THE NEW CALIBRATION SYSTEM FOR MAGNETIC FIELD PROBES AT THE LNF-INFN MAGNETIC MEASUREMENT LABORATORY

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Abstract

Accurate calibration of probes is essential for high-quality magnetic-field measurements. Within the PNRR IRIS project, the Magnetic Measurement Facility (MMF) at LNF-INFN has implemented a new dedicated calibration system designed and manufactured by CAYLAR. The setup includes a 2.23 T dipole magnet with a 35 mm gap, a 5 ppm four-quadrant power supply for low-field operation, and three NMR probes with associated electronics, covering the 20 mT to 2.2 T range. The probes are mounted on a dedicated holder positioned in a highly uniform field region, ensuring that all sensors experience the same magnetic environment. Achieving excellent homogeneity over a large volume and wide field range was a key challenge; this was addressed through a genetic-algorithm-optimized magnet design complemented by active shimming coils. This contribution presents the design, construction, and factory acceptance tests of the system, along with the first calibration results obtained at MMF. Future improvements include thermostating the probe holder, potentially using cryogenic liquids, to extend the temperature range for calibrations, an important capability for probes used in superconducting magnets.

INTRODUCTION

The INFN Frascati Laboratories have a long-standing tradition in magnetic measurements, supported by instrumentation that has enabled, over the years, the testing of magnets for particle accelerators (DAFNE, SPARC, CNAO, ELI, STAR, etc.) as well as for experimental applications. In recent years, a major upgrade of both the existing instrumentation and the facility infrastructure has been carried out, including civil engineering and technical systems. The LATINO project, funded by the Regione Lazio, enabled the installation of a rotating coil bench and a stretched-wire bench, as well as the refurbishment of existing infrastructure (cooling system, flooring, main gate) [1].

More recently, the IRIS project (Innovative Research Infrastructure for applied Superconductivity), funded by Next Generation EU (PNRR), has extended the capabilities of the laboratory toward superconductivity, particularly in the context of room-temperature measurements of superconducting magnets [2]. The instrumentation has been further enhanced through upgrades to the Hall probe positioning system, the acquisition of three-axis probes, a vibrating wire bench, a laser tracker and precision alignment accessories, power converters of various ranges, and additional ancillary equipment for laboratory activities. A mezzanine has also been constructed within the existing building to improve the organization of space and equipment [3,4]. The flexibility of the instruments will allow to cover a large range of magnetic measurements, from point maps to integrated fields, from multipolar analysis to fiducialization.

Within this framework, the laboratory has been equipped with a new calibration system developed by CAYLAR[1], described in this contribution. The study and implementation of this system have led to a strong collaboration between CAYLAR and the INFN research group, driven by evolving requirements in magnetic field intensity and homogeneity. This joint effort focuses on performance optimization, improved space efficiency through precise probe positioning and reduced pole gap, and continuous system enhancement.

THE CALIBRATION SYSTEM

The system is based on a reference dipole electromagnet powered by a dedicated four-quadrant power converter. The objective is to achieve high magnetic field intensity and homogeneity. A larger homogeneous volume allows simultaneous calibration of multiple Hall sensors, improving throughput, while precise probe positioning ensures measurement repeatability and accuracy.

The electromagnet features a 35 mm gap and elliptical pole faces of 140 mm diameter, optimized using a genetic algorithm to balance field intensity and homogeneity. The central field reaches up to 2.23 T, with a homogeneity better than 0.02 % within a 15 × 15 × 15 mm^3 volume across the full operating range.

The power supply operates in four quadrants, enabling smooth polarity reversal and accurate low-field operation. It delivers up to 70 V and 150 A (10.5 kW), with a long-term stability of 5 ppm over 8 hours, a thermal drift of 2 ppm/°C, and low ripple (2 mV). Field stability is ensured through NMR-based feedback regulation, allowing sub-ppm stability by actively controlling the current based on real-time magnetic field measurements.

Absolute field measurements rely on three NMR probes covering the range from 20 mT to 2.2 T, with overlapping regions for cross-calibration. A high-precision gaussmeter provides measurements with 10 nT resolution and better than 0.5 μT accuracy.

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The system is integrated on a mobile platform including readout electronics and a four-channel preamplifier multiplexer. The thermalized chamber where the probe holder is integrated ensures stable environmental conditions and reproducible probe positioning. Future developments include active temperature regulation (20 °C to 65 °C), with potential extension to lower temperatures.

Magnetic Field Characterization

A measurement campaign was conducted at the end of production to verify field homogeneity within a 40 mm diameter region, and to compare experimental results with design predictions. Measurements were performed at 0.5 T, 1 T, and 2 T using a three-axis Hall probe mounted on a six-axis robot scanning a volume of $200 \times 20 \times 20$ mm^3.

Figure 1: Magnetic field characterization system of the electromagnet, with a Hall probe mounted at the end of a six-axis robot.

NMR probes were used in the feedback loop of the power supply to ensure high temporal stability during measurements.

The homogeneous region was defined based on a field variation criterion of 1 G, relevant for Hall sensor calibration. Under these conditions, the homogeneous area is approximately 25 mm in diameter, allowing all probes to be positioned within the chamber.

Implementations of PCB Shimming Coils

To further improve homogeneity, active shimming coils were investigated. While magnet poles are typically optimized for a single field value, shimming coils enable fine tuning of the field distribution across different operating conditions.

This approach allows the homogeneous region to be maintained over the full field range through current adjustment, extending performance beyond the intrinsic pole geometry.

Simulations and experimental validation at 0.5 T, 1 T, and 2 T show that the homogeneous diameter can be increased from approximately 25 mm to about 50 mm using single-axis active shimming. The field variation between NMR and Hall probe positions remains below 1 G within the chamber.

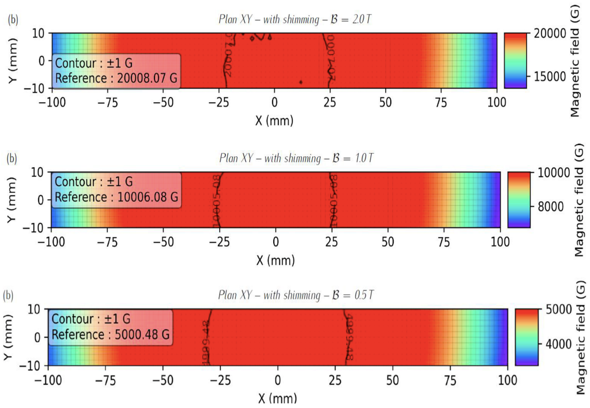

Figure 2: Magnetic field maps in the XY plane. The magnetic field is configured with values 2 T, 1 T and 0.5 T. The contour lines correspond to local field variations of ±1 G (respectively, 0.005 %, 0.01 % and 0.02 % of the reference value).

Table 1: Characterization of the Magnetic Field Performances in Areas of Interest for Positioning of the Probes to be Calibrated. The Values in Columns Stand for the Maximum Deviation Observed from the Average Value of B_z Measured Over the Area.

Surface (mm^2)	$\overline{B_z}$**(T)**	**Maximum deviation**
40×20	5001	0.016 %
40×20	10008	0.017 %
40×20	20010	0.012 %
60×20	5001	0.030 %
60×20	10007	0.034 %
60×20	20010	0.023 %

The shimming coils were implemented as PCB structures positioned at the center of the magnet. A calibrated current table, covering the range from −2.2 T to 2.2 T, enables precise and automated control of the shimming system.

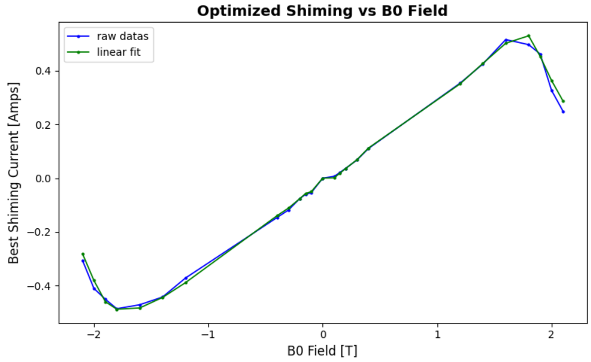

Figure 3: Evolution of the optimized shimming current I_{shim} as a function of the magnetic field intensity B_0. The blue markers correspond to the experimentally determined optimal shimming currents for each value of the magnetic field, while the green curve represents a linear fit of the measured values.

NMR-based Validation of Homogeneity

To further assess homogeneity and calibration accuracy, measurements were performed using two NMR probes positioned within the homogeneous region. One probe was used for field regulation, while the second provided an independent measurement at the calibration location.

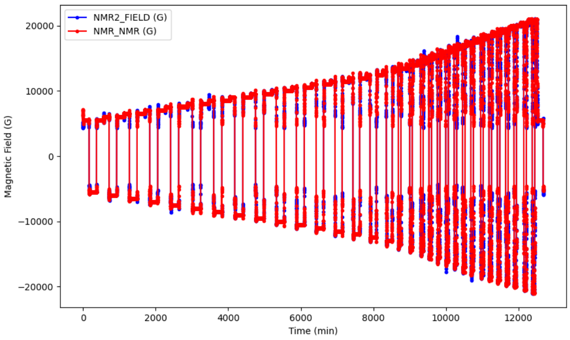

Figure 4: Temporal evolution of the magnetic field measured by both NMR probes. Although the horizontal axis represents time, the measurement was performed by applying successive current steps, corresponding to a sequence of magnetic field values.

The difference between the two probes typically ranges from 1 µT to 20 µT across most of the operating range, corresponding to only a few ppm at high fields. At lower fields, the relative error increases due to the constant absolute difference.

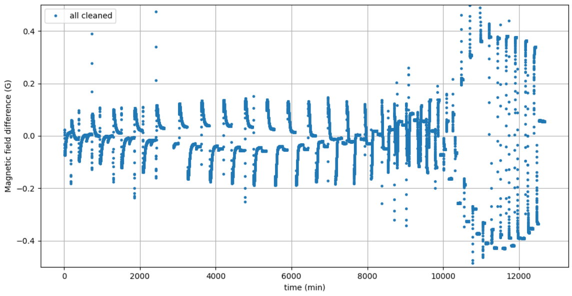

Figure 5: Field difference measured between two probes, one used for magnetic field regulation, and the other placed at the location intended for calibration. The field was varied continuously according to the previous picture.

These results confirm that the achieved field homogeneity and stability are compatible with high-precision Hall probe calibration.

High-end Hall teslameters typically specify accuracies on the order of 0.01 % (~ 100 ppm), although definitions may vary. The performance demonstrated here is therefore fully consistent with the requirements for calibrating high-accuracy Hall sensors.

CONCLUSION

For the magnetic measurement laboratory, the objective of the IRIS project was to provide the instrumentation required to perform measurements of magnets at room temperature. Such measurements are recommended during the manufacturing phase of superconducting (SC) magnets, as they enable validation of the assembly and early detection of defects before cryogenic testing is carried out. The next step is to enable probe calibration at low temperature and high magnetic field. This represents a particularly critical aspect for SC magnets, since probe calibration is typically performed at approximately room temperature and under moderate magnetic fields.

The LNF-INFN group is a partner of the ASTRA project, newly funded by the Italian Ministry of University and Research (MUR). Within this project, the goal is to develop a probe holder compatible with the magnet system presented here but cooled to cryogenic temperatures by means of a cryocooler. A further step will be the integration of this probe holder, equipped with both NMR probes and probes to be calibrated, into a high-field superconducting magnet developed by the other project partners.

Beyond the technological developments presented in this paper, the work has established a strong and effective collaboration between the INFN research institute and the CAYLAR company. This partnership has led to excellent results and a reinforced commitment toward shared objectives. The authors look forward to continuing this collaboration on topics of mutual interest in the future.

ACKNOWLEDGEMENTS

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