Systematic Effects in Strontium Optical Lattice Clocks

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***Abstract*— In this work, we present an investigation of several systematic effects of two optical lattice clock systems with strontium atoms. We propose a new measurement of the hyperpolarizability of the clock transition, with its dependency with the polarization of the trapping laser. We also propose a method for temperature insensitive measurement of those coefficient, suitable for reproducible experimental condition for a clock operating in the 10^{-18} level. As an outlook, we present the design and characterization of an updated vacuum environment, expected to enable a one order of magnitude reduction of the blackbody radiation shift uncertainty, and more reliable operation of the clock.**

Keywords—Clock; Atomic measurement; Measurement uncertainty; Time measurement; Spectroscopy; Optical Metrology

I. INTRODUCTION

Optical clocks [1-3] consist in the stabilization of an ultra-stable laser on a narrow electronic transition of the optical domain. In case of neutral atomic species, an ultra-cold atomic gas is trapped in an optical lattice of dipole trap. LNE-SYRTE is currently developing three of those systems, including two strontium optical lattice clocks. With an uncertainty reaching the low 10^{-17}, and confirmed through both local and international comparisons, they have already contributed to the steering of TAI. Further improvement is constrained by the reduction of the systematic effects uncertainty in the clock accuracy budget. Here, we propose an in-depth investigation of the main limiting systematic effects. First, we present a measurement of the AC-Stark shift due to the lattice trap, with a refined study of the hyperpolarizability (second order effect), and an atomic temperature insensitive measurement of the scalar polarizabillity. We also discuss new vacuum environment design enabling reduced temperature inhomogeneities and in turn a reduction of the uncertainty due to the black-body radiation shift correction.

II. LATTICE LIGHT SHIFT

The presence of the lattice trap during the clock interrogation of the atomic cloud induces a frequency shift, due to the differential AC-Stark effect on the clock states. A milestone in the development of the optical lattice clocks was the use of the magic wavelength, at which the differential polarizability of the clock transition is mostly reduced [4]. Nevertheless, high order interactions, such as multipolar and hyperpolarizability are to be considered to improve further the cancellation of the lattice light shift [5-8].

We present here investigation of the strontium polarizability, including residual scalar and tensor coefficients of the dipole electric expansion, and the hyperpolarizability. The sensitivity of these coefficients with the lattice polarization was also experimentally explored, for the first time in the case of hyperpolarizability of the strontium clock transition. Nevertheless, those measurements require an accurate knowledge of the effective trap depth, which demands a precise determination of the atomic distribution in the lattice sites. As a consequence, their calculation is affected by the experimental difficulty to ensure precise and reproducible atomic temperature calibrations, especially as part as long and repetitive integration such as TAI calibrations. In addition with the usual normalization procedure to reduce this dependency, we present a temperature insensitive measurement of the residual scalar polarizability, by exploring distortion and translation of the carrier clock lineshape in presence of a detuned trap laser [9]. This temperature free measurement can be used to cancel the temperature dependency of the other coefficient.

III. BLACK-BODY RADIATION SHIFT

The black-body radiation shift is the major uncertainty source of our strontium clock systems, with a contribution at the 10^{-17} level. Its reduction requires a more precise knowledge of the temperature distribution of the environment surrounding the interrogated atoms [10]. To do so, a new experimental system is under assembly at LNE-SYRTE. It consists in a compact UHV copper designed chamber, with shielded optical accesses, and equipped with temperature sensors. Its installation inside a primary vacuum contributes to reduce thermal exchange with the experimental environment via conduction and convection. It will also benefit from the thermal decoupling of the surrounding thermal load. As a consequence, we expect a one order of magnitude improvement on the uncertainty of the black-body radiation shift.

With this new system, the strontium clock is expected to show an improved reliability, and ease regular operations. In addition to the reduction of the black-body radiations shift, this system is designed for future investigations of other systematic effects. A double resonant cavity is installed inside the chamber, making it compatible with the implementation of a cavity enhanced non-destructive detection scheme. It also comprises electrodes for DC-Stark shift investigation.

IV. CONCLUSIONS

We presented here studies of the main systematic effects in our strontium clock systems, and possible improvement in agreement for a clock operating in the 10^{-18} level. The investigation of the AC-Stark shift of the clock states beyond the linear regime is important to constrain the residual light shift in presence of the trap laser, and those high order effect needs a refine trap scheme. The non-linearities of those interactions are also problematic since atomic distribution calibration may differ from the one during clock interrogation. We presented a temperature insensitive method for the atomic polarizability, required for reproducible clock operations. The uncertainty due to thermal inhomogeneities of the current system is expected to be lowered by one order of magnitude with the new design, and enable reliable and robust operations of the clock, compatible with regular contribution to the TAI.

ACKNOWLEDGMENT

We acknowledge funding support from Agence Nationale de la Recherche (Labex First-TF ANR-10-LABX-48-01, ANR-16-CE30-0003-01), Conseil Régional Île-de-France (DIM SIRTEQ), and W. Moreno acknowledge funding support from the Fonds National Suisse de la Recherche Scientifique (FN-SNF P2NEP2 184396). This work has been supported by the European Commission through the QuantERA ERA-NET Cofund in Quantum Technologies projects "Q-Clocks". This project 18SIB05 ROCIT has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

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