Final Publishable JRP Summary for EXL01 QESOCAS
Quantum Engineered States for Optical Clocks and Atomic Sensors

Overview

High precision clocks are key to the determination and dissemination of the SI unit of time, particularly for the realisation of the international atomic time, global navigation satellite systems and the exploration of fundamental physical laws. The new generation of optical atomic clocks, which could redefine the second, are limited by their stability (the amount the frequency changes over time). This project explored ways to make optical clocks more stable, with decreased uncertainty, than is currently possible. Quantum mechanics offers the potential to generate, detect and use specially designed states of atoms or ions for the clock. This project made significant advances in developing concepts and methods to enable optical clocks to be more stable and reach their full potential. This project developed several key enabling technologies, including a commercially available innovative crystalline mirror coating; a key enabling technology for the next generation of ultra-stable lasers. The outputs will have a direct impact on a wide range of quantum sensors such as accelerometers, gravimeters, gyrometers and magnetometers.

Need for the project

Clocks with the highest stability and accuracy are needed for applications such as the realisation and dissemination of the SI second, the realisation of international atomic time, global navigation satellite systems and the exploration of fundamental physical laws and phenomena. Improvements in clock accuracy and stability in the low 10^{-18} range or better could lead to new applications for clocks, for instance in geodesy and earth science.

Clock stability is the time needed to reach a given measurement uncertainty. The best atomic clocks have an accuracy around 1 part in 10^{18} and short term instabilities of 10^{-15} over one second, improving with the square root of the averaging time. Technological developments may improve instabilities to the low 10^{-18} range in the near future. However, investigating the physical phenomena which cause shifts of the clock frequency is hindered by the prohibitively long time needed to measure such shifts and to compare clocks at this level.

The stability is limited by two main causes. Firstly the quantum projection noise which is inversely proportional to the square root of the number of particles. Therefore increasing the number of ions could reduce the noise. The second limitation is called the Dick effect, which is due to the large amount of 'dead' time in the probe sequence which means the probe laser noise is also a problem.

A potential solution to solve both these stability issues is to use quantum entanglement. Entanglement of two atoms to exhibit the same properties as one another without being physically linked, means that one can be observed without destroying the state of the other.

This project focused on techniques for achieving the short term stability necessary to reach uncertainties at the 10^{-18} level in practicable times in the order of minutes to hours. These techniques will be based on quantum entanglement. This project was designed to maximise the exchange of knowledge between the fields of optical clocks and atom interferometry, quantum gases, quantum information processing.

Report Status: PU Public

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Scientific and technical objectives

The goal of the project was to identify, to develop and to implement methods that can improve the stability of optical clocks and of atom-based sensors, whilst taking into account the specific requirements of precision measurements. The objectives are:

1. To investigate the generation of entangled states using (i) interactions in neutral atom systems and (ii) interactions in trapped-ion systems.
2. To investigate the generation of entangled states by performing measurements in neutral atom systems.
3. To develop the necessary technologies for the above objectives. To characterise these entangled states, notably in terms of the degree of quantum correlation and coherence lifetime.
4. To design and implement protocols where the use of the above methods can improve the spectroscopy and the clock stability.
5. In one or several of the systems under study, the spectroscopy and stability beyond that imposed by the Dick effect for the same system will be demonstrated In one or several of the systems under study, spectroscopy and stability beyond that imposed by the standard quantum limit will be demonstrated, for the same system in the same configuration.

Results

The project has improved technologies and methods to enable optical clocks using quantum entangled states. It has developed high yield parallel fabrication of micro-fabricated ion traps on 4 inch wafers. The project has also developed methods to test and characterise such traps, and assess their suitability for optical clocks. Non-destructive detection of trapped atoms for clocks, based on the dispersive effect of the atomic sample on a probe light, has been experimentally demonstrated. A novel detection scheme was used to measure the transition probability in optical lattice clocks with unprecedented sensitivity. A system was developed to produce quantum engineered states of atoms in optical lattice clocks.

By studying factors that influence the trade-off between destruction and detection, schemes were optimised for application in optical clocks. A control system was developed which was capable of fast acquisition of the information delivered by this detection and of fast actions on the atomic system based upon this information.

Theoretically investigating whether squeezed light could improve non-destructive detection schemes and taking into account realistic conditions such as optical losses, it was estimated that significant enhancement of the sensitivity of such detection is possible.

Using the non-destructive detection of hyperfine population difference of trapped atoms, a novel scheme where the phase difference between the atomic coherence and the interrogation oscillator is tracked without destroying the atomic sample was successfully, experimentally demonstrated. The scheme can be used to extend the interrogation of the atomic sample beyond the coherence time of the interrogation oscillator. By extending the interrogation duration, the clock stability was improved.

A scheme where an optical lattice clock was used to extend the interrogation time of an optical single ion clock beyond the coherence time of the interrogation laser was studied. As in the previous result, it provided a way to improve, for a given ultra-stable laser, the stability of the ion clock.

Novel ultra-stable lasers were developed. A room temperature laser based on a long 48 cm cavity at 698 nm was designed, implemented and characterised against two cryogenic silicon cavities. State-of-the-art thermal noise floors of 6×10^{-17} and 4×10^{-17}, were demonstrated. With the room temperature laser, state-of-the-art stability of 1.6×10^{-16} at one second was demonstrated on a strontium optical lattice clock.

Crystalline coating technology is key to further improve such lasers and has been improved through this project. Repeatable, high yield manufacturing of aluminium gallium arsenide (AlGaAs) crystalline mirror coatings with low optical losses were developed. The process of transferring such coatings onto crystalline silicon substrate that can withstand operation at cryogenic temperature was demonstrated. This is a key enabling technology for next generation ultra-stable lasers.

It was demonstrated that interactions and spin dynamics can offer the reliable production of squeezed vacuum states, which were then characterised. A prototype microwave clock was designed where such states were used to demonstrate stability beyond the standard quantum limit, thereby experimentally proving the applicability of a squeezed vacuum for quantum-enhanced atom interferometry.

In a multiple ion trap, with strings of up to 20 ions, a protocol was demonstrated using spectroscopy to perform precise characterisation of systematic shift inhomogeneity across the ion string. This is an important capability for enabling highly accurate multiple ion clocks. A second promising key result was the demonstration of a novel scheme for generating an entangled state of multiple ions. Limits of the scheme were analysed and ways to produce a higher level of entanglement were defined, highlighting the need for a trap with lower heating rates.

In conclusion, several new key enabling quantum engineering methods for improving optical clock stability and their accuracy in a variety of systems were demonstrated by the project. These methods can benefit both the quantum regime, to go beyond the standard quantum limit, and the classical regime, to make a better use to existing ultra-stable oscillators. Key technologies for future ultra-stable oscillators have also been developed. State-of-the-art ultra-stable lasers were realised and used to demonstrate clock stability close to 10^{-16} at one second.

Actual and potential impact

The project demonstrated several novel concepts and methods which will be used, and further improved, to enhance the sensitivity of quantum sensors such as optical clocks and atom interferometers. Several of these concepts will be applicable to other atomic sensors such a magnetometers, and others may contribute to the broader field of quantum technologies.

A start-up company Crystalline Mirror Solutions GmbH is now offering cryogenic cavity end mirrors developed from the work in the project. They have also developed improved coatings for use in new applications, such as high-power lasers and mid-infrared coatings.

Research undertaken within this project will continue being highly relevant and timely. In particular, it is connected to the new Future and Emerging Technology Flagship on Quantum Technologies which is being started by the European Commission. Outcomes of the project will feed into new activities under the quantum sensing & quantum metrology pillar of this programme. Clocks and atomic sensors are explicitly identified as important area of applications, where readiness for transfer toward industry is high. Advanced optical time and frequency metrology is also a potential resource for other pillars of the flagship programme such as quantum telecommunication or computation.

The project led to new metrological capabilities within the NMIs of Europe, several of which have enhanced their operational measurement capability for optical frequency standards. For instance, the project developed improved ultra-stable lasers as well as non-destructive detection for operational lattice clocks. It also gave high yield procurement scheme for micro-fabricated ion traps which will facilitate the development of multi-ion clocks as operational frequency standards. These improved capabilities are and will be used in upcoming optical fibre link inter-laboratory comparisons, which will keep European laboratories at the forefront of the work towards a redefinition of the second based on optical frequency metrology.

Dissemination

The project produced 23 publications in high-ranking peer-reviewed scientific journals and 46 presentations at international conferences and workshops, including several invited talks. A final international workshop was organised to disseminate the outcomes of the project, which took place in association with the European Time and Frequency Forum, one of the most important international conferences in the field. It attracted companies, stakeholders and organisations active in field of time and frequency metrology, and from laboratories and metrology institutes outside Europe. Further information on the workshop can be found at this link: http://www.eftf2016.org/satellite-workshop.html.

14 training courses were provided in international or European schools which were specifically oriented towards students, PhD students and early stage researchers. The project co-organised a training school

together with the Initial Training Network FACT (Future Atomic Clock Technology) and gave lectures at this school. Similarly, project partners gave lectures at another school organised by another European Initial Training Network QTEA (Quantum Sensor Technologies and Applications).

Contributions to standards committees and regulations

Many partners of this project are members of scientific committees, working groups and consultative committees of international conferences, international and European regulation bodies or organisations. They presented the outputs of the project to these committees and contributed to defining programs of the main international conferences.

The project contributed the Working group on frequency standards within the Consultative Committees for Time and Frequency of the Bureau Internationale des Poids et Mesures (BIPM). It also contributed to the JRC Science for Policy Report: The impact of quantum technologies on the EU's future policies and to roadmap for the Future and Emerging Technology Flagship on Quantum Technologies of the European Commission.

Potential Impact

In the long term, the work undertaken within the project will translate into increased levels of performance of operational optical clocks and atomic sensors. These future optical clocks will be used to the redefine the second of the international system of units and to improve timescale and timekeeping. The higher accuracy is important for International Atomic Time (TAI) or time references of Global Navigation Satellite Systems. More accurate optical clocks will also yield new applications in the investigation of the fundamental laws of physics beyond the current standard models and in the search for dark matter.

The crystalline mirror technology developed in the project will also find application in other fields of science such as earth rotation sensing and gravitational wave detection.

List of publications

[1]. B. Lücke, J. Peise, G. Vitagliano, J. Arlt, L. Santos, G. Tóth, C. Klempt, *Detecting Multiparticle Entanglement of Dicke States*, Phys. Rev. Lett. 112, 155304 (2014), https://doi.org/10.1103/PhysRevLett.112.155304

[2]. M. Scherer, B. Lücke, J. Peise, O. Topic, G. Gebreyesus, F. Deuretzbacher, W. Ertmer, L. Santos, C. Klempt, J. J. Arlt, *Spontaneous symmetry breaking in spinor Bose-Einstein condensates*, Phys. Rev. A 88, 053624 (2013), https://doi.org/10.1103/PhysRevA.88.053624

[3]. T. Vanderbruggen, R. Kohlhaas, A. Bertoldi, S. Bernon, A. Aspect, A. Landragin, and P. Bouyer, *Feedback Control of Trapped Coherent Atomic Ensembles*, Phys. Rev. Lett. 110, 210503 (2012), https://doi.org/10.1103/PhysRevLett.110.210503

[4]. T. Vanderbruggen, R. Kohlhaas, A. Bertoldi, E. Cantin, A. Landragin, and P. Bouyer, *Feedback control of coherent spin states using weak nondestructive measurements*, Phys. Rev. A 89, 063619 (2014), https://doi.org/10.1103/PhysRevA.89.063619

[5]. Sebastian Häfner, Stephan Falke, Christian Grebing, Stefan Vogt, Thomas Legero, Mikko Merimaa, Christian Lisdat, and Uwe Sterr, 8×*10−17 fractional laser frequency instability with a long room-temperature cavity*, Opt. Lett. 40, 002112 (2015), https://doi.org/10.1364/OL.40.002112

[6]. Ali Al-Masoudi, Soren Dörscher, Sebastian Häfner, Uwe Sterr, Christian Lisdat, *Noise and instability of an optical lattice clock*, Phys. Rev. A 92, 063814 (2015), https://doi.org/10.1103/PhysRevA.92.063814

[7]. R. Kohlhaas, A. Bertoldi, E. Cantin, A. Aspect, A. Landragin, and P. Bouyer, *Phase Locking a Clock Oscillator to a Coherent Atomic Ensemble*, Phys. Rev. X 5, 021011 (2015), https://doi.org/10.1103/PhysRevX.5.021011

[8]. J. Peise, B. Lücke, L. Pezzé, F. Deuretzbacher, W. Ertmer, J. Arlt, A. Smerzi, L. Santos & C. Klempt, *Interaction-free measurements by quantum Zeno stabilization of ultracold atoms*, Nat. Comm. 6, 6811 (2015), https://doi.org/10.1038/ncomms7811

[9]. Iagoba Apellaniz, Bernd Lücke, Jan Peise, Carsten Klempt and Géza Tóth, *Detecting metrologically useful entanglement in the vicinity of Dicke states*, New J. Phys. 17, 083027 (2015), http://doi.org/10.1088/1367-2630/17/8/083027

[10]. J. Peise, I. Kruse, K. Lange, B. Lücke, L. Pezzè, J. Arlt, W. Ertmer, K. Hammerer, L. Santos, A. Smerzi, C. Klempt, *Satisfying the Einstein–Podolsky–Rosen criterion with massive particles,* Nat. Commun. 6, 8984 (2015), https://dx.doi.org/10.1038/ncomms9984

[11]. K. U. Schreiber, R. J. Thirkettle, R. B. Hurst, D. Follman, G. D. Cole, M. Aspelmeyer, J.-P. R. Wells, *Sensing Earth rotation with a helium-neon ring laser operating at 1.15 μm*, Opt. Lett. 40, 1705 (2015), http://dx.doi.org/10.1364/OL.40.001705

[12]. J. Steinlechner, I. W. Martin, A. Bell, G. D. Cole, J. Hough, S. Penn, S. Rowan, S. Steinlechner, *Mapping the optical absorption of a substrate-transferred crystalline AlGaAs coating at 1.5 μm*, Class. Quantum Grav. 32, 105008 (2015), http://doi.org/10.1088/0264-9381/32/10/105008

[13]. T. Chalermsongsak, F. Seifert, E. D. Hall, K. Arai, D. Follman, G. D. Cole, M. Aspelmeyer, E. K. Gustafson, R. X. Adhikari, *Coherent Cancellation of Photothermal Noise in GaAs/Al0.92Ga0.08 As Bragg Mirrors*, arXiv:1506.07088v1 and LIGO-P1500054, http://arxiv.org/abs/1506.07088

[14]. Erik Benkler, Christian Lisdat, Uwe Sterr, *On the relation between uncertainties of weighted frequency averages and the various types of Allan deviations*, Metrologia 52, 565 (2015), http://doi.org/10.1088/0026-1394/52/4/565

[15]. V. P. Mitrofanov, S. Chao, H.-W. Pan, L.-C. Kuo, G. Cole, J. Degallaix, B. Willke, *Invited review: Technology for the next gravitational wave detectors*, Science China Physics, Mechanics & Astronomy 58, 120404 (2015), http://doi.org/10.1007/s11433-015-5738-8

[16]. T. Chalermsongsak, F. Seifert, E. D. Hall, K. Arai, D. Follman, G. D. Cole, M. Aspelmeyer, E. K. Gustafson, R. X. Adhikari, *Coherent cancellation of thermo-optic noise in GaAs/Al0.92Ga0.08As Bragg mirrors*, Metrologia 53, 860 (2016), http://doi.org/10.1088/0026-1394/53/2/860

[17]. J. Lodewyck, S. Bilicki, E. Bookjans, J.-L. Robyr, C. Shi, G. Vallet, R. Le Targat, D. Nicolodi, Y. Le Coq, J. Guéna, M. Abgrall, P. Rosenbusch, S. Bize, *Optical to microwave clock frequency ratios with an operational strontium optical lattice clock*, Metrologia 53, 1123 (2016), http://dx.doi.org/10.1088/0026-1394/53/4/1123

[18]. S. Vogt, S. Häfner, J. Grotti, S. Koller, A. Al-Masoudi, U. Sterr, C. Lisdat, *A transportable optical lattice clock*, Journal of Physics: Conference Series 723, 012020 (2016), http://dx.doi.org/10.1088/1742-6596/723/1/012020

[19]. Kruse, K. Lange, J. Peise, B. Lücke, L. Pezzè, J. Arlt, W. Ertmer, C. Lisdat, L. Santos, A. Smerzi, C. Klempt, *Improvement of an Atomic Clock using Squeezed Vacuum*, Phys. Rev. Lett. 117, 143004 (2016), http://dx.doi.org/10.1103/PhysRevLett.117.143004

[20]. S. Häfner, *Ultrastabile Lasersysteme für Weltraum- und Boden-Anwendungen*, PhD Dissertation, http://edok01.tib.uni-hannover.de/edoks/e01dh16/84568972X.pdf

[21]. Al-Masoudi, *A strontium lattice clock with reduced blakbody radiation shift*, PhD Dissertation, Approved, available at: https://opac.tib.eu/DB=1.12/SET=1/TTL=1/CMD?ACT=SRCHA&IKT=1004&SRT=YOP&TRM=al-masoudi

[22]. D. G. Matei, T. Legero, Ch. Grebing, S. Häfner, Ch. Lisdat, R. Weyrich, W. Zhang, L. Sonderhouse, J. M. Robinson, F. Riehle, J. Ye, U. Sterr, *A second generation of low thermal noise cryogenic silicon resonators*, Journal of Physics: Conference Series 723, 012031 (2016), http://dx.doi.org/10.1088/1742-6596/723/1/012031

[23]. D. G. Matei, T. Legero, S. Häfner, C. Grebing, R. Weyrich, W. Zhang, L. Sonderhouse, J. M. Robinson, J. Ye, F. Riehle and U. Sterr, *1.5 μm lasers with sub 10 mHz linewidth*, arXiv:1702.04669 (2017)

[24]. B Barrett, A Bertoldi and P Bouyer, *Inertial quantum sensors using light and matter*, Physica Scripta 91, 053006 (2016), http://dx.doi.org/10.1088/0031-8949/91/5/053006

[25]. A Bertoldi, R Kohlhaas , E Cantin , A Aspect, A Landragin and P Bouyer, *Phase locking an atom interferometer*, Proceedings of the 2016 EFTF, http://ieeexplore.ieee.org/document/7477819/

[26]. R. Kohlhaas, *Feedback control of coherent spin states for atom interferometry*, PhD dissertation, https://tel.archives-ouvertes.fr/tel-01123747

[27]. E. Cantin, *Cavité à haute finesse pour la production et la detection de sources atomiques cohérentes*, PhD dissertation, https://tel.archives-ouvertes.fr/tel-01238892

[28]. G. D. Cole, W. Zhang, B. J. Bjork, D. Follman, P. Heu, C. Deutsch, L. Sonderhouse, J. Robinson, C. Franz, A. Alexandrovski, M. Notcutt, O. H. Heckl, J. Ye, M. Aspelmeyer, *High-performance near- and mid-infrared crystalline coatings*, Optica 3, 647(2016), http://dx.doi.org/10.1364/OPTICA.3.000647

[29]. G. Vallet, E. Bookjans, U. Eismann, S. Bilicki, R. Le Targat, J. Lodewyck, *A noise-immune cavity-assisted non-destructive detection for an optical lattice clock in the quantum regime*, arXiv:1703.04609

JRP start date and duration:	1st July 2013 36 months
JRP-Coordinator: Sébastien BIZE, Dr., OBSPARIS, Tel:+33 1 40 51 20 97 E-mail: sebastien.bize@obspm.fr JRP website address: http://syrte.obspm.fr/jrpexl01/	
JRP-Partners: JRP Partner 1: OBSPARIS, France JRP Partner 2: LNE, France JRP Partner 3: NPL, United Kingdom	 JRP Partner 4: PTB, Germany JRP Partner 5: INRIM, Italy
REG-Researcher (associated Home Organisation):	Philippe Bouyer IOTA, France
REG-Researcher (associated Home Organisation):	Carsten Klempt LUH, Germany
REG-Researcher (associated Home Organisation):	Christian Roos OAdW, Austria
REG-Researcher (associated Home Organisation):	Garrett Cole XMS, Austria

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union