**EMPIR Call 2020 – Fundamental, Industry and Normative**

Selected Research Topic number: **SRT-f03**
Version: 1.0

# Title: Quantum sensing with single electrons

## Abstract

Quantum devices have the potential to yield advantages in computation and sensing but tend to have complex requirements for control and readout. Additionally, quantum current standards are needed to support the redefined SI but accurate operation at high speed is difficult. The ability to prepare and readout the quantum state of single-electron wave packets provides new pathways for on-chip signal measurement and device readout using elementary electronic excitations as these schemes operate on picosecond time scales and are well-suited for integration into cryogenic quantum technology platforms. Therefore, proposals addressing this SRT should aim at the development of novel methods and techniques, which are necessary for sensing/readout and for enhancing the accuracy of quantum current standards.

## Keywords

Single electron wave packet, quantum sensing, quantum technology, quantum standards, phase-space/Wigner distributions

## Background to the Metrological Challenges

Quantum technologies are expected to play a crucial role in a data-driven economy, where even marginal technological advantages in capability will lead to competitive advantage. The distinctive capabilities of quantum systems could support new businesses and help to solve global challenges. The integration of quantum technologies into the metrology infrastructure has been at the leading edge of the exploitation of quantum effects. A remaining goal is the development of a robust quantum current standard to act as a primary electrical measurement tool in the small current measurement regime and demonstrate the internal consistency of the electrical measurement units. State-of-the-art quantum current standards based on single-electron transfer have been tested at the sub part per million level against other quantum standards, with a record uncertainty of 0.16 ppm at 600 MHz. While this is an improvement by several orders of magnitude in the last ten years, this is not enough in terms of current (around 100 pA) or accuracy to enable practical use in many applications or provide closure of the metrological triangle to the accuracy required.

European NMIs have established themselves as world leaders in the subject of single-electron devices, single-electron charge transfer and wave packet metrology. Several sources of single-electron excitations exist, all operating at cryogenic temperatures and ~GHz repeat rates. Single-electron wave packets emitted at high energy (~100 meV) from on-demand single electron source have a long mean free path and tuneable energy and an extremely narrow (~ 10 picosecond) time of arrival distribution. The extreme time-selectivity of single-electron motion in quantum Hall edge states provides the capability of high-speed sampling of on-chip voltage signals present on gates in the beam path. The resolution in such systems is determined by physically different parameters to a conventional system, for instance the phase-space distribution of the single-electron wave packets, which may be at the uncertainty limit. The extension of single-electron time-selective sensing via quantum interference effects is under study in the ongoing EMPIR 17FUN04 SEQUOIA project. In that project, tomographic reconstruction of the energy-time phase space or Wigner function of single electrons has been reported, and single-shot thermalisation and readout for electron quantum optics circuits has been developed. Additionally, the broader development of electron quantum optics techniques in graphene is also underway. However, further developments are required to establish single-electron wave packets as a quantum resource for developing scalable quantum device architectures, achieving quantum-limited measurement sensitivity, and supporting the requirements of the quantum SI by enhancement of quantum electrical standards.

The implementation of solid-state quantum device architectures involves some common challenges, for instance of application of accurate control signals and readout of quantum state information. Weak signals (sometimes approaching the single photon limit), small energy scales (often requiring deep cryogenic refrigeration) and short device operation times (requirements for high bandwidth) create an evolving requirement for advanced measurement techniques beyond conventional hardware (i.e. room temperature semiconductor devices and conventional waveguides).

Semiconductor single-electron systems based on the control and readout of single-electron wave packets fulfil the criteria of cryogenic compatibility, high bandwidth and close integration. But their implementation requires the technical design and fabrication of single-electron wave packet device components and theoretical work for modelling key components. The experimental demonstration of sensing schemes combined with modelling could reveal the potential of these systems as a quantum measurement resource. This may include the use of the wavefunction itself, e.g. phase space information in a tomography probe of an electron wavefunction. To enhance and validate the performance of quantum electrical standards using single-electron wave packet analysis, novel and validated methods are required.

## 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 development and characterisation of single-electron metrology devices and techniques based on the quantum state of single electron wave packets for sensing in novel quantum technologies and for the enhancement of quantum electrical standards.

The specific objectives are

1. To develop device components to interrogate the phase-space/Wigner distributions of single excitations. This should include (i) single-shot readout schemes suitable for single electron optics readout, and (ii) methods to integrate single-electron sensing devices into other device systems via on-chip integration or cryogenic coupling between chips.
2. To develop and evaluate the metrological performance of electron quantum optics component models (e.g. single-electron source, wave-guide, beam-splitter, dynamical switch) that account for quantum uncertainty and enable circuit-level modelling of sensing devices (e.g. interferometer, signal-sampler and integration with the load to be measured).
3. To develop measurement capability device-readout schemes or on-chip sensing for microwave electromagnetic fields based on the quantum state of single electrons (using e.g. quantum tomography or other probes of the electron state).
4. To develop and validate novel methods for the enhancement and validation of the performance of quantum electrical standards using single-electron wave packet analysis. This should include tomography or other probes of electrons injected into edge channels by single-electron sources.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (e.g. CEN and IEC) and end users in the areas of i) solid-state quantum information processing and communication, ii) nanoelectronics, iii) cryogenic quantum electronics and sensors, and iv) fundamental metrology.

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, 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. In particular, proposers should outline the achievements of the EMPIR project 17FUN04 SEQUOUIA and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.5 M€, and has defined an upper limit of 1.8 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 40 % of the total EU Contribution across all selected projects in this TP.

## 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,
- 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 EMPIR 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.