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NEW IMPROVEMENTS IN MAGNETIC MEASUREMENTS LABORATORY OF THE ALBA SHYNCHROTRON FACILITY

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Abstract

ALBA synchrotron facility has a complete insertion devices (ID) laboratory to characterize and produce magnetic devices needed to satisfy the requirements of ALBA's user community. The laboratory is equipped with a Hall-probe bench working in on-the-fly measurement mode allowing the measurement of field maps of big magnetic structures with high accuracy, both in magnetic field magnitude and position. The whole control system of this bench is based on TANGO. The Hall probe calibration range extends between sub-Gauss to 2 Tesla with an accuracy of 100 ppm. Apart from the Hall probe bench, the ID laboratory has a flipping coil bench dedicated to measuring field integrals and a Helmholtz coil bench specially designed to characterize permanent magnet blocks. Also, a fixed stretched wire bench is used to measure field integrals of magnet sets. This device is specifically dedicated to ID construction. Finally, the laboratory is equipped with a rotating coil bench, specially designed for measuring multipolar devices used in accelerators, such as quadrupoles, sextupoles, etc. Recent improvements of the magnetic measurements laboratory of ALBA synchrotron include the design and manufacturing of very thin 3D Hall probe heads, the design and manufacturing of coil sensors for the Rotating coil bench based on multilayered PCB, and the improvement of calibration methodology in order to improve the accuracy of the measurements. ALBA magnetic measurements laboratory is open for external contracts, and has been widely used by national and international institutes such as CERN, ESRF or CIEMAT, as well as magnet manufacturing companies, such as ANTEC, TESLA and I3M. In this paper, we will present the main features of the measurement benches as well as improvements made so far.

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Abstract
ALBA synchrotron facility has a complete insertion devices (ID) laboratory to characterize and produce magnetic devices needed to satisfy the requirements of ALBA's user community. The laboratory is equipped with a Hall-probe bench working in on-the-fly measurement mode allowing the measurement of field maps of big magnetic structures with high accuracy, both in magnetic field magnitude and position. The whole control system of this bench is based on TANGO. The Hall probe calibration range extends between sub-Gauss to 2 Tesla with an accuracy of 100 ppm. Apart from the Hall probe bench, the ID laboratory has a flipping coil bench dedicated to measuring field integrals and a Helmholtz coil bench specially designed to characterize permanent magnet blocks. Also, a fixed stretched wire bench is used to measure field integrals of magnet sets. This device is specifically dedicated to ID construction. Finally, the laboratory is equipped with a rotating coil bench, specially designed for measuring multipolar devices used in accelerators, such as quadrupoles, sextupoles, etc. Recent improvements of the magnetic measurements laboratory of ALBA synchrotron include the design and manufacturing of very thin 3D Hall probe heads, the design and manufacturing of coil sensors for the Rotating coil bench based on multilayered PCB, and the improvement of calibration methodology in order to improve the accuracy of the measurements. ALBA magnetic measurements laboratory is open for external contracts, and has been widely used by national and international institutes such as CERN, ESRF or CIEMAT, as well as magnet manufacturing companies, such as ANTEC, TESLA and I3M. In this paper, we will present the main features of the measurement benches as well as improvements made so far.

Keywords: **Magnetic measurements, accelerator magnets, Hall probe bench, rotating coil bench**

1 Introduction

In synchrotron light source accelerators, magnetic fields are used both for guiding the accelerated particles along the orbit and for producing synchrotron light.

Regarding the first, particle beam dynamics is very dependent on the quality of magnetic fields, especially high order multipoles that can introduce instabilities in the orbit. This requires that the fields generated by accelerator magnets be carefully characterized to test if they meet specifications and also to determine the deviations in order to obtain an accurate model of the accelerator. Moreover, in third generation synchrotron light sources, X-rays are generated mainly in the so-called Insertion Devices (IDs) that are long arrays of magnets producing wiggles or undulations in the trajectory of charged particles. At each wiggle, charged particles emit synchrotron radiation that is combined with the radiation emitted in the other wiggles to produce highly collimated, brilliant and energetic X-rays. In this kind of devices, the energy of emitted light is related to the energy of the charged particles as well as to the curvature of the wiggle.

Ideally, IDs should not affect the nominal orbit of charged particles, i.e. being inserted in straight sections, electrons should exit the devices at the same vertical and horizontal position and with the same angle they had at the entrance. This requirement imposes that the field integral along the insertion device should be null. Also, there is a special type of ID, the undulator, in which the radiation emerging at one undulation should interfere with the radiation emitted at other undulations. This requirement imposes that the undulations of the trajectory determined by the magnetic field should have a very regular phase advance pattern, i.e., the time elapsed by a charged particle to cross each undulation period should be the same for all undulations inside the device.

In general, magnet characterization for accelerators is based on two approaches: fieldmaps and integral measurements. Fieldmaps come from the measurement of magnetic induction vector B at nodes of a given grid. Grid can be defined in a line, a plane or a volume. This kind of measurements are done to identify local variations of magnetic field in a given volume, or to characterize the phase advance in the undulators. The other type of characterization involves integral measurements, for instance those used to characterize the field integrals (accounting for the kicks received by a particle after crossing a magnet) or to measure the high order modes of multipole magnets (quadrupoles, sextupoles, etc.). Integral measurements are also used to determine the average or local magnetizations of pure permanent blocks used to build insertion devices. Both requirements imply that high magnetic fields (~1 T or higher) confined in long volumes ($\sim 10^{-2}$ x 10^{-2} x 1 m^3) should be mapped with an accuracy of 10^{-4} T and 10^{-5} m at least. Also, field integrals (the integral of the field along a trajectory) that account for the forces applied to accelerated particles should be determined with a relative accuracy of 0.1% with respect to the actual integral field value, or better

2 Improvements of fieldmap measurements at CELLS

Fieldmap measurements are done using a Hall-probe bench using F.W.Bell GH700 sensors. It was built some years ago (Beltran, Bordas, Campmany, Molins, Perlas, & Traveria, 2001), but the control software has been upgraded in order to allow on-the-fly measurements and the measurement methodology has been improved to increase the measurement accuracy.

Figure 1: Hall probe bench at CELLS magnetic measurements laboratory

The bench can measure a volume of 2.5 m long, 0.5 m wide and 0.25 m high. The global accuracy of Hall probe positioning is ~30 µm, and repeatability of probe positioning is ~1 µm. The planarity, linearity and straightness of the Hall probe movement is within the ±50 µm and 50 µrad. Global accuracy of measured field is less than $1 \cdot 10^{-4}$ T in the range 0 – 2 T, and repeatability is $< 0.5 \cdot 10^{-4}$ T.

To reach this accuracy in the magnetic field measurement using a Hall probe we have developed a new calibration methodology. This method calibrates 3D Hall probe using a matrix approach assuming that the 3 sensitive areas are not exactly orthogonal and therefore accounting for their angular deviations and resulting cross-talking. The non-linearity of the sensors as well as contributions such as the planar Hall effect are taken into account. In addition to that, temperature is recorded. Also the Hall probe offsets are systematically measured at the beginning and end of each measurement run. We have also developed a methodology to calibrate and account for the fact that the 3 sensitive areas of the 3D Hall probe are not co-located and therefore an additional correction is needed when measuring fieldmaps. More details about calibration are given elsewhere (Campmany, Marcos, Massana, & Martí, 2007).

One important issue in fieldmap measurements with Hall probes assembled in 3D benches is its alignment with respect to gravity and to the structure to be measured. In order to align the probe with respect to gravity, we have developed a reference magnet (Figure 2, left) made of permanent magnetic blocks (Massana & Campmany, 2013) (Marcos & Massana, Characterization of a dipole magnet for alignment purposes, 2014). The upper plate of the magnet is a reference surface aligned with respect gravity using a level. Once aligned, the magnetic field in the central region of the gap is vertical with an accuracy of ±50 µrad. In Figure 2 right we show the angular quality of the magnetic field in the middle plane of the magnet.

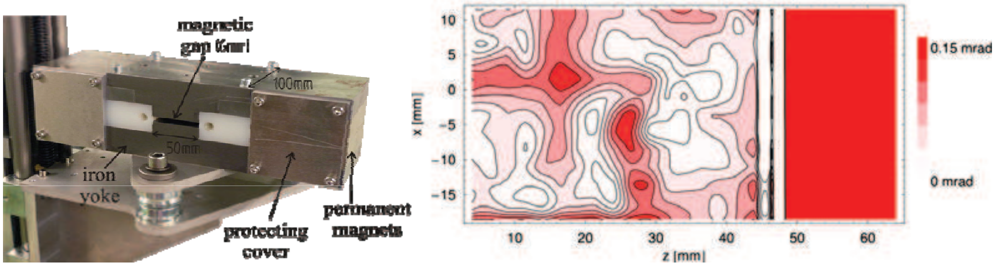

Figure 2: Reference magnet (left) used to align horizontally the Hall probes, and the polar angle of the magnetic field vector inside gap. Each contour corresponds to 25 µrad

This magnet allows the determination of the angular deviations of the 3D Hall probes assembled on the tip of the 3D mechanical bench.

Provided that for each measurement we know the zero field offsets, the distances, relative positions and angles of sensitive areas, calibrations for each Hall sensor, the angular deviations of the whole 3D Hall probe assembly and the temperature at which the measurement is done, we can use all these data to reconstruct the 3D field from Hall probe voltages. All these improvements have been presented elsewhere (Marcos, Campmany, Massana, & Martí, 2007), and they allowed us to increase the accuracy of field measurements with this bench from an initial value of $\pm 2 \cdot 10^{-4}$ T to the current value of $\pm 0.5 \cdot 10^{-4}$ T.

Another field we have improved is fiducialization and alignment. Measured fieldmaps should be referred to geometrical coordinates of the magnet, so there is a need to transfer coordinates from magnetic to a mechanical reference that can be fiducialized using a laser-tracker or any similar instrument. To this end we adopted the concept developed at SLAC (Wolf, 2005) (Vasserman, 2004), improving the portability and spatial resolution, passing from «magnetic needles» to a «cone system» approach, allowing the fiducialization of Hall probes assembled on different supports. A picture of the cone system built at CELLS is shown in Figure 3.

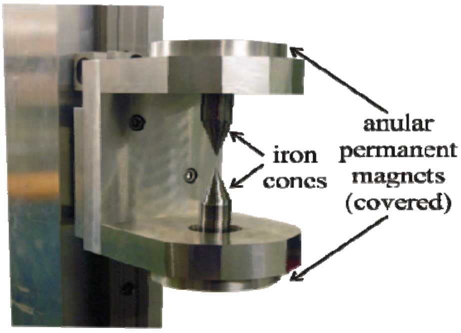

Figure 3: Cone system used to transfer coordinates from magnetic to mechanical reference

The accuracy of the position definition using this system is better than ±10 μm in all directions. Given that the translation of the geometrical cone-system coordinates to the magnetic structure to be measured is done using a laser-tracker, with a maximum error of ±20 μm, the overall fiducialization error is ±23 μm.

In addition to the presented Hall probe bench, we have developed a new bench based in a new concept that is presented and described in more detail in another paper presented to this conference (Figure 4). It can measure a volume of 1.2 m long, 0.5 m wide and 0.25 m high with a global accuracy of positioning of ~20 μm, and repeatability of probe positioning of ~1 μm. Global accuracy of measured field is less than $1 \cdot 10^{-4}$ T in the range 0 – 2 T, and repeatability is $< 0.5 \cdot 10^{-4}$ T.

Figure 4: Picture of the new Hall probe bench developed at CELLS. This bench is specifically conceived to measure closed big magnetic structures.

3 Improvements of integral measurements at CELLS

3.1 Rotating coil bench

CELLS magnetic measurements laboratory has a rotating coil bench. The key element of such a bench is the plate containing the coil units (Walckiers, 1992) (Davies, 1992). The accuracy of measurements depends on coil manufacturing. To this end, CELLS adopted the new multi-PCB technology in order to avoid the uncertainties associated to conventional winding of thin wires.

Figure 5: Rotating coil bench at CELLS magnetic measurement laboratory

A set of shafts with radial coils with diameters between 20 to 40 mm have been developed. The length of the coils are ~ 0.5 m. Optical measurements were used to characterize the accuracy in the position of the coils, and the resulting positioning error of each coil with respect to the theoretical expected position was ±2 μm. An image of the multilayered coils is shown in Figure 6 left and the shaft with the coils assembled inside in Figure 6 right.

Figure 6: Multilayered PCB with radial coils developed at CELLS outside and inside the shaft used for carrying out integral measurements of multipole magnets

Each shaft is provided with 5 coils in order to combine the outcoming signals and perform compensated measurements of quadrupole magnets, which are the most extended type of multipole magnets used in accelerators . This feature increases the accuracy in the high harmonics determination. The performance of CELLS measurement system with the 40mm shaft has been tested using the quadrupole magnets of ALBA Storage Ring, with a field gradient of 20-25Tesla/m, a bore radius of 30.5mm, and harmonics evaluated at a reference radius of 25mm. According to our tests, the repeatability in the determination of the main harmonic is better than $1\cdot10^{-4}$, and the repeatability in the determination of the higher order harmonics up to the 15th is better than 0.1% (Campmany, et al., 2013).

The rotating coil is installed in a mechanical assembly with a bench that can hold up to 1000 kg.

One of the most relevant parameters of multipole magnets used in accelerators is the magnetic axis of the device. The procedure to determine it is the following:

1. The axis of rotation of the Rotating Coil is determined using the laser tracker once the rotating coil is inserted into the magnet. The determination of rotating axis has therefore a maximum error of ±25 μm at each edge, corresponding to 60 μrad. This corresponds to a

GUM Combined standard uncertainty of 12 μm / 10 μrad (Bureau International des Poids et Mesures , 2008).

2. The magnet is positioned on this measured axis according the drawings provided by the manufacturer (assuming that drawings correspond to as-build device) using the laser tracker. Therefore, the magnet is positioned according its geometrical axis. Depending on the shape of the magnet, this can lead to errors of 250 μrad. This corresponds to a GUM Combined standard uncertainty of 12 μm / 42 μrad.
3. Then the magnetic axis is measured using the rotating coil. The displacement of the magnetic axis with respect to the geometrical axis (same as rotating axis) is calculated. Measurement errors have a GUM standard uncertainty of 5 μm.

These three error sources being independent, overall positioning error is within ±50 μm and the GUM combined standard deviation is therefore 17 μm / 43 μrad.

3.2 Long flipping coil

CELLS magnetic measurements laboratory also has a flipping coil system developed at ESRF specially designed for field integral measurements of insertion devices. Length of the device is 4 m, and accuracy of first field integral measurements is < 10^{-5} T·m

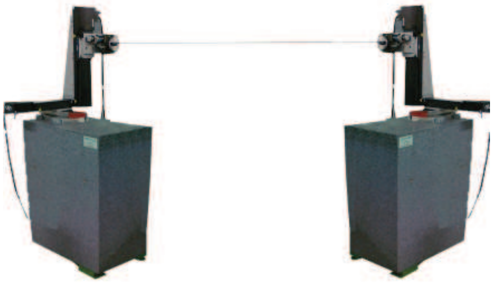

Figure 7: Flipping coil system at CELLS, with two motion stages on granite blocks.

It is particularly well suited to measure long (up to 2 or 3 m) and small aperture (down to ~4 mm gap) devices with field integral values close to zero. It consists of two reference x-y (horizontal-vertical) motion tables with a coupled rotational stage mounted on granite blocks (Figure 7). The copper multiturn-wire coil is arranged along the z-axis (longitudinal) and stretched between both stages (only the slave stage can be manually moved), and connected to a Digital Voltmeter (DVM). The x- and y-stages are used to position the coil for measurement and the rotational stage is used to rotate it around the z-axis. In our case, the coil has the following dimensions: 4.1 m long, 4 mm width (nominal value) and has 15 turns. The default values of the translation speed and the angular speed are 60 mm/s and π/2 rad·s-1, respectively. The horizontal and vertical scanning ranges are 240 mm and 250 mm, respectively. All parameters but the width of the coil can be manually modified by the operator (Marcos, 2010).

3.3 Benches for pure permanent block characterization

Insertion devices are in general made of arrays of magnets. CELLS magnetic measurements laboratory is equipped with characterization benches specifically conceived to characterize permanent magnet blocks.

3.3.1. Fixed stretched wire bench

Stretched wire systems allow calculating field integrals generated by magnetic structures. In the fixed stretched wire system, the magnetic structure is moved with respect to a stationary pick-up coil with a straight segment. The return path of the wire closing the pick-up coil is taken well away from the magnetic field. The relative displacement is always perpendicular to the direction of the stretched wire, which defines the direction of integration of the magnetic field. The measured component of the field integral is the one perpendicular to both the stretched wire and the displacement direction. This layout is convenient for the measurement of small units, such as individual magnet blocks or magnetic modules. They allow characterization of the inhomogeneities of the building blocks. This information is used thereafter to cancel out the residual field integrals of the insertion device to be built. At CELLS we designed and built our own stretched wire bench (figure 8, left) based on the concepts developed at ESRF and BESSY (Marcos, Campmany, & Einfeld, The study of ALBA fixed stretched wire bench, 2006) (Massana, Optimització del procés de construcció d'un ondulador d'imants permanents per a una font de llum de sincrotró,, 2013). Overall accuracy is < 3 μT·m

3.3.2. Helmholtz coils bench

The Helmholtz coil is known to produce a very flat field in its centre. In our case, a magnetic block placed in the centre is rotated 180º with respect to an axis perpendicular to the coils axis, and the magnetic flux change is proportional to the magnetization of the block along coils axis. The bench therefore provides the value of the average magnetization of the block. A holder is specifically designed to guarantee the repeatability of the measurement as well as the possibility to measure the magnetization in all 3 axis of the block. This bench has been built by Sincrotrone Trieste Spa. Usually, magnetic blocks used to build insertion devices have uniaxial anisotropy. In this case, the bench accuracy in magnetization components determination is $\pm 5\cdot 10^{-4}$ at easy axis, and $\pm 2.7\cdot 10^{-2}$ for the other axes (Massana, 2013, p. 55-62).

Figure 8: Fixed stretched wire bench (left) and Helmholtz coils (right) at CELLS.

4 Consistency of measurements

Given that we have different sensors for characterizing magnetic structures, we have verified the consistency of the results comparing Hall probe with Flippling coil measurements, (Marcos & Massana, 2007), as well as Hall probe with Rotating coil measurements (Campmany, Marcos & Massana, 2014) for the same magnetic structure.

First comparison show an agreement between the field integrals calculated from Hall probe data and those directly measured using flipping coil bench at the level of $10\cdot 10^{-6}$T·m rms. Regarding the second, in terms of integrated multipoles the use of Hall probe measurements is worst compared with those based on rotating coils, but still provides useful data with an accuracy of few parts in 10^4.

5 Conclusion

CELLS magnetic measurements laboratory is equipped with several characterization benches equipped to measure with high accuracy magnetic structures for accelerators. Main improvements implemented last years were: the new calibration method developed to calibrate 3D Hall probes, the cone system and the reference magnet made to increase the accuracy of referring the magnetic fieldmaps to mechanical fiducials, the new Hall probe bench equipped with a small sensor specially developed to measure closed magnetic structures, and the new shafts based on the multi-PCB technology developed to improve the accuracy of Rotating coil bench.

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