# Publishable Summary for 17FUN03 USOQS
# Ultra-stable optical oscillators from quantum coherent and entangled systems

## Overview

Optical clock short term stability is generally limited by fundamental noise, either atom shot noise or laser phase noise. Better stability is highly desirable to accelerate the redefinition of the SI second as well as enable new applications for innovative sensors and clock-based geodesy. A possibility to improve the stability, is to exploit advanced quantum technologies. The overall objective of this project was to study and enhance state-of-the-art quantum techniques on optical systems such as quantum coherent and entangled systems to enable a new generation of ultra-stable optical oscillators which take advantage of quantum properties of light and matter. During the project new theoretical and experimental protocols were developed to allow exploitation of quantum techniques in optical clocks, also important steps were achieved in the realization of active optical clocks based on superradiance emission and toward the realization of scalable ion traps to realize entangled multi ion systems. These results can be taken and exploited by the clock maker community aiming at the realization of next generation optical clocks and atomic sensors.

## Need

Optical clocks based on ultra-stable laser radiation are nowadays of prominent importance both in scientific and industrial activities. They are already the pillar of primary frequency metrology and are foreseen to become in the near future pillars of ICT industry, navigation and sensing, progressively replacing microwave clocks and thus becoming a key enabling technology at all effects. Optical fibre links will disseminate stable frequency standards for accuracy studies and comparisons on a continental scale, as well as allowing tests of fundamental physical laws. At the same time, ultra-low-noise synthesis of RF and microwave oscillators by means of optical frequency combs will impact aero-space navigation, very long baseline interferometry (VLBI) and telecommunication. Frequency stabilisation techniques based on a classical measurement approach and passive optical resonators seem now to be close to their maximum potential of exploitation. In current state-of-the art optical clocks (laser plus stabilisation cavity), the frequency stability is limited by two main causes: the first limitation is the thermal noise of the mirror coating and of the reference cavity itself, which affects the stability of the clock through the Dick effect (aliasing of laser frequency noise in the clock sequence). The second, more fundamental limitation is the standard quantum projection noise (QPN) of the quantum absorber, which is proportional to the inverse square root of the number of particles contributing to the signal.

The application of quantum techniques based on the creation of and measurements on correlated atomic quantum states provides a possibility to overcome these two limitations. In particular, multi-particle entangled states may exhibit a reduced sensitivity to quantum phase fluctuations, thus reducing the imprinted noise into the stabilised oscillator, as well as a mean to go beyond the fundamental noise limit known as QPN, allowing to approach instead the Heisenberg limit (i.e. a frequency instability scaling like the inverse of the number of atoms instead of its square root). On the other hand, collective excitation and interaction of atoms with quantised modes of the electromagnetic field, for instance in an optical cavity, may generate coherent optical radiation with a phase noise lower than the current 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 effect to be measured.

## Objectives

The overall objective is to implement, study and characterise both established and brand-new methods to develop quantum-enhanced optical oscillators toward $10^{-17}$ instability at one second integration time. This will enable the operation of optical clocks and atomic sensors at their projected accuracy limits of $10^{-18}$ with practical measurement times ranging from minutes to less than an hour. Non-classical techniques will be introduced to overcome current noise limitations and approach the Heisenberg noise limit.

The specific objectives of the project are:

1. To demonstrate entanglement-enhanced spectroscopy in optical lattice-based and ion-based clocks. In particular, to study spin-squeezing via 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 clocks 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 investigate the development of 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.
5. To disseminate the results among the quantum optics and cold atoms community in order to advance fundamental research in metrology and enable further applications for innovative sensors in clock-based relativistic geodesy.

**Progress beyond the state of the art**

This project addressed the need for merging quantum coherent measurement and quantum state engineering techniques with optical oscillators based on ultra-cold atoms and ions at the state-of-the-art level and beyond. It represents the natural continuation and exploitation of the achievements of the EMRP project EXL01 QESOCAS. This project has represented a first step towards quantum-enhanced frequency metrology.

The field of ultrastable optical oscillators from quantum coherent and entangled systems has undertaken significant progress over the last few years since the start of the project. Concerning enhanced optical stability from many-body entangled systems, few proof-of-principle experiments have shown interesting prospects by employing Rydberg dressing in strontium atoms trapped in optical tweezers, while a first experiment using entangled "optical qubits" in a neutral optical clock (Yb, MIT) transition has been demonstrated (at a non-metrological level). Regarding active generation of ultrastable optical oscillators from superradiance, several technological advances have been made in providing continuous cold atomic sources suitable for continuous superradiance generation and for other applications like e.g. the first realisation of a continuous Bose Einstein Condensate (BEC) of strontium atoms (Amsterdam Univ.).

Quantum engineered systems are studied both to better understand subtle predictions of quantum mechanics and as tools to realise quantum computer prototypes, and exotic states of matter and light, whose statistical behaviour strongly diverges from the classical ones. This project aimed to apply for the first time to optical clocks a series of tools, derived from quantum engineered states, like collective atomic spin-squeezing, superradiant emission, strong atom-cavity coupling, which have not yet fully been demonstrated in the optical domain.

Theoretical studies on entanglement protocols are an essential part of the project, aiming to identify the most adequate and effective approaches to be used in the optical domain and specifically in optical clocks to exploit potentialities offered by quantum engineered states without compromising their accuracy.

The EMRP project EXL01 QESOCAS showed that quantum enhanced sensors are becoming practical devices to improve the sensitivity of metrology sensors, with signal-to-noise ratios deep in the quantum regime. This project will go beyond the state of the art by furthering exploit those achievements and adapt novel quantum engineered states to overcome the QPN limit in optical clocks at the $10^{-16}$ instability level at 1 s. The latter includes systems such as the collective atom-cavity strong coupling regime.

State-of-the-art optical atomic clocks rely heavily on narrow lasers obtained with the aid of ultra-stable cavities used as frequency reference. This project aimed to new methods based on collective quantum effects and nonlinear optical response of atomic quantum states based on ultra-narrow optical transitions in alkali-earth atoms inside an optical cavity. New methods were studied and tested to generate or stabilise a local oscillator with short-term stability matching that of state-of-the-art passive optical resonators. Removal of highly sensitive to environmental perturbation and massive high-finesse cavities from the optical clock systems would be a milestone towards their simplification and miniaturisation, and in consequence facilitating reliable and commercially available optical atomic clocks.

This project went beyond the state of the art by exploring the advantages and limitations of entanglement in trapped ion systems directly from a metrological perspective beyond the proof-of-principle stage (done in EMRP project EXL01 QESOCAS). In particular, this project addressed systematic effects potentially detrimental to accurate measurements, developed and tested an alternative approach to scalable entanglement, explore the scalable approach geared towards state-of-the-art application in quantum metrology in its platform technology. The demonstration of scalability will offer a firm perspective on the true potential of trapped-ion systems with non-classical techniques in metrology.

The achievements of the project are fundamental for the next generation of clocks and sensors, even if further research and development is required in order to make them fully exploitable in reliable metrological devices.

## Results

*Creation of quantum engineered states in neutral and ion optical clocks (objectives 1, 2 and 4)*

The project has achieved relevant results in several domains, both theoretical and experimental. In particular the project has demonstrated applicability of i) Quantum Non Demolition measurement (QND) to create spin squeezing in Optical Lattice Clocks (OLC) ii) sub-Quantum Projection Noise (sub-QPN), iii) obtaining long superradiant laser pulses and iv) extending the Ramsey interrogation time beyond the laser coherence time, using a technique called dynamical decoupling, v) theoretical protocols to create spin squeezed states. The latter can be developed and applied to optical lattice clocks, without compromising the metrological properties of the devices.

The project has partially achieved the objective of demonstrating entanglement-enhanced spectroscopy in optical lattice-based and ion-based clocks. Despite the fact that the experimental characterization has not yet been fully completed, major experimental advances have been achieved to realise quantum states in a bad cavity regime, to generate a continuous superradiant laser (active clock), and to demonstrate scalability of multi-ion systems for the realisation of clocks based on a multiple entangled ions approaching the Heisenberg noise limit.

*Realisation of sub QPN detection in optical clocks (objective 2)*

This project further investigated the techniques from EMRP project EXL01 QESOCAS and demonstrated that non-destructive measurement can be effectively implemented in optical lattice clocks, paving the way for the realisation of spin squeezing in the optical domain. Also, the design of a high finesse cavity to achieve atomic entanglement has been finalised and the experimental apparatus realised and tested. Two systems capable of achieving Sub-QPN via non NDM in a weakly coupled cavity have been produced and demonstrated the capability to achieve sub-QPN regime using NDM squeezing protocol. These systems are currently being used to observe quantum correlations, to test the theoretical protocols developed and to study appropriate techniques to fully exploit this regime in metrological applications.

Two new protocols have been theoretically investigated to interrogate optical clocks with noise below the standard quantum limit. One focused on the realisation of Rabi type interrogation in a weakly coupled cavity regime (based on QND dispersive measurements), capable of achieving 8dB noise reduction below the standard quantum limit (SQL), the second one focused instead on Ramsey and uses a hybrid clock system with two atomic samples, one classic and one squeezed. The hybrid interrogation technique allows the spin squeezing noise gain also to be protected for large phase fluctuations of the local oscillator, allowing thus longer interrogation times with unchanged laser noise.

The project has (partially) achieved the objective of stabilising an optical oscillator at the QPN limit in the collective atom-cavity strong coupling regime as well as identifying suitable strategies to surpass the QPN limit with intrinsic field-shift compensation. New theoretical protocols were developed both for the Rabi and the Ramsey interrogation schemes, demonstrating a possible way to effectively operate an optical clock based on entangled atomic sample in the atom-cavity strong coupling regime.

*Realisation of an active optical oscillator (objective 3)*

By realising strong collective coupling between a sample of thermal Sr atoms and an optical cavity, superradiant pulsed laser has been demonstrated, using as atomic gain the narrow intercombination line of $^{88}$Sr. In this case after the primary pulse, several revivals of the laser power can be identified as the coherent excitation oscillates between the cavity and atomic modes. The experimental investigation has progressed with the use of cold Sr atoms, continuously repumped to the excited state extending the pulse duration by more than one order of magnitude and showing the possibility to maintain the superradiant laser emission for several ms; in this case the pulse duration is limited by the losses (heating) of the cold atoms in the trap. A new experimental set-up was assembled, to achieve a continuous replenishing of the cold atom losses capable thus of sustaining continuous superradiant laser emission. The realisation of an active clock will represent a breakthrough for optical clocks, since it will significantly relax the requirements of reference ultra-stable optical cavity.

The project has achieved the objective of realising a quasi-continuous superradiant laser emission and characterizing its spectral behaviour. In addition, the project investigated and developed an active frequency standard based on optically-trapped ultra-cold atoms, with engineered lattice topologies, to supersede mechanical/thermal noise limited optical cavities. The project also realized a new experimental system capable of sustaining continuous superradiant emission.

*Engineered scaling-of-entanglement and trap geometries of ion string operations (objective 4)*

Mølmer-Sørensen-Gates have been successfully implemented and show fidelities of 85% on the axial-IP modes and 90% on the OOP modes respectively. Current work focuses on filtering the laser-light in order to suppress the high-frequency noise of the laser for the entangling gates, which is presumed to be the main limitation of increasing gate-fidelities (both for IP gates and OOP gates). Single ion addressing on a two ion-crystal has been successfully demonstrated (cross-talk <1%).

Pulse sequences for generating a magnetically insensitive entangled state in a 2-ion Ca+ crystal have been devised and are being implemented. The initial preparation of the magnetically insensitive ground state superposition was achieved by single ion addressing, subsequent pulses are done using a global beam which has effective single ion addressing due to frequency selectivity.

The project has achieved the objective of demonstrating elementary scaling-of-entanglement operations with ion strings across multiple trapping segments towards increased sensitivity of measurement beyond classical limits. Also the project demonstrated trapping and storage capabilities of ions at low heating rates, which are then entangled using high-stability laser systems.

**Impact**

It is widely recognised that optical clocks are presently limited in their ultimate performances by their short-term stability (single ion QPN and local oscillator Dick effect). This project has explored the potential of non-classical measurement technologies in metrology for a step change in optical clocks and quantum-enhanced sensor systems. The implementation of non-classical techniques in such systems will greatly reduce short term instabilities and consequently the averaging time needed for accuracy evaluation. Simplification of the realisation of ultra-stable laser and cavity systems enables robustness and reliability gains. Designed entangled systems enable practical high-resolution sensing in noisy environments. Results from the project will have a major impact on fundamental research, opening at the same time realistic perspectives for industrial applications and commercialisations of state-of-the-art, reliable and robust clocks and sensor systems. The scientific results obtained so far indicate that superradiant emission on one side and dynamic decoupling on the other side are powerful techniques in principle capable of reducing the Dicke effect limits of local oscillators. Further investigation is needed to allow practical exploitation in clock design.

The project has reported twice its scientific results to the TC-TF general meetings, updating and informing the wide European time and frequency community about its main achievements. USOQS coordinator is also a member of the European Metrology Network on quantum technologies, engaging thus the wider quantum metrology community.

The project has published 40 peer reviewed publications in journals, plus other 3 proceedings papers as well as 5 Master/PhD thesis. The consortium has been invited to give 11 presentations at international scientific conferences such as IFCF-EFTF and presented other 38 works either as oral or poster presentation. Throughout the project, the consortium has been regularly engaging with stakeholders to ensure work is tailored to their needs, consortia participated in at least 5 exhibition activities involving industries active in the quantum field like. Multiple training activities, a total of 18 events, for the scientific community and graduate students were held, with several hundred people attending. 21 other dissemination activities such as seminars, open days and exhibitions were organised in 5 different countries targeted to the general public, broader scientific attendance and industrial end users, reaching thousands of people from a general audience. Ion traps were exhibited at the UK National Quantum Technologies Showcase and collaboration with industrial stakeholders (such as Teledyne e2v, Toptica, NKT Photonics, Acktar, Chronos, British Telecommunications) has commenced in cross-correlation with the H2020 FETF lag program. In addition, two training lectures have been given by members of the consortium: by LUH at PIER Graduate Week in October 2018 and by NPL at UCL's Centre for Doctoral Training in Delivering Quantum Technologies in January 2019. The project website has been updated.

*Impact on industrial and other user communities*

Ultra-stable oscillators are used in many technological fields like telecommunications, radar systems, interferometry etc. The development of new, more compact and robust optical oscillators will represent an important technological breakthrough in all these fields. Such oscillators also have applications in geodesy (monitoring environmental changes or volcanic processes), geological exploration (energy and mining), astronomy (VLBI timing), space exploration (gravity and field sensing, deep space navigation), defence (autonomous navigation and timing) and in the telecommunications industry (frequency standards and timing, secure communications). The techniques developed in the project will advance knowledge in the field of quantum computing, with future applications e.g. in quantum cryptography, but also in the field of quantum simulations of complex chemical processes in pharmaceutical R&D, which could yield a disruptive effect through time and cost reduction for bringing new products to the market. Contacts have been with some selected laser industries for them to contribute to the development of specialised laser sources.

As a result of the involvement of industrial stakeholders further collaboration has been initiated through the establishment of two new industrial research projects that involve partners from USOQS and European industries. 1) Project HORIZON-CL4-2021-DIGITAL-EMERGING-02-20 AQuRA aims at demonstrating a high TRL transportable optical clock. 2) Project H2020-MSCA-ITN-2019 MoSaiQC aims at training 15 early stage researchers (ESRs) in this quantum technology, giving them hands-on experience in all aspects of optical clocks, from theoretical foundations, over the development of advanced components (e.g. laser systems, vacuum, electronics), to applications in all relevant industry sectors. MoSaiQC exploits the excellent research of both H2020-FETFLAG-2018-2020 iqClock and USOQS, and goes one step beyond in their goals. The project will result in modules for a portable clock with high integration will prepare the foundations for a portable superradiant clock.

*Impact on the metrology and scientific communities*

This project will push forward the use of quantum techniques that can improve the stability of optical oscillators and linked devices beyond their current limitations. In particular, 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 present ion traps. The use of a large ensemble of quantum entangled ultra-cold atoms as an active device may supersede the use of macroscopic optical resonators affected by thermal noise. Improved atomic clocks at the NMIs are also critical for high-profile science, such as the European VLBI Service, for whom the availability of precise frequency standards enables synchronisation of large arrays of radio telescopes, giving astronomers images with unprecedented resolution and at shorter wavelengths not previously available.

Important results were achieved in this direction: 1) pulsed superradiant emission as a first step toward continuous superradiant lasing, 2) innovative laser phase reconstruction technique to allow very long interrogation times beyond the intrinsic laser coherence time, 3) new theoretical scheme to achieve innovative quantum states, 4) preliminary steps toward scalability of ion traps 5) new experimental platforms to implement strong cavity coupling regime. These results were the subject of a multitude of scientific publications on peer reviewed journals and presentations to scientific conferences. According to Web of Science database, scientific papers acknowledging funding from USOQS project have achieved an h-index of 11, accounting for 300 citations, quite a significant result considering the short time elapsed. This data testifies the significant impact of the project outcomes in the scientific community. In addition, the consortium has also produced an end user guide on further development of quantum enhanced clocks for the scientific community.

*Impact on relevant standards*

Although not directly aimed at the realisation of new frequency standards, the most direct impact of this project will be on future realisations of the SI second. Approaching $10^{-17}$ instability at 1 s will impact accuracy studies on optical frequency standards, accelerating the process for the redefinition of the SI second. The atoms/ions studied in this project are already included in the list of secondary representations of the second. Improved stability and reduced uncertainty will represent a benefit in the realisation of TAI.

*Longer-term economic, social and environmental impacts*

The importance of quantum technology was recognised by the European Commission in the "Quantum Manifesto" to formulate a common strategy for Europe to lead the second Quantum Revolution. The engagement in the new field of quantum technologies will help to keep Europe at the forefront of state of the art capabilities. It will support and enable the development of new world-leading industries in instrumentation (clocks, sensors, quantum computers and simulators, associated electronic and optical hardware, defence systems) and services (communication, computing, timing and navigation, security). Development of these technologies will stimulate the growth of a highly-skilled work-force in the advanced manufacturing sector of the European economy. Benefits to defence and civilian security, as well as autonomous navigation systems, will have significant impact on the way of life.

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These papers are available here: https://www.euramet.org/repository/research-publications-repository-link/

| Project start date and duration: | | 01 June 2018, 48 months |
|---|---|---|
| Coordinator: Filippo Levi, INRIM | Tel: +39 011 391 9241 | E-mail: f.levi@inrim.it |
| Project website address: http://empir.npl.co.uk/usoqs/ | | |
| Internal Funded Partners: | External Funded Partners: | Unfunded Partners: |
| 1 INRIM, Italy<br>2 NPL, United Kingdom<br>3 OBSPARIS, France<br>4 PTB, Germany | 5 CNR, Italy<br>6 ICFO, Spain<br>7 KU, Denmark<br>8 LUH, Germany<br>9 UDUR, United Kingdom<br>10 UMK, Poland | |
| Linked Third Parties: 11 CNRS, France (linked to OBSPARIS) | | |
| RMG: - | | |