Q 59: Precision Measurements and Metrology II (joint session Q/A)

Time: Thursday 16:30–18:30 Location: P

Q 59.1 Thu 16:30 P

Experimental and theoretical investigations for an all optical coherent quantum noise cancellation scheme — •Bernd Schulte[1,2], Jonas Junker[1,2], Mariia Matiushechkina[1,2,3], Roman Kossak[1,2], Nived Johny[1,2], and Michèle Heurs[1,2,3] — [1]Max Planck Institute for Gravitational Physics and Institute for Gravitational Physics, Hannover, Germany — [2]Quantum Frontiers — [3]PhoenixD

Optomechanical detectors can and have been used successfully for the ultra-precise measurement of weak forces. The sensitivity of such detectors is limited by the standard quantum limit (SQL) which is defined by the shot noise of the probe beam and the quantum radiation pressure back action noise. To surpass the SQL Tsang and Caves suggested a scheme [1] with an anti-noise (ancilla cavity) path which is coupled to the measurement device (meter cavity) to destructively interfere the radiation pressure back action noise. In this scheme the anti-noise path contains a two-mode squeezer and a beam splitter interaction. To achieve perfect coherent quantum noise cancellation (CQNC), exact matching of the respective coupling strengths is required. Additionally, the linewidths of the ancilla cavity and mechanical oscillator needs to be matched and the ancilla cavity needs to be sideband-resolved. Our group has conducted a detailed analysis of the proposed method under experimentally feasible conditions and has shown that even for non-perfect matching one can surpass the SQL [2].

[1] M. Tsang and C. Caves, Phys. Rev. Lett. 105, 123601, (2010)
[2] M. H. Wimmer et al, Phys. Rev. A 89, 053836 (2014)

Q 59.2 Thu 16:30 P

Towards magneto-optical trapping of Zinc — •Marc Vöhringer Carrera, David Röser, and Simon Stellmer — Physikalisches Institut, University of Bonn, Germany

In the pursuit of increasingly precise time and frequency standards, optical lattice clocks belong to the prime candidates. Among the various approaches and elements currently under investigation, it remains unclear which element will eventually turn out to be the most suitable for the numerous applications.

We investigate the element Zinc as a potential candidate for an optical lattice clock. This study is motivated by various favorable properties of Zinc, including a very low sensitivity to black-body radiation shifts [1]. Its core advantage however is the possible derivation of its clock transition frequency as the fifth harmonic of 1547.5 nm [2], lying in the telecom C-band, thus allowing convenient frequency transfer via optical fibers.

To construct an optical lattice clock based on Zinc, many challenges lie ahead. One of them is the construction of a 214 nm laser system for the first cooling stage, as well as the implementation of a two-stage MOT. We report on progress from the lab regarding these challenges.

[1] Dzuba et al., J. Phys. B 52, 215005 (2019)
[2] Büki et al., Appl. Opt. 60, 9915-9918 (2021)

Q 59.3 Thu 16:30 P

Current status of the Al^+ ion clock at PTB — •Fabian Dawel[1,2], Johannes Kramer[1,2], Marek B. Hild[1,2], Steven A. King[1,2], Ludwig Krinner[1,2], Lennart Pelzer[1,2], Stephan Hannig[1,2], Kai Dietze[1,2], Nicolas Spethmann[1], and Piet O. Schmidt[1,2] — [1]QUEST Institute for Experimental Quantum Metrology, Physikalisch Technische Bundesanstalt, 38116 Braunschweig — [2]Leibniz Universität Hannover, 30167 Hannover

Since 1967 time is defined via a hyperfine transition in caesium-133. Optical clocks offer advantages over microwave clocks in terms of statistical and systematic uncertainties. A particularly promising candidate is the $^1S_0 \rightarrow {}^3P_0$ transition of $^{27}Al^+$. The advantageous atomic properties resulting in small uncertainties in magnetic, electric and black-body shifts. Here we report on the design and operation of the $^{27}Al^+$ clock at PTB. In our clock implementation, Al^+ is co-trapped with $^{40}Ca^+$ in a linear Paul trap. The working principle of quantum logic spectroscopy and a lifetime-limited excitation rabi cycle on the Al^+ logic transition is demonstrated. We will present an evaluation of systematic frequency shifts using the more sensitive Ca^+ as a proxy. All investigated shifts have an uncertainty below 10^{-18}. We will show measurements of the ac-Zeeman shift of our trap and unveil first measurements on the Al^+ clock transition with a power-broadened linewidth of 48 Hz.

Q 59.4 Thu 16:30 P

Towards testing Local Lorentz Invariance in a Coulomb crystal of $^{172}Yb^+$ ions — •Kai C. Grensemann[1], Chih-Han Yeh[1], Laura S. Dreissen[1], Henning A. Fürst[1,2], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover,Welfengarten 1, 30167 Hannover, Germany

We report on our recent progress towards testing Local Lorentz Invariance on a Coulomb crystal of $^{172}Yb^+$ ions. The F-state of $^{172}Yb^+$ is highly sensitive to low-energy Lorentz violation (LV) and the ion offers excellent experimental controllability [1]. While the Earth rotates, the quantization axis of our setup probes different directions in space. Thus, a potential LV would manifest itself in a modulation of the energy splitting between Zeeman sublevels throughout the sidereal day. However, the octupole transition to the F-state strongly suffers from a large AC-Stark shift of a few 100 Hz and a first order Zeeman sensitivity [2]. Therefore, to achieve efficient excitation of all ions, spatial homogeneity of the laser beam's intensity and the magnetic field is needed. We address these challenges with simulations and experimentally, using ions as precise quantum sensors. In addition, we will discuss robust dynamical decoupling schemes [3] that make the measurement insensitive to slow magnetic field and intensity fluctuations.

[1] V.A. Dzuba et al., *Nature Physics* **12**, 465-468 (2016). [2] H. A. Fürst et al., *Phys. Rev. Lett.* **125**, 163001 (2020). [3] R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018).

Q 59.5 Thu 16:30 P

Uncertainty Characterization of an In^+ Single Ion Clock — •Moritz von Boehn[1], Hartmut Nimrod Hausser[1], Tabea Nordmann[1], Jan Kiethe[1], Nishant Bhatt[1], Jonas Keller[1], Oleg Prudnikov[3], Valera I. Yudin[3], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Leibniz Universität Hannover, Hannover, Germany — [3]Institute of Laser Physics SB RAS, Novosibirsk, Russia

Nowadays optical ion clocks achieve fractional frequency uncertainties on the order of 10^{-18} and below. Due to its low systematic shift sensitivities, $^{115}In^+$ is a promising candidate to go beyond this uncertainty level. Moreover, it has favorable properties for scaling to multiple clock ions, such as a transition for direct state detection [1]. We present the first clock operation in our setup using an $^{115}In^+$ ion sympathetically cooled by an $^{172}Yb^+$ ion in a linear Paul trap and its uncertainty characterization at the 10^{-17} level.

The In^+ ion's residual thermal motion causes a time dilation frequency shift. A way to further decrease the resulting frequency uncertainty is via a reduced final temperature of the cooling process. We report on our progress towards direct laser cooling of indium. Indium offers a narrow intercombination line $^1S_0 \leftrightarrow {}^3P_1$ ($\gamma = 360\,\mathrm{kHz}$), enabling temperatures close to the motional ground state. Cooling on this transition could sufficiently decrease the time dilation related frequency uncertainty, to allow for overall systematic uncertainties at the 10^{-19} level [2]. [1] N. Herschbach et al., *Appl. Phys. B* **107**, 891-906 (2012). [2] J. Keller et al., *PRA* **99**, 013405 (2019).

Q 59.6 Thu 16:30 P

Characterization of a Laser System for a Rubidium Two-Photon Frequency Reference — •Daniel Emanuel Kohl[1,2], Julien Kluge[1,2], Klaus Döringshoff[1,2], and Markus Krutzik[1,2] — [1]Institut f. Physik - Humboldt-Universität zu Berlin — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik

Global navigation satellite systems and deep space navigation require precise clocks with stringent requirements on size, weight and power budgets. Besides advanced RF clocks, optical clocks are envisioned for application in next generation GNSS. Laser spectroscopy of atomic vapor in conjunction with optical frequency combs may provide such compact, high precision frequency standards with fractional instabilities comparable to optical state-of-the-art GNSS systems.

Rubidium offers narrow linewidth two-photon transition at 778 nm from 5S to 5D, which can be detected via monochromatic fluorescence at 420 nm. In this poster, we present a two-photon Rubidium frequency reference featuring an extended cavity diode laser applied to a heated and magnetically shielded vapor cell. With this setup we achieved a fractional frequency instability of $7 \cdot 10^{-13}$. Recent spectroscopy results will be presented as well as considerations for the most suitable transition within the Manifold. We further report on details of the lasers system including power stabilization and suppression of residual amplitude modulation.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50RK1971.

Q 59.7 Thu 16:30 P

Frequency stability of a cryogenic silicon resonator with crystalline mirror coatings — •Jialiang Yu[1], Thomas Legero[1], Fritz Riehle[1], Daniele Nicolodi[1], Sophia Herbers[1], Chun Yu Ma[1], Dhruv Kedar[2], Eric Oelker[3], Jun Ye[2], and Uwe Sterr[1] — [1]Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany — [2]JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado, USA — [3]University of Glasgow, UK

The state-of-the-art performance of ultra-stable lasers is limited by various noise contributions like Brownian thermal noise of the optical coatings. In our 21 cm long optical resonator at 124 K, made from single-crystal silicon with low noise $Al_{0.92}Ga_{0.08}As/GaAs$ crystalline mirror coatings, we have investigated a new type of noise associated with the birefringence of these coatings.

To elucidate its nature we have expanded our set-up to lock two independent laser frequencies to two polarization eigenmodes of the resonator, separated by 200 kHz. The observed anti-correlated fluctuations allowed us to cancel the birefringence noise by taking their mean, resulting in an instability below $3.5 \cdot 10^{-17}$. We investigated spatial noise correlations by observing the fluctuations of the difference frequency between TEM_{00} and TEM_{01} modes, and find that local noise like Brownian thermal noise of the coating is below 10^{-17}, consistent with previous estimates. However, there is significant excess noise; most likely from the coating's semiconducting properties.

Q 59.8 Thu 16:30 P

PTB's transportable Al^+ ion clock - concept and current status — •Constantin Nauk[1], Benjamin Kraus[1,2], Stephan Hannig[1,2], and Piet O. Schmidt[1,2,3] — [1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — [2]DLR-Institute for Satellite Geodesy and Inertial Sensing, 30167 Hannover, Germany — [3]Leibniz Universität Hannover, Institut für Quantenoptik, 30167 Hannover, Germany

Optical atomic clocks provide significantly lower fractional systematic and statistical frequency uncertainties compared to state-of-the-art microwave atomic clocks. A particularly promising candidate for high-accuracy applications is $^{27}Al^+$ as its $^1S_0 \rightarrow {}^3P_0$ transition is relatively insensitive towards external electromagnetic fields, especially to black body radiation. However, direct laser cooling of $^{27}Al^+$ is more than challenging. Instead, the clock ion can be cooled sympathetically by a co-trapped and well-controllable $^{40}Ca^+$ ion, which additionally allows state detection of the Al^+ ion via quantum logic spectroscopy.

Besides its design, we present the current status of our transportable ion quantum logic optical clock towards fractional frequency uncertainties on the order of 10^{-18} and review compact and robust breadboarding for UV laser systems.

Q 59.9 Thu 16:30 P

Decreasing ion optical clock instability by multi-ion operation — •Hartmut Nimrod Hausser[1], Tabea Nordmann[1], Jan Kiethe[1], Jonas Keller[1], Nishant Bhatt[1], Moritz von Boehn[1], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Leibniz Universität Hannover, Hannover, Germany

The statistical uncertainty of single-ion clocks is fundamentally limited by quantum projection noise which can be reduced by scaling up the number of ions [1]. We are working on a demonstration of a multi-ion clock using $^{115}In^+$ clock ions, sympathetically cooled by $^{172}Yb^+$ in a linear segmented Paul trap. This trap is optimized for multi-ion operation and offers e. g. low axial micromotion for spatially extended linear Coulomb crystals and low heating rates [2]. We discuss sympathetic cooling of mixed-species crystals and its dependence on the cooling ion positions. To ensure reproducible conditions in the presence of decrystallizing background gas collisions, we experimentally implement crystal ordering sequences and characterize their reliability. Chains up to 10 In^+ ions can be ordered with reliabilities >90%. We show multi-ion spectroscopy results with a fixed crystal configuration, obtained by conditionally triggering such sequences when required.

[1] N. Herschbach et al., *Appl. Phys. B* **107**, 891-906 (2012)
[2] J. Keller et al., *Phys. Rev. A* **99**, 013405 (2019)

Q 59.10 Thu 16:30 P

Towards a miniaturized, all diode laser based strontium lattice clock demonstrator — •Christoph Pyrlik[1,5], Vladimir Schkolnik[1,5], Ronald Holzwarth[2], Robert Jördens[3], Enrico Vogt[4], Andreas Wicht[5], Markus Krutzik[1,5], and the SOLIS1G team[1,2,3,4,5] — [1]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, 12489 Berlin — [2]Menlo Systems GmbH, Bunsenstr. 5, 82152 Martinsried — [3]QUARTIQ GmbH, Rudower Chaussee 29, 12489 Berlin — [4]Qubig GmbH, Balanstr. 57, 81541 München — [5]Ferdinand Braun Institut gGmbH, Gustav-Kirchhoffstraße 4, 12489 Berlin

SOLIS1G is a joint project targeting to develop critical technologies for future space-born optical lattice clocks and verify these by operating a miniaturized, all diode laser based strontium lattice clock demonstrator.

We will report on the current design of the SOLIS1G clock and give an overview on the technological concepts to be developed towards reducing the size, weight and power budget such as micro-integrated laser and distribution modules, compact optical modulators, miniaturized physics package and robust frequency combs.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR50WM2151 and DLR50RP2190B.

Q 59.11 Thu 16:30 P

Active optical clocks: Towards continuous superradiance on the clock transition of strontium — •Sheng Zhou, Francesca Famà, Camila Beli Silva, Stefan Alaric Schäffer, Shayne Bennetts, and Florian Schreck — Institute of Physics, University of Amsterdam

Active optical clocks based on superradiance have been proposed to directly obtain light with the stability of an atomic transition [1]. This approach decouples clock performance from limitations in ultrastable resonators, and could dramatically reduce limitations due to cavity pulling and required averaging times.

Superradiant pulses have been experimentally demonstrated on the 1S0-3P0 'mHz' transition of 87Sr [2]. However, continuous operation is needed to achieve state-of-the-art performance.

We will describe a continuous superradiant laser using the mHz clock transition of strontium. Our approach is based on loading a cold atomic beam [3] of 3P0 excited atoms into a moving magic lattice propagating along the mode of a bow-tie cavity. In this way, large numbers of atoms can be loaded along the cavity mode while maintaining low atomic densities and long lifetimes [5]. Using the fluxes from [3] and [4], an estimation of emitted powers of 0.3 pW for 87Sr and 9 pW for 88Sr should be possible with our setup.

[1] Meiser et al., PRL 102, 163601 (2009). [2] Norcia et al., Phys. Rev. X, 8, 021036 (2018). [3] Chen et al., Phys. Rev. Applied 12, 044014, (2019). [4] Escudero et al., Phys. Rev. Research 3, 033159 (2021). [5] Cline et al., E08.09, DAMOP (2021).

Q 59.12 Thu 16:30 P

Correlation spectroscopy on a $^{40}Ca^+$ two ion system for optical atomic clocks — •Kai Dietze[1,2], Ludwig Krinner[1,2], Lennart Pelzer[1,2], Fabian Dawel[1,2], Johannes Kramer[1,2], Nicolas Spethmann[1,2], and Piet O. Schmidt[1,2] — [1]QUEST Institute for Experimental Quantum Metrology, Physikalisch Technische Bundesanstalt, 38116 Braunschweig — [2]Leibniz Universität Hannover, 30167 Hannover

Time and Frequency are the most accurately determined physical quantities. Though for optical clocks based on trapped ions like $^{40}Ca^+$ the reachable statistical uncertainty is limited by the interrogation time due to decoherence processes and a low signal-to-noise ratio (SNR). Both can be significantly enhanced by employing correlated interrogation techniques within a decoherence-free subspace (DFS) of multiple ions. We utilize Bell-states of opposing magnetic quantum numbers to create a two-particle state whose phase evolution is independent of the ambient magnetic field. Using a pair of fully entangled ions the SNR of this measurement technique can even surpass the standard-quantum-limit (SQL). In our experiments, the correlation of both ions within a Ramsey-interferometer is used to disseminate the differential phase evolution against our clock laser. We present measurements showing the preparation of entangled and correlated two-ion states, demonstrating the increased interrogation time as well as first results showing the potential of the correlation spectroscopy used in an optical atomic clock.

Q 59.13 Thu 16:30 P

Proceedings on Ultrastable Cryogenic Cavities and Ring-Cavities used as Spectral Pre-Filters — •Erich Günter Leo Pape, Marc Kitzmann, and Achim Peters — Humboldt Universität zu Berlin, AG QOM, Newtonstr. 15, 12489 Berlin, Germany

Cryogenic Cavities: We present our new cryogenic sapphire cavities in order to reach relative frequency stability of $10^{-16}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ towards a modern Michelson Morley experiment testing for possible Lorentz violations.

Filter Cavity: We present our new triangular ring cavity used as a spectral prefilter in double pass. We stabilize the cavity to a laser with a piezo ring actuator while using the tilt lock method.

Q 59.14 Thu 16:30 P

2D phase sensitivity beyond the shot-noise limit in an SU(1,1) interferometer. — •Ismail Barakat[1], Klaus Mantel[2], Mahmoud Kalash[1], Norbert Lindlein[1], and Maria Chekhova[2] — [1]University of Erlangen-Nuremberg,Institut für Optik, Information und Photonik, Staudtstraße 7/B2 91058 Erlangen,Germany — [2]1Max-Planck Institute for the Science of Light, Staudtstr. 2, Erlangen D-91058, Germany

2D phase measurements are necessary for characterizing rough and smooth surfaces. In classical interferometry, these measurements are always bounded by the shot-noise limit (SNL). To overcome the SNL, we use a wide-field SU(1,1) interferometer where spatially multimode bright squeezed vacuum is sensing the phase. This non-linear interferometer promises to enhance the overall phase sensitivity in quantum and optical metrology and in imaging. The 2D phase is extracted using the N-steps phase shifting interferometry algorithm. We compare the obtained 2D phase values with the SNL and use the repeatability as a measure of precision for the extracted phase maps. We also test the 2D phase sensitivity by sensing the strain applied to an optical surface.

Q 59.15 Thu 16:30 P

Measuring small coefficients of thermal expansion with Fabry-Perot resonators — •Nina Meyer, Maryam Ghazi Zahedi, Tobias Ohlendorf, Uwe Sterr, and Thomas Legero — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Materials with small coefficients of thermal expansions (CTEs) are needed for industrial and scientific applications as in extreme-ultraviolet lithography, in telescopes or ultra-stable resonators [1]. Such materials, like Zerodur and Corning ULE glass, show a very small CTE of about $10^{-8}\,\mathrm{K}^{-1}$, with zero crossing near room temperature. CTE measurements based on two-beam Michelson interferometers for measuring length have reached $10^{-9}\,\mathrm{K}^{-1}$ uncertainties [2].
In this poster, we present a multiple-beam approach based on a Fabry-Perot resonator, consisting of a test-material spacer and two optically contacted reflecting endcaps in a temperature-controlled vacuum chamber. We discuss a refined uncertainty budget taking the temperature homogeneity of the spacer and the impact of the CTE mismatch between the end caps and the spacer into account [3]. This allows us to determine the CTE with uncertainties in the range of $10^{-9}\,\mathrm{K}^{-1}$.

[1] F. Riehle, Meas. Sci. Technol. **9**, 1042−1048 (1998).
[2] R. Schödel, Meas. Sci. Technol. **19**, 084003 (2008).
[3] T. Legero et al., J. Opt. Soc. Am. B **27**, 914-919 (2010).

Q 59.16 Thu 16:30 P

Towards a continuous wave superradiant Calcium Laser — •David Nak and Andreas Hemmerich — Institut für Laserphysik, Universität Hamburg, Hamburg, Deutschland

Superradiant Lasers are suitable as narrow light sources with ultralow bandwidth, as their emission frequency is only weakly dependent on an eigenfrequency of the laser cavity. They can be used as a read-out tool for precise optical atomic clocks. Currently, our experiment loads cold Calcium-40 atoms from a magneto optical trap into a one-dimensional optical lattice prepared inside a cavity. By incoherent population of the metastable triplet state, pulsed superradiant emission on the intercombination line was realized [1].

At present, the setup is being extended by an incoherent repumping mechanism, which will allow continuous wave operation.

[1] T. Laske, H. Winter, and A. Hemmerich, Pulse Delay Time Statistics in a Superradiant Laser with Calcium Atoms, Phys. Rev. Lett. 123, 103601 (2019).