Operation of NIM5 fountain with 1.5×10^{-15} uncertainty and design of new NIM6 in NIM

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Abstract. The cesium fountain primary frequency standard NIM5 started to operate since 2008 and started to report to BIPM since 2014. The major constrains of NIM5 is a relatively large background signal at the detection and microwave leakages due to the Ramsey cavity. A new fountain clock NIM6 is under construction. Besides some improvements on the vacuum system, a new Ramsey cavity and a microwave synthesizer are made to reduce the Type B uncertainty. Another feature of NIM6 is collecting atoms from a MOT loading optical molasses to get more atoms with a more uniform density distribution. With a new frequency synthesizer based on cryogenic sapphire oscillator (CSO), NIM6 is aiming to reach the quantum projection noise, thus leading to a reduced Type A uncertainty compared with NIM5.

1. Introduction

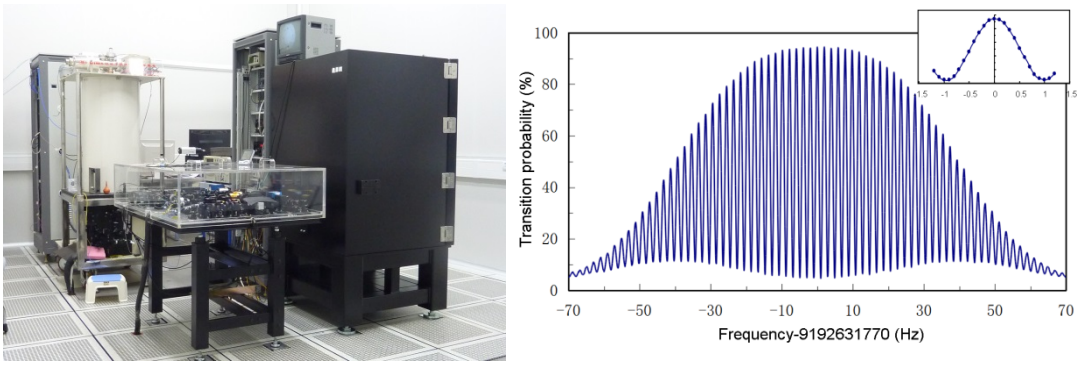
The cesium fountain primary frequency standard NIM5 started to operate since 2008 and 9 evaluations were reported to BIPM in 2014 and 2015 with a typical fractional frequency instability of 3×10^{-13} $(\tau/s)^{-1/2}$ and a Type B uncertainty of 1.4×10^{-15}, which was dominated by the microwave-related frequency shifts. Since its first operation, NIM5 underwent a series of improvements, including laser locking, adding a microwave interferometric switch and monitoring the transit phase in real time, reducing the microwave leakage effect by selecting atom signals in certain range, and so on. The major constrains of NIM5 now is a relatively large background signal at the detection and microwave leakages. A new cesium fountain clock NIM6 is under construction. Besides some improvements on the vacuum system, Ramsey cavity and microwave synthesizer to reduce the Type B uncertainty. NIM6 will collect atoms from a MOT loading optical molasses and increase number of atoms with optical pumping to get a better signal to noise ratio. The atom density will be more uniform compared with a 2D MOT loading optical molasses, and the diameter of the cloud can be adjusted by the intensity and detuning of lights during the post cooling to keep the collisional shift low. With a new cryogenic sapphire oscillator (CSO) based microwave frequency synthesizer, NIM6 is aiming to reach the quantum projection noise, thus lead to a reduced Type A uncertainty compared with NIM5.

2. The current status of NIM5

The NIM5 consists of a physical package, a laser-optics system and a microwave-electronics control system on two racks. The detailed description of NIM5 design is in the reference [1]. In a routine operation, atoms are collected in the optical molasses for 600 ms, then accelerated for 1 ms in a moving molasses, and further cooled for another 1.5 ms by adiabatically reducing the cooling beam intensities and red offsetting the frequencies by 60 MHz. The atoms are launched 810 mm above the centre of OM and cooled to a temperature of about 2 μK. The $|F=4, m_F=0\rangle$ atoms are transferred to the $|F=3, m_F=0\rangle$ state by a microwave pulse in the state selection cavity. Atoms remaining in the $|F=4\rangle$

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state are removed by the detection beam on the way up. A photo of NIM5 and a typical Ramsey fringe pattern is shown in the figure 1.



(a) (b)

Figure 1. (a) A photo of NIM5, (b) A typical Ramsey fringes with a frequency scanning step of 0.1 Hz and no averaging. The inset shows the central Ramsey fringe, and the FWHM width is around 1 Hz.

2.1. Statistical (type A) uncertainty of NIM5

In a routine evaluation period, NIM5 is running at high and low densities alternatively and typical relative frequency instabilities against a hydrogen maser are expressed in the figure 2.

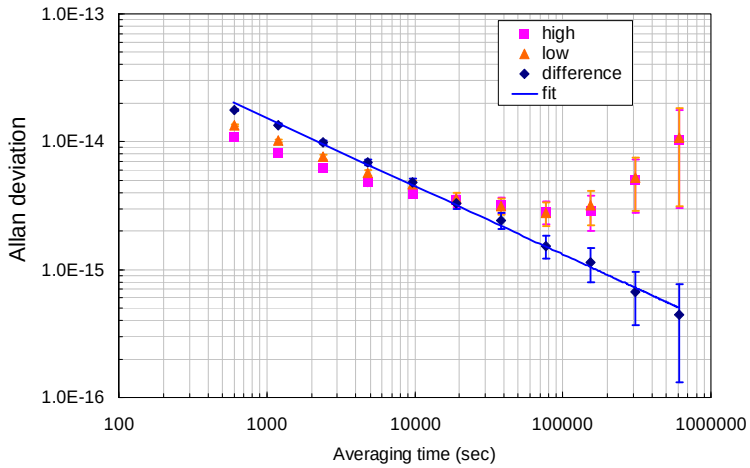


Figure 2. Standard Allan deviation $\sigma_y(\tau)$ of NIM5 measured against the H271 H-maser over a period of 15 days. The triangles and squares denote the stabilities at low and high atom density respectively. The diamonds represent the stabilities of the frequency difference between the low and high densities.

Collisional free frequency f_0 at zero density is derived by extrapolating the experimental data using:

$$f_0 = \frac{k\bar{f}_L - \bar{f}_H}{k-1} \tag{1}$$

Here k is the ratio between high and low densities (n_H/n_L), and f_H and f_L are the measured frequencies at high and low densities respectively. The uncertainty in eliminating the collisional frequency shift is derived as [2]:

$$\sigma_0^2 = \left(\frac{k}{k-1}\right)^2 \sigma_L^{\,2}(\tau_L) + \left(\frac{1}{k-1}\right)^2 \sigma_H^{\,2}(\tau_H) + \left(\frac{\bar{f}_L - \bar{f}_H}{(k-1)^2}\right)^2 \sigma_k^{\,2} \tag{2}$$

Here, the first two terms are related to the statistical frequency uncertainties at the low and high densities respectively, and the last term is the cold-collision-induced type B uncertainty, which includes the nonlinearity between the measured atom numbers and the average density as stated in the references [3, 4].
In the figure 2, it shows that for averaging time above 10^4 seconds, the instability is limited by the H-maser, with the Allen deviation drifting up for both cases. The contributions from the H-maser are common-mode, and rejected in the differential measurement provided that the switching rate between different densities is faster than the H-maser drifting. The frequency difference between high and low densities falls according to the square root of the averaging time. Assuming it keeps square root of averaging time law, 15 days of averaging will give instabilities of 0.26×10^{-15} and 0.31×10^{-15} for low and high densities. The combined type A uncertainty of NIM5 is calculated to be 0.67×10^{-15}.

2.2. A typical Type B uncertainty of NIM5

The major contributions to the frequency shifts are from the second-order Zeeman shift, microwave related frequency shift, the collisional shift (mentioned in the above section), AC Stark shift due to black-body radiation and the gravitational redshift [5-8]. A summary of a typical systematic frequency shift evaluations for NIM5 is listed in the Table 1 and the combined relative Type B uncertainty for NIM5 is evaluated to be about 1.4×10^{-15}.

Table 1. A typical uncertainty budget of NIM5

Physical Effect	Bias (10^{-15})	Uncertainty(10^{-15})
2nd order Zeeman	73.4	0.2
Collisional shift	-1.1*	0.2
Microwave interferometric switch	0.0	1.2
Microwave leakage	0.0	<0.1
DCP	0.0	0.5
Microwave spectral impurities	0.0	<0.1
Blackbody radiation	-16.2	0.1
Gravitational red shift	11.8	0.1
Majorana transition	0.0	<0.1
Light shift	0.0	<0.1
Rabi and Ramsey pulling	0.0	<0.1
Cavity pulling	0.0	<0.1
Collision with background gases	0.0	<0.1
Total	67.9*	1.4

* The collisional shift is calculated at low density.

The dominate frequency uncertainty of NIM5 comes from the microwave-power-related frequency shift. We found NIM5 has a relatively large microwave leakage, and an interferometric RF switched is applied to reduce this effect. The detailed evaluations of the NIM5 are stated in detail in [1].

3. The design of NIM6

A cutaway figure of the NIM6 physical package is shown in the figure 3. The entire physics package is enclosed in a layer of soft iron and the flight tube is surrounded with another three layers of μ metal shielding with a measured shield factor of about10^4. Atoms are collected in the lower MOT chamber and then launched to the upper optical molasses chamber with a small angle (10°) to reduce the background Cs atoms flying into the detection chamber directly. The lower MOT chamber is pumped by a 20 l/s ion pump and the upper OM chamber is pumped by a 40 l/s ion pump. A getter pump is on the top of the flight tube to keep the ultra-low pressure in the atom interrogation region. A new TE_{011} Ramsey cavity has been made with 4 rectangular waveguides to feed the microwaves in. A measured loaded Q factor is about 15000. Also, the new cavity is well sealed with indium to reduce the microwave leakage.

3.1. Isothermal liner heat pipe

The new fountain will be operated in a lab with temperature fluctuations less than 0.3 K, and no active temperature control system will be added outside the flight tube. Instead, an isothermal liner

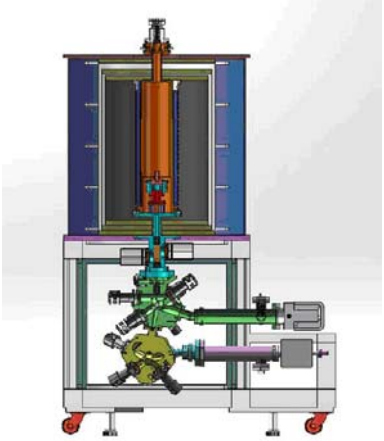


Figure 3. Schematic of the NIM6 cesium fountain clock.

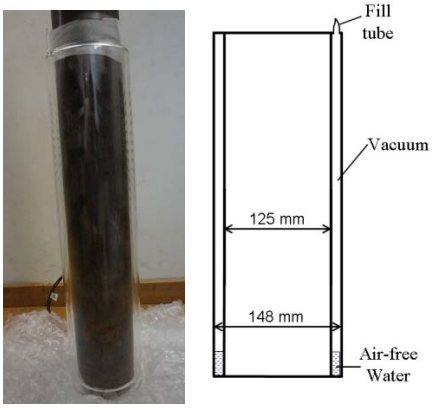


Figure 4. Picture of a mock up isothermal liner made of glass.

will surround the flight tube. It is a special type of heat pipe, made of a thin glass layer of vacuum tube filled with pure water. A mock up isothermal liner heat pipe is shown in the figure 4. High purity air-free water is filled in glass vacuum tube. When there is a temperature gradient, liquid water around the hot part absorbs heat, transforms into vapour and flows toward the condensate section (cold part). This phase transitions inside the heat pipe redissipate the heat, block corresponding changes in the inner chamber temperature, regulate thermal transport and dampen temperature oscillations. The performance of this mock-up isothermal liner is tested [9].It reduces the temperature fluctuations and improves the temperature gradients. With precision PT standard thermometers which have a temperature uncertainty of less than 10 mK, hopefully, the total temperature uncertainty will be less than 50 mK, keeping blackbody-radiation-induced frequency shift less than one part in 10^{16}.

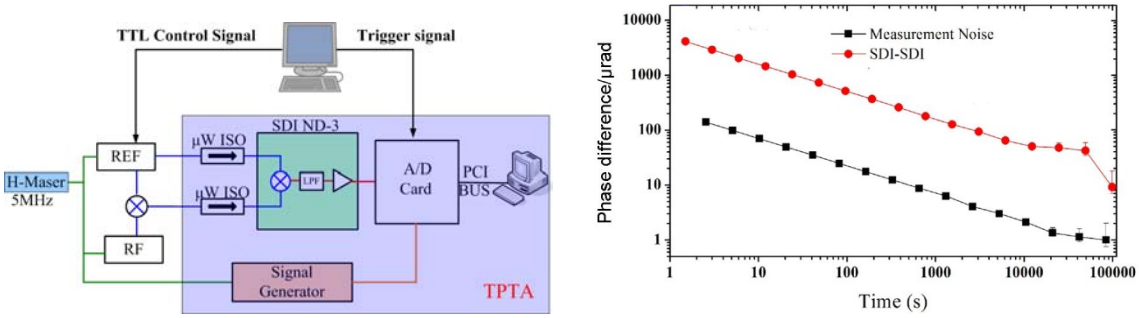
3.2. MOT loading optical molasses

In NIM6, Cs atoms will be collected in the lower MOT chamber and launched to the centre of the OM chamber. The separation between these two centres is 280 mm, the flying time is about50 ms with a launching velocity of 5.5 m/s. The final temperature of the cloud after launching can be adjusted by the intensity and detuning of the post cooling beams to make sure the cloud expanding enough when reaching the OM centre to keep collisional shift low. The velocity and temperature of atoms will be re-adjusted in the optical molasses region. Then, atoms are launched vertically to the flight tube. The advantage of this design is not only being able to collect more atoms compared to a direct optical molasses loading like NIM5, the background Cs gas in the detection chamber is also reduced due to a differential pumping. Furthermore, the atom density distribution is more uniform than loading OM from a 2D-MOT.Another feature here is that the cooling beams for MOT and OM are applied at different times. The lights for the MOT cooling and OM cooling can be provided by only one tapered amplifier with a total output power of about 800 mW.

3.3. Home-made microwave inspection system

The major uncertainty of NIM5 comes from an RF interferometric switch in the microwave synthesizer chain. A triggered-phase transient analyzer (TPTA) [10] was developed in our laboratory to measure the phase difference of the two Ramsey pulses. A schematic of TPTA is shown in figure 5a. The TPTA has the ability to measure the phase variations of two pulsed microwave switch a fixed interval in one cycle. Therefore, by measuring the phase discontinuity between two switching on states in one fountain cycle, the frequency uncertainty induced by interferometric switch or other components which affect the instability of the interrogation microwave phase can be checked. The

figure 5b shows the measurement noise floor of this inspection system and the results with two SDI microwave synthesizers.



(a) (b)

Figure 5 (a) The schematic of Triggered-Phase Transient Analyzer (TPTA).It consists of the microwave demodulator (ND-3 and microwave isolators), analog-to-digital sampling board, and a high performance computer. (b) Noise floor of the measurement system.

4. Summary and future plans

With NIM5 is operational. A new cesium fountain clock NIM6 is under construction in the National Institute of Metrology China, and aiming to operate in 2016. Besides some improvements on the design of the Ramsey cavity to reduce the distributed cavity phase shift and microwave leakage, NIM6 is also aiming to collect more atoms from a MOT loading optical molasses (OM) and optical pumping [11,12], leading to a better signal to noise ratio at the detection. A new cryogenic sapphire oscillator (CSO) based frequency synthesizer [13] and ultra-stable microwave generated from ultra-stable laser are also under developing to reduce the microwave phase noise in order to reach the quantum projection noise, thus leading to a lower Type A uncertainty of the new fountain.

Acknowledgments

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