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1 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.

2 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.

3 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.

4 Results

4.1 Objective 1

To demonstrate entanglement-enhanced spectroscopy in optical lattice-based and ion-based clocks. In particular, to study spin-squeezing via quantum non-demolition (QND) 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.

Description of the work:

The possibility to go beyond the Standard Quantum Noise limit is a breakthrough in frequency metrology and sensing because it implies the possibility to achieve higher resolution in shorter measurement time. Experiments for the demonstration of spin squeezing through quantum non-demolition measurements were performed at NPL (with contribution from UDUR) and at OBSPARIS with theoretical contributions from ICFO showing the capabilities of this technique to achieve almost 8 dB of gain with respect to the SQN limit. Within the same object, UDUR has planned experiments to observe spin squeezing utilizing Rydberg atoms: Rydberg atoms were observed with two different trapping methods: MOT trapping a tweezer trapping The latest is a promising technique since allows to address manipulate and interrogate each single atom autonomously. However, significant delays in the experimental realization of the system did not allowed to achieve relevant results toward the realization of entangled systems and spin squeezing observation.

Experiments and theoretical studies have been performed during the project. A clear demonstration of spin squeezing of Sr atoms through QND measurement was demonstrated in both laboratories, with a strong research focus on the applicability of the developed protocol to atomic clocks, meaning that the QND protocol do not result in a frequency shift of the clock.

A heterodyne non-destructive detection system has been designed and operated at OBSPARIS. This detection system is based on a dispersive counting of the ground state atoms in an optical lattice clock by measuring the displacement of the resonance frequency of an optical cavity; the cavity is used as well to form the optical lattice in which the atoms are trapped. The system is based on the simultaneous injection of two second order phase-modulation sidebands in two consecutive longitudinal modes of the cavity respectively, located on each side of the $^1S_0$ $^1P_1$ transition of Sr atoms at 461 nm. The counting of the atoms is then derived from the optical beat note between a strong local oscillator (the modulation carrier, resonant with the atomic transition and anti-resonant with the cavity) and the sidebands reflected by the cavity. Given the cavity length of 41 mm, the phase modulation frequency is thus a quarter of the cavity free spectral range (FSR = 3:66 GHz) and the heterodyne demodulation frequency is half the FSR.

The noise of the detection was measured to be $\delta_N = 22$ atoms$= p n_\gamma$, where n_γ is the number of scattered photons per atom during the detection process. This noise level is only a factor 5 above the fundamental light shot-noise limit. Therefore, the quantum regime (defined by $n_\gamma < 1$) could in principle be reached with a detection noise lower than the quantum projection noise for a number of atoms $N > 500$.

In order to further improve this detection scheme OBSPARIS designed an alternative high frequency modulation based on 2 electro-optic modulators (EOMs). The detection system has been implemented as part of this project, and characterized by probing about 5000 atoms of ^{87}Sr in the ground state, and by observing the decay of the atoms in the optical lattice due to long term photon scattering from the non-destructive probe.

The detection noise, normalized by the scattering rate, is evaluated at δN = 47 atoms=pn_γ, which is sufficient to implement a spin-squeezing protocol with about 10^4 atoms.

Also NPL has developed a cavity QND measurement apparatus with few changes compared to OBSPARIS setup, aimed at making it easier to enter the quantum regime as shown in figure 1.

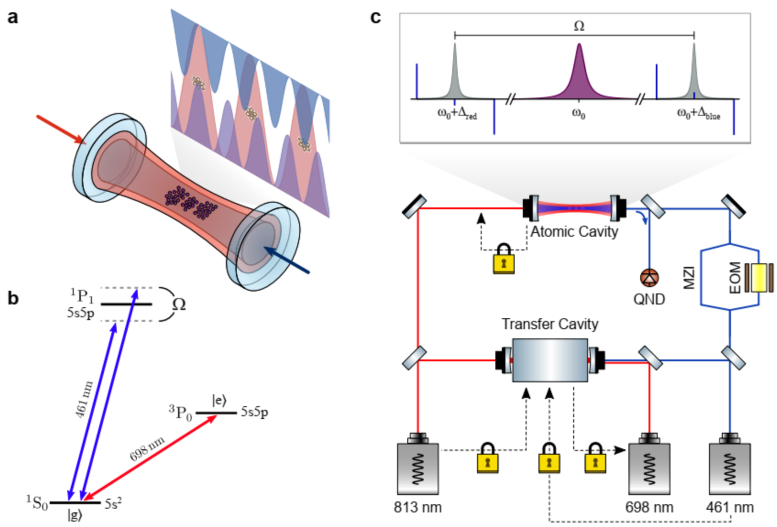

Figure 1: NPL set up for QND: (a) Sketch of the dual-wavelength in-vacuum cavity used to trap the atoms and to carry out the QND measurement. Atoms are trapped at the 813 nm intensity maxima represented in red, while they also interact with the nearest blue- and red-detuned cavity modes at 461 nm represented in blue and purple. (b) Simplified level scheme for Sr showing the 461 nm transition used for non-destructive detection and the 698 nm optical clock transition. (c) Diagram of the optical setup used for the QND measurement, and a sketch of the optical spectrum transmitted through the Mach-Zehnder interferometer (MZI). The six probe frequency components generated by the electro-optic modulator (EOM) chain are depicted in blue, interacting with the cavity modes in grey which surround the atomic transition in purple. The padlocks represent Pound-Drever-Hall (PDH) loops used to stabilise the laser frequencies and the cavity lengths.

An important result was obtained building on the ability to carry out weak QND measurements, NPL implemented an ‘atom phase lock’ of the clock laser phase to the atom phase. Using the fact that the atomic coherence is preserved after each measurement, the consortium repeatedly measured the phase accumulated by one sample atoms and steered the clock laser phase toward the atoms’ phase.

The theoretical group at ICFO, in collaboration with OBSPARIS, developed also a novel measurement protocol for Alkaline Earth Like (AEL) atoms that uses Quantum Non Demolition (QND) measurements to reduce Quantum Projection Noise (QPN) in Rabi spectroscopy, and thus is directly applicable to state-of-the-art Optical Lattice Clocks (OLCs) as presently employed. The key point of the protocol is a multi-pulse interrogation sequence. The multiple measurements serve a dual purpose. First, to obtain information about the population difference between the clock states i.e., to perform standard Rabi spectroscopy. Second, the measurement back action will squeeze the atomic state, allowing sub-shot noise determination of the atomic observables in successive measurements. The need to develop such protocol comes from the impossibility (inherent to the AEL atoms) to address simultaneously the two clock states.

Regarding the development in ions entanglement and scalability experimental developments have been undertaken at LUH and NPL. LUH demonstrated 2-ion entanglement with 95 % fidelity. Work towards the use of a magnetic-field insensitive, decoherence-fee subspace (DFS) realisation for measurements with the 40Ca+ ion pairs has been carried out combining 2 different linear Zeeman shifted qubit transitions. To date, a classical realisation of this approach used Ramsey spectroscopy with 5 ms dark-time on an unentangled pair was used at LUH to stabilise the laser. A fractional instability of $1.6\times10^{-14}/\sqrt{\tau}$ has been measured in a noisy magnetic field out to 1000 s averaging time, which is within one order of magnitude of the standard quantum limit for a single ion. The realisation with entangled ions is ongoing.

At NPL steps have been undertaken to address scalability to higher number of ions on a multi-segment ion trap platform. Studies have been performed to resolve limitations in the microfabricated design of a compact system. While a scalable design of a 3-dimensional trap electrode geometry realised in a monolithic parallel fabrication process is highly desirable for long-term trapping and repeatable performance "off the shelf", a compromise between the desire for high-motional frequency operation and limitation on the rf voltage amplitude to avoid electrical breakdown had to be found, so that operation at desirable, i.e. low, trap-stability parameters could be maintained even during shuttling and splitting operations with ion strings in the complex trap geometry. The experimental system confines a 2-ion string with lifetimes of up to a few days and can show loss-free transport of up to 4 ions using the optimised trap parameters. Ground state cooling of a 2-ion string on the axial and stretch modes has been shown. Using a 2-ion string cooled to the ground state of the axial motion, the consortium have observed high contrast Rabi flopping on the blue axial sideband of the optical qubit transition. This coherent control of the ions' motion is a key step towards 2-ion entanglement.

Key outputs and conclusion:

Important steps toward the realization of spin squeezed stated realized by means of QND protocols and their application to optical lattice clocks have been achieved, showing that sub-shot-noise detection is currently achieved and that proper clock protocols can be identified allowing to operate Optical Lattice Clock using this technique. Also, it was demonstrated that QND can be exploited to perform a kind of phase locking of the laser to the atoms, reducing thus the impact of the laser phase noise and thus reducing the need of better optical cavities.

Two ions entanglement was demonstrated using Mølmer Sørensen gates. This is a crucial step toward the demonstration of scalability of multi ion system, needed to realize a multi ion optical clock. Microfabricated ions trap was realized allowing to demonstrate scalability of ions entanglement to a higher number.

4.2 Objective 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

Description of the work:

The work was carried on along two directions:

1. The development of a new apparatus and methods for a strongly coupled atom-cavity system nearly resonant to both the $^1S_0 - {}^3P_0$ and $^1S_0 - {}^3P_1$ by INRIM
2. The theoretical study and engineering of metrologically useful entangled states for the case of a strongly coupled atom-cavity system by CNR-INO

With respect to the first point INRIM, with theoretical inputs from ICFO have designed a new cavity-enhanced Sr optical clock according to the following criteria: i) achieving the collective strong-coupling regime on both the closed $^1S_0$ -$^3P_1$ transition and clock transition to generate atomic entangled states and superradiance; ii) making the atom-cavity coupled system in the so-called "bad cavity" regime, i.e. $\kappa > \Gamma^3P_1$; iii) maximizing the light-atom coupling homogeneity by trapping the atoms in a magic-wavelength lattice with commensurate spacing with respect to the probe cavity standing wave. The system, depicted in figure 2, will then consist of two overlapped cavities, a Fabry-Perot cavity for the cQED system and a bow-tie ring cavity to obtain lattice confinement at the clock magic wavelength.

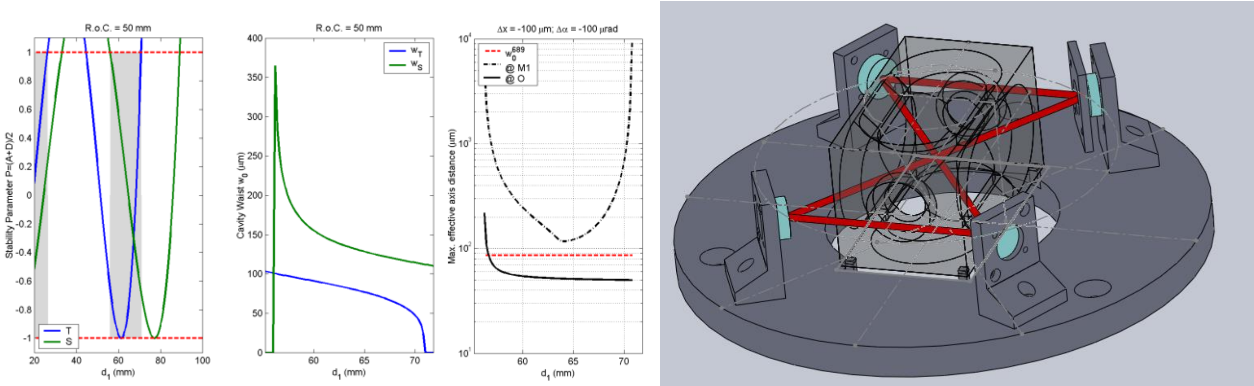

Figure 2, design of the lattice bow-tie cavity system developed at INRIM. Plots of the calculated stability region (left plot), cavity waist dimensions (centre plot) and beam displacements for mirror misalignment on one mirror and at the cavity centre (right plot). On the left is reported the technical drawings of the double cavity set up of INRIM Sr clock.

The second topic was addressed by CNR-INO. CNR researchers have studied the optimal use of spin-squeezed states in an atomic clock. The sensitivity of a Ramsey interferometer using spin-squeezed states is characterized by a trade-off between squeezing and bandwidth. As a consequence, for a given Ramsey time, there is an optimal value of the squeezing parameter s that minimizes the mean phase uncertainty and thus also the Allan variance. It is possible to see that the optimal Allan variance scales as $\sigma^2 \sim 1/N^{4/3}$ this limit is far from the Standard Quantum limit and represents a major limitation in the exploitation of quantum states to improve clock short term stability. CNR researchers have shown that this result can be overcome by a joint interrogation method that uses two (or more) atomic ensemble interrogating in parallel the same local oscillator in the so-called hybrid clock interrogation scheme (figure 3).

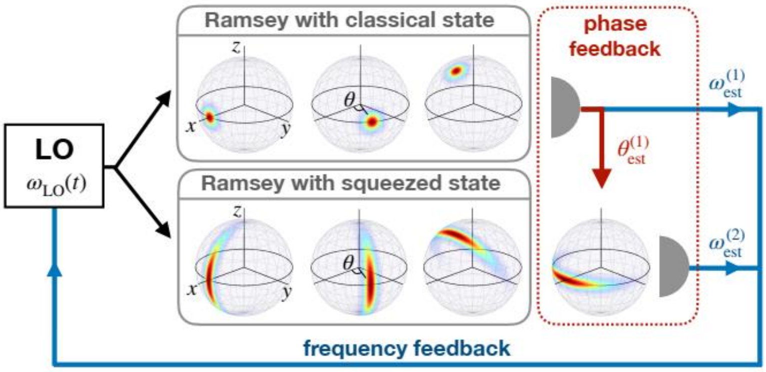

Figure 3: Hybrid clock with two atomic ensembles are interrogated by the same local oscillator (LO). Both Ramsey interferometers consist of state preparation (left-hand side), phase shift (central - the accumulated phase is the same for both ensembles) and π/2 rotation about the x axis (right). Ramsey 1 uses a coherent spin state, while Ramsey 2 uses a squeezed state. The readout of Ramsey 1 is used to phase-feedback (red line) Ramsey 2 in order to bring the squeezed state to its most sensitive phase estimation optimal region with a final rotation about the y axis The frequency estimations are combined to steer the frequency of the local oscillator (blue lines).

Key outputs and conclusion:

INRIM designed and developed a new concept of optical cavity system capable of realising a strong coupling between the atoms and the optical laser field, maximising the light-atom coupling homogeneity making the lattice site spacing commensurable with the laser spacing. The bow type cavity was designed, assembled, and tested without atoms. From a theoretical point of view CNR and ICFO analysed the strong coupling regime and identified innovative protocols capable of achieving almost one order of magnitude improvement of the detection noise (8dB), meaning that a typical clock can in principle achieve a 1s stability well below the SQL. Theoretical studies also identified an innovative, smart solution to one of the most critical problems of using coherent state for Ramsey spectroscopy. The protocol developed uses two atomic samples, one classical and one squeezed to improve the S/N gain and approximate more closely the Heisenberg noise limit.

4.3 Objective 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.

Description of the work:

An active optical clock can represent a straightforward solution to overcome the noise limitations posed by optical cavities. In fact, if the laser radiation is directly emitted by the atoms, the physical function of the cavity changes, becoming a standard optical resonator that sustains the laser oscillation (bad cavity regime) providing a gain to the oscillating optical system. This research was performed by researchers at UMK and KU.

The key idea to overcome the noise imprinted onto the laser by cavity length fluctuations is to integrate an atomic ensemble with a suitably narrow electronic transition into a cavity, such that the dispersive (or absorptive) response of the combined system is dominated by the interaction of the ensemble with the intra-cavity field. To enter this regime, the cavity bandwidth should be wider than the (inhomogeneous) linewidth of the atomic reference transition i.e., the so called bad-cavity regime is entered. In this regime the collective atomic coherence stores major part of the phase information and the impact of the interaction of intra-cavity photons with the (noisy) cavity mirrors on the system response gets suppressed.

At the same time the atom-light interaction is still enhanced by the cavity finesse with respect to the interaction in free space, which is beneficial when working with narrow and hence weak optical transitions. The concept can be applied to passive interrogation of the atomic transition (cavity enhanced spectroscopy), but also to active operation as a laser in the bad-cavity regime using the atomic ensemble as the gain medium. This second active approach is of considerable interest as it can dramatically relax the requirements on the spectral quality of the lasers used to pump the atomic ensemble to achieve population inversion. In the following both the passive and active schemes using laser cooled atoms coupled to an optical resonator are detailed. The experimental system developed at KU is described in figure 4.

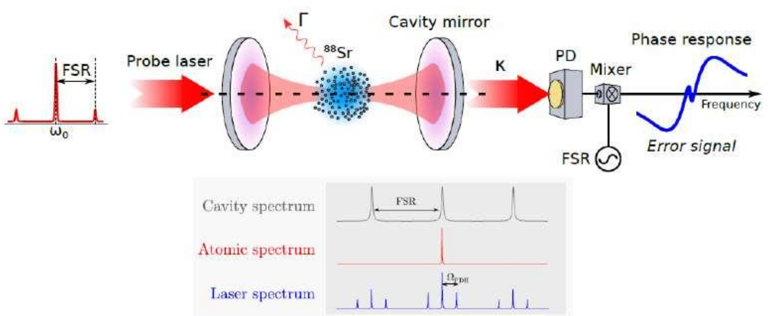

Figure 4: Schematic setup for NICE-OHMS interrogation of cold Sr atoms. Probing in transmission with modulation sidebands at the cavity FSR as local oscillators cancels the empty cavity dispersion and noise in the phase response

The enhanced atom-light interaction mediated by the optical resonator can also be employed to generate active laser output from the atomic ensemble. To demonstrate this the KU experimental apparatus has been substantially upgraded during the project. With those modifications ensembles at µK temperatures containing 3 10^7 atoms could be coupled efficiently to the cavity mode putting the system deep into the bad cavity regime.

The ensemble after cooling can be inverted using a π-pulse and collectively emits a short superradiant burst (1 µs) with peak powers of several µW. More interesting for applications as a frequency reference are longer pulses, which can be obtained by continuous incoherent pumping to the upper laser level. To achieve this a pumping scheme as shown in figure 5 was employed.

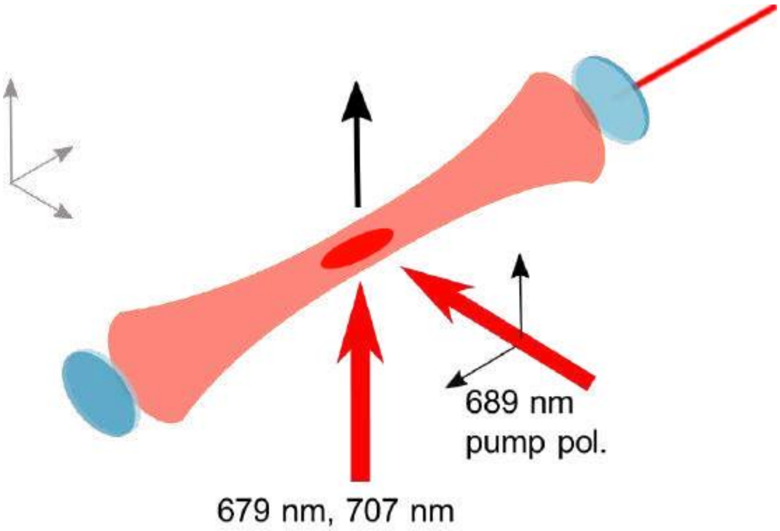

Figure 5: Sketch of the pump/repump geometry for quasi-continuous laser operation on the kHz transition. A magnetic bias field in the vertical direction (solid black arrow) is applied in the vertical direction.

The first step performed was to continuously restore the cold Sr atoms, repumping them in the excited state. Obviously this repumping technique produces atom losses and heating, and thus can’t be exploited to obtain CW emission. However, it was possible to achieve much longer superradiant pulses and better characterize the laser emission spectrum. Using this pumping scheme laser emission with millisecond time scale duration at power levels of about 100 nW could be achieved. This output power level, corresponding to a photon flux above 10^{10} s^{-1}, allows to phase lock a more powerful oscillator with high bandwidth to the active Sr laser output.

To characterize the spectral behaviour in time a beat-note between the reference laser and the cavity output was recorded and analysed as a spectrogram, the spectrogram revealed a narrow linewidth, limited by the Fourier width of the chosen spectrogram analysis.

Work toward the realization of a CW superradiant laser emission was performed at UMK as well. There a new experimental apparatus was conceived capable of continuously restoring the atomic losses in the cavity, so to sustain a CW emission. The conceptual scheme of a CW superradiant system can be understood according to the following figure 6.

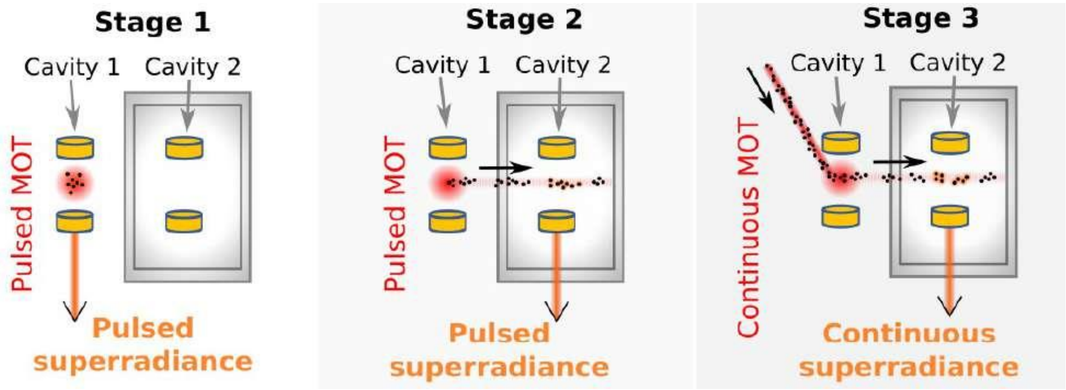

Figure 6: conceptual steps for turning pulsed superadiance into CW superadiande

Stage 1 focuses on creating a pulse of superradiant light emitted from Sr atoms on the mHz (in 87-Sr) or sub-mHz (in 88-Sr) clock transition. The hot Sr atoms are opto-magnetically slowed down in a Zeeman slower and cooled down sequentially by blue and red MOTs. After switching off the red MOT, the atoms are trapped in a 2D magic optical lattice, preventing collision-induced decoherence inside the high-Q cavity (cavity 1), and pumped into the $^3P_0$ state (the clock transition excited state). The stage-1 scheme can operate in the pulsed regime only, because the blue MOT operation quickly destroys the coherence of the superradiant ensemble. The second stage changes the pulsed superradiance into a continuous coherent output with the help of the second cavity, where the atoms will be transferred to by a moving magic-wavelength lattice. This cavity must be isolated from the strong magnetic fields and MOT light, maintaining lasing during preparation of the new atomic ensemble. Stage 2 focuses on transferring atoms optically pumped to the excited clock state into the cavity in sufficient numbers to repeat the superradiant pulsed emission. In Stage 3 the Zeeman slower source is replaced by the μK-temperature Sr beam source (developed by F. Schreck group). The red MOT operates both in pulsed or continuous mode and the excited atoms are transferred into cavity 2 by a conveyor belt as a sequence of overlapping packets or a continuous beam. The new atoms arrive before the end of the previous pulse, enabling the transfer of the superradiant laser's phase onto them, keeping the emission coherent and continuous.

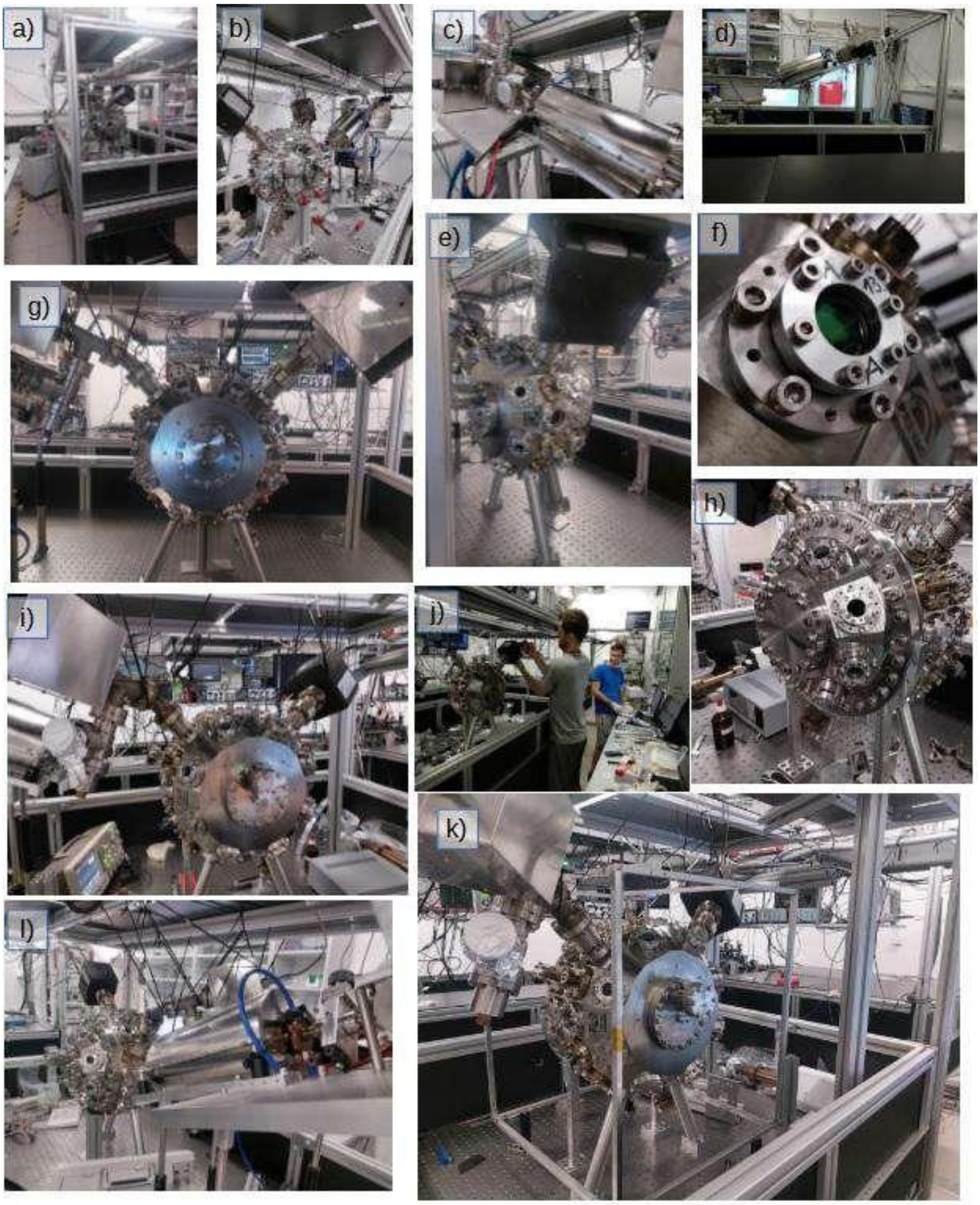

Figure 7: experimental system developed at UMK. Vacuum setup assembly. a) Overview of the optical table for superradiance set-up with vacuum element visible and the cage made of Bosh-Rexroth profiles for installation of the apparatus b) A vacuum chamber with blank flanges during the first vacuum tests. c) and d) The oven and the Zeeman slower part of the set-up. The Zeeman slower is installed inside a magnetic shield. This part is aligned at 22.5º angle with respect to the horizontal plane. g), e), i) and h) The science chamber with different elements attached at different stages of installation. f) Close-up on the installed non-magnetic viewport, made of aluminium, titanium and glass, and with an indium wire sealing. l) The science chamber, the oven and the Zeeman slower visible from different angles k) The science chamber with the layout of the compensation coils

Looking at the problem of the laser noise from another perspective allowed PTB researchers to develop an innovative protocol, called dynamic decoupling, to control the laser noise and consequently extend the maximum duration of Ramsey time in OLC (figure 8). Typically, the Ramsey time is limited by the phase noise of the interrogating laser, in fact when the accumulated phase noise reaches pi the contrast of the fringes goes to zero. The protocol is based on the idea of interrogating two atomic samples with the same laser, the first sample is the simplest system and is interrogated with a short cycle time to track the laser phase, this information is then used to pre-correct the phase of the laser used to interrogate the clock operated with a long Ramsey time. In this way it was demonstrated that it is possible to extend to several seconds the Ramsey time of the clock, without the need of further improving the laser phase noise (i.e., the reference cavity).

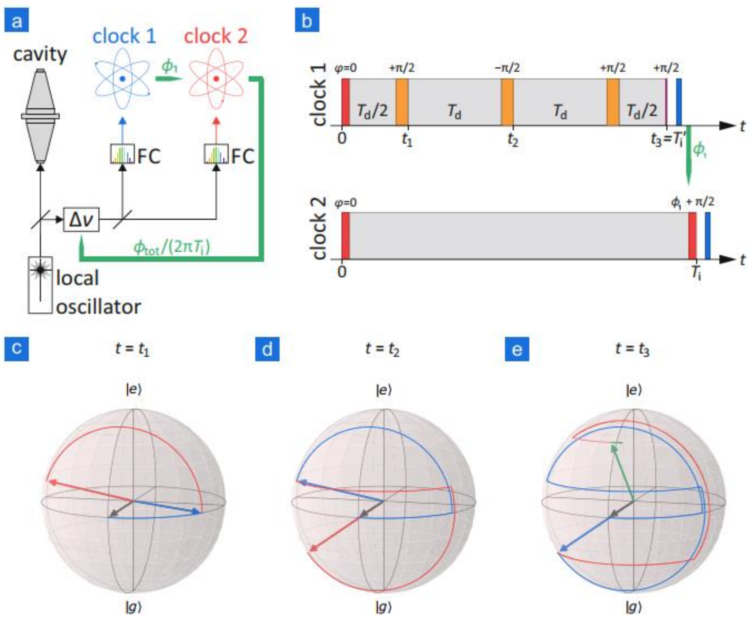

Figure 8 Compound clock scheme using dynamically decoupling interrogation. a Schematic setup of a compound clock for operation beyond the laser coherence limit. The two clocks share a common local oscillator (LO) that is pre-stabilised to an ultrastable cavity. The frequency stability of the LO is transferred to interrogation lasers, e.g. by a frequency comb (FC). Using the spectroscopic sequences shown in b, clock 1 provides a coarse estimate (ϕ1) of the laser phase deviation to clock 2, which then re*fi*nes this measurement. Their combined measured phase deviation (ϕtot) feeds back into a frequency shifter (*Δv*) to stabilise the LO frequency. Note that the measured phase and frequency deviations need to be scaled by the frequency ratio when transferred to a clock or LO operating at a different frequency, which has been omitted here for the sake of simplicity. b Pulse sequences of clocks 1 and 2 as a function of time *t* (example). After an initial π/2 excitation pulse (red), the interrogation sequence of clock 1 interleaves free-evolution times of duration *T*d or *T*d/2 (light grey) and '*fl*ip' pulses (orange) of pulse area π - ϵ and phase φ = ±π/2 with respect to the initial pulse. It ends with a pulse of area ϵ/2 (magenta) and state read-out (blue). Clock 2 uses a two-pulse Ramsey sequence. It receives laser phase information (ϕ1) from clock 1 in time to adjust the phase of the second π/2 pulse such that the fringe centre is shifted to maximise the signal slope. The delay *T*i *T*0i must be kept short to avoid excess phase noise (see "Methods" section). c–e Evolution of the atomic state in clock 1 on the Bloch sphere for constant laser detuning at times *t*1 through *t*3, as marked in b (example). *g* and *e* indicate the ground and excited state of the clock transition, respectively. After accumulating phase during the *fi*rst dark time *T*d/2 (c, blue), a *fl*ip pulse nearly reverses this precession of the Bloch vector and maps it onto a small change of excitation probability (c, red). The process is repeated twice with dark time *T*d (d and e, red). Finally, another free-evolution time *T*d/2 (e, light red) and the *fi*nal laser pulse with area ϵ/2 (e, green) are applied.

Key outputs and conclusion:

During the project it was demonstrated for the first time at our knowledge, the realization of a semi-cw superradiant laser system with pulses exceeding several ms duration. Also it was experimentally shown that the linewidth of the laser emission is Fourier limited by the duration of the pulses.

A new apparatus was designed and realized to allow true cw superradiant laser emission by replenishing of cold atom losses, via a continuous Sr cold atom beam.

The problems related to laser noise was approached also from a different perspective, showing that, with the availability of two atomic systems, it is possible to use the first one to extract the information of the laser excess phase noise, so that the second one can be interrogated for much longer time as if a much quitter laser was available.

4.4 Objective 4

To demonstrate elementary scaling-of-entanglement operations with ion strings across multiple trapping segments towards increased sensitivity of measurement beyond classical limits.

Description of the work:

While the time it takes an optical lattice clock to realise its uncertainty is on the order of a few, the time it takes a single-ion optical clock to realise its uncertainty would currently be at least half a month of continuous operation. The signal-to-noise ratio (SNR) can be enhanced by employing correlated interrogation techniques like spin squeezing. The research carried on during the project was aimed at demonstrating the possibility to realise arrays of ion microtrap in a scalable configuration to further proceed in the entanglement of single ions. NPL and LUH were involved in the development of Mølmer-Sørensen Gates, capable of creating entanglement between ions stored in a linear Paul trap.

In entanglement operation on optical qubits in ions in a cooled string (or crystal) stored in a single trapping potential in a linear ion trap, the correlation is communicated via the shared motion. Coherent manipulation of the qubits and motional states utilizes a qubit laser system, similar to a clock laser system, interacting directly with the qubit carrier transition or on the motional sidebands. These systems include fully agile control of intensity, phase, and frequency of the fixed frequency ultrastable cw laser light to cover addressing of all Zeeman states, micromotion sidebands and motional sidebands with one laser for entanglement as well as precision spectroscopy on the transitions. This enables to keep control of the optical phase during and in between entanglement and precision spectroscopy steps. Entanglement can be scaled up by adding more ions to the string, or when using segmented linear ion traps, by ion transfer between different traps with splitting and shuttling operations followed by further entanglement steps. Many demonstrations of operations have been carried out, mostly in quantum computation and simulation experiments, covering radiofrequency Zeeman, hyperfine microwave, or optical qubit transitions. The goal of the project, performed by the group working at NPL and LUH was to work on such schemes with high-fidelity entanglement and precision spectroscopy. To this end the Mølmer-Sørensen gate was utilized at LUH on a pair of $^{40}Ca^+$ ions and at NPL on a pair of $^{88}Sr^+$ ions achieving a fidelity as high as 95(3) % and 96(3) %. In both cases a major limiting factor has been identified in the frequency noise or fluctuations between the qubit and the laser source. In part these originate from the use of Zeeman transitions in non-perfect magnetic field environments, but also to a great extend in limited spectral purity of the ultrastable laser sources. This is despite the fact that fractional frequency instabilities on the level of 2×10^{-15} or better at 1 s averaging times have been demonstrated.

The MS gate scheme enables the realization of a maximally entangled state of an even number of qubits in ions in a shared motional state by applying bichromatic laser light globally. The 2 frequencies are symmetrically detuned slightly by δ from the red and blue motional sideband resonances of a motional mode, commonly the center-of-mass mode (COM). The gate is applied in a way that the excitation of any single ion is energetically forbidden, while the excitation of all ions at once is allowed. An additional asymmetric detuning Δac of the bichromatic light from the undisturbed transitions is required to compensate for an ac-stark shift caused by the light's presence. During the ideal gate time τ_{gate} the qubits are first entangled with their shared motion and then fully disentangled from the motion, with only the maximal entanglement of the qubits remaining. Continuing the gate beyond that time would entangle the motion with the qubits again in a periodic fashion. Only with the right detuning δ does disentanglement from the motional mode and the 50 % excitation probability needed for a maximally entangled state (Greenberger-Horne-Zeilinger state) occurs.

A measurement of the inversion time, t_{inv}, directly measured on the blue motional sideband of a single ion is used as a starting point to approximate $\tau_{gate} = t_{inv} * (N_{ion})^{-1/2}$, with N_{ion} the even number of ions in the string. This works for all motional modes in an ion-pair, but not for $N^{ion} > 2$. In that case the ions do not equally participate in the motion and couple differently to the qubit laser, so the gate won't work. The symmetric detuning is then $\delta = 2\pi/\tau_{gate}$ to achieve the maximally entangled state. The remaining parameter to be fixed is the asymmetric detuning to compensate for ac-Stark shifts. One independent way of measuring it would be to run a Ramsey experiment with a single ion and single frequency light and interleaving experiments with bichromatic light on and off during the Ramsey dark time and comparing the difference to extract the ac-Stark shift. If the bichromatic light detuning is set to $> 5 \times \delta$ the likelihood of direct excitation of the ion is strongly reduced but has little effect on the ac-Stark shift. This set of parameters should be close enough to reveal initial signs of entanglement and can be used as a starting point for the fine tuning with the iterative procedure for the case of ion-pair entanglement. Figure 9, shows the typical signature for an MS gate on an ion pair consisting of the excitation probabilities for none, either one, or both ions as function of the duration of the bichromatic pulse and parity oscillations measured at the gate time.

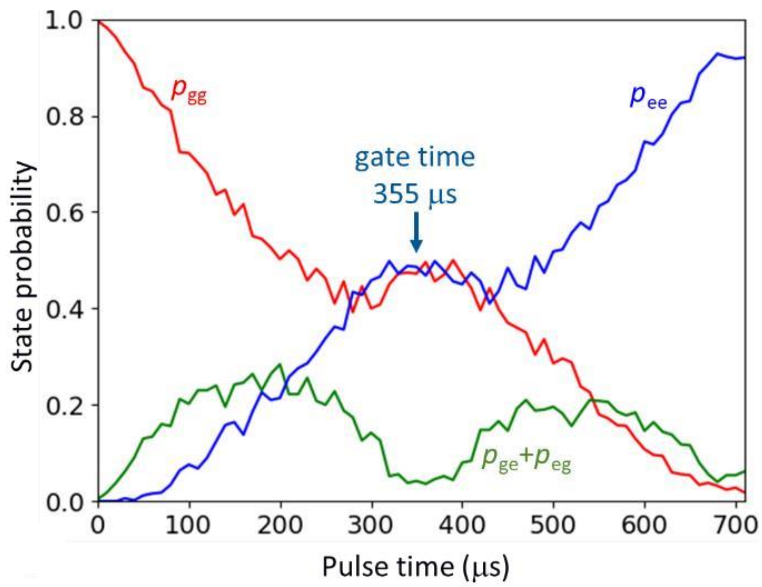

Figure 9: entanglement signature of a 2-ion pair in the $^{88}Sr^+$ experiment at NPL. In a) Probabilities to find the ion-pair with both ions in the ground state (p_{gg}), one of the two ions in the excited state (p_{ge} + p_{eg}), or both ions in the excited state (p_{ee}) as function of the bichromatic pulse time. At 0.355 ms = τ_{gate} the signature for a maximally entangled ion pair, $p_{gg} = p^{ee} = 0.5$ and $p_{ge} + p_{eg} = 0$, is closely realized.

Key outputs and conclusion:

Two ions entanglement via Mølmer-Sørensen gate implementation was achieved, observing a very high fidelity, in excess of 95%. The result is likely limited by fast frequency noise of the laser used for entanglement operation.

A prototype microtrap capable of hosting up to 7 operation zones was designed and extensive simulations were performed to develop proper entanglement protocols to be used with $^{88}Sr^+$ ions. Work still remains ahead in order to experimentally demonstrate scaling of number of entangled ions in a working clock.

5 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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