EMRP
European Metrology Research Programme
Programme of EURAMET

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# Publishable JRP Summary for Project T4 J03 JOSY

## Next generation of quantum voltage systems for wide range applications

The main objective of this project is to introduce quantum-based measurement systems into AC metrology. This is the first step towards establishing intrinsically referenced AC standards on the workshop floor providing much faster calibrations while at the same time ensuring much better uncertainties to support the electronic measurement and test equipment used in research and development. It addresses the frequency band from sub 1 Hz to 1 MHz where the majority of high performance measurement and control applications are to be found (Figure 1).

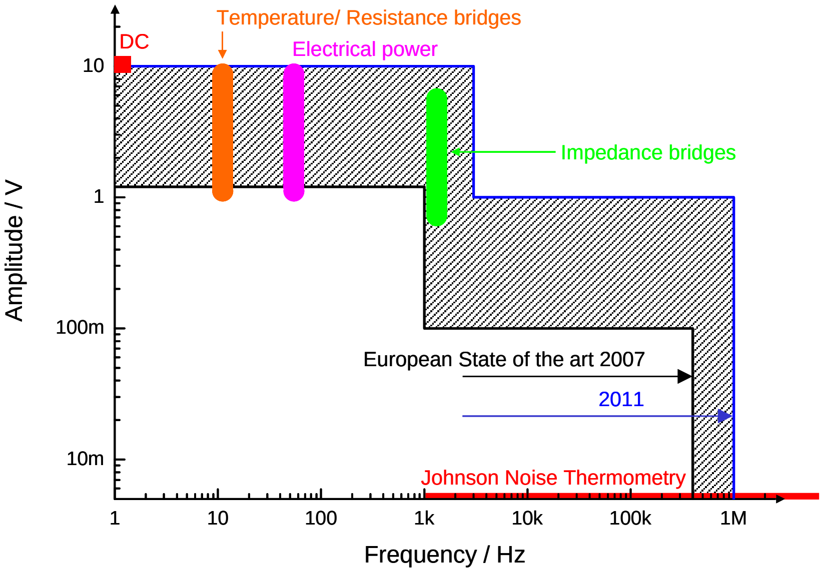

**Figure 1**. Voltage and frequency ranges addressed in this project compared to the current state of the art in Europe. The coloured areas illustrate the most important frequency and voltage ranges of various AC measurements.

The deployment of micro-electronic circuits for measurement and control applications in commercial devices and systems is ever increasing. Such control systems, in combination with state of the art sensors, have enabled large advances in both the performance and efficiency of mass-produced items. For example, electronic management systems in electrical motors have led directly to reduced energy consumption and, as a consequence, improved economy and reduced emissions to the atmosphere. These leading-edge control systems rely on high performance electronic components including analogue to digital converters (ADCs), digital to analogue converters (DACs) and amplifiers. The systems are almost entirely digital and operate with harmonically complex waveforms. Ultimately, the end-to-end performance of the ADC, signal processing and DAC combinations has to be repeatable and reliable. High-resolution, repeatable electronic test equipment plays a crucial role during the development and testing phases. Such repeatable and high-resolution measurements can be achieved only through accurate measurements obtained by calibration traceable to the SI.

At the National Measurement Institute (NMI) level, DC voltage metrology is already well supported by a quantum standard based on the Josephson-effect. The Josephson voltage standard is an *intrinsic standard*, a standard that reproduces a unit of measurement in terms of fundamental physical constants, which provides independence of place, time and environment. Such a standard does not require calibration. AC voltage metrology, however, only benefits indirectly from this quantum standard; measurement traceability is via sampling methods at low frequencies and elsewhere through thermal transfer devices to DC voltages, which only give information on the root mean square (RMS) value of the waveform, not on its amplitude as a function of time or its phase. By developing a novel measurement system for AC waveforms of arbitrary shape directly traceable to electrical quantum effects, the project will close this metrology gap and address the EMRP2007 requirement for intrinsically referenced electrical measurements, based on quantum standards, to support new technologies and improved production in industry.

Quantum standards for AC metrology are still a research topic with measurement not yet demonstrated over an adequate range of voltage and frequency. To achieve the project aim, four main technical barriers need to be overcome:

A) To obtain practical voltage levels, the Josephson junctions, which are the fundamental component of a quantum voltage standard, have to be integrated into large series arrays of typically 50 000 to 70 000 junctions. This has already been achieved for the measurement of steady voltages but arrays of junctions suitable for the measurement of alternating voltages are still the subject of research. Technical challenges include array-junction layout together with on-chip microwave design to fulfill the demanding requirements of high frequency synthesis and the fabrication of Josephson junctions to the required tolerances and small (sub-µm) dimensions.

B) To employ these Josephson arrays in the generation of alternating voltages, specialized electronic bias units that cover the whole amplitude and frequency range are required. In addition, apparatus for mounting the arrays at cryogenic temperatures including transmission line connections between the superconducting circuit and room temperature needs to be developed.

C) To form a complete measurement system capable of characterizing alternating voltages with quantum-based accuracy, high resolution and high speed null detector circuits, precision amplifiers and an overall control logic system must be realized. To meet the longer term aim of developing easy to operate and reliable quantum standards, these measurement systems will have to be developed to an advanced stage of integrity and ease of use.

D) Prototype systems, when assembled and working, will require considerable characterization to demonstrate that quantum-based accuracy is being obtained. This will include characterization of individual system components, theoretical analysis of uncertainty contributions and comparison with existing and accepted standards of alternating voltage at the part per million (ppm) level.

The technological advances outlined in A to D above will be built on achievements that the project partners have made so far. These achievements are the result of collaborative work undertaken by most members of the consortium, partly within previous EC-funded research projects (PROVOLT and JAWS – Josephson Arbitrary Waveform Synthesis) in this area. These projects produced technology (published in peer-reviewed journals) which includes systems to generate AC voltages up to 1 V and frequencies up to 1 kHz using binary-divided arrays of 8192 junctions and technology to generate voltages over a wider range of frequencies up to 100 kHz but with reduced output voltage of 10 mV to 100 mV using a smaller number of junctions driven by high speed pulse trains. In the USA, NIST (who is a non-funded collaborator in this project) has recently demonstrated pulse driven synthesizers at 300 mV and in Europe PTB has shown waveform generation using binary-divided arrays up to 10 V. Details of the state of the art at the beginning of the project are shown in Figure 1. Initial (published) demonstrations of feasibility for the application of these waveforms have included: calibration of AC-DC transfer standards, characterization of high precision ADCs (not shown in Figure 1 due to their broadband nature), primary standards for electrical power, and Johnson noise thermometry.

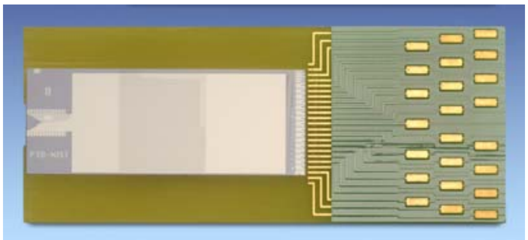

Fig.1: Photo of the a 10-V Josephson array based on $Nb_xSi_{1-x}$-SNS junctions.

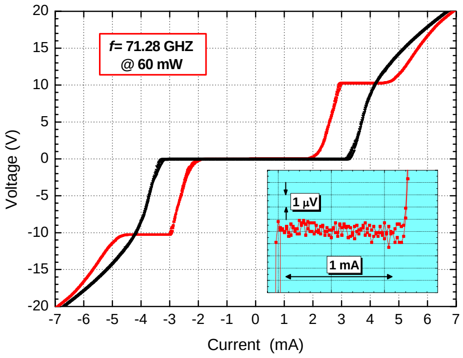

Fig.2: *IV*-curve for the 10-V Josephson array shown on the left.

Due to these premises the project has started successfully. Within the first 20 months of the project a lot of progress has been achieved even though all activities and tasks are still ongoing. Josephson arrays for pulse driven, binary and for elevated temperature applications have been fabricated. The arrays for pulse drive – developed and fabricated with 5 000 junctions – have reached the 100-mV level. So far, parameters of these arrays do not meet the required margins for perfect pulse drive operation, but higher harmonics can be suppressed by more than 70 dB. Optimization of the fabrication process is in work.

Based on a 250 mV array from our collaborator NIST, VSL has automated the time consuming tuning procedure for the pulse driven synthesizer and has performed measurements with margins for rms voltages up to 125 mV and up to 1 MHz.

A promising new technology based on a more robust barrier material, $Nb_xSi_{1-x}$, developed in collaboration between NIST and PTB, has the potential to replace the SINIS barriers while keeping the advantages of high frequency operation and well-developed microwave design. Some wafers containing binary-divided 10-V Josephson series arrays, fabricated for operation at 70 GHz and consisting of about 70,000 junctions, showed wide constant-voltage steps with a width of up to 1 mA.

Work on Josephson junctions for elevated temperatures, Nb/Al-$AlO_x$/Nb and ramp-type S/B/S junctions, has been started. Small arrays with Nb/Al-$AlO_x$/Nb junctions show very good behavior and are ready for the next higher level of integration.

First filter structures have been developed, tested and discussed. Also different cryoprobe wirings and array mountings are presently under investigation. Practical testing is underpinned by modelling.

Transients have been investigated, theoretically and practically. Models for the transients now take into account the *IV* characteristic of the arrays and also reflections of the sharp changes in biasing signals within the set-up. These investigations have led to a much better understanding of the physics behind Josephson stepwise approximated waveforms. Limiting parameters are presently investigated by refined models. Moreover, METAS in cooperation with MIKES experimentally verified that for the first harmonic the influence of transients is sufficiently attenuated to reach the targeted accuracy. The realization of this standard is presently under development.

Buffer-, difference amplifiers and other versions of Josephson synthesizers in combination with common semiconductor synthesizer have been investigated. Very good progress has been made in combining the advantages of binary Josephson systems – stable and highly accurate – together with those from Silicon synthesizers – low harmonic distortion and current driving capabilities. These systems can be combined very flexibly with different measurement systems e.g. fast sampling systems. Also low-noise buffer amplifier and differential preamplifier have been further developed, built and tested successfully.

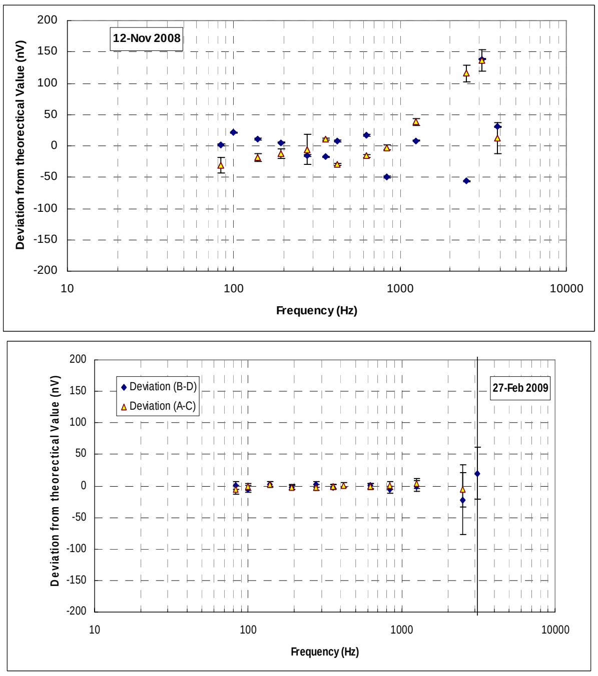

Fig.3: Comparison of two pre-amplifiers using 4-sample Josephson sine wave: Magnicon amplifier (left) and differential NPL amplifier (right).

New 10-V arrays have already been used to further test the quantum voltmeter principle. Very good results, better than 1 part in $10^8$ for frequencies up to 1 kHz, have been achieved for 4-sample waveforms. Combining both, 10-V sampling systems and preamplifiers, requires perfect synchronization of the systems.

A new synchronization box has been made to allow synchronization of Josephson waveforms with other synthesizers or sampling voltmeters.

Measurements towards impedance ratios have been started by performing resistance measurements at DC.

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| JRP-Coordinator: | Ralf Behr |
| Name, Title, Organisation: | Physikalisch-Technische Bundesanstalt  (PTB), Germany |
| Tel.: | +49 531 592 2242 |
| Fax: | +49 531 592 2105 |
| E-mail: | ralf.behr@ptb.de |
| JRP website address: | |
| Other JRP partners: | BEV, CEM, INRIM, LNE, METAS, MIKES, NMi VSL, NPL, SMU |
| Organisation, Country: | Bundesamt für Eich- und Vermessungswesen (BEV), Austria<br>Centro Español de Metrología (CEM), Spain<br>Instituto Nazionale di Ricerca Metrologica (INRIM), Italy<br>Laboratoire national de métrologie et d'essais (LNE), France<br>Federal Office of Metrology (METAS), Switzerland<br>Mittatekniikan keskus Mätteknikcentralen (MIKES), Finland<br>NMi Van Swinden Laboratorium B. V. (NMi VSL), The Netherlands<br>NPL Management Limited (NPL), UK<br>Slovenský Metrologický Ústav (SMU), Slovakia |

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