

## **Title: High-accuracy ion-based optical clocks**

### **Abstract**

Currently, the smallest systematic uncertainty of an optical clock is achieved using the reference transition of a single trapped ion. Whilst the use of a single trapped ion can provide high accuracy for optical clocks, it requires nearly 20 days of averaging time to reduce the statistical uncertainty below  $10^{-18}$ . Composite clock systems could provide a promising alternative, but they require the combined operation of multi atom clocks, with an additional single ion clock interrogated with pre-stabilised laser radiation, and this dramatically increases experimental complexity. Another alternative is to reduce the statistical uncertainty by simultaneously interrogating multiple ions. Initial experiments have shown that this can be done with multi-ion clocks where control of trap-related frequency shifts can be used to achieve an uncertainty below  $10^{-18}$  and with improved stability. However, further work is needed to determine the highest possible accuracy of ion-based optical clocks, as well as to demonstrate their performance via inter-comparisons.

### **Keywords**

Optical clocks, single trapped ions, cooled ions, frequency standards, frequency comparisons, SI second

### **Background to the Metrological Challenges**

The international roadmap for the redefinition of the SI second defines important milestones that need to be achieved for the redefinition. These include the validation of the uncertainty of at least three systems and at least three independent comparisons of optical clocks in different laboratories with fractional uncertainty below  $5 \times 10^{-18}$ . Optical atomic clocks currently outperform the fractional frequency stability and accuracy achievable with caesium microwave primary frequency standards by more than two orders of magnitude. However, no atomic system has yet been identified as the most promising candidate for the future redefinition of the SI second.

Recent investigations to increase scientific understanding of the origins and the control of systematic frequency shifts in ion-based optical clocks has led to proposals for novel reference systems with higher immunity to field-induced systematic shifts such as a low-energy nuclear transitions in  $^{229}\text{Th}$  and transitions in highly charged ions. However, optical clocks based on these transitions are experimentally challenging and need further work.

Techniques such as quantum-logic spectroscopy, have also been recently used in the first realisation of an atomic clock based on a highly charged ion. But whilst these systems benefit from higher transition frequency, further investigations are needed on their clock transitions with traceable vacuum-ultraviolet (VUV) laser radiation.

To reach higher accuracies with ion-based optical clocks, improved methods are needed for trapping and cooling larger ensembles of ions, together with studies of the frequency shifts of such multi-ion clocks. This is particularly important for frequency shifts resulting from collisions between trapped ions and background gas molecules, which have not been measured directly yet. A better understanding of collision processes in ion-based clocks with lower frequency instability will help to make more reliable predictions of the shifts and to reduce the corresponding uncertainty.

For the verification of the accuracy and performance of high accuracy ion-based optical clocks, clock comparisons need to be undertaken. Local interspecies frequency comparisons are currently the most promising method to verify performances.

## 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 protocol.

The JRP shall focus on the traceable measurement and characterisation of high-accuracy ion-based optical clocks.

The specific objectives are

1. To develop improved methods for trapping and cooling large ensembles of ions, for use in advanced ion-based optical clocks. This will include the study of (i) ion traps with ultra-low heating rates, (ii) the use of superconducting materials at cryogenic temperatures for shielding of electromagnetic fields, (iii) the confinement of ions in engineered static electric and optical fields, (iv) narrow atomic transitions for fast motional ground-state cooling and (v) the minimum temperature rise of the ion crystal during state detection.
2. To increase the frequency stability of ion-based optical clocks by a minimum of factor of 2 by simultaneously interrogating 4 or more ions. This will include an assessment of technical noise sources so that the maximum number of quantum absorbers can be used. In addition, the use of (i) quantum control techniques, (ii) entanglement and (iii) spin squeezing, to increase ion-based optical clock performance, will be investigated.
3. To develop multi-ion based optical clocks with uncertainties below  $10^{-18}$  and to verify their performance via interspecies clock comparisons. In addition, to assess their frequency shifts resulting from (i) external electric fields, (ii) magnetic fields including thermal radiation, (iii) collisions between the trapped ions and (iv) background gas.
4. To develop improved and reliable techniques for optical clocks, using novel reference transitions of highly charged ions and  $^{229}\text{Th}$  nucleus, in the VUV and XUV ranges. This will require the development of dedicated laser sources, their integration with the ion trap system and the traceability of their output frequency.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, research organisations (European Quantum Technology Flagship, EMN Quantum), standards developing organisations (BIPM CCTF, EURAMET TC-TF) and end users (in the time and frequency and optical sectors).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, including other European Partnerships, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMPIR and Partnership projects 17FUN07 CC4C, 20FUN01 TSCAC and 22IEM01 TOCK and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.0 M€ and has defined an upper limit of 2.5 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 40 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

## Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,

- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the time and frequency and optical sectors.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of the Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. 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 EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

### **Time-scale**

The project should be of up to 3 years duration.