XXXIII Consultative Committee for Electricity and Magnetism

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INRIM Progress Report: Apr 2021 - Feb 2023

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

The boxes are national, European or international projects in collaboration with other institutions.

Branch 1-3: DC voltage, current and resistance

INRIM has declared new Calibration and Measurement Capabilities in the field of low dc electric currents. The calibration uncertainty in the range from 100 pA to 5 μA have been strongly improved by introducing a Ultrastable Low-noise Current Amplifier (Magnicon ULCA), having a nominal transresistance of 1 GΩ, calibrated with a cryogenic current comparator. Contact: l.callegaro@inrim.it

A new 10 V Programmable Josephson Voltage Standard (PJVS) from Supracon AG, operating in liquid helium, has been acquired and is now installed in a dedicated laboratory. The PJVS system will replace the former primary DC quantum voltage standard based on hysteretic Josephson junctions for the italian volt realization and will participate in international comparisons. Contact: p.durandetto@inrim.it

Branch 4: Impedance up to the MHz range

The inductance and capacitance scales of INRIM, presently based on a three-voltage comparator, are under revision. A fully-digital bridge, which can compare four terminal-pair impedances with arbitrary phase difference, has been employed for the realisation of inductance and capacitance from ac resistance and is being incorporated in the national standard of electrical impedance. Contact: l.callegaro@inrim.it

M. Marzano, V. D'Elia, M. Ortolano, L. Callegaro, "Primary Realization of Inductance and Capacitance Scales With a Fully Digital Bridge", IEEE Trans. Instr. Meas. 71, 1-8 (2022).

GIQS	EMPIR 18SIB07 GIQS - Graphene Impedance Quantum Standard. General info: https://www.ptb.de/empir2019/giqs/home/ . The project produced a set of videos available in a dedicated YouTube channel. The project has produced a Good Practice Guide for the graphene-based AC-QHE realisation of the farad which is open access. L: Callegaro, S. Bauer, B. Jeanneret, M. Kruskopf, M. Marzano, M. Ortolano, F. Overney, Good practice guide on the graphene-based AC-QHE realization of the farad, arXiv:2205.04915 The main INRIM contribution is the realisation of a fully-digital four terminal-pair bridge for the direct traceability of the farad unit to the AC quantum Hall effect. An on-site comparison between the INRIM bridge and a PTB Josephson bridge has been performed with success. M. Marzano, Y. Pimsut, M. Kruskopf, Y. Yin, M. Kraus, V. D'Elia, L. Callegaro, M. Ortolano, S. Bauer, R. Behr, "PTB–INRIM comparison of novel digital impedance bridges with graphene impedance quantum standards", Metrologia 59(6) 065001 (2022).

Branch 5-7: AC voltage, current and power

The primary power and energy standard of INRiM is based on simultaneous sampling of voltage and current waveforms by synchronized digital multimeters. Recently, a new modular digital sampling power standard has been developed allowing both traceable power and energy measurements in the kHz range as well as traceable measurements of power quality parameters. The traceability is ensured through the calibration of its main components. Its validation, at power line frequency, has been performed in the framework of the EURAMET-EM-K5.2018 international comparison.

B. Trinchera and D. Serazio, "A Power Frequency Modular Sampling Standard for Traceable Power Measurements: Comparison and Perspectives," *IEEE Trans. Instr. Meas.* vol. 71, pp. 1-8, 2022, Art no. 1500608, doi: 10.1109/TIM.2021.3132346

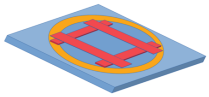
Quantum Power	INRiM is a WP leader of the EMPIR project 19RPT01 QuantumPower "Quantum traceability for AC power standards", https://quantumpower.cmi.cz/ The main contributions of INRIM concerns: i) the development of a new programmable Josephson voltage standard (PJVS) based on a 1-V SNS array operating in LHe for the synthesis of AC staircase waveforms up to the kHz range; ii) the development of a multiplexer for single and three-phase power measurements based on a single Josephson chip; iii) the integration and adaption of PJVS system and multiplexer into a quantum power standard (QPS) for power measurement using its modular macro-setups based on DMM 3458A and wideband digitizers. Contact: Bruno Trinchera (b.trinchera@inrim.it) B. Trinchera, D. Serazio, P. Durandetto, L. Oberto and L. Fasolo, "Towards a novel programmable Josephson voltage standard for sampled power measurements," in. 25th IMEKO TC-4 International Symposium, Brescia, Italy, Sept. 2022.
	The agreement between the Ministero dello Sviluppo Economico (Ministry of Economic Development, MISE) and INRIM entitled "Collaboration for the development of validation methods for electrical energy meters under realistic conditions, towards market surveillance and consumer protection" was completed in November 2022. The new setup based on a ZERA MTS310 phantom power generator and a COM5003 reference wattmeter allows for the automation of many calibration procedures. A final report to the MISE has been issued including inputs for the update of national regulation in legal metrology for the active energy meters. Contact: l.callegaro@inrim.it L. Callegaro et al., "A calibration-verification testbed for electrical energy meters under low power quality conditions." Measurement: Sensors 18 (2021): 100188.

Branch 8: High voltage and current

DC Grids	20NRM03 DC grids aims to address these issues, in response to needs expressed by CLC TC8X WG1 (Physical characteristics of electrical energy) and IEC TC13 WG11 (Electricity metering equipment). This project's goal is the traceable measurement and characterisation of PQ parameters to support standardisation in the further development and future use of DC grids and to ensure future customer confidence. INRIM is developing and testing algorithm for the detection of DC power quality events. Moreover, INRIM is setting up a procedure to generate PQ events in order to investigate on the reliability of the developed algorithm. Contact: Domenico Giordano d.giordano@inrim.it
IT4PQ Instrument Transformers for Power Quality	INRIM coordinates the EMPIR project 19NRM05 IT4PQ "Measurement methods and test procedures for assessing accuracy of *I*nstrument *T*ransformers *for P*ower *Q*uality measurements". The IT4PQ project is developing of the metrological framework for the traceable calibration of instrument transformers used for Power Quality (PQ) measurements in electrical distribution grids. Results are being obtained in terms of instrument transformer (IT) PQ validated performance indices, reference measurement systems and test procedures. Outputs of the project are provided to IEC TC 38 Instrument transformers WG 47 to serve as a basis for future standardisation. INRIM specific contribution deals with the set upof reference laboratory calibration methods and systems and their use for the investigation of the performances of ITs under realistic PQ events. Contact: Gabriella Crotti (g.crotti@inrim.it) G. Crotti, D. Giordano, G. D'Avanzo, P.S: Letizia, P.S., M. Luiso, "A New Industry-Oriented Technique for the Wideband Characterization of Voltage Transformers", Measurement, 2021, doi.org/10.1016/j.measurement.2021.109674. G. Crotti, G. D'Avanzo, P.S: Letizia, P.S., M. Luiso "The Use of Voltage Transformers for the Measurement of Power System Subharmonics in Compliance With International Standard, in *IEEE Trans. Instr. Meas.* vol. 71, 2022, DOI: 10.1109/TIM.2022.320431

HV-com²	EMPIR 19NRM07 HV-com², Support for standardisation of high voltage testing with composite a combined wave shapes. https://www.ptb.de/empir2020/hv-com2/home/. The aim of this pre-normative research is to realize the necessary metrology required for the standardisation of high voltage testing with composite and combined wave shapes. Input will be provided to IEC TC 42 'High-voltage and high-current test techniques' which revises relevant standards IEC 60060 series. The main INRiM contributions are in the project of reference divider and in the characterization of digitizers for composite and combined wave shapes. Contact: Paolo Roccato (p.roccato@inrim.it) F. Galliana, S. E. Caria, P. E. Roccato, "Towards a traceable divider for composite voltage waveforms below 1 kV", Springer Electrical Engineering, August 2021, ISSN: 1432-0487, doi: 10.1007/s00202-021-01368-5

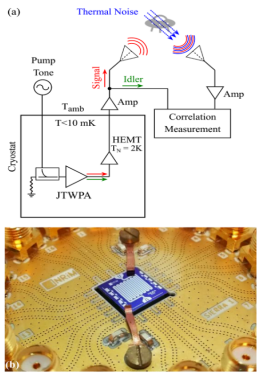
Branch 10: Electric and magnetic fields

STASIS	EMPIR 21NRM05 STASIS, Standardisation for safe implant scanning in MRI. https://www.ptb.de/stasis/home. The overall objective of the project, which started on October, 1st 2022, is to support standardisation for safety assessment of medical implants in MRI scanners. Medical implants can refer to passive implants (e.g., orthopaedic prostheses) or active implants (e.g., cardiac pacemakers or deep brain stimulators). More specifically, it aims to contribute to the standards development work of ISO 10974, ASTM F2182 and IEC 60601-2-33. A. Arduino, O. Bottauscio, M. Chiampi, U. Zanovello, L. Zilberti, "A contribution to MRI safety testing related to gradient-induced heating of medical devices", Magnetic Resonance in Medicine, 88,930–944, 2022.
QUIERO	INRIM coordinated the EMPIR project 18HLT05 "QUIERO", Quantitative MR-based imaging of physical biomarkers. https://quiero-project.eu/. The main technical activity carried out by INRIM, was 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). An open source library of EPT methods, named *EPTlib* (https://eptlib.github.io/) is available. EPTlib was used to develop an example of application of the GUM in the framework of the EMPIR project 17NRM05 EMUE, where it played to role of the computational "engine" in the evaluation of the uncertainty associated with the repeatability of EPT experiments. INRIM also developed tissue mimicking materials and phantoms (including heterogeneous, anatomically shaped ones) which mimic biological tissues in MRI experiments. Contact: Luca Zilberti, l.zilberti@inrim.it. Arduino A., "EPTlib: An Open-Source Extensible Collection of Electric Properties Tomography Techniques", Appl. Sci. 2021. Martinez J. et al., "Evaluation and Correction of B+1-Based Brain Subject-Specific SAR Maps Using Electrical Properties Tomography", IEEE Journal of Electromagnetics, RF, and Microwaves in Medicine and Biology (in press).
 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/. Closing date 31 Aug. 2023 Novel products based on magnetic steel sheets require accurate magnetic loss measurements and modelling under high temperature, 2D excitation, distorted flux with high harmonic content, skin effects and dc currents. Several round robins have been carried out among the project partners 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 O.de la Barrière,E.Ferrara,A.Magni,A.Sola,C.Ragusa,C.Appino,F.Fiorillo, Wideband magnetic losses and their interpretation in HGO steel sheets, J. Mag. Magn. Mater. 565, 170214 (2023)

RaCHy Radiotherapy Coupled with Hyperthermia	INRIM coordinated the EMPIR Project 18HLT06 RaCHy *"Radiotherapy coupled with hyperthermia"* (https://rachy-project.eu/), ended in 2022. The objective was 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 phantom*, *in vitro* and *in vivo* tests were covered. INRIM designed and developed an rf applicator operating at 434 MHz, which was successfully tested both *in phantom* and *in vitro*. Regarding magnetic hyperthermia, advances were achieved in collaboration with TUBITAK UME (Turkey) on both modeling and characterization of magnetic nanomaterials acting as heating agents under ac excitation. *In silico* models were developed to simulate nanomaterial interactions with biological systems, focusing on transport in blood vessels, release in tissues and evaluation of hyperthermia therapeutic efficacy in mice and rats. Contacts: Giovanni Durando, g.durando@inrim.it; Alessandra Manzin, a.manzin@inrim.it M. Vicentini et al., *In silico evaluation of adverse eddy current effects in preclinical tests of magnetic hyperthermia*, Computer Methods and Programs in Biomedicine 223, 106975 (2022). R. Ferrero et al., *Design and Characterization of an RF Applicator for In Vitro Tests of Electromagnetic Hyperthermia*, Sensors 22(10), 3610 (2022). M. Vassallo et al., Improvement of Hyperthermia Properties of Iron Oxide Nanoparticles by Surface Coating, ACS Omega 8(2), 2143–2154 (2023).
iMet-MRI	INRIM is involved in the EMPIR Project 20NMR05 iMet-MRI *"Improved metrology for quantitative MRI"*, started in June 2021 and coordinated by NPL. The aim is to provide test objects, analysis tools and best practice guidance for various quantitative Magnetic Resonance Imaging (MRI) techniques and demonstrate them in an international multi-site trial. The need of metrological harmonization arises for MRI routine clinical practice, which typically produces images designed for single use, to be looked at by individual human experts, and lacks consistency when comparing images acquired on different scanners or at different times. In particular, INRIM is involved in the development of an MRI simulator and digital twins for calibration of MRI scanners. The MRI simulator, based on Bloch equations, will be presented at the upcoming *Mathematical and Statistical Methods for Metrology* (MSMM) workshop in Torino. Contacts: Alessandra Manzin, a.manzin@inrim.it; Riccardo Ferrero, r.ferrero@inrim.it

Branch 11: Radio Frequency measurements

DART WARS	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) L. Fasolo, et. al., Bimodal Approach for Noise Figures of Merit Evaluation in Quantum-Limited Josephson Traveling Wave Parametric Amplifiers,, IEEE Trans. on Applied Superconductivity, (2022) S. Pagano, et. al., Development of quantum limited superconducting amplifiers for advanced detection, IEEE Trans. on Applied Superconductivity, Vol. 32, no. 4, 1500405, June 2022, (2022)
SUPERGALAX	HORIZON2020 Project - Call H2020-FETOPEN-2018-2019-2020-01. *https://supergalax.eu/*. Detection of single photons in the microwave range has a number of applications ranging from galactic dark matter axions searches to quantum computing and metrology. A novel approach to acquisition of extremely low energy microwave signals (~1 GHz), based on a passive quantum detection is proposed. The key novel concept which is intended to use is the coherent quantum network composed of a large amount of strongly interacting superconducting qubits embedded in a low dissipative superconducting

	resonator. INRiM is involved in the development of a Parametric Down Conversion (PDC) microwave photon source based on the Traveling Wave Josephson Parametric Amplifier (TW-JPA) with a clock frequency of few kHz. Contact: Giorgio Brida (g.brida@inrim.it) A. Greco, L. Fasolo, A. Meda, L. Callegaro, E. Enrico, A quantum model for rf-SQUIDs based metamaterials enabling 3WM and 4WM Travelling Wave Parametric Amplification,, Phys. Rev. B 104, 184517 (2021)
	QUANTUM RADAR. The project aims to investigate new quantum techniques based on quantum states of microwave radiation (1-10 GHz band), in particular of "twin" "entangled" beams, for the creation of a prototype of "Quantum Radar" with increased precision (increase of signal-to-noise ratio (SNR)) of interferometric measurements, indispensable in the detection of location of non-cooperating targets, and reduction of destructive effects due to noise environmental. Indeed, quantum states of radiation make it possible to detect objects and carry them out sensing and communication protocols with a performance not achievable if limited to use traditional "classical" sources, i.e. without quantum correlations such as lo squeezing and entanglement. Contact: Emanuele Enrico (e.enrico@inrim.it) L. Fasolo, A. Greco, E. Enrico, F. Illuminati, R. Lo Franco, D. Vitali, P. Livreri, *Josephson Traveling Wave Parametric Amplifiers as non-classical light source for Microwave Quantum Illumination, Measurements: Sensors, 18, 100349 (2021).*
Super Quant	The project EMPIR 20FUN07 SuperQuant - Microwave metrology for superconducting quantum circuits - will lead the way to fundamental microwave metrology at cryogenic temperatures to support the quantum technology industry. The project will enable, e.g., a quantum standard of microwave power and a quantum-traceable cryogenic sampling oscilloscope with 1 THz bandwidth. INRiM is involved in the development of a platform for traceable measurements of scattering parameters in cryogenic environments in the mK range and in the metrological characterization of superconducting quantum power sensors. Contact: Luca Oberto (l.oberto@inrim.it) M. Bieler, *et. al.*, "Microwave metrology for superconducting quantum circuits", Proceedings of CPEM 2022, Wellington, New Zeland, 12-16 December 2022

Branch 12: Measurements on materials

INRIM continued the activity of numerical modeling of nano/microstructured magnetic materials and devices providing support to experimental analysis and design. Advances were achieved in the modeling of new magnetic field sensors, for possible integration in lab-on-chip devices. These exploit ferromagnetic resonance (FMR) phenomena in magnonic crystals, i.e., magnetic thin films with periodic non-magnetic inclusions (holes), recently proposed as magnetic field sensor elements operating in the gigahertz (GHz) range. Possible applications include magnetic immunoassays, using magnetic nano/microbeads as probes for biomarker detection, and biomaterial manipulation.

In the framework of magnetic material modeling at the nanoscale, INRIM is also involved in the national project IT-SPIN *"The Italian factory of micromagnetic modeling and spintronics"*, funded by the Ministry of University and Research. 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"*.

A. Manzin, R. Ferrero, M. Vicentini, Application of Magnonic Crystals in Magnetic Bead Detection, Nanomaterials 12(19), 3278 (2022).

INRIM is active on both theoretical and experimental aspects of magnetic spintronics. Specifically on two activities. i) The formulation of chiral magnetism by means of gauge field theory. The activity has led to the correlation between the DMI constant and the crystal structure and in particular to the point group symmetries. ii) The experimental determination of the spin current through the measurement of the spin Hall efficiency (related to the spin Hall angle and the spin diffusion length). The activity has been carried out by the measurement of the spin Hall magnetoresistence in Pt/Ta/W - FeCoB bilayers. Contact: v.basso@inrim.it

P. Ansalone, E. S. Olivetti, A. Magni, A. Sola and V. Basso, *Gauge theory applied to chiral magnets* AIP Advances 12, 035135 (2022); A. Di Pietro, P. Ansalone, V. Basso, A. Magni, and G. Durin. *Gauge theory applied to magnetic lattices*. Europhysics Letters 140, 46003 (2022)

A. Magni, V. Basso, A. Sola, G. Soares, N. Meggiato, M. Kuepferling, W. Skowroński, S. Lazarski, K. Grochot, M. Khanjani, J. Langer, B. Ocker, *Spin Hall magnetoresistance and spin orbit torque efficiency in Pt/FeCoB bilayers*, IEEE Transactions on Magnetics 58, 4400205 (2022)

COMET	EMPIR 20FUN03 COMET - "Two dimensional lattices of covalent- and metal-organic frameworks for the Quantum Hall resistance standard" (2021 - 2024, website). The project aims to investigate materials based on covalent/metallic organic frameworks (COF/MOF), as an alternative to graphene for an improved industrial quantum standard. The research activity at INRIM is focused on the implementation of electrical conductivity mapping by means of electrical resistance tomography (ERT) and low frequency noise measurements on samples to be provided by the consortium partners. A new socket for the INRIM's ERT and noise setups is being developed to fit packaged devices. A new low noise, voltage regulated bias source for 1/f noise measurements is being implemented. INRIM is also in contact with IEC TC 113 WG8 "graphene and related materials", to which regular updates are made.

EMPIR EURAMET The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States	The EMPIR projects 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.