EMPIR Call 2017 – Industry, Fundamental, Normative and Research Potential

Selected Research Topic number: **SRT-f17**
Version: 1.0

Title: Ultra-stable optical oscillators from quantum coherent and entangled systems

Abstract

More accurate and stable clocks are needed to accelerate the redefinition of the SI second, bring excellent fundamental science to metrology and enable applications for innovative sensors in clock based geodesy. The development of stable optical oscillators has up to now been based on classical approaches which are now close to their maximum potential of exploitation. The current limitations, standard quantum projection noise and thermal noise, associated with frequency stability can be overcome with the use of quantum measurement strategies via multi-particle state engineering and light-matter interactions.

Keywords

Optical frequency standard, quantum-projection noise, quantum coherence, scalable entanglement, cavity quantum electrodynamics, quantum squeezed and engineered atomic states, atomic sensors

Background to the Metrological Challenges

To strengthen the capability of European metrology, clocks and atomic sensors need to be improved. Studies of higher accuracy at 10^{-18} with practical measurement time scales taking minutes to hours on optical frequency standards, are needed to accelerate the redefinition of the SI second, bring excellent fundamental science to metrology and enable applications for innovative sensors in clock based geodesy such as earth science, oceanography and time-keeping.

In current optical oscillators the state of the art for frequency stability is limited by the standard quantum projection noise of the quantum absorber and the mirror coating thermal noise of the local oscillator. Recent developments have mainly benefited from the technical progress both in opto-mechanical engineering, such as the creation of ultra-low thermal expansion and ultra-low losses optical materials or the emergence of thin-layer films for mirrors deposition, and in passive stabilisation to a quantum absorber (ultra-cold atoms or ions). These technical advances based on classical measurement approach seem now to be close to their maximum potential of exploitation. The application of quantum techniques based on the creation of and measurements on correlated atomic quantum states and quantum engineering light-matter interaction has been envisaged to overcome these two limitations.

Multi-particle entangled states may exhibit a reduced sensitivity to quantum phase fluctuations and therefore reducing the imprinted noise into the stabilised oscillator, as well as a fundamental limit beyond the quantum protection noise (QPN) with a frequency stability scaling like the inverse of the number of atoms. The realisation of collective spin-squeezing of a multi-particle system may be tremendously beneficial for optical clocks and atomic sensors based on a few-particle system, such as current ion traps and optical lattices.

Also, collective excitation and interaction with quantised modes of the electromagnetic field, for instance in an optical cavity, may generate coherent optical radiation beyond the current thermal noise limit of optical resonators. The entanglement of different states can be used to design an optimised sensor with intrinsic cancellation of unwanted field sensitivities and enhanced sensitivity to the field to be measured. The use of a large ensemble of quantum entangled ultra-cold atoms as an active frequency standard may supersede the use of monolithic optical resonator affected by thermal noise.

First steps are needed towards quantum-enhanced frequency metrology targeting the ambitious goals of an optical oscillator with mHz instability at 1 s and the demonstration of an entanglement enhanced atomic sensor scalable to larger number of ions.

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 techniques for optical oscillators and atomic sensors to achieve uncertainties of 10^{-18} with practical measurement time scales of minutes to hours.

The specific objectives are

1. To demonstrate entanglement-enhanced spectroscopy in optical lattice based and ion based clocks. In particular, design and study quantum non-demolition methods to go beyond the quantum projection noise (QPN) at the 10^{-16} instability level at 1 s and study entanglement techniques in ion based systems to overcome the single-ion 10^{-15} QPN limit.
2. To stabilise an optical oscillator at the QPN limit in the collective atom-cavity strong coupling regime, identifying suitable strategies to surpass the QPN limit with intrinsic field-shift compensation.
3. To develop an active frequency standard based on optically-trapped ultra-cold atoms with engineered lattice topologies to supersede thermal-noise limited optical cavities.
4. To demonstrate elementary scaling-of-entanglement operations with ion strings across multiple trapping segments towards increased sensitivity of measurement beyond classical limits and to design optimised trap geometries for ion string operations to minimise and control systematic shifts.
5. To disseminate the results among the quantum optics and cold atoms community in order to advance fundamental research to metrology and enable further applications for innovative sensors in clock-based geodesy.

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 EMRP project EXL01 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 to the project.

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,

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.