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Development of CEM's Traceable Magnetic Measurements Laboratory

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ABSTRACT
The establishment of a magnetic measurements laboratory at CEM addresses the lack of a national reference standard in Spain, which could meet the stakeholders' needs and ensure magnetic measurements traceability. The laboratory is equipped to measure both magnetic field intensity and magnetic flux density for direct current (DC) and alternating current (AC) up to 50 kHz. This capability is made possible by the development of primary Helmholtz coils standards for generating magnetic fields. Traceability is ensured throughout the use of a Nuclear Magnetic Resonance (NMR) sensor, which measures the DC magnetic field by providing a frequency signal linked to the frequency standard. For low and medium magnetic flux density measurements, the main source of uncertainty is due to the environmental magnetic fields, making the use of a cancellation system essential. To ensure measurement accuracy, an active compensation system is employed.

Section: RESEARCH PAPER

Keywords: Active magnetic field compensation; nuclear magnetic resonance; traceability; magnetic measurements

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1. INTRODUCTION

Currently, there is a significant gap in the magnetic metrological infrastructure, resulting in a lack of services in various sectors, including the automotive industry, navigation, geomagnetic exploration [1], space exploration, medical diagnostics [2], safety regulations related to electromagnetic field exposure [3], as well as emerging technologies such as fusion power generation and quantum sensing and computing. Moreover, the demand of traceable magnetic measurements is increasing due to the advances in fields such as biomedicine, water remediation, energy conversion and smart grids.

INRIM, NSAI and CEM, the National Metrology Institutes (NMIs) of Italy, Ireland and Spain respectively, were part of the European metrology project "Traceable Routes for Magnetic Measurements" (TRaMM 21SCP02) [4], funded under the 2021 Small Collaborative Projects (SCP) call. The main objective is to identify the existing needs of EU stakeholders in the field of magnetic measurements and associated calibration services, and to lay the groundwork for ensuring the future availability of magnetic references to meet these needs.

The project aims to transfer knowledge and expertise from developed NMIs to less experienced ones, taking into account the principles of smart specialisation. This paper outlines the magnetic measurement systems developed by CEM to meet the national and international stakeholder needs.

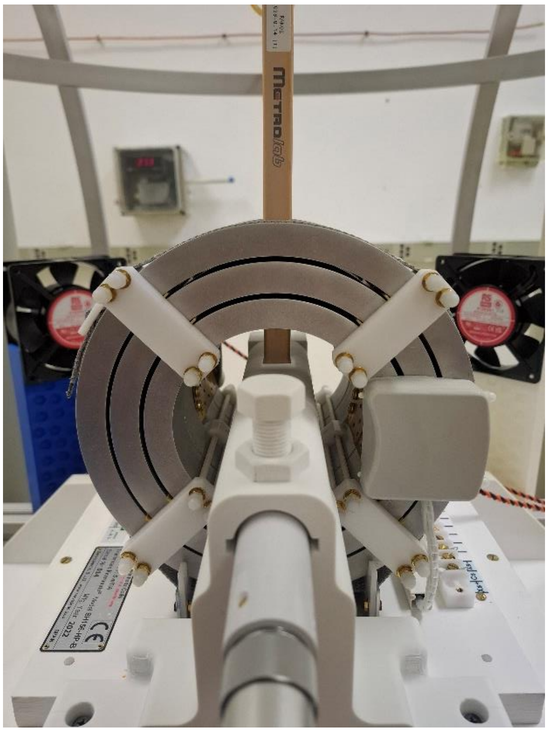

Figure 1. Primary standard NMR probe placed vertically in the centre of standard Helmholtz coils. Also, a fluxgate probe used for the environmental magnetic field compensation is places horizontally into the coils system.

2. TRACEABILITY CHAIN

The traceability chain of magnetic measurements requires a primary standard as its first link. In the case of the CEM it consist of a Nuclear Magnetic Resonance (NMR) sensor. These sensors operate according to the Larmor equation (Equation (1)), relating the nuclear precession frequency (ω_0) to the gyromagnetic ratio (γ) and the magnetic field (B_0) surrounding the sensor's probe.

$$\omega_0 = \gamma \cdot B_0 . \quad (1)$$

The CEM's NMR primary standard is based on relaxation with synthetic rubber probe. Therefore, a magnetic field over 38 mT is needed to start measuring correctly, as it is established in the manufacturer specifications, Metrolab Technology S.A. [5].

This kind of sensors are non-oriented, meaning the probe can be placed in any orientation, as long as the magnetic field is uniform enough. As it is shown in Figure 1, the NMR at CEM is placed vertically, enabling more probes to be placed near it and allowing the full homogeneous magnetic field region to be used.

As it is shown in Figure 2, the NMR provides traceability to Hall probes, permanent magnets and standard coils. These other standards provide traceability to sensors like fluxgates, and to generators, as small coils systems and solenoids. Depending on the dimensions or the desired calibration range different standards are used.

3. ENVIRONMENTAL MAGNETIC FIELD

The environmental magnetic field is one of the main sources of uncertainty during measurements with Helmholtz coils and single coil systems. Although the Earth's magnetic field is the main contributor to this environmental field, it is not the only one. Railway tracks, power cables, other laboratories and even large moving metallic objects can also change the environmental field causing it to vary from the initial value.

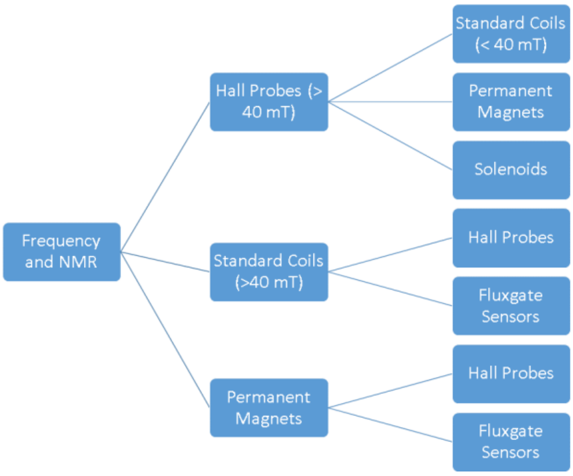

Figure 2. Traceability Chain at CEM.

There are several approaches to solve the problem as magnetic shielding, passive environmental field cancellation and active environmental field cancellation. CEM has developed an active cancellation system based on a passive system

3.1. CEM active compensation system

The system developed by CEM is based on a tri-axial coils configuration, three Helmholtz coils aligned along the Cartesian axis, as it is shown in Figure 3, to cancel each of the environmental magnetic field axis, which are shown in the figure. A fluxgate sensor is used to assess the environmental magnetic field in each axis.

The design was initially planned as a passive environmental magnetic field compensation system. However, using this approach, it was not possible to reduce the environmental magnetic field below 0.1 µT.

The active system uses exactly the same devices as the passive system, but every signal is digitalized and sent to the computer. Then a PID is added, which analyses the error signal in each axis between the desired magnetic field (0 nT in modulus) and the

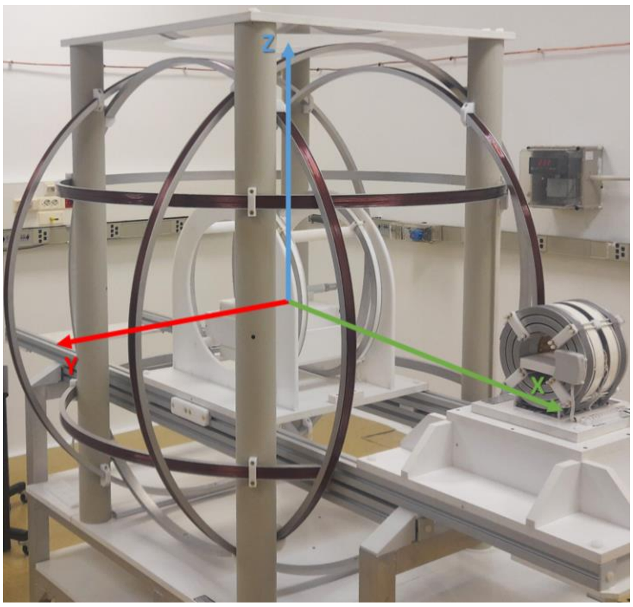

Figure 3. Environmental magnetic field cancellation system in CEM.

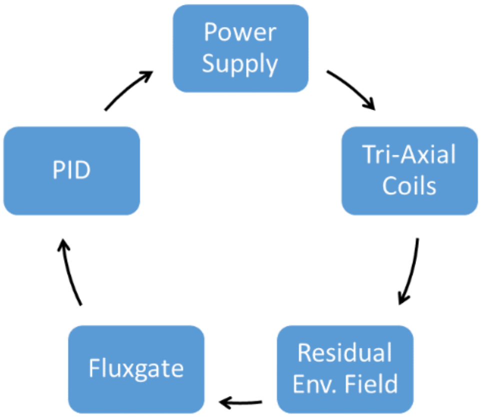

Figure 4. Environmental magnetic field compensation active loop.

measured magnetic field. The active compensation loop is the depicted in Figure 4, where it is possible to appreciate that in each iteration the PID is going to modify the current supplied to the system, eventually achieving the desired environmental magnetic field.

This technique is also used for other applications, such as setting a certain background noise which direction can be controlled.

In Table 1, the statistical results of several days of measurements are analysed, where over 8 500 measurements were performed. It is possible to appreciate that the average value of every axis is centred at 0 nT. Also, the axis which presents more dispersion is the Y-axis shown in Figure 3, this might be due to the direction of Earth's magnetic field and it is usually around 2 μT, while the Z-axis and the X-axis are usually over 20 μT. However, this values change every day due to the Earth's magnetic field fluctuations. Although the module average value and mode value do not fit, a Gaussian distribution can be assumed as both values are smaller than the total dispersion.

The variations minimized by the PID, are mostly of human-cause, since those of natural cause are much slower, with changes occurring over hours or even days. Human-caused variations can be triggered by people carrying magnetic materials while walking, moving large metal or magnetic devices (such as doors or laboratory racks), using high currents in the nearby laboratories or even by train's power line.

A study of the environmental field variations over a 24 hour period was made, and its result is shown in Figure 5. In order to obtain this figure, a magnetic field compensation was first made, obtaining values under 10 nT. Then, the PID was turned off, but the passive compensation system was still turned on, obtaining the variations of the environmental magnetic field over time. A key result of this study is the decrease is short term noise between the 24:00 h and the 05:30 h, which may be caused due to the train's power line.

Table 1. Magnetic field compensation statistics for more than 8 500 measurements for each axis of measurement and the module.

Magnetic Field	Average (nT)	Mode (nT)	Standard Deviation (nT)
B_x	0	-1	2
B_y	0	2	5
B_z	0	0	2
$B_{tot} = \lvert B \rvert = \sqrt{B_x^2 + B_y^2 + B_z^2}$	4	2	4

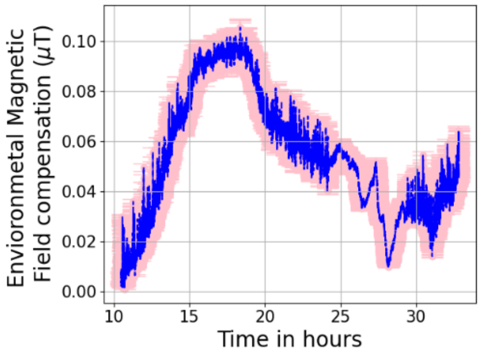

Figure 5. Study of environmental magnetic field variations over time.

4. MAGNETIC FIELD STANDARDS

4.1. Standard Helmholtz coils

Helmholtz coils are used as a standard due to the large homogenous magnetic field region that generate between their coils. This region, theoretically, is equal to half the radius of the coils that conform the system, under the assumption that they are separated one radius of distance between them.

Three different Helmholtz coils with different ranges were obtained:

- Up to 50 mT: Small field homogeneous region, can be directly calibrated with NMR.
- Up to 20 mT: Is made up by 2 different Helmholtz coils, which can be connect in series, parallel or to two different power sources depending on the needs. They receive traceability from Hall sensors.
- Up to 2 mT: Big field homogeneous region, can work in AC mode, generating 0.2 mT at 500 Hz and achieving a maximum frequency of 50 kHz. It receives traceability from Hall sensors in DC and give traceability in AC.

The positioning inside the coil's magnetic field homogenous region is important to reduce the uncertainty and measurement errors. Thus, the 3D printing technique is used for developing positioners optimised for each set of magnetic probes. The material used for this technique is PLA (polylactic acid) plastic, which can be printed at high speed with an accuracy of 0.2 mm and can operate at temperatures up to 60 °C.

4.2. Permanent magnets

Permanent magnets are passive magnetic field generators, so they cannot change their field value with current. However, there are simple electromagnets which are built with a coil inside that allows small changes into the magnetic field value.

These kinds of standards do not need to have an external magnetic compensation system, as the metal that makes up the magnet acts as a magnetic shield.

Currently, CEM has 2 magnets with simple coils inside them, which have nominal values of 50 mT and 100 mT.

4.3. Hall sensor

Hall sensors use Hall Effect samples to measure the magnetic field. The generated signal voltage depends on the supply current, the transversal magnetic field, the dimensions of the sample and the material. So Hall effects are axial depending sensors.

Moreover, several manufactures build Hall sensors that can measure in the three Cartesian axis; as, thanks to the small size of the samples, is possible to assemble 3 samples in a small millimetre region.

These sensors are used in several calibrations as the range depend on the input current, allowing a measurement range between µT and T, and they are able measure DC and AC magnetic fields. However, each range must be calibrated individually.

5. CALIBRATIONS

CEM is currently preparing five main calibration types:

5.1. Standard Helmholtz coils field strength calibration

Using a calibrated probe as standard, it is placed in the coils system's centre, where the field is homogeneous. Then several field points are measured for several source current values. Calculating the linear regression, the obtained value of the slope is the field-current ratio or the Helmholtz constant of the coils system. For the calibration of these coils the environmental magnetic field compensation system is needed.

5.2. Permanent magnets field strength calibration

A calibrated probe must be placed in the most homogeneous field possible and measures the magnetic field strength comparing it to its nominal value.

5.3. Magnetic field generators field homogeneity

The homogeneity of the generated magnetic field is key for correct measurements. That homogeneity is tested in the axis of the magnetic field generator. A length measurement system is fixed at a certain distance from the generator and a probe is set in one side of the generator. This probe is moved along the axis, measuring the value of the magnetic field at the same time that the relative distance is being measured.

This way, a map of the generated magnetic field for each value of distance along the generation axis is obtained.

5.4. Sensors Calibration

Sensors can be calibrated by two methods:

- Comparing the signal obtained by both, the standard calibrated sensor and the sensor under test. This is achieved as long as both probes are placed in the same homogeneous magnetic region.
- Using a calibrated magnetic field generator.

5.5. AC Calibration

There are two main devices with AC capabilities:

- AC Helmholtz Coil: First calibrated in DC, obtaining the traceable Helmholtz constant. The power supply used for the AC measurements has low noise and controlled harmonics. The harmonics control is key for achieving lower uncertainties as they distort the final measurement.
- Hall Sensor: Directly calibrated with the AC Helmholtz Coil.

As previously stated, the maximum field generated by the coils is constrained by the frequency. This is due to the system's impedance increase with frequency, needing a greater voltage for higher frequencies and easily achieving the wire voltage limit.

In comparison with the DC measurements, AC measurements have a larger uncertainty, as more calibrations are needed in order to obtain the first chain's element. Moreover, more uncertainty sources are present in AC measurements, as the harmonics' contribution.

6. FUTURE PLANS

New projects are in the pipeline, which are planned not only to improve the state of art level of magnetic measurements, but also to establish an international partnership between worldwide NMIs and Designated Institutes (DIs), under the concept of smart specialization.

In addition, CEM is developing higher field standards to increase the calibration ranges.

7. CONCLUSIONS

CEM has developed with INRIM's support a full magnetic measurements laboratory, which is able to measure and generate magnetic field in the range from a few µT to 100 mT. Measurements can be performed in DC and AC. It is equipped with an environmental magnetic field compensation system, which achieves 4 nT of compensated field with a standard deviation of also 4 nT.

As a result of this work CEM is ready to perform various types of calibrations and to participate in magnetism projects at an international level.

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