrad

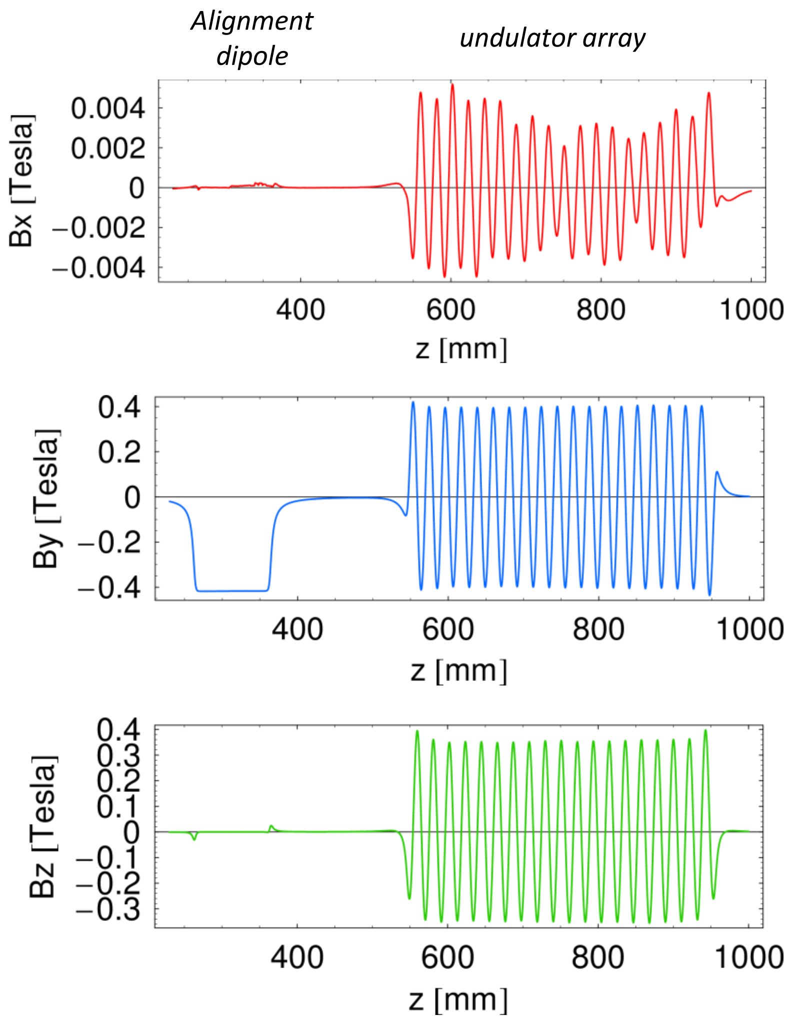
Parameter	Specification	Measured
X positioning error (wrt encoder)	50 µm	7 µm ✓
Y positioning error (wrt encoder)	50 µm	5 µm ✓
Z positioning error (wrt encoder)	50 µm	10 µm ✓
Roll angle error	50 µrad	3.5 µrad ✓
Pitch angle error	50 µrad	25 µrad ✓
Yaw angle error	100 µrad	20 µrad ✓

Latest developments

- **Magnetic tests** at ALBA

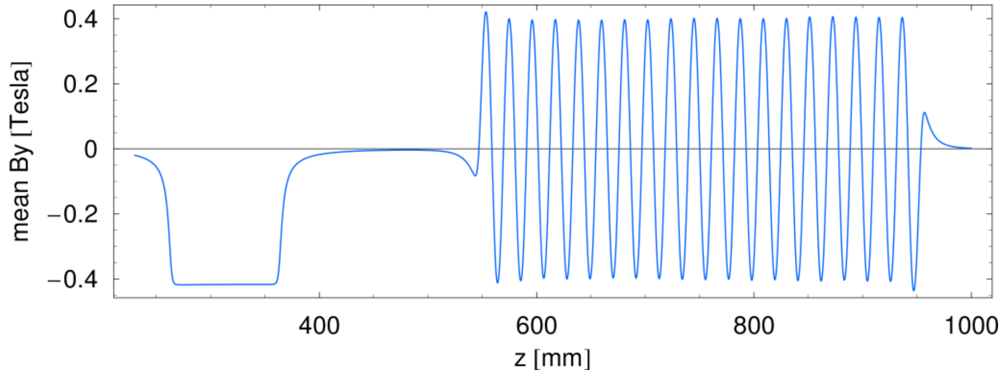


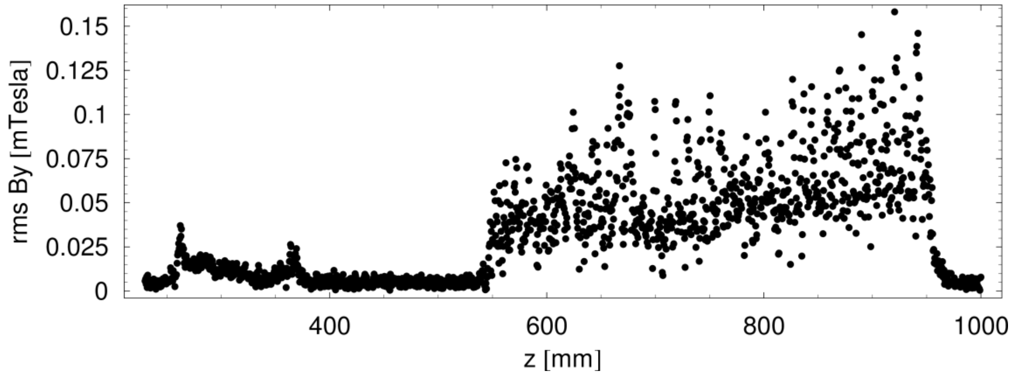
on-the-fly measurements



Latest developments

- **Magnetic tests:** Comparison of **10** successive measurements.





Homogeneous field
$\sigma_B = 10\ \mu\text{Tesla}$

Oscillating field
$\sigma_B = 60\ \mu\text{Tesla}$

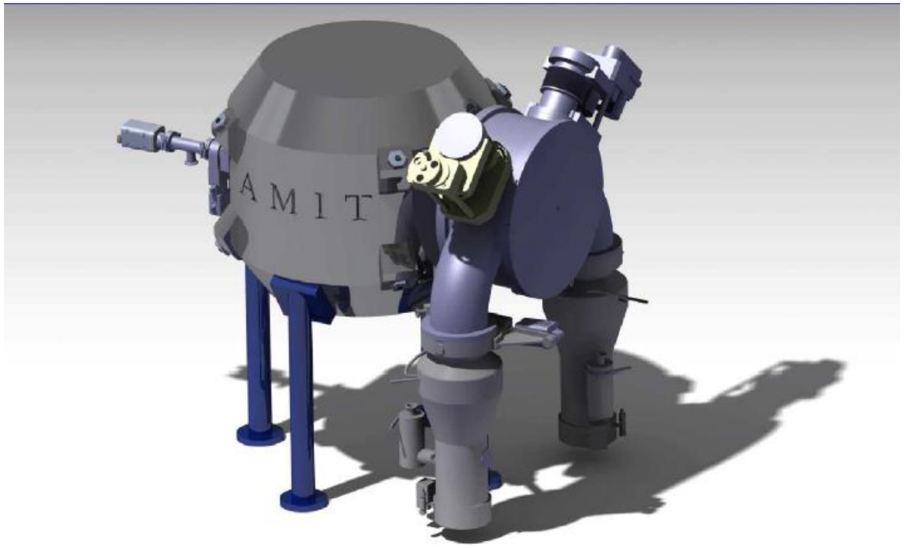
By identifying the pole positions of the undulator using the condition $\frac{\partial B_y}{\partial z} = 0$:

- *rms* error of the **pole locations** is $\boldsymbol{\sigma_z \sim 1\mu m}$
- *rms* error of **field strength** at the poles is $\boldsymbol{\sigma_B \sim 40\ \mu Tesla}$
- Calculated **optical phase error** is **reproducible** within **0.01º**

Latest developments

Compact Superconducting Cyclotron for ^{11}C and ^{18}F production being developed by **CIEMAT** within AMIT project (Advanced Molecular Image Technologies).

GOBIERNO DE ESPAÑA | MINISTERIO DE CIENCIA E INNOVACIÓN | Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas



OPTIMIZING THE RADIOISOTOPE PRODUCTION WITH A WEAK FOCUSING COMPACT CYCLOTRON
C. Oliver *et al.*
Proceedings of Cyclotrons2013, Vancouver, WE4PB03

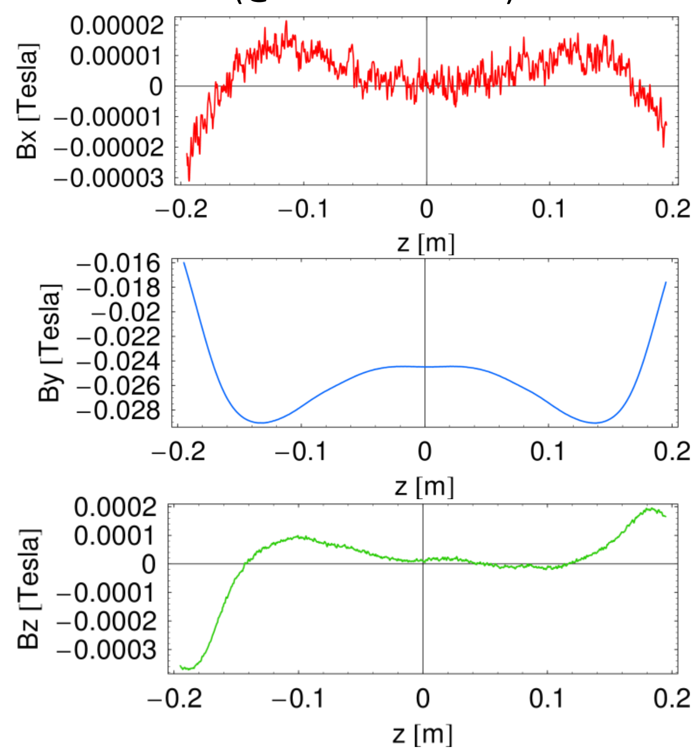
GENERAL	
Energy	>8.5 MeV
Current	>10 µA
Cyclotron type	Classical
MAGNET	
Type	Low Tc SC
Configuration	Warm Iron
Superconductor	NbTi
Central Field	4 Tesla
Nominal current	110 Amp
RF SYSTEM	
Configuration	One 180º Dee
Acc. Voltage	>60 kV
ION SOURCE	
Type	Internal
Ions	H^-

Latest developments

- «Longbow» bench moved to CIEMAT premises on 24th October 2016

Check of magnetic field distribution in good field region

First test with warm coils on 27th Oct (@100mA current)

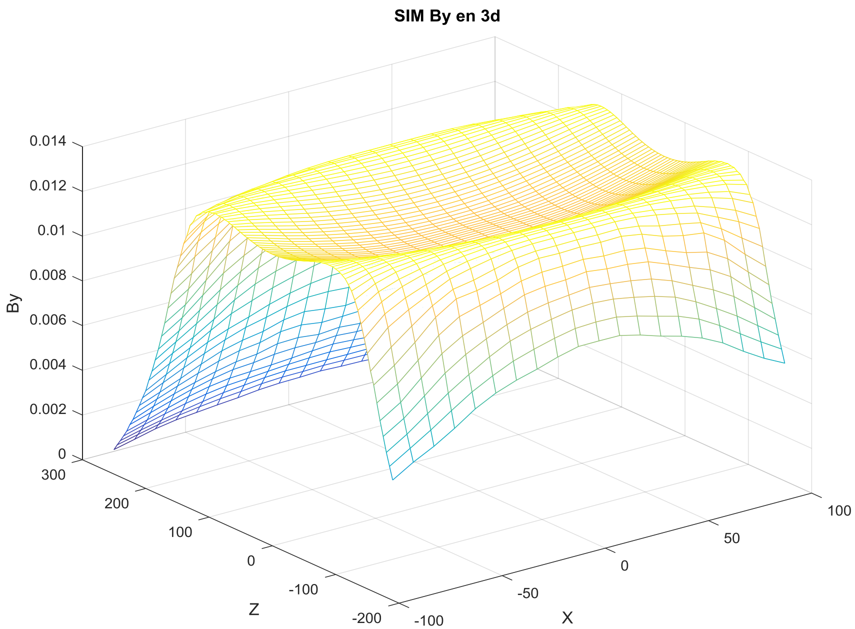


Latest developments

- Warm tests at 100mA at magnet center

Data courtesy of J.Munilla (CIEMAT)

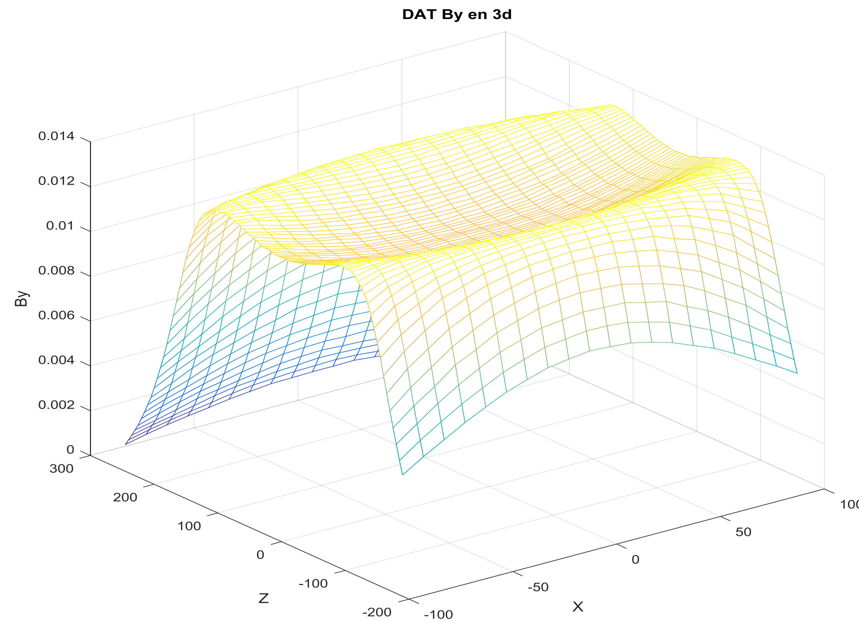
OPERA 3D simulation



Real measurement

$11 \times 11 \times 226$ ($N_x \times N_y \times N_z$)=27346 points

4 hours measurement time



- Deviations from the model are smaller than **1 mT** for the whole volume.
- Most of the points are well bellow **0.5 mT** of deviation.

Outline

1
Introduction

2
Activities

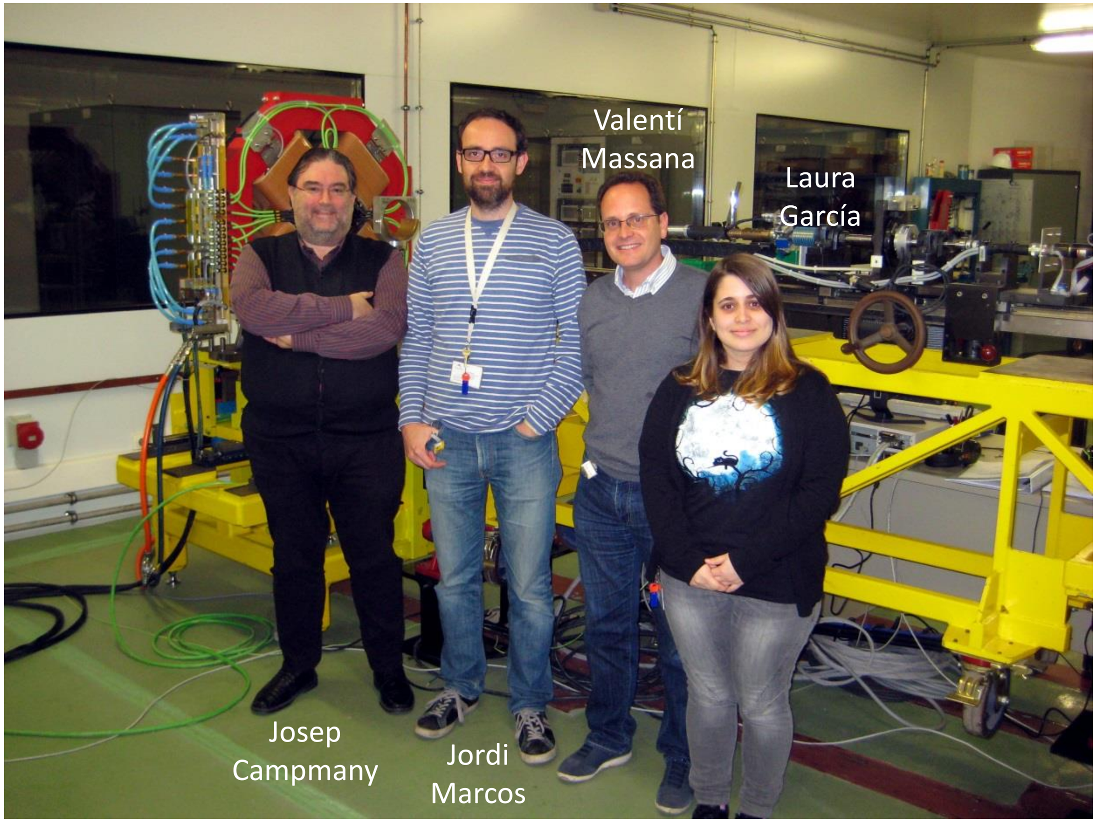
3
Latest developments

4
Conclusions

Conclusions

- A magnetic measurements laboratory associated to the project to build a Synchrotron Light Source in Barcelona (LLS $\rightarrow$ CELLS/ALBA) has been active during the last 20 years.
- The laboratory has been and is still used to test magnetic structures for ALBA (accelerator magnets, insertion devices, etc), but also receives many requests from other institutions and manufacturing companies.
- Different experimental techniques are available, for measuring both local and integrated fields. One of our main areas of expertise are Hall probe measurements, and along the years we have introduced several methodological and instrumental improvements in order to improve the accuracy of our system.
- Our last development has been a Hall probe bench for measuring closed and small aperture magnetic structures. A proof of concept prototype has been built and successfully tested at ALBA.
- The prototype is currently in CIEMAT premises (Madrid), being used to check a superconducting cyclotron magnet.

Thank for your attention!



Insertion Devices Section at ALBA