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# Evaluation of the Cs atomic fountain frequency standard at NMIJ/AIST

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*Abstract* -**We have developed the first cesium atomic fountain frequency standard (JF-1) at National Metrology Institute of Japan. The accuracy evaluation is in progress and the uncertainty of the JF-1 is currently estimated to be 1.4 $\times$ $10^{-15}$.**
***Keywords* - Atomic fountain, frequency standard, accuracy**

## I. INTRODUCTION

Magneto-optical Trap (MOT) is now widely used as a common technique to produce cold atomic samples. In the Cs atomic fountain frequency standard, however, the high atomic density resulting from the MOT introduces a large collisional frequency shift and limits the attainable accuracy [1]. Therefore, an optical molasses is preferred to the MOT in spite of the small number of available atoms.

The JF-1 is operated using a MOT, because it provides large signal, which is advantageous for the frequency stability. In order to reduce the collisional frequency shift, we employed state selection recently. In addition, we developed two techniques to lower the initial density of the atomic cloud so that the collisional frequency shift is reduced without reducing the number of atoms. The first one is to use an atom trap that produces lower density atomic cloud than a normal MOT. The second one is to expand the atomic cloud quickly. These techniques allowed us to observe a linear relationship between the atom number and the collisional frequency shift and to estimate the collisional frequency shift with an uncertainty below $10^{-15}$ by extrapolation method.

In this paper, we present the recent results of the accuracy evaluation of the JF-1together with the methods used to reduce the collisional frequency shift.

## II. METHODS USED TO REDUCE THE COLLISIONAL FREQUENCY SHIFT

The techniques developed for the atomic density reduction could be employed without modifying the original design of the JF-1. The detail of the structure of the JF-1 is described elsewhere [2]. We first capture cesium atoms using a low density MOT in a vapor cell. Then, we expand the atomic cloud and launch the atoms upward using a moving molasses technique. The atoms are cooled to ~ 1.4 μK by polarization gradient cooling at the final phase of the launch and are state selected immediately priory to the Ramsey interrogation.

### *A. Rapid Expansion of an Atomic Cloud*

We expand the atomic cloud using the heating effect of the laser. The procedure is illustrated in Fig.1. When an atomic cloud is subjected to one- or two-dimensional optical molasses, it expands along the direction in which laser beam is absent. By applying two- and one-dimensional optical molasses sequentially, the atomic cloud is expanded three dimensionally in six milliseconds.

Usually, we expand the atomic cloud until the signal amplitude is reduced to ~ 80 %. The size of the atomic cloud after expansion has not been measured precisely. From the magnitude of the collisional frequency shift, we estimate that it is close to the size of the atomic cloud in the optical molasses.

In the illustration of Fig.1, the atomic cloud is expanded to a spherical shape. It is also possible to expand the atomic cloud to a cigarette shape so that it becomes larger than the intersection volume of the six laser beams. This will allow to reduce the collisional frequency shift below the value in the case of an optical molasses.

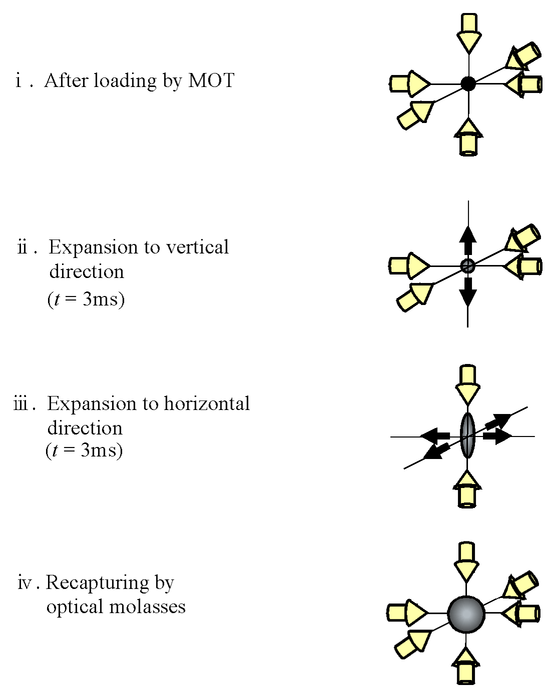


Fig.1 The process of expanding the atomic cloud by means of laser light

### *B. Low Density (multi-frequency) MOT*

The atom trap that is ideal for the Cs atomic fountain frequency standard is the one having a large capture velocity and a weak confining force. One method to realize such a trap is to use an octupole magnetic field instead of the quadratic magnetic field in the MOT [3]. Alternatively, we reduce the confining force of the MOT by using more than two laser frequencies.

The JF-1 uses a standard six beam MOT with four beams in the horizontal (*x*-*y*) plane and two beams in the vertical (*z*) direction as shown in Fig. 2 (a). The laser frequencies of the horizontal beams ($\nu_x = \nu_y$), the up going beam ($\Delta\nu_{z,\ \mathrm{up}}$) and the down going beam ($\Delta\nu_{z,\ \mathrm{down}}$) are adjusted independently by means of accousto-optical modulators in the light source system. Fig.2 (b) - (c) show the images of the atomic cloud obtained by operating the MOT in various conditions. In the normal condition, in which all the laser beams have same detuning, $\Delta\nu$ = -12 MHz, the MOT produces a spherical atomic cloud as shown in Fig. 2 (b). In Fig.2 (c), the confining force is weak along the vertical direction and a "stick shape" atomic cloud is obtained. The condition for this trap is; $\Delta\nu_x = \Delta\nu_y$ = -8 MHz and $\Delta\nu_z$ = -17 MHz, where $\Delta\nu_i$ ($i = x, y, z$) represents the detuning of the laser beam propagating in the *i*-direction. In Fig.2 (d), the confining force is weak along the horizontal direction and a "disk shape" atomic cloud is obtained. The condition for this trap is; $\Delta\nu_x = \Delta\nu_y$ = -12 MHz, $\Delta\nu_{z,\ \mathrm{up}}$ = -13 MHz and $\Delta\nu_{z,\ \mathrm{down}}$ = -11 MHz. In this case, the atomic cloud is located a few mm below the center of the trap. In these traps, the number of atoms varies depending on the parameter and can be same as that in the normal MOT. We currently operate the JF-1 using the third type (disk shape) of MOT, whose atomic density is estimated to be a few times smaller than the normal MOT.

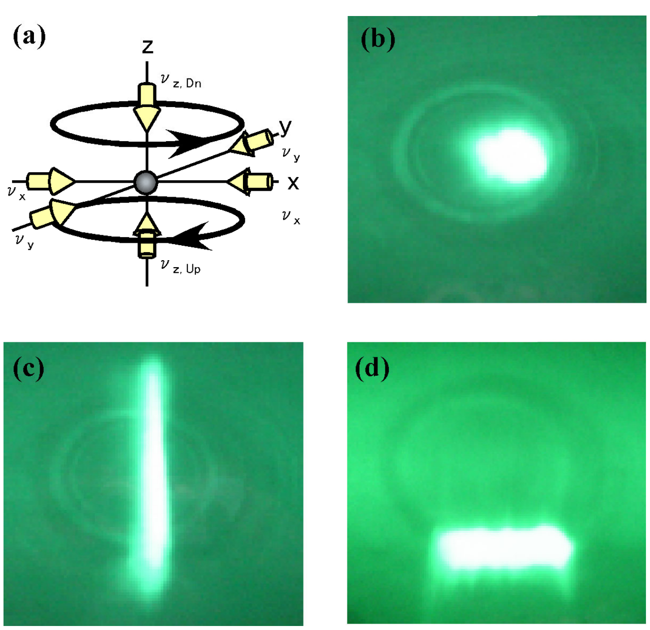

Fig.2. Configuration of the MOT (a) and the images of the atomic cloud in different operating conditions (b)-(d)

The characteristics of the multi-frequency MOT are currently under study. Since the confining force of the new MOT is weak only in one or two dimension, the reduction of the atomic density is not remarkable. If sufficiently low atomic density is achieved with the new MOT, it will not be necessary to expand the atomic cloud. Aiming to reduce the atomic density by one or two orders of magnitude, we are trying to reduce the confining force of the MOT in all directions by using phase modulated laser beams.

### *C. State selection*

The atoms in the $|F = 4, m = 0\rangle$ state are transferred to the $|F = 3, m = 0\rangle$ state inside the interaction chamber, in which the transition was excited using a $TE_{011}$ microwave cavity. The atoms remaining in the $F = 4$ state are rejected by a resonant laser pulse. The number of atom is actively stabilized by controlling the microwave power applied to the state selection cavity. Fig. 3 shows the typical Ramsey fringes (FWHM linewidth = 0.85 Hz) of the clock transition, to which the microwave frequency is stabilized. The signal amplitudes of other transitions from the $m \neq 0$ states are smaller than 2 %.

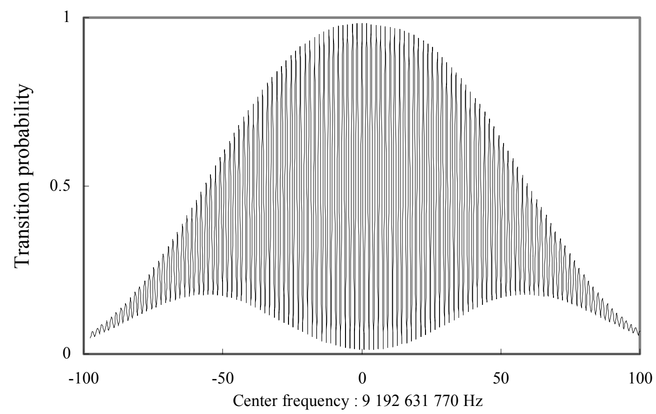

Fig.3. Ramsey fringes of the clock transition observed with state selection

## III. UNCERTAINTY OF THE JF-1

We started the evaluation of the JF-1 about two years ago. The preliminary results including the measurements of the second order Zeeman shift and the gravitational red shift are already reported [4]. Here, we present the estimation of the collisional frequency shift and the distributed cavity phase shift. We planed to measure the collisional frequency shift after replacing a microwave synthesizer to a new one, which has an exceptionally low phase noise and high temperature stability [5]. However, since there was a room for the improvement in the performance, we decided to make a modification to the new synthesizer and performed the measurements using an old synthesizer having a relatively high phase noise.

### *A. Cold Collision Frequency Shift*

We studied the atom number dependence of the frequency using a differential measurement. The atomic fountain was operated switching the atom number between two values every four launching cycles and the frequency difference between the two conditions were measured. The value in one condition was $N = 10$ and the value in another condition was varied from $N = 20$ to 80, where $N$ represents the relative number of detected atoms. The averaging time was about 47 hours in one measurement and it took three weeks to take all the data. In Fig. 4, the frequency difference, $\Delta \equiv f(N) - f(10)$, is plotted as a function of $N$, where $f(N)$ is the frequency of the atomic fountain operated with an atom number of $N$. The observed linear relationship between the atom number and the frequency allows estimation of the frequency at $N = 0$ by extrapolation. By the least square fit of a straight line passing the point $(N, \Delta) = (10, 0)$, the slope is determined as $\alpha = -0.27 \pm 0.05$ and $f(N = 0)$ is calculated to be $2.7 \times 10^{-15}$.

When we measure the frequency of the TAI, the JF-1 is operated with an atom number of $N = 10$. The relative collisional frequency shift at this condition is estimated to be $\Delta f / f = -2.7 \times 10^{-15}$ with an uncertainty of $0.6 \times 10^{-15}$ (22 %). The uncertainty takes into account the statistical uncertainty of the slope determination (20 %) and the temporal variation of the proportional constant between the atom number and the density (10 %).

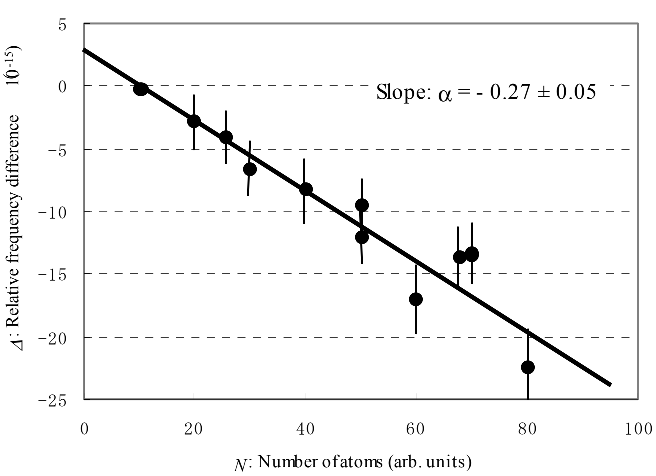


Fig.4. Atom number dependence of the frequency of the JF-1 measured by differential measurement; reference is $N = 10$. The line is a least square fit to the data.

In these measurements, the frequency stability of the JF-1 was $\sigma_y(\tau) = (5 \sim 6) \times 10^{-13} \times \tau^{-1/2}$ mainly limited by the local oscillator phase noise. For comparison, we operated the JF-1 using an optical molasses with lin ⊥ lin polarization. The best frequency stability was $\sigma_y(\tau) = 8 \times 10^{-13} \times \tau^{-1/2}$ with the maximum atom number of $N = 5$. This implies that much longer time is required for the estimation of the collisional frequency shift if an optical molasses is used instead of the MOT.

### *C. Distributed Cavity Phase Shift*

The $TE_{011}$ microwave cavity used for the Ramsey excitation has a central hole of $\phi = 10$mm and a quality factor of $Q = 12{,}000$. The microwave field is excited symmetrically using two feeds. We calculated the phase distribution in the microwave cavity using a finite element method. The central axis of the cavity is chosen as $z$-axis and the line connecting the two feeds is chosen as $x$-axis. Fig.5 (a) and (b) show the transversal ($x$-$y$ plane) phase distribution at $z = 0$ and vertical ($x$-$z$ plane) phase distribution at $y = 0$, respectively.

The large cloud size ($\phi > 4$ mm), which is realized by the expansion technique, is advantageous for the distributed cavity phase shift because the influence of the phase distribution is reduced by the averaging effect. The calculation taking into account the atom trajectory estimates the uncertainty of the distributed cavity phase shift to be smaller than $0.5 \times 10^{-15}$.±

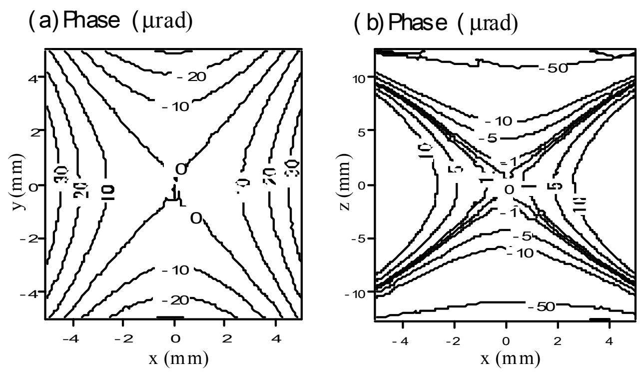


Fig.5. Distribution of the microwave phase in the (a) horizontal plane and (b) vertical plane

## IV. CONCLUSION

The current uncertainty budget of the JF-1 is summarized in Table 1. At present, the accuracy evaluation is limited by the available microwave power and the absence of a stable reference. We have just finished the modification of the new microwave synthesizer and replacement of the synthesizer can be done immediately. Therefore, the values expected after the replacement of the microwave synthesizer are presented in Table 1. A second atomic fountain, which has been constructed in the same design as the first one, is going to be operational in a few months. We expect to reduce the uncertainty below $1 \times 10^{-15}$ by the experiments using two atomic fountains.

We started the comparison of the JF-1 with the international atomic time scale (TAI). Up to now, enough data to confirm the estimated uncertainty of the JF-1 have not been obtained because the frequency measurements, which have to last at least five days successively, are often interrupted by the earthquakes, which occur extraordinarily frequently this year.

TABLE I. Current uncertainty budget of JF-1

| Effect | Magnitude ($\times 10^{-15}$) | Uncertainty ($\times 10^{-15}$) |
|---|---|---|
| Second order Zeeman | 59.6 | 0.3 |
| Blackbody | -17.1 | 0.4 |
| Cold collision | -2.7 | 0.6 |
| Gravitational Redshift | 1.5 | < 0.1 |
| Distributed Cavity Phase | – | 0.5 |
| Cavity pulling | – | < 0.1 |
| Light Shift | – | < 0.1 |
| Background Gas Collision | – | < 0.3 |
| Spectral Impurity | – | < 0.1* |
| Microwave Leakage | | |
| Ramsey Pulling, Rabi Pulling | – | < 1* |
| Majorana Transition | | |
| Total Uncertainty | | 1.4* |

*Projected value after replacement of the microwave synthesizer

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