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TABLE OF CONTENTS

1 Executive Summary

Introduction
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) through 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.

The Problem
The unit of time plays a central role within the SI system of units because it can be realised with much higher accuracy 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 clocks have reached a degree of reproducibility that exceeds that of primary caesium 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 a system that permits the observation of unperturbed atomic frequencies. Ultra-precise optical clocks using laser-cooled trapped ions can provide a nearly ideal system but their performance needs to be optimised in order to reach their full potential.

The Solution
In response that need, this project addressed the development of ultra-precise optical clocks using laser-cooled trapped ions. The combination of laser cooling and ion trapping provides an ideal spectroscopic system that permits the observation of unperturbed atomic frequencies, thus laying the foundation for atomic clocks of the highest accuracy. This project has made substantial progress in ensuring that optical ion clocks reach their full potential by preparing a selection of clocks with the potential to become primary clocks, based on accuracy, stability, operational reliability and technical complexity of the overall system.

Impact
The most important impact of this project was its input into a future redefinition of the SI base unit of time. The consortium 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. In total, this project has reported absolute frequency measurements of three of the Secondary Representations based on trapped ion optical transitions with primary caesium clocks and 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. This data set has been used by the CCTF-CCL working group during their meeting in September 2015 where updated values of recommended frequencies for Secondary Representations of the Second have been determined with reduced uncertainty. After approval by the CIPM these results will be published on the BIPM. As a result of this project, the optical clock developed at PTB based on the electric octupole (E3) transition in $^{171}Yb^+$ currently holds the record in clock accuracy of 3.2×10^{18}. Impact on the scientific community can be seen in that the high accuracy of this frequency standard makes it possible to exploit the high sensitivity of the Yb^+ $^2F_{7/2}$ state energy to the value of the fine structure constant α in searches for temporal variations. It has also been pointed out that the system possesses a strong sensitivity in searches for violations of Lorentz invariance and ultralight scalar dark matter.
The project partners are supporting new projects on the development of optical frequency standards with trapped ions through consulting, training and the transfer of technology, including designs of ion traps, electronic and optical systems. A company that is developing a portable accurate microwave frequency standard for applications in telecommunication networks has consulted the consortium about the technology of trapping and laser excitation of ytterbium ions.

2 Project context, rationale and objectives

Motivation and context for this project was the issue of a possible redefinition of the second via an optical transition frequency, a topic that has been identified as one of the "*Grand challenges on fundamental metrology*" within the EMRP Outline 2008. The main objective as detailed in the EMRP outline was the "*Development of novel atomic clocks with unprecedented accuracy*: To overcome the limitations of today's best primary frequency standards based on laser cooled caesium atoms, atomic clocks using transitions with frequencies in the optical regime or even based on nuclear transitions have to be investigated. To this end the potential of the different approaches such as single ions or large numbers of optically confined neutral atoms have to be explored in order to identify the best candidates for a future redefinition of the second."

Whilst an iMERA optical lattice clock project has facilitated progress for neutral atoms and has led to a coordinated effort of the European NMIs active in that field, this is also highly desirable for the alternative optical clock architecture based on single ions, which was addressed in this project. The project results will allow the international standards community to make an informed decision for a redefinition of the second, because, as stated in the EMRP Outline 2008, a "best of all" candidate is not yet defined. In parallel, these instruments will be brought to a level of reliability similar to today's microwave clocks, which again requires considerable and challenging improvements. Applications and impact of this research are described in the EMRP Outline 2008, which states: "The novel clocks will also contribute to fundamental science…" and describes the "Utilisation of atomic clocks for specific space applications".

The concept of an optical clock based on a forbidden transition in a single, laser-cooled, trapped ion and interrogated via the observation of quantum jumps was proposed by Hans Dehmelt in the mid-1970s and contributed to his award of the Nobel Prize in physics in 1989. This proposal predicted an achievable relative uncertainty of 10^{-18}. A major extension to this idea surfaced with the proposal for a quantum logic clock made by David Wineland, recognised with the Nobel Prize in 2012. It proposed the separation of laser cooling from the interrogation of the reference transition by trapping two different species of ions as a Coulomb crystal in one trap. This makes a wider choice of ions with suitable reference transitions available.

The project aimed at i) improving the most important key components that are specific and critical for trapped ion optical clocks, ii) evaluating improved and reliable uncertainty budgets and iii) providing data on absolute 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. <u>Advanced trap design</u>
   - 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. <u>Laser frequency control and clock interrogation</u>
   - 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. <u>Evaluation of frequency shifts</u>
   - 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. <u>Clock performance evaluation and frequency measurements</u>
   - 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.

3 Research results

3.1 Advanced Trap Design

The work of the 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. Two topics of particular importance have been the thermal analysis of the parts of the ion trap assembly and the diagnosis of motional heating of the trapped ion. The former is required for an analysis of the systematic frequency shift induced by thermal radiation (see also Section 3.3), whereas the latter determines the maximum applicable interrogation time for an uncooled ion and hence the spectral resolution and short-term stability of the frequency standard.

Single-ion Traps

New endcap traps for single ions have been built and tested at PTB and NPL. An important advantage of endcap traps is the large open solid angle that is accessible for laser excitation from different directions and for fluorescence detection. In conjunction with the improvement of the thermal design it was found that considerable improvements in the mechanical, electrical and thermal characteristics can be obtained in a design that reduces the capacity and the electrical field strength at the position of the insulators. An improved version of the endcap trap that addresses these problems is shown in Fig. 1. A trap based on this design has been built and tested at NPL. The rf is carried into the trap via a bulk copper body, through which the inner molybdenum electrodes are sunk. The outer electrodes are mounted to the copper body using fused silica insulators, which have better electrical properties than alumina, which has been used in previous versions of endcap traps. The choice of an insulator material with lower loss tangent significantly reduces the heat generated by dielectric losses.

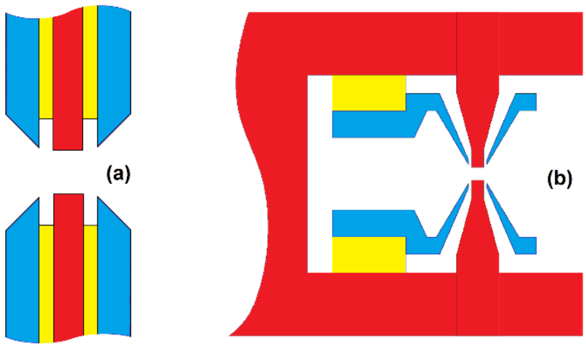

FIG. 1. Endcap trap electrodes with dielectric insulators as spacers (cross section), (a) - established design; (b) - improved design. The rf electrodes are shown in red, dc electrodes are in blue, and insulators are in yellow.

In cooperation with PTB and NPL, the group at the University of Sussex has investigated an important extension of the endcap trap design by integrating optical access via fibres into the endcap electrodes. This allows one to deliver laser light to the trapped ion and to collect the ions' fluorescent in an efficient way, eventually eliminating the need for vacuum windows that form a fragile part of the vacuum system.

Traps for multiple ions

NPL and PTB have developed segmented linear traps for the trapping of multiple ions and for the application in a frequency standard with improved stability resulting from the higher signal-to-noise ratio. Fig 2 shows a scalable segmented trap design that was developed at PTB for the operation of an optical clock based on multiple ions. This design will be used for a clock based on $^{115}In^{+}$ ions sympathetically cooled by $^{172}Yb^{+}$ and for the 2nd generation of the $^{27}Al^{+}$ ion clock at PTB. The trap is optimised for minimal axial micromotion and a prototype trap is in operation. The trap consists of four aluminum nitride (AlN) wafers (50 mm x 50 mm x 0.38 mm). The electrode stack forms a linear Paul-trap with additional electrodes to compensate micromotion. The electrodes are formed by a sputtered and laser-structured gold layer of 4 µm thickness.

Noise on the dc voltages is low-passed by on-board SMD filter electronics made of Al_2O_3 ceramics. Two Pt100 SMD temperature sensors are integrated on the two inner trap chips. To avoid heating by rf fields the sensors are protected by two capacitors placed in parallel. The AlN wafers are separated by 1 mm and 0.254 mm thick AlN spacers placed at the four corners. In cooperation with PTB, a group at the Laser Zentrum Hannover has investigated and developed the critical processes in the fabrication of the wafers: femtosecond laser cutting and microstructuring of ceramic materials selected as substrates and the laser writing of electrodes for the fabrication of linear traps for multiple ions.

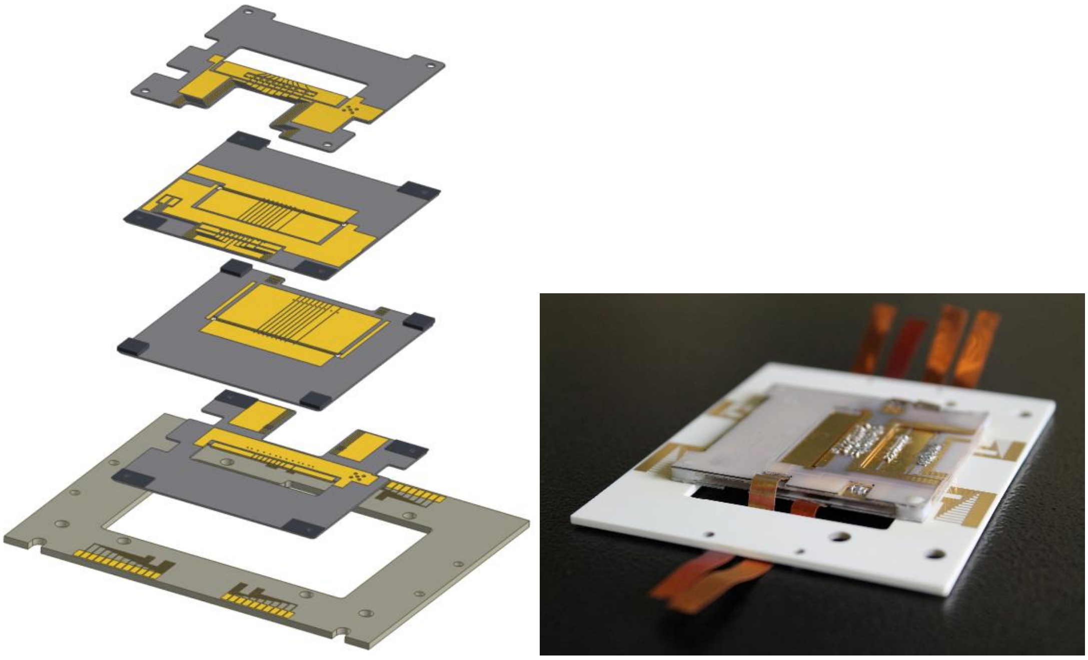

FIG. 2. Left: Exploded drawing of the chip-based segmented linear Paul trap. Right: Photograph of the assembled structure showing the electrical connections made by wire bonding for the DC voltages and by copper stripes for the RF field

Heating rates

The motional quantum state of trapped ions is prone to heating and decoherence. High-accuracy frequency standards based on clock transitions in single trapped ions require a quantitative characterisation of the ion's motional state. In particular, the coupling to the noisy electric field of the environment causes a continuing kinetic energy gain of the ion in its harmonic confinement. The quantity of interest in such a system is the associated heating rate measured in units of harmonic oscillator quanta per second. For an optical clock based on a single ion the heating rate may finally limit the duration of the interrogation period during which the ion is not laser-cooled. PTB and NPL have therefore made measurements of heating rates in their single-ion and linear traps and have investigated methods for reducing the heating.

Measurements were implemented for PTB's endcap trap by spectroscopically interrogating the stored $^{171}Yb^{+}$ ion on its narrow 435 nm E2 clock transition. Referencing the employed clock laser to a stabilized frequency comb ensures drift-free operation. Rabi frequencies around 2 kHz make it possible to observe several oscillation periods without being limited by excited state lifetime (52 ms for the 435 nm E2 transition) or laser linewidth. By introducing a variable wait time between the end of the laser cooling phase and the application of the Rabi pulse one can obtain the mean oscillator quantum number $\langle n \rangle$ as a function of heating time. Typical Rabi flopping datasets obtained after different wait times together with corresponding fits are plotted in Figure 3. Figure 4 displays the resulting heating rates.

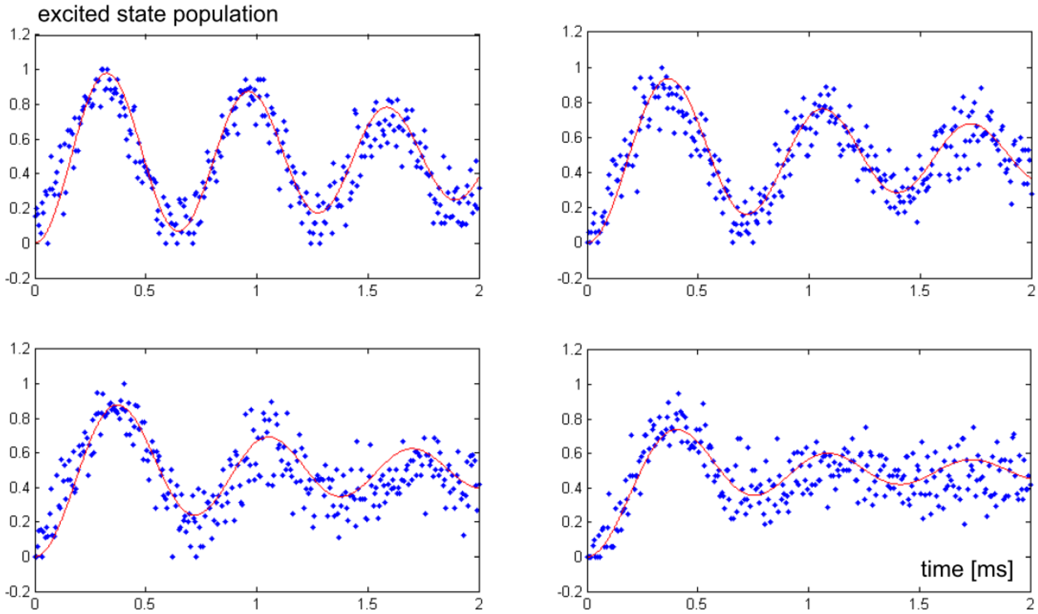

FIG. 3. Rabi flopping datasets (blues points) and resulting fits (red curves). Each blue datapoint reflects the outcome of 20 excitation attempts at the given pulse duration. From the fits one finds for <n> the values 10, 18, 27 and 53, respectively.

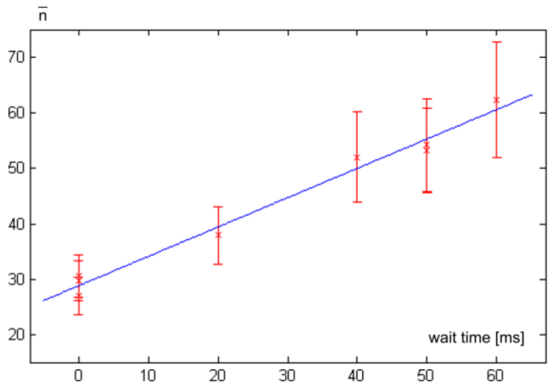

FIG. 4. Heating rate extracted from Rabi flopping datasets obtained for various wait times. The blue line represents a linear fit to the datapoints. Assigned uncertainties are purely statistical.

Overall the heating process increases the ion's kinetic energy linearly with time over the first tens of milliseconds. The fitted rate amounts to d<n>/dt =530±70 quanta/s. For secular frequencies within a factor of two from the stated standard values the heating rate did not explicitly depend on the trap frequencies. Presuming carefully filtered trap drive and compensation voltages, studies suggest that microscopic surface impurities and associated patch potentials play an important role in the heating process. Therefore it is reasonable to expect a reduced heating rate from appropriate electrode surface cleaning efforts. However*, in situ* attempts of cleaning via slow electron impact (~100 eV) or softly focused pulsed nitrogen laser radiation did not significantly affect the measured rates. More "aggressive" *ex-situ* methods could be considered.

Lower heating rates have been observed in PTB's linear ion trap, consisting of gold-plated electrodes and electrically filtered by on-board SMD capacitors. To make a precise characterisation of heating in this trap, we have performed ground state cooling on the ion. We used the narrow 411 nm transition from the ground state to the $D_{5/2}$ state to perform sideband cooling and spectroscopy on a single $^{172}Yb^+$ ion. Figure 5 shows the mean phonon number increasing at a measured heating rate of d<n>/dt= (1.3 ± 0.5) phonons per second, allowing interrogation periods without laser cooling within the Lamb-Dicke regime for many seconds and representing a negligible effect on the frequency instability of the proposed multi-ion clock.

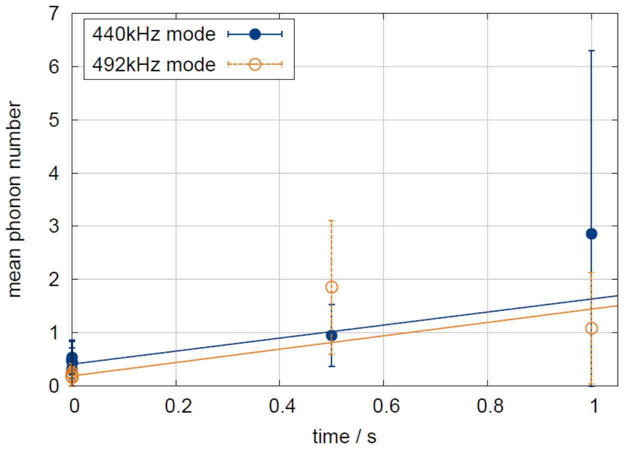

FIG. 5. Heating rate observed with Yb^+ in the PTB linear ion trap, deduced directly from sideband amplitude ratios for various wait times.

The group at the University of Siegen has studied the effect of quantum information transfer in linear ion traps in cooperation with NPL. One aspect was the physical transfer of ions holding quantum information from one trapping zone to another; a second aspect was the transfer of quantum information from one qubit to another within the same ion.

In a study of a critical component of the trap setup, VTT has investigated the feasibility of using commercially available Sr sources for the loading of ion traps. Desired properties are low operating temperature, fast turn off, and aperturing in order to enable efficient trap loading with minimal contamination of the trap structures. Figure 6 shows 461-nm fluorescence of Sr atoms in front of the dispenser. VTT endcap trap has been successfully loaded with ions from the dispenser and a trap loading time of about 60 s was obtained.

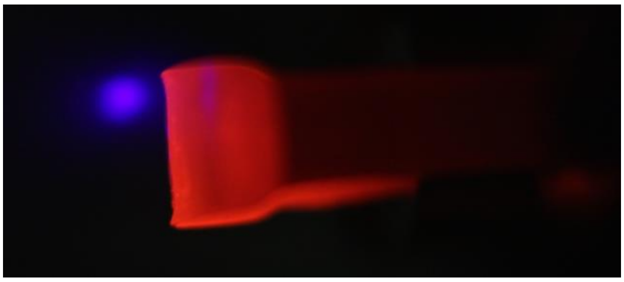

FIG 6: 461 nm resonance fluorescence of Sr atoms in front of the Sr dispenser (glowing red) at VTT.

The results of the project have led to strongly improved trap designs, both for single ions and for multiple ions. These traps will be further tested in experiments at all project partners.

3.2 Laser frequency control and clock interrogation

While the ion trap is the essential element for the preparation of the atomic reference, an optical clock also requires a frequency stable laser as an oscillator and the means for locking it to the atomic transition. The short-term stability of the laser oscillator is derived from a passive Fabry-Perot cavity that is well isolated from environmental perturbations like vibrational noise and temperature fluctuations. The long-term stability is obtained by locking the laser to the signal derived from the ion. This project has investigated reliable and efficient means to solve this problem. Besides the clock laser, a cooling laser and several auxiliary lasers need to be stabilised to transitions of the ion and need to maintain lock over extended measurement periods of several days. The quality of lock of the reference laser is directly relevant for the stability of the clock, and hence for the required averaging times in frequency measurements. Obtained from a single or a few ions, the signal is usually limited by quantum noise, but an optimised timing of the interrogation sequences can provide improved stability.

Reference cavities

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.

Thermal noise in optical cavities imposes a severe limitation to the stability of the most advanced frequency standards at a level of a few 10^{-16} at 1 s. PTB has investigated two schemes for reducing the effect of thermal noise in a reference cavity. In the first approach, we investigated the potential and limitations of operating the cavity close to instability, where the beam diameter on the mirrors becomes large. The analysis has shown that even a 10 cm short cavity can achieve a thermal noise limited fractional frequency instability in the low 10^{-16} regime. In the second approach, we increased the length of the optical cavity. We showed that a 39.5 cm long cavity (see Fig. 7) has the potential for a fractional frequency instability even below 10^{-16}, while it seems feasible to achieve a reduced sensitivity of $< 10^{-11}/(m/s^2)$ for vibration-induced fractional length changes in all three directions.

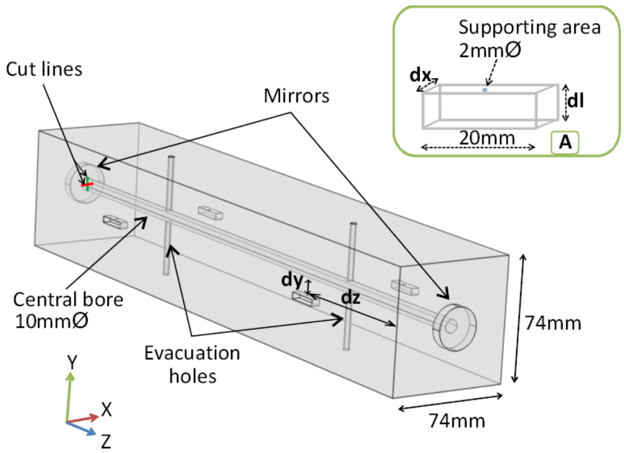

FIG 7: Parameters of the 39:5 cm long cavity developed at PTB. The inset shows the parameters for one of the cut-outs by which the cavity will be supported, and the blue point indicates the fixed contact position of the mechanical support.

VTT has studied the vibration and temperature sensitivity of the VTT 300-mm-long horizontal reference resonator. Fused silica 1” dielectric mirrors (AT-films) optimised for the clock transition in Sr^+ (674 nm) were optically contacted to the spacer, followed by ULE compensation-rings. The resonator is housed in an aluminium vacuum enclosure and three heat shields. The thermal stability of the reference resonator was evaluated. Following a step-change in the set-point temperature of the outer active heat-shield we determined the time-constants for the middle and inner heat shields as 23 h and 24 h (see Figure 8).

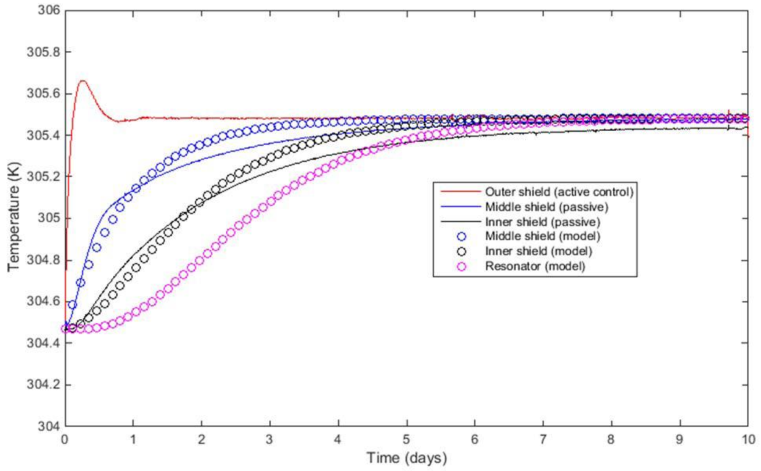

FIG. 8: Thermal response of the heat shields of the VTT reference resonator following a step change in the set-point of the temperature controller of the outer heat shield. Solid lines show measurements using Pt100 sensors. The circles show the step response of a quantitative model which accounts for heat transfer by thermal radiation only.

The acceleration sensitivity was characterised statically by tilting the cavity with relation to gravity and measuring the static frequency shift against a hydrogen maser referenced frequency comb. The cavity vacuum chamber is located on a large concrete pillar that is detached from the rest of the VTT building. The pillar rests on about a metre of gravel on top of solid bedrock. The vibration of this pillar in all three dimensions has been characterised by a sensitive gravimeter. A large granite stone rests on Sorbothane anti-vibration pads on top of the pillar. Finally, a passive anti-vibration platform is put between the granite stone and the cavity vacuum chamber. Using the measured acceleration sensitivity values, an estimate for the resonator fractional frequency noise due to vibrations shown in Figure 9 could be derived. The results fulfilled the design goals and support a quantum projection noise limited instability of a Sr^+ single-ion clock.

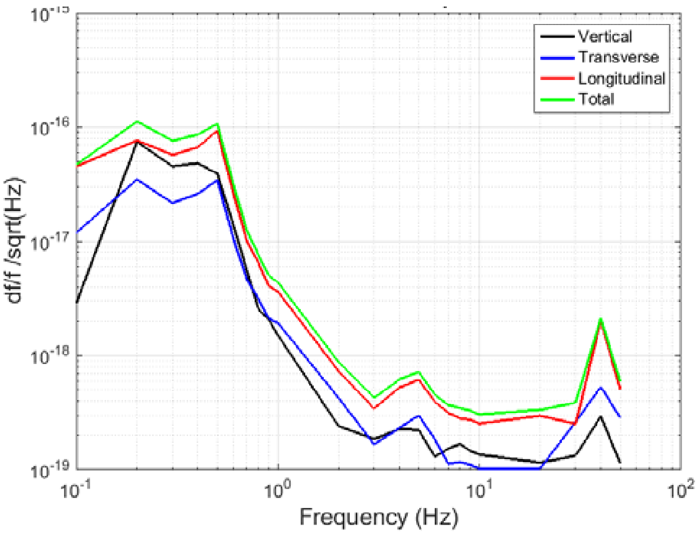

FIG. 9: Estimate for the fractional frequency noise of the VTT resonator due to vibrations.

For the use in future transportable optical clocks, compact and reliable light sources need to be developed. VTT has developed broadband, unpolarized repumper and state clearout sources for Sr^+ single-ion optical clocks (see Figure 10). These turn-key devices require no frequency stabilisation or external modulators. They are fibre based, inexpensive and compact. Key characteristics for clock operation have been characterised, including optical spectra, induced light shifts and required extinction ratios. Tests with an operating single-ion standard show a clear-out efficiency of 100 %. Compared to a laser-based repumper, the achievable fluorescence rates for ion detection are a few tens of percent lower. The resulting ion kinetic temperature is 1–1.5 mK, near the Doppler limit of the ion system. Similar repumper light sources could be made for Ca^+ (866 nm) and Ba^+ (650 nm) using semiconductor gain media.

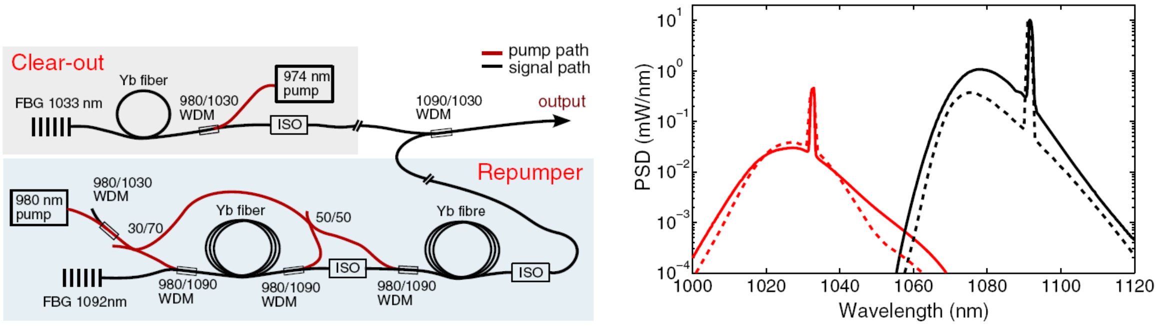

FIG. 10: left: Layout of amplified spontaneous-emission clear-out and repumper sources for Sr^+. WDM, wavelength division multiplexer; FBG, fiber Bragg grating; ISO, optical isolator. Right: Measured clearout (solid red) and repumper (solid black) output power spectral densities (PSD). Also shown are spectra based on a numerical model (dashed).

Computer-control systems

This project has also focused on the development of automatic control procedures to improve the reliability, robustness and performance of ion clock operation by computer control of all critical laser sub-systems via laser stabilisation and relocking routines. Routine operation of the optical clock is required for measurement campaigns over several days and there is also a long-term requirement for unattended operation in remote environments, such as on a satellite or at an observatory or a tracking ground station. At NPL and PTB software algorithms have been developed which enable the automatic relocking of multiple laser sources to optical cavities or wavemeters. The procedures have been tested and continuous operation of up to 100 h has been achieved. This work was an important prerequisite for highly precise frequency and frequency ratio measurements of the single ion clocks reported below, because these required extended averaging times. As an example for the employed logic, Figure 11 presents the flow chart indicating the measurement processes involved for stabilizing the 674 nm laser to the $^2S_{1/2}$–$^2D_{5/2}$ optical clock transition at NPL.

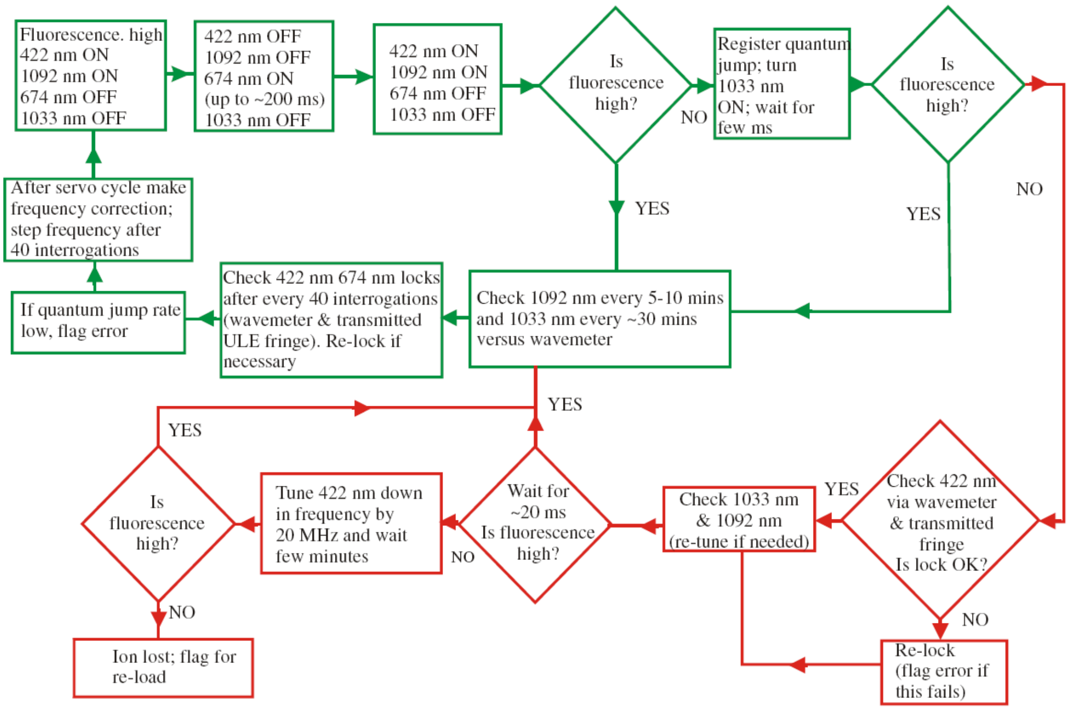

FIG. 11: Flow chart indicating the measurement processes involved for stabilizing the 674 nm laser to the $^2S_{1/2}$–$^2D_{5/2}$ optical clock transition at NPL.

Optimised techniques for quantum logic clocks

Optical clocks based on ensembles of trapped ions promise record frequency accuracy in combination with good short-term stability. Many suitable ion species lack closed transitions for state detection, so the clock signal must be read out indirectly by transferring the quantum state of the clock ions to co-trapped logic ions using quantum logic operations. Existing methods of quantum logic readout require a linear overhead in either time or number of logic ions. PTB together with a group from theoretical physics at the Leibniz University Hannover has developed a quantum algorithmic readout whose overhead scales logarithmically with the number of clock ions in both of these respects. It was shown that the readout can be performed with a single application of a multi-species quantum gate, which was investigated in detail for the combination of Al^+ and Ca^+ ions.

The work developed has led to more stable and more robust reference lasers and has improved the optical clock setups at PTB and NPL to the point were extended measurement campaigns can be undertaken with high duty cycle and with a minimum of manual intervention. The newly developed light sources and control algorithms will find application in future realisations of optical clocks.

3.3 Evaluation of frequency shifts

A key specification of an optical clock is its systematic uncertainty, describing the degree to which external influences that shift the frequency away from the unperturbed atomic resonance frequency can be controlled, avoided or compensated. For a clock to be considered candidate to the redefinition of the unit of time it is one of the most important selection parameter. The reduction of systematic uncertainties has been a main motivation of research on optical clocks and progress in this field has been rapid.

The main contributions to the systematic uncertainty in optical clocks with trapped ions come 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, strontium and ytterbium. 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, together with the detailed modeling and measurements of the thermal radiation emitted by the trap structure performed by CMI has led to a reduction in the blackbody radiation (BBR) related uncertainty 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 world-wide.

A detailed thermal analysis performed by CMI with infrared imaging, measurements in dummy traps with temperature sensors and FEM modeling 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. We have studied the temperature increase of different designs of radio frequency ion traps. Construction materials, electrical and thermal design and surface quality all play a role in determining the resulting temperature of the components of the trap structure. The work provided improved knowledge of the perturbed blackbody radiation environment experienced by the ion in the trap, and hence significantly reduced the uncertainty in the blackbody radiation shift in state-of-the-art optical ion clocks. Based on their operational ion clock designs, PTB and NPL have fabricated three different dummy traps that were used as test systems for the study. A major complication in the determination of the BBR shift for trapped ions is that the strong radio frequency electric fields used to confine the ions will heat the dielectrics that are necessarily incorporated into the structure of an ion trap to electrically insulate various components. This heat generation means it is no longer appropriate to use the room or vacuum chamber temperature to estimate the BBR shift, as the trap structure subtends a large fraction of the solid angle visible to the ion and may be at a very different temperature than the chamber temperature. One way of determining the effective temperature of the thermal radiation would be through the use of *in situ* sensors. This approach is difficult to use for ion traps due to the strong rf field which will cause heating of the sensor, and any electronics attached to the sensor will experience strong interference unless precautions are taken.

CMI has measured the temperature distribution under typical operating conditions with an infrared camera and thermometers, and created a finite element method (FEM) model for each dummy trap. The models were refined until an agreement of better than 10% of the measured temperature rise at critical test points was reached. FEM models for several new, improved trap designs were developed and issues critical for trap heating and its predictability were identified and design recommendations developed. We have identified two sources of heat generation in the trap, rf absorption in insulators and joule heating in conductors, as well as two ways of heat removal from the trap, radiation and conduction. Radiative heat dissipation from the trap is problematic since this radiation will be seen by the ion and give rise to BBR shifts. Decreasing the emissivity, and thus thermal emission of the hot components (especially those in the field of view of the ion), decreases the temperature rise seen by the ion. A decrease of the emissivity can be obtained by polishing or coating. It is also advisable to increase the emissivity of cold parts, in particular, the vacuum chamber and windows. Conduction turned out to be the most important mechanism of heat disposal. A design recommendation is to use good heat conductors with large cross section. Attention should be paid to establish good thermal contacts between the parts, since these very often appear to be decisive for the heat dynamics in the trap.

As an example of the analysis, Figure 12 shows the modelled temperature distribution for the surface of the NPL design improved endcap trap (see also Fig. 1). If the temperature rise in the feedthrough was controlled by heat-sinking the atmosphere-side at room temperature then the temperature rise of the hottest part (the fine molybdenum wires which connect the grounded endcaps to copper wires) was about 0.15 K, while the temperature rise seen by the ion was only 0.05 K.

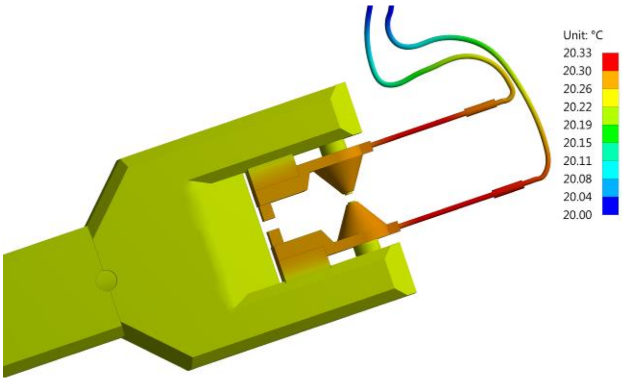

FIG. 12. Modelled temperature distribution calculated at CMI for the surface of the NPL design endcap trap for an applied rf potential of 900V amplitude at 21 MHz, with feedthrough temperature fixed to ambient temperature 20°C.

For five traps investigated in this project the temperature rise of the hottest parts ranged from 2.9 K to 9.8 K at standard working conditions. The effective temperature rise of the radiation seen by the ion ranged from 0.8 K to 2.1 K. In all cases, the heating of the trap structure no longer made limiting contributions in the clocks' uncertainty budgets, even for those traps that were constructed when low heating and thermal homogeneity were not design criteria of high priority. The BBR shift therefore does not present an obstacle to obtaining systematic uncertainties in the low 10^{-18} range for optical clocks based on the Sr^+ and Yb^+ E2 transitions, and even lower for Yb^+ E3, In^+ and Al^+ because of the lower differential polarizabilities.

For Sr^+ and the Yb^+ E3 transition new measurements of the differential polarizabilities have been performed with significantly reduced uncertainties. Depending on the maximum wavelength of the transitions contributing to the differential polarisability, its value can be inferred from measurements with infrared radiation. It is also possible to use the electric field that forms the trap potential. Following the latter idea, our collaborators from the Institute for National Measurement Standards, National Research Council Canada have measured the static differential polarizability of the reference transition of the Sr^+ frequency standard by determining the trap drive frequency at which the Stark shift and the second-order time dilation, both induced by the trap field, cancel each other. Note that the differential polarisability is negative in the case of Sr^+, while it is positive for the other investigated species. For the case of the Yb^+ E3 transition PTB has performed light shift measurements using fibre lasers at 1545 nm and 1310 nm with a maximum output power of about 110 mW, a Nd:YAG at 1064 nm (500 mW) and a laser diode at 852 nm (300 mW) (see Figure 13). To measure the induced frequency shift, an interleaved stabilisation technique was used. A mechanical shutter blocks the additional laser in all parts of the interrogation scheme, except during the corresponding probe pulse period. Since it is experimentally difficult to determine the intensity of the light shifting laser at the position of the ion, the laser beam profile was moved over the ion and the light shift profile was determined, fitted to an intensity distribution similar to that of the lowest-order Hermite-Gaussian modes and the field strength related to the integral power in the laser beam. As a result, corrections of the blackbody induced Stark shift at room temperature with an uncertainty in the 10^{-18} range and below are possible and no longer limit the achievable accuracy, as it is also the case for Al^+. Due to the relatively large differential polarisability of the E2 transition of Yb^+ and the difficulties in the theoretical description of the system, presently no such high-accuracy data is available for this transition.

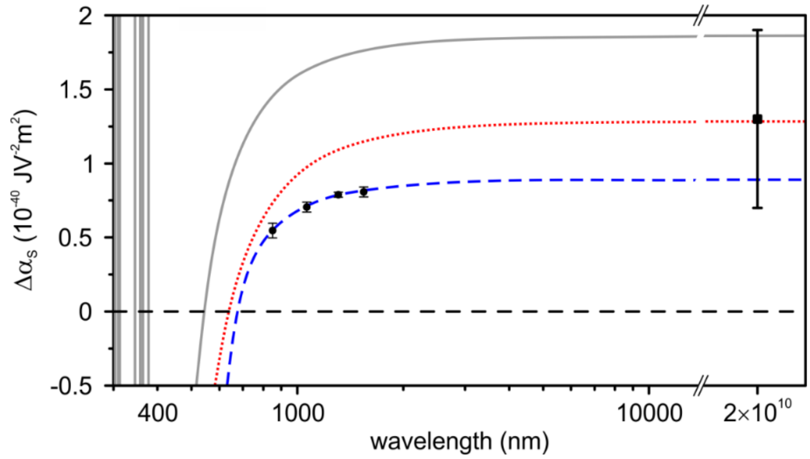

FIG. 13: Scalar differential polarizability $\Delta\alpha$ of the Yb^+ octupole transition as a function of the wavelength. The solid gray line is calculated using tabulated oscillator strengths, and for the dotted red line the data were corrected according to experimental lifetimes. The circles show the results of light shift measurements performed in this project using near-infrared laser radiation and the square shows the result obtained with a quasi-static field. The dashed blue line is a fit to the experimental values.

The results of this project have led to a reduction in the total systematic uncertainty of the Yb^+ E3 optical clock at PTB by more than a factor of 20. Similarly significant improvements have been obtained for the Yb^+ E2 and for the Sr^+ optical clocks developed at NPL, VTT and at the Canadian collaborator INMS/NRC. As a consequence, the selection of candidates for a possible primary optical of the highest accuracy has been widened with respect to the start of the project, when Al^+ possessed a singular status with an uncertainty in the 10^{-18} range. Important applications are envisaged not only in the field of metrology but also within the scientific community, as the high accuracy of the Yb^+ frequency standard makes it possible to exploit the high sensitivity of the Yb^+ $^2F_{7/2}$ state energy to the value of the fine structure constant α in tests of the foundations of physics.

3.4 Clock performance evaluation and frequency measurements

The performance of the newly developed and improved optical clocks can be better characterised by intercomparisons of similar systems and with existing primary caesium clocks. The latter will also provide measured values of the absolute optical transition frequencies in SI Hertz, which are required as input data for recommended values of secondary representations of the second in the optical frequency range.

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 dataset from optical clock comparisons worldwide with results from a single consortium.

For the measurement of absolute frequencies with a primary caesium fountain clock, PTB has developed and implemented a method where the frequency of the microwave oscillator that interrogates the caesium atoms is stabilized by the laser that excites the Yb^+ E2 reference transition. The stability is transferred to the microwave oscillator with the use of a fibre laser based optical frequency comb generator that also provides the frequency conversion for the absolute frequency measurement. The frequency comb generator is configured as a transfer oscillator so that fluctuations of the pulse repetition rate and of the carrier offset frequency do not degrade the stability of the frequency conversion. In this way, the stability of the fountain clock is improved and the statistical uncertainty of the frequency measurement reduced. Within an averaging time of 65 hours the frequency of the Yb^+ E2 transition was measured with a relative statistical uncertainty of

2.8×10^{-16}. Figure 14 shows the results of frequency measurements of this standard at PTB (against the two caesium fountains CSF1 and CSF2) and NPL. It can be seen that the consistency and uncertainty of the dataset is now considerably better than the uncertainty for the secondary representation of the second (SRS) of 3×10^{-15} recommended by CIPM in 2013.

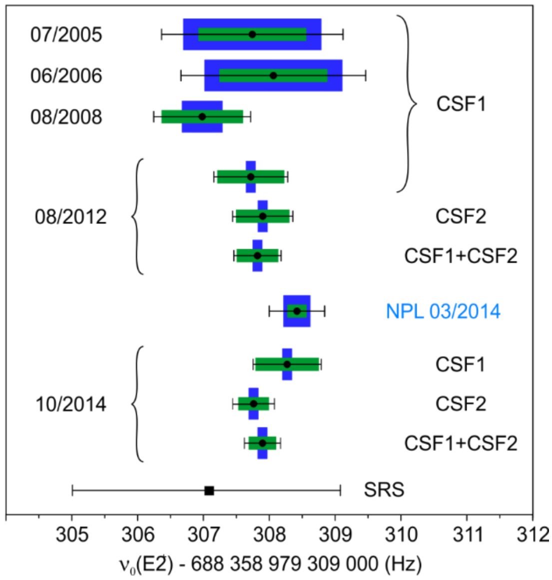

FIG. 14: Results of absolute frequency measurements of the Yb^+ E2 transition at PTB and NPL from 2005 until today, including the results from 2012 and 2014 that have been obtained within this project. The widths of the colored bands indicate the systematic uncertainty contributions of Yb^+ (blue) and caesium (green) to the total uncertainty (black error bar, including statistical uncertainty). It can be seen that for the most recent measurements the uncertainty is dominated by the systematics of the Cs clock, i.e. the uncertainty in the realization of the SI Hz. The bar marked SRS indicates the value and its uncertainty of the 2013 recommendation of CIPM for the use of this frequency standard as a secondary representation of the second. The dataset presented here has been used to recommend an updated SRS value with reduced uncertainty in 2015, presently awaiting approval by CIPM and publication.

Improved control of systematic frequency shifts has reduced the dominant uncertainty contributions, like discussed above for the light shift from blackbody radiation, and has made it possible to measure optical frequency ratios with an uncertainty below that of primary Cs clocks. At NPL the frequencies of two nominally identical $^{88}Sr^+$ trapped single ion optical clocks, based on the 674 nm $5s\ ^2S_{1/2}$–$4d\ ^2D_{5/2}$ electric quadrupole clock transition, have been compared over a period of nine months. The frequencies of the two clocks were found to agree within a total uncertainty of 4×10^{-17}, demonstrating that the individual $^{88}Sr^+$ optical clocks are reproducible at the 3×10^{-17} level. 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. Making use of the unique property of Yb^+ of possessing two transitions that are suitable for highly precise optical clocks and are accepted as secondary representations of the second, NPL has performed the first direct measurement of the frequency ratio of these two clock transitions without reference to a caesium primary standard, and using the same single ion. Figure 15 shows the schematic of the experimental setup. A fractional uncertainty of 3×10^{-16} has been achieved.

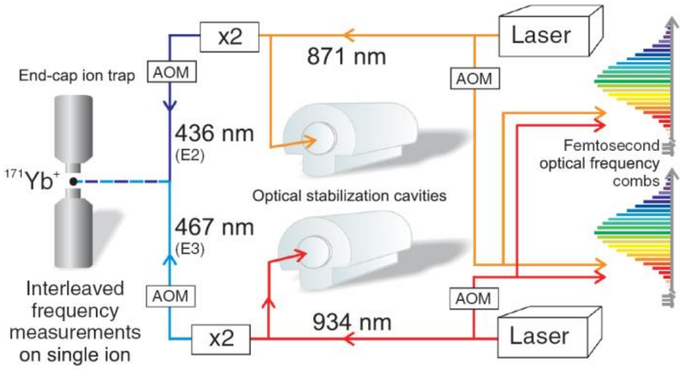

FIG. 15: Schematic experimental arrangement used at NPL for measuring two clock transition frequencies simultaneously in a single ion.

In October 2014, a joint measurement campaign of the $^{171}Yb^+$ frequency standards at NPL and PTB has been performed, comparing the frequencies using signals from the Global Positioning System (GPS) and geodetic data post processing, the so called Precise Point Positioning, a well-established GPS carrier-phase frequency transfer method. This was the first direct comparison of remote optical clocks via GPS. At both institutes an active hydrogen maser served as a flywheel oscillator. It was connected to a GPS receiver as an external frequency reference and compared simultaneously to a realisation of the unperturbed frequency of the electric quadrupole transition in $^{171}Yb^+$ via an optical femtosecond frequency comb. 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. Extrapolating over data gaps in the optical clock to maser comparisons introduces maser noise to the frequency comparison but improves the uncertainty from the GPS link. We determined the total statistical uncertainty consisting of the GPS link uncertainty and the extrapolation uncertainties for several extrapolation schemes (see Figure 16). Using the extrapolation scheme with the smallest combined uncertainty, we found a fractional frequency difference y(PTB)-y(NPL) of -1.3(1.2) × 10^{-15} for a total measurement time of 67 h. This result is consistent with an agreement of both optical clocks and with recent absolute frequency measurements against caesium fountain clocks.

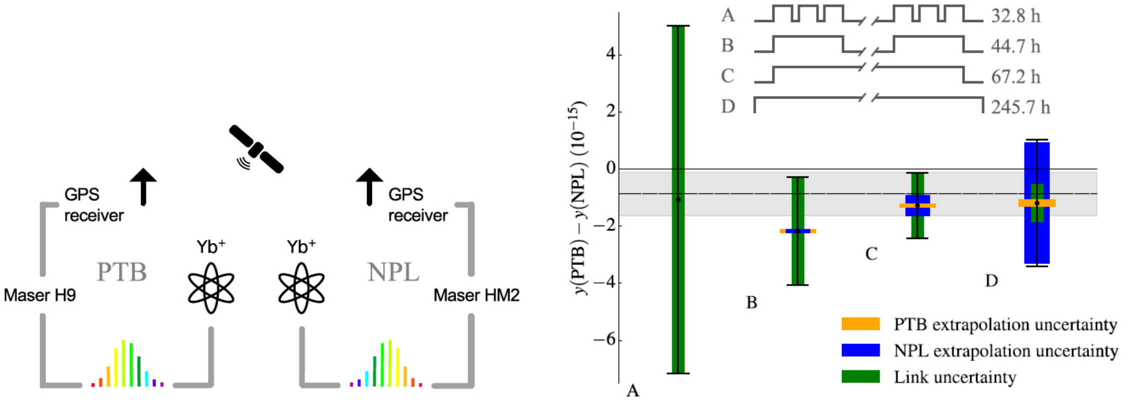

FIG. 16: Left: Experimental setup for the GPS comparison between PTB and NPL. A maser serves as an external frequency reference for a GPS receiver and is compared to the optical frequency standard via a frequency comb. Right: Fractional frequency difference y(PTB)-y(NPL) of the $^{171}Yb^+$ E2 transition with statistical uncertainties for four different extrapolation cases (A-D), shown as sketches of the data structure for the four extrapolation cases and the corresponding total averaging times. The dashed line and the shaded region show the result from absolute frequency measurements against caesium fountain clocks and its uncertainty.

Addressing a pertinent question related to one of the foundations of physics, PTB and NPL have independently evaluated the frequency measurements in terms of a possible temporal variation of the fine structure constant α and the proton-to-electron mass ratio μ. Because of strong relativistic contributions to the level energies, especially the electric octupole transition in $^{171}Yb^+$ possesses a strong sensitivity to changes of α. The comparison with caesium clocks based on hyperfine structure brings nuclear properties into the analysis and, via a simple parametrisation, the proton-to-electron mass ratio μ. Figure 17 shows in a two-dimensional plot how the different experimental results constrain changes in both constants. Besides confirming limits on $d\alpha/dt$ in the low 10^{-17}/yr range, the data provide the most stringent limit on $d\mu/dt$ from a laboratory experiment. Two independent papers on the measurements and data analysis by NPL and PTB have been published in the same issue of Physical Review Letters.

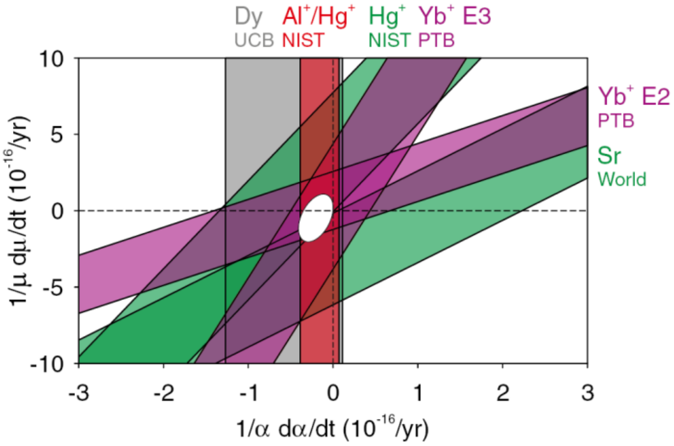

FIG. 17: Constraints on temporal variations of α and μ from comparisons of atomic transition frequencies from different experiments world-wide and from this project (PTB analysis shown here). Filled stripes mark the 1σ- uncertainty regions of individual measurements and the central blank region is bounded by the standard uncertainty ellipse resulting from the combination of all data.

Based on the data provided from this project, the joint working group of CCTF-CCL on Secondary Representations of the Second and the *Mise en Pratique* of the Metre has lowered the uncertainty in the recommended value of the Yb^+ E3 frequency by more than a factor of two in their latest deliberations in September 2015. Since this uncertainty is now strongly dominated by the uncertainty of the caesium clock, further progress and improved consistency checks will only be obtainable based on the measurement of optical frequency ratios. This project has performed ratio measurements of Yb^+ and the Sr optical lattice clock, providing the most comprehensive set of optical frequency measurements available today. Methods for the comparison of remote optical clocks have been introduced and tested here based on satellite links, and in the accompanying project SIB02 NEAT-FT based on telecommunication fibre links. This will enable comparisons of optical clocks in more laboratories world-wide and at improved accuracy.

3.5 Summary

Overall, the project has largely achieved its objectives. The key results and conclusions achieved in this project are:

- Optimised trap designs for single and multiple ions for the use in optical clocks of high accuracy and high stability have been developed and tested.
- Improved laser sources and experimental control procedures are now available for long-term operation of the clocks.
- Yb^+ and Sr^+ have been proven as suitable atomic references and established as the first single-ion optical clocks in the 10^{-18} uncertainty range, complementing the Al^+ quantum logic clock and optical lattice clocks with neutral atoms.
- An extensive and consistent set of absolute frequencies and optical frequency ratios for a number of recommended ion-based secondary representations of the second has been obtained.
- The setup of highly precise optical frequency standards at VTT and CMI has advanced considerably.
- Cooperation within Europe and world-wide have been strengthened or initiated.

4 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 (see Fig. 18).

The community of stakeholders of this project came from academia, metrology, and industry and participated in numerous official and informal contacts with project partners, at conferences, in research networks, and on other occasions. The project partners have hosted exchange students from several university groups.

FIG. 18: Group photo of the participants at the workshop “Frequency standards with trapped ions” that was organized by this project on June 27, 2014 at the University of Neuchâtel.

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 (such as Les Houches, Bad Honnef, Vienna, Paris, and London), ii) a topical workshop at the Japanese National Institute of Communication Technology in Tokyo in 2013 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 like the International Conference on Atomic Physics ICAP, the International Conference on Laser Spectroscopy ICOLS, the DAMOP meeting of the American Physical Society 2015, the 2015 Marcel Grossman meeting and the 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 like 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 $^{171}Yb^{+}$” from 2012 has been cited 134 times until December 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 project consortium has achieved noticeable interest for its work in the media, including national press and radio in several European countries, focussing on the development of precision timekeeping, optical clocks, and applications in science.

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 will be 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 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 has 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 due to the results if 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.

5 Website address and contact details

A public project website is accessible, providing general information on the project activities: http://www.ptb.de/emrp/ion-clocks-home.html

The contact person for general questions about the project and for the work performed at PTB is Dr. Ekkehard Peik, PTB, ekkehard.peik@ptb.de

The contact person at CMI is Dr. Petr Balling: pballing@cmi.cz

The contact person at VTT is Dr. Mikko Merimaa: Mikko.Merimaa@vtt.fi

The contact person at NPL is Prof. Patrick Gill: patrick.gill@npl.co.uk

6 List of publications

6.1 Papers published in scientific journals with peer review

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)*

15 M. Dolezal et al.: *Analysis of thermal radiation in ion traps for optical frequency standards.* Metrologia **52**, 842 (2015)

16 J. Keller et al.: *Precise determination of micromotion for trapped-ion optical clocks.* J. Appl. Phys. **118**, 104501 (2015)

17 N. Scharnhorst et al.: *High-bandwidth transfer of phase stability through a fiber frequency comb.* Opt. Expr. **23**, 019771 (2015)

6.2 Papers submitted to scientific journals with peer review

1 M. Schulte et al.: *Quantum Algorithmic Readout in Multi-Ion Clocks*. Phys. Rev. Lett. (submitted)

2 J. Leute et al.: *Frequency comparison of $^{171}Yb^+$ ion optical clocks at PTB and NPL via GPS PPP* IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control (invited paper, submitted)

3 M. Kazda et al.: *Phase analysis of frequency standards in the microwave and optical domains*. IEEE Trans. Ultrasonics Ferroelectrics and Frequency Control (submitted)

4 N. Huntemann et al.: *Single-Ion Atomic Clock with 3×10^{-18} Systematic Uncertainty.* Phys. Rev. Lett. (submitted)

6.3 PhD Theses

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 $^{171}Yb^+$ Octupole Transition*.Dt. Nat. Bibliothek, idn 1068342641, Leibniz Uni.Hannover 15.7.2014