The Second Cesium Fountain Clock NIM5: Construction and the First Evaluation in 2007

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***Abstract*—We have locked the 9.19 GHz reference frequency to the MOT and OM clock transition respectively on our second Cesium fountain clock NIM5. A master laser is stabilized through AOM frequency shift/modulation to produce modulation-free output for injection locking and for detections. A slave laser, a single-pass AOM and a custom SM PM 1x3 fiber-optics integrated coupler compose each of the identical two MOT/OM optical units (upward and downward). Each fiber outlet from the coupler provides more than 11 mW optical power for one of the three MOT/OM laser beams. The NIM5 adopts the (1,1,1) MOT/OM configuration with less than 2 arc minutes angle accuracy to load atoms by MOT or by direct OM. An alternative sampling-comparison is utilized to improve the frequency locking stability by reducing the locking period to one fountain circle for NIM5. The first evaluation of NIM5 MOT operation in April to May of 2007 showed a combined uncertainty of 3E-15 and an evaluation of NIM5 OM is on its way.**

I. INTRODUCTION

The first laser cooling - Cesium fountain clock NIM4 at NIM has been running since August, 2005 with an operation ratio (life time) of 95% (provides valid frequency data in 95 days per 100 days) and uncertainty of 5E-15 [1,2].

From 2004 we started to build the second transportable Cs fountain clock NIM5. The NIM5 is designed to operate accurately, robustly, continuously and to be transportable.

In this paper we report mainly the construction and preliminary results of NIM5 that are distinct from NIM4 because in substance NIM4 followed the design of fountain clock CsF1 of BNM-SYRTE France and the latter has been described in detail in many papers [see 3].

II. DESIGN AND CONSTRUCTION

The NIM5 consists of a 0.6 x 0.8 x 1.8 m^3 physical package, a 1.2 x 0.9 m^2 optical bench and two 0.6 x 0.6 x 1.8 m^3 electrical racks. All of the four units are connected with either optical fibers or electric cables from each other.

A. Physical part

The NIM5 clock adopts the (1,1,1) MOT/OM (Magneto Optical Trap / Optical Molasses) configuration and Figure 1 shows the drawing of its physical package.

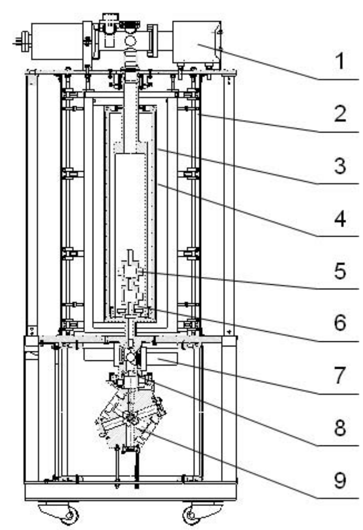

Figure 1. Physical part: 1, Ion pump; 2, soft iron shield; 3, μ-metal shields; 4, C-field coil; 5, Ramsey cavity; 6, upper selection cavity; 7, detection; 8, lower selection cavity; 9 MOT/OM.

The MOT/OM body was machined from an Aluminum block. The angles of the body were measured after machining and manually polished when necessary. Each MOT/OM laser beam of the six is delivered through fiber and collimated by a collimator after the fiber. Direction of each collimated MOT/OM beam was pre-adjusted. These procedures ensure the angles of the six MOT/OM beams to be accurate less than 2 arc minute among them and relative to the axis of fountain tube mounted on the top of the detecting body.

The magnetic shields consist of one soft iron cylinder and four μ-metal ones, surrounding the OFC (oxygen-free copper) fountain tube.

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An Aluminum detection body was put in between the fountain tube on top and the MOT/OM body below.

Two OFC TE_{011} microwave cavities, top one as the Ramsey cavity and lower as upper selective cavity (back-up), were positioned in the lower part within the fountain tube. Another lower OFC selective cavity (also TE_{011}) was inserted into the top part of the MOT/OM body just underneath the detection body.

Both ion pumps are connected to the MOT chamber in NIM4. While in NIN5 one pump is connected to the MOT/OM and another moved to the top of the fountain tube to keep the better vacuum (1E-8 Pa) in the upper part of the fountain tube where the atoms reach their fountain movement apogee.

B. Laser and optical part

An external cavity LD (ECDL) with 40 mW output as the master laser is frequency shifted and square-wave modulated by an AOM (Acoustic Optical Modulator) then digitally locked to the |F=4> - |F'=5> and |F=4> - |F'=4> crossover transition of the Cesium spectrum [4]. One 140 mW F-P slave diode laser, one single-pass AOM and one custom 1x3 SM (single mode) PM (polarization maintenance) fiber-optics integrated coupler compose either the up or down (1,1,1) MOT/OM laser optics unit. The PM characteristic of the fiber-optics coupler was tested and change of the splitting ratio with time is less than 0.5% over 3 months. The launch detuning frequency with (1,1,1) MOT/OM is 0.577 times smaller than with (0,0,1). Thanks to the smaller detuning frequency the coupling efficiency of the light into fiber changes only 3% between the atom preparing and launching even with the single-pass AOM to conduct the detuning. A modulation-free light with more than 11 mW is available from each of the three outlets of the coupler and collimated by a collimator to be as one of the six MOT/OM beams with diameter of 32 mm.

A collimated beam of 32 mm diameter and 12 mW power from the master laser is cleaved into two 3x20 mm^2 detection beams with vertical distance of 16 mm between each other.

A fluorescence collection optics unit, composed of a reflection mirror and a focus optics, doubles the detection efficiency to about 8% on NIM4 to enhance the S/N of the signal. On NIM5 only a regular focus optics is used for the sake of improving the correlation between the detections of the atom numbers in |F=4> and |F=3> state and reducing the vertical dimension of the detection zone but at the sacrifice of detection efficiency of above 5%.

C. Electronic - microwave and control part

The 9.19 GHz reference microwave frequency, synchronized to an H-maser H2, is square-wave modulated around the central frequency of the Ramsey central fringe to produce the transition probability comparisons on both sides of the Ramsey fringe. A PC servo locks the reference frequency according to probability comparisons with alternative sampling order so the servo-period is reduced to one fountain circle. This alternative data sampling - treating technique reduces the dead time in servo process (Dick effect) so improves the locking stability [5].

III. EXPERIMENTS AND THE FIRST EVALUATION WITH MOT

The atoms can be prepared with MOT (Magneto Optical Trap) or direct OM (Optical Molasses) on NIM5 rather than only MOT on NIM4.

NIM5 loads about 2E8 or 3E7 atoms by MOT or direct OM, the atoms were further cooled to below 2 μK and launched up to 81 cm high (30 cm above the center of the Ramsey microwave cavity). NIM5 loaded about 7 times less atoms by direct OM than MOT but fortunately for the less number of OM atoms the S/N (signal to noise ratio) is acceptable.

We found that the launching frequency detuning $\Delta\nu$ and -$\Delta\nu$ must be phase-locked to produce the stably moving OM but the average launching frequency, $\nu_L=(\nu_L+\Delta\nu) + (\nu_L-\Delta\nu)$, has not to be equal to the loading/cooling frequency ν_P. Instead it is better to have $\nu_P - \nu_L = 1$ MHz in our NIM5.

The C-field was mapped by the magneto-sensitive Rabi transition |F=3, m=1> to |F'=4, m=1> and is shown in Figure 2. The homogeneity of the C-field is less than 1 nT in the height of 56 - 82 cm above the MOT/OM center.

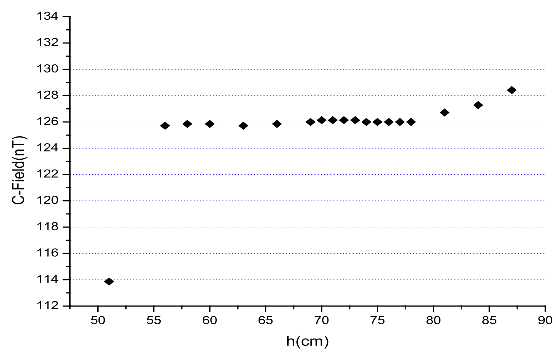


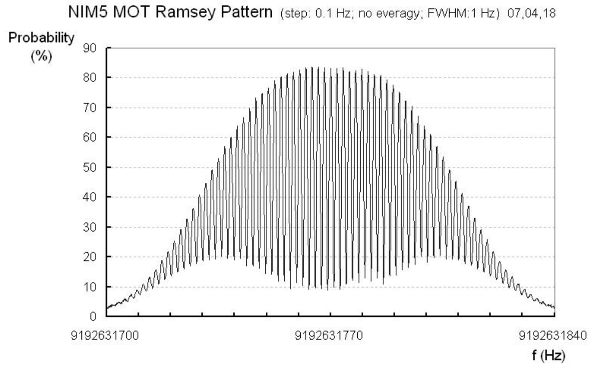
Figure 2. C-field map (without the compensation field on): Ramsey cavity center: 50.8 cm; top of the waveguide: 58.3 cm.

In the end of 2006 and beginning of 2007 we obtained the MOT and OM Ramsey patterns respectively on NIM5. Since then the NIM5 has been operating almost every day.

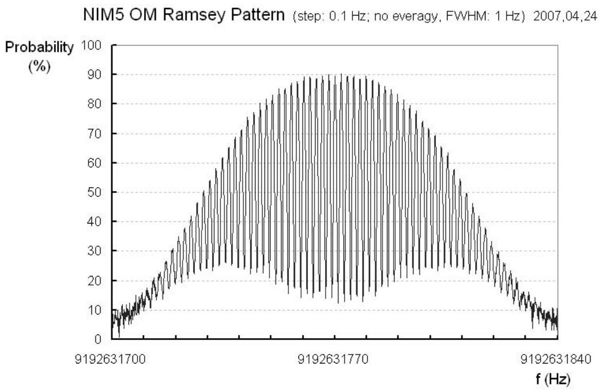
The atoms is launched up to 81 cm from the MOT/OM center and a typical MOT and OM Ramsey pattern with frequency scanning step of 0.1 Hz and no average is shown in Figure 3. More than 67 fringes could be recognized in the OM Ramsey pattern with FWHM (full width at half maximum) of 1 Hz and S/N of 400.

A continuous 10-day MOT frequency locking of the NIM5 gave a frequency stability of 2.6×10^{-15}/d (including the H-maser frequency drift).

For evaluating the atom collision frequency shift the density of the atom cloud is changed by 3 - 4 times by means of controlling the selection microwave power and the frequency stability at the low density mode is not deteriorated too much even for the direct OM. The low density operation is used for the day to day operation and only for the collision shift evaluation the high density is used. On NIM4 the ratio of high/low MOT density is 2 and the high density mode is used as the standard.



(a)



(b)

Figure 3. NIM5 MOT (a) and direct OM Ramsey pattern (b) (step: 0.1 Hz; no average; FWHM: 1 Hz).

As mentioned above there are two selective microwave cavities, the upper one located in the fountain tube above the detection zone and the lower in between the detection zone and the MOT/OM, and two push beams, one vertical and one horizontal (the upper detection beam). Using the lower selective cavity and the horizontal push beam has been chosen as the operation standard mode and the experiments reported below in this paper have been performed using this standard mode.

It took us four weeks to perform the first MOT operation frequency shift evaluations on NIM5 with a combined uncertainty of 3E-15 and the results are shown in Table 1. Obviously the microwave power shift uncertainty of 2.4E-15 dominates the error budget. The P_0, $P_0/2$, $3P_0/2$ microwave power (P_0 is the optimum Ramsey power) has been used to evaluate the power shift because it is demonstrated recently that the linearity of frequency shift versus microwave power is valid only for the power around P_0 [6]. Unfortunately the frequency stability with $P_0/2$ or $3P_0/2$ on NIM5 is deteriorated significantly introducing a larger evaluation uncertainty as shown in Table 1. In the past the extrapolating from the P_0 and $9P_0$ frequency was used in NIM4's evaluation. We tried to use the old P_0 and $9P_0$ technique to evaluate the power shift for NIM5 MOT the uncertainty turned out to be as less as 5E-16 and in this case the combined uncertainty of NIM5 MOT would be 1.22E-15.

TABLE I. THE FIRST FREQUENCY SHIFT EVALUATION OF NIM5 OPERATING WITH MOT IN APRIL - MAY 2007 (FWHM OF RAMSEY FRINGE: 1 HZ).

	Physical Effect	Shift (10^{-15})	Uncert. (10^{-15})	
1	2nd Zeeman:	74.83	0.4	H_C=126.85 nT
2	Cold collision:	-2.89	0.9	
3	Microwave power:	-2.54	2.4	
4	Blackbody:	-16	0.5	Cavity T: 23°C
5	Gravitation:	3.8	0.1	Above sea: 35m
6	Majorana:	0.0	0.0	
7	Light shift:	0.0	0.1	
8	Cavity pulling:	0.0	0.1	
9	Cavity phase difference:	0.0	0.1	Phase difference: 4 μradian
	Combined:	57.2	2.65	

The MOT frequency of NIM5 and NIM4 has been compared and the difference is less than 1E-14.

The NIM5 is being operated with the direct OM mode with a frequency stability of 3E-15/d. We are optimizing its operation and a first evaluation of NIM5 OM operation is on the way.

IV. DISCUSSION

The NIM5 is supposed to be able to resume normal operation after adjustments if it undergoes transportation so NIM5 can be moved in future to the NIM new campus 30 km away from the present site.

The NIM5 MOT frequency was evaluated for the first time with uncertainty of 3E-15. The NIM5 is running with direct OM loading and the evaluation of NIM5 OM operation is on the way at present.

The NIM5 clock will run side by side with NIM4 and they will be compared from each other to form the primary frequency standard for this country.

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