XXXII Consultative Committee for Electricity and Magnetism

14-15 April 2021, BIPM, Paris-Sèvres, France (Virtual meeting)

INRIM Progress Report: Mar 2019 - Mar 2021

The progress report is arranged according to the branches of the CCEM Classification.

Branch 1-3: DC voltage, current and resistance

The low dc current scale has been revised and is now based on a precision current transconductance/transresistance amplifier (Ultrastable Low Current Amplfiier, ULCA) and a capacitance-charging current source, covering in total the range 10 fA - 5 µA. A comparison of the two current generating systems allows to determine the ac-dc dependence of gas-dielectric capacitors. Contact: l.callegaro@inrim.it

L. Callegaro, C. Cassiago, V. D'Elia, E. Gasparotto, E. Enrico, M. Götz, "Comparison of low dc current traceability methods and gas capacitors ac-dc dependence," IEEE Trans. Instr. Meas., vol. 70, pp. 1-6 (2021).

Measurement of direct currents below the nA range are common in nanoscience experiments. Gain and offset thermal drifts of high-gain (G to T) transresistance amplifiers limit the measurement sensitivity and accuracy. A case study of simple and inexpensive thermostat focuses on improvements in the gain and offset stability of a commercial transresistance amplifier. Contact. e.enrico@inrim.it

E. Enrico, L. Cannataro, V. D'Elia, I. Finardi, L. Callegaro, "Simple thermal control of dc low-current amplifiers improves stability", Meas. Sci. Technol., 30, 037001 (2019)

In collaboration with National Institute for Standards and Technology (NIST) a graphene quantum Hall Kelvin *bridge-on-a-chip* for resistance calibrations has been designed and implemented. The bridge is based on a graphene integrated circuit with three quantum Hall elements and operates with ordinary laboratory electronic equipment, and can calibrate four terminal resistance artifacts with an accuracy of $1{\times}10^{-8}$ or better. Contact: m.marzano@inrim.it

M. Marzano, M. Kruskopf, A. Panna, A. Rigosi, D. Patel, H. Jin, S. Cular, L. Callegaro, R. Elmquist, M. Ortolano, "Implementation of a graphene quantum Hall Kelvin bridge-on-a-chip for resistance calibrations", Metrologia 57 (1) 015007 (2020).

Branch 4: Impedance up to the MHz range

VersICaL	EMPIR 17RPT04 VersICaL - *A versatile electrical impedance calibration laboratory based on digital impedance bridges*. INRIM has realized a fully-digital reference impedance bridge, suitable for realisation of primary inductance and capacitance scales, which is accessible as a virtual training lab. More info: https://sites.google.com/inrim.it/inrimtcem M. Ortolano, M. Marzano, V. D'Elia, N. T. M. Tran, R. Rybski, J. Kaczmarek, M. Kozioł, K. Musioł, A. E. Christensen, L. Callegaro, J. Kučera, O. Power, "A Comprehensive Analysis of Error Sources in Electronic Fully Digital Impedance Bridges," IEEE Trans. Instr. Meas., vol. 70, pp. 1-14, 2021.
GIQS	EMPIR 18SIB07 GIQS - Graphene Impedance Quantum Standard. INRIM is developing a fully-digital bridge for the realisation of the capacitance unit from the quantum Hall effect in graphene. More info: https://www.ptb.de/empir2019/giqs/home/ M. Marzano, M. Ortolano, V. D'Elia, A. Müller, L. Callegaro, "A fully-digital bridge towards the realization of the farad from the quantum Hall effect," Metrologia, vol. 58, n. 1, 015002, 2020.

Branch 5-7: AC voltage, current and power

MICEV

INRiM coordinates the EMPIR Project 16ENG08 MICEV *"Metrology for inductive charging of electric vehicles"* (https://www.micev.eu). The project aimed to advance inductive/wireless power transfer (IPT/WPT) for the charging of EVs by developing metrology techniques for measuring IPT efficiency as well as reliable demonstration of compliance with existing safety standards for human exposure.
INRiM developed a new resistive divider for voltage measurement at frequencies up to 200 kHz, for calibration of voltage meters dedicated to WPT. The divider operates both in DC and AC up to 1 kV from 10 kHz up to 200 kHz. The phase error is lower than 400 microrad at 100 kHz. The device relative measurement uncertainty is lower than 500E-6 up to 200 kHz. A voltage comparator and a step-up procedure for the calibration of voltage dividers, including the phase measurement, have been set up making use of the reference divider. INRiM has also developed a new measurement system called Power Measurement Unit (PwMU) to characterize WPT charging stations for electric vehicles, and a method for the uncertainty assessment of on-site measurements. INRiM has also developed systems for the measurement and for the "in silico" assessment of exposure to magnetic fields in WPT stations and, in collaboration with NPL, has published a best practice guide for the assessment of EMF exposure from vehicle WPT systems. Project ended on 28 Feb. 2021.
Contacts: Mauro Zucca, m.zucca@inrim.it

- "*Best practice guide for the assessment of EMF exposure from vehicle Wireless Power Transfer systems*". pp. 1-64, Editors: R. Guilizzoni, S. Harmon, M. Zucca, ISBN: 9788894532418, (2021)
- M. Zucca, Mauro, P. Squillari, U. Pogliano. *A Measurement System for the Characterization of Wireless Charging Stations for Electric Vehicles.* IEEE Transactions on Instrumentation and Measurement, vol. 70, p. 1-10, (2021)
- M. Zucca, M. Modarres, U., Pogliano, D. Serazio, *1 kV Wideband Voltage Transducer, a Novel Method for Calibration and a Voltage Measurement Chain*. IEEE Transactions on Instrumentation and Measurement, p. 1-12, (2020)

LF macro setup based on synchronized HP3458, voltage and current transducers and the open source software for active and reactive power measurements is under validation through INRiM participation in the EURAMET.EM-K5 international comparison. Research towards calibration methods for HF digitizers and transducers against national AC standards for the establishment of a Power Quality standard is being developed. Contact: Bruno Trinchera, b.trinchera@inrim.it

INRIM and the Ministero dello Sviluppo Economico (Ministry of Economic Development, MISE) have signed an agreement entitled "Collaboration for the development of validation methods for electrical energy meters under realistic conditions, towards market surveillance and consumer protection" The objectives of the agreement include the development of a new laboratory for meter calibration / verification under low power quality conditions and the development of guidelines for future evolution of the Italian regulation. Contact: l.callegaro@inrim.it

Branch 8: High voltage and current

INRIM coordinates the EMPIR project 16ENG04 MyRailS "Metrology for smart energy management in electric railway systems". The project aims to develop the metrological framework and measurement infrastructure that underpin the adoption of energy efficient technologies in the European railway systems. In particular, INRIM has developed a new reference system able to generate a DC voltage up to 6 kV with superimposed arbitrary ripple up to 10 kHz and DC current up to 300 A with arbitrary ripple up to some kilohertz [1-2]. Means and methods for the monitoring of PQ in the DC railway system have been developed and applied to data acquired during the measurement campaigns performed in metro and railway systems [3]. A methodology for the detection of the arc event occurring between overhead contact line and pantograph in the DC railway system has been developed. A

	formal patent application has been submitted. The methodology has been applied to the data acquired on-board; the identified events have been collected in the public dataset [4]. A. D. Femine, D. Gallo, D. Giordano, C. Landi, M. Luiso and D. Signorino, "Power Quality Assessment in Railway Traction Supply Systems," in *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 5, pp. 2355-2366, May 2020, doi: 10.1109/TIM.2020.2967162 Giordano, D.; & all (2020), "Pantograph Arcing in DC Railway Systems: Transient Behavior of Voltage and Current Recorded at Pantograph", Mendeley Data, V1, doi: 10.17632/74nz86wcgy.1
	INRIM coordinates the EMPIR project 19NRM05 IT4PQ "Measurement methods and test procedures for assessing accuracy of *I*nstrument *T*ransformers *for P*ower Quality measurements". The IT4PQ project aims to develop the presently missing metrological framework for the traceable calibration of instrument transformers used for Power Quality (PQ) measurements in electrical distribution grids. Results are expected in terms of instrument transformer (IT) PQ performance indices, reference measurement systems and test procedures to evaluate the ITs accuracy and uncertainty contributions to PQ parameters evaluation. Outputs of the project will be provided to IEC TC 38 Instrument transformers as a basis for future standardisation about the use of ITs for PQ. INRIM is contributing by setting up reference laboratory calibration methods and systems for the investigation and quantification of the performances of present and future technology based ITs under realistic PQ events. Contact: Gabriella Crotti (g.crotti@inrim.it)
	EMPIR 19NRM07 HV-com², Support for standardisation of high voltage testing with composite combined wave shapes. https://www.ptb.de/empir2020/hv-com2/home/. The aim of this pre-normative research is to realise the necessary metrology required for the standardisation of high voltage testing with composite and combined wave shapes. In order to address the current lack of traceability, traceable measurement systems and calibration services will be developed for composite and combined wave shapes, and the relationship between impulse voltages with High Voltage Alternating Current (HVAC) or High Voltage Direct Current (HVDC) measurements will be determined. Input will be provided to IEC TC 42 'High-voltage and high-current test techniques' which revises relevant standards, in particular the IEC 60060 series. Contact: Paolo Roccato (p.roccato@inrim.it)

Branch 10: Electric and magnetic fields

	EMPIR 17IND01 "MIMAS", Procedures allowing medical implant manufacturers to demonstrate compliance with MRI safety regulations. https://www.ptb.de/mimas/home/. Exposure of patients' carrying implants to gradient and radiofrequency fields during a MRI session was investigated by in silico experiments to evaluate temperature rise exceeding safety limits. On the basis of this wide analysis, evaluation tools have been made available to the radiologists and medical physics communities (10.5281/zenodo.4388310). Contact: Luca Zilberti, l.zilberti@inrim.it. Winter, L., Seifert, F., Zilberti, L., Murbach, M., Ittermann, B., MRI-Related Heating of Implants and Devices: A Review, Journal of Magnetic Resonance Imaging, 2020, DOI: 10.1002/jmri.27194. Arduino, A., Zanovello, U., Hand, J., Zilberti, L., Bruhl, R, Chiampi, M., Bottauscio, O., Heating of hip joint implants in MRI: The combined effect of RF and switched-gradient fields, Magnetic Resonance in Medicine, 2021, DOI: 10.1002/mrm.28666. Zilberti, L., Zanovello, U., Arduino, A., Bottauscio, O., Chiampi, M., RF-induced heating of metallic implants simulated as PEC: Is there something missing?, Magnetic Resonance in Medicine, 2021, 85(2), pp. 583–586

QUIERO	INRIM coordinates the EMPIR project 18HLT05 “QUIERO”, Quantitative MR-based imaging of physical biomarkers. https://quiero-project.eu/. In this project, the main technical activity carried out by INRIM, is the development, implementation and characterization of algorithms to perform Electric Properties Tomography (EPT), using as input the spatial distribution of the magnetic flux density acquired during Magnetic Resonance Imaging (MRI). The implementations available to date have been collected within an open source library, named *EPTlib*, distributed on GitHub (https://eptlib.github.io/). EPTlib has been used to develop an example of application of the GUM in the framework of the EMPIR project 17NRM05 EMUE, where EPTlib played to role of the computational “engine” in the evaluation of the uncertainty associated with the repeatability of EPT experiments. Contact: Luca Zilberti, l.zilberti@inrim.it. Arduino A., Bottauscio O., Chiampi M., Zilberti L., Uncertainty propagation in phaseless electric properties tomography, 2019 International Conference on Electromagnetics in Advanced Applications (ICEAA),,https://doi.org/10.1109/ICEAA.2019.8879147.
EFMAG	INRIM coordinates the EMPIR project 19ENG06 HEFMAG, “Metrology of magnetic losses in electrical steel sheets for high-efficiency energy conversion”. https://hefmag.inrim.it/. Magnetic steel sheets are the core of electric motors, generators, and transformers, which produce and convert virtually all the energy obtained from conventional and renewable sources. Novel products based on electrical steel require accurate magnetic loss measurements and modelling under high temperature, 2D excitation, distorted flux with high harmonic content, skin effects and dc currents. In this project, several round robins are planned among the NMI partners, steel producers and other industrial stakeholders to verify and improve the metrology of magnetic losses worldwide. The main technical activity carried out by INRIM, is the measurement and modeling of magnetic losses in a very wide range of excitation conditions. Contact: Massimo Pasquale, m.pasquale@inrim.it
RaCHy Radiotherapy Coupled with Hyperthermia	INRIM coordinates the EMPIR Project 18HLT06 RaCHy *“Radiotherapy coupled with hyperthermia”* (https://rachy-project.eu/). The objective is to provide a reliable metrology framework for the evaluation of radiation-based therapies coupled with different hyperthermia techniques, including radiofrequency (rf) hyperthermia and magnetically mediated hyperthermia. *In silico*, *in phantoms*, *in vitro* and *in vivo* tests are covered. In collaboration with Erasmus Medical Center (NL), INRIM has designed, via numerical modelling, an rf applicator operating at 434 MHz, to be used in *in vitro* and pre-clinical tests of rf hyperthermia. Regarding magnetic hyperthermia, advances were achieved on both modelling and experimental characterization of magnetic nanomaterials, acting as heating agents under ac magnetic fields. *In silico* models were also developed to simulate nanomaterial interactions with biological systems, focusing on transport in blood vessels, release in tissues and hyperthermia therapeutic efficacy. Contacts: Giovanni Durando, g.durando@inrim.it; Alessandra Manzin, a.manzin@inrim.it. A. Manzin, R. Ferrero, M. Vicentini, *From micromagnetic to in silico modelling of magnetic nanodisks for hyperthermia applications*, Advanced Theory and Simulations (in press). M. Vicentini, R. Ferrero, A. Manzin, *Modelling of magnetic bead transport in a microvascular network*, Journal of Magnetism and Magnetic Materials 513, 167234 (2020).

Branch 11: Radio Frequency measurements

	EMPIR 17FUN10 ParaWave, "Josephson travelling wave parametric amplifier and its application for metrology" https://sites.google.com/inrim.it/parawave The overall objective of this project is to develop a novel and practical broadband microwave amplifier capable of operation at and beyond the fundamental, or standard quantum limit, of sensitivity. Applications of this capability are strongly demanded across wide-ranging areas of fundamental and applied physics and engineering, including quantum information processing, quantum computing (for instance in the readout of qubits), quantum metrology (for instance microwave-photon counting), radio-astronomy, medical imaging, communications and other forms of sensing. Contact: Emanuele Enrico (e.enrico@inrim.it) L. Fasolo, "Superconducting Josephson-based metamaterials for quantum-limited parametric amplification: a review" in Condensed Matter Physics, by InTech Open, https://doi.org/10.5772/intechopen.89305
	INFN DARTWARS, "Detector Array Readout with Traveling Wave AmplifieRS" https://dartwars.unimib.it/ The aim of the project is to boost the sensitivity of INFN experiments based on low-noise superconducting detectors. This goal will be reached through the development of wideband superconducting amplifiers at microwaves with noise at the quantum limit and the implementation of a quantum limited read out in different types of superconducting detectors. Contact: Emanuele Enrico (e.enrico@inrim.it)

Branch 12: Measurements on materials

INRIM continued the activity of numerical modelling of nano/microstructured magnetic materials and devices providing support to experimental analysis and design. Advances were achieved in the calibration of miniaturized magnetic field sensors, scanning Hall probe microscopy and magnetic force microscopy (MFM) probes. In collaboration with other NMIs an extensive calibration methodology was developed to arrive at quantitative MFM imaging, focusing on magnetic reference samples, with calculable stray fields. Numerical modelling was combined to two MFM probe characterization techniques, based on the use of nanosize Hall sensors and metallic microcoil scanning. Progress was made on numerical code development, with the implementation of a 3D GPU-parallelized micromagnetic solver, fully validated by standard micromagnetic modeling problems (NIST). Contact: Alessandra Manzin, a.manzin@inrim.it.

A special issue of the scientific journal *Nanomaterials* is currently open for paper submission on the topic *"Magnetic Nanomaterials and Nanostructures"*.

R. Ferrero, A. Manzin, *Adaptive geometric integration applied to a 3D micromagnetic solver*, Journal of Magnetism and Magnetic Materials 518, 167409 (2021).

H. Corte‑León V. Neu, A. Manzin C. Barton, Y. Tang, M. Gerken, P. Klapetek, H. W. Schumacher, O. Kazakova, *Comparison and Validation of Different Magnetic Force Microscopy Calibration Schemes*, Small 16, 1906144 (2020).

R. Puttock, A. Manzin, V. Neu, F. Garcia‑Sanchez, A. Fernandez Scarioni, H. W. Schumacher, O. Kazakova, *Modal Frustration and Periodicity Breaking in Artificial Spin Ice*, Small 16, 2003141 (2020).

Quantum aspects of magnetism have been investigated by studying the relation between ferromagnetic spin waves and the presence of an electric field (italian project QUANTUMET). The study led to the formulation of the Ahronov-Chasher phase accumulated by the spin waves and to the possibility to envisage spin wave interference devices for the quantum measurement of the static electric field. The study of the relation between spin and heat currents in ferromagnetic insulators (spin Seebeck effect) has continued by: i) the verification of the Onsager reciprocity, ii) the test of the spincaloritronic effects as an imaging method for the bulk magnetization and iii) the assessment of the measurement method in the cryogenic temperature range. Contact: v.basso@inrim.it

V. Basso and P. Ansalone, *Electric field effect on spin waves: Role of magnetic moment current,* EPL, 130, 17008 (2020) doi:

10.1209/0295-5075/130/17008 (arXiv:1911.02902)

A. Sola, C. Barton, V. Basso, C. Dubs, M. Pasquale and O. Kazakova, *Local Spin Seebeck Imaging with a Scanning Thermal Probe*, Physical Review Applied 14, 034056 (2020) doi: 10.1103/PhysRevApplied.14.034056

	EMPIR 16NRM01 GRACE "Developing electrical characterisation methods for future graphene electronics" (2017-2020). http://empir.npl.co.uk/grace/. The project was aimed at the production of validated protocols for the measurement of the electrical properties of large area (cm^2) graphene. The research activity at INRIM was focused on the validation on graphene of common methods (van der Pauw, in-line four point probe) and on the implementation and validation of Electrical Resistance Tomography, a technique never used before for the mapping of electrical properties of graphene. The consistent cross-validation of these techniques (and others in charge of project partners NPL, CEM, das-Nano), provided i) two Good Practice Guides and ii) drafts for new projects at the International Electrotechnical Commission TC 113. A. Fabricius, A. Cultrera, A. Catanzaro, "Good Practice Guide on the electrical characterization of graphene using non-contact and high-throughput methods." (2020), ISBN: 978-88-945324-2-5. "Good Practice Guide on the electrical characterisation of graphene using contact methods." (2020), ISBN: 978-88-945324-0-1. A. Cultrera et al., "Mapping the conductivity of graphene with Electrical Resistance Tomography." Scientific reports 9.1 (2019): 1-9.
Metrology for topological spin structures 17FUN08 TOPS	INRIM is WP leader and leader of a round robin activity on the Dzyaloshinskii-Moriya interaction constant in the EMPIR project 17FUN08 TOPS "Metrology for topological spin structures". Topologically-protected spin structures (TSS) have the potential to revolutionise the Information and Communications Technology (ICT) sector (through novel magnetic data storage, magnetic logic, and microwave devices such as microwave nano oscillators) and might lead to new quantum reference standards. The importance of this field has been underlined by the 2016 Physics Nobel Prize. The goal of the project is to underpin fundamental research in this active field by developing metrological tools and methods for the characterisation of TSS and, thus, support future applications. The Dzyaloshinskii-Moriya interaction is considered to be the key-parameter in stabilizing TSS, therefore its accurate measurement is indispensable. Contact: Michaela Kuepferling, m.kuepferling@inrim.it https://www.ptb.de/empir2018/de/tops/home/ A.Casiraghi et al., "Individual skyrmion manipulation by local magnetic field gradients", Communication Physics 2, 145, 2019

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States	The EMPIR project mentioned in this report have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.