32nd URSI GASS, Montreal, 19-26 August 2017

Construction of multiple Cs fountain clocks for use in time and frequency metrology laboratories

K. Szymaniec[(1)], R. Hendricks[(1)], F. Ozimek[(1)], P. Dunst[(2)], B. Nagorny[(2)], J. Nawrocki[(2)], S. Beattie[(3)], B. Jian[(3)], K. Gibble[(4)], and W. Chen[(5)]
(1) National Physical Laboratory, Teddington, UK
(2) Astrogeodynamical Observatory, Space Research Centre, Borowiec, Poland
(3) National Research Council, Ottawa, Canada
(4) Department of Physics, The Pennsylvania State University, University Park, USA
(5) National Institute of Metrology, Beijing, China

Laser-cooled Cs fountain clocks were developed as metrological instruments in the early 1990s. Two decades later they have become indispensable for the calibration and steering of UTC/TAI as well as in improving the stability of local realisations of UTC [1]. They have set limits on the variation of fundamental constants and underpinned the development of a new generation of atomic frequency standards. The construction and operation of all of the existing primary standards has been done with significant development efforts from individual laboratories. Here we report the design and construction of a several Cs fountain frequency standards at NPL for operation at other laboratories. Taking advantage of NPL's experience has shortened the development process and enable the delivery of fully functioning systems. In this paper we describe the design and performance of these new systems.

A cold-atom primary fountain frequency-standard consists of a physics package (a vacuum vessel with cooling, detection and flight chambers, and microwave cavities), an optical assembly producing light for atom cooling and detection, microwave sources, and an electronic control system. The physics package of the new systems is largely based on the approach first developed with NPL-CsF2, a single-stage magneto-optical trap as the cold atom source, optical pumping into the $m_F = 0$ clock state, and a cancellation of the collisional shift to enable high accuracy [2]. This approach provides a relatively compact transportable device that offers robust operation with minimal maintenance without compromising performance. Differences from NPL-CsF2 include the reduction of the overall size of the structure, rigid fixing of the vacuum vessel to a supporting frame, and pre-aligned optics for cooling and detection, which attach directly to the vessel. Ramsey interrogation is performed in a state-of-the-art microwave cavity that minimises the distributed cavity phase frequency shift [3], which was first implemented in the NPL-CsF3 fountain. The new optical assembly has a small footprint and excellent stability. It is modular, with commercially-available laser heads, a separate saturated spectroscopy module and a beam distribution module. These modules are connected by optical fibres to ease transportation and maintenance.

Two complete primary-standard systems and one standalone physics package have been built, with more anticipated in the near future. One system has been installed at CBK-AOS in Borowiec, Poland and is fully functional. The standalone physics package has been delivered to the NRC lab in Ottawa. The assembly work was carried out at NPL in the UK with participation of staff from the recipient labs. Prior to shipment, the instruments were tested to demonstrate the signal-to-noise ratio and short-term stability $\sigma_y(\tau)$ against one of the NPL hydrogen masers. We measured a short-term stability of $\sigma_y(\tau) = 1.7 \times 10^{-13}$ (1 s), almost entirely limited by local oscillator phase noise. This is typical for a Cs fountain standard using microwaves synthesized from a high-quality room-temperature quartz crystal. We also carried out a preliminary evaluation of key systematic effects, including frequency shifts due to the 2nd order Zeeman effect, blackbody radiation and cold collisions. The results suggest that the systems are capable of achieving an accuracy at the low 10^{-16} level – similar to that of the best established primary standards. Full accuracy evaluations of the delivered systems are underway.

1. J. Guena, M. Abgrall, D. Rovera, P. Laurent, B, Chupin, M. Lours, G. Santarelli, P. Rosenbusch, M. E. Tobar, R. Li, K. Gibble, A. Clairon, and S. Bize, "Progress in Atomic Fountains at LNE-SYRTE", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, **59**, 2012, pp. 391-410, doi: 10.1109/TUFFC.2012.2208

2. K. Szymaniec, S. N. Lea, K. Gibble, S. E. Park, K. Liu and P. Glowacki, "NPL Cs fountain frequency standards and the quest for the ultimate accuracy", *Journal of Physics: Conference Series*, **723**, 2016, 012003, doi: 10.1088/1742-6596/723/1/012003

3. K. Gibble, S. N. Lea, and K. Szymaniec, "A microwave cavity designed to minimize distributed cavity phase errors in a primary caesium frequency standard", *Conference on Precision Electromagnetic Measurement*, 2012.