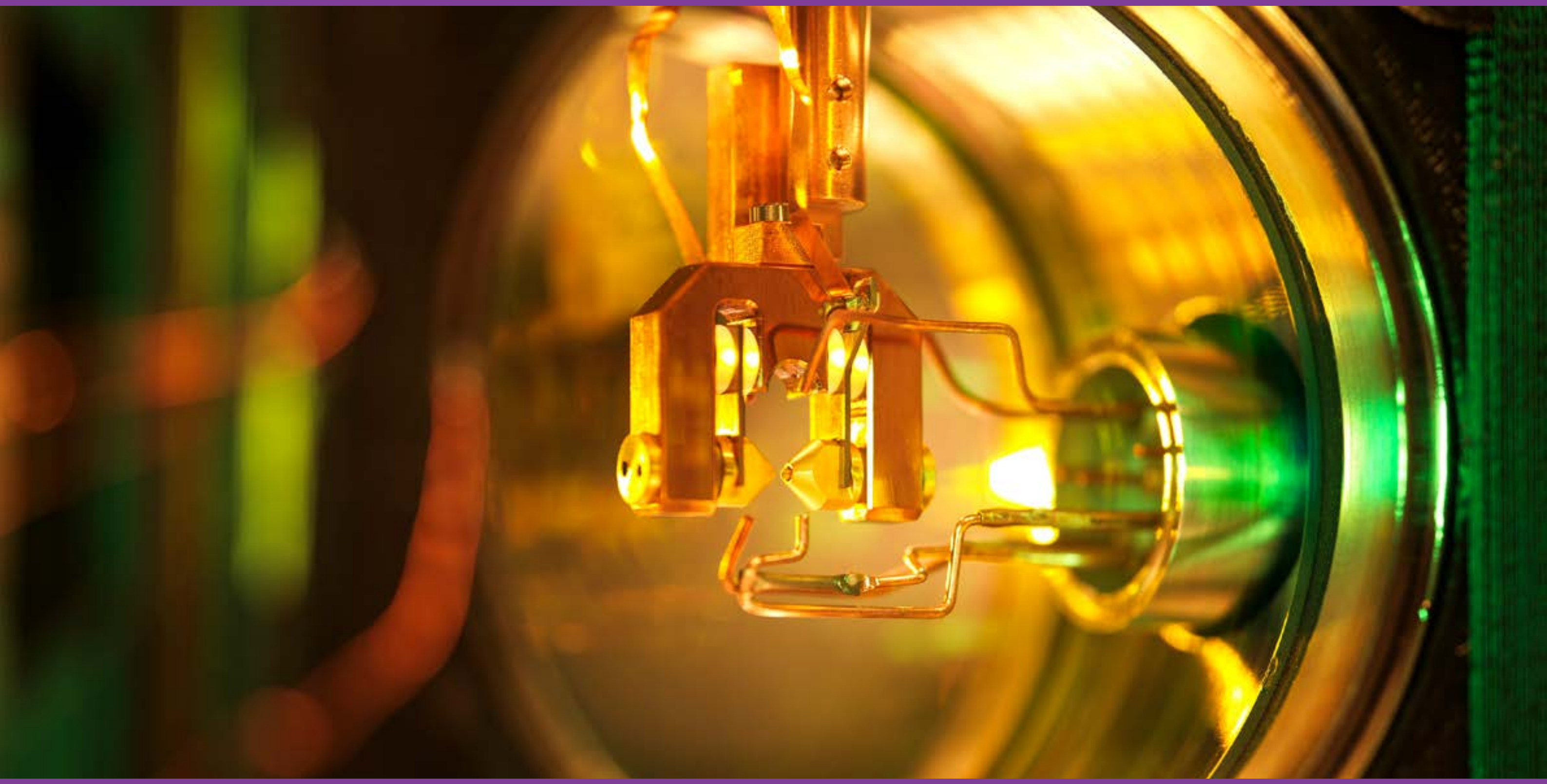
European Metrology Programme for Innovation and Research

Delivering Impact



Improving the useability of high accuracy optical clocks

Time underpins almost all of the SI units and the unit second is realised with microwave atomic clocks. Even higher accuracy can be obtained with optical clocks, but so far they are prohibitively large in size and complex to operate, limiting their application beyond fundamental research. To improve the useability of these clocks while maintaining performance, compact ion traps for optical clocks have been needed.

Challenge

The second, the unit for time, is a component of six out of the seven base SI units and its realisation underpins almost all areas of metrology. The most precise devices available to measure time are optical clocks, a type of atomic clock that utilises isolated ions or neutral atoms with energy transitions in the high-frequency optical range, which can reach relative uncertainties of 10^{-19}. However, due to their size and sensitivity, optical clocks are difficult to transport and must be operated by highly-trained personnel, which limits their application. As satellite-based techniques are not precise enough to compare clocks held at different National Metrology Institutes (NMIs) and suitable fibre optic links are not wide-spread enough to be used as a global alternative, travelling standards will be key to disseminating the second. Therefore, more portable clocks, which can be used with less specialised training, must be developed.

Most optical ion clocks are based on single ions, but clocks based on large ensembles of ions, called Coulomb crystals, provide higher signal-to-noise and improved stability. However, while research into optical clocks has advanced rapidly, Coulomb crystals have not been studied at the same level of detail – in particular, the effects of collisions between trapped ions and background gases. Collisions can cause inaccuracies or disturbances in optical clock measurements but, because they are very rare events, their effects are difficult to precisely characterise and so, in the past, have not been well understood.

Solution

The project CC4C developed metrology for optical ion clocks based on Coulomb crystals, including methods to reduce frequency shifts caused by collisions and the use of sympathetic cooling. In particular, the project investigated interactions between trapped Ytterbium ions (Yb^+) and background gases. As part of this work, project partner and NMI of Germany, PTB, developed a new design of ion trap, a device which can be installed at the heart of an optical clock where it applies electric fields to hold the target ion in place. The trap was developed to cause minimal perturbations to the ion as it is being held, while remaining compact in size.

Impact

TOPTICA Photonics AG, based in Germany, is a leading manufacturer of laser systems for applications in quantum technology, biophotonics and industrial metrology. This includes semiconductor lasers, optical amplifiers, optical frequency combs and frequency-stabilisation electronics, as well as laser rack systems which can condense complex experimental setups into 19" modular units. As part of the German Federal Ministry of Education and Research (BMBF) project opticlock, TOPTICA helped develop an optical clock prototype using the compact ion trap created by the CC4C project. This clock prioritises both useability and portability for end users, fitting inside a 19" rack format while limiting relative uncertainty and frequency instabilities to the 10^{-17} range. The clock therefore outperforms the current best microwave clocks by about an order of magnitude. The use of the ion trap developed by the CC4C project allows the clock to maintain this reduced size while ensuring minimum perturbations to the target ions.

The ion trap, as well as knowledge transfer from PTB, has allowed TOPTICA to extend the prototype further into a commercial system, saving years of research and development time. The clock is ideally suited to synchronise networks, maintain GPS hold-over, stabilise laser systems with ultra-low drift and serve as a time standard.

Collaboration with the project has allowed the company to improve their credibility in the time and frequency metrology market and ensure their customers have confidence in the new system. The portability of the clock and ease of use means that it is more accessible, accelerating the transfer of improved time measurements.

Developing the next generation of atomic clocks

The CC4C project investigated laser-cooled Coulomb crystals to increase the signal-to-noise of atomic clock measurements to improve the realisation of the second.

The project studied the structure and dynamics of Coulomb crystals, including interactions between the crystal and the ion trap as well as between the crystal and atoms from background gases, investigating and quantifying frequency shifts due to collisions. It also investigated sympathetic cooling in clock ions, extending techniques to be used for Coulomb crystals and building a 'world first' superconducting ion trap. The project also developed efficient Thorium-229 ion sources and developed transportable equipment for laser cooling, high resolution spectroscopy and optical frequency measurements.

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Ekkehard Peik
PTB, Germany
ekkehard.peik@ptb.de

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