

Title: Advanced quantum technology for metrology of electrical currents

Abstract

In many facets of quantum technologies in terms of applications (quantum information processing, quantum communications, quantum imaging, quantum sensing etc) and of physical systems (semiconductor devices, superconducting circuits, defects in solid states, trapped ions, etc), the ability to control individual electrons enables the investigation of quantum mechanical phenomena (for example, a single photon is emitted by a state transition of an electron). Single electron pumping, supplemented by combining Josephson and quantum Hall effect, provides a wide range direct link to the SI. Proposers should investigate the fundamental uncertainties of semiconductor single electron pumps, and develop advanced methods to close the impeding nA-gap in direct quantum current generation, while exploring novel device concepts based on solid state quantum technology.

Keywords

Electrical quantum metrology, quantum technology, quantum current source, single electron control, scaling, ampere

Background to the Metrological Challenges

The prime example of direct implementation of a robust primary quantum standard in electrical metrology at highest accuracy for a wide range of application is the Josephson voltage standard, which directly exploits the definition of the SI by fundamental constants. In contrast, the goal of a complementary direct and robust primary quantum standard for electrical currents with matching accuracy is still elusive for the whole range of small currents at the nanoampere level and below. A related, still elusive goal is to demonstrate the internal consistency of electrical quantum metrology, based on the elementary charge, the Josephson and the quantum Hall effect, with relevant accuracy below 1 part in 10^7 . The development of single electron based primary ampere standards would enable a consistent and robust future electrical metrology system. State-of-the art semiconductor single electron pumps generate currents of order 100 pA with reproducible transfer error rates below one part per million established by current measurements traceable to the quantum resistance and voltage standards. Recent advances in the physical modelling of single electron pumps underpin the experimental finding, that high fidelity transfer at higher GHz effective rates as needed to reach the nanoampere range, is not possible with a single device, but requires a significant scaling by parallelisation. A complementary approach is to directly combine a Josephson voltage source and a quantum Hall resistor. A dominating source of uncertainty for the realisation of small currents by Ohm's law is the thermal noise of the quantised reference resistor. An uncertainty below 1 part in 10^7 was achieved for electrical currents of 1 microampere or larger, however, the residual noise and insufficient investigation of uncertainties still prevent the application of these primary quantum current sources at the nanoampere range. Increasing the single electron pump current by large scale parallelisation requires scaling technologies akin to those required for solid-state quantum information processing technologies. In view of common concepts for single electron control and common needs in architecture and device control, the potential of utilising qubit devices and cryogenic control technologies for current metrology should be explored. The upscaling of single electron currents should also be complemented by extending the range of direct quantised current generation using Josephson voltage source and quantum Hall resistor to lower currents. This requires a further reduction of noise sources and of systematic uncertainties. Methods need to be established to assess the quality of single charge pumps. The progress in superconducting quantum technologies recently resulted in the first published demonstrations of the dual of the Shapiro steps in the current. Due to the novelty of these first realisations the potential for practical current metrological applications is unknown and initial explorations of robustness and accuracy should be undertaken.

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 JRP shall focus on the traceable measurement and characterisation of electrical currents.

The specific objectives are

1. To realise a wide range of primary quantum current sources for electrical currents from 1 fA to 1 mA. To investigate and evaluate the scaling of quantised currents into the nA range (i) via upscaling semiconductor single electron pumps to quantised currents > 1 nA by parallelisation and (ii) via downscaling the quantised currents generated by a direct combination of Josephson voltage sources and advanced quantum Hall resistance standards to currents < 10 nA.
2. To evaluate the uncertainties of semiconductor single electron pumps and provide traceable measurements of the quantised current, with target uncertainty below 1 part in 10^7 . To perform single electron detection of individual rare error events inside and outside the quantised current regime. To develop and experimentally evaluate advanced models of single electron capture and emission.
3. To explore the metrological potential of novel device concepts for direct quantised current generation, such as semiconductor qubit devices and dual Shapiro step based superconducting current sources. To experimentally realise quantised currents using these devices. To evaluate the intrinsic sources of systematic uncertainties (e.g. gate leakage, temperature dependence, etc.). To characterise their output currents using traceable current measurements, with target uncertainty less than 1 part in 10^6 .
4. To develop advanced technologies for devices, cryogenic device control and ultra-sensitive measurements required for the implementation and scaling of quantum electrical current standards over the relevant range of current. These may include single electron and quantum Hall standard arrays, multiplexers, cryogenic control modules and scalable integration schemes.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, research organisations (academia, research institutes), standards developing organisations (CEN, CCEM) and end users (fundamental metrology, solid-state quantum technologies).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, including other European Partnerships, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.0 M€ and has defined an upper limit of 2.5 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 40 % 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 JRP 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 quantum technology 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 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.

Time-scale

The project should be of up to 3 years duration.