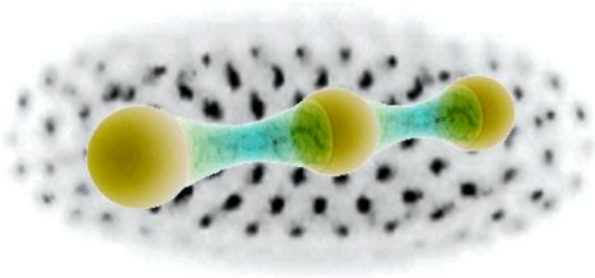


Novel movements for clocks and sensors

Monday 20th to Wednesday 22nd September 2021

Online workshop programme

Introduction

EU projects USOQS and CC4C, funded within the EMPIR programme organised a joint international online workshop on new perspectives to realise the next generations of quantum clocks and precision sensors.

Invited talks on techniques ranging from the realisation and control of large ion crystals to active lasers, and from quantum-mechanical squeezing to entanglement were given. The implementation and evaluation of the potential to go beyond the present state-of-the art in precision measurements was addressed.

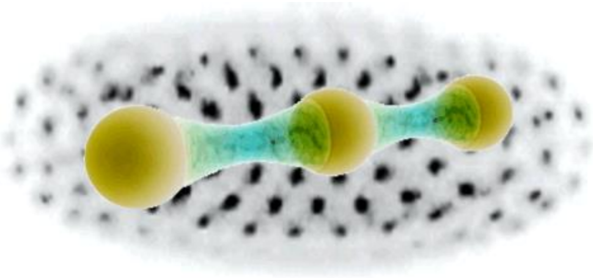
Experts from national metrology institutes and leaders in the wider academic field presented their results. For CC4C **José R. Crespo López-Urrutia**, MPIK Heidelberg, **Nils Huntemann**, PTB Braunschweig, and **Tanja E. Mehlstäubler**, PTB Braunschweig & Leibniz University Hannover. For USOQS **Luca Pezzè**, CNR-INO & LENS Firenze, **Uwe Sterr**, PTB Braunschweig, **Alvise Vianello**, NPL Teddington, and **Michał Zawada**, Nicolaus Copernicus University, Toruń. The external speakers are:

Nitzan Akerman, Weizmann Institute of Science, Rehovot, Israel
Yao Huang, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan
Adam M. Kaufman, JILA, NIST & Colorado University, Boulder
David R. Leibrandt, NIST & Colorado University, Boulder
Norbert M. Linke, JQI, University of Maryland

The online conference was held with talks in groups of four each day from 12:00 to 15:40 (UTC). With ample time for questions.

The organisers were Filippo Levi (INRIM), Thomas Lindvall (VTT), Ekkehard Peik (PTB) & Guido Wilpers (NPL).

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States



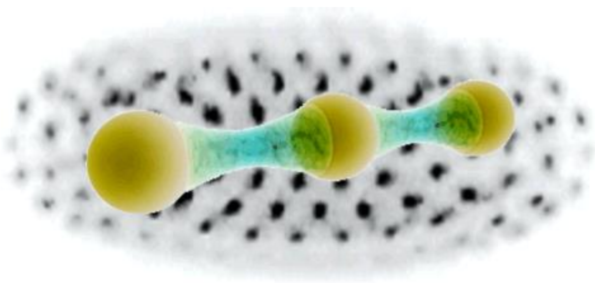
Novel movements for clocks and sensors

Monday 20th to Wednesday 22nd September 2021

All time are given as UTC. You can find your local time offset, e.g. here.

Workshop’s Teams etiquette

Won’t be needed any more. Sorry! We are grateful that it was well adhered to by all attendees, some of whom are shown here.



Novel movements for clocks and sensors

Monday 20th to Wednesday 22nd September 2021

Programme overview

All times given as UTC. You can find your local time offset, e.g. here.

	Monday, 20 Sep		
12:00	Welcome & introduction to projects	Filippo Levi & Ekkehard Peik	INRIM & PTB
12:20	Superradiant active atomic clocks	Michał Zawada	UMK
13:00	José R. Crespo López-Urrutia's talk moved to Tuesday at 15:00 UTC		
13:40	Trapped ion clocks meet many-body physics: a love story	David R. Leibrandt	NIST & CU
14:30	Yb$^+$/Sr$^+$ two-species optical clock	Nils Huntemann	PTB
	15:10 close		
	Tuesday, 21 Sep		
12:00	Quantum algorithms with trapped ions	Norbert M. Linke	JQI
12:50	Structure and dynamics of Coulomb crystals	Tanja E. Mehlstäubler	PTB & LUH
13:30	Luca Pezzè's talk moved to Wednesday at 15:00 UTC		
14:10	Metrology and entanglement with assembled arrays of atoms	Adam M. Kaufman	JILA, NIST & CU
15:00	Forbidden transitions in the extreme ultraviolet for future clocks	José R. Crespo López-Urrutia	MPIK
	15:40 close		
	Wednesday, 22 Sep		
12:00	Ca$^+$ and HCI optical clocks at APM	Yao Huang	APM, CAS
12:50	Challenges for squeezed state clocks due to laser coherence	Uwe Sterr	PTB
13:30	Interrogation methods for multi-ion optical clocks	Nitzan Akerman	WIS
14:20	Quantum non-demolition detection in an optical lattice clock	Alvise Vianello	NPL & ICL
15:00	Quantum phase estimation with spin-squeezed states: from atomic clocks to quantum algorithms	Luca Pezzè	QSTAR, INO-CNR & LENS
	15:40 close		

Each talk was followed by 15 minutes for questions and discussion.

Session 1

Chair Ekkehard Peik, PTB Braunschweig, Germany

Chat support Thomas Lindvall, VTT MIKES Espoo, Finland

Welcome

12:00 to 12:15 UTC

Filippo Levi, INRIM, Turin, Italy
Ekkehard Peik, PTB Braunschweig, Germany

Welcome notes and short introductions to the EMPIR projects USOQS and CC4C.

Superradiant active atomic clocks

12:20 to 12:45 UTC

Michał Zawada, Nicolaus Copernicus University, Toruń, Poland

One of the biggest limitations of the present generation of optical atomic clocks comes from the need of a macroscopic frequency reference, a flywheel that preserve the frequency while a new sample of ultracold atoms is prepared and loaded into the atomic standard. This frequency reference is a laser prestabilised to the length of an ultrastable high-Q cavity. The cavity must be exceptionally well isolated from the environment, requiring extensive thermal insulation and vibration isolation systems.

One of the proposed and actively developed solutions which allows omitting the external cavity limitations is the system with continuous superradiant lasing of an ensemble of atoms on the clock transition, producing light directly at the clock frequency. If superradiant lasing is sustained continuously, e.g. by replenishing the lasing ensemble from an external reservoir, there is no longer any need for bridging dead-time by an external reference oscillator. I will present a system of an active optical clock based on the superradiance in a bad-cavity regime that is currently under construction at UMK.

Forbidden transitions in the extreme ultraviolet for future clocks

13:00 to 13:25 UTC

José R. Crespo López-Urrutia, Max-Plank Institute für Kernphysik (MPIK), Heidelberg, Germany

Move to **Tuesday 15:00 to 15:25 UTC**.

Trapped ion clocks meet many-body physics: a love story

13:40 to 14:15 UTC

David R. Leibrandt, NIST & University of Colorado, Boulder, CO, USA

Single trapped ions offer an unparalleled level of isolation and quantum control, making them ideal systems for optical atomic clocks and precision tests of fundamental physics. However, quantum projection noise of the single ion fundamentally limits the measurement stability, and over the years it has proven challenging to scale trapped-ion systems up to many ions without sacrificing their pristine isolation.

In this talk, I will describe optical atomic clocks based on quantum-logic spectroscopy of single aluminum ions, which have achieved a record fractional accuracy of $9.4 \cdot 10^{-19}$ and been used to place constraints on dark matter models. I will present recent efforts to improve their measurement stability by coherently combining them with optical lattice clocks and by scaling up the number of aluminum ions. Finally, I will discuss prospects for truly many-body trapped-ion optical clocks that combine the pristine isolation of single-ion clocks with the large atom-numbers of optical lattice clocks.

Yb^+/Sr^+ two-species optical clock

14:30 to 14:55 UTC

Nils Huntemann, PTB Braunschweig, Germany

The extraordinary long excited state lifetime of the electric octupole (E3) transition of the Yb^+ ion enables long coherent interaction times. However, it is to date limited by anomalous heating typically observed in radio frequency (RF) ion traps. Resolved sympathetic sideband cooling of Yb^+ using Sr^+ ions can compensate for anomalous heating during long interrogation times in a linear ion trap. As a first step towards the realization of a two-species optical clock, we determine the frequency ratio of the clock transition of Sr^+ at 674 nm and the E3 transition of Yb^+ with a fractional uncertainty of less than $3 \cdot 10^{-16}$, using in-situ calibration of systematic shifts.

Close of session 15:10 UTC

Session 2

Chair Filippo Levi, INRIM Turin, Italy

Chat support Alastair Sinclair, NPL Teddington, UK

Quantum algorithms with trapped ions

12:00 to 12:35 UTC

Norbert M. Linke, JQI, University of Maryland, College Park, MD, USA

Our quantum architecture consists of a linear Coulomb crystal of trapped $^{171}\mathrm{Yb}^{+}$ ions with individual laser beam addressing and readout. The collective modes of motion are used to efficiently produce entangling gates between any qubit pair with the help of multi-tone laser pulses[1]. In combination with a classical software stack, this becomes in effect an arbitrarily programmable fully connected quantum computer, which we use to run a variety of quantum algorithms. As the capabilities of quantum computers grow, validation becomes a challenge. Much like in metrology, correlating results from different systems can provide a way forward. We present results from a recent cross-platform study involving multiple trapped-ion and superconducting machines[2]. We also discuss other current and future projects.

[1]R. Blümel, et al., *Phys. Rev. Lett.* **126** 220503 (2021).
[2]D. Zhu, et al., arXiv:2107.11387.

Structure and dynamics of Coulomb crystals

12:50 to 13:15 UTC

Tanja E. Mehlstäubler, PTB Braunschweig & Leibniz University Hannover, Germany

Trapped and laser-cooled ions allow for a high degree of control of atomic quantum systems. They are the basis for modern atomic clocks, quantum computers and quantum simulators. Our research aims to use ion Coulomb crystals, i.e. many-body systems with complex dynamics, for precision spectroscopy. This paves the way to novel optical frequency standards for applications such as relativistic geodesy and quantum simulators in which complex dynamics becomes accessible with atomic resolution. We will discuss the dynamics of trapped ion crystals and detail on our work on a multi-ion clock.

Quantum phase estimation with spin-squeezed states: from atomic clocks to quantum algorithms

13:30 to 13:55 UTC

Luca Pezzè, QSTAR, INO-CNR & LENS, Firenze, Italy

Moved to **Wednesday 15:00 to 15:25 UTC.**

Metrology and entanglement with assembled arrays of atoms

14:10 to 14:45 UTC

Adam M. Kaufman, JILA, NIST & University of Colorado, Boulder, CO, USA

Quantum science with neutral atoms has seen great advances in the past two decades. Many of these advances follow from the development of new techniques for cooling, trapping, and controlling atomic samples. As one example, the technique of optical tweezer trapping of neutral atom arrays has been a powerful tool for quantum simulation and quantum information, because it enables control and detection of individual atoms with switchable interactions. In this talk, I will describe ongoing work at JILA where we have explored a new direction for the optical tweezer platform: metrology. I will report our recent progress towards combining scalability and quantum coherence in a tweezer-based optical atomic clock platform, and our progress in using quantum information concepts and many-body dynamics to create entangled states that can enhance metrological performance. Much of this technology is based in the use of tweezer-trapping of a new family of atoms, alkaline-earth atoms — I will discuss the broader outlook of this direction and new pursuits on the horizon.

Forbidden transitions in the extreme ultraviolet for future clocks

15:00 to 15:25 UTC

José R. Crespo López-Urrutia, Max-Plank Institute für Kernphysik (MPIK), Heidelberg, Germany

With the development of frequency combs operating in the extreme ultraviolet by means of high-harmonic generation, a vast frequency space has been made available for metrology. Highly charged ions offer a great variety of forbidden transitions that can serve as references at energies reaching even into the soft x-ray region. The much-reduced polarizability of such ions and the strong effects from relativistic, quantum electrodynamics and finite nuclear size makes them also interesting for testing the boundaries of our understanding of the physics of interactions in bound atomic systems. I will present some recent developments in our group and discuss some of their possibilities.

Close of session 15:40 UTC

Session 3

Chair Carlo Sias, INRIM Turin & LENS Sesto Fiorentino, Italy

Chat support Ondřej Číp, ISI CAS Brno, Czech Republic

The progress on Ca^+ optical clocks and HCI optical clocks in APM

12:00 to 12:35 UTC

Yao Huang, Innovation Academy for Precision Measurement Science and Technology (APM), CAS, Wuhan, China

Here the recent progress on the Ca^+ optical clocks and highly charged ion (HCI) clocks in APM will be reported. For the Ca^+ optical clock, a cryogenic clock at the liquid nitrogen environment is constructed, and an uncertainty at the 10^{-18} level is achieved. A transportable Ca^+ ion clock was also built, with uncertainty of $1.3 \cdot 10^{-17}$ and an uptime exceeding 75 %. The clock was then transported over more than 1200 km to NIM in Beijing. An absolute frequency measurement was carried out there, achieving an uncertainty at the 10^{-16} level, about 5 times smaller than their previous result. For HCI optical clocks, we measured the four M1 clock transitions of highly charged Ni ions and indirectly measured one electric quadrupole (E2) clock transition. The fractional uncertainty of the measured wavelengths reaches the magnitude of 10^{-6}, which is 1-2 orders of magnitude smaller than the results in the NIST database.

Challenges for squeezed state clocks due to laser coherence

12:50 to 13:15 UTC

Uwe Sterr, PTB Braunschweig, Germany

The use of squeezed states in optical clocks promises a further improvement in their frequency stability. However, for clocks with single atomic ensembles, also the influence of the interrogation laser must be considered. Its coherence properties reduce the achievable stability through the Dick effect and through the maximum possible interrogation time that is limited by the laser coherence time. Modelling all effects, we find[1] that for clocks based on single atomic ensembles and currently available ultrastable lasers already for moderate numbers of atoms around a few thousands the gain by squeezing is no longer improving clock performance due to the limits set by the Dick effect and the laser coherence time. Finally, future developments towards improved clock stability will be discussed.

[1] M. Schulte, C. Lisdat, P. O. Schmidt, U. Sterr and K. Hammerer, Prospects and challenges for squeezing-enhanced optical atomic clocks, Nature Commun. **11** 5955 (2020).

Interrogation methods for multi-ion optical clocks

13:30 to 14:05 UTC

Nitzan Akerman, Weizmann Institute of Science (WIS), Rehovot, Israel

Operating a multi-ion optical clock has an obvious potential to improve the performance of clock stability. However, most ion clocks are limited to a single ion due to the challenges in controlling various systematic shifts along the chain of trapped ions. I will review a few methods and proof-of-principle experiments at WIS, which use dynamic decoupling and quantum state engineering to tackle some of these challenges. I will present the current status of our Sr^+ clock and our near future plans.

Quantum non-demolition detection in an optical lattice clock

14:20 to 14:45 UTC

Alvise Vianello, NPL Teddington & Imperial College London, UK

Recent demonstrations of cavity-based measurement schemes for optical lattice clocks have shown a promising route towards the realization of state-of-the-art optical frequency standards. In fact, quantum non-demolition measurements are a remarkable tool for the manipulation of quantum systems - allowing specific information to be extracted while still preserving fragile quantum observables of the system. Repeated interrogation of the atomic sample allows the Dick effect to be suppressed by reducing the measurement dead time needed for laser cooling. Furthermore, in the limit of weak measurement it is possible to preserve atomic coherence. In this regime of quantum non-demolition detection, one can use such systems to engineer quantum states which exhibit reduced quantum projection noise and operate optical lattice clocks beyond the standard quantum limit.

In this talk, I will report on the cavity-enhanced quantum non-demolition (QND) detection scheme that we have implemented in one of the two strontium optical lattice clocks at the National Physical Laboratory (NPL). I will then present how we applied this technique to stabilize the phase of an ultrastable laser to a coherent atomic state via a series of repeated QND measurements - achieving continuous tracking of laser-to-atom phase and realizing a phase lock of the clock oscillator to the atomic ensemble to extend the laser coherence time for Ramsey spectroscopy. Finally, I will give some updates on recent stability results from the synchronous interrogation of our two strontium optical lattice clocks.

Quantum phase estimation with spin-squeezed states: from atomic clocks to quantum algorithms

15:00 to 15:25 UTC

Luca Pezzè, QSTAR, INO-CNR & LENS, Firenze, Italy

Quantum phase estimation (QPE), namely the estimation of an arbitrary phase in a 2π interval, is the building block of known quantum computing algorithms providing exponential speedup, including the computation of the eigenvalues of Hermitian operators, such as molecular spectra, number factoring, and quantum sampling. The QPE problem is also central in atomic clocks. In this talk, I present an adaptive phase estimation protocol that uses Gaussian spin states to achieve a Heisenberg limited sensitivity with respect to the total number of qubits used[1]. The protocol overcomes existing QPE methods based on way more complex (and fragile) states, such as GHZ states, and its performance comes very close to the ultimate possible sensitivity limit.

We discuss possible applications in atomic clocks[2,3], taking into account realistic local oscillator noise as well as possible implementation imperfections. Our work paves the way toward an efficient implementation of the QPE, as well as applications of atomic squeezed states for quantum computation algorithms.

[1] L. Pezzè and A. Smerzi, Quantum Phase Estimation Algorithm with Gaussian Spin States, arXiv:2010.04001; *PRX quantum*, in press.

[2] L. Pezzè and A. Smerzi, Heisenberg-limited noisy atomic clock using a hybrid coherent and squeezed state protocol, Phys. Rev. Letters **125** 210503 (2020).

[3] W Li, S Wu, A Smerzi, L Pezzè, Improved absolute clock stability by the joint interrogation of two atomic states, arXiv:2104.14309

Close of session 15:40 UTC