Progress towards a ^{88}Sr^{+} ion clock at MIKES

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Abstract

The Centre for Metrology and Accreditation (MIKES) is developing an atomic clock based on a single trapped and laser-cooled ^{88}Sr^{+} ion. When operational, it will be the first Finnish primary frequency standard.

1 Introduction

Time and frequency are the two quantities that can be measured the most accurately, and the unit of time is considered the most fundamental base unit. Other units, such as the meter and the electrical units are either defined or realized from the second and the fundamental constants of physics. In 2015 the General Conference on Weights and Measures (CGPM) is likely to update the International System of Units and will possibly define all base units, including the kilogram, in terms of the second and fundamental constants.

Time and frequency metrology is itself going through the greatest changes since the first demonstration of the cesium atomic clock in the 1950s [1]. This revolution is caused by the arrival of optical atomic clocks [2, 3], the development of which was sparked by a technological breakthrough at the turn of the century: the ability to easily count optical cycles using self-referencing femtosecond frequency combs [4].

At the Centre for Metrology and Accreditation (MIKES), an optical single-ion clock is being built in collaboration with Aalto University, Physikalisch-Technische Bundesanstalt (PTB) in Germany, and the National Research Council of Canada (NRC). When it becomes operational, it will be the first Finnish primary frequency standard. A frequency comb will transfer the optical frequency phase coherently to the radio-frequency domain for comparison with the MIKES hydrogen masers that maintain the Finnish realization of the coordinated universal time UTC.

2 Clock design

An overview of the clock is shown in Fig. 1. Clock operation requires six continuous-wave lasers (Fig. 2). A single Sr atom will first be photoionized using two lasers at 461 nm and 405 nm and the resulting Sr^{+} ion is trapped in a radio-frequency endcap trap. The ion is then laser cooled at 422 nm, while also applying a "repumper" laser at 1092 nm. The repumper is required because the $5s^2S_{1/2} – 5p^2P_{1/2}$ Doppler cooling cycle would otherwise be interrupted by decay into the $4d^2D_{3/2}$ state. Detection of fluorescence photons emitted at 422 nm allows confirmation of a trapped ion. After laser cooling, an ultra-stable "clock laser" at 674 nm probes the $5s^2S_{1/2}$ to $4d^2D_{5/2}$ transition which has a natural linewidth of only 0.4 Hz. The clock laser is stabilized to a reference resonator made from Ultra Low Expansion (ULE) glass. Operation of the reference resonator in vacuum at a temperature where the ULE resonator has a vanishing thermal-expansion coefficient together with sufficient isolation of environmental disturbances (seismic, acoustic vibrations) enables the clock laser to reach a relative frequency instability of $\sim 10^{-16}$ during 1 s. After clock-laser interrogation the laser cooling is resumed. A clock transition to the $4d^2D_{5/2}$ state is detected as an absence of emitted fluorescence photons. A "state-clearout" laser at 1033 nm is then applied to return the ion to the laser cooling cycle.

When the clock laser is locked to the Sr^{+} clock transition at 444 779 044 095 484.6 Hz using the scheme outlined above, a frequency comb then makes the phase coherent leap from the optical domain (10^{15} Hz) to the radio-frequency domain (10^{9} Hz) of electronics.

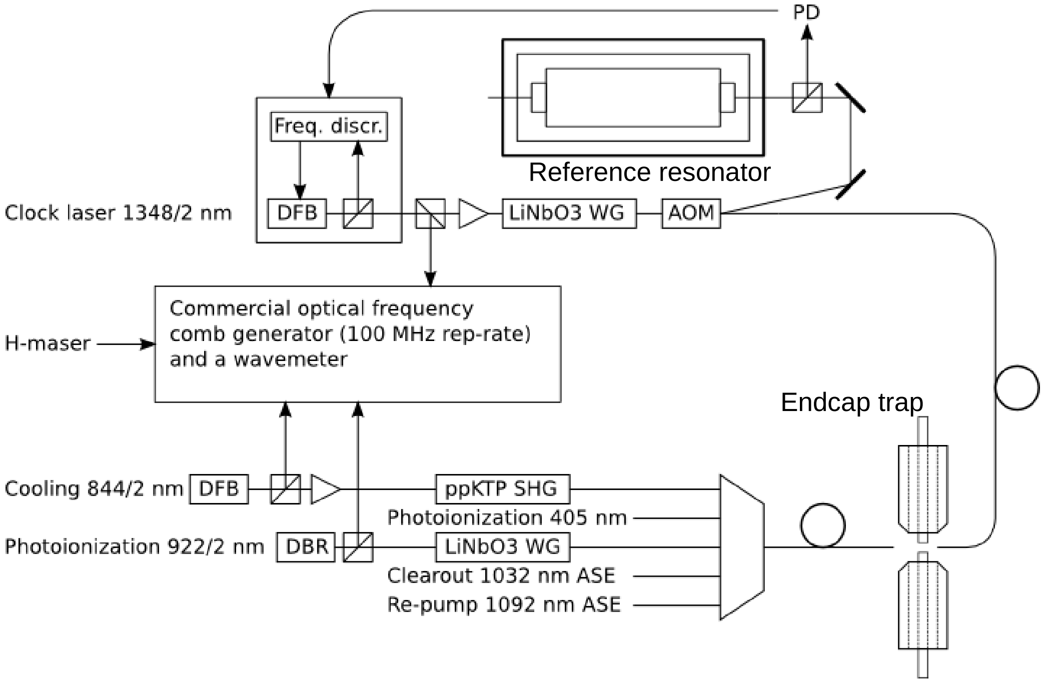

Fig. 1. Overview of the ion clock.

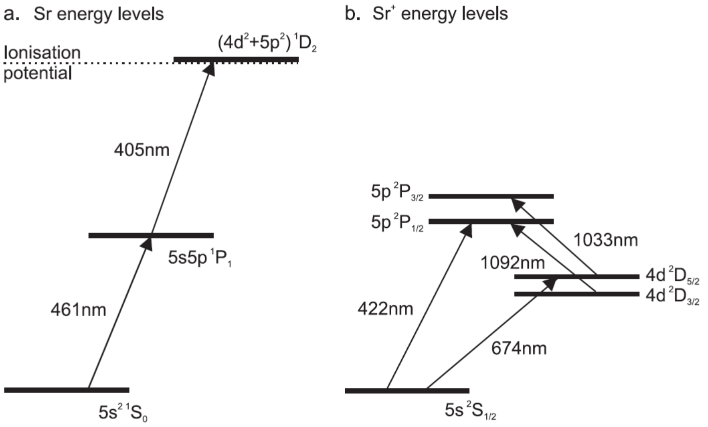

Fig. 2. Partial energy level diagram for (a) neutral strontium and (b) the Sr^+ ion.

3 Recent progress

An endcap ion trap has been designed in collaboration with NRC. Fig. 3 shows a photograph of the trap electrodes. The inner endcap electrodes have a diameter of 0.5 mm and the outer shield electrodes have an outside diameter of 2 mm. Blackbody radiation from the trap and its surroundings has been shown to cause one of the major systematic frequency shifts in the clock-transition [5]. For this reason we are studying the thermal behavior of several different trap geometries (with PTB, the National Physical Laboratory (NPL) in the UK, and Cesky Metrologicky Institut (CMI) in the Czech Republic) as well as ways to characterize the sensitivity and magnitude of the frequency shift.

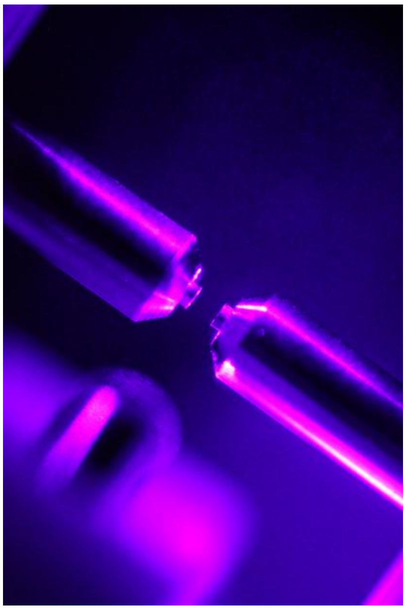

Fig. 3. MIKES endcap trap. A single Sr^+ ion will be captured and cooled between the electrodes. The trap is based on a design by Alan Madej (NRC). The distance between the electrodes is 0.56 mm.

The clock-laser reference resonator (Fig. 4) has been designed and assembled in collaboration with PTB. The vacuum enclosure and thermal shields for the cavity are currently being designed and manufactured. The frequency stability goal of the clock laser places strict limits on thermal, acoustic, and seismic disturbances to the resonator. We are working on reaching these goals by a combination of passive shielding mechanisms as well as active control.

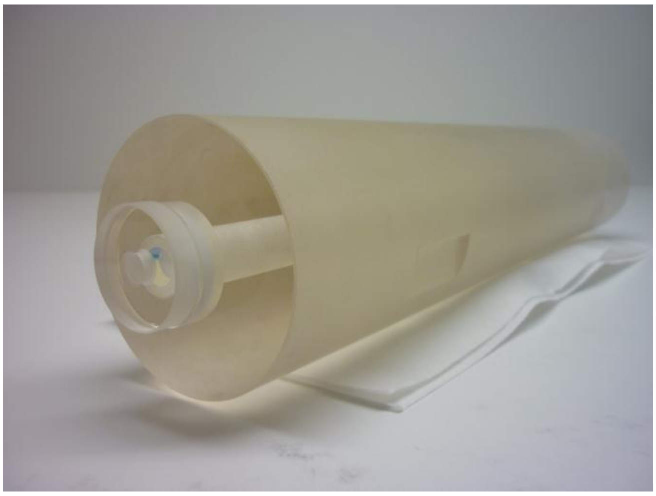

Fig. 4. Reference resonator for the clock laser. Fused silica mirrors are separated by a 30 cm long ULE-glass spacer.

In parallel with constructing the experimental setup, theoretical work on dark-state suppression and optimization of laser cooling and fluorescence in a trapped ion has been carried out. The theoretical simulations were compared to experimental data obtained at NRC [6]. As a novel way to avoid dark states from forming, we have recently proposed the use of an unpolarized, incoherent light source to drive the repumping transition in the $^{88}Sr^+$ ion [7]. Such a light source will be especially suitable for transportable clocks and space clocks.

4 Summary

The ultimate objective of the research at MIKES is to develop a transportable optical primary frequency standard which outperforms current cesium standards. This is being achieved through a compact combination of control electronics, physics package, and optical frequency counting.

Acknowledgements

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