25th IMEKO TC4 International Symposium
23rd International Workshop on ADC and DAC Modelling and Testing
IMEKO TC-4 2020
Brescia, Italy / September 12-14, 2022

Traceability routes for magnetic measurements

Marco Coïsson[1], Javier Diaz De Aguilar Rois[2], Yolanda Alvarez Sanmamed[2], Oliver Power[3], Robert Walsh[3]

[1]*INRIM, strada delle Cacce 91, 10135 Torino (TO), Italy, m.coisson@inrim.it*
[2]*CEM, calle Alfar, 2, 28760 Tres Cantos (Madrid), Spain*
[3]*NSAI, 1 Swift Square, Northwood, Santry, Dublin 9, Ireland D09 A0E4*

***Abstract* – Magnetic measurements are vital to support European challenges in areas such as electric vehicles; health; power transformation and harvesting; clean, affordable and secure energy; information and sensor technology. However, only very few European NMIs have the capabilities to perform traceable measurements of all of the most important magnetic quantities. Consequently, the adoption of novel technologies and materials is hindered by the lack of local metrological expertise that research and development activities in academia and industry could exploit. A new European project (TRaMM, 21SCP02), in the framework of the Small Collaborative Projects (SCP) call 2021, aims at transferring the expertise of INRIM (Italy) in the field of magnetic calibration and measurements to CEM (Spain) and NSAI (Ireland), thus addressing market and stakeholder requirements in the European Union and paving the way toward future smart specialisation concepts at the European level.**

I. INTRODUCTION

Magnetic measurements are relatively common in academia and in industrial research and development, as they are widely employed for the measurement of magnetic fields and for the characterisation of the magnetic cores in sensors or electronics. In addition, they are used in applications such as earth observation [1, 2], biomedicine [3, 4, 5] and health and safety requirements regarding exposure to electromagnetic fields [6, 7, 8] (The Electromagnetic Fields Directive 2013/35/EU). However, so far, the industrial and scientific communities have been unable to fully benefit from traceable and reliable measurement results because of limited access to suitable calibration facilities. With the global magnetic materials market continuously increasing at an annual growth rate of about 9.6 % [9], it is crucial to develop sustainable magnetic measurement capabilities that will support these end-users.

Even though the calibration of teslameters and coils, or the measurement of the magnetic properties of steel sheets for power applications (electrical motors, transformers) are already standardised, only few European NMIs are capable of providing a comprehensive set of measurement and calibration services in these areas, which require very specific instruments and techniques. In addition, new research activities and industrial products, in the fields of biomedicine [10], theragnostics [11], water remediation [12, 13], and security [14, 15] are expanding the need for traceable magnetic measurements for e.g. the characterisation of magnetic nanoparticles, rings, ribbons or bulk materials, or for sensing devices involving magnetoelectric phenomena [16, 17, 18, 19, 20].

Other fields requiring traceable and reliable magnetic measurements are all those where magnetic materials are exploited for energy conversion, harvesting and storage, such as automotive and powertrains, aerospace, and smart grids [21, 22, 23]. All these applications attract both scientific research and industry, and offer development and market opportunities especially for SMEs that wish to be dynamic and innovative, offering breakthrough technologies and solutions to new potential customers and markets. In spite of this exciting innovation and development, easy access to the measurement and calibration capabilities for magnetic field and magnetic material characterisations are still mostly lacking, leaving industry and academia with the unaddressed need to properly validate their technological solutions through traceable magnetic measurements.

To partially fill the gap between the available expertise at the European level, and the market and stakeholders needs, a new project labelled TRaMM (Traceability routes for magnetic measurements), within the Small Collaborative Projects call 2021 [24], has been funded for the September 2022 - February 2024 timeframe. The project aims at collecting as many stakeholders needs as possible in the field of magnetic calibrations and measurements, and to transfer the expertise of the Italian NMI (INRIM) in this field to two partners, CEM and NSAI, respectively the NMIs of Spain and Ireland, in order to strengthen the collaboration at the European level and to offer a set of measurement and calibration services to academia and industry that better address their current needs. Figure 1 shows the PERT diagram of the project.

II. NEED FOR THE PROJECT

Research relating to magnetic phenomena is well developed at the academic level in several European countries, with many groups and laboratories active in the charac-

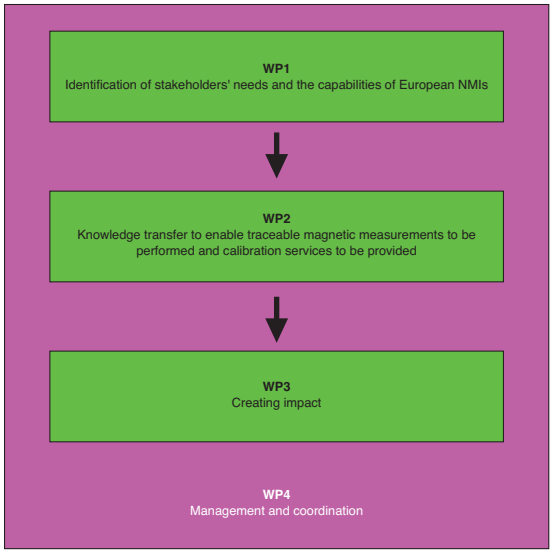

Fig. 1. PERT diagram of the TRaMM project.

terisation of magnetic materials, and a few groups particularly specialised in this subject. Scientific competence on magnetic measurements and on the characterisation of magnetic materials is therefore available in many European countries [25, 26], but most NMIs either do not offer any calibration and measurement capabilities, or just the most basic ones, leaving only very few NMIs (among which INRIM, CMI, PTB, VSL), which are able to provide a wide and complete offering on this topic [27].

The most developed measurement capability is magnetic flux density. While secondary standards which use calibrated coils or probes (Hall probes, fluxgates, etc.) are commercially available, their calibration status is often questionable. The reason for this is the lack of adequate metrological support throughout Europe. This, in turn, hinders the development of a mature industry that can exploit these technologies. A few academic laboratories and very few NMIs (e.g. INRIM, CMI, PTB) also offer competencies in the characterisation of magnetic materials. A few methods have been standardised, mostly within the framework of the IEC 60404 series of standards, especially concerning power losses in the steel sheets that are used in power technologies. Other methods have also been developed to the point that a few NMIs offer calibration and measurement capabilities approved under the CIPM Multilateral Arrangement for the measurement e.g. of magnetic permeability, power losses, (BH) product, DC polarisation, coercivity in hard magnets, etc. in some materials with specific geometries. However, specialised research laboratories have a plethora of different techniques which allow for the measurement of the magnetic properties of materials in different forms (nanoparticles, thin films, bulk samples, liquids), shapes (wires, ribbons, rings, strips, films, etc.), at different temperatures (from liquid Helium to approximately 1000 °C), and at different frequencies (from DC to GHz). Not all of these characterisations are possible in all conditions, but the academic research community and the instrumentation industry are continuously developing new methods and techniques to investigate the magnetic properties of materials in special or uncommon conditions. These techniques, although scientifically accepted, are rarely submitted to a true metrological validation, partly because, in materials research, the uncertainty deriving from the material under test, and the difficulty in measurement reproducibility, tend to hide, to a first approximation, the other uncertainty sources. In addition, ring comparisons among several laboratories have underlined the difficulty of obtaining compatible results with new measurement techniques (e.g. EU TD 1402 COST Action RADIOMAG) and even with apparently consolidated comparisons [28]. For this reason, new efforts have recently been made from a methodological point of view, to help to develop a metrological background in magnetic measurements, e.g. with new international standards (ISO/TS 198071, ISO/TS 198072) for the characterisation of magnetic nanoparticles [29, 30].

The task of extending the availability of traceable magnetic measurement and calibration services to more EU countries cannot rely only on the presence of a local scientific community that is expert in the field of magnetic measurements, because the scientific community is mostly oriented towards frontier research and rarely has the possibility, or the interest, to invest in a serious metrological infrastructure, providing traceability and calibration facilities. On the other hand, while the NMIs have the necessary experience in providing this type of infrastructure, most of them only have limited, if any, experience in magnetic measurements, which cover a very large domain requiring a wide set of competencies (magnetic measurements can broadly be divided into two groups: 1) the measurement of magnetic fields and 2) the measurement of the magnetic properties of matter; these two groups require different equipment and different approaches, and links to e.g. electrical, frequency and temperature metrology are required to guarantee a serious metrological infrastructure). In order to ensure the quickest possible means of spreading this knowledge, and to avoid duplicated efforts, a coordinated effort is envisaged, involving the NMIs wishing to develop their capabilities in magnetic measurements, and the NMIs that through a longstanding scientific activity in the field can offer high level training and a deep understanding of the required metrological background and infrastructure.

III. OVERVIEW OF THE PROJECT

Figure 2 presents schematically an overview of the project. While INRIM provides fundamental training on magnetic measurements and calibration to CEM and NSAI, the stakeholders' needs are collected and will pro-

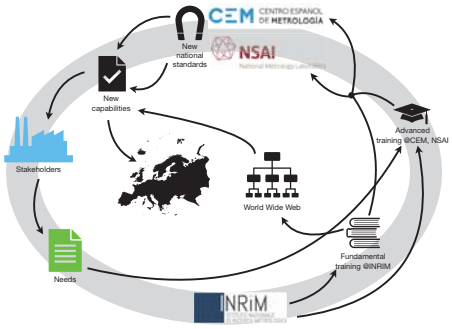

Fig. 2. Scheme of the TRaMM project.

vide the basis for the advanced training. The training materials and the stakeholders' needs will be shared online and will be available to any interested parties. Thanks to the newly developed national standards and to the newly acquired competences, the consortium of the project will be able to offer new services to the stakeholders and improve the EU capabilities in the field of magnetic measurements and calibration, thus closing the feedback loop.

IV. STAKEHOLDERS

Relevant stakeholders for the TRaMM project will therefore belong to (but are not limited to) the following categories: academia and research centres working on magnetic materials and applied magnetism (for energy transformation, actuation, sensing, biomedicine); industries belonging to electric vehicle supply chains (electric motors) and power application supply chains (electric motors and transformers); industries belonging to sensor supply chains (magnetic field probes, position, rotation, angle, speed, vibration, etc., detectors, bit detectors and systems for magnetic registration); industries belonging to the magnetic field monitoring supply chain (measurement of magnetic fields in or around industrial equipment, biomedical devices such as NMR, personal exposure meters, etc.); industries involved in medical device manufacturing; industries in the food supply chain (metal detection in food processing); industries involved in electric and electronic components (e.g. microwave components); academia and research centres working on geomagnetism; industries belonging to the steel supply chain (manufacturers and industries processing semifinished products) and to the weakly magnetic steel supply chains (aerospace, naval and military industries).

Even though not directly addressed at them, the TRaMM project is strongly focussed on stakeholders, as their needs will form the basis of the knowledge transfer that will take place among the NMIs making up the consortium. The stakeholders needs will therefore be collected to form a large set of requirements and expectations, in terms of needed magnetic calibration and measurement services (frequencies, intensities, kind of materials or samples, etc.), that will be used to analyse the alignment between the stakeholders high level needs and the metrology services provided or planned by the NMIs.

INRIM, CEM and NSAI will contact as many potential stakeholders as possible; however, any academic or industrial partner interested in magnetic calibration and measurement services is invited to contact the coordinator or one of the three NMIs to share their needs and expectations, and possibly to be part of the stakeholders committee, in order to help heading the training and knowledge transfer steps of the project.

V. TRAINING

The training process will involve expert personnel from INRIM and interested personnel from both CEM and NSAI, and will focus first on fundamental aspects of magnetic measurements and calibration, and then on more advanced topics of specific interest of the stakeholders community. Training events will be held both online and in person, and all training material will be made publicly and freely available online in order to reach as many potentially interested partners and stakeholders as possible. Additionally, interested NMIs that are not formally involved in the TRaMM project will have the possibility to attend the training events, with the aim of reaching the widest possible audience.

The training events will include several different approaches:

- classes on fundamentals of magnetism, magnetic materials and measurements;
- classes on advanced topics of magnetism, magnetic materials and measurements;
- laboratories on measurements of magnetic fields and magnetic properties of matter, calibration of measurement equipment;
- hands-on sessions and videos on specific equipments and measurement setups;
- classes and training on ensuring traceability of magnetic measurements and calibration.

The contents mentioned above will be developed according to the stakeholders' needs and the requests of the participating partners.

The following measurement and calibration techniques are among the ones that it will be possible to investigate in the framework of the TRaMM project:

- dc and ac calibration of magnetic field probes (e.g. Hall probes) under three-axial compensation of Earth magnetic field;

- calibration of a magnetic field standard through nuclear magnetic resonance;
- measurement of magnetic permeability of soft materials or ferrites;
- measurement of frequency-dependent power losses in steel sheets;
- measurement of frequency-dependent power losses of ferrites;
- measurement of static magnetic properties of nanoparticles and nanoparticles dispersions;
- measurement of magnetic properties of hard magnetic materials by vibrating sample magnetometer or B-H meter.

The specific measurement and calibration techniques that will be treated will be defined in agreement among the project partners after a thorough investigation of their and their stakeholders' needs.

VI. KNOWLEDGE TRANSFER AND IMPACT

The TRaMM project will create impact through its three objectives. With Objective 1, the involved NMIs will identify their stakeholders' needs for magnetic measurement and calibration facilities and plan the development of the services and measurement capabilities that they will offer, in order to meet these needs. With Objective 2, the involved NMIs will gain sufficient competencies to be able to offer the subset of magnetic measurement and calibration capabilities that will be relevant to their stakeholders' needs, as well as the required consultancy services that will create immediate impact for the stakeholders. Finally, with Objective 3 a smart-specialisation concept will be defined, to promote the coordination among the participating NMIs and other NMIs to pave the way for the future development of their capabilities in magnetic measurements and calibration according to the stakeholders' needs through a coordinated approach to identify priority areas and strengthened trust in capabilities. It is expected that the smart specialisation concept will create impact by widening the offering of magnetic measurement and calibration capabilities in the European Union, both through an increased number of expert NMIs in the field, and through an increased awareness, among the stakeholders, of the availability of these capabilities.

All of the aforementioned impacts will benefit existing stakeholders, which include magnetic materials properties research centres and universities, calibration laboratories, the Earth observation industry, and companies performing onsite testing of health and safety requirements regarding exposure to electromagnetic fields with respect to the Electromagnetic Fields Directive 2013/35/EU. They also include the logistics industry which is required to measure the magnetic fields of shipments sent by air freight, and the aviation industry which uses magnetic techniques for the nondestructive testing of airframes.

In the longer term, the outputs from this project will enable more NMIs to acquire capabilities in magnetic measurements and calibrations. This will even be possible after the end of this project, thanks to the availability of the training material online.

A long-term impact of the project will be the partners' ability to participate in the standardisation activities and committees relating to magnetic testing, as the project's outcomes will be shared with EURAMET Technical Committee for Electricity and Magnetism. The partners' competencies on magnetic measurements will offer the required knowledge to define the correct standardisation paths for new measurement techniques (e.g. the specific loss power for the materials that are used in biomedical applications), or for existing techniques that are currently used in non-standard conditions (e.g. magnetic fields at higher frequency values, high-intensity static magnetic fields in biological media, etc.).

To promote a wider impact, the TRaMM project will also organise a workshop, toward the end of its funding period (i.e. Fall 2023 - Winter 2024), where stakeholders, other NMIs, academia, any interested parties will be invited to join the project participants to share the experience developed during the project, and to analyse future routes for improving the collaboration at the EU level, for further extending the measurement and calibration capabilities on magnetism and magnetic properties of materials, for approaching standardisation bodies in order to drive the development of new standards and regulations at the international level toward the stakeholders requirements. All interested parties are invited to attend the workshop, and can get in touch with the project participants for further information and details.

REFERENCES

[1] M.J.S. Johnston, "Review of electric and magnetic fields accompanying seismic and volcanic activity", Surveys in Geophysics, vol. 18, 1997, pp. 441-476, doi: 10.1023/A:1006500408086.

[2] K.L. Verosub, A.P. Roberts, "Environmental magnetism: past, present, and future", J. Geophysical Research, vol. 100, 1995, pp. 2175-2192, doi: 10.1029/94JB02713.

[3] Y. Li, H. Cheng, Z. Alhalili, G. Xu, G. Gao, "The progress of magnetic sensor applied in biomedicine: a review of non-invasive techniques and sensors", J. Chinese Chem. Soc., vol. 68, 2021, pp. 216-227, doi: 10.1002/jccs.202000353.

[4] N.M. Shupak, F.S. Prato, A.W. Thomas, "Therapeutic uses of pulsed magnetic-field exposure: a review", URSI Radio Science Bulletin, vol. 2003, 2003, pp. 9-

32, doi: 10.23919/URSIRSB.2003.7909506.

[5] E.A. P'erigo, G.. Hemery, O. Sandre, D. Ortega, E. Garaio, F. Plazaola, F.J. Teran, "Fundamentals and advances in magnetic hyperthermia", Appl. Phys. Rev., vol. 2, 2015, pp. 041302, doi: 10.1063/1.4935688.

[6] A. Ahlbom, "A review of the epidemiologic literature on magnetic fields and cancer", Scand. J. Work Environ. Health, vol. 14, 1998, pp. 337-343, https://www.jstor.org/stable/40965589.

[7] P. Levallois, "Hypersensitivity of human subjects to environmental electric and magnetic field exposure: a review of the literature", Env. Heath Persp., vol. 110, 2002, pp. 613-618, doi: 10.1289/ehp.02110s4613.

[8] D.A. Savitz, "Overview of occupational exposure to electric and magnetic fields and cancer: advancements in exposure assessment", Env. Health Persp., vol. 103, 1995, pp. 69-74, doi: 10.1289/ehp.95103s269.

[9] "Magnetic Materials Market by Type (Semi-Hard Magnet, Soft Magnet, Hard/Permanent Magnet) & by Application (Automotive, Electronics, Industrial, Power Generation, and Others) - Global Forecasts to 2020", report code CH 3238, March 2016, https://www.marketsandmarkets.com/Market-Reports/magnetic-materials-397.html

[10] I. Andreu, E. Natividad, "Accuracy of available methods for quantifying the heat power generation of nanoparticles for magnetic hyperthermia", Int. J. Hyperthermia, vol. 29, 2013, pp. 739-751, doi: 10.3109/02656736.2013.826825

[11] V.I. Shubayev, T.R. Pisanic II, S. Jin, "Magnetic nanoparticles for theragnostics", Adv. Drug Delivery Rev., vol. 61, 2009, pp. 467-477, doi: 10.1016/j.addr.2009.03.007.

[12] A.G. Leone, A.A.P. Mansur, H.S. Mansur, "Advanced functional nanostructures based on magnetic iron oxide nanomaterials for water remediation: a review", Water Res., vol. 190, 2021, pp. 116693, doi: 10.1016/j.watres.2020.116693.

[13] R.D. Ambashta, M. Sillanpää, "Water purification using magnetic assistance: a review", J. Haz. Mat., vol. 180, 2010, pp. 38-49, doi: 10.1016/j.jhazmat.2010.04.105.

[14] W. Irnich, "Electronic security systems and active implantable medical devices", Pacing and clinical electrophysiology, vol. 25, 2002, pp. 1235-1258, doi: 10.1046/j.1460-9592.2002.01235.x.

[15] V. Zhukova, P. Corte-Leon, J.M. Blanco, M. Ipatov, J. Gonzalez, A. Zhukov, "Electronic surveillance and security applications of magnetic microwires", Chemosensors, vol. 9, 2021, pp. 100, doi: 10.3390/chemosensors9050100.

[16] C. Morón, C. Cabrera, A. Morón, A. García, M. González, "Magnetic sensors based on amorphous ferromagnetic materials: a review", Sensors, vol. 15, 2015, pp. 28340-28366, doi: 10.3390/s151128340.

[17] Y. Wang, J.Li, D. Viehland, "Magnetoelectrics for magnetic sensor applications: status, challenges and perspectives", Materials Today, vol. 17, 2014, pp. 269-275, doi: 10.1016/j.mattod.2014.05.004.

[18] S. Zuo, H. Heidari, D. Farina, K. Nazarpour, "Miniaturised magnetic sensors for implantable magnetomyography", Adv. Materials Tech., vol. 5, 2020, pp. 2000185, doi: 10.1002/admt.202000185.

[19] S. Wei, X. Liao, H. Zhang, J. Pang, Y. Zhou, "Recent progress of fluxgate magnetic sensors: basic research and application", Sensors, vol. 21, 2021, pp. 1500, doi: 10.3390/s21041500.

[20] B. Cao, K. Wang, H. Xu, Q. Qin, J. Yang, W. Zheng, Q. Jin, D. Cui, "Development of magnetic sensor technologies for point-of-care testing: fundamentals, methodologies and applications", Sensors and Actuators A: Physical, vol. 312, 2020, pp. 112130, doi: 10.1016/j.sna.2020.112130.

[21] C.M. Leung, J. Li, D. Viehland, X. Zhuang, "A review on applications of magnetoelectric composites: from heterostructural uncooled magnetic sensors, energy harvesters to highly efficient power converters", J. Phys. D: Appl. Phys., vol. 51, 2018, pp. 263002, doi: 10.1088/1361-6463/aac60b.

[22] F. Yang, L. Du, H. Yu, P. Huang, "Magnetic and electric energy harvesting technologies in power grids: a review", Sensors, vol. 20, 2020, pp. 1496, doi: 10.3390/s20051496.

[23] L. Sun, M. Cheng, H. Wen, L. Song, "Motion control and performance evaluation of a magnetic-geared dual-rotor motor in hybrid powertrain", IEEE Transactions on Industrial Electronics, vol. 64, 2017, pp. 1863-1872, doi: 10.1109/TIE.2016.2627018.

[24] https://msu.euramet.org/current_calls/scp_2021/

[25] https://www.magnetometry.eu

[26] https://magnetism.eu

[27] https://www.bipm.org/kcdb/cmc/quicksearch?includedFilters=&excludedFilters=cmcBranches.Density%2CcmcBranches.Fluid+flow%2CcmcRmo.APMP%2CcmcRmo.COOMET&page=0&keywords=magnetic

[28] MagNaStand Final Publishable Report: https://www.euramet.org/download/?L=0&tx_eurametfiles_download%5Bfiles%5D=41169&tx_eurametfiles_download%5Bidentifier%5D=%252Fdocs%252FEMRP%252FJRP%252FJRP_Summaries_2016%252FNormative%252F16NRM04_Final_Publishable_Report.pdf&tx_eurametfiles_download%5Baction%5D=download&tx_eurametfiles_download%5Bcontroller%5D=File&cHash=887a8ca2d84cc6137aef3d013cfc73e9

[29] ISO/TS 198071 Nanotechnologies Magnetic nanomaterials Part 1: Specification of characteristics and measurements for magnetic nanosuspensions. International Organisation for Standardisation, 2019.
[30] ISO/TS 198072 Nanotechnologies Magnetic nanomaterials Part 2: Specification of characteristics and measurements for nanostructured superparamagnetic beads for nucleic acid extraction. International Organisation for Standardisation, under development.