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A NEW BENCH CONCEPT FOR MEASURING MAGNETIC FIELDS OF BIG CLOSED STRUCTURES

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Abstract

The measurement of big closed magnetic structures is becoming a challenge of great interest. The main reason is the tendency towards building accelerators with high magnetic fields produced by small gap magnets, as well as the development of cryogenic or superconducting narrow-gap insertion devices. Usual approach, based on side-measurements made with a Hall probe mounted on the tip of a motorized arm based on a long granite bench is no more applicable to such closed structures. So, new concepts and approaches have been developed, mainly based on complex devices that insert a Hall probe inside the magnetic structure maintaining the desired position by close-loop controls. We present in this paper the characterization of a new bench that has been built at ALBA synchrotron that is simple, multi-purpose and can be a general solution for measuring big closed structures. Motion control is done via ICEpap motion driver system using the new trigger feature that has been implemented in this motor controller.

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A new bench concept for measuring magnetic fields of big closed structure

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Abstract
The measurement of big closed magnetic structures is becoming a challenge of great interest. The main reason is the tendency towards building accelerators with high magnetic fields produced by small gap magnets, as well as the development of cryogenic or superconducting narrow-gap insertion devices. Usual approach, based on side-measurements made with a Hall probe mounted on the tip of a motorized arm based on a long granite bench is no more applicable to such closed structures. So, new concepts and approaches have been developed, mainly based on complex devices that insert a Hall probe inside the magnetic structure maintaining the desired position by close-loop controls. We present in this paper the characterization of a new bench that has been built at ALBA synchrotron that is simple, multi-purpose and can be a general solution for measuring big closed structures. Motion control is done via ICEpap motion driver system using the new trigger feature that has been implemented in this motor controller.

Keywords: Magnetic measurements, Hall probe bench, accelerator magnets

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1 Introduction

In particle accelerators, magnetic fields used to guide charged particles along a given path should be produced and applied with high accuracy. Being particles confined, the magnetic structures used in accelerator field are designed to produce intense magnetic fields (~1 T or higher) in volumes with small cross sections (~1 cm x 1 cm) and considerable lengths (~1 m), the so-called magnet gap. In order to check that magnetic structures build according to simulations perform within specifications, Hall probe benches are used to measure magnetic fieldmaps with accuracies with at least 100 ppm.

The usual approach to measure fieldmaps of accelerator magnets is given in Figure 1. A 3D Hall probe is placed on a tip of a robotic arm that can be moved inside the volume where the magnetic field is contained.

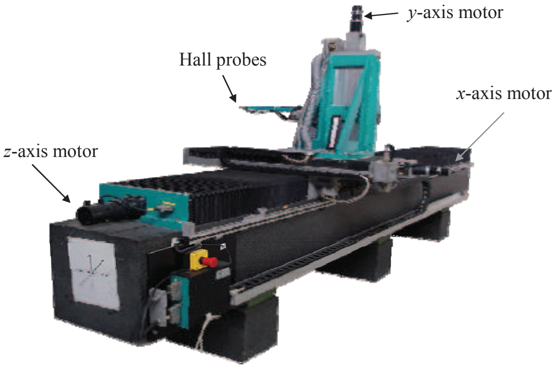

Figure 1: Typical appearance of a Hall probe bench for measuring accelerator magnets. This bench is currently in operation at CELLS magnetic measurements laboratory

Computing codes for measurement automation have been developed, not only for point-by-point measurements, but also for real time on-the-fly measuremens. Using the suitable closed loop control systems, positioning accuracy of probe tip can reach ±10 µm. Also, accuracies of Hall probes when measuring high fields can reach less than $\pm 10^{-4}$ T if they are accurately calibrated. These type of benches are widely used since long time ago (Henrichsen, 1992).

However, as it can be seen in Figure 1, the use of this concept requires the magnetic structure to be open in at least one side, in order to allow the access of Hall probe into the gap. This is a severe limitation in the case of closed magnetic structures, as superconducting devices (magnets are placed inside a cryostat), in-vacuum undulators (magnetic arrays are inside ultra-high vacuum chambers), or simply H-type long dipolar magnets. In all these cases, the only access to magnetic regions is through the flanges or apertures at both sides of the magnetic structure. In Figure 2 we show some of these devices that are or will be extensively used.

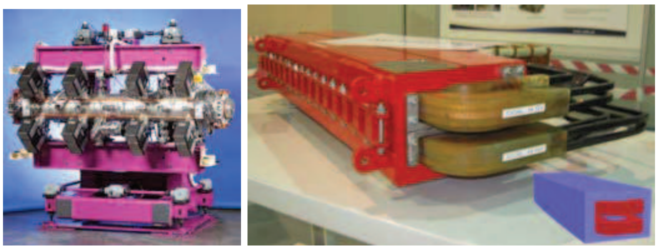

Figure 2: Typical Examples of «closed» structures: in-vacuum undulator installed at ALBA synchrotron (left), and H-type bending magnet used at ALBA booster accelerator (right). All these structures produce a magnetic field inside a gap that can only be accessed through edges.

In order to measure the magnetic field produced by such devices, a number of mechanical solutions have been applied, but all of them are so far specific for each case (Tanaka, Tsusu, Nakajima, Seike, & Kitamura, 2007) (Chavanne, Hahn, Kerservan, Kitegi, Penel, & Revol, 2008) (Doose & Kasa, 2013) (Grau, et al., 2012). Instead, we have been looking for a more general approach. The first concept we tried failed to fulfill the requirements, as reported at the International Magnetic Measurements Workshop, IMMW18 (Campmany, et al., 2013). In that whorshop we presented some alternative conceptual new designs. The detailed mechanical design of one of the concepts was presented at the International Workshop on Mechanical Engineering Design of Synchrotron Radiation Equipment, MEDSI (Ribo, Colldelram, Nikitina, & Campmany, 2014). Finally, in the present paper we present the bench mechanical characterization, confirming that its performance fulfills the requirements. The concept behind this new bench is sketched in Figure 3: a very light Hall probe placed on a flexible tape that can be easily introduced inside a closed magnetic system through edge apertures, simply detaching one edge, and pushing it from the entrance to the exit of the structure as threading a needle. The drawback of this design is that the object to be measured has to fit within the “C” aperture, and its length should be less than one third of that of the “C”.

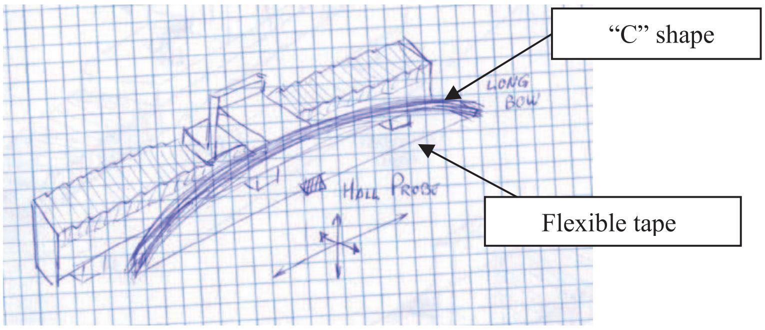

Figure 3: Sketch of the concept for a bench designed to measure closed structures. Note the conceptual similarity with the stick of a violin.

2 Accuracy specifications

The specifications for a mechanical bench being applied to accelerator magnet measurements are shown in Table 1.

Magnitude	Values	Magnitude	Values
X positioning tolerance	$\pm 25 \cdot 10^{-6}$ m	Pith angle tolerance	$\pm 50 \cdot 10^{-6}$ rad
Y positioning tolerance	$\pm 25 \cdot 10^{-6}$ m	Yaw angle tolerance	$\pm 100 \cdot 10^{-6}$ rad
Z positioning tolerance	$\pm 10 \cdot 10^{-6}$ m	Roll angle tolerance	$\pm 50 \cdot 10^{-6}$ rad
Z positioning resolution	$10 \cdot 10^{-6}$ m	Eigenfrequency (Z direction)	> 50 Hz

Table 1: General specifications for a Hall probe magnetic measurement bench. Values should be fulfilled on the Hall probe location.

3 Critical points and details of the design

A bench prototype has been designed and built as a proof of concept. Additional specifications for the prototype are listed in Table 2.

Magnitude	Values	Magnitude	Values
X stroke	0.2 m	Z stroke	1.2 m
Y stroke	0.1 m	On-the-fly velocity	$\sim 15\cdot 10^{-3}$ m/s

Table 2: Additional specifications for a bench prototype used as a proof of concept.

Critical points in our design were (1) positioning accuracy of the Hall probe, (2) vibrations of flexible belt and, (3) the alignment of Hall probe with respect to gravity.

In our design, the tape material is carbon fibre with a cross section of 16 mm x 1.6 mm. Tape can be attached and detached, and in operation mode a stretching force of 5000 N is applied to maintain the frequency of vibration modes far from low frequencies. The ends of the tape are attached to a structure shaped in "C" through a mechanism allowing the horizontal alignment of the Hall probe as well as the stretching of the tape. The "C" structure is designed to allow a tension up to 20000 N, if needed, to shift the tape vibration modes at convenience. Mechanism is shown in Figure 4.

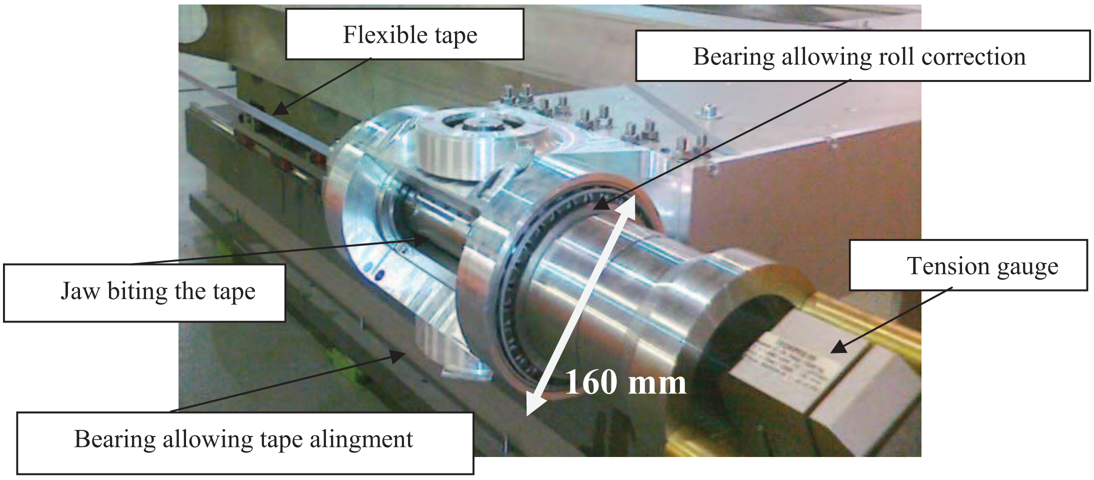

Figure 4: Mechanism used to attach the carbon fibre to the "C" shaped structure. It allows the tape detachment and reattachment, its stretching up to 20000 N and also the correction of the roll angle.

The "C" shaped structure is made of Al, and is assembled on top of a conventional granite 3D bench. In order to fulfil the positioning and angular specifications, the material for the bench basis is granite, and the linear guides and mechanical chain have been designed according to the usual high precision mechanics concepts. In this sense, bench dynamics benefit from the well known mechanics and controls of 3D benches. Regarding motion, and according CELLS standards, all movements are driven by step motors controlled by ICEpap motion driver system (ICEpap, 2013).

The first challenge faced by this design was related to the straightness, linearity and flatness of the whole bench. Being the position of the Hall probe recorded from encoders that are placed on the granite supports, it has to be checked that the real position of probe with respect of that measured by encoders is within specifications.

The second is related to the mechanical structure vibration modes: being the tape holding the Hall probe a stretched string, submitted to standing waves, the feasibility of the bench depends on their frequencies and maximum amplitudes.

Finally, the last challenge is related to the methodology used for measurements. As the tape should be detached and reattached in order to be introduced inside the magnetic structure to he measured, we have to develop a measurement methodology including the repeatability of this attachment and detachment exercise.

In Figure 5 we show a view of the detailed 3D design of the prototype bench, and in Figure 6 we show the real prototype built.

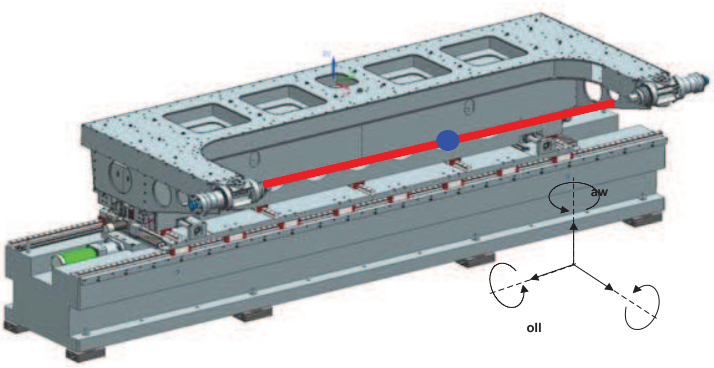

Figure 5: General layout of the Hall probe bench prototype and reference system. Stretched tape is painted red, and Hall probe position is marked with a blue dot

Figure 6: Picture of the prototype bench built at CELLS.

4 Mechanical performance

In order to check the mechanical performance of the prototype bench, measurements have been done using a laser interferometer Renishaw ML10. Resolution of this equipment is 10^{-9} m linear, $41 \cdot 10^{-9}$ rad angular, 5 kHz of sampling ratio, and $\sim 0.1 \cdot 10^{-9}$ m RMS noise level. Linear accuracy is ±0.7 ppm and angular linearity $\pm 0.5 \cdot 10^{-6}$ rad. With this setup we have tested the displacements along the X and Y axis and pitch and yaw angles. (Nicolás, 2015)

Table 3 summarizes the measured values for several magnitudes, including those specified in Tables 1 and 2 above. Some results are shown in Figures 7 and 8 below.

All measurements have been made at a longitudinal velocity of $13 \cdot 10^{-6}$ m/s.

As shown in Table 3, the prototype fulfils the specifications given in Table 1.

Magnitudes	**Values**	**Magnitudes**	**Values**
X stroke	0.233 m	X positioning error (wrt encoder)	$7 \cdot 10^{-6}$ m
Y stroke	0.092 m	Y positioning error (wrt encoder)	$5.41 \cdot 10^{-6}$ m
Z stroke	1.282 m	Z positioning error (wrt encoder)	$10 \cdot 10^{-6}$ m
Flatness error	$6.7 \cdot 10^{-6}$ m	Pitch angle error / deformations	$25 \cdot 10^{-6}$ rad
Straightness error	$7.8 \cdot 10^{-6}$ m	Yaw angle error / deformations	$20 \cdot 10^{-6}$ rad
Z resolution	$10 \cdot 10^{-6}$ m	Roll angle error / torsion errors	$35 \cdot 10^{-6}$ rad
Amplitudes in Z direction	$10 \cdot 10^{-9}$ m	Eigenfrequency in Z direction	90 Hz
Amplitudes in Y direction	$150 \cdot 10^{-9}$ m	Eigenfrequency in Y direction	43.5 Hz
Amplitudes of torsion	$3 \cdot 10^{-6}$ rad	Eigenfrequency for torsion (roll)	23.6 Hz

Table 3: Summary of measured performances. Errors are expressed in terms of peak values (2.6σ)

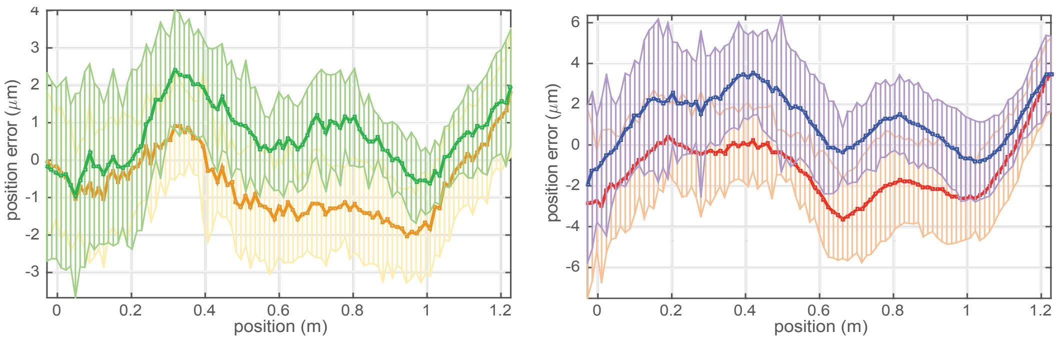

Figure 7: left: longitudinal position error (real with respect to encoder reading), forward (orange) and backwards (green). Right: straightness (horizontal error) along z axis forward (red) and backwards (blue). In both cases, thick lines link mean values and light lines the associated dispersion.

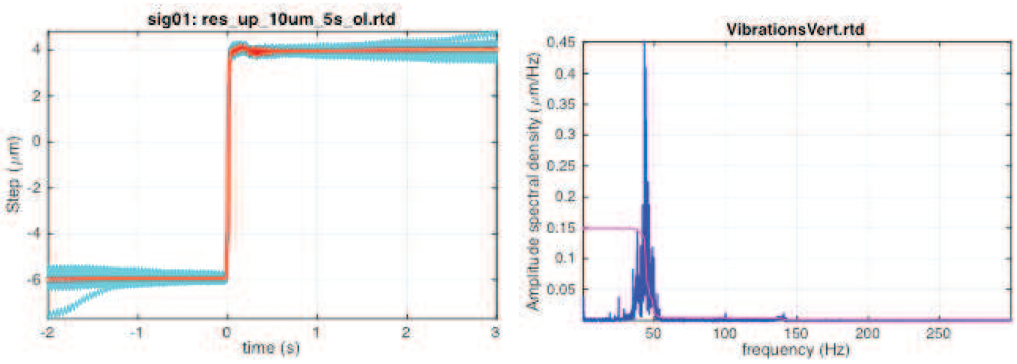

Figure 8: left: longitudinal position accuracy and reliability of a 10 μm step. In red the average value, in blue single repetitions. Right: amplitude spectrum for vertical vibration. Maximum peak value (blue line) is $450 \cdot 10^{-9}$ m, rms value (pink line) is $250 \cdot 10^{-9}$ m.

5 Measurement methodology

To measure magnetic fieldmaps of narrow gap devices, we developed a very thin (13 mm wide, 2 mm high, 25 mm long) 3D Hall probe head, which is shown in Figure 9. It also has an integrated Pt100 to record the temperature during measurement, allowing a post-processing correction. The weight of the head is 0.75 g. The Hall sensors mounted on the probe are F.W.Bell GH700, and the determination of positions and angles of each individual probe has been carried out according to the procedure which is described elsewhere (Campmany, Marcos, Massana, & Martí, 2007)

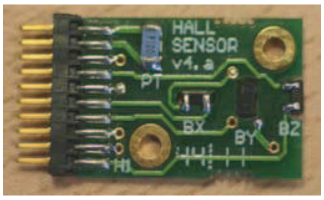

Figure 9: Hall probe head developed at CELLS

The Control system structure has been described elsewhere as well (Beltran, Bordas, Campmany, Molins, Perlas, & Traveria, 2001) and has been implemented in Tango (tango info, 2015). The core concept is that multimeters (model Keithley 2001) measuring Hall voltages are triggered directly at hardware level by Icepap motor controller (Icepap info, 2013).

Given that the tape in which the Hall probe head is attached should be detached to pass it through entrance and exit holes of structure to be measured, and afterwards it should be reattached to the "C" structure and stretched at 5000 N, the need of having a procedure to align the Hall probe is evident. To this end we have designed and built a reference dipolar magnet (Figure 10, left) powered by permanent magnetic blocks. This magnet produces a highly homogeneous vertical magnetic field in the central region that can be aligned with respect to the gravity with an accuracy in the range of $100 \cdot 10^{-6}$ rad. The reference magnet can be opened and closed again allowing its placement around the Hall probe attached to the tape. The repeatability of this operation is $<150 \cdot 10^{-6}$ rad.

Once the reference magnet is placed around the tape, it then can be aligned in roll and pitch to position the BY Hall probe parallel with respect to gravity with an accuracy of $< 100 \cdot 10^{-6}$ rad. After this operation, the reference magnet is taken out.

Once aligned, one has to fiducialize the Hall probe magnetic sensor with respect to an external mechanical mark, that will be used as a reference with respect to the system to be measured. In order to do this fiducialization, we manufactured a system of magnetic cones (Figure 10, right). They can easily be placed around Hall probe in the tape, and taken away after fiducialization measurement.

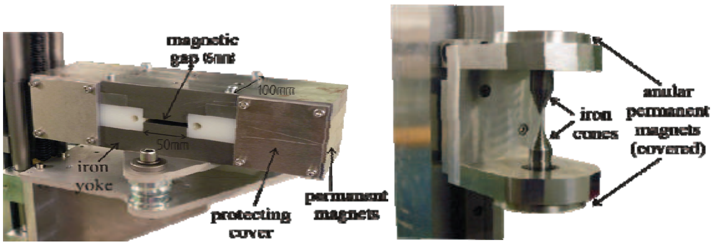

Figure 10: Left: reference magnet built at CELLS powered with permanent magnets. It produces a homogeneous vertical field with respect to gravity. Right: reference cones used for fiducialization.

The iron cones produce a point where the magnetic field is null. The position of this point with respect to fiducial marks placed on top and bottom of the structure has been determined with an accuracy of ±25 μm.

6 Conclusion

We developed a highly accurate magnetic measurement bench to measure magnetic fieldmaps of big closed magnetic structures adopting an original concept. The current prototype can scan a region of 1.282 x 0.233 x 0.092 mm^3, and we have proved that the mechanical solution invented and developed at CELLS is feasible, and performs according to the specifications.

7 Acknowledgment

Special acknowledgement is made to José Ferrer, head of the mechanical workshop at CELLS, responsible of mechanical assembly.

References

Icepap (2013). Retrieved from www.esrf.eu: http://www.esrf.eu/Instrumentation/DetectorsAndElectronics/icepap

tango info. (2015). Retrieved from www.tango-controls.org

Beltran, D., Bordas, J., Campmany, J., Molins, A., Perlas, J., & Traveria, M. (2001). An instrument for precision magnetic measurements of large magnetic structures. *Nuclear Instruments and Methods A, 459*, 285.

Campmany, J., Marcos, J., Massana, V., & Martí, Z. (2007). Construction and commissioning of a 3D Hall probe bench for Insertion Devices measurements at ALBA synchrotron light source. *International Magnetic Measurements Workshop IMMW15.* Batavia: Fermi National Laboratory.

Campmany, J., Massana, V., Ribó, L., Colldelram, C., Becheri, F., Gigante, J., et al. (2013). Looking for a Hall probe bench for closed big magnetic structures. *International Magnetic Measurents, IMMW.*

Chavanne, J., Hahn, M., Kerservan, R., Kitegi, B., Penel, C., & Revol, F. (2008). Construction of a cryogenic permanent magnet undulator at the ESRF. *Proceedings EPAC'08*, (p. 2243).

Doose, C., & Kasa, M. (2013). Magnetic measurements of the first superconducting undulator at the advanced photon source. *Proceedings of PAC13*, (p. 1238).

Henrichsen, K. N. (1992). Classification of magnetic measurement methods. *CERN Accelerator School. Magnetic measurement and aligment.* (p. 70-82). Montreaux, Swizerland.: CERN.

Grau, A., Baumbach, T., Casalbuoni, S., Gerstl, S., Hagelstein, M., Holubek, T., et al. (2012). In-vacuum, cryogen-free field measurement system for superconducting undulator coils. *Proceedings of IPAC12*, (p. 714).

Nicolás, J. (2015). *Motion tests Hall probe bench.* Bellaterra: CELLS.

Ribo, L., Colldelram, C., Nikitina, L., & Campmany, J. (2014). Hall probe bench prototype for closed magnet structures. *MEDSI.*

Tanaka, T., Tsusu, R., Nakajima, T., Seike, T., & Kitamura, H. (2007). In-situ undulator field measurement with the SAFALI system. *Proceedings FEL'07*, (p. 468). Novosibirsk.