Title: Cost-efficient primary voltage metrology up to 1 V (rms) and 1 MHz, and beyond

Abstract

Josephson voltage standards are fundamental to electrical metrology. National Metrology Institutes (NMIs) use various types: hysteretic Josephson junction arrays (JJAs) for direct current (DC) voltage, programmable non-hysteretic JJAs for automated DC and low-frequency alternating current (AC) measurements, and Josephson Arbitrary Waveform Synthesizers (JAWS) for AC applications. However, JAWS systems currently face limitations, including low output voltages and high costs, hindering widespread adoption. Proposals addressing these challenges should utilise optical pulse pattern generation using integrated photonics and pulsed lasers to drive cryogenic photodetectors and JAWS. This approach enables scalable distribution of control signals with minimal distortion and losses across multiple JJA segments and supports higher drive frequencies, facilitating increased voltage levels.

Keywords

AC voltage quantum standard, quantum electrical metrology, Josephson Arbitrary Waveform Synthesizer (JAWS), SI traceability, waveform metrology, photodetector, pulse pattern generator (PPG).

Background to the Metrological Challenges

Three types of Josephson voltage standards (JVS) are widely used for voltage metrology: (i) Hysteretic Josephson junction arrays (JJA) are reliable for precise DC voltage but require manual tuning. (ii) Programmable nonhysteretic JJAs allow automated DC and low-frequency AC voltage generation, but their voltage waveform generation accuracy suffers from non-quantized transients and possible ground currents due to the complex biasing circuitry. (iii) Josephson Arbitrary Waveform Synthesizer (JAWS) which use ultrafast current pulses, can generate arbitrary voltages and waveforms.

JAWS is the most conceptually advanced technology, but it has significant challenges: its dependence on high-speed control electronics restricts its use to the largest NMIs. The maximum reported voltage (4 V rms) is below the practical 10 V level needed in metrology. JAWS requires broadband electrical current pulses, which attenuate across long arrays, impacting quantization. Segmentation using Wilkinson power dividers mitigates this but remains limiting factor.

Optically driven JAWS, using pulsed lasers, optical fibres, and photodiodes, offers an alternative to traditional electrical control. This approach reduces heat transfer to cryogenic components and increases bandwidth, enabling higher voltage outputs. With future reductions in cost of optical components, scalability to 10 V may become feasible. Still, reliance on electrical signal generators for optical drive creation limits total system efficiency and bandwidth.

The European Metrology Network on Quantum technologies has identified the development of JAWS as a priority for achieving 10 V quantum voltage standards for both DC and AC signals up to several MHz [1]. In the long term, it promotes multi-purpose, cost-efficient JAWS systems using optically generated pulse patterns. Building on prior European projects, such as 15SIB04 QuADC and 20FUN07 SuperQuant, significant progress has been made on pulse-driven JJAs and optical driving techniques.

However, critical development is still needed. There is a strong need to develop optical PPG concepts into practical JAWS control equipment. Regarding the JAWS chip itself, e.g., the length of individual JJA segments driven with photodetectors and fast pulses is an open issue. While it is important to minimise crosstalk of drive signals between such JJA segments, they also need to be connected in series, maintaining the same phase of output signal such that the total JAWS voltage is the exact sum of individual segment voltages. The optimisation of the JAWS chip is closely related to the improvement of cryogenic optical packaging, i.e., to the ability to couple optical drive signals into multiple photodiodes, and the eventual electrical drive signals into the JJAs. Prior experiments with optical JAWS and cryogenic photodiodes indicate sensitivity to any discontinuities of electrical transmission lines. Also, optimisation of connections of two photodiodes to drive a single segment with bipolar pulses requires high-frequency simulations and optimization.

Finally, the JAWS output signal needs to be delivered to the room-temperature environment without attenuating and distorting the quantized signal and thus deteriorating its accuracy. Typically, the amplitude error using a 1.5 m-long coaxial cable at 1 MHz is of the order of 1 %. The load compensation bridge developed in 15SIB04 QuADC is a promising and conceptually proven way to minimise losses in the JAWS output cable, but it requires further optimisation to enable the accurate transmission of signals up to 1 MHz.

There is growing demand for higher frequency measurements in power quality. IEC standard 61000-4-30 includes measurements of supra-harmonics up to 150 kHz. Therefore, it is important to be able to scale the JAWS quantum voltage waveform to higher voltage levels of electrical power metrology. This can be done using wideband voltage dividers with accurately characterised division ratios. This work benefits from earlier EMRP, EMPIR and Metrology Partnership projects 22NRM06 ADMIT, ENG07 HVDC, 19NRM07 HV-com2 and 15SIB04 QuADC in which extremely stable wideband voltage dividers and characterisation technologies have been designed and realised.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The proposal shall focus on the traceable measurement and characterisation of cost-effective primary electrical voltage standards.

The specific objectives are

1. To develop cost-efficient, room temperature optical arbitrary pulse pattern generators (PPG) that deliver digital control signals for JAWS up to a pulse frequency of 20 GHz, and to determine technical requirements for extending the pulse frequency up to 50 GHz.
2. To develop JAWS chips containing up to 50 000 Josephson junctions for 20 GHz drive, enabling arbitrary bipolar output voltages from 1 nV to 1 V (rms), and to investigate subdivision of the total junction array into shorter segments – each driven with its own photodetectors – to optimise operating margins at 20 GHz, and facilitate future 50 GHz operation.
3. To develop reliable cryogenic optical packaging that distributes the optical drive signals delivered into the cryostat in single mode fibres to at least 16 cryogenic photodetectors, arranged in pairs to drive a JJA segment, and to implement flip-chip bonding for electrical integration of photodetectors on JAWS chips.
4. To develop load compensation techniques that minimise attenuation and distortion of the JAWS output from 4.2 K up to room temperature and to demonstrate relative calibration uncertainties of 10^{-10} at DC, < 2 ppm up to 100 kHz, and < 5 ppm up to 1 MHz at 1 V (rms); and to investigate external room temperature wideband dividers (e.g. 1:1000) for voltage expansion towards 1 kV, targeting uncertainties of 10 ppm at 1 kV and 10 kHz, 10 ppm at 100 V and 100 kHz, and 100 ppm at 10 V and 1 MHz.
5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, calibration laboratories, instrument manufacturers), standards developing organisations (IEC, IEEE, CENELEC) and end users (digital, energy, environment, advanced manufacturing and healthcare sectors).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources both within and outside Europe, plus engagement with existing European research infrastructures and European Partnerships is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry and end users. Where relevant, proposals are encouraged to build on, or seek collaboration with, existing projects and develop synergies with other relevant European, national or regional initiatives and funding programmes. In particular, links are encouraged with (i) the projects funded under earlier relevant topics of the Horizon Europe programme; or (ii) other relevant European Partnerships.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the 15SIB04 QuADC, 20FUN07 SuperQuant, 22NRM06 ADMIT, ENG07 HVDC, 19NRM07 HV-com2 projects and how their proposal will build on those.

Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.1 M€ and has defined an upper limit of 2.6 M€ for this proposal.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 25 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your proposal's results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability, or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the commercial sector.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of the Metrology Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Timescale

The project should be of up to 3 years duration.

Additional information

The links provided in this section are only correct at the time of publication up until the end of the Call year.

The references below were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] EMN Quantum Strategic Research Agenda, https://www.euramet.org/research-innovation/metrology-partnership/strategic-research-and-innovation-agendas