EMRP Call 2012 – Open Excellence, Industry and SI Broader Scope

Selected Research Topic number: **SRT-x06**
Version: 1.0

Title: Quantum engineered states for optical clocks and atomic sensors

Abstract

Within Europe, a number of different state-of-the-art optical clocks exist, the most advanced of which have reached a degree of reproducibility that exceeds that of primary caesium atomic clocks by more than an order of magnitude. However, in order to achieve the short term stability necessary to reach uncertainties at the 10^{-18} level, new techniques to overcome standard quantum limits are needed, such as scalable quantum-mechanical entanglement and squeezing. By increasing the stability and the accuracy of optical clocks, they can be used as innovative sensors in relativistic geodesy, to provide a wider range of quantum sensors, e.g. in gravimetry and magnetometry and to benefit the applications of optical clocks in global and deep space navigation and fundamental physics.

Conformity with the Work Programme

This Call for JRPs conforms to the EMRP Outline 2008, section on "Grand Challenges" related to Industry & Fundamental Metrology on pages 11, 26, 28 and 32.

Keywords

Optical clocks, atomic sensors, spin-squeezed atomic states, scalable quantum-mechanical entanglement, standard quantum projection noise, Dick effect

Background to the Metrological Challenges

Currently the most advanced atomic clocks have an accuracy of 1×10^{-17} and short term instabilities of 10^{-15} at 1 second. Many of these clocks, as well as newly proposed clocks, have the potential to achieve uncertainty levels of 10^{-18}, however, in order to demonstrate the benefits of such a level of accuracy the clocks short term instability needs to be reduced, so that uncertainties at the 10^{-18} level can be reached in practicable averaging times of the order of minutes to a few hours.

In current optical clock systems, there are two main limitations; the first is standard quantum projection noise. In state-of-the-art optical ion clocks, operating with single ions (N=1) their stability is limited by the quantum projection noise. The use of scalable quantum-mechanical entanglement can overcome this limit, i.e. N maximally entangled ions, and increase the short term stability by a factor of N. For example, measurement uncertainties of 10^{-18} which would require 12 days of continuous operation with a single ion, could be achieved in 3 hours by increasing the ion number to N=10. Furthermore, entangled ion states can be designed to cancel intrinsic systematic shifts. However, the challenge is to design optical clocks with a large N, whilst maintaining precise nanoscale control typical of a single-ion clock.

The second limitation is the Dick effect. Optical lattice clocks can operate with a large collection of atoms, e.g. $N=10^4$ or more. However, in such clocks, the limitation isn't quantum projection noise, but the probe laser noise which limits stability on account of the Dick effect which is due to poor duty-cycles and the large amount of dead time in the probing sequence. In such cases, quantum non-destructive detection measurements and spin-squeezed states could provide the solution. Quantum entangled spin-squeezed states can give the same quantum limit for a much reduced atom number. Furthermore, non-destructive detection reuses atoms from one cycle to the next, thereby reducing the need for large atom numbers and enabling a more favourable duty cycle. Operating the clock system with a reduced atom number is also beneficial for reducing collisional frequency shifts which are a concern in some optical lattice clocks.

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.

The JRP shall focus on techniques for optical ion and lattice clocks to achieve the short term stability necessary to reach uncertainties at the 10^{-18} level in practicable averaging times of the order of minutes to few hours. Techniques to overcome standard quantum limits shall be based on scalable quantum-mechanical entanglement and squeezing.

The specific objectives are

1. For ion clocks to:
    a. realise and characterise quantum entangled states of a few ions
    b. demonstrate elementary scaling operations with ion strings across multiple segments
    c. demonstrate entanglement-enhanced clock stability and spectroscopy.
2. For lattice clocks to:
    a. implement non-destructive detection schemes with a detection limit well below the atomic standard quantum noise
    b. realise and detect spin-squeezed states in optical lattice clocks
    c. demonstrate improved clock stability resulting from both non-destructive detection and spin-squeezing.

Proposers shall give priority to work that enables new metrological methods and techniques in the future through excellent science. The project need not address metrology directly.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this and how it will use or extend the knowledge developed in iMERA-Plus JRP T1 J2.1 ‘Optical clocks for a new definition of the second’ and JRPs IND14 ‘New generation of frequency standards for industry’ and SIB04 ‘High-accuracy optical clocks with trapped ions’.

The total eligible cost of any proposal received for this SRT is expected to be around 1.8 M€ guideline for proposals in this call. The available budget for integral Research Excellence Grants is 84 months of effort.

Potential Impact

The project should be designed to bring together the best scientists in Europe and beyond whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes. Significant non-NMI/DI and international participation in the projects is expected and proposers should make full use of the larger budget for Research Excellence Grants available for this SRT.

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

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 and includes 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 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.