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Traceability routes for magnetic measurements: filling the gap between the magnetism community and the European NMIs offering

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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 European project (TRaMM, 21SCP02), in the framework of the Small Collaborative Projects (SCP) call 2021, aimed at transferring the expertise of INRIM (Italy) in the field of magnetic calibration and measurements to CEM (Spain) and NSAI (Ireland), and to interested stakeholders.

Section: RESEARCH PAPER

Keywords: Magnetic measurements; magnetic calibrations; training

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1. 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]-[5], health and safety requirements regarding exposure to electromagnetic fields [6]-[8] (The Electromagnetic Fields Directive 2013/35/EU), non-destructive testing of materials and technological installations [9]-[11]. 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 covering the wide range of particular devices and applications. With the global magnetic materials market continuously increasing at an annual growth rate of about 9.6% [12], it is crucial to develop sustainable magnetic measurement capabilities that will support these end-users.

Even though the calibration of teslameters [13] and coils, or the measurement of the magnetic properties of steel sheets for power applications (electrical motors, transformers) are already standardised, only a few European National Metrology Institutes (NMIs) are capable of providing a comprehensive set of measurement and calibration services in these areas, because of the specific expertise required, and of the need to develop ad-hoc, complex laboratories. In addition, new research activities and industrial products, in the fields of biomedicine [14], theragnostics [15], water remediation [16], [17], and security [18], [19] are expanding the need for traceable magnetic

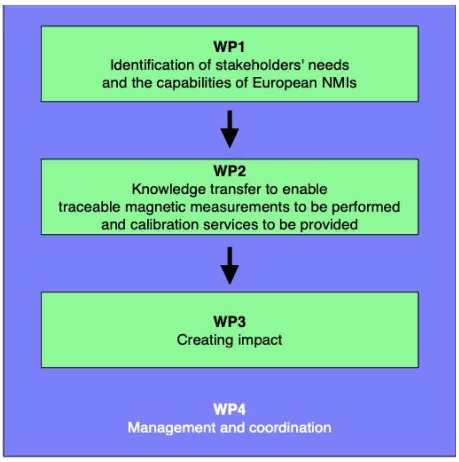

Figure 1. PERT diagram of the TRaMM project.

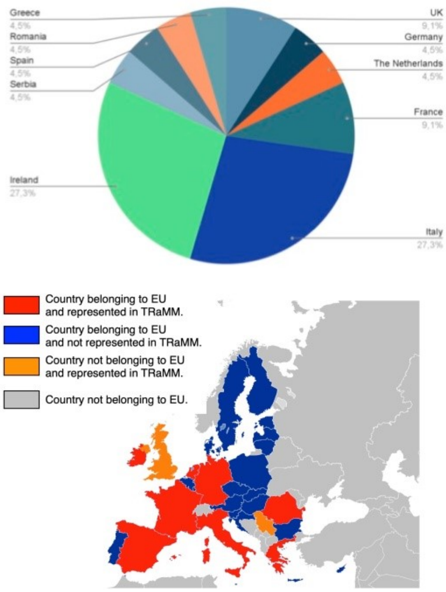

Figure 2. Geographical distribution of the stakeholders.

measurements for e.g. the characterisation of magnetic nanoparticles, rings, ribbons or bulk materials, or for sensing devices involving magnetoelectric phenomena [20]-[24]. In recent years, initial efforts have been done to start providing a suitable metrological framework for the characterisation of some magnetic properties of novel classes of materials, such as magnetic nanoparticles [25]-[27], of extensive interest in biomedicine. However, international standards for the measurement of most magnetic quantities, especially on novel classes of magnetic materials or on finished products and components, are still lacking. This is partly due to the intrinsic difficulty of comparing the measurements of magnetic properties of materials with an arbitrary shape, to specimens in reference conditions: even if the need dates back to many decades ago [28], little progress has been done so far. However, the modern technological applications, the emergence of 3D “printed” materials [29] and the concerns for energy saving and efficiency, especially for home appliances and electrical mobility, are driving a renewed interest in this problem [30].

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, smart grids but also user appliances and devices containing permanent magnets [31]-[35]. All these applications attract both scientific research and industry while offering development and market opportunities, especially for small and medium enterprises (SMEs) that wish to be dynamic and innovative, enabling them to offer 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. At the same time, this exposes customers, end-users, but also decision makers to products and technologies whose real performance has not been properly assessed.

To partially fill the disparity between the existing expertise at the European level, and the market and stakeholders needs, the TRaMM project (Traceability routes for magnetic measurements), within the Small Collaborative Projects call 2021 [36], has developed training material 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, and to interested stakeholders. At the European scale, the project aims at strengthening the collaboration among NMIs and at offering a set of measurement and calibration services to academia and industry that better address their current and possibly future needs. Figure 1 shows the PERT diagram of the project.

Among other conferences and dissemination events, preliminary and ongoing results of the TRaMM project have been presented at IMEKO TC4 meeting in 2022 and in 2023 [37], and at the CIM exhibition in 2023.

2. MAGNETIC COMMUNITY NEEDS

The TRaMM project lasted 18 months, from September 2022 through February 2024. Several stakeholders, belonging to academia and public research institutions, industries and companies were asked to participate in anonymous online surveys to identify their primary interests and needs in the field of magnetic measurements and calibrations, and to share their vision of the future. Figure 2 summarises the geographical distribution of the stakeholders that have decided to participate in the survey, updated at December 2023, when data collection ended. The potential stakeholders that were reached by the TRaMM project cannot cover the whole set of companies and research institutions that are active in magnetic measurements and calibrations within the European Union, and suffer from an unavoidable geographical bias where some countries (i.e. Italy and Ireland) are probably overrepresented because of the already existing links between the local magnetic community and the project’s partners. However, 10 different European countries are represented, identified by the red colour in the European map in Figure 2.

Figure 3 summarises the received responses in terms of applications of interest for the stakeholders. All the most important areas are significantly represented: research and development (34%), calibration and testing (45%), and manufacturing and in-field applications (20%).

Figure 4 reports the stakeholders' needs in terms of magnetic field measurements. More than half of the interested stakeholders declare their need to measure (or to calibrate probes capable of measuring) both DC and AC magnetic fields, whereas only a small percentage of them require only AC measurements.

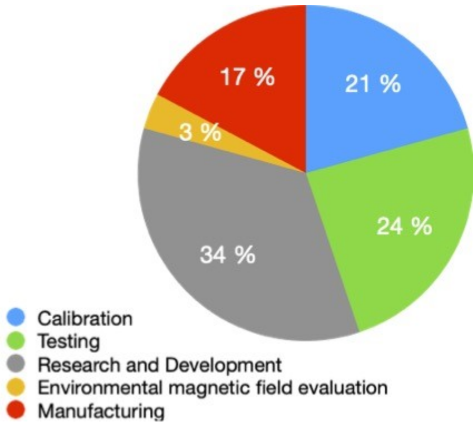

Figure 3. Distribution of applications of interest for the stakeholders.

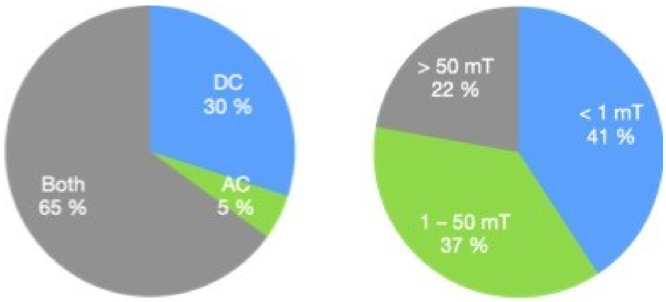

Figure 4. Distribution of magnetic field regimes (AC, DC, or both, left) and intensity (right) according to the stakeholders' needs.

The low to intermediate field ranges are the most representative, leaving only 22 % of the answers for the relatively high field range above 50 mT.

For those stakeholders aiming at characterising magnetic materials, there is a widespread interest in powders and nanoparticles, that may find applications in pigments [38], loading of polymers for multifunctional materials [39], environment applications [40] and cancer treatment [41]. These are all "new" applications, where a metrological framework for magnetic measurements is still lacking. "Traditional" materials such as steel sheets and ferrite rings (for which international standards are already available) are no longer the only materials taken into consideration, as thin films, ribbons, wires and nanostructures, which may find application in sensors and information and communication technology (ICT) [42], play a role of comparable importance in the stakeholders' interest, and are currently uncovered by measurement standards. Figure 6

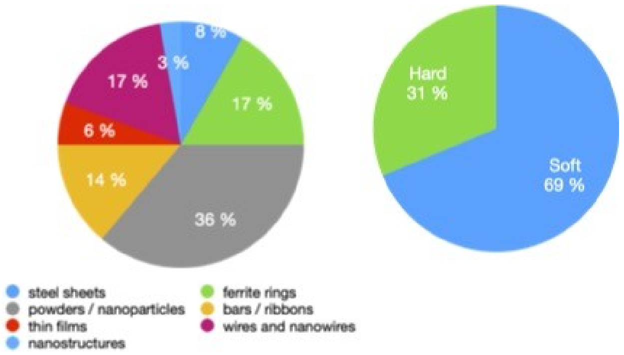

Figure 6. Distribution of the stakeholders' interests in the characterisation of magnetic materials (left), and their classification as either magnetically soft or hard (right).

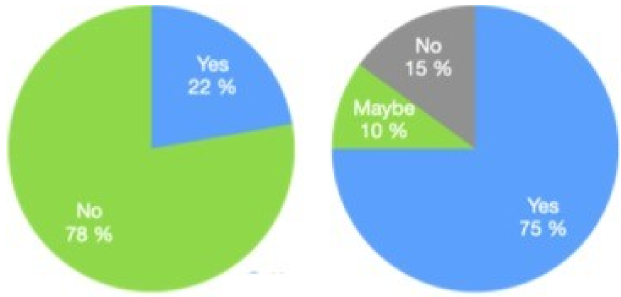

Figure 5. Existence of international standards (left) and perceived need of them (right) for the magnetic measurement and calibration activities performed by the stakeholders.

summarises the received responses. Overall, almost two thirds of the materials the stakeholders work with can be labelled as soft magnetic materials.

Interestingly, while 63% of the received responses point to the need for characterising the intrinsic properties of a material, there is already a significant request (37%) for methods to characterise finished products or components, which are much closer to the market or to application than the magnetic material used to make them and prepared in form and shape adequate for laboratory investigation. At present, there are neither recognised laboratory methods nor international standards available for such configurations. This suggests that possible future research lines could attempt to address these needs.

Finally, the stakeholders are clearly aware that international standards are still missing for many of the magnetic measurement and calibration activities that they are relying upon, as summarised in Figure 5. Interestingly, all of them declare they would benefit from the existence of an international standard, even though a few of them admit that its absence is not an impedance for their activities. Indeed, this suggests that the stakeholders perceive the dynamic nature of emerging technologies and markets, and it is up to the metrological community to evolve in time to address their emerging needs.

3. TRAINING FOR THE PROJECT PARTNERS AND FOR THE STAKEHOLDERS

The TRaMM project has delivered training on magnetic measurements and calibrations to CEM and NSAI (as project partners), but also to interested stakeholders, through online training material made of commented slides and videos that are available through the project website [43] and on the dedicated YouTube channel [44]. All the training material is publicly and freely available.

The training material includes:

- A recorded PhD course (7 lessons) treating fundamentals of magnetism and of magnetic materials, and of magnetic measurement techniques.
- A recorded lesson on the principles of measurement of magnetic fields.
- A recorded lesson on the principle of measurement of magnetic properties of materials.
- A recorded lesson on the principles of operation of different magnetic field sensors.
- Hands-on laboratory videos:

- Wattmeters for measuring power losses in soft magnetic materials.
- Ballistic method for measuring quasi-static magnetisation curves in soft magnetic materials (close circuit configuration).
- Inductive measurement methods (theory and laboratory) of the hysteresis loops and power losses of soft magnetic rings.
- Vector Network Analyzer (VNA)-based measurement method (theory and laboratory) of the complex magnetic permeability of soft magnetic rings at high frequency (up to a few GHz).
- Measurement method on hard magnetic materials according to the IEC 404 5 standard.
- Static magnetometers (theory) and specifically Vibrating Sample Magnetometer (VSM) (laboratory) for measuring hysteresis loops of semi-hard and hard magnetic materials, nanoparticles, and thin films (open circuit configuration).
- DC probes calibration methods in different magnetic field ranges.
- AC probes calibration methods.

Besides online training, specific events open to the project partners only have been organised in INRIM laboratories, to offer hands-on sessions focussed on utilising equipment for calibration of magnetic probes and for the characterisation of magnetic materials. Additional training sessions have been organised at CEM and NSAI sites, focussing on the analysis of the existing and new facilities installed or to be developed in their laboratories.

4. WORKSHOP AND FINAL OUTCOMES

To promote a wider impact, the TRaMM project has also organised a workshop [45], at the end of February 2024, where stakeholders, other NMIs, academia, any interested parties were invited to join the project participants to share the experience developed during the project. The workshop aimed at summarising the project results and at describing the training material that was specifically produced. Several invited speakers from academia, NMIs and industry shared their expertise in the field of international standardisation of magnetic measurements, development of traceable measurement techniques of magnetic properties of novel classes of magnetic materials, insights of magnetic sensors development and working. The programme of the workshop is available on the project website [45].

The desired outcomes were to analyse future routes for improving the collaboration at the EU level while further extending the measurement and calibration capabilities on magnetism and magnetic properties of materials and for approaching standardisation bodies with the intendment of driving the development of new standards and regulations at the international level toward the stakeholders requirements. The workshop was also an opportunity to draft possible applications to future funding calls.

5. CONCLUSIONS

The TRaMM project was the first systematic attempt to collect in an ordered and structured way information and resources concerning the metrological needs at the European level on magnetic measurements and calibrations. In spite of its small size and limited timeframe, TRaMM was capable of accomplishing these results:

- *Identification of new needs:* from the stakeholders' surveys, it clearly emerged that the "traditional" magnetic metrology based on standardised techniques and materials classes and shapes is no longer sufficient, as science, industry and market are moving towards new classes of materials that require new standardised measurement methods, yet to be developed.
- *Production of training material:* this is essential for establishing a common reference base to train new users working for companies, academia and NMIs.
- *Paving the path to new projects:* either as capacity building, or aiming at smart specialisation, new projects will benefit from the two previous goals and from the new competences and laboratories that were developed.

The TRaMM project can certainly be considered as a pathfinder for new collaboration concepts involving the development of new magnetic measurement laboratories and the standardisation of new magnetic measurement techniques for novel classes of materials, applications or technologies.

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