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Traceability routes for magnetic measurements

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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, is transferring the expertise of INRIM (Italy) in the field of magnetic calibration and measurements to CEM (Spain) and NSAI (Ireland), and to interested stakeholders. An update on the training material is given, and new stakeholders are actively sought.**

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 a few European NMIs are capable of providing a comprehensive set of measurement and calibration services in these areas. This requires 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 while offering development and market opportunities, especially for 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.

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 [24], is developing 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 needs. Figure 1 shows the PERT diagram of the project.

II. FEEDBACK FROM STAKEHOLDERS

The TRaMM project is now in full development. Several stakeholders, belonging to academia and public research institutions, industries and companies have been asked to participate in an anonymous online survey to identify their primary interests and needs in the field of magnetic mea-

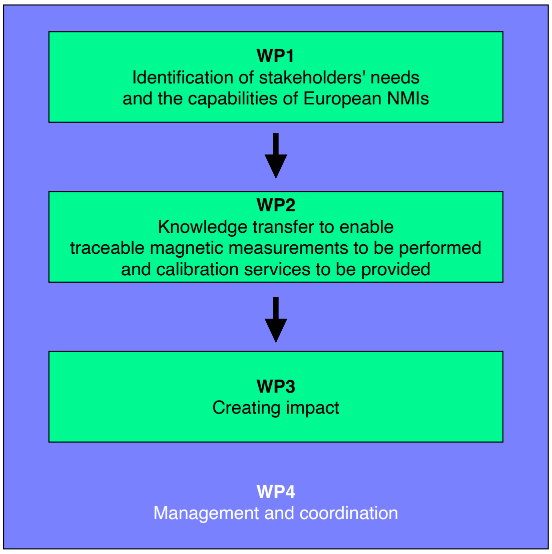

Fig. 1. PERT diagram of the TRaMM project.

surements and calibrations. Figure 2 summarises the geographical distribution of the stakeholders that have decided to participate in the survey, updated at May 2023, whereas Figure 3 summarises the received responses in terms of applications of interest for the stakeholders. All the most important areas are significanlty represented: research and development (34%), calibration and testing (45%), and manufacturing and in-field applications (20%).

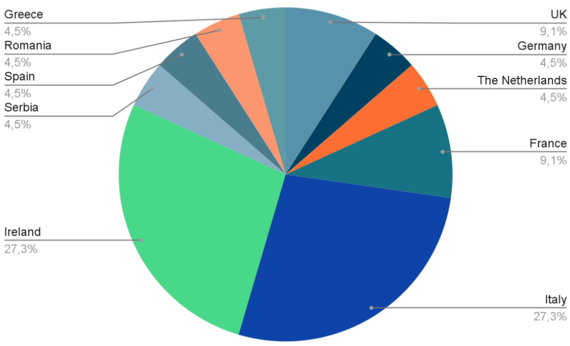

Fig. 2. Geographical distribution of the stakeholders.

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. 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

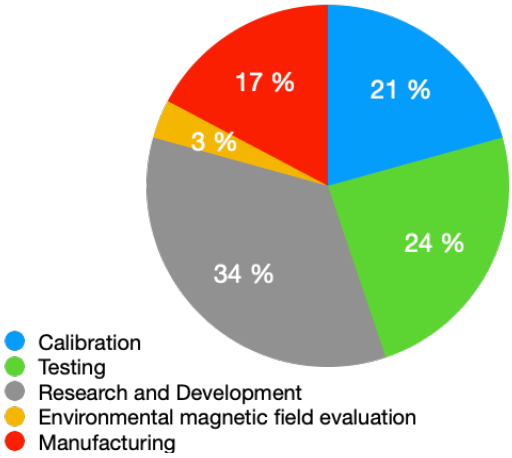

Fig. 3. Distribution of applications of interest for the stakeholders.

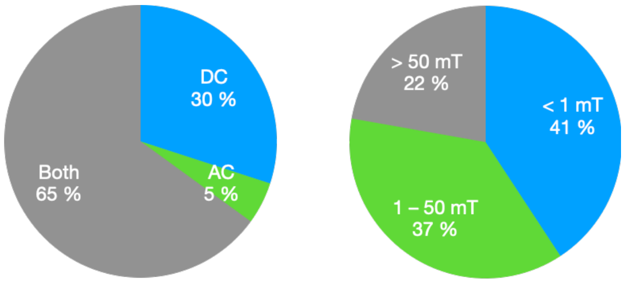

Fig. 4. Distribution of magnetic field regimes (AC, DC, or both, left) and intensity (right) according to the stakeholders' needs.

[31], loading of polymers for multifunctional materials [32], environment applications [33] and cancer treatment [34]. 'Traditional' materials such as steel sheets and ferrite rings are no longer the only materials taken into consideration, as thin films, ribbons, wires and nanostructures, which may find application in sensors and ICT [35], play a role of comparable importance in the stakeholders' interest. Figure 5 summarises the received responses. Overall, almost two thirds of the materials the stakeholders work with what 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. At present, there are neither recognised laboratory methods nor international standards available for such configurations. This suggests that possible future research line 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

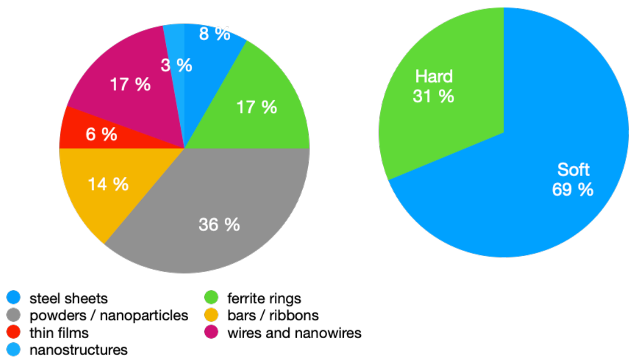

Fig. 5. Distribution of the stakeholders' interests in the characterisation of magnetic materials (left), and their classification as either magnetically soft or hard (right).

upon, as summarised in Figure 6. 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.

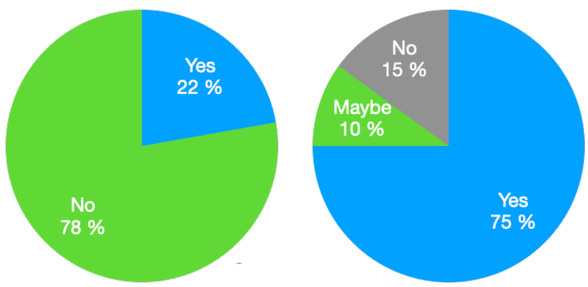

Fig. 6. Existence of international standards (left) and perceived need of them (right) for the magnetic measurement and calibration activities performed by the stakeholders.

III. TRAINING FOR THE PROJECT PARTNERS AND FOR THE STAKEHOLDERS

The TRaMM project is delivering 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 [36] and on the dedicated YouTube channel [37]. All the training material is publicly and freely available. Any academic group or company that would like to be involved as a stakeholder is invited to contact the project coordinator. Besides online training, specific events open to the project partners only have been and will be organised in INRIM laboratories. These offer hands-on sessions focussed on utilising equipment for calibration of magnetic probes and for the characterisation of magnetic materials.

IV. WORKSHOP AND FINAL OUTCOMES

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. The desired outcomes will be 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. All interested parties are invited to attend the workshop and can get in touch with the project participants for further information and details. The participation in the workshop will be free, and it will also be possible to join it online, although in-person participation is recommended for the best possible interaction among participants. This will also be an opportunity to draft possible applications to future funding calls. Details of the final workshop will be made available in due time on the project website [36].

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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.

[31] Kanika, G. Kedawat, S. Singh, B.K. Gupta, *A novel approach to design luminomagnetic pigment formulated security ink for manifold protection to bank cheques against counterfeiting*, Adv. Mater. Techn. **6** (2021) 2000973, doi 10.1002/admt.202000973.

[32] H. Zhang, J.-Y. Xia, X.-L. Pang, M. Zhao, B.-Q. Wang, L.-L. Yang, H.-S. Wan, J.-B. Wu, S.-Z. Fu, *Magnetic nanoparticle-loaded electrospun polymeric nanofibers for tissue engineering*, Mat. Sci. Eng. C **73** (2017) 537-543, doi 10.1016/j.msec.2016.12.116.

[33] J. Govan, *Recent advances in magnetic nanoparticles and nanocomposites cor the remediation of water resources*, Magnetochemistry **6(4)** (2020) 49, doi 10.3390/magnetochemistry6040049.

[34] JZ. Hedayatnasab, F. Abnisa, W.M.A. Wan Daud, *Review on magnetic nanoparticles for magnetic nanofluid hyperthermia application*, Materials and Design **123** (2017) 174-196, doi 10.1016/j.matdes.2017.03.036.

[35] J. Alam, C. Bran, H. Chiriac, N. Lupu, T.A. Óvári, L.V. Panina, V: Rodionova, R: Varga, M. Vazquez, A. Zhukov, *Cylindrical micro and nanowires: fabrication, properties and applications*, J. Magn. Magn. Mater. **513** (2020) 167074, doi 10.1016/j.jmmm.2020.167074.

[36] https://www.tracemag.eu

[37] https://www.youtube.com/@EURAMET-TRaMM/featured