Progress report on electrical metrology at VTT MIKES between 2023 and 2025

for the 34th meeting of the Consultative Committee for Electricity and Magnetism (CCEM), March 2025

Organization

National Metrology Institute VTT MIKES (about 50 employees) is a part of VTT Technical Research Centre of Finland Ltd (about 2400 employees), which is a fully state-owned not-for-profit-company. Since the beginning of 2025, VTT MIKES has been a Special Unit parallel to the three Business Areas of VTT. MIKES's Electrical Metrology Team with 15 researchers is responsible for Finland's national metrology activities in fields of electricity, time and frequency, and acoustics.

Applications of Josephson effect in electrical metrology and quantum technologies

VTT MIKES continues development of Josephson Arbitrary Waveform Synthesizers (JAWS) driven by pulsed lasers and photodiodes for DC and AC metrology and for quantum technology applications. In the recent years emphasis has been on developing broad band pulsed lasers [4] and pulse pattern generation techniques [3], investigating novel photodiodes, developing externally-shunted Josephson junction arrays as well as cryogenic high-precision packaging technologies. Utilizing the expertise on custom-made mode-locked lasers we have designed and realized femtosecond and picosecond lasers at different wavelengths to enable generation of optical and electrical pulse patterns with an aim at 100 GHz pulse rate. With various new optical-to-electrical converters operating in the 100 GHz regime our goal is to generate electrical pulse trains to drive JJAs with similar characteristic frequency. This would allow high-fidelity generation of arbitrary quantized waveforms both for conventional applications, like calibrations of high-accuracy ADCs and DACs, as well as driving superconducting qubits for quantum computing. With pulsed lasers and integrated optics, increasing the pulse rate by a factor of 10 compared to conventional high-speed RF synthesizers is envisioned. Besides performance advantages we believe the costs of hardware could be lower enabling wider take-up of JAWS technology within NMIs.

Development of a robust, stable and highly accurate package for mounting optical fibres on photodiodes with small aperture has turned out to be challenging. VTT has developed two material systems, one based on glass chips and another on silicon chips with vias for guiding fibres on the targets with µm accuracy. VTT has invested on tools which would allow scaling up the number of components coupled together using metals instead of epoxies in joints. At the moment, the main focus at VTT is to demonstrate driving a superconducting qubit with an optically driven JAWS with similar fidelity as typical with semiconductor-based instrumentation. If successful, paving the way towards scaling up the number of qubits will be targeted. JAWS as a base element of a quantum computer would possibly improve operations by e.g. stabilizing signals for control and readout of qubit states. In addition, replacing metallic coaxial cables for high-speed signal transfer by optical fibres can reduce thermal burden of cryostats considerably.

The multi-disciplinary work has been carried out in several European projects, such as aCryComm, Quantum E-leaps, SuperQuant, Qu-Test, and MetSuperQ, as well as in projects with national funding. Tampere University and ETH Zürich play a key role in developing ultrafast photodiodes. We are also collaborating with PTB in developing cryogenic electro-optic sampling for characterizing the performance of detectors in-situ in the cryostat with least invasiveness of the probing [2], [4]. PTB also develops and fabricates SNS JAWS chips compatible with flip-chip bonding detector chips close to the Josephson junction array. In European Metrology Partnership project MetSuperQ, VTT's target is to combine all developments and test our concept with VTT's 5-qubit quantum computer. Very recently VTT and Finnish quantum technology company IQM have completed and launched Europe's first 50-qubit superconducting quantum computer, also located at VTT's premises [https://www.vttresearch.com/en/news-and-ideas/vtt-and-iqm-launch-first-50-qubit-quantum-computer-developed-europe].

Impedance and graphene

VTT MIKES continues its research towards a universal quantum standard for electrical quantities. During EMPIR project GIQS we developed a liquefier cryostat for hosting both graphene-based quantum Hall impedance standards and Josephson voltage standards. An update of the cryostat for increased cooling power and a 1 K pot takes place in spring 2025. Subsequently, our aim is to design the required magnetic field shielding for setting up possibly optically driven JAWS standards. If both QHR and JVS can be operated simultaneously in a single cryostat we plan to design a Josephson impedance bridge with potentially shorter interconnections compared to what is possible when using different cooling systems for them.

High voltage and power metrology

Precision lightning impulse voltage measuring techniques have been studied in project 19ENG02 FutureEnergy, *Metrology for future energy transmission*. Empirical study of the deformation of transient waveform during propagation in coaxial cable was presented in [1]. Results of the verification of the precision and linearity of several lightning impulse voltage measurement systems with maximum voltage from 1000 kV to 4000 kV was completed [7]. Calibration and fine-tuning of one of these dividers is presented in [10].

Calibration and verification of high voltage measuring systems for combined and composite waveform (e.g. lightning impulse on ac) have been studied in project 19NRM07 HV-com², *Support for standardisation of high voltage testing with composite and combined wave shapes*. Characteristics of calibrators have been discussed in [8] and of the developed wideband reference divider in [11]. Demonstration of on-site calibration in summarised in [9].

Descriptions of two recently started European Metrology Partnership projects have been presented during CPEM 2024: 22NRM04 e-TRENY, *Metrology support for enhanced energy efficiency in DC transportation systems* [14], and 23IND01 ENSURE, *Electric energy and supply reliability* [12].

VTT MIKES coordinates 21NRM02 Digital-IT, *Metrology for digital substation instrumentation*, where our emphasis is on traceable techniques for digital substation timing. A method for absolute calibration of IEEE 1588 Precision Time Protocol (PTP) time links has been developed. The method is based on comparing PTP event message time stamps to actual measured message timing in 100Base-X links. The method is partly described in [15] and can be used for calibrating devices, which rely on PTP from time synchronicity as well as absolute calibration of PTP master clocks and slave clocks. VTT MIKES takes part also in other European metrology research projects, including 22NRM06 ADMIT, *Characterisation of AC and DC MV instrument transformers in extended frequency range up to 150 kHz*, and 23IND06 Met4EVCS, *Metrology for electric vehicle charging systems*.

Comparisons

Results of a COOMET.EM-S6 on ratio error and phase displacement on power frequency was finally completed and published [16]. Measurements were performed already in 2007-2011.

VTT MIKES participated combined comparisons (same transfer reference) EURAMET.EM-S46 (High voltage DC ratio up to 200 kV) and EURAMET.EM-S47 (High voltage 2 GΩ resistance). Participants sent their references to RISE, who performed the comparison measurements in March 2022. Draft Bs are waiting for acceptance.

In addition, VTT MIKES acts as the pilot laboratory for worldwide supplementary comparison EURAMET.EM-S36 (Partial discharge), coordinated by RISE. Draft B is waiting for acceptance. Problems encountered with PD rise time calibration have been discussed in [13].

VTT MIKES is coordinating the preparations of the first high voltage key comparison on ratio error and phase displacement up to 100 kV, with tentative designation CCEM-K14. First measurements should take place in late 2025.

Publications 2023 –

Articles

[1] Havunen, J., Passon, S., Hällström, J., Meisner, J. & Schlüterbusch, T.C., '*Empirical Characterization of Cable Effects on a Reference Lightning Impulse Voltage Divider*', IEEE Trans. Instrum. Meas. ***72***, 1005009 (2023). https://doi.org/10.1109/TIM.2023.3276028.

[2] Priyadarshi, S., Tian, H., Fernandez Scarioni, A, Wolter, S.,Kieler, O., Kohlmann, J., Nissilä, J. & Bieler, M., *'Cryogenic Fiber-coupled Electro-optic Characterization Platform for High-speed Photodiodes'*, J. Infrared, Millimeter, Terahertz Waves **45**, 159-170 (2024). https://doi.org/10.1007/s10762-024-00966-1.

[3] Cherchi, M., Bera, A., Kemppinen, A., Nissilä, J., Tappura, K., Caputo, M., Lehtimäki, L., Lehtinen, J., Govenius, J., Hassinen, T., Prunnila, M. & Aalto, T., *'Supporting quantum technologies with an ultralow-loss silicon photonics platform'*, Advanced Photonics Nexus **2**, 024002 (2023). https://doi.org/10.1117/1.APN.2.2.024002.

[4] Priyadarshi, S., Kieler, O., Fernandez Scarioni, A., Felgner, J., Widaa, A., Kohlmann, J., Fordell, T., Nissilä, J, Kemppinen, A. & Bieler, M., *'In-situ electro-optic sampling of microwave signals under cryogenic conditions and for superconducting applications'*, https://arxiv.org/abs/2411.00162v1, submitted for publication (2024).

Conference articles

[5] Priyadarshi, S., Kieler, O., Fernandez Scarioni, A., Felgner, J., Widaa, A., Kohlmann, J., Nissilä, J. & Bieler, M., *'In-situ electro-optic sampling of microwave signals applied to superconducting circuits'*, 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, 6-12 July, 2024. https://doi.org/10.1109/CPEM61406.2024.10646099.

[6] Kemppinen, A., Bera, A., Delrosso, G., Nissilä, J., Senior, J., Mykkänen, E., Tappura, K., Vesterinen, V., Selvasundaram, P., Kohopää, K., Ronzani, A., Wälchli, B., Hunnakko, J., Jabdaraghi, R.N., Fordell, T., Ribeiro, M., Hazra, D., Haatainen, T., Loreto, R.P., Hätinen, J., Prunnila, M., Aalto, T., Lehtinen, J., Manninen, A., Govenius, J., Cherchi, M. & Pursula, P., *'Toward the optical control of cryogenic quantum technologies'*, 2023 IEEE Photonics Society Summer Topicals Meeting Series, SUM 2023, Sicily, 17-19 July, 2023. https://doi.org/10.1109/SUM57928.2023.10224386.

[7] Hällström, J., Elg, A.-P., Nieminen, T., Havunen, J., Zhao, W., Splinter, I., Rietveld, G., Kamphuis, G., Termorshuizen, W., van Nes, P., Lahti, K., Kujda, M., Passon, S., Merev, A. & Li, C., *'Linearity extension of UHV class lightning impulse dividers up to 3000 kV',* 23rd International Symposium on High Voltage Engineering (ISH 2023), Glasgow, UK, 28 August – 1 September, 2023, pp. 8–13. https://doi.org/10.1049/icp.2024.0414.

[8] Treyer, P., Hammer, U., Saadeddine, H., Havunen, J., Hällström, J., Passon, S. & Meisner, J., '*Importance of impulse calibrator output impedance and method of all-waveform compensation',* 23rd International Symposium on High Voltage Engineering (ISH 2023), Glasgow, UK, 28 August – 1 September, 2023, pp. 548–553. https://doi.org/10.1049/icp.2024.0577.

[9] Pischler, O., Schichler, U., Meisner, J., Passon, S., Gerdinand, F., Havunen, J., Hällström, J., Lahti, K., Böhme, F., Pietsch, R., Kujda, M., Gamlin, M., Dowbysch, A. & Pampel, H.-P., '*Performance of universal voltage dividers for measurement of superimposed voltages'*, 23rd International Symposium on High Voltage Engineering (ISH 2023), Glasgow, UK, 28 August – 1 September, 2023, pp. 948–954. https://doi.org/10.1049/icp.2024.0704.

[10] Zhao, W., Splinter, I., Hällström, J., Van Nes, P., Castro Heredia, L., Madhar, S. A. & Rietveld, G., *'Calibration and Fine-Tuning of a 4000 kV Lightning Impulse Generator Circuit and Divider'*, 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, 6-12 July, 2024. https://doi.org/10.1109/CPEM61406.2024.10646161.

[11] Österbacka, D., Hällström, J. & Merev, A., *'Characterization of a wideband high voltage reference divider'*, 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, 6-12 July, 2024. https://doi.org/10.1109/CPEM61406.2024.10646093.

[12] Elg, A.-P., Rietveld, G., Hällström, J., Crotti, G., Ramirez, A., Rovira, J., Milojevic, V., Saadeddine, H., Ayhan, B., Zhao, W., Perez-Aragues, J.J., Mazza, P., Niasar, M.G., Arcones, E., Mor, A.R., Venugopal, P. & Frigo, G., *'High-Voltage Metrology for Electric Energy and Supply Reliability'*, 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, 6-12 July, 2024. https://doi.org/10.1109/CPEM61406.2024.10646152.

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[14] Giordano, D., Fernandez, J. Q., Gallo, D., Hällström, J., Istrate, D., Iordache, M., Mariscotti, A., Rietveld, G., Rovira, J., Venugopal, P. & Zhao, W. (2024). *Metrology support for enhanced energy efficiency in DC transportation systems*. 2024 Conference on Precision Electromagnetic Measurements (CPEM), Denver, 6-12 July, 2024. https://doi.org/10.1109/CPEM61406.2024.10646053.

[15] Lehtonen, T. A., Hanhijärvi, K., Poikonen, TY., Wallin, A. & Hällström, J., *Towards methodology for linking PTP slave clock time to 1PPS in a digital substation environment*, 2022 Conference on Precision Electromagnetic Measurements (CPEM), Wellington, New Zealand, Dec 12-16, 2022.

Comparison reports

[16] Kiselev, V., Bergman, A., Garnacho, F., Grishin, M., Dimitrov, E., Draxler, K., Dubrovskaya, T., Kikalo, V., Kopshin, V., Kumanova, G., Martin, R., Styblikova, R. & Hällström, J., *'Supplementary comparisons of national standards of ratio error and phase displacement of AC voltage of power frequency'*, COOMET 411/RU-a/07 (COOMET.EM-S6), Metrologia, **60**, 01011 (2023). https://doi.org/10.1088/0026-1394/60/1A/01011.