Final Publishable JRP Summary for SIB04 ion clock
High-accuracy optical clocks with trapped ions

Overview

This project has advanced the development of ultra-precise optical clocks using laser-cooled trapped ions through i) targeted improvements in key components and ii) evaluation and control of the dominant contributions to the uncertainty of the clocks. It has resulted in the development of the most precise trapped ion optical clock to date and in a comprehensive set of frequency measurements and clock comparisons that provide a leading European contribution to the realisation of a future SI second based on an optical clock.

Need for the project

The unit of time plays a central role within the SI system of units because it can be realised with much higher precision than other base units and it is therefore also applied in the realisations of other units, such as the metre, volt and ampere. Atomic clocks form the basis of international time keeping and are widely used in navigation, communications and network management. Optical clocks that use transitions with frequencies in the optical regime are designated as optical atomic clocks.

The most advanced optical frequency standards have reached a level of performance that exceeds that of the caesium fountain primary atomic clocks (currently used to define the SI second) by more than an order of magnitude, providing the direct evidence that higher frequencies lead to better clocks, and highlighting the potential and desirability for a redefinition of the SI second in terms of an optical frequency. In order to prepare for a redefinition of the unit of time using an optical frequency, the International Committee for Weights and Measures (CIPM) adopted the concept of secondary representations of the second, recommending eight different optical transition frequencies, five in ions and three in neutral atoms. The foundation for atomic clocks with highest accuracy requires an ideal system that permits the observation of unperturbed atomic frequencies. Ultra-precise optical clocks using laser-cooled trapped ions can provide this ideal system but their operational performance needs to be optimised in order to reach their full potential.

Scientific and technical objectives

To ensure this project set out to prepare a selection of clocks with the potential to become primary clocks, based on accuracy, stability, operational reliability and technical complexity of the overall system. We aimed at i) improving the most important key components that are specific and critical for optical clocks with trapped ions, ii) evaluating improved and reliable uncertainty budgets and iii) providing data on frequency measurements that will be crucial for the use of optical clocks as secondary representations of the SI second and to a future redefinition of the SI second in terms of an optical frequency.

The specific scientific and technical objectives were:

1. Advanced trap design
   - To develop robust single-ion physics packages for long interrogation periods
   - To develop trap designs for multiple ions to improve signal-to-noise ratio
2. Laser frequency control and clock interrogation
   - To develop reference cavities for the frequency stabilisation of laser oscillators for the interrogation with longer clock pulses
   - To develop optimised techniques for quantum logic clocks
   - To develop computer-control systems that give unattended averaging times of several days
3. Evaluation of frequency shifts

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- To determine accurate values of the coefficients of systematic frequency shifts for the proposed clock species in this project, for uncertainty budgets in the 10^{-17} range; in particular to characterise and control the shift produced by blackbody radiation.

4. Clock performance evaluation and frequency measurements

   - To deliver inter-comparisons of clock performance in terms of stability and accuracy and to achieve measurements of absolute optical frequencies at the uncertainty achievable with primary caesium clocks (about $1 \cdot 10^{-15}$) and of optical frequency ratios at lower uncertainty.

Results

Advanced trap design

The work of this project has led to optimised trap designs for single and multiple ions. For the first time, these novel ion traps combine features that allow the reduction and control of all systematic frequency shifts identified to date. New endcap traps for single ions have been built and tested at PTB and NPL. A detailed thermal analysis with infrared imaging, measurements in dummy traps with temperature sensors and FEM modeling, performed by CMI, has reduced the uncertainty in the thermal radiation field seen by the ions and has led to design guidelines that will help reducing heat and temperature differences in the trap structure. The analysis of the thermal radiation emitted by the ion traps under real operating conditions indicates that heating effects produce temperature differences of only a few degrees, less severe than the effect initially deduced from preliminary reports before the start of this project. The heating effect is dominated by the influence of the electric field on ceramic insulators and can be reduced by the choice of suitable materials and mechanical designs. Together with more precise values for the frequency shift coefficients that have been measured within this project this significantly reduced one of the most important contributions to the uncertainty budgets of the frequency standards.

Laser frequency control and clock interrogation

Novel reference resonators for laser frequency stabilisation and novel incoherent light sources for the efficient generation of the radiations required to excite and cool the ions have been developed at CMI and VTT. The group at VTT has observed the first trapped and laser cooled ions in their laboratory, achieving an important milestone in the realisation of a new optical frequency standard with Sr^+ in Finland. Also at VTT, a novel type of repumper light source based on amplified spontaneous emission has been developed and tested successfully. Together with researchers from the University Siegen, NPL has demonstrated ion shuttling in microtraps, a prerequisite for operation of traps with multiple ions and separated loading and interrogation regions. PTB has implemented novel interrogation schemes for operation of the Yb^+ frequency standard and of the Al^+ quantum logic clock with suppressed systematic frequency shifts.

Evaluation of frequency shifts

The main contributions to the systematic uncertainty in optical clocks with trapped ions arise from the interaction of the ions with electric and magnetic fields, including the field of thermal radiation emitted by the trap and vacuum system. Control of these fields and precise knowledge of the relevant atomic sensitivity factors has reduced the systematic uncertainty significantly. The project has evaluated systematic uncertainties and stabilities across three representative species: the positive ions of aluminium (Al), strontium (Sr) and ytterbium (Yb). The combination of a precise measurement of the static polarisability of Yb^+ using an extrapolation of light shift measurements with near-infrared lasers at PTB, with the detailed modeling and measurements of the thermal radiation emitted by the trap structure performed by CMI has led to a reduction of the uncertainty associated with the blackbody radiation of the frequency standard by more than a factor of 25 to below 2×10^{-18} for operation at room temperature. This gives Yb^+ one of the lowest evaluated systematic uncertainties amongst optical atomic clocks worldwide.

Clock performance evaluation and frequency measurements

PTB and NPL have performed improved measurements of absolute frequencies of single-ion optical clocks against primary caesium clocks and of frequency ratios of different optical frequency standards, including the optical clock with neutral strontium atoms. In total, this project has reported frequency ratio data between six optical clocks which are based on four optical transitions in three atomic species, the most comprehensive and consistent data set from optical clock comparisons world-wide with results from a single consortium.

Improved control of systematic frequency shifts has reduced specific uncertainty contributions and made it possible to measure optical frequency ratios with an uncertainty below that of primary Caesium clocks. NPL has obtained excellent agreement in a frequency comparison of two $^{88}Sr^{+}$ single ion optical clocks (4 parts in 10^{17}). These results show that the project has succeeded in addressing the most relevant issues towards an improvement of the accuracy of trapped ion optical clocks. A joint measurement campaign of the $^{171}Yb^{+}$ frequency standards at NPL and PTB has been performed, which compared the frequencies using signals from the Global Positioning System GPS and geodetic data post processing. This was the first direct comparison of remote optical clocks via GPS, demonstrating that this world-wide available method for frequency transfer can be used in an evaluation of optical clocks. Together with VTT, an adapted extrapolation method has been developed that makes optimal use of the data from the optical clocks over the required long averaging times of GPS observations.

In addition, PTB and NPL have independently evaluated the frequency measurements in terms of a possible temporal variation of fundamental constants, which resulted in the most stringent limits on this effect obtained in laboratory experiments thus far. Two papers have been published in the same issue of Physical Review Letters.

Within this project, PTB and NPL have developed their optical clocks further by implementing a next generation of ion traps and other key components, while VTT has completed the first optical clock in their institution and CMI has initiated the development of a first complete optical clock in Prague. Efficient work-sharing among the partners of this consortium in the design and characterisation of ion traps and laser systems has facilitated these developments. The results will further influence the development of the field as they are published and are likely to be adopted by groups in America and Asia.

Actual and potential impact

Dissemination

This project has created impact within the scientific community via publications, conference presentations and the organisation of a workshop on optical clocks with trapped ions in combination with the European Frequency and Time Forum (EFTF) in 2014. With more than 400 registered participants EFTF was the most widely attended conference in the field of atomic clocks and timekeeping in 2014. In order to maximise the impact of this project, a one-day workshop entitled “Frequency standards with trapped ions” was organised to take place immediately after the EFTF. More than 40 participants from 11 countries participated in the workshop, including delegates from BIPM, USNO, and NASA.

The participants in this project have given over 100 presentations at conferences and workshops/seminars, and 13 training activities, including lectures at i) renowned international physics schools in Europe, ii) a topical workshop at the Japanese National Institute of Communication Technology in Tokyo and iii) the first international school on cold atoms and applications in metrology in Africa, CAMAM 2015, in Carthage, Tunisia in March 2015. The high demand on training activities gives proof of the unique importance of the metrology of time and frequency for a wide range of applications and questions related to the foundations of physics in quantum theory and relativity. Scientists from this consortium have been invited as speakers at the most renowned international conferences in the field e.g. International Conference on Atomic Physics ICAP, International Conference on Laser Spectroscopy ICOLS, DAMOP meeting of the American Physical Society 2015, 2015 Marcel Grossman meeting and septennial Symposium on Frequency Standards and Metrology in 2015.

With final data evaluations and peer-review still ongoing, this project expects a publication record of at least 20 peer-reviewed publications including those in journals with high impact factor (e.g. Physical Review Letters, Optics Letters and Nature Communications), and 3 successfully defended PhD theses. The publications by NPL and PTB on limits to variations of constants have been featured in a Viewpoint in the online journal Physics of the American Physical Society. The PTB paper “High-Accuracy Optical Clock Based on the Octupole Transition in 171Yb+” from 2012 has been cited 112 times until July 2015 (Google scholar). Two of the group leaders of this consortium have been invited to write a major review paper on optical atomic clocks that has appeared in the Reviews of Modern Physics in June 2015 and is expected to be a reference for scientists working in this domain. The high rate of citations indicates that the results of this project are having an impact on the groups and institutions that work on the development of advanced atomic clocks and future improved time services.

Impact on the metrological and scientific communities

As a direct follow-on from this project, CMI has started the setup of an Yb^+ optical frequency standard. The present consortium plans to continue joint research activities and is preparing follow-on projects. Several National Metrology Institutes (China, India) and other research institutes (FEMTO-ST France, Inst. of Laser Physics of the Russian Academy of Sciences) have launched projects with the aim to develop optical frequency standards with trapped ions. Yb^+ in particular is gaining acceptance because of the favourable combination of operational reliability and high accuracy. The project partners are supporting these new projects through consulting, training and the transfer of technology, including designs of ion traps, electronic and optical systems.

The most important impact of this project was its input into a future redefinition of the SI base unit of time. The consortium worked closely with standardisation bodies and has disseminated results to different international working groups. The consortium gave presentations and provided reports to the relevant Consultative Committees of CIPM for Time CCTF, for Length CCL and to the joint working group of CCTF-CCL on Secondary Representations of the Second and the Mise en Pratique of the Metre. After consultation of the working group on primary and secondary frequency standards in 2013 (members: PTB, NPL), the BIPM has started using secondary frequency standards for calibrations of international atomic time (TAI). So far only a rubidium fountain microwave frequency standard has been reported (from LNE-SYRTE), but provisions have been made to also include the optical frequency standards with Sr^+, Yb^+, and Al^+ that have been recommended as secondary representations of the SI second by CIPM and that were investigated in this project. The project has carried out measurements of frequencies and frequency ratios for reports to the CCTF that met in Paris in September 2015. It is expected that several recommendations for secondary representations of the second will be updated with improved values and reduced uncertainties obtained in this project.

The results from this project will have a long and wide impact on the time and frequency community because the reference frequencies of the trapped ions studied in this project are now known with the uncertainty that is at the fundamental limit imposed by the best available caesium clocks. In addition, ratios of optical frequencies have been reported with an even lower uncertainty and will be important for the internal consistency of the recommended frequencies. During the lifetime of this project substantial interest has developed in a new application termed “relativistic geodesy”, a field that relies on portable optical clock and that will benefit from the more reliable and robust clock technology that has been developed here.

Impact on industrial and other user communities

Compact, accurate and stable low-power microwave frequency standards with performance specifications that exceed those of the available chip-scale caesium atomic clocks (CSAC) have the potential to be used in next generation mobile telecommunication networks. The consortium has been consulted by an international manufacturer of equipment for timing and synchronisation about the technology of trapping and laser excitation of ytterbium ions, because a frequency standard based on the ytterbium ground state hyperfine transition may be a suitable candidate for this important application.

List of publications

Journal articles:

(Only papers that have appeared in scientific journals with peer review are listed here.)

1 Sana Amairi, Thomas Legero, Thomas Kessler, Uwe Sterr, Jannes B. Wübbena, Olaf Mandel, Piet O. Schmidt: *Reducing effects of thermal noise in optical cavities*. Appl. Phys. B 113, 233-242 (2013).

2 Karsten Pyka, Norbert Herschbach, Jonas Keller, Tanja E. Mehlstäubler: *A high-precision segmented Paul trap with minimized micromotion for a multiple-ion clock*. Appl. Phys. B 114, 1-2, 231-241, (2014).

3 M. T. Baig, M. Johanning, A. Wiese, S. Heidbrink, M. Ziolkowski C. Wunderlich: *A scalable, fast, and multichannel arbitrary waveform generator*. Rev. Sci. Instrum. **84**, 124701 (2013).

4 Christian Tamm, Nils Huntemann, Burghard Lipphardt, Vladislav Gerginov, Nils Nemitz, Michael Kazda, Stefan Weyers, Ekkehard Peik: *A Cs-based optical frequency measurement using cross-linked optical and microwave oscillators*. Phys. Rev. A **89**, 023820 (2014).

5 Yong Wan, Florian Gebert, Jannes B. Wübbena, Nils Scharnhorst, Sana Amairi, Ian D. Leroux, Börge Hemmerling, Niels Lörch, Klemens Hammerer, Piet O. Schmidt: *Precision spectroscopy by photon-recoil signal amplification*. Nature Comm. **5**, 3096 (2013).

6 G. P. Barwood, G. Huang, H. A. Klein, L. A. M. Johnson, S. A. King, H. S. Margolis, K. Szymaniec, P. Gill: *Agreement between two $^{88}Sr^{+}$ optical clocks to 4 parts in 10^{17}*. Phys. Rev. A **89**, 050501(R) (2014).

7 T. Fordell, A.E. Wallin, T. Lindvall, M. Vainio, M. Merimaa: *Frequency-comb-referenced tunable diode laser spectroscopy and laser stabilization applied to laser cooling*. Appl. Opt. **53**, 7476-82 (2014).

8 H. Hachisu, M. Fujieda, S. Nagano, T. Gotoh, A. Nogami, T. Ido, S. Falke, N. Huntemann, C. Grebing, B. Lipphardt, Ch. Lisdat, D. Piester: *Direct comparison of optical lattice clocks with an intercontinental baseline of 9000 km*. Opt. Lett. **39**, 4072-5 (2014).

9 T. Fordell, T. Lindvall, F. Dubé, A.A. Madej, A. E. Wallin, M. Merimaa: *Broadband, unpolarized repumping and clearout light sources for Sr^{+} single-ion clocks*. Opt. Lett. **40**, 1822-5 (2015).

10 N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, E. Peik: *Improved Limit on a Temporal Variation of m_p/m_e from Comparisons of Yb^{+} and Cs Atomic Clocks*. Phys. Rev. Lett. **113**, 210802 (2014).

11 R. M. Godun, P. B. R. Nisbet-Jones, J. M. Jones, S. A. King, L. A. M. Johnson, H. S. Margolis, K. Szymaniec, S. N. Lea, K. Bongs, P. Gill: *Frequency ratio of two optical clock transitions in $^{171}Yb^{+}$ and constraints on the time-variation of fundamental constants*. Phys. Rev. Lett. **113**, 210801(2014).

12 Andrew D. Ludlow, Martin M. Boyd, Jun Ye, Ekkehard Peik, Piet O. Schmidt: *Optical Atomic Clocks*. Rev. Mod. Phys. **87**. 637 (2015).

13 G. P. Barwood, G. Huang, S. A. King, H. A. Klein, P. Gill: *Frequency noise processes in a strontium ion optical clock.* J. Phys. B: At. Mol. Opt. Phys. **48** 035401 (2015).

14 G. P. Barwood, G. Huang, H. A. Klein, P. Gill: *Automatic minimisation of micromotion in a $^{88}Sr^{+}$ optical clock*. Meas. Sci. Technol. **26** 075203 (2015).

PhD thesis:

1 Jannes Bernhard Wübbena: *Controlling Motion in Quantum Logic Clocks*. Dt. Nat. Bibliothek, idn=1063005981, Leibniz Uni. Hannover, 9.7.2014

2 Sana Amairi ep Pyka: *A Long Optical Cavity for Sub-Hertz Laser Spectroscopy*. Dt. Nat. Bibliothek, idn=1065398069, Leibniz Uni. Hannover, 29.7.2014

3 Nils Huntemann: *High-Accuracy Optical Clock Based on the 171Yb+ Octupole Transition*.Dt. Nat. Bibliothek, idn 1068342641, Leibniz Uni.Hannover 15.7.2014

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