EMRP Call 2011 - Health, SI Broader Scope & New Technologies

Selected Research Topic number: **SRT-s10**
Version: 1.0

Title: High-accuracy optical clocks with trapped ions

Abstract

This topic addresses the development of ultra-precise optical clocks using laser-cooled trapped ions. This can provide a leading European contribution to the research on a possible redefinition of the future SI second based on an optical frequency. The low level of perturbation available is exemplified by the recent estimated uncertainty of 9×10^{-18}. Research will evaluate systematic uncertainties and stabilities across a range of ion species. Clock performance will be improved through new approaches for interrogation methods and multiple ions within trap architectures providing extended operation. Outputs will contribute to timescale steering, to tests of fundamental physics, and to optical clock deployment in sectors such as space science and navigation.

Conformity with the Work Programme

This Call for JRPs conforms to the EMRP Outline 2008, section on “Grand Challenges” related to Health, New Technologies & Fundamental Metrology on pages 10 and 11.

Keywords

Optical clocks, SI second, international atomic time, ion trapping, laser frequency stabilization, optical frequency measurement.

Background to the Metrological Challenges

Atomic clocks form the basis of international time keeping, and find widespread applications in navigation, communications, network management etc. The realisation of the unit of time plays a central role within the SI because of its unequalled low uncertainty and because it is also used in the realisations of metre, volt and ampere. Optical clocks are candidates for the proposed redefinition of the second since the most advanced optical frequency standards have now reached a level of performance exceeding caesium fountain primary atomic clocks. In order to prepare for such a redefinition, the CIPM adopted the concept of secondary representations of the second and recommended 8 transitions, 5 in ions and 3 in neutral atoms [1]. The candidate standards have different characteristics in terms of their sensitivity to systematic frequency shifts and in terms of the technological requirements for their operation (lasers, atomic sources etc.). However, some problems are inherent to a wide class of candidates. Optimised techniques for extended operation and evaluated frequency shifts of single ion systems, multi-ion and dual-species designs are important for optimal performance and associated contribution to future science, metrology and technology applications. These ion clock platforms need a technology readiness shift to contribute to practical applications which requires robust ion clock performance with extended operational capability.

A major extension to the original optical clocks idea surfaced with the proposal for a quantum logic clock made by D. Wineland et al. in 2001 [2]. This 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.

Two types of reference clock transitions are studied: electric quadrupole or octupole transitions in ions with a single valence electron (eg Ca^+, Sr^+, Yb^+ and Hg^+) and hyperfine-induced transitions between levels with vanishing electronic angular momentum J=0 in two-electron ions Al^+ and In^+. In general, the single-electron systems require less technological effort for laser cooling whereas the J=0 levels are less susceptible to field-induced frequency shifts. With laser cooling the temperature of the ion is reduced to 1 mK or below. A laser that is prestabilised to a reference cavity allows one to obtain excitation spectra with a linewidth of a few Hz. The signal from the ion is used for the stabilisation of the laser frequency, reaching a quantum limited instability of a few 10^{-15} $(1s/\tau)^{1/2}$. Frequency comparisons of the same transition in two ions in independent traps have been done for Yb^+ [3] and for Al^+ [4]. Using a femtosecond frequency comb, an optical frequency ratio of Al^+ and Hg^+ has been measured [5].

The complementary approach of an optical clock based on trapping a number of neutral atoms within an optical lattice as proposed by H. Katori in 2001 [6] uses the J=0→J=0 transitions in Sr, Yb or Hg. The advantage of this approach is the higher signal-to-noise ratio obtainable from interrogating many atoms. The control of systematic shifts, however, seems more challenging than in the trapped ion clocks. In Europe, atom lattice clocks have been studied within the iMERA-Plus OCS project [7].

Scientific and Technological Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the JRP-Protocol.

This JRP shall focus on the development of optical frequency standards based on laser-cooled trapped ions with the aim of preparing standards for the use as high accuracy primary atomic clocks and to contribute to the international atomic time scale (TAI).

A comprehensive evaluation of the systematic uncertainty of such standards should be undertaken and methods to reduce the main contributions to the uncertainty budget be developed. New approaches should aim at reducing the quantum-limited frequency instability by the use of longer interrogation times and/or multiple ions. The reliability of the frequency standards should be improved to the level that will make them available for various frequency comparisons in the uncertainty ranges of 10^{-15} to 10^{-18} and for contributions to stable time scales.

The specific technological and scientific objectives are:

1. To develop:
   - Robust single-ion physics packages for long interrogation periods resulting in Fourier-limited linewidths at the Hz or sub-Hz level.
   - Trap designs to improve signal-to-noise ratio
   - Optimised techniques for multi-species ion clocks (quantum logic clocks)
   - Systems that give unattended averaging times of several days.
   - Reference cavities for the frequency stabilisation of laser oscillators for the interrogation with longer clock pulses.
2. To determine
   - Accurate values of the coefficients of systematic frequency shifts for the proposed clock species.
   - Relevant atomic parameters include static and dynamic polarisabilities, electric quadrupole moments and Landé factors.
   - Blackbody radiation
3. To deliver
   - Intercomparison of clock performance.
   - Measurements of absolute optical frequencies at the uncertainty achievable with primary caesium clocks ($1 \cdot 10^{-15}$) and of optical frequency ratios at lower uncertainty

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources outside Europe is recommended.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this. Proposers should also include references to any previous EMRP projects that involve these technologies, such as the iMERA-Plus OCS project.

The total eligible cost of any proposal received for this SRT is expected to be around the 2.7 M€ guideline for proposals in this call.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the "end user" community. This may be through the inclusion of unfunded JRP partners or collaborators, or by including links to industrial/policy advisory committees, standards committees or other bodies. Evidence of support from the "end user" community (eg letters of support) is encouraged.

You should detail other impacts of your proposed JRP as detailed in the document "Guide 4: Writing a Joint Research Project"

You should detail how your JRP results are going to:

- feed into the development of urgent documentary standards through appropriate standards bodies
- transfer knowledge to the time and frequency instrumentation sector;
- transfer knowledge to potential end users such as the space community, aerospace, telecommunications and energy network managers.

You should also detail how your approach to realising the objectives will further the aim of the EMRP to develop a coherent approach at the European level in the field of metrology. Specifically the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of Member States and countries associated with the Seventh Framework Programme whose metrology programmes are at an early stage of development to be increased
- outside researchers & research organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of up to 3 years duration.

Additional information

The references were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] CI-2009 Recommendation 2: Updates to the list of standard frequencies

(http://www.bipm.org/cc/CIPM/Allowed/98/REC_CIPM2009_C2_LIST_OF_ST_FREQUENCIES_18_DEC_2009.pdf).

[2] D. J. Wineland, J. C. Bergquist, J. J. Bollinger, R. E. Drullinger and W. M. Itano: Quantum computers and atomic clocks. In: Proc. 6th Symp.Frequency Standards and Metrology, Ed. P. Gill, World Scientific (2002)

[3] T. Schneider, E. Peik, Chr. Tamm: Sub-hertz optical frequency comparisons between two trapped $^{171}Yb^{+}$ ions, Phys. Rev. Lett. **94**, 230801 (2005)

[4] C.W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband; "Frequency Comparison of Two High-Accuracy Al^{+} Optical Clocks", Phys. Rev. Lett. **104,** 070802 (2010)

[5] T. Rosenband et al. Frequency Ration of Al^{+} and Hg^{+} single-ion clocks: Metrology at the 17th decimal place, Science **319**, 1808 (2008)

[6] H. Katori: Spectroscopy of strontium atoms in the Lamb-Dicke confinement. In: Proc. 6th Symp.Frequency Standards and Metrology, Ed. P. Gill, World Scientific (2002)

[7] iMERA-Plus Joint Research Project OCS (Optical clocks for a new redefinition of the second - T1.J2.1)