Title: Non-classical approaches for quantum-enhanced metrology

Abstract

Optical atomic clocks are at the forefront of metrology with precision spectroscopy, realising frequency references pushing beyond the 10^{-18} level of uncertainty, and as highly sensitive quantum sensors in fundamental research into new physics beyond the standard model and violations of general relativity. The present challenge is to realise instabilities at the level of inaccuracy reached on practical time scales. Non-classical approaches utilising entanglement can overcome those limits, e.g. by scaling the 1-s averaging time for a given instability for a number N of entangled states with N^2. The target is to implement those techniques on experimental platforms suited to optical and microwave clock systems and quantum sensors.

Keywords

atomic sensors, scalable entanglement, quantum-projection noise, Heisenberg uncertainty limit, quantum non-demolition, cavity quantum electrodynamics, Rydberg states, atom chips, ion microtraps, quantum squeezed and engineered atomic states

Background to the Metrological Challenges

Optical atomic clocks are at the forefront of metrology with precision spectroscopy, realising frequency references pushing at the 10^{-18} level of fractional frequency uncertainty and projecting the potential for a 10^{-19} level in ion clocks. Microwave atom and ion clocks have the potential as compact systems for long-term high stability applications in timing and navigation. Realising the precision required to a) reach the instability at the accuracy level and, b) investigate systematic effects at practical times scale is an important next step and a problem common to all those systems. The instability of optical lattice clocks has progressed rapidly in recent years, now reaching close to a quantum projection noise limit of a few parts in 10^{-17} at 1 second. One method to reduce the quantum projection noise would be to increase the number of atoms, potentially improving the 1-s instability by $N^{-1/2}$. However, increasing the atom loading rate becomes technically difficult, while extending the loading time would come at the cost of an increased Dick instability. Meanwhile, the lowest systematic uncertainty in an optical lattice clock is 1.4×10^{-18}, competitive with the state-of-the-art optical clocks based on trapped ions. However, no optical lattice clock has yet been demonstrated using squeezed atoms. A key element in the next generation of optical lattice clocks will therefore be to develop robust methods to prepare medium to large samples of atoms in an entangled, squeezed state.

Single ion optical clocks are limited by quantum-projection noise. The fundamental limit is typically $1 \times 10^{-15}/t^{-1/2}$ with $3 \times 10^{-15}/t^{-1/2}$ demonstrated. Efforts to reduce systematic uncertainties are ongoing. However, the fundamental limit for the single ion optical clock instability would require a 12-day integration time to demonstrate operation at the 10^{-18} level. Scaling to higher number of ions ($N > 1$) is essential. In combination with maximal entanglement scaling of 1-s instabilities with N^{-1}, this would enable reaching a 10^{-18} level in 3 h with 10 ions rather than 12 days (an N^1 improvement in averaging time). Entanglement of different states, for instance Zeeman states, can be used to design entangled states with increased sensitivities to external fields or compensate for sensitivities to optimise clocks. An advanced system applying entanglement to metrology is the quantum logic clock on which recent results report a systematic uncertainty below 10^{-18}.

Optical clocks based on arrays of optical tweezers each containing a single atom offer full control over the system dimension in 3D. When these are combined with Rydberg excitation, they can be used to create large entangled states, which makes them well suited to study and minimise collisional shifts and long-range interactions relevant for optical frequency metrology. The microwave atomic clock with magnetically trapped atoms at SYRTE has a fractional frequency instability $5.8 \times 10^{-13} \tau^{-1/2}$. It operates close to the Standard Quantum Limit (SQL). For compact trapped-atom microwave clocks, the need for surpassing the SQL by spin squeezing is particularly relevant since collisional shifts impose a large uncertainty given the typical atom densities in

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these devices, which have often a limited atom number.

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 metrology research necessary to support standardisation in quantum-enhanced metrology.

The specific objectives are

1. To implement, investigate and improve non-classical approaches in experimental platforms suited for optical and microwave atomic clocks and highly sensitive quantum sensors. To demonstrate their potential to overcome limits to short-term instability due to the quantum-projection noise limit (QPN) and the Dick-Effect. To overcome the QPN limit with entanglement, enhancement and scalability.

2. To enhance entanglement and scalability in singular and arrays of ion-strings and optical tweezer arrays with Rydberg atoms. To characterise entanglement in driven-dissipative optical atomic clocks with cavity-mediated interactions.

3. To perform weak-measurement based squeezing and atomic phase locking in microwave atom-chip clocks. To explore entanglement-based atomic states for evaluation and compensation of systematic effects in multi-ion clocks.

4. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (quantum sensors, optical and microwave atomic clocks, NMIs, DIs), standards developing organisations (CIPM CCTF, EURAMET TC-TF) and end users (telecoms, broadcasting, energy, security).

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 EXL01 QESOCAS and EMPIR 17FUN03 USOQS projects 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.